THE PRIVATE SECTOR'S CAPACITY TO MANAGE CLIMATE RISKS AND FINANCE CARBON NEUTRAL ENERGY INFRASTRUCTURE

by

Craig A. Hart

B.A., University of California at Berkeley, 1990
J.D., University of California at Berkeley, 1994
M.A., New York University, 1997

Submitted to the Interdepartmental Committee in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Energy & Environment: Technology, Policy and Finance

at the

Massachusetts Institute of Technology

February 2007

Signature of Author ....
Craig A. Hart
September 19, 2006

Certified by ....
Nazli Choucri
Professor of Political Science
Massachusetts Institute of Technology
Thesis Supervisor

Accepted by ....
Isaac M. Colbert
Dean for Graduate Students
Massachusetts Institute of Technology

V. 1

THE PRIVATE SECTOR'S CAPACITY TO MANAGE CLIMATE RISKS AND FINANCE CARBON NEUTRAL ENERGY INFRASTRUCTURE

By

Craig A. Hart

Submitted to the Interdepartmental Committee
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Energy & Environment: Technology, Policy and Finance

DISSERTATION ABSTRACT

This dissertation examines the financial aspects of climate change relating to the private sector's capacity to manage climate risks and finance carbon neutral energy infrastructure. The dissertation examines (a) potential risks posed by climate change to private sector investment in critical infrastructure, (b) the potential effectiveness of standard private contractual methods for mitigating risks posed by climate change, (c) the capacity of private capital markets to finance carbon neutral energy infrastructure, and (d) the potential for market failure in developing carbon neutral energy infrastructure.

The dissertation first identifies climate risks to infrastructure by examining scientific evidence concerning climate change from studies and atmospheric models. Based on this data, it modifies a framework widely used by practitioners in the finance field for purposes of evaluating financial risks in infrastructure projects. Using the modified risk assessment framework, the dissertation identifies financial risks posed by climate change to financing and developing infrastructure.

The dissertation then assesses whether these climate risks can be mitigated and managed by employing private contractual methods typically used in infrastructure finance, such as insurance, derivatives, and carbon offsets. Each contract is evaluated based on the following six criteria: (a) scope of risk covered, (b) geographic coverage, (c) contract duration, (d) availability, (e) price, and (f) market capacity. Based on these criteria, the potential for these private contractual methods to address long-term climate change risks is assessed.

The evaluation of climate risk and methods to address these risks are similar to the identification, allocation, and mitigation of risks that is commonly preformed by banks and project sponsors in order to evaluate the risks of an infrastructure investment.

The conclusion of the dissertation's analysis is that climate risks will pose fundamental problems for infrastructure finance, including that no party may be best positioned to accept and mitigate climate risks, and that private contractual methods typically used by the private sector will be inadequate to address climate risks in a comprehensive and cost-effective manner. If this is true, climate risks should reduce the private sector's willingness or ability to invest in or develop infrastructure.

The risk assessment analysis will be supplemented by three case studies focusing on different financial aspects of climate change in sectors of the economy that are critical to developing carbon

neutral energy infrastructure: (i) the capacity of capital markets to supply adequate investment capital to develop a portfolio of carbon neutral electricity infrastructure providing 10-15 TW of power within a 50-year period, (ii) the financial effects of increasingly intense storms on the electric utility industry in the Eastern United States from 1990 to 2005, and (iii) the financial effects of the increasing frequency and intensity of natural catastrophic events on the insurance industry from the 1970's to 2005, especially in connection with underwriting risks for energy infrastructure.

The research is supported by a survey of the insurance, derivatives, banking, and energy industries with respect to their use of private contractual risk management methods and an examination of the models used to price these contractual instruments.

This dissertation is intended to contribute to economic and policy literature concerning climate change by providing an analysis of how the financial aspects of climate change might influence the capacity and willingness of the private sector to invest in carbon neutral energy infrastructure.

Committee:

Nazli Choucri, Committee Chair
Professor of Political Science
Massachusetts Institute of Technology

Kelly Sims Gallagher
Director, Energy Technology Innovation Project
John F. Kennedy School of Government, Harvard University

Gordon Kaufman
Morris A. Adelman School of Management
Sloan School of Business
Massachusetts Institute of Technology

Jefferson Tester
H.P. Meissner Professor of Chemical Engineering
Massachusetts Institute of Technology

Acknowledgements

This dissertation was completed under an MIT Interdepartmental Doctoral Program in Energy & Environment: Technology, Policy and Finance.

My committee provided the primary faculty supervision and support for this dissertation. Nazli Choucri, Kelly Sims Gallagher, Gordon Kaufman, and Jefferson Tester together shared their time and expertise in the areas of energy and environmental policy, energy resource economics, and energy technology and engineering. The committee provided guidance in defining the dissertation's scope, questions, methodology, overall research plan, and selection of cases. They reviewed outlines and draft chapters, and provided feedback on an ongoing basis. Their support was essential for completing the dissertation according to the research plan and schedule.

In addition to my committee, faculty in various disciplines supported my research by reviewing dissertation research proposals and providing comments on earlier chapter drafts in their particular areas of expertise. They include Professor Nicholas Ashford of MIT's Technology and Law Program, Mr. Stephen Connors of MIT's Analysis Group for Regional Energy Alternatives, Dr. Christopher Forest of the MIT Department of Earth, Atmospheric and Planetary Sciences, and Professor Fred Moavenzadeh of the MIT Department of Civil and Environmental Engineering.

Several administrators deserve special mention. Dean Issac M. Colbert, Dean for Graduate Students, provided his time, guidance and support for completing my degree though MIT's Interdepartmental Doctoral Program. Mr. Ed Ballo, Professor Roger Petersen, and Ms. Susan Twarog of MIT provided their guidance and assistance with the administrative aspects of completing an interdepartmental doctoral degree.

Fellow students participating in the MIT Joint Program on the Science and Policy of Global Change provided a sounding board and intellectual forum that contributed to my work on this dissertation. I am especially grateful to Jason Cohen and James McFarland for their time and suggestions in our various discussions.

Finally, Professors Richard Buxbaum and Melvin Eisenberg of Boalt Hall School of Law (University of California at Berkeley), and Professor Yuk Yung of the California Institute of Technology provided guidance in my decision to pursue a doctoral degree in the energy and climate change field.

Table of Contents

ABSTRACT 3
ACKNOWLEDGEMENTS 5
LIST OF APPENDICES 9
LIST OF FIGURES 10
LIST OF TABLES 12
LIST OF CLIMATE RISK DIAGRAMS 14
LIST OF ACRONYMS 15

1 INTRODUCTION 16

1.1 DISSERTATION QUESTIONS AND HYPOTHESIS 17
1.2 NOTE ON TERMINOLOGY 17
1.3 OVERVIEW OF DISSERTATION AND METHODOLOGY 18
1.4 CONTRIBUTIONS TO KNOWLEDGE 20
1.5 NOTE ON SOURCES AND CITATIONS 22

2 ENERGY AND CLIMATE CHANGE CHALLENGES OF THE 21ST CENTURY 23

2.1 TIMING OF TRANSITION TO CARBON NEUTRAL INFRASTRUCTURE AND PETROLEUM RESOURCES 23
2.2 THE PRIVATE SECTOR'S ROLE IN DEVELOPING INFRASTRUCTURE 27
2.3 THE SHRINKING ROLE OF GOVERNMENT IN INFRASTRUCTURE DEVELOPMENT 31
2.4 RESOURCES REQUIRED FOR DEVELOPING CARBON NEUTRAL ENERGY INFRASTRUCTURE 34
2.5 THE PRIVATE SECTOR'S CAPACITY TO TRANSITION TO CARBON NEUTRAL INFRASTRUCTURE 43
2.6 CLIMATE RISK AND DEVELOPMENT OF INFRASTRUCTURE 46

3 CLIMATE CHANGE RISKS 49

3.1 OVERVIEW OF CLIMATE CHANGE SCIENCE 49
3.2 CLIMATE CHANGE PRIMARY PHYSICAL EFFECTS 58
3.2.1 Higher Minimum and Maximum Temperatures 59
3.2.2 More Intense Flooding and Drought 61
3.2.3 Increased Summer Drying and Wildfires 65
3.2.4 Increased Storm Intensity 66
3.2.5 Sea Level Rise 68
3.3 SUMMARY OF CLIMATE CHANGE RISKS 70

4 CLIMATE RISKS TO FINANCING INFRASTRUCTURE 72

4.1 CONVENTIONAL INFRASTRUCTURE FINANCE RISK ASSESSMENT FRAMEWORK 73
4.2 REEVALUATING THE CONVENTIONAL INFRASTRUCTURE FINANCE RISK FRAMEWORK 76
4.3 VALIDATING THE CLIMATE RISK ASSESSMENT MATRIX 78
4.4 CLIMATE RISKS AND DYNAMIC INTERACTIONS 84
4.4.1 Supply Risk 85
4.4.2 Market Risk 88
4.4.3 Technology-Engineering-Infrastructure Risk Cluster 90
4.4.3.1 Technology Risk 90
4.4.3.2 Engineering Risk 92
4.4.3.3 Infrastructure Risk 94
4.4.4 Environmental Regulatory Risks 96
4.4.4.1 Regulatory Risk 96
4.4.4.2 Recovery Risk 97
4.4.4.3 Litigation Risk 98
4.4.5 Political Risk 101
4.4.5.1 Unrest 102
4.4.5.2 Deadlock/Uncertainty 105

4.4.5.3 Intermittent or Incomplete Institutional Arrangements 106
4.4.6 Legal Risk 107
4.4.7 Force Majeure Risk 110
4.4.8 Operating Risk – Cost 112
4.4.9 Operating Risk – Management Capacity 114
4.4.10 Capital Markets/Finance Risk 116
4.4.11 Participant Risk 119
4.4.12 Governance Risk 120
4.5 DYNAMIC INTERACTIONS AMONG CLIMATE RISKS AND CRITICAL RISKS 121
4.6 IMPLICATIONS FOR FINANCING CARBON NEUTRAL INFRASTRUCTURE 122
4.7 SUMMARY OF ANALYSIS AND RESULTS 125

5 PRIVATE CONTRACTUAL METHODS TO MITIGATE CLIMATE RISKS 126

5.1 IMPORTANCE OF RISK MANAGEMENT IN INFRASTRUCTURE FINANCE 127
5.2 EVALUATION OF RISK MANAGEMENT INSTRUMENTS IN LIGHT OF CLIMATE CHANGE 128
5.3 SUMMARY OF RISK MANAGEMENT SURVEY METHODOLOGY AND RESULTS 131
5.4 PRIVATE INSURANCE 132
5.4.1 Scope of Risk Coverage 133
5.4.2 Geographic Coverage 134
5.4.3 Contract Duration 134
5.4.4 Availability 134
5.4.5 Price 135
5.4.6 Market Capacity 138
5.4.7 Prospects for Addressing Climate Change 141
5.5 COMMODITIES DERIVATIVES 142
5.5.1 Scope of Risk Coverage 142
5.5.2 Geographic Coverage 142
5.5.3 Contract Duration 143
5.5.4 Availability 145
5.5.5 Price 146
5.5.6 Market Capacity 149
5.5.7 Prospects for Addressing Climate Change 152
5.6 WEATHER DERIVATIVES 153
5.6.1 Scope of Risk Coverage 153
5.6.2 Geographic Coverage 154
5.6.3 Contract Duration 155
5.6.4 Availability 156
5.6.5 Price 158
5.6.6 Market Capacity 163
5.6.7 Prospects for Addressing Climate Change 164
5.7 CARBON OFFSETS 167
5.7.1 European Union Emissions Trading Scheme 167
5.7.1.1 Scope of Risk Coverage 168
5.7.1.2 Geographic Coverage 168
5.7.1.3 Contract Duration 168
5.7.1.4 Availability 169
5.7.1.5 Price 170
5.7.1.6 Market Capacity 172
5.7.2 Clean Development Mechanism 173
5.7.2.1 Scope of Risk Coverage 173
5.7.2.2 Geographic Coverage 174
5.7.2.3 Contract Duration 174
5.7.2.4 Availability 174
5.7.2.5 Price 179
5.7.2.6 Market Capacity 182
5.7.2.6.1 CDM Project Risks 182

5.7.2.6.2 Additionality 183
5.7.2.6.3 Regulatory Uncertainty 184
5.7.3 Prospects for EU ETS and CDM to Address Climate Risk 185
5.8 CATASTROPHE BONDS 186
5.8.1 Catastrophe Bond Fundamentals 186
5.8.2 Scope of Risk Coverage 187
5.8.3 Geographic Coverage 188
5.8.4 Contract Duration 189
5.8.5 Availability 190
5.8.6 Price 190
5.8.7 Market Capacity 193
5.8.8 Prospects for Addressing Climate Change 194
5.9 LIMITS OF PRIVATE CONTRACTUAL METHODS FOR ADDRESSING CLIMATE CHANGE 195

6 CASE STUDIES 201

6.1 CAPITAL MARKETS CAPACITY TO FINANCE CARBON NEUTRAL ELECTRICITY INFRASTRUCTURE 202
6.1.1 Projected Capital Requirements for Carbon Neutral Electricity 206
6.1.2 Capital Expenditures in the U.S. Utilities and Energy Sectors 207
6.1.3 Projected Global Capital Expenditures for Conventional Electricity Sector 208
6.1.4 Required Growth of Renewable Energy Technology Sector 209
6.1.5 U.S. Public Debt and Equity Capital Markets Activity 210
6.1.6 U.S. Private Equity Transactions – Venture Finance 213
6.1.7 U.S. Private Equity Transactions – Energy and All Sectors 214
6.1.8 U.S. and Global Bank Lending 216
6.1.9 Global Bond Markets 217
6.1.10 Internal Funds 219
6.1.11 International Disparities 220
6.1.12 Capital Market Volatility and Effects on Firms 223
6.1.13 Relative Contributions of Capital Markets Segments 227
6.1.14 Growth Potential of Capital Markets 229
6.1.15 Waiting and Its Potential Costs 231
6.1.16 Capital Markets Case Study Main Findings 232
6.2 STORM EFFECTS ON UTILITIES AND ENERGY SECTOR 234
6.2.1 Storm and Hurricane History of the United States Atlantic Coast 1990-2005 234
6.2.2 Economic Damage Caused by Storms and Hurricanes 237
6.2.3 Financial Effects of Storms and Hurricanes on Utilities and Energy Sectors 241
6.2.4 Utility and Energy Storm Damage Case Study Main Findings 245
6.3 NATURAL CATASTROPHIC EVENTS EFFECTS ON INSURANCE INDUSTRY 246
6.3.1 Insurance Industry Fundamentals 246
6.3.2 Recent History of Natural Catastrophic Events and Insurance Losses 247
6.3.3 Financial Effects of Natural Catastrophes on Insurance Industry 250
6.3.4 Natural Catastrophe Effects on Insuring Energy Sector 256
6.3.5 Insurance Case Study Main Findings 257
6.4 CASE STUDIES CONCLUSIONS 258

7 RESULTS AND POLICY RECOMMENDATIONS 260

7.1 PRIMARY FINDINGS 260
7.2 POLICY RECOMMENDATIONS 262
7.3 AREAS FOR FURTHER RESEARCH 265
7.4 CONCLUSION 266

REFERENCES 275

List of Appendices

Appendix A: Climate Risk Assessment Matrix 267
Appendix B: Risk Management Survey Participants 268
Appendix C: Form of Insurance Survey 270
Appendix D: Form of Derivatives Survey 273

List of Figures

Figure 2.1: 12 EIA World Conventional Oil Production Scenarios 24
Figure 2.2: Real Price of Oil and U.S. Recessions, 1969-2005 26
Figure 2.3: Real GDP, Equipment and Technology Capital Spending, 1990-2008 27
Figure 2.4: U.S. Federal Outlays by Category (% of GDP), 1950-2075 33
Figure 2.5: U.S. Federal Revenues and Outlays (% of GDP), 1950-2075 33
Figure 2.6: Relative Price to Book Ratio – Utilities versus S&P 500, 1972-2005 44
Figure 2.7: Global Annual Investment in Renewable Energy, 1995-2004 46
Figure 3.1: Observed Carbon Dioxide Concentrations, 1960-2000 50
Figure 3.2: Observed Global Average Temperature, 1880-2000 50
Figure 3.3: Global Fossil Carbon Emissions, 1800-2000 51
Figure 3.4: The Present Carbon Cycle 53
Figure 3.5: Radiative Forcing and Level of Scientific Understanding 54
Figure 3.6: Predicted Global Warming under Six SRES Emissions Scenarios 55
Figure 3.7: Stabilization Scenario for CO_2 at 550 ppm, 2000-2300 56
Figure 3.8: Historic and Projected Carbon Dioxide Emissions, 1970-2030 57
Figure 3.9: Historic Changes in Global Precipitation (%/century), 1900-1999 62
Figure 3.10: Projected Changes in Global Precipitation 63
Figure 3.11: U.S. Forest Fire Damage, 1960-2005 66
Figure 4.1: Project Finance Participants and Relationships 75
Figure 4.2: European Union Emissions Allowance Prices, April-May 2006 118
Figure 5.1: Climate Risk Assessment Matrix – Risks Covered 129
Figure 5.2: Climate Risk Assessment Matrix – Other Evaluation Criteria 131
Figure 5.3: Global Catastrophic Losses, 1970-2005 136
Figure 5.4: U.S. Catastrophe Reinsurance Price Indices, 1984-Q1 2006 136
Figure 5.5: U.S. P&C Policyholder Surplus (US$ billions), 1975-2005 139
Figure 5.6: Number of OTC Weather Contracts by Region, 2000/1-2005/6 155
Figure 5.7: Notional Value Weather Risk Contracts (US$ millions), 2000/1-2005/6 157
Figure 5.8: OTC Weather Risk Contracts by Type, 2000/1-2005/6 157
Figure 5.9: Example of Detrended Data versus Original Data 159
Figure 5.10: European Union Emissions Allowance Prices, April-May 2006 170
Figure 5.11: Catastrophe Bond Exceedance Curve 191
Figure 5.12: Post-Katrina Catastrophe Bonds Yields in Secondary Market 192
Figure 5.13: Climate Risk Assessment Matrix – Risks Covered 196
Figure 5.14: Climate Risk Assessment Matrix – All Other Evaluation Criteria 197
Figure 6.1: Global Annual Investment in Renewable Energy, 1995-2004 210
Figure 6.2: External Debt by Region, 2001 221
Figure 6.3: Domestic Savings and Investment by Region, 2000 222
Figure 6.4: NASDAQ, September 2000-July 2006 224
Figure 6.5: Price-to-Book Ratios – Utilities versus S&P 500, 1972-January 2005 225
Figure 6.6: Interest Rates Cycles and Utility Rate Cases, Q1 1980-2006 226
Figure 6.7: U.S. Public Debt and Equity Transactions, 1993-2005 230
Figure 6.8: Real Value of U.S. Electricity Industry Fixed Assets, 1925-2005 232
Figure 6.9: Natural Perils and Losses by Type, 1950-2004 237
Figure 6.10: U.S. Hurricane Losses, 1915-2000 238
Figure 6.11: Causes of North American Electricity Service Disruption, 1982-2002 241
Figure 6.12: Major Storm Costs (2003 millions US$), 1994-2004 242
Figure 6.13: Major Storm Costs per Customer (2003 US$), 1994-2004 242
Figure 6.14: Ratio of Storm Cost/Net Operating Income (2003 US$), 1994-2004 243
Figure 6.15: Storm Costs as % of T&D Expenses (2003 US$), 1994-2004 243
Figure 6.16: Existing and Projected U.S. Liquid Natural Gas Infrastructure, 2005 244
Figure 6.17: Gulf of Mexico Oil and Gas Fields, 1947-2005 245
Figure 6.18: Number of Natural Catastrophic Events, 1970-2005 248
Figure 6.19: Natural Catastrophe Insured Losses (2005 US$ billions), 1970-2005 248
Figure 6.20: U.S. Insured Catastrophic Losses by Category, 1985-2004 249

Figure 6.21: Adjusted Annual Insured Losses due to Hurricanes, 1949-1999 250
Figure 6.22: Combined Ratio of P&C Reinsurers v. P&C Insurers and Reinsurers, 1999-2004 251
Figure 6.23: U.S. P&C Underwriting Gain/Loss (US$ millions), 1975-2005 251
Figure 6.24: U.S. P&C Net Income After Taxes (US$ millions), 1991-2005 252
Figure 6.25: Insurance Company Reserve Trends, 1994-2004 253
Figure 6.26: U.S. Catastrophe Loss Growth v. GDP, Premiums, Population, 1970-2004 253
Figure 6.27: U.S. P&C Insurance Company Insolvency Rates, 1993-2004 254
Figure 6.28: Reasons for P&C Insolvencies, 1993-2002 255
Figure 6.29: Insurance Company Upgrades and Downgrades, 1993-2000 255
Figure 6.30: U.S. Catastrophe Reinsurance Price Indices, 1984-Q1 2006 256

List of Tables

Table 2.1: Private/Public Participation in Developing Country Infrastructure, 1990-2004 28
Table 2.2: Global Project Finance Transactions (US$ millions), 1994-2005 29
Table 2.3: External Financing of Emerging Economies (US$ billions), 1990-2003 29
Table 2.4: Net Income and Sales of Seven Largest Petroleum Companies, 2005 30
Table 2.5: Energy R&D Budgets of the Seven Top Spending Countries, 2005 30
Table 2.6: U.S. Public Infrastructure Capital Expenditure (1997 US$ millions), 1956-1998 32
Table 2.7: Current Non-Renewable Energy Technologies 35
Table 2.8: Current Renewable Energy Technologies 36
Table 2.9: Speculative Energy Technologies 37
Table 2.10: 10 TW Actual Generation Capacity: 50-Year Technology Wedge Scenario 39
Table 2.11: Investment Rates with Replacement for Solar and Wind Technology Wedges 40
Table 2.12: 1 TW Global Energy Storage Capacity 40
Table 2.13: 10 TW Years 1-50 Daily Investment with CCS, Energy Storage, and Solar and Wind Equipment Replacement (US$ millions) 41
Table 2.14: Expected Lifetimes of Selected Infrastructure 47
Table 3.1: Regulated Greenhouse Gases 52
Table 3.2: 21st Century Warming Predictions for Selected Countries 60
Table 3.3: Projected Climate Effects on Selected Eurasian River Systems 64
Table 3.4: Potential Asian Land Loss and Population Exposure from Sea Level Rise 69
Table 3.5: Effects of Potential Extreme Climate Events 70
Table 3.6: Potential Climate Change Effects on Infrastructure 71
Table 4.1: Infrastructure Finance Risk Assessment Framework 74
Table 4.2: x-Axis of the Climate Risk Assessment Matrix 77
Table 4.3: Tabulation of Banking Industry Responses to Carbon Disclosure Project 80
Table 4.4: Carbon Disclosure Project Frequency of Banks' Identification of Climate Risks 82
Table 4.5: Carbon Disclosure Project Banks Identification of General Climate Effects 84
Table 4.6: Climate Events and Property Damage 92
Table 4.7: Carbon Disclosure Project Banks Frequency of Identification of Climate Risks 122
Table 5.1: Debt Tenor for Infrastructure Finance Projects Completed in 2005 127
Table 5.2: Third Party Contractual Methods to Address Project Risk 128
Table 5.3: Other Risks Not Covered by Risk Management Instruments 130
Table 5.4: Pre- and Post-Katrina Reinsurance Price Changes 137
Table 5.5: RAA/ABIR Property Reinsurance Survey Results (US$ billions), 2006 139
Table 5.6: Private Property & Casualty Insurance Summary 141
Table 5.7: Selected NYMEX Futures Contracts Open Interest, April 2006 143
Table 5.8: Commodities Derivative Survey Results 144
Table 5.9: Options Pricing Comparison – Effects of Duration and Volatility 147
Table 5.10: Options Pricing Comparison – Effects of Inflation of Asset Prices 148
Table 5.11: Options Pricing Comparison – Duration, Volatility, and Inflation 148
Table 5.12: Selected Futures Contracts as Percentage of Global Commodities Trade 151
Table 5.13: Commodities Derivatives Summary 153
Table 5.14: Chicago Mercantile Exchange Standard Weather Futures 155
Table 5.15: Weather Derivative Survey Results 156
Table 5.16: Call on CDD, New York City/La Guardia, May 1 to September 30, 2006 160
Table 5.17: Weather Derivatives Summary 166
Table 5.18: Open Interest in European Climate Exchange CFI Contracts, April 2006 169
Table 5.19: Russia and Ukraine Projected CO_2 Allowances (metric tonnes) 172
Table 5.20: CDM Validated versus Verified Emissions Reductions, August 2006 175
Table 5.21: CDM Project Risks 183
Table 5.22: EUA and CDM Summary 185
Table 5.23: Catastrophe Bond Triggers, 1997-2005 188
Table 5.24: Catastrophe Bonds Principal Amounts by Risk (US$ millions), 1997-2005 189
Table 5.25: Catastrophe Bond Tenors, 1999-April 2006 189

Table 5.26: Catastrophe Bond Ratings by Principal Amount (US$ millions) and Number of Transactions, 1997-2005 191
Table 5.27: Catastrophe Bonds Summary 195
Table 5.28: Other Important Risks Not Covered by Risk Management Instruments 198
Table 6.1: Case Study Variables 201
Table 6.2: 10 TW Years 1-50 Global Daily Investment with CCS, Energy Storage, and Solar and Wind Equipment Replacement (US$ millions) 206
Table 6.3: 10-15 TW Years 1-20 Global Daily Investment with CCS and Energy Storage 206
Table 6.4: 10-15 TW Years 1-20 Global Annual Investment with CCS and Energy Storage 207
Table 6.5: U.S. Capital Markets Share of 10-15 TW Years 1-20 Global Annual Investment with CCS and Energy Storage 207
Table 6.6: S&P 500 Utilities and Energy Sector Capital Expenditures, 1994-2005 208
Table 6.7: 10-15 TW Years 1-30 Global Annual Investment with CCS, Energy Storage, and Wind Equipment Replacement (US$ billions) 209
Table 6.8: U.S. Public Debt and Equity Transactions – Energy (US$ millions), 1993-2005 211
Table 6.9: U.S. Public Debt and Equity Transactions – All Industries (US$ millions), 1993-2005 211
Table 6.10: U.S. Public Debt and Equity Transactions – Averages (US$ millions), 1996-2005 212
Table 6.11: U.S. Public Debt and Equity Average (2001-2005) versus U.S. Capital Markets Share of 10-15 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure 212
Table 6.12: U.S. Energy/Industrial Venture Capital Fund Capital, 2004-2005 213
Table 6.13: U.S. Venture Finance Transactions (US$ millions), 1996-2004 213
Table 6.14: U.S. Private Equity Transactions – Utilities, Energy, Oil and Gas, 1996-2005 215
Table 6.15: U.S. Private Equity Transactions – All Sectors, 1996-2005 215
Table 6.16: U.S. Bank Lending (US$ billions), 2001-2005 216
Table 6.17: Global Bonds Outstanding and 2-Year Average Growth (US$ billions), 2004-2005 217
Table 6.18: Global Bonds Annual Average Growth in All Issuances (2003-2005) versus 10-15 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure 218
Table 6.19: Global Bonds Outstanding by Issuer (US$ billions), December 2005 218
Table 6.20: Global Bonds Annual Average Growth in Corporate and Financial Issuances (2004-2005) versus 10-15 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure 218
Table 6.21: U.S. Shareholder-Owned Electric Utility Earnings (US$ millions), 2004-2005 220
Table 6.22: U.S. Public Debt and Equity Transactions – Computer, Electronics and Telecommunications Industries (US$ millions), 1993-2005 223
Table 6.23: U.S. Capital Markets Utilities Sector versus U.S. Capital Markets Share of 10 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure (US$ billions) 227
Table 6.24: U.S. Capital Markets All Sectors Activity versus U.S. Capital Markets Share of 10 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure (US$ billions) 228
Table 6.25: Average Annual Growth in All Global Bond Issuances (2004-2005) versus 10 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure (US$ billions) 229
Table 6.26: Saffir-Simpson Hurricane Scale 235
Table 6.27: Average Annual Number of Storms by Period, 1851-2004 235
Table 6.28: Hurricane Direct Hits on U.S. Coastline Texas to Maine, 1851-2004 236
Table 6.29: Ten Deadliest U.S. Hurricanes, 1900-2005 236
Table 6.30: Twenty Costliest Mainland U.S. Tropical Cyclones, 1900-2005 238
Table 6.31: Estimated Capital Stock Destroyed by Hurricanes Katrina and Rita 239
Table 6.32: Estimated Net Effect of Hurricane Katrina on Real GDP (2005 US$ billions) 239
Table 6.33: Federal Disaster Relief Payments (2005 US$ millions), 1974-2007 240
Table 6.34: U.S. P&C Insurance Company Insolvencies, 2000-2004 254

List of Climate Risk Diagrams

Diagram 4.1: Potential Climate Risk Interactions....85
Diagram 4.2: Supply Risk Interactions....88
Diagram 4.3: Market Risk Interactions....90
Diagram 4.4: Technology-Engineering-Infrastructure Risk Cluster Interactions....96
Diagram 4.5: Regulatory Risk Interactions....101
Diagram 4.6: Political Risk Interactions....107
Diagram 4.7: Legal Risk Interactions....110
Diagram 4.8: Force Majeure Risk Interactions....112
Diagram 4.9: Operating Cost Risk Interactions....113
Diagram 4.10: Management Capacity Risk Interactions....115
Diagram 4.11: Capital Markets Risk Interactions....119
Diagram 4.12: Potential Climate Risk Interactions....121
Diagram 4.13: Risks and Carbon Neutral Technology and Infrastructure....123

List of Acronyms

AAU	Assigned Amount Units
bbl	barrel of oil
btu	British thermal unit
CCS	carbon capture and sequestration
CDD	cooling degree days
CDM	Clean Development Mechanism
CER	Certified Emissions Reduction Certificate
CME	Chicago Mercantile Exchange
DOE	Designated Operational Entity
ECX CFI	European Climate Exchange Carbon Financial Instrument
EIA	U.S. Energy Information Administration
EJ	exajoules
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ERU	Emissions Reduction Unit
EUA	European Union Emissions Allowance
EU ETS	European Union Emissions Trading Scheme
g	gram
Gt	gigatonne (metric)
GW	gigawatt
HDD	heating degree days
HFCs	hydrofluorocarbons
IEA	International Energy Agency
IGCC	integrated coal gasification combined-cycle
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
kg	kilogram
kl	kilolitre
$ktCO_2$	kilotonne (metric) of carbon dioxide
kW	kilowatt
kWh	kilowatt-hour
mWh	megawatt-hour
MW	megawatt
NASDAQ	National Association of Securities Dealers Automated Quotations
NYMEX	New York Mercantile Exchange
NYSE	New York Stock Exchange
O&M	operations and maintenance
OTC	over-the-counter
OECD	Organization for Economic Cooperation and Development
P&C	property and casualty
Pg	petagram (equivalent to gigatonne (metric))
ppb	parts per billion
ppm	parts per million
PV	photovoltaic
RMU	Removal Units
TW	tera-watt
tcf	trillion cubic feet
toz	troy ounce
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

This dissertation examines the private sector's capacity to manage financial risks relating to climate change and to finance carbon neutral energy infrastructure. It poses three specific questions concerning (a) how climate risks might impair the private sector's ability to finance and develop infrastructure, (b) whether private contractual methods relied upon by the private sector to mitigate risk can be effective in addressing climate risks, and (c) what kinds of government policies are suggested by the foregoing analysis to prevent potential market failure.

The purpose of the inquiry is to assess the private sector's ability to transform our current fossil fuel infrastructure to a carbon neutral energy infrastructure. The importance of the question was recognized by the U.S. National Academy of Science in a 1992 report on the policy implications of climate change when it stated: "Even though inventions and their adoption may occur quickly, we must ask whether the broad spectrum of current capital investments could be changed fast enough to match a change in climate in 50 to 100 years." Based on anecdotal evidence, but without engaging in any systematic analysis, the report concluded that putting in place "technology that is adjusted to a changing climate" "can be done without extraordinary measures given reasonably accurate information about the future" (US NAS 1992).

This dissertation concludes that developing carbon neutral infrastructure will be a difficult task that cannot be accomplished by the private sector within a single lifetime of the longest duration infrastructures we currently employ. To support this conclusion, the dissertation reviews evidence from climate change science concerning the financial risks posed by climate change to infrastructure. Based on the scientific evidence, the dissertation develops a framework to assess infrastructure finance risks in the context of climate change. The framework is used both to identify specific risks posed by climate change and to evaluate commonly used private contractual methods for addressing risks based on a set of criteria that shows the extent to which these methods can be effective in mitigating climate change risks. The framework focuses on the financial aspects of infrastructure development and can be used by the private sector to make investment decisions as well as by policymakers to identify areas where government policy is necessary or desirable to avoid potential market failure.

Following the risk assessment, the dissertation presents three case studies examining different aspects of the financial implications of climate change for energy infrastructure: (i) the capacity of capital markets to supply adequate investment capital to develop a portfolio of carbon neutral electricity infrastructure providing 10-15 TW of power generation within a 50-year period, (ii) the financial effects of storms on the utility industry in the East Coast of the United States, and (iii) the financial effects of natural catastrophes on the insurance industry, especially in relation to insuring utility and energy infrastructure.

The framework, analysis of private contractual methods to manage risk, and the case studies are relevant to assessing capital-intensive approaches to addressing climate change, and support the dissertation's conclusion that financing and developing carbon neutral energy infrastructure poses significant challenges for the private sector.

1.1 Dissertation Questions and Hypothesis

This dissertation addresses three questions with respect to climate risk and infrastructure development:

(a) What risks does climate change pose to infrastructure, and how might those risks impair the private sector's ability to finance infrastructure?

(b) To what extent can private contractual methods mitigate risks posed by climate change?

(c) What kinds of government policies are suggested by the foregoing analysis to prevent potential market failure?

The dissertation's major hypothesis is that private firms and capital markets will experience difficulty financing and developing physical infrastructure under conditions of heightened climate risks. Specifically, climate change may pose a fundamental problem for private infrastructure finance in that no one project party appears well positioned to accept and mitigate climate risks. Climate risks are beyond the scope of traditional operational and financial risk analysis methods employed by industry and financial institutions. Currently available contractual risk management techniques are inadequate to measure and protect against climate risks on a long-term basis. Without adequate methods to measure and protect against climate risks, climate risks could reduce the private sector's willingness or ability to finance or develop infrastructure, including carbon neutral infrastructure.

The climate risk analysis conducted in this in dissertation is applicable to all kinds of large-scale physical infrastructure, however the dissertation focuses on infrastructure in the energy sector because of its direct relationship to greenhouse gas emissions and its contribution to climate change.

1.2 Note on Terminology

This term "carbon neutral" means that energy systems emit no more greenhouse gases to the atmosphere than they remove from the atmosphere over a period of time matched to the life of the infrastructure. As used here, the term does not reflect a full cradle-to-grave environmental life cycle analysis of energy infrastructure and technology, but rather focuses on emissions from fuel conversion during the operational phase of energy infrastructure.[1]

The term "infrastructure" as used here means physical facilities that provide basic services to a country and its citizens, which make economic and social activities possible.

---

[1] The analysis also does not take into account incidental releases of greenhouse gases, such as from the use of sulphur hexafluoride (SF_6) as a dielectric fluid for electricity generation and transmission systems.

The term includes transportation, energy and power systems, communications, water, and sewage systems. A broader definition of physical infrastructure might also include housing, health, and education. As noted above, this dissertation focuses on large-scale physical infrastructure in the energy sector because of its direct relationship to greenhouse gas emissions and its contribution to climate change.

The term "infrastructure finance" means the financing of infrastructure projects, typically on a non-recourse basis. The term is synonymous with "project finance". The significance of infrastructure finance is that it demands that a project be financially justified on a stand-alone basis and proscribes that all project risks must be carefully identified, allocated, and addressed. This risk analysis informs investment decisions concerning large infrastructure projects, particularly those financed with private sector resources. Significantly, the same risk analysis can be applied to infrastructure projects financed using government funds or on a corporate finance basis. Nevitt and Fabozzi (2000), Tinsley (2000), and Hoffman (2001) are authoritative references on infrastructure finance.

The term "climate risk" refers to several kinds of weather-related risks that are caused by or correlated with an increase in the frequency and/or severity of weather events beyond their normal ranges as a result of anthropogenically-induced climate change. These risks can be categorized as follows: (a) greater volatility in short term weather patterns, such as variation in heat and precipitation; (b) increased severity and likelihood of catastrophic risks, such as storms, floods, and hurricanes; and (c) longer-term weather trends, such as gradual warming, and their consequences, such as polar ice melt. The dissertation treats all three kinds of risks under the term "climate risk" because they all have the potential to adversely affect the financial results of firms, and therefore can be analyzed as financial risks under the Climate Risk Assessment Matrix developed in this dissertation.

1.3 Overview of Dissertation and Methodology

This chapter presents the dissertation's primary research questions, its hypotheses, the methodology that will be employed in testing them, and describes how this dissertation will contribute to other areas of research.

Chapter 2 introduces the challenges faced by society in the 21st century in the areas of energy and climate change. It reviews a critical variable concerning the timing of transition away from petroleum resources and describes the magnitude of the challenge of developing carbon neutral infrastructure in terms of cost and construction rates. It explains the rationale for focusing on the private sector's role in financing and developing infrastructure in meeting these challenges.

The dissertation's questions are addressed in chapters 3 through 7.

Chapter 3 identifies climate risks to infrastructure by examining scientific evidence concerning climate change from studies and atmospheric models. Chapter 4 incorporates these climate risks in a qualitative risk assessment framework commonly used in infrastructure finance. The revised framework separately identifies and isolates each risk in the context of climate change. The revised framework is then used to assess how climate risks could affect the development of carbon neutral infrastructure.

Chapter 5 examines whether the risks defined and identified in the prior chapter can be addressed through various private contractual methods. These contractual methods include insurance, commodities and weather derivatives, carbon offset contracts, and catastrophe bonds. These private contractual methods are evaluated using six criteria: (a) scope of risk covered, (b) geographic coverage, (c) contract duration, (d) availability, (e) price, and (f) market capacity. The analysis is supported by a survey conducted by the author of brokers, dealers, and risk managers concerning the use of these risk management methods.

The results of Chapters 3, 4 and 5 are characterized in terms of a three-dimensional Climate Risk Assessment Matrix, located in Appendix A to this dissertation. The Climate Risk Assessment Matrix is in the shape of a cube, where the x, y and z axes are Climate Risks, Methods to Mitigate Risks, and Criteria for Evaluating Methods, respectively. The Matrix will be used as an analytical tool to conceptualize and summarize the dissertation's results concerning climate risk.

Chapter 6 presents three case studies focusing on different financial aspects of climate change in relation to energy infrastructure: (i) the capacity of capital markets to supply adequate investment capital to develop a portfolio of carbon neutral electricity infrastructure providing 10-15 TW of electricity generation within a 50-year period, (ii) the financial effects of increasingly intense storms and hurricanes on the electric utility industry in the Eastern United States from 1990 to 2005, and (iii) the financial effects of the increasing frequency and severity of natural catastrophic events on the insurance industry from the 1970's to 2005, especially in connection with underwriting risks for energy infrastructure.

These cases present examples of how climate risk may affect industry's ability to develop carbon neutral energy infrastructure. The capital markets case study examines the ability of the private sector to finance the cost of carbon neutral electricity infrastructure over a 50-year period in order stabilize electric utility sector greenhouse gas emissions. The electric utility and insurance cases demonstrate how catastrophic risks can increase the cost of operations and cause curtailment of insurance coverage for high-risk areas, making the financing of infrastructure difficult. All three cases show the immediacy of climate change and the challenges it poses for the private sector to finance and develop infrastructure.

Chapter 7 concludes by proposing government policies that may prevent potential private sector failure in infrastructure finance and development due to climate risk. The analysis focuses specifically on government policy that supports private sector initiatives to finance and develop carbon neutral infrastructure based on the risk analysis and case studies presented in the dissertation.

1.4 Contributions to Knowledge

This dissertation contributes to knowledge in three distinct but closely related areas of research: (a) the development of carbon neutral infrastructure, (b) the financial risks of climate change, and (c) the institutional literature concerning the private sector's role in addressing climate change.

The literature concerning developing carbon neutral infrastructure is varied and has addressed issues such as the historical development of infrastructure (Grubler 1990, 1998; Smil 2003), problems of carbon-path dependency due to infrastructure (Unruh 2000, 2002; Unruh and Carrillo-Hermosilla 2006), and the impact of climate change on infrastructure (Revelle 1983; Cogan 1989). There is a distinct literature on climate-driven innovation and technology diffusion, which encompasses but does not typically focus exclusively on infrastructure (Grubler et al. 2002; Nakicenovic and Grubler 1989). The IPCC has contributed to the literature, specifically linking technology adoption as part of a long-term development strategy that necessarily affects choices of infrastructure to address climate change (IPCC 1995). Another strand of thought within this area focuses on the magnitude of the transformation and the timeframe necessary to preclude or prepare for a change in climate in the next 50 to 100 years (Lewis 2005; Hoffert et al. 2002). Contributions to this line of inquiry include research motivated by the goal of escaping dependence on petroleum that involves rigorous engineering assessments of the infrastructure necessary (US NAS 1979), as well as conceptual research motivated by climate change (Pacala and Socolow 2004).

Research in this area has not addressed the financial aspects of large-scale infrastructure transformation or the magnitude of the challenge in relation to the private sector's ability to develop carbon neutral infrastructure. Financial cost, time and physical resources are threshold issues for proposals to address energy infrastructure and climate change. Yet, these issues are commonly ignored, assumed to be outside the scope of the inquiry, or assumed to be within the financial and management capacity of the private sector based on past examples of private sector technology innovation (Wood 1999; US NAS 1992). This dissertation is an effort to address several fundamental questions regarding technology innovation in response to climate change, which are motivated by the scale of the transformation required, the long time horizons, the changing risks associated with developing infrastructure due to climate change, and the financial and management capacity of the private sector to implement such a transformation.

The second area where this dissertation contributes is analysis of the financial risks of climate change. The financial risks of climate change are a relatively new area of research. This dissertation contributes to this area by analyzing the financial risks associated with climate change and the private sector's capacity to finance and develop critical infrastructure in the context of climate change.

Most economic studies of climate change are focused on the macroeconomic effects of policies designed to address climate change. This literature often uses top-down macroeconomic or bottom-up engineering cost models linked to climate system models to analyze the costs of public policy, such as taxes or emissions trading programs and their effect on technology adoption and emissions reductions. These models necessarily rely on generalized assumptions about technology adoption and investment (see, e.g., Weyant 1999; Weyant and Hill 1999; Reilly and Paltsev 2006; Clarke and Weyant 2002). The macroeconomic literature typically does not explicitly address the financial capacity of the private sector or government to finance and develop the infrastructure needed to address climate change. Rather, these studies often assume these issues will be addressed through market adjustment.

A new literature is emerging that focuses on the financial cost of climate change to firms, industries, cities, and countries. An example of research focusing on municipalities is a study sponsored by EPA on the effects of sea level rise and other climate changes on the Boston metropolitan area (Kirshen et al. 2004). The UNEP Finance Initiative and the Carbon Disclosure Project promote planning among financial institutions, including banks, insurance companies, and institutional investors on the potential effects of climate change on companies and investment (Cogan 1989; Innovest Strategic Value Advisors 2005; Whittaker 2003). Research on insurance and climate change was advanced by the Intergovernmental Panel on Climate Change (IPCC) in the IPCC Third Assessment Report, which conducted analysis of the potential effects of climate change on the financial sector, focusing largely on the insurance industry. The major insurance and reinsurance companies have also devoted significant resources to studying climate change and have produced their own reports on the subject (CERES 2005a).

The literature concerning the financial risks of climate change and its implications for infrastructure development is limited. Notable research in this area includes work on financing renewable energy technologies (Olivier 2003), risks posed by climate change to investment (Olivier 2003; Tang 2005), and a World Bank position paper calling for development of an investment framework for clean energy with the purpose of addressing climate change (World Bank 2006a). In addition, the Equator Principles, a set of voluntary guidelines adopted by banks to promote socially responsible investment in project finance, focus on the effects of infrastructure projects on the natural environment.

This dissertation expands on the existing literature by examining the financial risks of climate change for critical infrastructure, especially in the energy industry. This is an important and understudied area of research. According to the World Bank, of the over five hundred infrastructure projects developed by the bank during the past ten years, only 2% of these projects considered climate change in the approval process (Mirza 2006a). Yet, in developed countries, an estimated 40% of damage caused by weather is to infrastructure, while in developing countries, this percentage increases to an estimated 70% to 80% (Mirza 2006b).

There is a need to further develop this literature because the financial community presently lacks the tools to evaluate and manage long-term climate change risks within its traditional financial and operational risk frameworks. Without appropriate methods to analyze and mitigate climate risks, it is not clear how the private sector will manage climate risks and pursue sustainability objectives.

There is considerable interest in the potential use of financial instruments to manage climate risk, but very little critical work has been done in this area. To fill this gap, this dissertation identifies the risks posed by climate change and evaluates the limits of private contractual methods to address them. This dissertation first critically appraises the traditional infrastructure finance approach, which has assumed climate to be largely static, and revises the risk analysis framework to incorporate climate and energy issues based on recent scientific research. The dissertation then examines the risk management markets (e.g., insurance, derivatives) that are essential for managing risk and financing modern infrastructure. It evaluates these risk management methods based on a set of criteria that shows the extent to which these methods can be effective in mitigating climate change risk.

Finally, this dissertation contributes to the growing body of literature concerning the role of private sector institutions in addressing climate change. Specifically, it focuses on the increasingly important role of the private sector in developing carbon neutral infrastructure. This particular topic has not been adequately addressed by the existing literature. A few researchers have focused on the private sector role in financing infrastructure (Miller and Lessard 2000; Scholte and Schnabel 2002), and several have focused on the relationship between infrastructure and climate change (see, e.g., Unruh 2000, 2002; Unruh and Carrillo-Hermosilla 2006; Grubler 1998; Smil 2003; Schrattenholzer et al. 2005). Others have addressed the role of private institutions in solving collective action problems (see, e.g., Ostrom 1990; Dolsak and Ostrom 2003), and the private sector's role in financing sustainable development in light of climate change (Schmidheiny et al. 1996; Schmidheiny et al. 1992). However, to my knowledge, no research has been published on the role of the private sector in developing infrastructure in the context of climate change.

This dissertation seeks to fill that gap by examining the private sector's capacity to manage climate risk and to develop carbon neutral infrastructure from the perspectives of financial and management capacity. This is a critical area of research because the government plays a limited role in most market economies, and the financial and management capacity of the private sector will be essential to successfully addressing climate change. As described in Chapter 2, trends during the last half of the 20th century suggest that the role of the private sector in infrastructure development and finance is increasing, whereas the government's role and capacity to finance and develop infrastructure is diminishing.

1.5 Note on Sources and Citations

Proprietary datasets were provided courtesy of Dealogic, Institute of International Finance, Standard & Poor's, State Street Bank, Thomson Financial, and VC Experts. These datasets are cited in the text and referenced in the bibliography. The datasets are on file with the author. Graphs and other information obtained from the Internet are cited and listed in the bibliography with the link and date accessed.

2 Energy and Climate Change Challenges of the 21st Century

One of the 21st century's greatest challenges is to meet society's increasing demand for energy in order to support human and economic development, while stabilizing atmospheric greenhouse gas levels in an effort to prevent dangerous climate change. Global development patterns, population growth, and dependence on fossil fuels are of such a magnitude that the transition is unprecedented in human history. The quickening pace of global economic growth further increases the magnitude of the required transition and decreases the time available for society to successfully transition to a sustainable path.

This chapter introduces the challenges faced by industrial society in the 21st century in the areas of energy and climate change and explains the rationale for focusing on the private sector's role in developing infrastructure in meeting these challenges. Central to this chapter is the concept of carbon neutral infrastructure, defined earlier as energy systems that emit no more greenhouse gases to the atmosphere than they remove from the atmosphere over their operating life cycle.

2.1 Timing of Transition to Carbon Neutral Infrastructure and Petroleum Resources

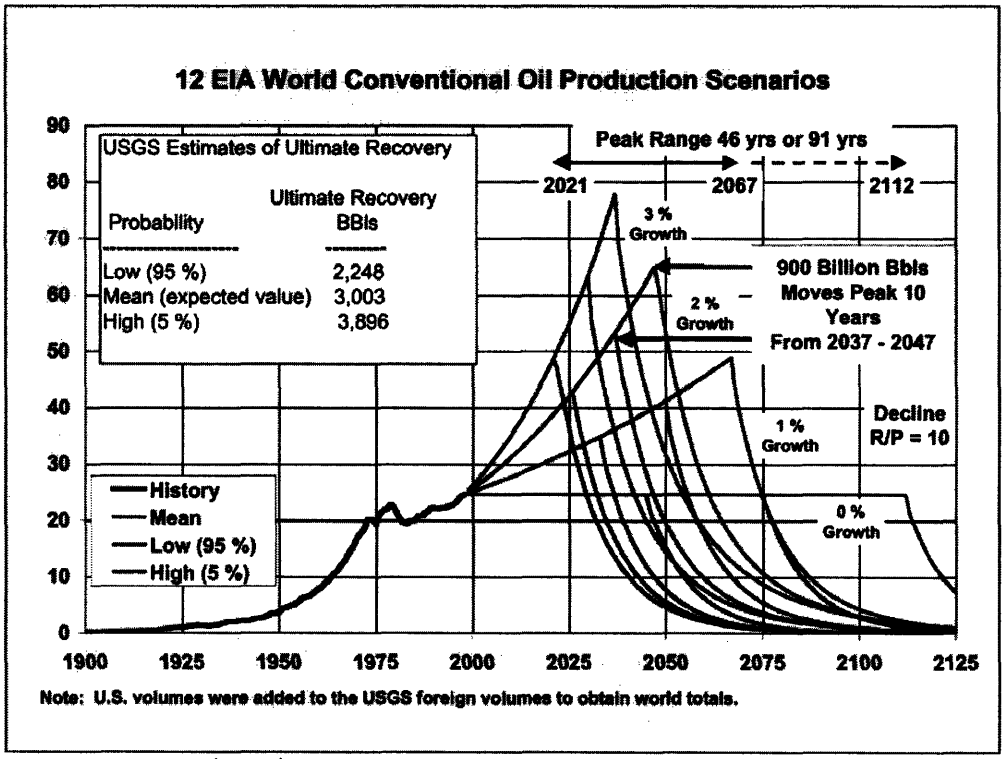
The timing of the transition to carbon neutral infrastructure will likely be influenced by the economic, political, and regulatory conditions surrounding the current fossil fuel infrastructure. This section focuses on economic factors, specifically on the effects of increasing costs of locating and exploiting petroleum resources. While economists generally regard increasing petroleum prices as an appropriate market incentive to conserve resources and to seek substitutes, if the transition to carbon neutral energy infrastructure is delayed or we are unable to successfully develop substitutes on a scale necessary to support economic development, society's ability to transition to a sustainable path may be adversely affected by economic conditions associated with rising petroleum costs or even scarcity.

Whether society will deplete petroleum resources before deploying technologies that depend on alternative resources at comparable prices to fossil fuels is actively debated among geologists and technologists. The two sides of the debate are represented by those who contend that economics and technological advances largely determine the petroleum resource base, and those who emphasize the finite nature of the resource base (McCabe 1998).[2] A number of studies by geologists of the latter viewpoint have predicted that the peak of global conventional petroleum production will occur within this century, depending upon global economic growth rates, actual conventional petroleum resources, petroleum consumption rates, and advances in petroleum exploration and production technology (Wood et al. 2004; Campbell and Laherrere 1998; Deffeyes 2001). While future trends in resource depletion have proven inherently difficult to predict, these estimates are nevertheless important for purposes of anticipating the eventual transition to other sources of energy.

[2] See Adelman (1995) for an explanation of the economics of the "cornucopian" viewpoint.

For illustrative purposes, Figure 2.1 below presents the results of a 2004 U.S. Energy Information Administration study using data from the most recent U.S. Geological Survey global petroleum resource assessment in 2000. The study's assumptions are supported by a large set of empirical observations of existing petroleum fields. The study incorporates uncertainty into its analysis by modeling twelve scenarios using Monte Carlo techniques. Based on assumptions of global annual GDP growth rates of 0%, 1%, 2% and 3%, and high, mean, and low estimates for recovery of petroleum resources, the EIA presented twelve potential scenarios for peak conventional petroleum production. Eleven of the twelve scenarios predict global petroleum production will peak within the 21st century. The mean of the distribution occurs between years 2030 to 2075 at a peak volume of 24.5 to 63.3 billion barrels per year.

Figure 2.1: 12 EIA World Conventional Oil Production Scenarios



Source: Wood et al. (2004).

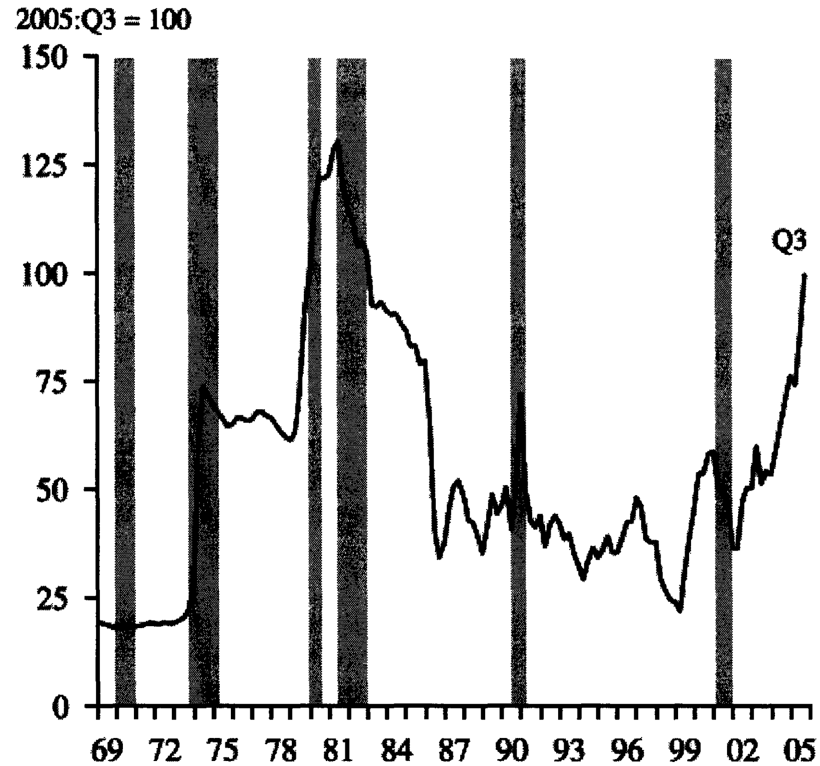
Sensitivity analysis performed by the EIA study's authors shows that demand rather than the resource base largely determines the timing of the production peak. Increasing the estimated mean resource base by 900 billion barrels, an amount of oil greater than the amount produced from the discovery of oil to year 2003, only delays the estimated peak by 10 years in the 2% economic growth rate scenarios. In contrast, a 1% decrease in the pre-peak economic growth rate is approximately equivalent to adding 900 billion barrels to the estimated resource base (Wood et al. 2004).

Importantly, the EIA study shows that once petroleum production peaks, global production is expected to rapidly decline. This aspect of the EIA study is consistent with recent data published by ExxonMobil and Wood Mackenzie. ExxonMobil published its own graph showing peak oil production occurring by 2010, followed by a sharp decline (ExxonMobil 2004). The authors of the EIA study compared the rate of decline in their model against the rate of decline projected by ExxonMobil and confirmed that the two rates are close approximations (Morehouse 2005). WoodMackenzie reports that petroleum producers have been experiencing increasing exploration costs and declining production from new investment, a phenomenon consistent with a peak production scenario (Wood Mackenzie 2004).

The EIA study does not account for the anticipated growth of proven non-conventional fossil fuels, such as heavy oils, tar sands, oil shale, and further reliance on gas and coal using the Fischer-Tropsch process to develop gas-to-liquids and coal-to-liquids technology. However, if EIA is correct that consumption rates now have a greater influence on the timing of peak petroleum production rather than potential increases in the resource base and that conventional production will decline rapidly following its peak, the late entry or inadequate supply of non-conventional resources could have unprecedented adverse economic effects. Further, the introduction of non-conventional fossil fuels without pollution abatement measures will have adverse environmental consequences, which also could be costly to address.

While the energy industry will benefit from increasing petroleum prices, most other industries and consumers will suffer. Since the 1970's, recessions in the United States have typically been preceded by increases in the relative price of oil. Combined with other factors such as monetary policy, rapid increases in oil prices clearly have contributed to past recessions (Hamilton 1983, 1996, 2003; Bernanke et al. 1997).

Figure 2.2: Real Price of Oil and U.S. Recessions, 1969-2005



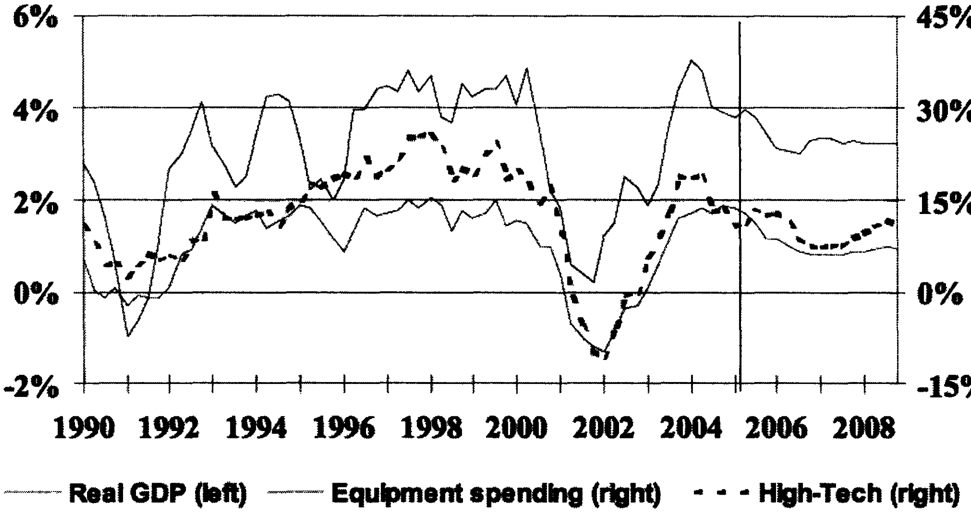
Source: Federal Reserve Bank of San Francisco (2005). Note: Price of petroleum imports divided by the price index for personal consumption of expenditures. Gray bars denote recessions.

Generally, economic research on the effects of rising oil prices on GDP has focused on incremental price increases, as opposed to peak oil conditions. For example, a recent study compared results among several economic models for a $10 increase in the cost of oil from $30 to $40. These models estimate that GDP would be reduced between 0.2% to 1.7% over a two-year period, depending upon the state of the economy, expectations, and monetary policy (EIA 2005a).

Post-peak economic conditions could produce larger price increases, greater volatility, and produce an unfavorable investment environment. Little research has been conducted on the economic effects of peak scenarios. The limited research that has been conducted in this area, however, suggests that the economic effects of peak production without an adequate transition planned in advance would be devastating to a fossil fuel economy (Sterman 1980, 1981, 1982).

Typically, infrastructure is financed in anticipation of economic growth and development, not in periods of economic contraction. If the transition is delayed and resource depletion causes economic contraction, our society's ability to finance new infrastructure could be adversely affected. Figure 2.3 below shows the close correlation between capital spending and gross domestic product during the 1990 to 2005 period (projections from 2006 to 2008).

Figure 2.3: Real GDP, Equipment and Technology Capital Spending, 1990-2008



Source: Standard & Poor's (2005a).

2.2 The Private Sector's Role in Developing Infrastructure

Much of the burden of financing and developing carbon neutral infrastructure is likely to fall upon the private sector. Society increasingly relies upon the private sector for the investment capital, and the planning, implementation and management capabilities for developing infrastructure. The private sector's role in financing global infrastructure probably began in Great Britain during the 1700's with the private financing of transportation canals (Grubler 1990). Private infrastructure development experienced a renaissance in the 1970's in response to the inability of national governments to finance, build and manage large infrastructure projects without private sector assistance.

The private sector's role in providing capital and know-how has become increasingly important in both developing and OECD countries. Table 2.1 below shows the growth of total public and private investment from 1990 to 2004 in 149 low and middle-income countries for infrastructure projects that included private sector investment in the energy, transportation, telecommunications and water sectors.

Table 2.1: Private/Public Participation in Developing Country Infrastructure, 1990-2004

Year	Investment (US$ millions)
1990	8,466.60
1991	13,720.40
1992	17,699.30
1993	27,957.10
1994	36,358.70
1995	46,755.00
1996	63,919.40
1997	111,141.50
1998	99,525.30
1999	66,679.00
2000	89,296.60
2001	70,605.50
2002	58,953.80
2003	55,904.50
2004	64,020.10
Total	831,002.60

Source: World Bank (2006b).

Private financing of infrastructure is even more significant in developed countries. In 2005, loan commitments to infrastructure projects worldwide reached approximately $121 to $140.3 billion, reflecting a continuing trend toward increasing private investment in infrastructure (Dealogic 2006b; Thomson Financial 2006a).[3] Borrowers domiciled in OECD countries accounted for approximately 71% of private infrastructure loans (Thomson Financial 2006b). Private lending, bonds and equity investments in infrastructure have all increased during the past decade as shown in Table 2.2 below.

[3] Industry categories include power, transportation, oil and gas, leisure and property, telecommunications, petrochemicals, industry, water and sewage, mining, water and recycling, agriculture, and forestry.

Table 2.2: Global Project Finance Transactions (US$ millions), 1994-2005

	Loans	Bonds	Equity	Total PF Amount	Deals
1994	28,683	564	4,381	33,628	86
1995	59,365	3,921	14,048	77,335	322
1996	113,541	13,789	47,327	174,657	647
1997	136,863	18,654	53,527	209,044	557
1998	114,362	18,118	52,586	185,066	481
1999	112,552	23,635	32,636	168,824	436
2000	143,931	23,755	42,286	209,973	434
2001	95,041	14,719	27,585	137,345	310
2002	60,200	8,071	11,719	79,990	257
2003	75,366	19,583	18,375	113,325	354
2004	120,170	22,530	29,996	172,696	442
2005	120,989	22,155	30,645	173,790	483
Total	**1,181,065**	**189,496**	**365,111**	**1,735,672**	**4,809**

Source: Dealogic (2006b).

The increasingly important role of the private sector in global economic development is demonstrated by comparing the volume of net private capital flows into emerging market countries relative to the volume of net bilateral and multilateral lending. Table 2.3 below shows the growth of private sector capital flows from 53.3% of total net flows in 1990 to over 100% of total net flows since 2002 for twenty-nine emerging market countries in Asia, Latin America, Africa, and the Middle East. Net private flows of over 100% indicate net repayment of bilateral and multilateral loans, which are more than offset by increases in private sector inflows.

Table 2.3: External Financing of Emerging Economies (US$ billions), 1990-2003

	1990	1991	1992	1993	199	1995	1996	199	199	1999	2000	2001	2002	2003
Current account balance	-16.2	-1 .2	-50.	- 9.9	- 1.	- 2.5	-9 .6	- 1.5	-9.	26.6	2.	2 .	.3	11 .2
External financing, net:														
rivate flows, net	3.	.0	119.3	1 9.5	1 .	229.	323.9	29 .6	13 .5	166.	203.0	156.5	112.3	225.1
E uity investment, net	1 .	2 .9	6.	96.1	9 .9	105.5	125.	1 2.1	131.	166.	153.6	153.0	121.	133.5
Direct investment, net	13.	23.0	30.6	.0	65.3	5.5	92.6	11 .0	122.0	15 .1	136.2	1 0.5	121.5	96.
ortfolio investment, net	2.6	.9	15.	52.0	32.5	30.0	33.0	2 .1	9.	12.	1 .	12.5	0.3	36.
rivate creditors, net	2 .9	9.2	3.0	93.	0.9	12 .2	19 .2	152.5	2.6	-0.	9.	3.5	-9.5	91.6
Commercial banks, net	10.1	22.1	2 .6	2 .2	3 .5	91.	11 .9	61.	-59.6	- 3.	3.	-16.2	-13.	2 .
Nonbanks, net	1 .	2 .1	.	66.2	2.	32.	9.3	90.	62.2	3.	6.0	19.	.3	63.9
fficial flows, net	3 .0	35.	35.0	2 .	30.2	39.1	.6	.0	55.	12.	-2.0	10.6	-3.0	-20.
IFIs	11.2	12.	.	9.	6.1	1 .	.0	29.9	3 .1	3.2	1.	23.0	.2	-6.3
ilateral creditors	26.	22.	2 .2	19.2	2 .1	20.3	-2.5	1 .0	1 .5	9.6	-3.	-12.3	-10.1	-1 .
Resident lending other, net[1]	-36.	-50.1	-5 .9	- .0	-92.	- 9.	-1 .	-22 .5	-132.6	-150.1	-1 3.5	-10 .	-36.	-53.6
Reserves (- increase)	-2 .	- .3	- .5	-6 .3	- .6	-96.5	- 6.0	- 2.5	- .1	-55.	-69.9	- .3	-150.1	-26 .9
rivate Flows as ercentage of Total	53.3%	6 . %	.3%	6. %	5.6%	5. %	9 .6%	.0%	0. %	92.9%	101.0%	93.6%	102. %	110.2%

e estimate, f IIF forecast

[1]Including net lending, monetary gold, and errors and omissions.

Emerging market countries are Asia: China, India, Indonesia, Malaysia, hilippines, South orea, Thailand Latin America: Argentina, ra il, Chile, Columbia, Ecuador, Mexico, eru, ruguay, Venezuala; Europe: Bulgaria, Czech Republic, Hungary, Poland, Romania, Russian Federation, Slovakia, Turkey; and Africa/Middle East: Algeria, Egypt, Morocco, South Africa, and Tunisia.

Source: Institute of International Finance (2006).

Comparing the relative magnitude of corporate net income and revenues against government expenditures for energy R&D indicates the potential contribution the private sector can make in transitioning society to a low-carbon economy. The tables below present fiscal year 2005 net income and revenues of seven of the world's largest public petroleum companies, and the 2005 energy R&D budgets of the seven top-spending countries.

Table 2.4: Net Income and Sales of Seven Largest Petroleum Companies, 2005

Company	**Net Income (US$ millions)**	**Sales (US$ millions)**
ExxonMobil	36,130	328,213
Royal Dutch/Shell Group	25,311	306,731
BP	26,785	295,242
Chevron	14,099	184,922
Total S.A.	14,525	169,439
ConocoPhillips	13,617	162,405
Occidental	5,281	15,208
Total	$135,748	$1,462,160

Source: Hoover's Online (2006).

Table 2.5: Energy R&D Budgets of the Seven Top Spending Countries, 2005

Country	**Total R&D 2005 Budget (US$ millions)**
Japan	3,905.3
United States	3,017.8
Germany	513.3
South Korea	412.9
Italy	320.5
Canada	298.9
Switzerland	155.5
7 Country Total	$8,624.0
Est. Total R&D for all IEA Countries	$9,586.3

Source: International Energy Agency (2006). Note: Energy R&D includes expenditures for energy conservation, fossil fuels, nuclear, renewable, power and storage, and other energy technology research. Data for France was unavailable.

A study of R&D budgets of the major U.S. oil companies found that R&D expenditures were 0.41% to 0.95% of total revenues from 1970 to 1995 (Enos 2002). If this rate of R&D spending is representative of current practice, combined R&D budgets of the seven largest petroleum companies could be as high as approximately $13.9 billion, which is 1 ¾ times the energy R&D budgets of the seven top-spending countries. However, it should be noted that oil and gas companies may define R&D differently than government, typically devoting a greater portion of corporate R&D budgets to development or deployment costs rather than basic research (Tester 2006).

The potential private sector investment in energy R&D could be much greater. Aggregate annual net income of these seven companies was almost 16 times greater than the seven countries' combined energy R&D budgets, and over 14 times the estimated combined energy R&D budgets of all IEA member countries.

2.3 The Shrinking Role of Government in Infrastructure Development

At the same time that private sector investment in infrastructure has been increasing, government expenditure on infrastructure has been decreasing as a percentage of GDP. According to the Congressional Budget Office, U.S. federal capital expenditure on transportation and water infrastructure decreased from almost 1% of U.S. GDP during the 1960's to less than 0.45% in the late 1990s. Combined federal and state capital expenditure on transportation and water infrastructure similarly decreased from almost 2% of GDP during the 1960's to approximately 1% in the 1990s (U.S. Congressional Budget Office 1999). Canadian government infrastructure spending has followed a similar pattern, peaking at 4.95% of GDP in 1966 and then decreasing to 2.32% of GDP during the 5-year period 1998 to 2002 (Kovacs 2006). Thus, in North America during the latter part of the 20th century, government capital expenditure on infrastructure has decreased by about half as a percentage of GDP. Table 2.6 below presents U.S. federal and state investment in infrastructure in the highway, mass transit, rail, aviation, water treatment, drinking water, and wastewater areas.

In contrast to the transportation and water infrastructure areas where government plays a dominant role, government expenditure in energy infrastructure is limited. In the United States, energy infrastructure is generally financed, owned and operated by the private sector. Private firms account for 66.4% of U.S. power generation (U.S. Congressional Budget Office 1997). The U.S. federal government owns and operates the Tennessee Valley Authority and five power-marketing associations, which together produce approximately 8.2% of the nation's electricity. With the exception of the Tennessee Valley Authority, revenues from sales of power generally exceed expenditures for operations, new construction and interest repayment. Thus, U.S. federal capital expenditures for energy infrastructure are negligible. In addition to federal power generation, municipally-owned power accounts for another 9.6% of electricity generation (U.S. Congressional Budget Office 1997).

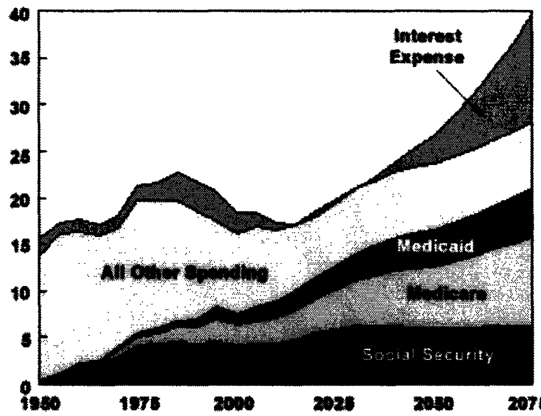
Table 2.6: U.S. Public Infrastructure Capital Expenditure (1997 US$ millions), 1956-1998

Year	Federal Capital	State/Local Capital	Total Capital	Federal Capital/GDP	Combined Capital/GDP
1956	7,969	32,686	40,654.7	0.31%	1.58%
1957	9,127	33,007	42,134.4	0.36%	1.66%
1958	13,236	33,697	46,933.5	0.52%	1.86%
1959	20,035	33,073	53,108.5	0.74%	1.97%
1960	22,449	29,618	52,066.9	0.78%	1.80%
1961	21,744	33,730	55,473.7	0.73%	1.86%
1962	22,763	35,163	57,926.5	0.73%	1.86%
1963	24,330	37,017	61,346.7	0.75%	1.89%
1964	27,335	36,152	63,486.9	0.80%	1.86%
1965	28,966	36,893	65,859.4	0.81%	1.83%
1966	28,421	38,402	66,822.2	0.75%	1.76%
1967	27,852	40,258	68,109.8	0.70%	1.71%
1968	27,726	40,098	67,823.5	0.68%	1.66%
1969	26,248	42,050	68,297.5	0.62%	1.61%
1970	24,868	40,534	65,402.2	0.60%	1.57%
1971	26,278	41,008	67,286.3	0.64%	1.64%
1972	25,836	42,318	68,153.7	0.61%	1.62%
1973	26,153	37,995	64,147.4	0.61%	1.49%
1974	26,613	34,015	60,628.1	0.62%	1.40%
1975	25,793	33,620	59,413.1	0.65%	1.50%
1976	31,484	29,275	60,758.9	0.76%	1.47%
1977	35,215	23,014	58,228.9	0.78%	1.29%
1978	33,028	24,899	57,927.2	0.69%	1.20%
1979	35,970	28,916	64,886.2	0.72%	1.30%
1980	38,561	28,946	67,507.4	0.79%	1.39%
1981	32,565	28,071	60,636.2	0.67%	1.24%
1982	28,272	26,297	54,569.4	0.60%	1.16%
1983	27,737	27,459	55,196.3	0.56%	1.12%
1984	30,382	28,392	58,773.6	0.55%	1.07%
1985	32,881	32,075	64,956.7	0.57%	1.13%
1986	34,385	35,185	69,570.1	0.57%	1.16%
1987	29,739	42,824	72,562.8	0.49%	1.20%
1988	30,608	45,299	75,906.8	0.49%	1.20%
1989	29,758	47,492	77,250.3	0.45%	1.16%
1990	31,093	48,741	79,833.9	0.46%	1.17%
1991	31,732	49,368	81,100.3	0.46%	1.18%
1992	32,667	49,621	82,288.2	0.45%	1.14%
1993	33,319	48,350	81,669.4	0.45%	1.09%
1994	33,795	48,764	82,559.3	0.44%	1.08%
1995	33,662			0.43%	
1996	32,746			0.42%	
1997	31,812			0.40%	
1998*	33,323			0.42%	

Source: U.S. Congressional Budget Office (1999). *Values for 1998 are estimated.

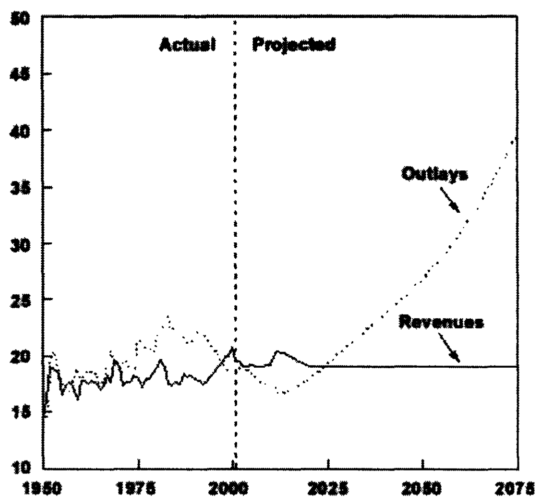
In the future, government capacity to invest in infrastructure is likely to be constrained by budget considerations due to the growing volume of public debt. The Congressional Budget Office projects that government spending on Medicare, Medicaid and debt service will increase substantially relative to current expenditures. These projections are partly influenced by an aging population, a trend that will be pervasive in all OECD countries during the first part of the 21st century (OECD 2006).

Figure 2.4: U.S. Federal Outlays by Category (% of GDP), 1950-2075



Source: U.S. Congressional Budget Office (2002).

Figure 2.5: U.S. Federal Revenues and Outlays (% of GDP), 1950-2075



Source: U.S. Congressional Budget Office (2002).

If government spending and revenue trends follow these projections, the public sector's capacity to develop carbon neutral energy and other types of infrastructure will diminish. Unless there is a dramatic change in government spending priorities, the private sector's role in infrastructure development will continue to increase in importance.

2.4 Resources Required for Developing Carbon Neutral Energy Infrastructure

The time, capital and resources required to transform physical infrastructure are the threshold requirements for the transition to meet the energy-climate change challenge. Each energy technology that might be a substitute for petroleum or other fossil fuels requires substantial investment in, and development of, carbon neutral infrastructure.

To place the magnitude of the energy-climate change transition into perspective, consider that annual global production of primary energy from all sources in 2000 was 400 EJ or 13 TW (Tester et al. 2005; Lewis 2005). Demand for primary energy is expected to grow to as much as 30 TW to 40 TW by 2050 (Hoffert et al. 1998). Stabilizing CO_2 levels below 550 ppm, 450 ppm, or 350 ppm are estimated to require emission-free energy of 15, 25, or 30+ TW by 2050 (Hoffert et al. 2002).

No single technology is capable of solving the energy-climate change challenge. Transition to a carbon neutral energy system would require maximizing energy efficiency, fuel switching to lower-carbon fuels, and adopting various renewable technologies such as geothermal, nuclear, wind, solar, and biofuels, as these have the potential to supply large volumes of energy on a carbon neutral basis. However, substantial advances in technology and investment in infrastructure are needed before these technologies could make a significant contribution to displacing fossil fuel. None of these technologies have yet been deployed on the scale necessary to meet future demand for emission-free energy.

Tables 2.7, 2.8, and 2.9 show the energy options available to society at the present time and potential new technologies and resources that may become available during the first half of the 21st century to meet the energy-climate change challenge.

Table 2.7: Current Non-Renewable Energy Technologies

Technology	Total Breakeven Busbar Price Cents/kWh (assumed fuel cost)	Cost of Construction $/kW Construction Time	Carbon Dioxide Emissions Constraints	Global Annual Private Investment 2002 US$	Global Annual Public R&D 2004 US$ million	Mean Global Annual Generation	Average Annual Global Growth Rate 1995-2002
Oil	5.7-10.8 ($20-50/bbl)	$800 3-5 Years	•1,671 lb/mWh	$92 billion	$480*	4.52 TW	1.69%
Coal	3.9-7.3 ($15-100/ton)	$1,200 3-5 years; IGCC: $1,890 5-7 years	•2,191 lb/mWh •Land/Water Waste	$12 billion (estimate)	$569	2.96 TW	1.49%
Natural Gas	2.6-4.9 ($1-4 Mbtu)	$600 1-2 years	•1,212 lb/mWh	$95 billion	$480*	2.7 TW	2.43%
Nuclear Fission	7.3	$2,400 3-6 years	•Waste •Opposition •1 GW Limit	$7 billion (estimate)	$3,115	0.828 TW	2.24%
Tar Sand and Oil Shale	Profitable at $30-45/bbl	$5-7 billion (50,000 barrel/day facility)	•5,580 lb/mWh •Land/Water Waste	6.2 billion Canadian Dollars (2004)	$18	Negligible	Not Available

Source: Lewis (2005); Tester et al. (2005); Rand (2005); International Energy Agency (2003, 2006); Herzog (2006); MIT (2006); Golay (2006); Geothermal Energy Association (2005); Woynillowicz et al. (2005); Bartsch and Muller (2000). All costs assume new baseload capacity in 2003 US$. *Note: R&D for combined Oil and Gas.

Table 2.8: Current Renewable Energy Technologies

Technology	Electricity Cost Cents/kWh	Cost of Construction $/kW	Constraints	Global Annual Private Investment 2003 (unless noted)	Global Annual Public R&D 2004 US$ million	Global Annual Technical Potential	Mean Global Annual Contribution 1998	Average Annual Growth Rate 2000-2004
Geothermal	4.7-26.7	$1,000-2,500	•Geology •Drilling	$720 million	$46	106 TW	0.3 TW	2.4% power 13% heat
Hydro*	1.9-18.6	$1,000-6,500	•Erosion •Sediment	Large: $20-25 billion Small: $4.5 billion (2005)	$29	1.5 TW	0.286 TW	2% large 7% small
Solar PV	25-50	$1,500-4,000	•Land •Intermittent •Storage	$12 billion	$500	60 TW (10% conversion)	.000013 TW	61% grid 17% off-grid
Wind	5-10	$1,500	•Land •Raptor kill •Intermittent •Storage	$8.8 billion (2005)	$121	2 TW land	.002 TW	29%
Biomass**	5-12	$2,000	•Land •Water	$960 million	$231	5-12 TW	1.21 TW	2-3%

Source: Lewis (2005); Tester et al. (2005); International Energy Agency (2003, 2006); Martinot (2006); REN21 Renewable Energy Policy Network (2005); Tester (2006). *Cost of electricity generated from hydropower is calculated assuming the construction costs cited in the table, a capacity factor ranging from 60-90%, and an annual fixed charge rate of 15%. **Note: Figures for biomass include non-renewable biomass.

Table 2.9: Speculative Energy Technologies

Technology	Estimated Minimum Time to Commercialize	Predicted Cost of Electricity Cents/kWh	Estimated Cost of Plant and Infrastructure	Other Constraints	Estimated Required R&D Investment (billions)	Estimated Global R&D (millions)
Carbon Capture and Sequestration	10 years	Additional 1.5-3 cents/kWh	Additional \$430-800/kW (approximately 37% increase)	•Geology •Leak Rates •Ocean •Regulation •100 year capacity	\$4-6	\$400-600
Gas Hydrate	25+ years (ice), Unknown (ocean)	Unknown	Unknown	•Ocean •Mining •Regulation	Unknown	U.S. \$9 (2003); Japan \$65 (2004)
Nuclear Fusion	30-50 years	5.6-16.4	Unknown	•Unproven •Low Level Nuclear Waste •Large Scale •Public Perception	\$10-15 (ITER facility)	\$707 (2004)

Source: Lewis (2005); Tester et al. (2005); International Energy Agency (2003); IPCC (2005); Herzog (2006); Tester (2006).

To illustrate the magnitude of the infrastructure change necessary to introduce these technologies on the needed scale, it is useful to consider the construction and expenditure rates to develop 10 TW of carbon neutral electricity infrastructure by 2050. To provide 10 TW of power from nuclear, the highest density fuel stock presently available, Lewis (2005) estimates that it would be necessary to build over 10,000 new 1 GW nuclear plants over the next 50 years, requiring a new nuclear plant to be built every other day for 50 years. At the present cost of \$1.5 to \$2 billion per 1 GW capacity plant, each requiring approximately six years to build (Golay 2006), such a program would cost \$17.5 trillion, or approximately \$1 billion each day for 50 years.

Achieving 10 TW of electricity using solar PV would require an even larger capital investment and a similarly challenging construction schedule. Assuming average global insolation of approximately 200 w/m^2, a system capacity factor of 15%, and solar PV panels operating at 10% efficiency, the build-out would require installation of solar photovoltaic panels covering a land mass of approximately 3.3 trillion m^2, at an installation rate of 182.6 million m^2 each day for 50 years. Cost estimates for such a project would be significantly influenced by manufacturing learning curves, [4] advances in energy conversion efficiency of

[4] Learning curves are based on the observation that repetition of the same operation results in less time or cost expended on a particular operation. For various industries, it has been shown that the time or cost required to complete a unit of production will decrease by a constant percentage each time the production quantity is doubled. If the rate of improvement is 20% between doubled quantities, then the learning curve percentage is 80% (100-20=80). See Deutch and Lester (2004) for an overview of learning curves.

solar PV technology, costs of materials used in the solar panels, installation costs, and land costs. Additional cost for energy storage would also be necessary.

To build 10 TW of generation over a 50 year period assuming a 90% learning curve, the efficiency gain of 10% is first achieved with the initial doubling of production at two million square meters of production,[5] and a nameplate price of $8/w, the total cost is estimated at $54.4 to $64.1 trillion in the aggregate, or an average of $3.0 to $3.5 billion per day for materials and installation. If a learning curve of only 95% is assumed, the total costs would increase to as much as $189.5 trillion, with average daily investment of $9 to $10 billion. These calculations do not take into account other costs such as for land, grid interconnection, operation and maintenance, and storage.

Both the nuclear fission and the solar photovoltaic technology options are limited by material constraints. We presently do not have the materials required for solar photovoltaic on this scale. Global uranium resources are also limited. Uranium resources are sufficient to operate 10,000 1 GW plants for approximately 6 to 30 years, assuming a once-through fuel cycle (Hoffert et al. 2002).

Pacala and Socolow (2004) proposed that carbon dioxide emissions could be stabilized over a 50-year period by dividing expected growth in carbon dioxide into seven equal triangles, each representing a different technology or method of decarbonizing global energy production. By dividing the 10 TW goal into equal pieces, the burden of meeting the energy-climate change challenge is shared by a broad set of technologies, companies, materials and supply chains.

Table 2.10 below presents seven carbon neutral technology wedges that might be employed to produce 10 TW of electricity generation within 50 years: nuclear fission, solar photovoltaic, wind, two wedges of coal with carbon capture and sequestration, geothermal, and the introduction of more efficient technology. Each technology provides 1.43 TW of energy.

---

[5] The historic learning curve for solar photovoltaic has been approximately 82% (EPRI 2004). However, there is evidence that the learning curve is beginning to flatten. See Nemet (2006a) for an evaluation of the factors contributing to learning effects and the limits of learning curves in solar photovoltaic technology. Learning curve calculations in the text were made using NASA's Learning Curve Calculator, available at http://www1.jsc.nasa.gov/bu2/learn.html.

Table 2.10: 10 TW Actual Generation Capacity: 50-Year Technology Wedge Scenario

Technology	50 Year Goal	Construction Rate	Expenditure Rate
Nuclear Fission	1,429 1 GW Plants	1 plant every 12 days	$139 million/day
Solar PV	476.2 billion m^2	26.1 million m^2/day	$575-$1,738.9 million/day
Wind	794,444 3 MW land turbines	44 turbines/day	$130.6 million/day
	595,833 3 MW offshore turbines	33 turbines/day	$196 million/day
Coal Plus Carbon Capture and Sequestration	6,730 500 MW IGCC Plants	1 plant every 2.5 days	$348 million/day
	692.8 billion metric tonne CO_2 sequestration capacity	Additional 543.3 million metric tonne CO_2 capacity/year	$39.7-$1,071.7 million/day*
Geothermal	21,200 75 MW plants	1.2 plants/day	$87-$218 million/day
Improved Efficiency	1.43 TW saved	0	0

Note: Nuclear estimates are based on Lewis (2005), described in the main text preceding this table. Solar estimates are based on a 15% capacity factor (Connors 2006), and 10% peak efficiency panels rendering 20 w per square meter starting at $8/w installed cost on a nameplate basis (Lewis 2006). Solar costs are average daily cost over a 50-year period based on a learning curve of 90% to 95%, with the first doubling of production occurring upon completion of the second million square meters of solar panels. Actual first day cost would start at approximately $2.9 billion. Learning curve calculations were made using NASA's Learning Curve Calculator, available at http://www1.jsc.nasa.gov/bu2/learn.html. Wind installed cost is $1 million/MW onshore (Lyons 2006) and $2 million/MW offshore; 30% capacity factor onshore and 40% capacity factor offshore (Connors 2006). IGCC estimates assume an 85% capacity factor and $1,890/kWe capital costs (Herzog 2006; and MIT 2006). Carbon sequestration capital costs are assumed to be $26.67/metric tonne based on a $5/tonne annual levelized cost for oil or gas reservoir storage (Herzog 2006), 20% O&M costs and a 15% capital charge factor (Herzog 2006; MIT 2006; Heddle et al. 2003); other sequestration data is from MIT (2006). Geothermal estimates assume a 90% capacity factor, average plant size of 75 MW, and construction costs of $1,000 to $2,500/kW. *Because the amount of carbon sequestered increases each year due to additions of capture-ready generation facilities, daily sequestration cost figures range from $39.7 million at the beginning of the 50-year period to $2.0 billion by the end of the 50-year period if reserves are not set aside to cover future costs.

Developing 10 TW of carbon neutral electricity generation capacity will require periodic replacement of equipment. Coal, nuclear and geothermal plants are assumed to have 50-year lifetimes and thus the rate of expenditure in Table 2.10 must be maintained for these technologies in order to maintain their respective share of 10 TW of generation. This is a conservative assumption with respect to cost estimates because all of these technologies require substantial upgrades during their assumed operating life. Solar and wind technology are assumed to have much shorter lifetimes, and thus the figures above must be augmented to maintain their respective share of 10 TW of capacity. The average lifetime of a solar PV cell is approximately 30 years (Moritz 2006); the average life of a wind turbine is approximately 20 to 30 years (Iowa Energy Center 2006). Table 2.11 sets forth the estimated construction and investment rates for the solar and wind technology wedges once replacement of equipment is necessary starting in years 31-50 for solar PV and years 21-50 for wind.

Table 2.11: Investment Rates with Replacement for Solar and Wind Technology Wedges

Technology	Lifetime	Construction Rate (with replacement)	Expenditure Rate (with replacement)
Solar PV	30 years	52.2 million m^2/day from years 31 to 50	\$722.2-\$2,748.5 million/day from years 31 to 50*
Wind	20 years	88 land turbines/day from years 21 to 40; 132 land turbines/day from years 41 to 50	\$261.2 million/day from years 21 to 40; \$391.8 million/day from years 41 to 50
		66 offshore turbines/day from years 21 to 40; 99 offshore turbines/day from years 41 to 50	\$784 million/day from years 21 to 40; \$1,176 million/day from years 41 to 50

*Solar PV figures are based on the final unit of production costs for the 50-year build out, assuming 90% and 95% learning curves.

Solar and wind power are intermittent sources. Sun is available 50% of the time at best, with intensity varying with time of day and local conditions. A global capacity factor is difficult to determine, but 15% can be used for purposes of estimation (Connors 2006). Wind generation capacity factors are approximately 30% onshore and 40% offshore (Tester et al. 2005; Connors 2006). Due to the intermittency of these sources, supporting storage capacity is necessary to ensure supply. Table 2.12 below presents the estimated capital cost and build-out of pumped hydropower and compressed air energy storage technologies for 1 TW of global energy storage capacity, taking into consideration inefficiency losses. The 50-year storage goal is intended to be illustrative only and would change depending on actual usage patterns and advances in technology.

Table 2.12: 1 TW Global Energy Storage Capacity

Storage Technology	50 Year Goal	Construction Rate	Expenditure Rate
Pumped Hydropower	1,333 500 MW systems to store 0.5 TW	1 system every 14 days	\$29.2 million/day
Compressed-Air Energy Storage	1,539 500 MW systems to store 0.5 TW	1 system every 12 days	\$33.7 million/day

Note: Pumped hydropower assumes 75% net efficiency and \$800/kWe capital costs. Compressed-air storage assumes 65% net efficiency and \$800/kWe capital costs (Tester et al. 2005). Net efficiency estimates include both input and output efficiency losses.

Using the technology wedge approach, the material and capital required to meet a 10 TW goal of carbon neutral electricity is substantial. Required infrastructure investment for generation starts at $1.5 to $2.8 billion per day. Replacement costs would increase capital investment starting in year 21 from $2.2 to $3.5 billion per day, in year 31 from $2.3 to $4.5 billion per day, and in year 41 from $2.9 to $5.0 billion per day. If reserves are not set aside for future carbon sequestration costs, carbon sequestration capital costs associated with coal-fired generation could grow from approximately $40 million per day to $2.0 billion per day by 2050. Developing 1 TW of storage to supplement intermittent wind and solar generation would add an additional $63 million investment per day.

Table 2.13: 10 TW Years 1-50 Daily Investment with CCS, Energy Storage, and Solar and Wind Equipment Replacement (US$ millions)

Year	Generation Investment	Storage Capacity Investment	Average Carbon Sequestration Investment	Total Investment
1-20	1,475.7 – 2,770.5	62.9	416.8	1,955.4 – 3,250.2
21-30	2,194.3 – 3,489.1		1,012.2	3,269.4 – 4,564.2
31-40	2,341.4 – 4,498.7		1,409.1	3,813.4 – 5,970.7
41-50	2,864.0 – 5,021.3		1,806.1	4,733.0 – 6,890.3

Source: Author's calculations. See Table 2.10 through Table 2.12.

A number of points should be taken into consideration in relation to these estimates. These estimates are for electricity generation only. Currently, approximately 4 TW of global primary energy consumption is electricity generation (Tester 2006), which accounts for approximately 25% of primary energy consumption in industrialized countries, and about 18% worldwide (Tester et al. 2005). Electricity demand is expected to double by 2025 (EIA 2005b; International Energy Agency 2003), and increase as a portion of primary energy consumption within the earlier part of this century due to increased development (Connors 2006). Stabilizing CO_2 levels below 550 ppm, 450 ppm, or 350 ppm are estimated to require 15, 25, and 30+ TW of emission-free power by 2050, respectively (Hoffert et al. 2002). Demand for 10 TW of emission-free electricity with the goal of stabilizing emissions in the electricity sector over a 50-year period is a reasonable projection. Because these estimates focus exclusively on electricity generation, additional investment in infrastructure will be necessary to address other energy demands, especially for liquid fuels and transportation.

The cost estimates presented in Table 2.10 through Table 2.13 do not include the cost of maintaining or replacing existing and future conventional energy infrastructure. The International Energy Agency estimates that global conventional energy investment from 2000 to 2030 will exceed $16 trillion. Of this amount, approximately $3 trillion is required for each of oil and gas, $400 billion for coal, and $10 trillion for electricity infrastructure (International Energy Agency 2003). This requires investment in fossil fuels and related infrastructure of approximately $1.5 billion per day for the next 30 years. Of the IEA's total $16 trillion estimate, more than half is to maintain infrastructure (International Energy Agency 2003). Similarly, of the $10 trillion projected investment in electricity infrastructure, over half of total investment will be to replace or maintain existing and future capacity (International Energy Agency 2003).

These figures do not include operation and maintenance costs for carbon neutral electricity generation, which can be considerable. Nor do these figures fully include capital equipment upgrades and replacement. Replacement costs are included for solar and wind plants, but are omitted for coal, geothermal, and nuclear plants. Although coal, geothermal, and nuclear plants are assumed to have 50-year lifetimes, all of these plants require capital equipment upgrades within that time frame.

Costs to connect to the grid or additional investment in reserve, transmission and distribution infrastructure are not reflected in these estimates. Also additional investment in resource extraction and supply infrastructure, such as for coal and uranium, are not included in these estimates.

No analysis was performed to determine whether the selected technologies or other technologies share common attributes with respect to supporting infrastructure that would allow their integration on the most cost-efficient basis. A technology cluster analysis may lead to selection of a different set of technologies with different direct and supporting infrastructure cost characteristics (Schrattenholzer et al. 2005).

These estimates do not include the cost of land, which can add substantial costs, particularly in the cases of solar and wind. Nor do these estimates include the cost and time of conducting site surveys, site preparation, and obtaining approvals and meeting regulatory requirements. All of the technologies require significant amounts of time to locate and verify appropriate sites for plants and to obtain regulatory approvals. For example, carbon sequestration and geothermal require extensive geologic surveys and site preparation.

Costs associated with protecting energy infrastructure from climate change or adaptation to climate change are not included in these estimates. The World Bank estimates that climate change could impose adaptation costs of $10 billion to $40 billion per year world-wide, approximately two thirds of which would fall on the private sector (World Bank 2006a). Other estimates range from $61 to $335 billion (1990 dollars) per year for the United States alone (Gallon 2002), and from $40 to $522 billion (with standard deviation $150 billion) for the world, depending upon how losses to different countries are valued and weighted (Tol 2002). The wide variability in these estimates reflects the range of different assumptions used in producing these estimates, lack of data, and the difficulty of estimating costs (Tol 2002).

These estimates are also subject to a number of important assumptions stated in the notes to the respective tables. As demonstrated above in the case of solar, increasing efficiency due to learning can significantly reduce technology costs. A learning curve was assumed in the case of solar. No learning curve was attributed to any other technology. With respect to carbon sequestration, economies of scale may be available to larger projects (Herzog 2006), which are not reflected in the cost analysis.

The absence of learning effects is not a standard assumption. However, the magnitude of learning effects is highly uncertain. The IEA's 2003 study of energy infrastructure investment for the 2001-2030 period estimated a large learning curve for solar technologies, and relatively small learning curves for other technologies (International

Energy Agency 2003). In some cases, such as in the case of wind technology, recent increases in materials costs and market conditions have caused energy technologies to increase in overall cost (Lyons 2006).

These estimates assume that each industry segment can meet demand, has adequate supply of inputs, and can complete construction at the rates specified. Nuclear, solar, and wind generation industries would have to grow exponentially to achieve these growth rates. As described in Chapter 4, supply of raw materials and skilled labor are substantial risks to the ability of the private sector to meet these targets.

Natural gas-fired generation technology was not selected as one of the technologies because the long-term cost of electricity from coal with carbon capture and sequestration is expected to be lower than electricity produced from natural gas with carbon capture and sequestration (Connors 2006). This assumption is contrary to projections that reliance on natural gas for electricity generation will increase substantially in the future. IEA estimates that conventional gas-fired electricity generation without carbon capture will double in the 2001 to 2030 period (International Energy Agency 2003). Changing the energy mix to include natural gas-fired generation would increase the cost estimates for carbon neutral electricity infrastructure if carbon capture and sequestration technologies are implemented with new natural gas-fired generation plants.

Finally, several of these technologies are not truly sustainable over extended periods of time. Pacala and Socolow (2004) acknowledged that the technology wedge approach only provides a 50-year bridge, and that new technologies must be identified and commercialized during the latter part of this century to solve the energy-climate change challenge. Carbon sequestration could provide approximately 100 years of storage based on an estimated 2,000 Gt of global carbon dioxide storage capacity and current emissions rates of approximately 23.5 Gt of carbon dioxide per year from fossil fuels (IPCC 2005; Herzog 2006). Given the magnitude of nuclear technology adoption contemplated here, uranium resources are probably adequate for approximately 40 to 300 years based on current projections (Hoffert et al. 2002) and reprocessing would only be capable of extending uranium a matter of decades on this scale. A build-out on the scale contemplated here would ultimately require a transition to fast breeder nuclear reactor technology (Bunn 2006). Only a few fast-breeder reactors are in operation today due to concerns over proliferation and their comparatively high costs, however the future goal is to achieve costs that are equal to or approximately 20% higher than light water reactors (Bunn 2006). Similarly, increased dependence on coal may also be unsustainable during this century for certain countries. For example, at projected rates of consumption, coal resources in China could provide less than 100 years of supply, much less than historic estimates based on past consumption rates (Yu Bing 2006).

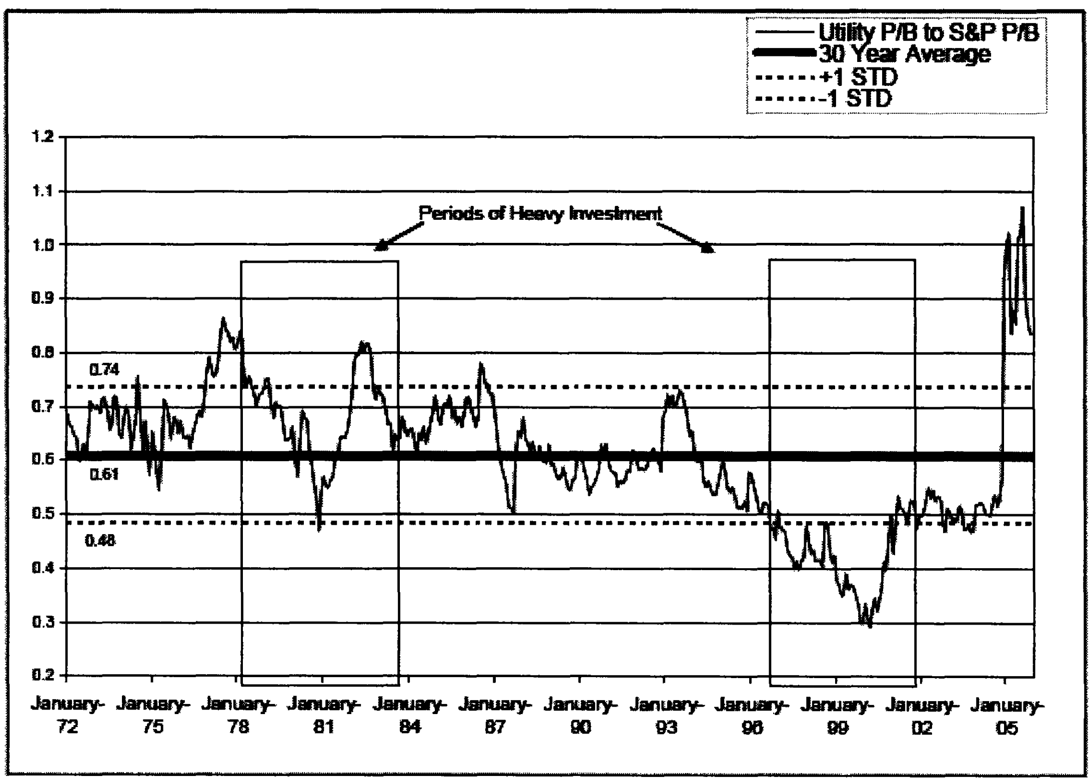
2.5 The Private Sector's Capacity to Transition to Carbon Neutral Infrastructure

It is important to consider the capacity of the private sector to undertake a transition of this magnitude and its effects on private firms.

Some companies will benefit while others may face substantial risk. Suppliers of materials and labor will clearly benefit. However, for the utilities that purchase these materials, evidence suggests that an expansion of generation of the magnitude contemplated here will have negative effects on firm profits, stretch debt capacity, and depress stock prices due to the delay in recovering capital and return on investment. Further, the transformation of infrastructure within a time frame designed to prevent the build up of potentially dangerous concentrations of greenhouse gases in the atmosphere would likely require early retirement of some existing energy infrastructure. Pre-mature retirement of capital equipment results in losses on account of prior capital investment, places additional demands on firms for new capital investment, and could adversely affect the financial stability and competitiveness of firms.

Figure 2.6 below demonstrates the effect of increases in capital investment on the price to book ratios of utilities from 1972 to 2005. In general, increases in capital investment in the utilities industry are accompanied by lower industry performance as financial markets anticipate that recovery of capital investment will occur many years in the future, increase overall firm risk, and worsen key financial ratios measuring current performance, such as return-on-assets.

Figure 2.6: Relative Price to Book Ratio – Utilities versus S&P 500, 1972-2005



Source: Lehman Brothers (2006).

The availability of capital will also likely be an important variable in developing carbon neutral infrastructure. The magnitude of investment required to achieve 10 TW of carbon neutral electricity using the technology wedge approach is approximately $2 billion to $5.2 billion per day for 50 years. To place this in perspective, current private investment in all forms of infrastructure on a global project finance basis was estimated to be $120 billion in 2005 (Dealogic 2006b).

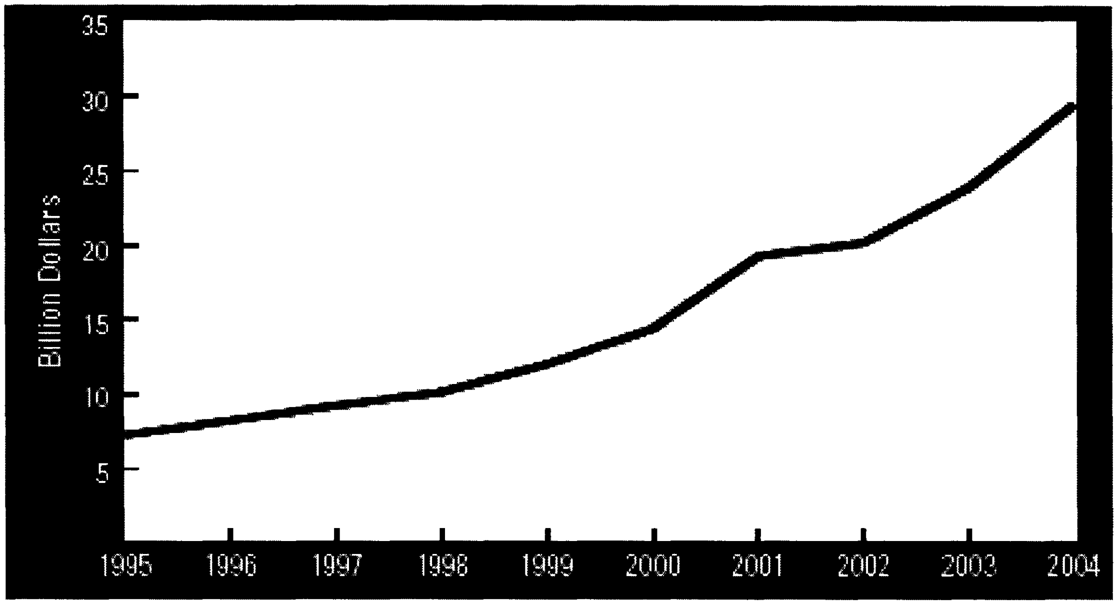
The investment required to meet this challenge could strain capital markets and companies. Capital investment on such a large scale will expose firms to greater risk from increases in interest rates. Large capital investments also make these companies more vulnerable to risks from economic downturn and competition.

Finally, this challenge will require an abrupt change in capital expenditure patterns. Current capital and material flows must be redirected towards nuclear and renewable energy technologies. As noted in Table 2.7, the majority of primary energy investment is for fossil fuel and related infrastructure. Annual investment in oil and gas is $92 and $95 billion, respectively. Approximately 850 conventional coal plants are under construction (Hoffert 2006). Annual coal industry investment is estimated at $12 billion per year. In addition, conventional power generation, transmission and distribution is projected to require investment of approximately $250 billion annually through 2030 (International Energy Agency 2003).

In contrast, investment in nuclear and renewable energy are currently far behind required levels for the development of a carbon neutral energy infrastructure. Today, approximately twenty-four nuclear plants are under construction (Thomas 2005). With an average construction time of six years, annual investment in nuclear is approximately $7 billion, representing 3.7% of aggregate annual investment in oil and gas.

Renewable energy technologies, while growing rapidly, are starting from a small base and are similarly a small fraction of investment in oil and gas. From 2000 to 2004, solar PV grew at an annual average growth rate of 60%, the largest percentage increase of any renewable energy technology (REN21 Renewable Energy Policy Network 2005). During the same period, wind power grew at an average annual growth rate of 28% (REN21 Renewable Energy Policy Network 2005). To place these investment levels in perspective, wind generation investment was $8.8 billion in 2005, the largest of any renewable energy technology (Dealogic 2006a), which represents only 4.5% of aggregate annual investment in oil and gas. At the end of 2005, wind provided only approximately 17 GW of energy globally (REN21 Renewable Energy Policy Network 2005).

Figure 2.7: Global Annual Investment in Renewable Energy, 1995-2004



Source: REN21 Renewable Energy Policy Network (2005). Note: includes wind, solar PV, solar thermal, geothermal, small hydropower, biomass power and heat.

In light of current energy investment patterns, a 50-year time frame to achieve a carbon neutral energy infrastructure appears unrealistic. Yet, the urgency of addressing climate change is growing. Because of the long-time frame for implementing carbon neutral infrastructure, we must now factor climate change risk into infrastructure investment decisions. Transforming our energy infrastructure is preferably taken before irreversible damage is done to the climate and while society has the capacity to implement these changes. Importantly, waiting could mean transforming fossil fuel infrastructure to carbon neutral infrastructure after the onset of increased climate risk or petroleum resources become expensive or scarce. Thus, an early start to developing carbon neutral infrastructure is essential if we are to ultimately succeed in making this transition.

2.6 Climate Risk and Development of Infrastructure

If society's transition to carbon neutral infrastructure starts after the effects of climate change have begun to be felt, climate change itself may present significant risks to the private sector's ability or willingness to develop physical infrastructure to meet this challenge.

Energy and other critical infrastructure play a profound role in the ability of a society to develop towards a more sustainable carbon path. Critical infrastructure defines the technology options available to society at any given time (Schrattenholzer, et al. 2005). Further, the choice of energy infrastructure strongly influences society's carbon output because energy systems convert, transport and consume fuel, and they are platforms for other energy-intensive technologies.

In total, critical infrastructure and related technologies determine society's carbon generation path for the period during which they are operational (Unruh 2000, 2002; Unruh and Carrillo-Hermosilla 2006; Grubler 1998; Smil 2003). In the cases of buildings and structures, energy conversion systems, and transportation infrastructure, the lifetime of dominant infrastructure is typically measured in decades or centuries (Grubler 1998). Any competing technology that requires the development of new infrastructure can be expected to compete at a cost disadvantage to established fossil fuel technologies because the dominant physical infrastructure favors incumbent technologies.

The private sector's ability to finance development of infrastructure may be adversely affected by increased climate risk. Although the transition to a low-carbon economy and climate change can be expected to encourage development of new technologies, it is not clear that they will produce favorable conditions for investment in new infrastructure. This is partly due to the longer time horizons and large capital commitments required for infrastructure investment.[6] Infrastructure development involves large engineering projects that often require ten to twenty years from the planning stage to completion, and often that many additional years or more to recover the original investment. The large capital commitments and long time frames for recovery of investment exposes infrastructure to the longer-term risks posed by climate change.

Table 2.14: Expected Lifetimes of Selected Infrastructure

Infrastructure	Phase	Typical Expected Life
Buildings	Alterations Demolition	15-20 years 50-100 years
Bridges	Maintenance Resurface Concrete Reconstruction	Yearly 20-25 years 60-100 years
Seaports	Major refurbishment Reconstruction	10-20 years 50-100 years
Rail	Major Refurbishment Reconstruction	10-20 years 50-100 years
Hydropower plant	Decommissioning	75+ years
Coal Plant	Decommissioning	45+ years
Nuclear plant	Decommissioning	30-60 years
Gas turbines	Replacement	12-20 years

Adapted from: WBCSD (2005); Auld and MacIver (2005). Note: Estimates reflect rates at which new technologies are expected to enter the economy.

[6] A distinction should be made between infrastructure finance, which is the dominant model for financing infrastructure, and venture finance, which is a method for financing technology. In contrast to infrastructure finance, venture finance typically involves financing the development of individual technologies, usually with the intention of commercializing a technology within a 3-5 year period and then achieving a liquidity event for investors through a public offering of equity or the sale of the company. Given these short time frames, venture finance does not develop large infrastructure and climate risk does not play a significant role for venture finance investment.

It is possible that the risks posed by climate change will make large capital investments in new energy and other infrastructure more risky, thereby slowing transition to carbon neutral energy infrastructure. For example, increasing climate risk could jeopardize the private sector's capacity to plan, finance, implement, and manage the development of infrastructure. Climate risk could undermine the ability of firms to accurately evaluate and allocate risk, and thus reduce their ability or willingness to invest in carbon neutral infrastructure in a timely manner.

3 Climate Change Risks

The chapter reviews the state of climate change science and, based on models and scientific literature, describes global changes that are expected to occur in this century.

The purpose of this chapter is to provide a foundation for Chapter 4, which analyzes how climate change may potentially increase financial risks for the development of infrastructure.

This chapter first provides an overview of climate change science. It then analyzes the expected primary physical effects of global warming that directly affect infrastructure:

Higher minimum and maximum daily temperatures;
More intense flooding and drought;
Increased summer drying and wildfires;
Increased storm intensity; and
Sea level rise.

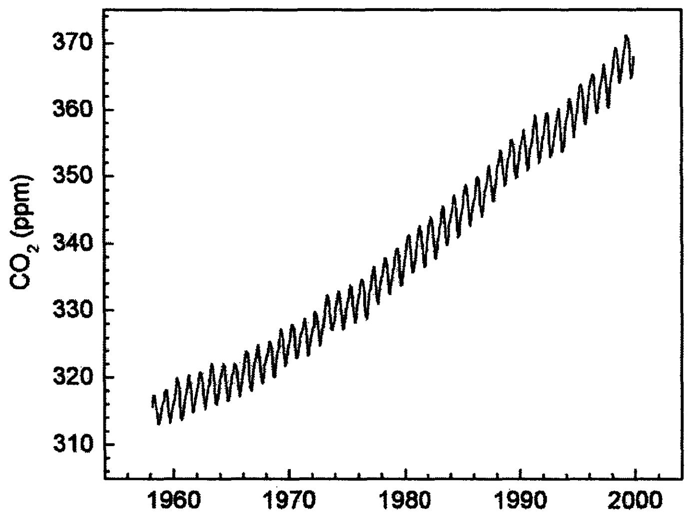
The chapter concludes by summarizing climate risks and their potential effects on infrastructure.

3.1 Overview of Climate Change Science

The basic science of global climate change was first developed in the 19th century. In 1827, Jean Fourier, a French mathematician and physicist, discovered that heat from the sun absorbed by the earth was reflected back to the Earth by its own atmosphere. Fourier identified carbon dioxide as the gas responsible for trapping solar heat in the atmosphere and coined the term "greenhouse effect". In 1860, John Tyndall, an English scientist, determined that water vapor and carbon dioxide are the two most powerful heat-absorbing gases in the atmosphere. In 1896, the Swedish chemist Svante Arrhenius predicted that our increasing reliance on fossil fuels, particularly coal, would cause large quantities of carbon dioxide to be released into the atmosphere. He predicted that if atmospheric carbon dioxide doubled, the Earth would become warmer by as much as 5 to 6°C. Arrhenius was the first to identify burning fossil fuels as a potential cause of climate change (King 2005).

Climate change science advanced rapidly during the latter half of the 20^{th} century due to data collection, experimentation, and the use of models to characterize the chemistry and physics of the role of greenhouse gases in maintaining the climate of the atmosphere, oceans, and terrestrial systems. In 1957, Roger Revelle and Hans Seuss, scientists at the Scripps Institute of Oceanography, observed that the oceans do not absorb much of the carbon dioxide emitted to the atmosphere, leaving significant amounts in the atmosphere, which could eventually warm the Earth. In 1958 Revelle and Charles D. Keeling established the National Oceanic & Atmospheric Administration's Mauna Loa Observatory, which was the first center for monitoring carbon dioxide far from industrial sources. After only two years, the Mauna Loa Observatory confirmed a trend of increasing levels of carbon dioxide in the atmosphere. Plotted temporally, the data shows seasonal changes in carbon dioxide as plants absorb and release carbon dioxide. This seasonal cycle is driven by the land-based vegetation absorbing carbon dioxide during the summer and then releasing it through decay in the fall and winter. With more land surface in the northern hemisphere, this leads to a minimum during the northern hemisphere summer and a maximum in the northern hemisphere winter.

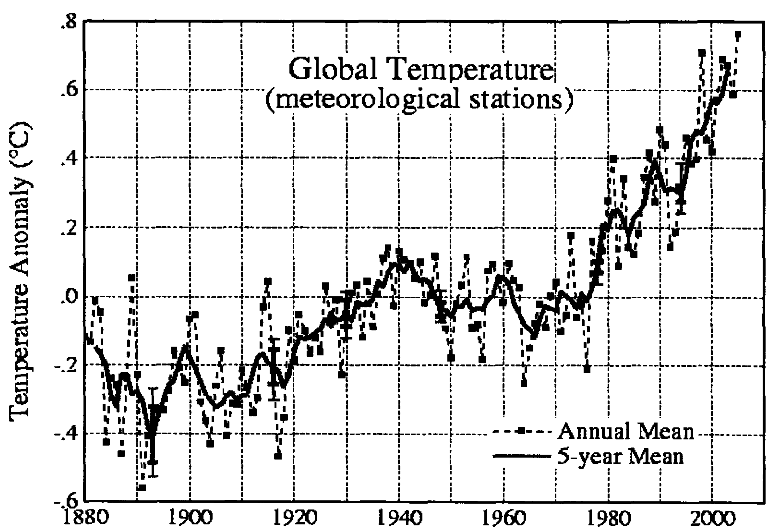
Figure 3.1: Observed Carbon Dioxide Concentrations, 1960-2000



Source: NOAA Mauna Loa Observatory (2006).

Global mean temperature has also steadily increased during the 20th century.

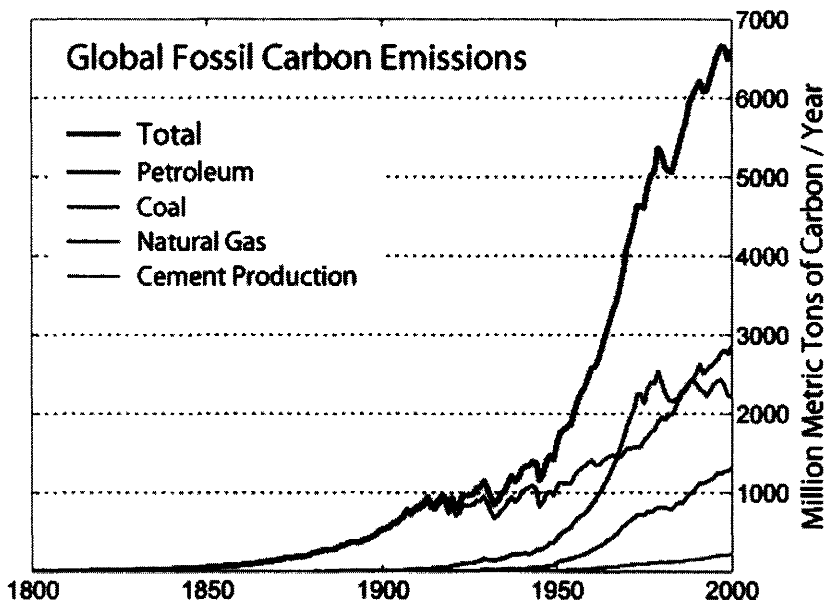
Figure 3.2: Observed Global Average Temperature, 1880-2000



Source: GISS (2006).

Consistent with Arrhenius's predictions, increasing carbon dioxide levels and global average temperature correlate with carbon emissions from burning fossil fuels.

Figure 3.3: Global Fossil Carbon Emissions, 1800-2000



Source: Marland, G., T.A. Boden, and R. J. Andres (2003).

In 1979, the First World Climate Conference was held in Geneva to study erratic weather patterns during the prior decade (Northern Territory University 2006). The U.S. National Academy of Sciences and the U.S. Environmental Protection Agency soon thereafter completed their own studies concluding that anthropogenic sources of carbon dioxide were likely responsible for observed changes in carbon dioxide levels and that waiting to take action on climate change could result in permanent damage to the environment and potential disruption to society. The National Academy reported that a doubling of atmospheric carbon dioxide from pre-industrial times would eventually warm the Earth by 3°C +/- 1.5°C (Ad Hoc Study Group on Carbon Dioxide and Climate 1979). In 1988, the United Nations established the Intergovernmental Panel on Climate Change (IPCC), bringing together scientists from a broad range of disciplines to study climate change. According to the IPCC, carbon dioxide concentrations in the atmosphere have increased from the pre-industrial level of 280 ppm and now exceed 377 ppm, methane (CH_4) has increased from 700 ppb to 1745 ppb, and nitrous oxide (N_2O) has increased from approximately 270 ppb to about 314 ppb (IPCC 2001; Blasing and Smith 2006). There is evidence that carbon dioxide levels in excess of 450 ppm may pose a "dangerous" level of interference with the climate system (O'Neill and Oppenheimer 2002).

With the exception of water vapor, the Kyoto Protocol regulates the emission of the six most significant greenhouse gases. In addition, the Montreal Protocol regulates the production of chlorofluorocarbons.

Table 3.1: Regulated Greenhouse Gases

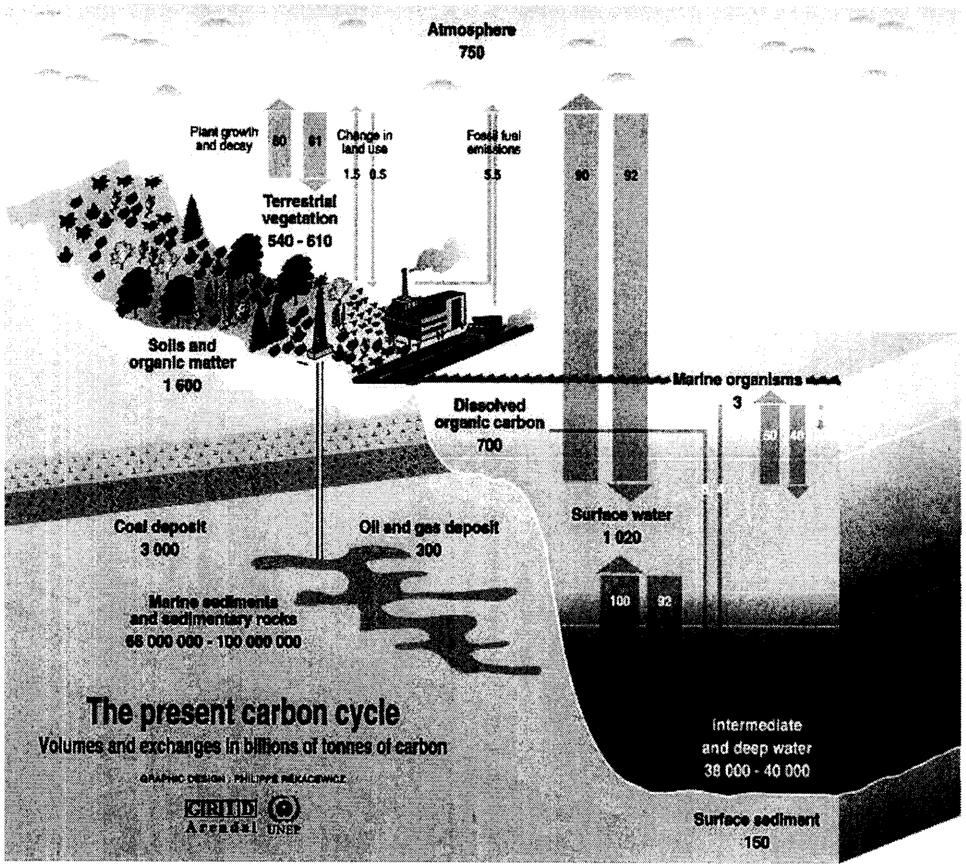
Gas	Global Warming Potential	Pre-Industrial Concentration	Concentration in 1998	Lifetime (years)	Primary Sources
Carbon Dioxide (CO_2)	1	278,000 ppb	377,300 ppb (2004)	5-200	•Fossil fuels •Land use •Cement production
Methane (CH_4)	23	700 ppb	1,745 ppb	12 (varies with local atmospheric pollution)	•Fossil fuels •Rice paddies •Waste dumps •Livestock
Nitrous Oxide (N_2O)	296	270 ppb	314 ppb	120	•Fertilizer •Combustion •Industrial processes
CFC-12	6,200-7,100	0	0.503 ppb	102	•Coolants •Foams
Hydrofluorocarbons (HFCs)	12-12,000	0	0.105 ppb	12, 1	•Coolants
Perfluorocarbons (PFCs)	5,700-11,900	0	0.070 ppb	50,000	•Aluminum production
Sulphurhexafluoride (SF_6)	22,000	0	0.032 ppb	3,200	•Dielectric fluid

Source: IPCC (2001); Blasing and Smith (2006). Note: ppb is parts per billion by volume.

The Earth, its oceans, and atmosphere are characterized by a carbon cycle, in which carbon is trapped by land, ocean, or atmosphere. Land sinks include vegetation, geologic formations, and living organisms. Ocean sinks include both living organisms and chemical interaction with surface waters. A balanced carbon cycle releases carbon to the atmosphere (through decay or combustion) at a rate equal to carbon absorbed by vegetation or ocean mixing, or destroyed through chemical interactions in the atmosphere.

Because land and oceans absorb and release carbon gradually, the rapid introduction of large-scale carbon-emitting industry can overwhelm nature's ability to maintain the carbon balance. Today, approximately 3 gigatons of carbon (or carbon equivalent) released into the atmosphere each year are not absorbed by land or ocean sinks (University of Washington 2002).

Figure 3.4: The Present Carbon Cycle

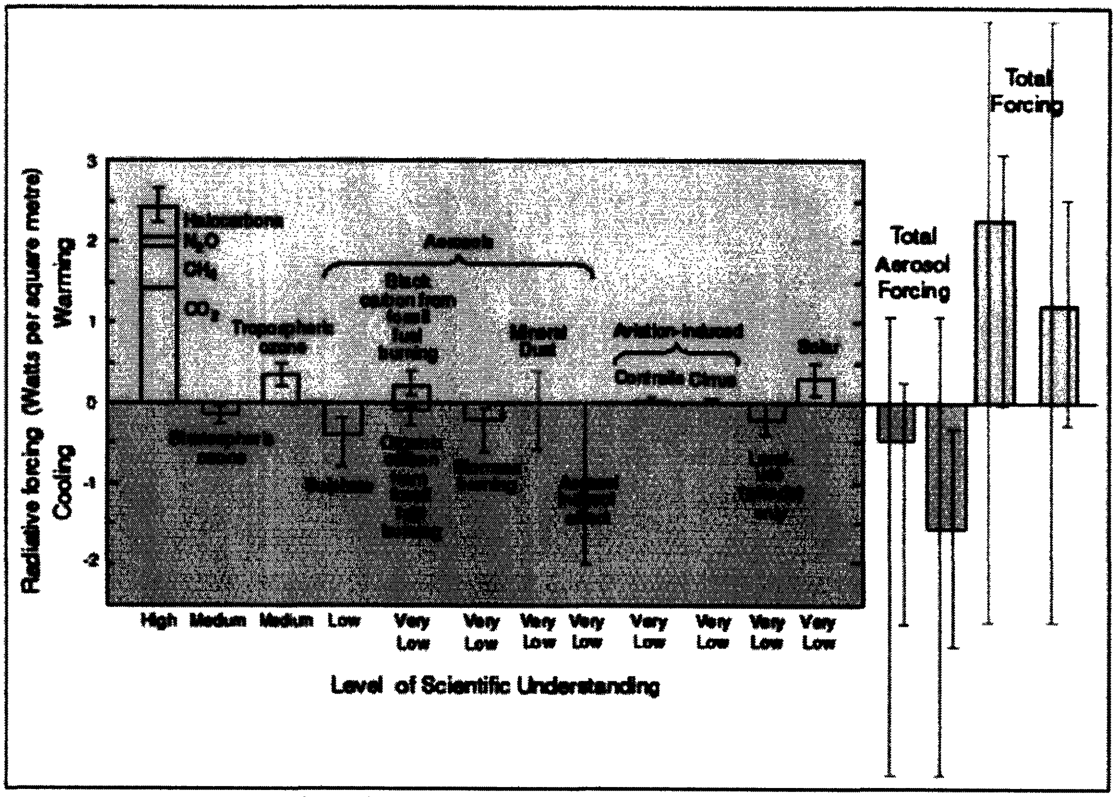


Sources: Center for climatic research, institute for environmental studies, university of Wisconsin at Madison; Okanagan university college in Canada, Department of geography; World Watch, November-December 1998; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge press university, 1996.

Source: UNEP Grid Arendal (2006).

Although there is near unanimity in the scientific community that global warming is occurring primarily as a result of carbon dioxide building up in the atmosphere, there is considerable debate and uncertainty over the magnitude of the risks presented by climate change and their timing (Oreskes 2004). Uncertainty persists for several reasons. First, climate change data remains incomplete and subject to significant measurement error. Second, we still possess a limited understanding of the complexity of interactions among oceans, atmosphere and terrestrial sinks, and the effects of clouds, aerosols, and the transport and interactions among gases. As a result, our ability to accurately predict the extent of future temperature change is subject to error. Further, recent research suggests that many models have underestimated the future potential increase in temperature change due to gaps in our scientific understanding of climate interactions (Forest et al. 2006). Finally, evaluating the potential physical and economic effects of climate change is difficult. Physical and economic damage estimates are further complicated by the fact that climate change will affect different areas in unique ways, and have uncertain effects on agriculture.

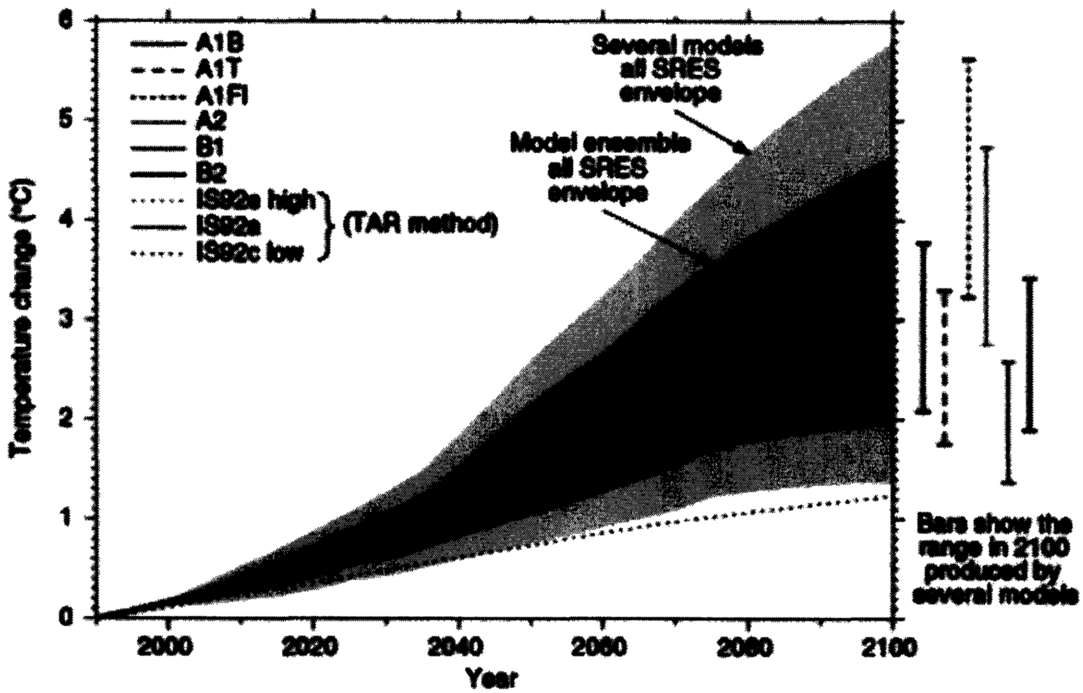
Figure 3.5: Radiative Forcing and Level of Scientific Understanding



Source: Schwartz, S.E. (2004)

To manage the complexity of climate interactions, researchers have developed computer models to estimate emissions of greenhouse gases and other relevant substances from human activities, the resulting atmospheric carbon dioxide levels, and associated global temperature change. These models range in methodology and complexity, but all of them are limited in their utility by lack of observational data and their output is subject to the accuracy of assumptions that were made in their design. Current models are either too complex to provide calibrated predictions or too general to provide information relevant for local effects. Models that include an economic component often lack or possess only a rudimentary method for calculating damages to the environment and economy due to climate change. Despite these shortcomings, climate models represent our best understanding of climate science and are valuable tools to characterize the relationships between the various natural and anthropogenic factors that affect global climate and to analyze potential carbon emission trajectories and policies. Figure 3.6 below summarizes projections for global average temperature increases from several leading climate systems models assuming six illustrative emissions scenarios. These scenarios range from reductions in carbon intensity and the introduction of clean and resource-efficient technologies, to a scenario featuring high energy and carbon intensity and correspondingly high greenhouse gas emissions.

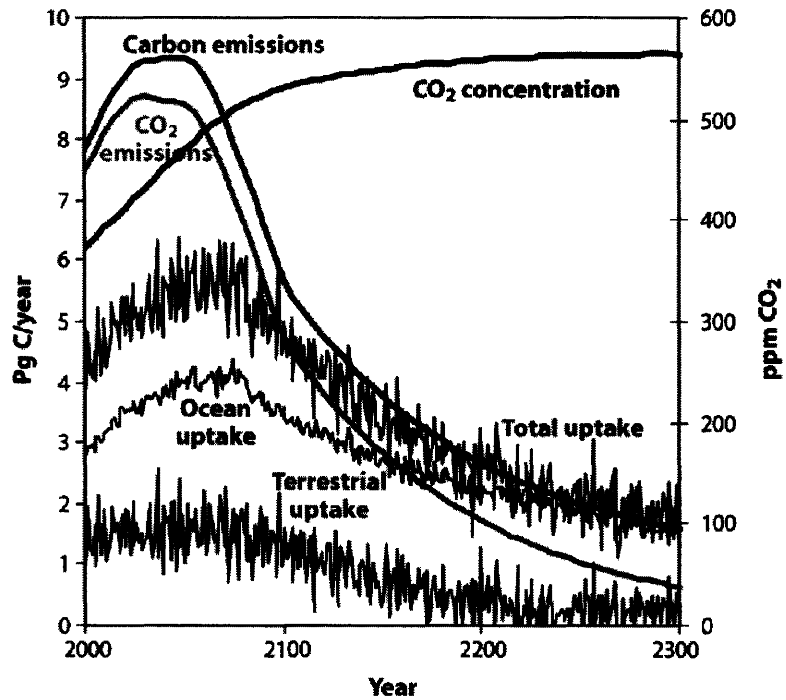
Figure 3.6: Predicted Global Warming under Six SRES Emissions Scenarios



Source: IPCC (2001).

Climate systems models that estimate future carbon uptake of the Earth's atmosphere, ocean, and terrestrial systems show that stabilizing atmospheric carbon dioxide levels requires greenhouse gas emissions to decrease to close to zero emissions (Sarofim et al. 2004; Hoffert et al. 2002). The MIT Integrated Global System Model (MIT IGSM) predicts a 95% probability that global mean temperature will increase from 1 to 5°C by 2100 if no climate policy is implemented (Webster et al. 2003).

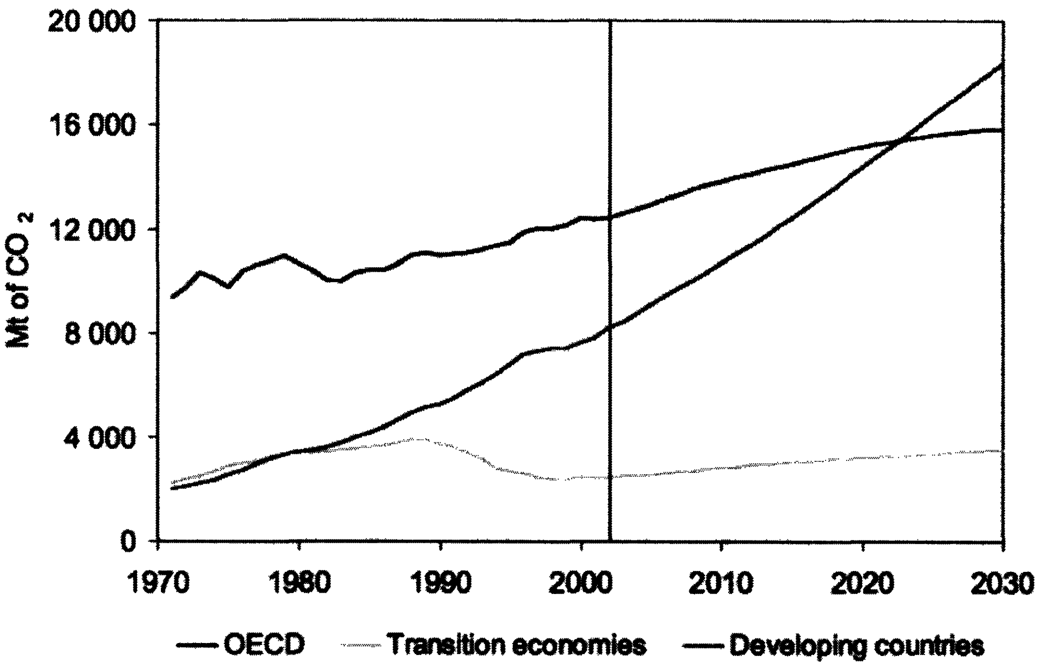
Figure 3.7: Stabilization Scenario for CO_2 at 550 ppm, 2000-2300



Source: Sarofim et al. (2004). Note: Annual average uptake, emissions and concentrations are shown based on restricting carbon dioxide emissions only. Because other greenhouse gases emissions continue, the pictured scenario does not stabilize radiative forcing.

Based on results from the MIT IGSM, stabilizing carbon concentrations at 550 ppm by 2300 requires reducing carbon emissions to less than 2 Pg/year by 2200 (Sarofim et al. 2004). Experiments with a simplified version of the MIT IGSM show that these reductions require an almost 100% shift to non-fossil energy sources by all major industrialized nations and large developing countries or the ability to sequester carbon emissions on a global scale (Hart 2004). Such a transition is not realistic in the near future from either a political or technical point of view given current trends. Emissions of the United States, China, India, and Brazil are presently not subject to any limits and all are expected to increase substantially in the future. By 2020, carbon emissions are projected to double compared to levels at the end of the 20th century due to population growth, increasing energy consumption levels, and increasing reliance on fossil fuels (EIA 2001).

Figure 3.8: Historic and Projected Carbon Dioxide Emissions, 1970-2030



Source: International Energy Agency (2004).

Greenhouse gas emissions are certain to further increase as long as current demographic and energy consumption patterns continue. The potential effects of unabated greenhouse emissions include increasing global mean temperatures, glacial ice melt, more volatile weather patterns, and sea level rise. Significantly, a modest increase in global mean temperature causes more extreme warming near the poles, which already has caused significant glacier melt in the Arctic and at high elevations around the world. Warming is already contributing to loss of biological diversity (Parmesan and Galbraith 2004). If these trends continue, they will cause changes in land use, availability of water, agricultural patterns, and disease patterns.

The physical effects of climate change and the resulting economic impacts will be unevenly divided among countries. Wealthier countries are generally expected to have greater adaptive capability than poorer nations. For example, island nations in the Pacific and Indian Oceans are vulnerable to moderate sea level rise, which could severely damage their economies and potentially displace their populations entirely (Pacific Island Regional Assessment Group 2001).

This next section examines the current scientific evidence concerning some of the most immediate potential effects.

3.2 Climate Change Primary Physical Effects

Scientific research suggests that a number of physical effects will occur with varying degrees of likelihood as a result of climate change within this century. This section reviews current scientific literature and research concerning the following potential physical effects of climate change:

Higher minimum and maximum daily temperatures;
More intense flooding and drought;
Increased summer drying and more wildfires;
Increased storm intensity; and
Sea level rise.

Notably, this section does not address human health, agriculture or biodiversity issues. Heat waves, increase in disease vectors and sanitation issues associated with increasing temperature and precipitation may increase mortality rates by some estimates over 100,000 deaths per year (Gallon 2002) and can dramatically increase heath care costs which will increase cost to business and to the insurance industry (IPCC 2001; Hayhoe 2004c). Likewise, climate change's effects on agriculture and loss of biodiversity can adversely affect populations and disrupt markets and supply chains (Parry 1990; Whittaker 2003). Agricultural conditions are especially difficult to predict because climate system models are typically designed to model climate interactions over large areas and are too inexact to provide reliable estimates for local conditions. Climate change could benefit agricultural production in some regions and cause tremendous loss for other regions (Watson 2001; Reilly et al. 1996). However, research indicates that there will be greater uncertainty in crop yields, changes in growing patterns and selection of crops, and, where water become scarce, highly adverse conditions for agriculture and affected populations (Watson 2001; Smith et al. 1995). Because this dissertation focuses on climate's potential effects on physical infrastructure, these issues are not separately addressed in this section.

This section focuses primarily on climate change events that have been deemed by the IPPC to be "highly likely" (90-99% chance) or "likely" (66-89% chance) to occur within this century.

The focus on likely and very likely scenarios excludes consideration of abrupt or non-linear climate change. Omitting abrupt climate change is justified for several reasons that should be stated explicitly. The primary reasons are that the research of abrupt climate change is at an early stage and there is lack of historical data for these events (US NAS 2002). As a result, the scientific community is presently unable to quantify the likelihood of abrupt climate change, to test hypotheses concerning them, and climate system models do not include them in their projections (Forest 2006). Accordingly, abrupt climate events are not addressed in the Climate Risk Assessment Matrix presented in this dissertation.

In contrast, more gradual climate change has been observed and modeled. The relatively more complete understanding of gradual climate phenomena and scientific confirmation that gradual climate change is occurring justify their inclusion in the Climate Risk Assessment Matrix at this time.

While the omission of abrupt climate change leaves a growing body of important scientific research unaddressed, this is not meant to suggest that abrupt climate change is not an important potential risk. Indeed, if abrupt climate change occurs, it would substantially change the risks identified in this section and Chapter 4. When our understanding of abrupt climate change improves, their inclusion in a Climate Risk Assessment Matrix would be highly desirable.

Finally, it is important to note that the model results cited in this section to describe potential local effects are subject uncertainty. As one attempts to predict future events on smaller temporal or spatial scales, the accuracy of model results is reduced and the range of possible outcomes necessarily increases. At these smaller scales, the choice of model and the assumptions used in its development increasingly influence model results. Further a number of meteorological, land use, local and other factors outside or not well specified by the models can influence actual outcomes, and therefore model results represent a subset of possible outcomes, the proximity of which to the true range of possible outcomes is unknown. Significantly, models tend to underestimate the observed variability of climate systems on smaller temporal and spatial scales (Forest 2006). Accordingly, where possible, several studies or studies relying on multiple models are cited as evidence of potential climate physical effects.

3.2.1 Higher Minimum and Maximum Temperatures

Global warming is expected to cause higher temperatures throughout the year, with the effects increasingly pronounced at distances farther from the tropics. Summer heat waves are expected to become more common and winters milder.

The effect of higher temperatures will differ by region. The Tyndall Center produced a country-by-country analysis of past and future mean temperature change based on an average of five climate system models from leading climate change research centers. According to this research, during this century, New Zealand is expected to experience the least temperature increase, from 0.5 to 3.1°C, and Canada is expected to experience the greatest increases, from 5.3 to 8.8°C (Mitchell and Hulme 2000). Table 3.2 below reports the results of this study for selected countries.

Table 3.2: 21st Century Warming Predictions for Selected Countries

Country	21st Century Predicted Warming (°C)		
	Minimum Annual	**Mean Annual**	**Maximum Annual**
Australia	3.0	4.1	4.8
Brazil	3.4	4.5	5.8
Canada	5.3	6.3	8.8
China	4.5	5.3	7.0
France	2.0	4.1	5.2
Germany	1.7	4.0	5.3
India	3.7	4.4	5.7
Indonesia	2.3	3.3	4.3
Iran	4.8	5.5	7.0
Japan	2.2	3.8	5.2
New Zealand	0.5	2.1	3.1
Russian Federation	5.4	6.7	8.5
South Africa	3.6	4.6	5.7
United Kingdom	1.4	3.1	4.5
United States	4.2	4.9	6.1

Source: Mitchell and Hulme (2000).

A number of regional studies have also been conducted. Hulme (1997) estimates that the United Kingdom will experience an increase in mean annual temperature of approximately 1°C by 2035 compared to the 1961-1990 mean. As a result, summer heat waves that would normally occur 1-in-300 years (such as the summer of 1995) could occur 1-in-10 years on average during the 2021 to 2050 period.

Stott et al. (2004) estimates that the occurrences of extreme heat waves in Europe are now twice as likely as a result of human activity. The estimate is based on comparing two sets of simulated European summer temperatures from a climate model, one set that incorporated the effect of human contributions to climate change, and another that accounted only for natural influences on climate. The study estimates that European summers as hot as 2003 will be 100-times more likely by mid-century.

Hayhoe et al. (2004) estimate that by mid-century summer temperatures in California may increase by 1.1 to 2.2°C under low emission scenarios and by 1.4 to 3.1°C under high emissions scenarios. Towards the end of the century, summer temperatures are expected to increase by 2.2 to 4.7°C under low emission scenarios and by 4.2 to 8.6°C under high emissions scenarios. Winter temperatures are expected to increase by 1.1 to 2.2°C by mid-century and by 2.2 to 3.9°C by end of century (Hayhoe et al. 2004a). Extreme heat waves in California are expected to become more frequent, more intense, and last longer, doubling in frequency by mid-century and becoming as high as 5 times more common by the end of the century. In Los Angeles, the heat wave season is expected to increase from 14 weeks per year during the 1990's to as long as 37 weeks per year by the end of the century depending upon emissions (Hayhoe et al. 2004b).

The potential effects of heat waves during summer months were demonstrated by the summer of 2003, which is believed to be the hottest summer in European history. The 2003 summer heat wave is estimated to have caused 22,000-35,000 heat-related deaths across Europe and more than $12 billion in crop losses (US EPA 2006a).

During the winter months, warmer climate may also cause changes in the hydrological cycle resulting in less predictable precipitation patterns. In areas where temperatures are below freezing, changes in the hydrological cycle could produce heavier snowfall and ice storms (Francis and Hengeveld 1998). Ice storms can produce substantial damage. For example, a January 1998 ice storm in the northeastern United States and Canada caused an estimated US$1.2 billion of insured losses (IPCC 2001).

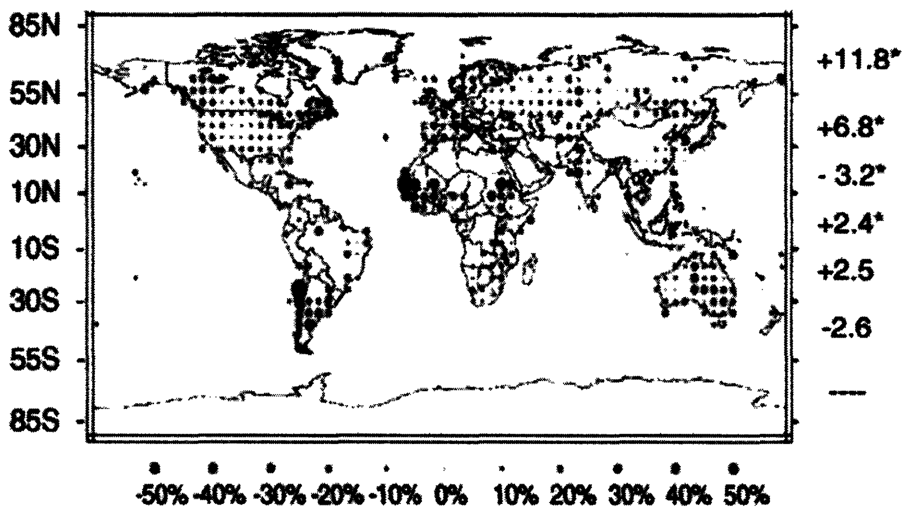
In areas where climate change results in less precipitation and reduced surface-water supplies, communities will pump more ground water, causing aquifers to deplete, which could also lead to increasing levels of land subsidence. High population areas such as the Southern and Western United States may be especially vulnerable to land subsidence (Leake 2006).

3.2.2 More Intense Flooding and Drought

Climate change is expected to cause more intense flooding and drought due to changes in precipitation and the melting of glaciers and snow pack.

Precipitation events in the middle and high latitudes of the Northern Hemisphere have increased during the past century with a higher incidence of heavy precipitation events (Karl et al. 1996; Kattenberg et al. 1996; Nicholls et al. 1996).

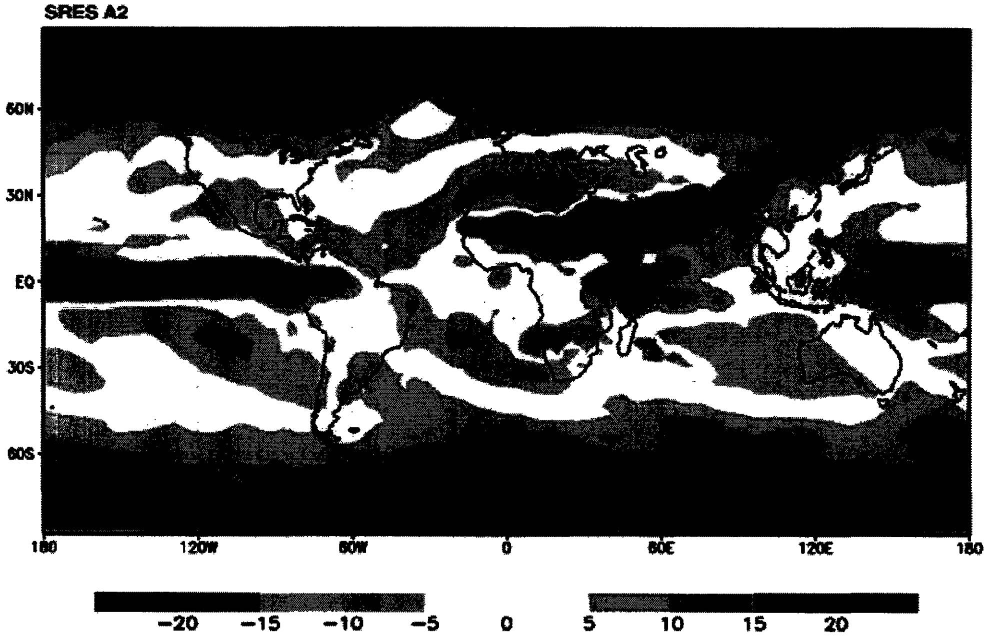
Figure 3.9: Historic Changes in Global Precipitation (%/century), 1900-1999



Source: Watson (2001).

While specific precipitation patterns are difficult to predict, the models generally show that precipitation will increase at high latitudes and decrease at low and mid-latitudes. Therefore, in low and mid-latitude regions, evapotranspiration will be greater than precipitation and there will exist the potential for more severe, longer-lasting droughts in these areas. Increased volatility in temperature, precipitation, and evapotranspiration will affect snowmelt, runoff, and soil moisture conditions. Early climate system models predicted that global precipitation could increase 7-15%, while global evapotranspiration could increase 5-10% (U.S. Office of Technology Assessment 1993). Some models estimate that precipitation could increase by as much as 50% in high and low latitudes, and decrease by as much as 50% in mid-latitudes by mid-century (Rind and Lebedeff 1984; Watson 2001; Titus 1987). Kharin and Zwiers (2005) estimate that 20-year precipitation events will become 10-year events by the end of the 21st century, and that extreme events are expected to increase compared to daily mean precipitation.

Figure 3.10: Projected Changes in Global Precipitation



The effect of climate change on water resources had been modeled for the major river systems of Asia, Eurasia and the Indian Subcontinent using climate change scenarios based on Hadley Centre model simulations. The results show that some areas are expected to experience increases in water availability, while other areas are expected to experience a reduction in water resources through 2050. Disruption to precipitation patterns and glacier melt will further exacerbate water resource problems (Arnell 1999).

Table 3.3: Projected Climate Effects on Selected Eurasian River Systems

River System	Territory	Annual Flow Cubic km/year	Projected Flow Change 2050
Ganges	India	1389	-14%
Yangtze	China	1003	+37%
Tigris	Iraq, Turkey, Syria	43-52.6	-22%
Euphrates	Iraq, Turkey, Syria	28.7-30.5	-25%
Indus	China, Pakistan, India	207	-27%
Yellow River	China	627	+26%
Yenisey	Siberia	630	+15%
Lena	Siberia	521	+27%
Ob	Siberia	534	+12%
Amur	Siberia	346	+14%

Source: IPCC (2001); Tibet Environmental Watch (2006). Note: Yellow River annual flow measured at Tibet.

The Himalayas possess the largest accumulation of glaciers outside the Arctic and Antarctic. The Himalayas provide approximately 8,600 cubic km of water per year, supporting the Brahmaptura, Ganges, Indus, Mekong, Salween, Yangtze, and Yellow rivers (Dyurgerov and Maier 1997). Climate change has been identified as the primary cause of retreat for an estimated two thirds of Himalayan glaciers (WWF 2005). Snowpack melt during the summers are expected to increase the severity of summer monsoons, increasing the likelihood of severe floods on the Indian Subcontinent in the near term. In the long term, the loss of glaciers will produce drought in areas that depend upon these glaciers for water.

In the Western United States, the snowpack is expected to decline by 25-40% by mid-century, and by 30-70% under low emissions scenarios and by 70-90% under high emissions scenarios by the end of the century (Hayhoe et al. 2004d). Loss of snowpack is expected to create severe water shortages during the summer months. Snowpack provides as much as 75% of water supply in the Western United States (USGS 2006). In California, 80% of precipitation occurs during the winter, and 75% of water consumption occurs during the spring and summer. Stream flows fed from the Sierra Nevada are expected to be reduced 10-25% by mid-century, and 40-55% by end of century (Hayhoe et al. 2004d). At the same time, California's population is expected to double by mid-century and triple by the end of the century (Hayhoe et al. 2004d).

In South America, accelerating glacier melt has also been observed in glacier systems that supply water to Chile, Argentina, Peru, Ecuador and Bolivia. A 2003 study conducted by NASA measured changes in the volume of the 63 largest glaciers of the Patagonian ice fields. These ice fields are the largest non-Antarctic ice masses in the Southern Hemisphere and are essential source of water for Chile and Argentina. Based upon a comparison of conventional topographic data from the 1970s and 1990s with data collected in 2000 by NASA's Space Shuttle program, the study confirmed that the ice sheets are thinning at an accelerating rate. Runoff from the ice fields contributed an estimated 0.04 millimeters (0.0016 inches) per year to sea level rise during the period 1975 through 2000, roughly nine percent of the total annual global sea level rise from mountain glaciers according to the 2001 IPCC assessment. From 1995 through 2000, however, the rate of runoff doubled, to an equivalent sea level rise of 0.1 millimeters (0.004 inches) per year. Melting of the Patagonian ice fields account for almost 10% of sea level rise from 1975 to 2000 (Rignot et al. 2003).

In Europe, glacier melt has accelerated in the European Alps. Since 1980, 10% to 20% of glacier ice in the Alps has melted. Since 1850, these glaciers have lost about 30% to 40% of their surface area and about half of their volume (Haeberli and Beniston 1998).

In Africa, tropical glaciers on Mt. Kenya (Kenya), Mt. Kilimanjaro (Tanzania), and in the Ruwensori Mountains (Uganda and Congo) have decreased in area by 60-70% on average since the early 1900s (Prentice and Karlen 2003).

In all of these cases, glacier melt is expected to contribute to floods in the immediate future followed by drought and serious water scarcity problems by the middle or end of the century.

3.2.3 Increased Summer Drying and Wildfires

Hotter and drier summer weather dehydrates forest biomass, increasing the likelihood of severe wild fires. Extensive research on climate change and wildfire has been conducted using fire risk assessment models specific to the fuel characteristics and conditions of the locality coupled with general circulation models of the climate. Models are run using different greenhouse gas scenarios that incorporate temperature, wind, humidity, and precipitation variables in order to assess fire danger. Results from recent studies of the United States, Canada, Russia and Australia are described below.

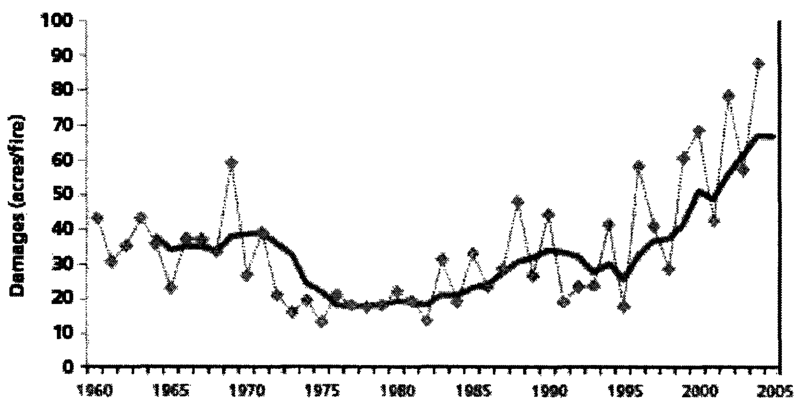
A recent study of the Western United States concluded that wildfire danger will increase, especially in the Northern Rockies, Great Basin and Southwest, due to warmer and drier conditions. The study compared a base period 1975-1996 with a period when carbon dioxide levels are projected to double from present day, approximately 2070. By 2070, the number of high-risk days are projected to increase by as much as one to two weeks per year in much of the Western and Southwestern United States (Brown et al. 2004).

In another study focusing on California and Nevada, warmer and windier conditions associated with a doubled carbon dioxide scenario will cause more intense and faster spreading fires. Fires that escape their initial containment limits are projected to increase by 51% in the South San Francisco Bay Area, 125% in the Sierra Nevada, and remain at the same levels along California's Northern Coast. Contained fires are expected to burn larger areas in those locations by 41%, 41%, and -8%, respectively. Model results extrapolated for the entire Northern California region predict the number of escaped fires to double in number to over 100 per year, and an additional 5,000 hectares to be burned by contained fires annually (Fried et al. 2004).

A study of Canadian and Russian boreal forests similarly shows increased fire risk. The study used four leading climate system models and analyzed fire risk assuming a doubling of atmospheric carbon dioxide. The study predicted increased severity of fires during the summer months of May through August and a longer fire season in both countries using 1980-1989 as the baseline period. Model results predict that fires in the extreme and high-risk categories will increase substantially (Stocks et al. 1998; see also Wotton et al. 2004).

A recent study of Southeast Australian wildfires employing two climate system models modeled risk for seventeen locations in Southeast Australia. The study predicts that for the locations studied, fire risk could increase 4-25% by 2020 and 15-70% by 2050. For example, in Canberra, very high or extreme forest fire risk danger days could increase from the present 23.1 days per year up to 28.6 days per year by 2020 and up to 38.3 days per year by 2050 (Hennessy et al. 2005).

Figure 3.11: U.S. Forest Fire Damage, 1960-2005



Source: National Interagency Fire Center, as presented in CERES (2005a).

Significantly, increased severity of forest fires has already been observed. In the United States, wildfires have doubled in severity of damage since 1960 (CERES 2005a).

3.2.4 Increased Storm Intensity

At the time the 2001 IPPC Third Assessment Report was completed, there was no consensus regarding likely future occurrences of tropical and extratropical windstorms. Since 2001, scientific research has not detected an increase in storm and hurricane frequency from either the historical record or based on climate models. However, several prominent researchers have recently found correlations between increased surface ocean temperatures, water vapor and the intensity of storms and hurricanes.

Trenberth (2005) found that the observed increase in sea surface temperatures and water vapor levels support theoretical and model results predicting more intense storms. Increased sea surface temperatures and water vapor levels provide more potential energy to create or intensify storms. Although Trenberth points to model results that predict the recent shift towards extreme storms and hurricanes, the results are limited by inadequate statistical evidence to prove that these trends are the result of human influence or will continue in the future.

Emanuel (2005a, 2005b) examined historical data for storms and has found that since the 1970's there have been strong statistical correlations between increase in sea surface temperatures, peak wind speed, and storm life. Emanuel calculates the integral of peak wind speed over storm life to determine the total power dissipation of a storm. Emanuel's research predicts that an increase in sea surface temperature of 2°C should produce an increase in wind speed of 10%, which combined with longer storm life, increases power dissipation by 40-50%. Emanuel estimates that the historical increase in sea surface temperature of 0.5°C over this century should have increased observed power dissipation by 8-12%, not the 50-60% increase observed in the North Atlantic and western North Pacific. Emanuel further notes that monetary losses, which have been observed to increase at a rate approximately the cube of wind speed, also follow the power dissipation of storms.

Knutson and Tuleya (2004) also found a strong relationship between sea surface temperature and storm intensity. They used nine leading climate models to produce various climate states as data for the Geophysical Fluid Dynamics Laboratory's hurricane prediction system. The models consistently predict that greenhouse gases will cause a 6% increase in peak wind speed, 7% increase in average rate of precipitation, and 14% increase in central pressure fall in cyclones by 2080. The results suggest a gradual increase in the number of highly destructive Category 5 hurricanes toward the end of the century.

Several prominent researchers have contested the research conducted by Emanuel, Knutson and Tuleya. Specifically, they have questioned Emanuel's use of the power dissipation measure, the quality of the underlying data, his manipulation of data which may have underrepresented the intensity of storms during the first half of the 20th century, and the strength of the claimed statistical relationship between sea surface temperatures and power dissipation (Pielke 2005; Landsea 2005).

Michaels et al. (2005) criticized Knutson and Tuleya (2004) for overstating the potential effect of carbon dioxide on storms. In their models, Knutson and Tuleya (2004) assumed that carbon dioxide concentrations will increase 1% each year, as opposed to an increase closer to the historical trend of 0.5% per year. This may have caused the study to overstate the potential effects of warming. Using historic averages for future carbon emissions, critics argue that the models should predict wind speeds to increase by approximately 3%, precipitation to increase by 4%, and central pressure fall to increase by 7% by 2080.

Even in the absence of a proven causal relationship between human activity and increasing severity of storms, all of these researchers agree that the present level of storm activity coupled with increasing concentrations of population and infrastructure in coastal areas will result in storms causing increasing economic losses. The historical pattern of storm and hurricanes are described more fully in the case studies in Chapter 6 concerning the effect of storms and hurricanes on the U.S. utility industry and on the insurance industry.

3.2.5 Sea Level Rise

In 2001, the IPCC stated that sea level poses "a major potential risk to coastal zones, especially if they are associated with an increase in storminess". Thermal expansion has already raised sea level by 10 to 20 centimeters. The IPPC forecasts potential increases in sea level from 26 to 72 cm by 2100 with the mid-range estimate at 49 cm (IPCC 2001).

In 2004, the Arctic Climate Impact Assessment completed a four-year study of the Arctic, which involved over 300 scientists and employed a number of climate models. The study found that average temperatures in Alaska and Western Canada have already increased by approximately 3 to 4°C in the past fifty years, nearly twice the global average. Temperatures in these areas are projected to rise an additional 4 to 7°C by the end of the century. According to the study, the rising temperatures are likely to cause at least half of the Arctic Ocean's ice and a significant portion of the Greenland ice sheet to melt by the end of the century (Arctic Climate Impact Assessment 2004).

Arctic ice concentrations have been consistent with yearly changes in surface temperatures. In the 1980's, ice concentrations increased and then decreased in the 1990's consistent with surface temperatures (Cosimo 2004). During the 2002, 2003 and 2004 summers, total Arctic Ocean ice areas have been at or near minimum record levels. The Arctic's perennial ice cover appears to be decreasing 9-10% per decade while the winter air temperatures in Alaska and western Canada have increased 3-4ºC in the past fifty years (Arctic Climate Impact Assessment 2004).

Rates of ice sheet melt in Greenland and Antarctica have been shown to correlate strongly with historical increases in carbon dioxide levels (Alley et al. 2005). Greenland's melting rate is estimated to have doubled during the 1996 to 2005 period, with losses reaching as high as 224 +/- 41 cubic kilometers per year. According to NASA's Goddard Space Flight Center, current loss rates are approximately 30 to 40 cubic kilometers per year based on the most recent data (Kerr 2006). The Greenland ice sheet alone contains enough water to raise global sea level by about 7 meters.

The West Antarctic Ice Sheet is approximately 10% of the volume of the entire Antarctic ice sheet and is estimated to contain enough water that it could cause mean sea level to rise by 5 meters (Oppenheimer 2004). While the East Antarctic Ice Sheet is increasing in mass as a result of increased snowfall, the West Antarctic Ice Sheet is losing mass at a much faster rate, more than offsetting the other's gains. Differing loss estimates for the Antarctic ice sheets have ranged from 47 cubic kilometers per year to 148 cubic kilometers per year (Kerr 2006; Velicogna and Wahr 2006). To place these losses in perspective, Los Angeles consumes approximately 1 cubic kilometer of water per year (Kerr 2006).

As described above in the section "More Intense Flooding and Drought", Patagonian ice fields are also melting at an accelerating rate, accounting for almost 10% of sea level rise from 1975 to 2000 (Rignot et al. 2003).

Since the 2001 IPCC assessment, the rate of glacier melt has increased substantially. The Arctic Climate Impact Assessment study predicts that melting glaciers and ice sheets will have potentially catastrophic consequences on a global scale, resulting in substantial economic, social, and environmental impact in low-lying areas. Global and Arctic Ocean sea levels have already risen 10 to 20 cm in the past 100 years. The study estimates that an additional 50 cm of sea level rise is expected by the end of the century within a 10 to 90 cm range (Arctic Climate Impact Assessment 2004).

More than 65% of North America's population live in coastal communities (Changnon 1999). In the United States, a 50 cm rise in sea level would flood low-lying coastal areas in Florida and Louisiana, causing the coastline to recede 45 meters inland (Arctic Climate Impact Assessment 2004). Similar problems are expected in Europe and Asia (IPCC 2001). Table 3.4 below presents estimates of potential land loss and population exposure for Asian countries.

Table 3.4: Potential Asian Land Loss and Population Exposure from Sea Level Rise

Country	Sea Level Rise (cm)	Potential Land Loss		Population Exposed	
		(km^2)	(%)	(millions)	(%)
Bangladesh	45	15,668	10.9	5.5	5.0
	100	29,846	20.7	14.8	13.5
India	100	5,763	0.4	7.1	0.8
Indonesia	60	34,000	1.9	2.0	1.1
Japan	50	1,412	0.4	2.9	2.3
Malaysia	100	7,000	2.1	0.05+	0.3+
Pakistan	20	1,700	0.2	n.a.	n.a
Vietnam	100	40,000	12.1	17.1	23.1

Source: IPCC (2001), based on Nicholls and Mimura (1998); Mimura et al. (1998).
n.a. = not available.

3.3 Summary of Climate Change Risks

The events described above in the preceding sections are all deemed "likely" or "very likely" by the IPCC in its 2001 assessment, meaning that the IPCC assigned a 66% to 99% chance of them occurring within this century. Although these events and their impacts are subject to considerable uncertainty concerning their magnitudes and frequency, they are a useful starting point for discussion of risks. The potential climate events summarized in Table 3.5 provide a foundation for Chapter 4's discussion of climate-sensitive financial risks.

Table 3.5: Effects of Potential Extreme Climate Events

Projected Changes during the 21st Century	Chance per IPCC 2001	Representative Examples of Projected Impacts
Higher maximum temperatures; more hot days and heat waves over nearly all land areas	Very Likely 90-99%	Increased incidence of death and serious illness in older age groups and urban poor
		Increased heat stress in livestock and wildlife
		Shift in tourist destinations
		Increased risk of damage to a number of crops
		Increased electric cooling demand; reduced energy supply reliability
Increasing minimum temperatures; fewer cold days, frost days, and cold waves over nearly all land	Very Likely 90-99%	Decreased cold-related human morbidity and mortality
		Decreased risk of damage to some crops; increased risk to others
		Extended range and activity of some pest and disease vectors
More intense precipitation events	Very Likely over many areas 90-99%	Reduced heating energy demand
		Increased flood, landslide, avalanche, and mudslide damage
		Increased soil erosion
		Increased flood runoff could increase recharge of some floodplain aquifers
		Increased pressure on government and private flood insurance systems and disaster relief
Increased summer drying over most mid-latitude continental interiors and associated risk of drought	Likely 66-90%	Decreased crop yields
		Increased damage to building foundations caused by ground shrinkage
		Decreased water resource quantity and quality
		Increased risk of forest fire
Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities	Likely 66-90%	Increased risks to human life, risk of infectious disease epidemics, and many other risks
		Increased coastal erosion and damage to buildings and infrastructure
		Increased damage to coastal ecosystems such as coral reefs and mangrove
Intensified droughts and floods associated with El Niño events in many different regions	Likely 66-90%	Decreased agricultural and rangeland productivity in drought- and flood-prone regions
		Decreased hydro-power potential in drought-prone regions
Increased intensity of mid-latitude storms	Little Agreement between models.*	Increased risks to human life and health
		Increased property and infrastructure losses
		Increased damage to coastal ecosystems

Source: IPCC (2001). * Since 2001, research has confirmed an increased likelihood of storm and hurricane damage.

Most of the effects of climate change are likely to be adverse. There are a few cases in which climate change is expected to have beneficial effects. The table below summarizes expected beneficial and adverse consequences of climate change with respect to infrastructure.

Table 3.6: Potential Climate Change Effects on Infrastructure

Climate Event	**Positive/Negative**	**Effect on Infrastructure**
Inundation and flooding	Negative	Damage to physical infrastructure
Sea level rise	Negative	Sinking of harbor facilities, coastal structures; greater risks of storm surge
Rise in sea water temperature	Negative	Disruption of marine ecosystems
	Positive	Reduction in freezing in harbor areas in winter
Rain pattern changes	Negative	Increased demand on storm-water system
	Indeterminate	Changing water demand and supply
Decrease in freezing	Negative	Ice roads no longer safe
	Positive	General improvement in transportation
	Positive	Reduction of pavement cost
Reduction of snow	Negative	Less snow pack water storage
	Positive	Improve transportation
	Positive	Reduce maintenance costs
Loss of permafrost	Negative	Damage to infrastructure
Increase in storm intensity	Negative	Increase wear on infrastructure

Source: Adapted from Mirza et al. (2005).

Give the increasing likelihood of the climate change risks described in this chapter, we would expect that lenders and long-term investors in infrastructure would consider these risks in making investment decisions and would seek to insure against them where possible. Individuals and firms typically seek insurance for much lower probability risks, such as house fires, automobile accidents, and medical coverage.

Chapter 4 considers the scientific evidence presented in this chapter in order to develop a financial risk framework for the purpose of assisting the private sector and government in evaluating climate change risk. Chapter 5 then evaluates the extent to which private risk management methods are capable of providing protection against these climate change risks.

4 Climate Risks to Financing Infrastructure

This chapter addresses the question: "What risks does climate change pose to infrastructure, and how might those risks impair the private sector's ability to finance infrastructure?"

For purposes of addressing this question, risk is defined as "the possibility of loss, injury, disadvantage, or destruction" (Webster's 2002).

This is an important question because it has been recognized for some time within the scientific community that climate change will adversely affect infrastructure (Revelle 1983; IPCC 1995). However, traditional infrastructure finance analysis has assumed the natural environment to pose risks that can be identified, allocated and managed by conventional means.

While the natural environment was understood to pose significant risks to infrastructure projects, the range of risk was believed to be sufficiently well defined within an acceptable range so that large-scale infrastructure projects could be financed without further consideration to long-term climate trends in making investment and risk management decisions. Recent observed weather patterns exhibiting increased volatility and the availability of climate models capable of characterizing long-term climate trends require reevaluating traditional infrastructure finance risk assessment frameworks in light of evidence from climate science.

In order to address this question, this chapter considers infrastructure finance risks in light of the climate science presented in Chapter 3 and develops the "Climate Risk Assessment Matrix". The Climate Risk Assessment Matrix is intended to provide a systematic method for analyzing climate risk in the context of financing and developing infrastructure. For investment analysis, it provides practitioners concerned with the risks of financing long-term infrastructure with a framework that incorporates climate risks. For policy analysis, the framework demonstrates the difficulties the private sector should be expected to experience in transitioning to carbon neutral energy infrastructure.

This chapter develops the Climate Risk Assessment Matrix in several steps. The chapter first presents the traditional infrastructure finance risk assessment framework commonly used by project developers, lenders, investors, and their advisors in financing infrastructure projects worldwide. Specifically, this framework is used to identify, allocate, and mitigate risks of infrastructure projects.

Based on the scientific literature and evidence from climate models presented in Chapter 3, the chapter identifies specific risks posed by climate and updates and expands the traditional framework to accommodate these risks. The reevaluation of the traditional framework demonstrates that some traditional risks are exacerbated by climate and these enhanced risks will not be provided with adequate visibility within the traditional infrastructure finance framework. For example, in the traditional framework, the concept of force majeure is used to analyze a broad set of risks: acts of nature (such as flood, fire, earthquake), acts of man (riots, war), impersonal acts (financial system collapse), and acts of government (general strife). Given the increasing importance of climate events, the force majeure category as a catchall or residual category of risk provides inadequate visibility to the climate-related risks. The Climate Risk Assessment Matrix proposes several new categories of risk to explicitly accommodate risks posed by a changing climate and identifies the climate aspects of each particular risk.

The chapter then compares the Climate Risk Assessment Matrix with responses from banks and insurance companies participating in the Carbon Disclosure Project. This comparison verifies that the financial community anticipates that a number of climate risks will increase in the long-term and that the Climate Risk Assessment Matrix correctly identified certain risks as critical. A survey of these disclosures also suggests that the financial community still lacks a framework for systematically analyzing climate risks.

Next, each risk presented in the Climate Risk Assessment Matrix is separately evaluated, and dynamic interactions among these risks are identified. These interactions suggest that an increase in one risk may increase the magnitude of other risks, leading to a general increase in the level of risk due to climate change. This creates the potential for a cascade effect of increased risk.

Finally, the chapter examines the potential implications of these risks for financing carbon neutral infrastructure on the scale and the pace intended to adapt infrastructure in this century. This analysis suggests that the private sector should experience substantial barriers and delays in developing carbon neutral infrastructure.

4.1 Conventional Infrastructure Finance Risk Assessment Framework

In infrastructure finance, a project is generally analyzed in isolation from other activities or other assets of a project sponsor. Thus, infrastructure finance requires project-centered analysis. A proposed project must demonstrate sufficient projected cash flow to be capable of repaying debt and provide a rate of return to equity investors that is competitive with other rates of return available in the market for comparable risk, in order to justify the investment decision (Nevitt and Fabozzi 2000).

Infrastructure projects typically require large capital expenditures and the resulting assets have long lifetimes. Privately financed infrastructure projects typically require long time periods to repay debt, recover investment, and provide a market return to investors. As discussed further in Chapter 5, debt repayment may require 20-30 years with longer durations not uncommon (Dealogic 2006b).

As a result of the large capital outlays and long recovery periods, infrastructure finance relies on quantitative and qualitative risk assessment methods for assessing long-term risk. The quantitative methods comprise cash flow analysis. The qualitative methods involve risk assessment for risks that cannot be reliably quantified. The purpose of these methods is first to identify risks, and then to allocate each risk through the negotiation process to the party best positioned to address each particular risk. Each party is then required to mitigate and bear liability for the risks allocated to it as part of its contractual obligations to the project. In order to minimize the overall risk of the project, each individual project risk should be separately identified, allocated, and mitigated in this manner.

The conventional infrastructure finance risk assessment framework characterizes risks by category. Table 4.1 below presents a commonly accepted formulation of the framework.

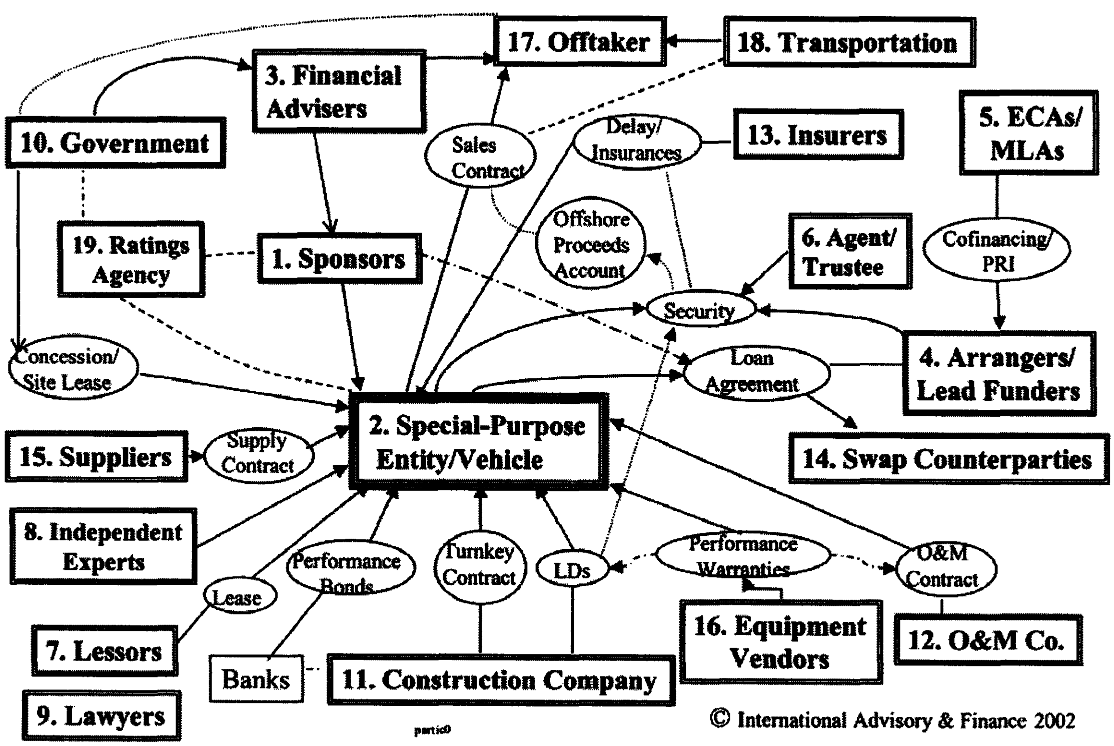
Table 4.1: Infrastructure Finance Risk Assessment Framework

Risk	Description/Example
Supply Risk	Supply interruption or input price increase.
Market Risk	Price or demand drop.
Foreign Exchange Risk	Mismatch revenues and costs due to currency fluctuation.
Technology Risk	Technology failure or inefficiency.
Operating Risk – Management Capacity	Failure in management performance.
Operating Risk – Cost	Increase in cost of inputs and services.
Environmental Risk	Environmental liability or regulation.
Infrastructure Risk	Interconnection to other critical infrastructure (i.e. roads, utilities).
Force Majeure Risk	Acts of nature (flood, fire, earthquake), man (riots, war), government (general strife), impersonal acts (financial system collapse).
Completion Risk	Construction delay, cost overrun, defects.
Engineering Risk	Failure in engineering analysis, design, data.
Political Risk	War, unrest, nationalization, creeping expropriation (regulation), change of government, environmental activism, corruption.
Participant Risk	Competency and financial stability of participants such as project sponsors, lenders, equipment vendors, and contractors.
Interest Rate Risk	Floating rate interest loan.
Syndications Risk	Lead banks ability to sell portion of loan to other banks.
Legal Risk	Enforcement of project contracts.

Source: Tinsley (2000).

The complexity of risk management in an infrastructure development context is illustrated in Figure 4.1 below which shows the various parties to a typical privately financed infrastructure project and the contractual arrangements between them. The number of parties and complexity of these contractual relationships adds to both the cost and time required to finance and develop infrastructure.

Figure 4.1: Project Finance Participants and Relationships



Source: Tinsley (2000).

The various contractual arrangements allocate project risk, and obligate each party responsible for its assigned risks to take appropriate mitigation efforts. In a pure project financing, lenders are repaid from project revenues and, in the event of loan default, may only satisfy their claims against the project's assets or continued operation. Pursuant to the project agreements, lenders typically have limited or no recourse against other financial assets of project sponsors (Hoffman 2001). Project revenues must be sufficient to repay lenders, meet the obligations of the project as they come due, and to provide an adequate return for equity investors. Because projects must succeed on their own without reliance on the assets of its sponsors, the identification, allocation and mitigation of risks are essential to the success of privately financed infrastructure.

In order to evaluate the traditional risk assessment framework and to revise the framework to reflect climate-related risks, the next section considers each traditional risk category in light of climate change science.

4.2 Reevaluating the Conventional Infrastructure Finance Risk Framework

This section reevaluates the traditional infrastructure finance risks in light of scientific evidence of climate change. The reevaluation results in the adaptation of the traditional framework to accommodate climate risks that are expected to increase in this century, potentially affecting the upcoming generation of infrastructure.

Reevaluating the current framework is necessary for reasons that bear directly on infrastructure and its financing. First, recent observed weather patterns and projections of future climate both exhibit increasing volatility and severity. In the past several decades, the scientific community has discarded its earlier view that climate is "virtually static" (Gibbas 2002). Dynamic weather patterns involve greater risks than the static climate conditions that are implicit in the traditional framework. Ultimately, changing climate conditions must be factored into project design, budgeting and management. Second, climate poses a fundamental problem for infrastructure finance: no party may be best positioned to accept and mitigate climate risks. Such a situation may hinder the ability of project parties to successfully complete negotiations and manage risks. Ultimately, these risks must be clearly identified and given appropriate visibility so that they can be properly addressed.

Accordingly, the revised framework presented in this dissertation provides new categories of risk in order to elevate the visibility of climate-sensitive risks. For example, the traditional "force majeure" category subsumes climate-related risks with a number of other kinds of risks, and thereby fails to provide adequate visibility to climate-related risks. The Climate Risk Assessment Matrix considers climate in each traditional category of risk and divides force majeure risks among existing and new risk categories to provide climate risks appropriate visibility.

Macroeconomic risks, such as foreign exchange and interest rate risks, are excluded from this presentation of the Climate Risk Assessment Matrix. These risks are important and may affect the further development of carbon neutral infrastructure. For example, in the case of nuclear energy, high interest rates coupled with high capital costs, regulatory delays and public opposition, contributed to the abandonment of plans to further expand the industry. However, macroeconomic risks are likely to be dependent upon general economic conditions, which are beyond the scope of this dissertation. Accordingly, there is presently inadequate basis to determine how climate might affect macroeconomic risks for purposes of developing the Climate Risk Assessment Matrix.

The analysis of risk in this section provides the foundation for the x-axis of the revised Climate Risk Assessment Matrix presented in simplified form in Appendix A to this dissertation. Table 4.2 presents the complete set of risks comprising the x-axis of the Climate Risk Assessment Matrix, and identifies specific examples of risk within each risk category. Each risk category is considered in turn in the sections that follow.

Table 4.2: x-Axis of the Climate Risk Assessment Matrix

Risk	Potential Cause of Increase in Risk
Supply Risk	New technology rare materials/energy Weather disruption of supply chains Carbon credits
Market Risk	Climate affects short/long term demand/market Changing consumer attitude and preference Reputation risk for emissions/environment
Technology Risk	Accelerate new carbon neutral technology More complex carbon neutral technology More costly technology/infrastructure
Engineering Risk	Changing environmental conditions Increasing complexity of challenges Increasing scale of climate protection projects
Infrastructure Risk	Damage to transmission & distribution Grid connection of new technologies Natural support for infrastructure Uncertain government commitment to support
Environmental Regulatory Risk	Cost recovery for carbon neutral technology Cost recovery for climate-related events Taxation Regulation (including competitive effects) Litigation or liability Increasing complexity of regulation Uncertain or fragmented regulation Increased disclosure obligations
Political Risk	Deadlock/uncertainty Unrest/Violence Expropriation Protectionism Incomplete institutional arrangements
Legal Risk	Increased chance of breach of contracts Increased use of changed circumstances defense Decreased flexibility once committed to law
Force Majeure Risk	Increased chance of severe climate events Reduced insurance coverage for climate events Increased chance of financial erosion/collapse
Operating Risk – Cost	Climate events increase operations costs Complex technology increase O&M
Operating Risk – Management Capacity	Reduced capacity estimate risk and plan Increased demands on technical capacity Climate demand more management resource Climate reduce ability to pursue strategic plan Reduced capacity to undertake prevention

Capital Markets/Finance Risk	Credit, Default, Collateral Impairment Financial asset values Accounting/financial disclosure Innovation causes capital obsolescence Market disruption/volatility Scale/transaction cost
Participant Risk	Financial stability/creditworthiness Inadequate administrative or technical capacity
Governance Risk	No party best positioned, willing or capable to accept and mitigate climate risk.

Source: Author's adaptation based on review of climate change literature.

4.3 Validating the Climate Risk Assessment Matrix

The Climate Risk Assessment Matrix is validated using survey responses of banking, insurance, and energy firms to the Carbon Disclosure Project. The Carbon Disclosure Project is sponsored by over one hundred-fifty institutional investors and periodically surveys Financial Times 500 companies in various industries concerning their strategies for adapting to climate change and their carbon emissions reductions programs. The Carbon Disclosure Project survey was used as a method to validate the Climate Risk Assessment Matrix because of the relevance of its substantive questions and the high response rates among banks and insurance companies, the primary industries of interest to this dissertation.

At the time of writing, the Carbon Disclosure Project had completed three annual surveys, which were used in this dissertation. Overall response rates were 47%, 59% and 71% for each of the three surveys, respectively. In the third survey, 50% of the companies were located in North America, 30% in Europe, and the remainder in Asia, Latin America and the Middle East. The third survey included sixty-nine banks, 84% of which submitted responses or information, twenty-seven utilities, 100% of which provided submissions, and thirty insurance and reinsurance companies, 67% provided submissions (Innovest Strategic Value Advisors 2005).

For this dissertation, the author reviewed responses by the banking, insurance, energy, and utilities industries to the Carbon Disclosure Project questionnaire. All three year's of responses were reviewed, or a total of one hundred ninety-eight submissions.

Almost all banks that responded recognized climate change as a risk to their lending business. All insurance companies surveyed in the Carbon Disclosure Project recognized climate change as a potential risk to their property and casualty businesses. Utilities and energy industry respondents similarly recognized climate change as significant to their business, in some cases presenting opportunities, but in most cases identifying significant increases in risk.

The banking industry responses were of particular interest because of their role as lenders and advisors to infrastructure projects. The author tabulated banking industry responses, the results of which are presented below in Table 4.3. Over three years of surveys, the Carbon Disclosure Project surveyed sixty-nine commercial banks.[7] Of the sixty-nine lending banks surveyed, forty-seven banks responded by answering the survey or providing information in one or more years. Responses from these forty-seven banks were coded and tabulated with respect to specific risks. Most of the responses were coded from the banks' responses to the first question in the survey: "Do you believe climate change, the policy responses to climate change and/or adaptation to climate change represent commercial risks and/or opportunities for your company?" However, survey responses were read in their entirety and answers were coded from any part of the document or supplemental materials submitted by respondents.[8]

Significantly, banks in the Carbon Disclosure Project surveys specifically identified most of the risks in the Climate Risk Assessment Matrix, but because the banks were not responding to the set of risks presented in the Climate Risk Assessment Matrix, some interpretation was necessary. To be coded affirmatively for a particular risk, a bank must explicitly identify or discuss the particular risk as a risk in one of its submissions for any of the three Carbon Disclosure Project surveys. In the case of operating risks, responses were either counted towards "Operating Risk – Cost" where a cost element was stated, or "Operating Risk – Management Capacity" where a management element was stated or the specific reason for identifying operating risk was not stated. Where banks identified both a cost and management element, both risks were credited. Because this interpretation of banks' responses is subject to error, it may be more accurate to aggregate both subcategories of risk. Aggregating both subcategories as "Operating Risk" produces a total of twenty-four responses, as adjusted to eliminate double counting. On an aggregate basis, it is the fourth most commonly cited risk, with over 50% of respondent banks identifying it.

In some cases, the coding policy may have led to an underestimate of the banks' perception of climate risk. There is evidence from bank responses that the banking industry understands the magnitude of risk presented by climate change, however, if bank responses were general in nature, it could not be counted affirmatively toward any risk. Table 4.3 below sets forth the tabulation of bank responses counted towards specific risks.

---

[7] The Carbon Disclosure Project did not categorize Citigroup as a bank, possibly due to its insurance and other business lines. It is included here as one of the sixty-nine banks.
[8] Carbon Disclosure Project survey questionnaires and responses are available for review at the Carbon Disclosure Project's website http://www.cdproject.net/.

Table 4.3: Tabulation of Banking Industry Responses to Carbon Disclosure Project

Risk	**Examples of Climate Risk**	**Banks Identifying Risk**
Supply Risk	New technology rare materials/energy Weather disrupt supply chains Carbon credits	ABN, ANZ, Bank of America, Credit Suisse, Hang Seng, KeyCorp, Bank of Ireland, HBOS, Hypovereinsbank, KBC, Toronto-Dominion, WestPac
Market Risk	Climate affects short/long term demand/market Changing consumer attitude and preference Reputation risk for emissions/environment	ABN, ANZ, Banco Itau, Barclays, CIBC, Citigroup, Dexia, HBOS, HSBC, Bank of Ireland, Dexia, Royal Bank of Scotland, SocGen
Technology Risk	Accelerate new carbon neutral technology More complex carbon neutral technology More costly technology/infrastructure	ANZ, Dexia, Hypovereinsbank
Engineering Risk	Changing environmental conditions Increasing complexity of challenges Increasing scale of climate protection projects	
Infrastructure Risk	Damage to transmission & distribution Grid connection of new technologies Natural support for infrastructure Uncertain government commitment to support	Banco Itau, Scotiabank, Toronto-Dominion, Wachovia
Environmental Regulatory Risk	Cost recovery for carbon neutral technology Cost recovery for climate-related events Taxation Regulation (including competitive effects) Litigation or liability Increasing complexity of regulation Uncertain or fragmented regulation Increased disclosure obligations	ABN, ANZ, Banco Itau, Bank of Montreal, Barclays, CIBC, Citigroup, Credit Suisse, Dexia, Hang Seng, HBOS, HSBC, Hypovereinsbank, PNC, Scotiabank, KBC, Malayan, RBC, SocGen, Standard Chartered, SunTrust, Svenske Handelbanken, UBS, Wachovia, WestPac
Political Risk	Deadlock/uncertainty Unrest/Violence Expropriation Protectionism Incomplete institutional arrangements	ANZ, Royal Bank of Scotland, Westpac
Legal Risk	Increase chance of breach of contracts Increase use of changed circumstances defense Decreased flexibility once committed to law	Banco Itau, KeyCorp

Force Majeure Risk	Increased chance of severe climate events Reduced insurance coverage for climate event Increase chance of financial erosion/collapse	ABN, ANZ, Banco Itau, Bank of Ireland, Bank of Montreal, Barclays, CIBC, Citigroup, Credit Agricole, Credit Suisse, HBOS, HSBC, Hypovereinsbank, KBC, KeyCorp, Lloyds, Malayan, RBC, Royal Bank of Scotland, Scotiabank, Standard Chartered, Toronto-Dominion, Wachovia, WestPac
Operating Risk – Cost	Climate events increase operations costs Complex technology increase O&M	ABN, ANZ, Banco Itau, Bank of America, Citigroup, Credit Suisse, HBOS, HSBC, Hypovereinsbank, Malayan, KeyCorp, KBC, Bank of Ireland, Royal Bank of Scotland, WestPac
Operating Risk – Management Capacity	Reduced capacity estimate risk and plan Increased demands on technical capacity Increased demands on management resources Climate reduce ability to pursue strategic plan Reduced capacity to undertake prevention	ABN, Banco Itau, Banco Santander, BBVA, Credit Agricole, Scotiabank, SocGen, Standard Chartered, Svenske Handelbanken, UBS, Unicredito, WestPac
Capital Markets/Finance Risk	Credit erosion, default, collateral impairment Financial asset values Accounting/financial disclosure Innovation causes capital obsolescence Market disruption/volatility Scale/transaction cost	ABN, ANZ, Barclays, Banco Itau, Banco Santander, Bank of America, Bank of Montreal, BBVA, Citigroup, Credit Suisse, Scotiabank, HBOS, HSBC, Hypovereinsbank, Lloyds, Malayan, RBC, Royal Bank of Scotland, San Paolo, Standard Chartered, SunTrust, Svenske Handelbanken, Scotiabank, SocGen, Toronto-Dominion, UBS, Unicredito
Participant Risk	Financial stability/creditworthiness Inadequate administrative or technical capacity	See Capital Markets See Management Capacity
Governance Risk	No party best positioned, willing or capable to accept and mitigate climate risk.	

Source: Author's tabulation of banks' responses to first three years of Carbon Disclosure Project survey.

Tabulation of bank responses to the Carbon Disclosure Project survey based on the Climate Risk Assessment Matrix criteria are set forth in Table 4.5 below.

Table 4.4: Carbon Disclosure Project Frequency of Banks' Identification of Climate Risks

Risk (Number of banks = 56).	**Number of Responses**	**Percentage Total Responses**
Capital Markets Risk	27	57%
Environmental Regulation Risk	25	53%
Force Majeure	25	53%
Operating Risk – Cost and Management Capacity	24	51%
Operating Risk – Cost	15	32%
Market Risk	13	28%
Operating Risk – Management Capacity	12	26%
Supply Risk	12	26%
Infrastructure Risk	4	9%
Political Risk	3	6%
Technology Risk	3	6%
Legal Risk	2	4%
Engineering Risk	0	0%
Participant Risk	0	0%
Governance Risk	0	0%

Source: Author's tabulation of banks' responses to first three years of Carbon Disclosure Project.

One method for evaluating the Climate Risk Assessment Matrix is to assess whether the importance of risks identified in the framework is consistent with the banks' responses to the Carbon Disclosure Survey.

The banks' responses to the Carbon Disclosure Project survey identified risk clusters that are consistent with those noted here as critical nodes. The banks focused primarily on capital markets, regulatory, force majeure, operating, market and supply risks.

Of those surveyed, twenty-seven banks identified capital markets risks as a potential risk magnified by climate change. Capital markets risks were the most frequently cited risk of climate change, identified by twenty-seven banks. Within the capital markets risk category, twenty-four banks identified credit risk, default risk and impairment of collateral as important capital markets risks.

Following capital markets risks, regulatory and force majeure risks were the second most commonly cited risks of climate change. Twenty-five banks identified increasing environmental regulatory risk and increasing risk of force majeure events as effects of climate change. Banks identifying regulatory risks associated with climate change commonly cited the costs of regulatory measures to control carbon emissions and potential liability arising from legal actions.

Of the twenty-five banks that identified force majeure as a risk of climate change, twenty-one banks identified the potential for increased climate events, and sixteen banks expressed concern that climate change could lead to curtailment of insurance coverage. Significantly, all insurance companies that submitted responses to the Carbon Disclosure Project survey recognized climate change to increase the potential for force majeure events, causing an increase in risk to their property and casualty businesses.

Fifteen banks in the Carbon Disclosure Project identified operating cost risk as a potential area of increased risk as a result of climate change. Many of the responses specifically mentioned increasing costs of energy as a source of risk. Management capacity risk was identified by twelve banks in the Carbon Disclosure Project as a potential area of increased risk as a result of climate change. The most common comment concerned the decreased capacity for management to properly assess risk and to plan.

As noted above, due to difficulties in distinguishing between operating cost and management capacity risk, these two categories should also be analyzed as an aggregate category – "Operating Risk". On an aggregate basis, a total of twenty-four banks identified operating risk as increasing due to climate change. As an aggregate risk, operating risk becomes the fourth most commonly cited risk, with over 50% of respondent banks identifying it.

Thirteen banks participating in the Carbon Disclosure Project identified increasing market risk as a potential result of climate change. Twelve of these banks specifically indicated that a company's reputation might be adversely affected by being linked with carbon emissions or environmental damage. Four of the thirteen banks indicated that climate change could influence consumer preferences or changes in demand.

Twelve banks responding to the Carbon Disclosure Project survey cited potential supply problems as a risk posed by climate change. Most of these responses related to increasing cost of energy and electricity. One bank identified vulnerability due to dependence on imported petroleum as a supply risk issue (See HBOS's responses to Carbon Disclosure Project surveys).

Notably, only four banks identified infrastructure risk, only three banks identified technology risk, and no banks identified engineering risk. The comparatively few responses mentioning technology-related risks may reflect the fact that banks' responses focused on the more immediate or familiar risks associated with their business or a failure to recognize that climate change will exert important pressures on technological development. Technology risk is a traditional risk and its importance has been recently reaffirmed by rating agencies in connection with IGCC technology (Foster 2005a and 2005b).

Only three banks identified political risk as a concern. One possible explanation is that banks equated political risk with regulatory risk, the most commonly cited risk, and the coding of the surveys conflated these risks.

Legal risk was identified by two banks, and participant and governance risks were not identified by any banks. We know from experience that these risks are important. A possible explanation is that the omission of these risks may reflect that they are viewed as secondary to loan default and preservation of collateral.

Bank respondents also made various general statements that were difficult to classify within any one particular risk category and were therefore not counted toward any of the above risks. Samples of these statements are given in Table 4.5 below.

Table 4.5: Carbon Disclosure Project Banks Identification of General Climate Effects

Climate Change Impact	**Carbon Disclosure Project Banks**
Agriculture	ANZ, Barclays, HSBC, Credit Agricole, Scotiabank, CIBC, Standard Chartered, Toronto-Dominion, WestPac
Biodiversity	BBVA, SocGen, WestPac
Loss of Operating Capabilities	Bank of Montreal
Relocation of Business	HSBC
Business Interruption, Commercial Risks	CIBC, Toronto-Dominion
Shifts in Weather	Dexia
Effects on Industry	Standard Chartered
Coastal Zone Business	Wachovia
"Impact on all aspects of modern life"	HSBC
"One of the most serious problems facing humanity"	Mitsubishi

Source: Author's review of banks' responses to first three years of Carbon Disclosure Project survey.

There is evidence that the banks' understanding of climate change improved during the period of the Carbon Disclosure Project. In some cases, this learning was dramatic. Several banks responded in the first or second years of the survey that climate change has no effect on their business or indicated that they had not studied the issue. In subsequent responses, these banks indicated that they had changed their earlier view and provided detailed responses comparable with other survey participants (See, e.g. Bank of America and Bank of Ireland responses).

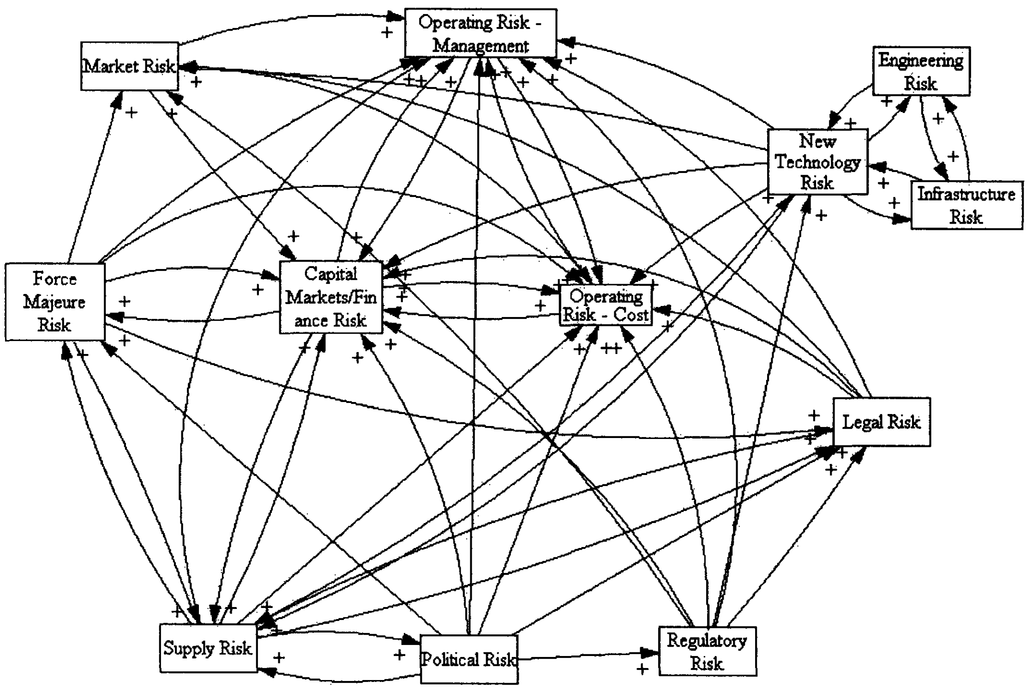
One of the purposes of the Climate Risk Assessment Matrix is to identify and provide greater visibility to financial risks associated with climate change. Therefore, although the banks did not cite some of these risks, it is not appropriate to abandon the less cited categories. If the omissions are because banks have not completely considered the implications of climate change, the survey was not structured to specifically identify these risks, or the risks are outside the scope of their day-to-day credit risk assessment, the inclusion of these risks in the revised framework may help draw attention to them.

4.4 Climate Risks and Dynamic Interactions

This section examines each risk within the Climate Risk Assessment Matrix separately based on the most recent scientific data and other evidence currently available. In addition, it analyzes the interactions among these various risks.

Diagram 4.1 below presents the cumulative potential interactions among the risks described in this chapter. Participant risk and governance risk are omitted because all other risks contribute to them.

Diagram 4.1: Potential Climate Risk Interactions



Source: Author's review of literature. See main text for description.

Diagram 4.1 suggests that the various types of risk interact and increase with climate change; i.e., there is substantial positive correlation among these risks. Multiple interactions can occur between many of the risks, with secondary and tertiary effects, and the patterns become complex. For example, the technology-engineering-infrastructure cluster of risks increases risks associated with market, supply, capital markets, and operations. Further, regulatory risk can increase technology cluster risks. Thus, in the case of technology cluster risks, these risks both affect and are affected by other risks. Of course, the representation of risk in this section is simplified. Specific interactions depend upon the conditions and facts prevailing in a particular situation.

We now turn to analysis of each risk and their potential interactions with other risks.

4.4.1 Supply Risk

Supply risk is the potential for disruption of supply or increased cost of inputs. Climate change can be expected to increase supply risks through several means.

Building a carbon neutral energy infrastructure will require new technologies, which will require new materials. Technologies such as fuel cells and solar photovoltaic panels involve materials that are expensive or rare (platinum in the case of fuel cells) or highly processed (silicon in the case of solar), which add cost and time to the production cycle. Importantly, while economies of scale may result in decreased costs where materials are abundant and the major cost is processing them, large-scale production will place increasing demands on rare commodities. This may lead to increasing costs of rare metals and/or greater emphasis on their recycling. Where recycling is economically feasible, such as in the case of platinum, it adds additional cost to materials. Further, a substantial percentage of metal may be irretrievably lost the in recycling processes.[9] Developing country demand for precious metals at rates of consumption similar to developed countries would ultimately place limits on technology diffusion for those technologies that require rare inputs (Gordon et al. 2006).

Changes in technology prompted by climate change may also create shortages of qualified labor to develop and install new technologies. For solar PV, for example, the cost of installation and balance of system is approximately the same as the cost of solar panels. The experience of renewable technology developers shows that issues such as shortages of labor and changes in work patterns can significantly increase cost and delays in clean technology projects (Vincent 2006).

Climate change may directly disrupt supply chains for all sorts of commodities or services, temporarily or permanently. Storms and extreme heat could damage supply infrastructure on a temporary basis. Increases in sea level, changing water resource patterns, prolonged extreme heat or repeated storms could cause dislocation of industry and populations, resulting in the permanent relocation or abandonment of supply infrastructure. To the extent that supply chains cannot be relocated or require time to relocate, disruption in supply can occur on a regional or extra-regional level.

Due to the global nature of markets, a disruption in a particular geographic region could potentially cause supply disruptions with implications for industry in other places. Hurricane Katrina provides a recent example of supply disruption. In August 2005, Katrina damaged 167 offshore platforms and 183 pipelines in the Gulf of Mexico, shutting down approximately 70% of gas production and 90% of crude oil production in the Gulf, which in the case of oil production, represents about 2% of global production and 20% of U.S. refining capacity (U.S. Congressional Budget Office 2005). As of March 2006, 87 platforms were still evacuated and approximately 23% of oil production and 14% of gas production remained unrestored (U.S. Minerals Management Service 2006).

Another example of supply risk is the potential for climate to change the cost of commodities due to increases in transportation costs. A study of commercial navigation on the Great Lakes-St. Lawrence River system using several climate system models predicts that a doubling of carbon dioxide would result in lower water levels due to evapotranspiration and precipitation changes. In turn, this will limit vessel size and the types of commodities that can be transported. The study predicts prices for grains, cement, salt, iron, coal, petroleum

[9] For example, Gordon et al. (2006) estimate that approximately 26% of copper and 19% of zinc is irretrievably lost in recycling processes.

and other commodities could increase by as much as 40% depending on the climate scenario and choice of model (Millerd 2005).

Other studies predict that global warming will open new transportation routes through the Northwest Passage of the Arctic Ocean (Arctic Climate Impact Assessment 2004). By mid-century, large shipping may be able to navigate the Artic Ocean year-around (Arctic Climate Impact Assessment 2004), reducing the shipping distance between Asia to Europe by 9,300 kilometers (5,800 miles) compared to the current route through the Panama Canal. This could significantly decrease the costs of transportation and commodities.

Supply risks associated with water can also affect manufacturing processes. Perennial water shortages in Taiwan threatened to disrupt the supply of semiconductors in 2002. Taiwan, which manufactures a large portion of global production in semiconductors, flat panel displays and printed circuit boards, consumes large volumes of water required to manufacture these products. The 2002 drought caused the government to institute water rationing and large firms to adopt conservation measures (Bradsher 2002; Hesseldahl 2002).

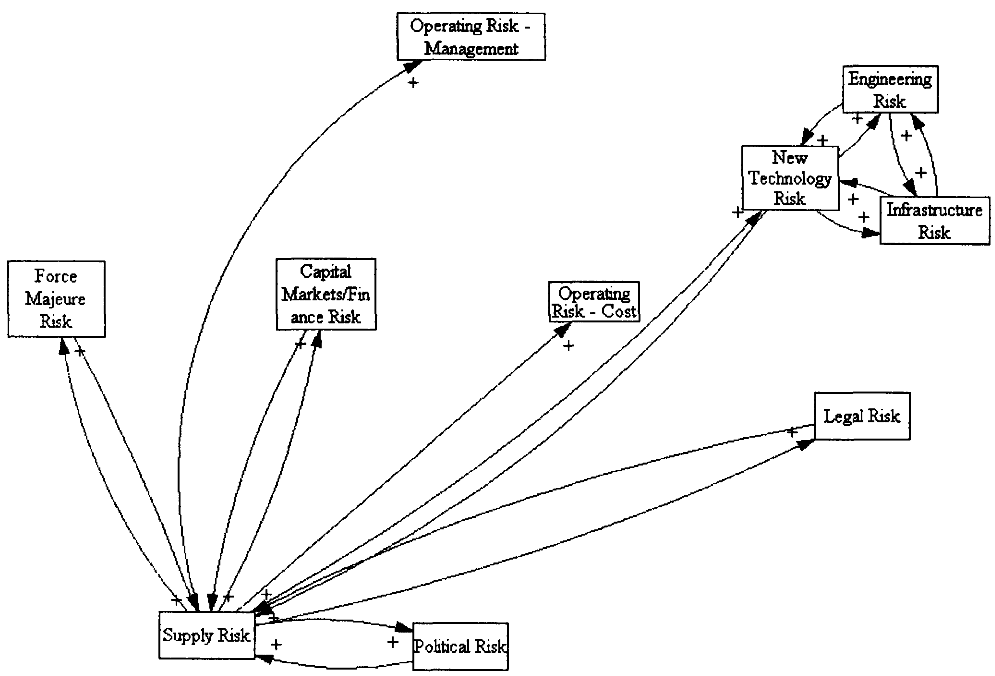
Another potential supply risk involves the supply of greenhouse gas allowance permits for companies subject to mandatory cap and trade regimes. This issue is addressed further in this chapter in the section "Regulatory Risk" and in Chapter 5 in the section "Carbon Offsets".

Significantly, twelve banks responding to the Carbon Disclosure Project survey cited potential supply problems as a risk posed by climate change. Most of these responses identified potential increases in the costs of energy and electricity as the primary supply risk. One bank identified vulnerability due to dependence on imported petroleum as a supply risk issue (See HBOS's responses to Carbon Disclosure Project surveys).

Importantly, supply risk interacts with other risks, such as force majeure, legal, political and capital markets risks. Supply risk and force majeure events interact to create a positive feedback loop. As already discussed above, an increase in the risk of a major catastrophic event (a force majeure risk) potentially increases supply risk. Supply risk also increases force majeure risk because increasing cost of materials increases replacement cost following major catastrophic events, an issue discussed in Chapters 5 and 6 in connection with insurance losses. Supply risk and technology risk interact, as introduction of new technologies may rapidly shift demand towards new materials, and inadequate supply of materials can increase the risk associated with new technologies. Supply risk increases legal risk because tightening commodity markets increase the leverage of producers, thereby increasing legal risks of contract breach and renegotiation. Legal risk also potentially increases the likelihood that a company will be unable to obtain supply, particularly if suppliers perceive an increased risk of default. Thus, there is a positive feedback loop between supply and legal risk. Supply risk and political risks also interact. In the case of oil, increases in political risks in producing regions often increase supply risk if markets perceive these risks to potentially interfere with production or transportation of oil. Tighter oil markets have provided producing countries with greater leverage to make political and economic demands. Thus, in the case of oil, there is a positive feedback loop between political risk and supply risk. The issue of political risk and supply risk will be discussed more thoroughly in the section below titled "*Political Risk*". Finally, supply risk affects capital markets, operating cost, and management capacity risks. For a particular company experiencing difficulty in obtaining reliable supply of inputs, capital markets can respond negatively with respect to that company's value and ability to raise financing. On a systemic level, increased volatility of prices or disruption of supplies of oil or other key commodities that co-vary with financial markets could increase the volatility of, or depress, capital markets. To the extent that commodities are increasingly linked to financial instruments that are traded in capital markets, capital markets risk can also affect the price of underlying commodities and the financial condition of companies that trade in commodities-linked instruments. Thus, there is a positive feedback loop between capital markets risk and supply risk.

Diagram 4.2 below shows potential supply risk interactions.

Diagram 4.2: Supply Risk Interactions



Source: Author's review of literature. See main text for description.

4.4.2 Market Risk

Market risk concerns reductions in, or volatility in, the price or quantity demanded of products. Climate change potentially increases market risks for infrastructure in several significant ways.

One way that climate change can increase market risk is by affecting a company's reputation. A company associated with poor environmental practices may potentially lose market share to competitors with better reputations for care of the environment or as a result of boycotts (e.g., ESSO in Europe).

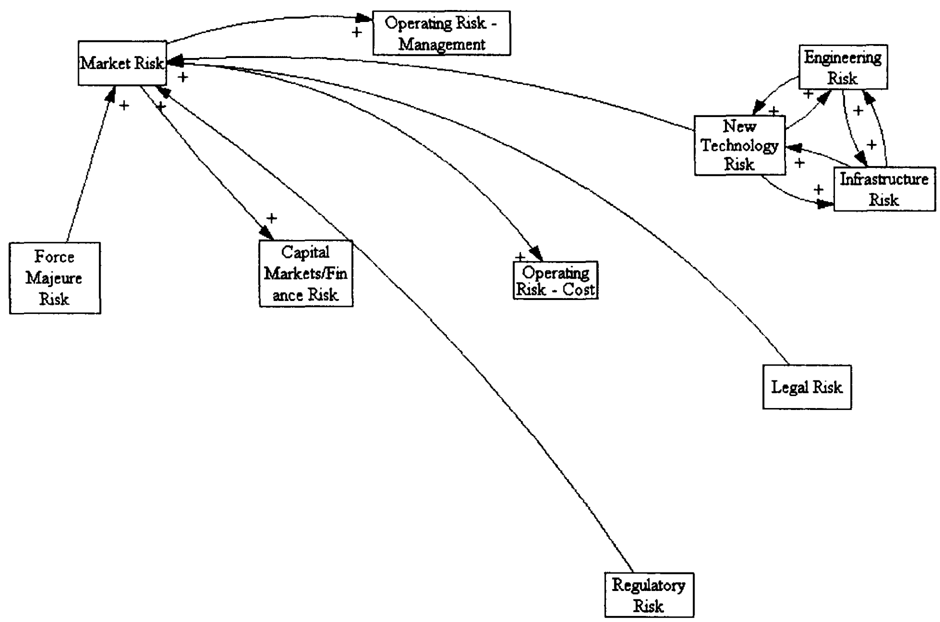
Another way that climate change can increase market risk is through short-term or long-term changes in climate. For example, extreme heat or cold affects demand for utility services. Utility company revenues are directly affected by climate. Chapter 5 discusses the use of weather derivatives by utilities and other businesses to address short-term climate risks. Long-term change in climate, such as gradual warming, will have a more fundamental effect on the demand for utility services. A recent study of the effects of climate change on the Boston metropolitan area to year 2050 predicts that climate change will cause slight decreases in winter demand for electricity and dramatic increases in summer electricity usage, requiring increased capital investment in peaking facilities that may only be utilized during the summer period. Although the projection indicates a net increase in overall electricity demand in the Boston area, low utilization rates of infrastructure to service summer demand could adversely affect the financial performance of utilities (Kirshen et al. 2004). Other studies have indicated substantial national investment may be required to meet increased electricity demand as a result of climate changes. These projected increases in electricity consumption due to climate change are in addition to anticipated growth in electricity demand resulting from increasing population and electrification (EIA 2005b; International Energy Agency 2003). One study estimated that the marginal increase in U.S. electricity consumption resulting from climate change will be from 12% to 22%, requiring capital investment of an additional $200 to $400 billion in generating capacity from climate change alone (Linderer 1988; as described in US NAS 1992).

Thirteen banks participating in the Carbon Disclosure Project identified increased market risk as a potential result of climate change. Twelve of these banks specifically indicated that a company's reputation may be adversely affected by being linked with emissions or environmental damage. Four of the thirteen banks indicated that climate change could influence consumer preferences or changes in demand.

Market risks interact dynamically with force majeure, regulatory, market, legal, capital markets, management capacity, and operating cost risks. Increases in force majeure, regulatory, technology, and legal risks potentially intensify market risks. With respect to capital markets, a reduction in demand for a company's products or services or lower utilization rates of firm fixed assets could reduce a company's market valuation, leading to greater difficulty to raise capital through capital markets. With respect to management capacity and operating costs, reduced demand for a company's products could potentially require greater management attention and resources to reverse such a trend.

Diagram 4.3 below shows potential market risk interactions.

Diagram 4.3: Market Risk Interactions



Source: Author's review of literature. See main text for description.

4.4.3 Technology-Engineering-Infrastructure Risk Cluster

Technology risk, engineering risk, and infrastructure risks are all risks related to the design, implementation, efficiency, and support of large engineering projects. They are different aspects of risks associated with new technologies and their infrastructure platform. Due to their close relationship, they are addressed together below.

4.4.3.1 Technology Risk

Technology risk is the risk of technology failure or inefficiency (Tinsley 2004). Climate change should increase technology risk, especially for new energy technologies.

Attempts to develop carbon neutral infrastructure will necessarily require the deployment of new technologies. New technologies present important issues such as whether the particular technology will work, reliability, health and safety, uncertainty regarding initial capital investment, operation and maintenance costs, comparative performance to competing technologies, and whether the particular technology will emerge as an industry standard (US NAS 1979).

For these reasons, banks and credit rating agencies generally resist unproven technologies, and financing them on a project finance basis is difficult. For example, integrated coal gasification combined cycle (IGCC) technology is recognized as superior in terms of efficiency and emissions in comparison to traditional coal-fire electricity generation technology. Yet, the electric utility industry has been slow to embrace IGCC technology and only four plants are currently in operation worldwide (Deutch and Lester 2004; Rosenberg 2004). Credit rating agencies have identified technology risk as the reason why IGCC has not been more rapidly adopted. In comparison to standard coal plants, IGCC plants require higher capital expenditures and several additional years to build (Bartsch and Muller 2000). Widespread adoption of IGCC will require industry to address several problems that are common to new technologies: higher capital costs, construction delays, inexperienced personnel, and uncertain operating and maintenance costs (Foster 2005a and 2005b).

The inherent bias against new technology among banks and credit rating agencies means that new technology will be adopted more slowly than is generally anticipated by the science and engineering community. Furthermore, the economic incentive to commoditize infrastructure finance projects means that once a technology is embraced by project parties and rating agencies, the preference for established technology is reinforced by the goal of reducing the transaction costs of financing infrastructure.

New technologies are also untested with respect to insurance, government regulations, building codes, and corporate buying standards. Locating trained personnel to install and maintain new equipment can be difficult. While these issues are routine, they are time consuming to resolve and adversely affect the economics of new technologies (Vincent 2006).

In general, carbon neutral technologies can be more complex and thus more costly than older technologies to operate. All else being equal, this makes the older, less costly, technology less risky from a financial point of view because it offers more predictable overall revenues. This requires new technology to be proven to a higher standard than may be feasible prior to its having been in operation on a commercial basis for some years.

Additionally, new technologies often raise the issue of public acceptance, which presents a threshold issue whether the technology can be practically adopted on a widespread basis (Schrattenholzer et al. 2005). Nuclear power provides the most dramatic example of the risks associated with acceptance of technology (Smith, E. 2002; Mehta 2005; MIT 2003). Offshore carbon sequestration demonstration projects have also experienced public opposition where such projects have been proposed (de Figueiredo 2003). Even renewable technologies, such as the proposed project to locate wind turbines off Cape Cod on the Massachusetts coast, face public opposition, which can slow or prevent energy infrastructure projects from going forward.

This is not intended to suggest that new technologies will not be adopted. However, their adoption will be much slower than is commonly assumed by the science and engineering community, or reflected in technology adoption models used for climate change research.[10] The goals of satisfying energy demand while reducing greenhouse gas emissions will place great emphasis on the introduction of new technologies in this century. When assessing the introduction of new technologies, the science and engineering community should take into account the time lags and biases exerted through the finance process.

4.4.3.2 Engineering Risk

Engineering risk is the risk relating to gathering accurate and meaningful data and integrating that data to design appropriate infrastructure (Tinsley 2000).

Climate change will likely increase engineering risk for large infrastructure projects as changing environment will challenge the ability of engineers to assess project requirements and design infrastructure. For example, the Canadian government estimates that 5% of infrastructure construction costs are due to safety for current climate conditions. Estimating the costs of making structures more resilient to weathering is difficult, but it is believed this cost is increasing. Significantly, the 5% estimate does not include the added cost of climate change (Auld 2006).

Designing structures that can withstand high impact events is important because the cost of repair is extraordinarily high. For example, the Norwegian government estimates that the annual cost of repair due to storm damage is approximately 5% of the annual investment in new infrastructure (Auld and MacIver 2005). Similarly, retrofitting existing structures for climate events is extremely expensive and the costs increase with time (Auld 2006; Kirshen 2006).

Climate change is expected to increase risk to infrastructure. For example, one insurer estimated that a 25% increase in wind strength can increase insurance claims for building damage by 650% (Coleman 2002). Table 4.6 provides other examples of how slight changes in weather conditions increase the risk of infrastructure failure.

Table 4.6: Climate Events and Property Damage

Windstorm	Doubling of windspeed 2.2 °C mean temperature increase	Four-fold increase in damages Increase of 5-10% in hurricane wind speeds
Extreme temperature episodes	1 °C mean temperature increase	300-year temperature events occur every 10 years
Floods	25% increase in 30 minute precipitation	Flooding return period reduced from 100 years to 17 years
Bushfire	1 °C mean summer temperature increase Doubling of CO2	28% increase in wildfires 143% increase in catastrophic wildfires

Source: Coleman (2002), adapted from Mills et al. (2001).

[10] The hybrid car illustrates the longer-than-expected time periods required to adopt new technologies. A recent study estimated that it will be approximately mid-century before hybrids are competitive and penetrate the market to significantly reduce U.S. energy consumption (MIT Laboratory for Energy and the Environment 2005).

Large-scale engineering projects to protect cities along coastal areas provide a cogent example of how climate change will potentially increase engineering risk. The magnitude and complexity of such projects alone will necessarily involve substantial engineering risk. To protect a city from climate risk requires the complex integration of water, energy, transportation, public health, population growth and socio-economic factors. For example, a recent study of the potential effects of climate change on the Boston metropolitan area proposed the introduction of adaptive measures including changes of building codes and construction of barriers to protect highly developed areas from storm surge. The scope of the study covered over one hundred towns in the Boston metropolitan area and projections for climate and economic conditions through 2050 (Kirshen et al. 2004).

Another example of engineering risk is the Venice floodgate project. The City of Venice regularly floods during the winter period due to storm surge. The problem has been made worse by subsidence of the city by approximately 4 millimeters per year due to pumping ground water until the practice was stopped in the 1970's, and increases in sea level of about 1.6 millimeters per year (Bras 2006). The Italian government is sponsoring the construction of 79 large moveable floodgates that are projected to require eight years to construct at an estimated cost of $5 billion (Bras 2006). Critics of the project claim that the models used to design the floodgates did not take into account the IPCC's most recent projections for sea level rise (AGU 2002). Proponents of the project believe the floodgates as originally designed are adequate to withstand a half-meter increase in sea level (Bras 2006; Harleman et al. 2000). They acknowledge, however, that more frequent operation of the gates and other measures would be needed to protect the city if sea levels continue to increase beyond that point (Bras 2006)

The City of London is currently assessing the increasing risk of floods due to climate change and faces similar engineering challenges in designing a floodgate capable of withstanding future sea level increases and storm surge associated with climate change. A major flood in London could cause from £12 to £16 billion of damage. The Association of British Insurers estimates that climate change could increase river and coastal flood risk by a factor of 8 to 12 times. The Thames Barriers were designed to protect against 7-meter storm surge, which had a probability of 1 in 2000 years. Increases in sea level are expected to reduce their protection to 1 in 1000-year flood risks by the year 2030. In response, the City of London is studying options for upgrading the existing barriers to meet the higher protection standards (London Assembly 2005).

The Canadian Council of Professional Engineers (CCPE) has specifically identified engineering risk as a concern raised by climate change. The CCPE is responsible for the accreditation of Canadian engineering schools and professional requirements. CCPE believes climate change poses fundamental challenges for the engineering profession, including the need for engineers to design for uncertain future conditions that will differ significantly from past experience, and lack of statistically meaningful data to conduct risk assessment on engineering designs (Auld and MacIver 2006; Auld, MacIver and Klaassen 2006). The CCPE is undertaking a national assessment of public infrastructure vulnerability to climate change, and is considering changes to codes and standards, professional education requirements, and accreditation requirements for Canadian engineering programs to prepare the engineering profession for climate change (Lapp 2006; Canadian Council for Professional Engineers 2006).

The engineering profession is developing tools and models for assessing the effects of climate change. Some of these models link a climate system model with engineering estimation models for planning and design purposes (Arisz and Burrell 2005). Other tools include infrastructure information databases intended to provide guidance to government planning and emergency response (Williamson 2005), and support risk assessment efforts to integrate climate change into infrastructure engineering practices (Bell 2005).

4.4.3.3 Infrastructure Risk

Infrastructure risk is risk that new infrastructure will not interconnect with, or adequately be supported by, surrounding infrastructure (Tinsley 2000). For purposes of this analysis, supporting infrastructure includes both man-made and natural infrastructure. Climate change will require introduction of new technologies, which will increase infrastructure risk associated with man-made support infrastructure, and result in changes in natural support infrastructure.

Distributed renewable technologies pose several significant infrastructure risks that will require changes to the electricity grid and other infrastructure. For example, the intermittency of wind and solar resources will limit their use unless electricity grids possess adequate reserve capacity to insure reliable service and safe operating conditions. Additional reserve capacity may cause generators to incur substantial additional capital costs (Namovicz, C. 2006), unless existing fossil fuel generation plants are used to provide the necessary reserve capacity (Lyons 2006).

The upper limit for the percentage of electricity generation from renewable sources is difficult to predict due to infrastructure risk. Based on experience with geographically diversified portfolios of wind assets in Canada and models simulating large-scale wind generation, it appears feasible to meet 10% of electricity demand through wind power in Alberta, Canada without major technical changes in infrastructure or cost (Milborrow 2004). Denmark and Northern Germany have reported up to 20% of electricity demand satisfied by wind, however these regions are integrated with neighboring grids and thus the reported number does take account of extra-regional reserves. If extra-regional reserves are counted, the overall wind percentage would be considerably lower (Namovicz, C. 2006). The Energy Information Administration's NEMS wind model currently uses 40% of total electricity generation as the upper limit for modeling the potential contribution of wind power. However, EIA is presently unable to reliably estimate the changes to infrastructure or the costs required to implement wind technology on such a scale (Namovicz, C. 2006).

Infrastructure issues must be solved to fully integrate renewable technology into the existing infrastructure. In the meanwhile, the penetration of new technologies may be slowed due to infrastructure risk.

Another aspect of infrastructure risk is the dependence of infrastructure on natural infrastructure that could be impaired due to climate change. An example of this is the potential effects of climate change on hydroelectric power generation due to reductions in stream flows (US NAS 1979). Regions that are dependent upon hydropower for electricity and are subject to long periods of drought have already experienced electricity shortages and blackouts (McCulley and Wong 2004).

Climate changes that create unpredictable precipitation patterns or periods of drought could adversely affect hydropower electricity generation. Reductions in river flows disproportionately decrease hydropower production because reduced river flows reduce the amount of water available to power turbines and reduce water pressure. According to the U.S. Environmental Protection Agency, for the Colorado River's lower basin, a 10% decrease in runoff reduces power production by 36% (U.S. EPA 2006b). Canadian studies show that warming, changes in precipitation, and water withdrawals for agriculture and industry during the past century have combined to reduce summer river flow by 20% to 84% in some Western Canadian rivers (Schindler and Donahue 2006). As described in the "Supply Risk" section, this is expected to significantly affect the cost of transportation and commodities, including electricity generated by hydropower (Millerd 2005).

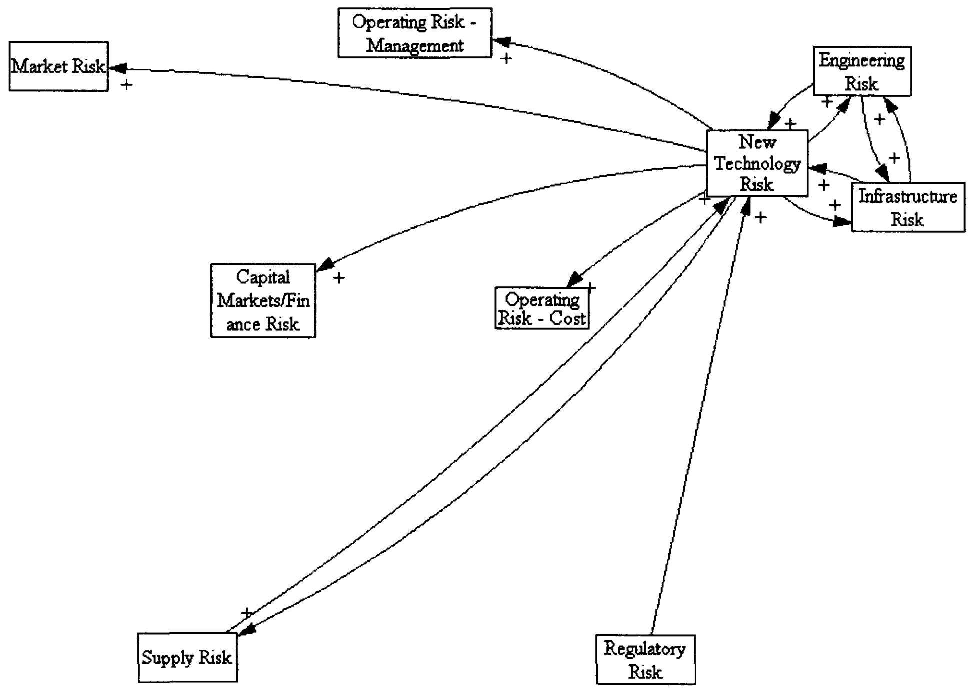
Technology risk, engineering risk, and infrastructure risk are closely related because they all concern the ability of firms to design and implement technology appropriate to changing environmental, regulatory, and competitive conditions. They directly affect the cost, effectiveness, and the rate of implementation of new technology and infrastructure. As suggested by the examples of hydropower and wind intermittency in the infrastructure risk section, these risks may also place an absolute or practical limit on the application of certain technologies.

In the Carbon Disclosure Project surveys, four banks identified infrastructure risk and three banks identified technology risk as a concern posed by climate change. No banks identified engineering risk.

Technology risk, engineering risk, and infrastructure risk interact dynamically with each other exhibiting positive feedback loops among them. These risks are intensified by regulatory risk, which exerts pressure to develop new technology. Supply risk also interacts with the technology-engineering-infrastructure risk cluster, as introduction of new technologies may rapidly shift demand towards new materials, inadequate supply of materials can increase the risk associated with new technologies, and increasing infrastructure risk resulting from loss of natural support systems may cause commodities prices to increase. In turn, technology, engineering and infrastructure risks contribute to increased market risk, capital markets risk, operating cost risk, and management capacity risk.

Diagram 4.4 below shows potential technology-engineering-infrastructure risk cluster interactions.

Diagram 4.4: Technology-Engineering-Infrastructure Risk Cluster Interactions



Source: Author's review of literature. See main text for description.

4.4.4 Environmental Regulatory Risks

Environmental regulatory risks are divided into three distinct subcategories of risk: regulatory risk, recovery risk, and litigation risk. Regulatory risk is the potential for increased or fragmented regulation relating to climate change. It includes risks associated with compliance with new and untested regulations. Recovery risk relates to the ability to recover cost of new technology, environmental remediation or catastrophic losses where the approval of a regulatory authority is required to increase the price of services provided to consumers. Litigation risk relates to lawsuits based on climate change.

4.4.4.1 Regulatory Risk

Multinationals face regulatory risk due to climate change in multiple jurisdictions. Countries that have adopted the Kyoto Protocol and are subject to emissions limits are in the process of adopting implementing legislation and regulations. Emitters in the European Union will face higher operations cost due to compliance with the Kyoto Protocol. In the United States, where there is currently no federal law regulating carbon emissions, and individual states in the northeast and California are pursuing their own regulations, regulatory risk takes a different form, presenting uncertainty and the potential for fragmented regulation.

Regulatory risk affects the cost of plant and equipment in the energy sector. The cost of complying with environmental regulations accounts for a large portion of the increasing cost of new electricity generation and capital improvements to existing plants (Joskow and Rose 1985).

Because regulatory risk is so closely linked to the financial performance of the energy sector, one might expect any effort to impose additional cost through regulation to be resisted. This resistance will slow the implementation of best available technologies. However, an alternative strategy is for industry to seek regulation in a form that is acceptable to it (Stigler 1971). Industry may seek regulation in order to obtain certainty across multiple jurisdictions, to preclude more onerous regulation, and to provide a competitive advantage for companies better positioned to comply with the regulatory scheme. A third strategy is for the business community to address political and public concern by participating in voluntary arrangements. Groups like the World Business Council for Sustainable Development have promoted self-regulation as a means to avoid more onerous government regulation (Hancock 2003).

4.4.4.2 Recovery Risk

Regulated industries in the United States and other countries are often required to obtain the approval of a governmental entity to increase consumer rates for services. Climate change can increase recovery risk because it potentially increases the costs of environmental compliance, preventive expenditures and catastrophic losses. Recovery risk is particularly significant for the utilities and insurance industries.

Approximately 58% of electricity generation in the United States is regulated and their rates are subject to approval by governmental entities (Edison Electric Institute 2006a). A majority of utilities therefore face risk that their applications to regulators for rate increases will be declined or delayed (Edison Electric Institute 2005).

Utility rate increase applications for catastrophic losses are generally expected to be approved (Oldack 2006). However, rate applications are a political process and there are real risks associated with recovering disaster costs through rate cases (Edison Electric Institute 2005). There are similar concerns with recovery of environmental compliance costs (Furey 2006). Additionally, when costs are ultimately recovered, these recoveries are delayed. The average time to obtain approval to recover costs varies by jurisdiction and is closely watched by investment analysts and credit rating agencies in evaluating utility companies (Furey 2006; Lehman Brothers 2006).

Difficulty in passing the costs of capital improvements to consumers has limited the wider adoption of measures that could prevent damage from climate events and mitigate further climate change. Preventive or mitigation costs may be more difficult to justify to regulators than catastrophic losses because they are discretionary in nature and their benefit may be speculative. Examples of precautionary measures that have not been widely adopted due to recovery risk include the use of underground transmission lines in the state of Florida and neighboring Gulf states. Over 80% of U.S. transmission lines are currently aboveground. The Edison Electric Institute estimates that underground transmission costs are approximately 10 times greater than the cost of aboveground wires, and have one-third the failure rate of overhead systems. A study of the issue in North Carolina estimates its three utilities would require twenty-five years and a 125% rate increase to transition to underground lines (Utilipoint 2004). An example of mitigation technology that has been slowed by recovery risk includes IGCC technology. Credit rating agencies have attributed the slow adoption of IGCC technology in part to uncertainty whether regulators will permit the increased costs associated with this technology to be passed on to consumers (Foster 2005a and 2005b).

Insurance companies in the United States are regulated by state insurance commissions and are also subject to recovery risk. All states posses some form of approval or review process for insurance rate increases (Insurance Information Institute 2004). Recovery risk can directly affect the availability of insurance to the energy sector, which can in turn affect the ability to finance energy infrastructure (Spudeck 2006). The case of insurance will be discussed further in Chapter 6.

Recovery risk is particularly important in the context of climate change because utilities must recover the capital expenditures required to develop carbon neutral energy infrastructure, and insurance companies must recover the increasing cost of risk coverage, if these firms are to play their roles in supporting the successful transition of infrastructure. Due to the magnitude of the potential costs to the energy and insurance sectors, the importance of recovery risk will increase with the severity of climate change.

4.4.4.3 Litigation Risk

Increasing scientific evidence of climate change increases the potential for litigation. At the time of writing, approximately ten climate-related cases have been filed in seven countries (Climate Law 2006a; Congressional Research Service 2005a).

In the United States, several lawsuits have been filed against utilities due to their carbon emissions. In July 2004, the attorney generals of the states of Connecticut, California, Iowa, New York, Vermont, Wisconsin, New Jersey, Rhode Island, and the City of New York filed a suit in United States federal district court seeking to hold a group of power companies liable for damages caused by their emissions and to enjoin further emissions. The defendant utilities together account for 650 million tons of carbon dioxide emissions each year, constituting approximately 25% of all utility emissions in the United States, and 10% of all anthropogenic emissions in the United States. The suit is grounded on the federal common law and various state laws of public nuisance. It alleges that global warming presents an imminent danger to human health and private and public property, and endangers the viability of state and city infrastructure in coastal areas (Connecticut et al. v. American Electric Power Company et al., 2004).

In October 2003, a number of states filed a suit against the United States government for failing to enforce the U.S. Clean Air Act. The suit contends that the U.S. Environmental Protection Agency (EPA) has failed to meet its mandatory duty to review new sources of pollution every eight years pursuant to Section 111(b)(1)(B) of the Clean Air Act, and in the case of carbon dioxide, to promulgate regulations that require the latest abatement technologies available for carbon dioxide, sulfur dioxide and particulate emissions. The states argue that because proven affordable technologies exist that can reduce carbon dioxide emissions, EPA must promulgate a revised standard and require that abatement technologies be implemented (Commonwealth of Massachusetts et al. v. U.S. Environmental Protection Agency, 2006).

Both of the U.S. cases were dismissed at the lower court level and are currently being appealed (Connecticut et al. v. American Electric Power Company et al., 2005; Commonwealth of Massachusetts et al. v. U.S. Environmental Protection Agency, 2006).

In addition to developing U.S. law on the subject of climate change, these cases may encourage plaintiffs in other countries to file similar suits in their legal systems. Other legal jurisdictions may be more willing to extend jurisdiction and award damages to local plaintiffs against foreign companies. Thus, climate litigation represents a significant risk to multinational companies, particularly the energy industry. In a recent example, a Nigerian court in April 2006 ordered Shell to stop gas flaring in its Nigerian petroleum operation by April 2007. A recent study found flaring is the largest source of greenhouse gas emissions in Nigeria and costs Nigeria an estimated $2.5 billion annually due to energy loss and environmental degradation (Climate Law 2006b). The Nigerian court's ruling is significant because it shows that developing countries may be fertile ground for climate change suits against the energy industry.

These cases are important because they demonstrate the use of traditional tort law to address climate change. However, there will be difficult legal issues that must be addressed if these cases will affect industry practices. Common law systems do not recognize a cause of action for general damage to the environment (Hancock 2003). The willingness of courts to extend jurisdiction over these cases will depend in part on the their perception that these cases present legal issues, and are not political matters. The determination that an issue is legal in nature depends in part upon the ability of courts to administer the law in a technical fashion.

One of the most formidable obstacles to successfully bringing a tort case is proving causation. The continuing development of climate science and the IPCC's unequivocal position that human activity is causing global warming is important support for the causation element. Cases for sea level rise, disruption of water resources due to glacier melt, and damage to equipment due to permafrost melt may already be provable as a matter of law (Grossman 2003). However, even if climate damage can be proven, attribution to a particular defendant remains a difficult legal hurdle. Liability for climate change based on tort could follow a line of product liability cases that determine liability and fashion a remedy based upon a company's market share (see Perry 1987).

In addition to domestic tort law, international law may provide a foundation for climate change claims. International law develops through treaty and customary practices. Several treaties already recognize transboundary environmental harm as a valid basis for legal claims. Principle 21 of the United Nations' Stockholm Declaration on the Human Environment provides that states possess the "sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or areas beyond the limits of national jurisdiction" (United Nations 1972). In disputes between countries, article 8(2)(b)(iv) of the Rome Statute of the International Criminal Court applies criminal sanction against states that knowingly and intentionally cause "widespread, long-term and severe" damage to the environment. Article 130R of the Treaty of European Union adopts the goal of sustainability, the precautionary principle, and supports the rectification of environmental damage. These provisions may provide a legal foundation for claims brought within the European Union based on European Union law.

Customary international law has not yet developed a firm foundation for climate change claims. However, a clean environment and access to vital resources necessary for human survival are increasingly recognized in international legal documents and scholarship. For example, the 1994 Draft Declaration on Principles of Human Rights and the Environment codified twenty-seven environmental human rights. Numerous scholars have considered whether environmental norms may rise to the level of fundamental human rights or international law (Hancock 2003; Hill 2003; Drumbl 1988; Mowery 2002; Vicuna 1998; Rosencranz 2003). Although not legally enforceable in a court of law, these sources are considered persuasive evidence concerning the formation of customary international law (Nijhawan 2003).

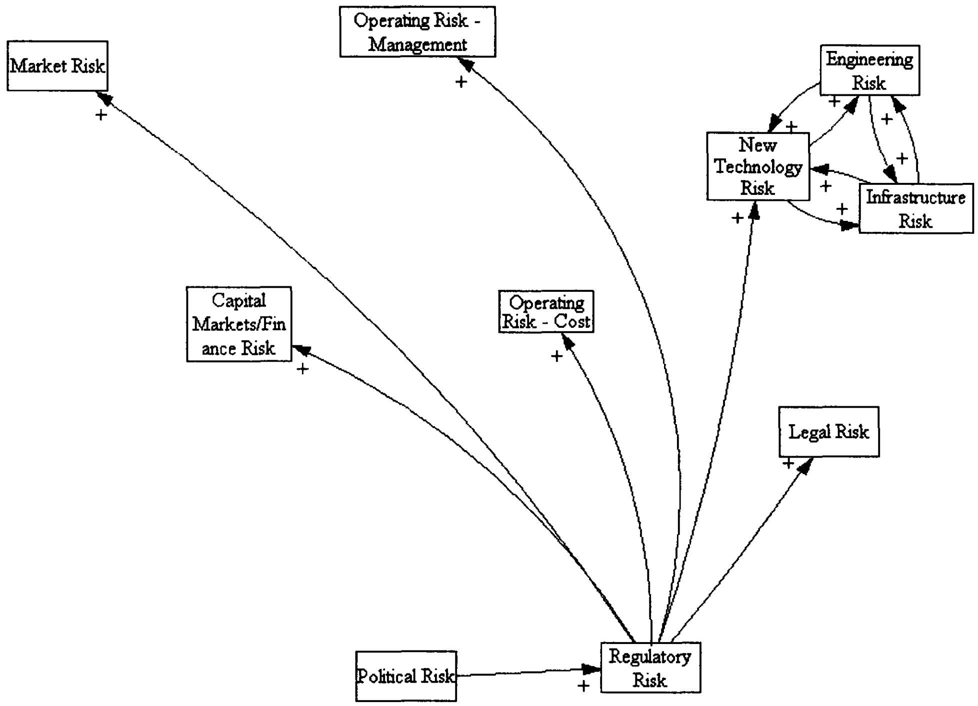
Importantly, there is evidence that climate change cases are prompting a change in social perception. These cases encourage publicity and have prompted institutional investors to raise climate change as a priority with the companies that they hold in their portfolios (Baue 2003).

In the Carbon Disclosure Project survey, twenty-five banks identified increasing environmental regulatory risk as one of the effects of climate change. Significantly, this was the second most commonly cited risk of climate change.

Environmental regulatory risks interact dynamically with other risks. Political risk increases environmental risk. Environmental risk increases operating cost risk, management capacity risk, capital markets risk, legal risk, and new technology risk. As discussed further below, environmental (in particular the regulatory risk component) is one of the primary drivers for the adoption of new technology. Regulation also can affect competitive relationships and therefore can significantly affect market risk.

Diagram 4.5 below shows potential regulatory risk interactions.

Diagram 4.5: Regulatory Risk Interactions



Source: Author's review of literature. See main text for description.

4.4.5 Political Risk

Political risk traditionally involves risks associated with war, unrest, expropriation, creeping expropriation (regulation intended to gradually eliminate an activity or set of rights), change of government, environmental activism, and corruption.

In the context of climate change, there are several additional types of political risk that are separately identified and described: deadlock/uncertainty and incomplete institutional arrangements.

This section will describe the traditional subcategory of unrest in the context of climate change, and the new categories of deadlock/uncertainty and incomplete institutional arrangements.

4.4.5.1 Unrest

This section explores the potential relationship between climate change and political unrest. In assessing these linkages, it is necessary to consider a broad set of natural resource, environmental and energy issues that are increasingly associated with climate change. While this section suggests that climate change potentially increases the chances of political unrest, it is not intended to deterministically predict the outcomes of political events, which will depend upon the actions of institutions and individuals, as well as the particular circumstances.

There are important linkages between water scarcity, fossil fuel production, environmental pollution, and climate change. For example, the melting of glaciers due to climate change is expected to intensify water scarcity in the mid to latter part of this century in many regions of the world that depend on glacier and snowpack for summer water supply. The problem will affect millions of people in Asia, South America, the Indian subcontinent, and the Western United States (WWF 2005; Hayhoe et al. 2004b). Increases in sea level could make the heavily populated coastal areas uninhabitable, causing mass migration (Tol 2002). In turn, these changes could disrupt food supply, lead to famine, disease, and economic hardship, ultimately threatening political stability (Tol 2002).

Fossil fuel production and consumption is the primary source of greenhouse gas emissions and many environmental pollution problems. As petroleum supplies tighten, climate change and environmental issues may lend support to political actors who desire to withhold oil from the market for economic, political or other reasons.

Political unrest and political risk in general can impair private sector operation in extractive industries and exacerbate resources supply risk. The politicization of petroleum markets started with the expropriation of oil concessions by Iran in 1953, Iraq in 1961 and Libya in 1971. These expropriations prompted other countries to demand increased participation rights in revenue sharing with private companies, and eventually led to outright nationalization during the 1970's in Algeria, Nigeria, Abu Dhabi, Kuwait, and Saudi Arabia (Choucri 1976; EIA 1997). The cessation of petroleum exports was first used as a political instrument in 1973 by the Organization of Arab Petroleum Exporting Countries against the United States and other western countries that supported Israel in the Yom Kippur War with Syria and Egypt (Yergin 1991; Choucri 1976). Today, the threat of withholding oil production remains a popular political weapon. In the first half of 2006, governments and opposition groups have sought to exploit tight oil markets by threatening to cut production in Venezuela (political standoff with United States), Iran (nuclear standoff), Chad (payment of revenues), Ecuador (civil unrest), Saudi Arabia (terrorist attack on refinery), Iraq, (civil unrest and terrorism), and Nigeria (civil unrest) (Financial Times 2006a, 2006b, 2006c, 2006d).

More recently, there is increasing anecdotal evidence that the politics embodied in the oil nationalization movement may re-emerge in the context of natural resources and climate change. In the area of water resources, resistance to the privatization of the water system in

Cochabamba, Bolivia led to the expulsion of a Bolivian subsidiary of the Bechtel Corporation in January 2005. Under an exclusive franchise arrangement granted by the Bolivian government to a private international consortium led by Bechtel, Cochabamba's citizens faced rapid increases in water prices at rates as high as 300%. The rates were so high that the World Bank declined to support the project (Samii 2005). Resistance to the project was led by Oscar Olivera, a labor union leader, on the grounds that it violated fundamental human rights concerning natural resources. According to Olivera,

> "The first is a change in the economic model and the second, a change in the dominant political structure. The economic change fundamentally depends on reclaiming our homeland, which has been marginalized and handed over to transnational corporations, and more importantly today in reclaiming our gas and petroleum as fundamental sources of energy for the rest of the world. And also, reclaiming water, a collective right, a human right, a right of all living creatures" (Olivera, 2005).

In May 2006, the Bolivian government announced the nationalization of the gas industry and ordered the military to seize all production fields. In his speech announcing the nationalization, Bolivia's President Evo Morales, sounding similar to Olivera, stated: "The time has come, the awaited day, a historic day in which Bolivia retakes absolute control of our natural resources. ... The looting by the foreign companies has ended." Despite the nationalization policy, the Bolivian government allowed foreign gas companies six months to renegotiate their contracts with the government and to continue to operate in Bolivia (Zuazo, 2006). As in the case of petroleum, the control over other natural resources is a method to provide greater leverage to developing country governments vis-à-vis multinational companies.

Increasingly, there is recognition that exploitation of natural resources often does not produce any measurable benefits for the general population (Blanco 2005; Ross 2001; Kutting 2004). Worse, producing countries have generally failed to save and invest profits from natural resource exploitation for future generations (Davis et al. 2003). If this trend continues, when water resources become scarce due to population growth and climate change, the risks of civil opposition in developing countries to multinational corporations operating in the water, energy and other extraction industries can be expected to increase.

In the area of petroleum, there are numerous recent examples of civil unrest, human rights abuse, resistance to the operation of foreign energy companies, domestic corruption, and even war associated with extraction industries. Petroleum and mineral resources played a significant role in financing wars waged by countries such as Angola, Burma, Congo, Columbia, Indonesia, Nigeria, Sierra Leone, and Sudan (Human Rights Watch 2004). Further, the presence of major extractive industries within a country and human rights abuses by the local government have been shown to correlate strongly. These abuses include intimidation and violence by security forces, forced labor, failure to protect indigenous populations, and complicity between industry and the local government at the expense of providing citizens with due process of law (Morton 2003; Ross 2001). In some cases, private firms have been implicated directly in the abuses.[11]

Increasingly, human rights advocates are recognizing that economic motives, especially the control of resources, are the motivation for human rights violations and political violence. According to a recent United Nations study,

> "... close examination of present-day intra-state conflict reveals that the underlying motive for these conflicts, and the players involved, have changed. With the emergence of national and international non-state actors as central and prominent players, it is becoming increasingly evident that many of the recent violent conflicts are provoked by the desire to capture or control strategic resources" (Makkonnen 2002).

Klare (2001) demonstrates how natural resources such as petroleum, minerals and timber have been a source of actual or potential conflict in the past, and predicts that resource scarcity will increasingly be a cause of war.

Theorists have suggested that the political stability of producing countries is directly related to the revenues derived from exploiting natural resources. Noreng (2002) describes a four-stage evolution for countries that derive primary income from extraction industries: (1) development of a rentier state and an elite class of insiders who are the principal beneficiaries, (2) consolidation of elite power at the expense of the local private sector, (3) elite opposition to demands to share or cede power, and (4) eventual loss of power by these elites. The second and third phases of Noreng's evolution, consolidation of power and resistance to ceding power, are often characterized by violence and human rights violations.

If Noreng's hypothesis is correct, as petroleum production peaks in various producing countries or oil revenues decline for other reasons, we can expect elites in these states to be weakened, possibly losing power. Noreng contends that historical declines in oil revenues preceded, and were a partial cause of, the fall of the Shah's government in Iran, and the implosion of the Soviet Union during the Gorbachev period. Both of these governments were highly dependent on oil revenues (Noreng 2002). Noreng's theory is further supported by quantitative research that shows a statistically significant positive correlation between mineral revenues and authoritarian government behavior based on a sample of 113 countries (Ross 2001). This research suggests that oil wealth reinforces a stronger, more authoritarian state.

While climate change may increase the potential for political violence and unrest, the actual effect will depend on the actions of political and private institutions in producing and

[11] See, e.g., Doe v. Unocal (2003) (human rights violations allegedly committed in Burma; case later settled and dismissed); Bowota v. Chevron Texaco Corp. (2004) (defendant allegedly transported Nigerian military troops to site of demonstration against defendant's operations, resulting in deaths of several protesters); Wiwa v. Royal Dutch Shell (2000) (defendant allegedly aided and directed Nigerian government in human rights abuses, causing wrongful death of two environmental and human rights activists).

consuming countries. How private sector companies conduct themselves in developing countries may contribute to their capacity to mitigate political risk. Research shows that although the presence of major extractive industry correlates with human rights violations, there is also evidence that corporations can play a positive role in strengthening human rights principles in host countries (Meyer 2003). Corporations have a role to play in working with humanitarian organizations and foreign governments to assist in conflict resolution in countries they are doing business (Nelson 2002). An increasing number of corporations are adopting codes of conduct that incorporate human rights principles (Wawryk 2003). Corporations that can credibly offer a better future to a country's population may enjoy popular support, which can help reduce the risks associated with political unrest.

4.4.5.2 Deadlock/Uncertainty

Responses to climate change may involve politically controversial or unpopular technologies or policies. Often, these political controversies are the product of competing interests groups over a particular issue. Nuclear energy, oil drilling in coastal areas, and petroleum or carbon taxes provide common examples of political deadlock linked to interest group politics (Mehta 2005; Gramling 1996). Proposals to engineer planetary-wide solutions to climate change, such as space-based mirrors to reduce albedo or ocean-based carbon sequestration, would likely produce deadlock if ever proposed (Keith 2002).

Political deadlock can lengthen the time required to adopt new technology. For private sector companies, the potential for deadlock can affect the cost and profitability of projects. These considerations can reduce the willingness of private sector companies to embrace technology or projects that may be subject to deadlock or uncertainty with respect to government approval, regulation or other issues.

Nuclear energy provides a leading example of deadlock. Nuclear fission is perhaps the only carbon neutral technology currently deployable on a large scale. Taking into consideration costs associated with safety, waste and decommissioning, nuclear energy is slightly more expensive than electricity generated using fossil fuels without carbon sequestration, and is basically competitive at approximately 7.3 cents/kWh for new baseload capacity (Tester et al. 2005). Further, the high energy density of nuclear materials makes it an advantageous substitute for fossil fuel resources. Yet, worldwide, only twenty-four nuclear power plants are under construction today (Sell 2006). Most U.S. nuclear plants are expected to be decommissioned by approximately 2050 unless steps are taken to revive the industry (Golay 2006).

New nuclear plant licensing and siting, environmental regulation, and waste removal and storage have all been the subject of controversy and litigation in the United States, Canada, Europe, and many other countries (Mehta 2005). Political opposition to nuclear technology, licensing delays, and high interest rates in the late 1970's and early 1980's increased the financing costs of nuclear power technology, causing several companies to abandon existing nuclear projects and stopped further expansion of the nuclear industry in the United States and many other countries. Public support for expansion of nuclear power in the United States has dropped considerably with the maturation of the technology.

Surveys indicate that only 9% to 37% of Americans support expansion of nuclear power, depending upon age group (Smith 2002).

Importantly, risks of deadlock continue after introduction of a new technology, as occurred in the case of nuclear energy. Additionally, these risks may increase for more complex technologies after the public and politicians have become more familiar with their risks.

Because climate change will require introduction of new and increasingly complex technologies, the potential risk of deadlock increases. Deadlock is therefore a very real possibility that may adversely affect firms that are engaged in energy and environmental infrastructure projects. Deadlock may significantly slow the introduction of new technology and policy.

4.4.5.3 Intermittent or Incomplete Institutional Arrangements

The risk of intermittent or incomplete institutional arrangements is closely related to the issue of deadlock. Intermittency relates to policies that are temporary, subject to uncertainty as to their continuation, or temporarily suspended and then reintroduced. When deadlock occurs, the result is often intermittent policy or incomplete policy.

With respect to climate change, examples of intermittent or incomplete arrangements in the United States include the intermittent provision of U.S. tax credits for renewable technology, fragmented state laws regarding renewable electricity generation portfolios, and varied automobile emissions requirements among states.

At the international level, the Kyoto Protocol is the most important example of incomplete institutional arrangements. The Kyoto Protocol governs carbon emissions until 2012 for industrialized countries that signed and ratified the treaty. The Kyoto Protocol is part of a framework that was not intended to be complete, but rather was meant to evolve. However, the lack of participation by the United States and Australia, and the lack of emissions limits on developing countries including Brazil, China, and India threaten the viability of the arrangement. Thus, the Kyoto Protocol in an incomplete arrangement in terms of participation, emissions constraints, and temporal coverage (Wicke 2005; Baumert 2002). The incomplete nature of the Kyoto Protocol undermines it efficaciousness and creates uncertainty concerning its continuation.

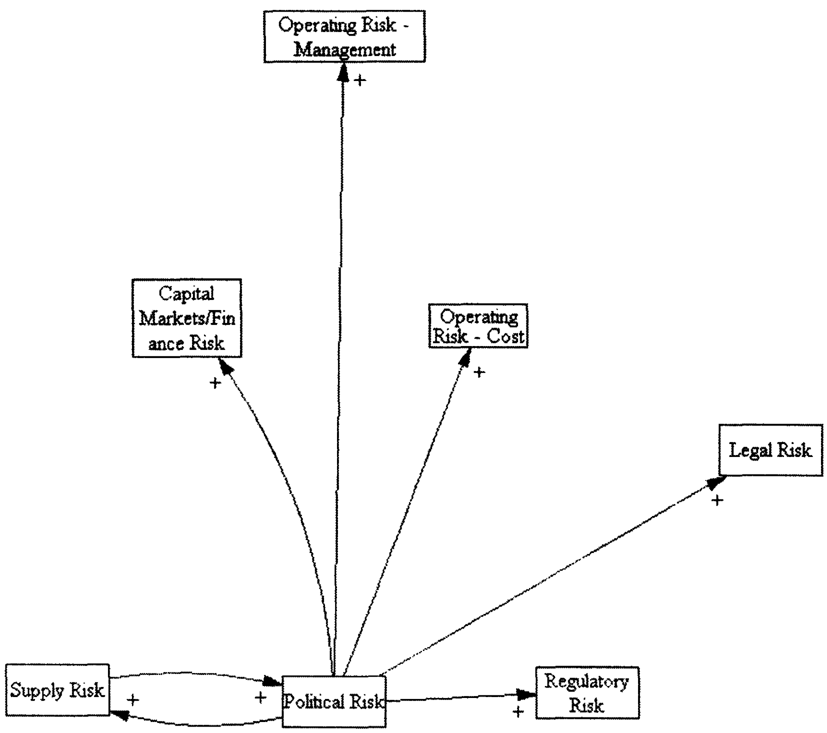
Negotiations over the future greenhouse gas regime is similarly fragmented, progressing on potentially competing tracks. Within the UNFCCC, there are two tracks for discussions concerning post-2012 arrangements: the Kyoto Parties, and a second track that includes the United States and all other parties in the Framework Convention. Two significant negotiations are occurring outside the UNFCCC as well. The Gleneagles talks are held between the G8 countries, Brazil, China, the European Union, Indonesia, Mexico, Poland, South Africa, and South Korea. Finally, the United States has engaged Australia, China, India, Japan, and South Korea in talks designed to create a separate Pacific greenhouse gas reductions agreement (Maynard 2006).

In the Carbon Disclosure Project, three banks identified political deadlock as a potential risk resulting from climate change. However, as noted above in connection with environmental regulatory risk, twenty-five banks identified concerns over regulatory regimes as a concern raised by climate change. No banks discussed political violence as a potential risk of climate change.

Political risk interacts dynamically with other risks. Political risk and supply risk both contribute to each other, forming a positive feedback loop. Political risk increases regulatory risk. Finally, political risk increases legal risk, capital markets risk, operating cost risk and management capacity risk.

Diagram 4.6 below shows potential political risk interactions.

Diagram 4.6: Political Risk Interactions



Source: Author's review of literature. See main text for description.

4.4.6 Legal Risk

Legal risk is the risk that contracts may not be enforceable under applicable law, or legal liability may arise due to an act or omission constituting a breach of a duty. Legal risk is likely to increase with climate change. Climate change could be used by parties as grounds to rely on legal defenses to contract performance, or to pursue release of contractual obligations through the bankruptcy process. Legal risk may increase due to inadequate statutory frameworks for new private contract arrangements entered into pursuant to the Kyoto Protocol or other climate change regime. Finally, legal risk may also arise in the fiduciary or corporate context as a breach of a fiduciary obligation to act upon or to disclose climate change-related risks.

Climate change may enable parties to rely on legal defenses to contract performance, such as the defense of changed circumstances. The doctrine of changed circumstances provides a defense to a party that does not meet its contractual obligations where the party can show it is no longer possible to meet its obligations, and the risk was not foreseen or assumed by any party (Fuller and Eisenberg 1990). One court described the doctrine of changed circumstances as follows:

> "Impossibility excludes a party's performance only when the destruction of the subject matter of the contract or the means of performance makes performance objectively impossible. Moreover, the impossibility must be produced by an unanticipated event that could not have been foreseen or guarded against in the contract" (Kel Kim Corp. v. Central Markets, Inc. 1987).

Climate change could provide any number of justifications for a changed circumstances defense. Catastrophic storms, sea level rise, or extreme heat could destroy property or render a party unable to perform their contractual obligations.

Bankruptcy also provides a means for parties to pursue release from contractual obligations with judicial approval. A company that is unable to meet its financial obligations as they come due or whose assets exceed liabilities, are eligible to file for protection under the bankruptcy laws of the United States. Once a debtor has filed for bankruptcy protection, all other judicial proceedings against the debtor are stayed, and other parties must seek approval from the bankruptcy court to compel the debtor to perform contracts or meet other obligations. The bankruptcy court may, among other remedies, relieve a debtor from its obligations to perform under its contracts (Jordan and Warren 1991). Generally, bankruptcy courts exercise their authority to relieve a debtor from its contractual obligations when it assists the debtor in reorganizing its business or the debtor is liquidating. The court may award damages for breach of contract, however, these awards typically compensate creditors with a small fraction of the value of the contract as most bankruptcy estates have inadequate assets to pay all of their obligations in full. Additionally, bankruptcy cases typically require over a year to resolve, and the court awards are often further reduced in value due to collection delays (Fenning and Hart 1996). The bankruptcy laws of other countries vary in detail, but generally follow the same basic principles as those described for the United States (Riesenfeld 1993).

Inadequate statutory frameworks that govern private contractual arrangements may also increase legal risk. For example, implementation of the Kyoto Protocol requires adoption of international standards and domestic legislation implementing the legal framework to support emissions allowances, the Clean Development Mechanism (CDM), and Joint Implementation (Freestone and Streck 2005; Rodi 2005). A number of the challenges faced by governments in adopting domestic regulations to implement the Kyoto Protocol are discussed in Chapter 5 in the section on carbon offsets programs.

Adoption of the statutory framework may raise novel legal issues that entail legal risk and uncertainty. For example, under the Kyoto Protocol, there are legal issues over the ability to promote the use of CDM over purchases of Russian and Ukrainian emissions allowances in order to meet emissions targets. Although purchases of Russian and Ukrainian emissions allowances do nothing to encourage implementation of clean technology or reduction of emissions, to promote CDM and discourage the use of Russian and Ukrainian allowances may constitute discrimination and thus violate the Kyoto Protocol and other laws (Kristiansen 2006).

Legal risk may also arise for investment managers and corporate executives in the climate change context as a breach of fiduciary duty to ascertain or disclose risks associated with climate change, or to fail to affirmatively act upon such risks. The duty of care for investment managers, commonly known as the prudent investor rule, imposes "a duty to the beneficiaries to invest and manage the funds of the trust as a prudent investor would, in light of the purposes, terms, distribution requirements, and other circumstances of the trust." This standard requires the exercise of reasonable care, skill, and caution, and is to be applied to investments in the context of the overall trust portfolio (American Law Institute 1992).

Company boards of directors and top executives are subject to a separate duty of care that also could apply to their conduct in the context of climate change. According to the American Law Institute's Principle's of Corporate Governance, the basic objective of the corporation should be "the conduct of business activities with a view to enhancing corporate profit and shareholder gain" (American Law Institute 1994). In pursuing these objectives, "a director or officer has a duty to the corporation to perform the director's or officer's functions in good faith, in a manner that he or she reasonably believes to be in the best interest of the corporation, and with the care that an ordinarily prudent person would reasonably be expected to exercise in a like position and under similar circumstances" (American Law Institute 1994).

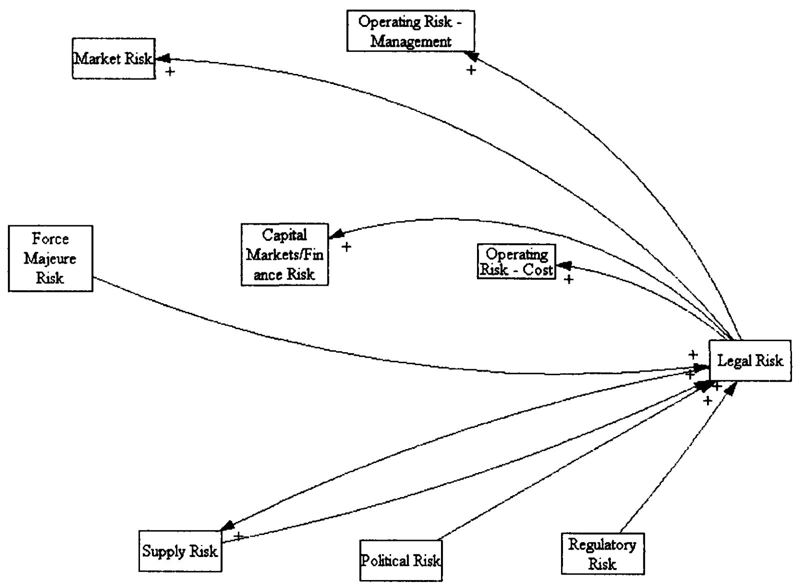
As of September 2006, fiduciary legal issues in the context of climate change remain untested in the courts of any jurisdiction to the knowledge of the author. However, for over a decade, investors and their advisors have been considering these fiduciary obligations in the climate change context. Cogan (1989) was one of the first efforts to understand how the prudent investor rule applies in the context of climate change and today a number of pension funds, mutual funds and other institutional investors in the United States and Europe are urging corporations to disclose and address their climate change risks (CERES 2005b). The United Kingdom requires pension funds to disclose how environmental considerations are taken into account in investment decisions (Wheeler and Woodward 2004), and a number of other jurisdictions allow for environmental and social considerations to be taken into account by fiduciaries in making investment decisions without breaching their duties, provided they comply with fiduciary requirements embodied in the prudent investor rule (Freshfields Bruckhaus Deringer 2005). An increasing number of public corporations have been required by shareholder resolutions to disclose climate risks in annual reports and other public documents (CERES 2005b; Canadian Institute of Chartered Accountants 2004). Significantly, an international investment consultant and a leading international law firm have issued advice that risks associated with climate change are legitimate issues that fiduciaries may be required to address in order to comply with their legal duty of care (Mercer 2006; Freshfields Bruckhaus Deringer 2005).

In the Carbon Disclosure Project, three banks identified breach of contract as an increased concern due to climate change. Twenty-five banks identified default or impairment of credit as a risk magnified by climate change.

Legal risk interacts dynamically with other risks. Legal risk increases supply risk and perceived increases in legal risks may also increase supply risk. Thus, supply risk and legal risk exhibit a positive feedback loop. Force majeure, political, and regulatory risks increase legal risk. In turn, legal risk increases market risk if the perception that a firm will not perform its contractual obligations decreases the marketability of its products and services. Finally, legal risk also increases operating cost, management capacity and capital markets risks.

Diagram 4.7 below shows potential legal risk interactions.

Diagram 4.7: Legal Risk Interactions



Source: Author's review of literature. See main text for description.

4.4.7 Force Majeure Risk

Force majeure is a generic term that in the traditional framework includes risks caused by nature (such as flood, fire, earthquake), acts of man (riots, war), impersonal acts (financial system collapse), and acts of government (general strife).

Because of the increasing importance of climate events, the force majeure category as a catchall or residual risk category provides inadequate visibility to climate risk. Accordingly, the revised Climate Risk Assessment Matrix redefines force majeure. The more narrow definition only includes risks caused by nature and the potential that these risks may be uninsurable at a commercially reasonable price. The other risks in the traditional force majeure category are addressed separately. Acts of man (riots and war) and acts of government (general strife) are addressed as political risks. Impersonal acts (financial system collapse) are addressed as capital markets risk.

With respect to force majeure as redefined by the Climate Risk Assessment Matrix, natural risks are increasingly likely under climate change scenarios. These risks include severe storms, sea level rise, flooding, and drought. These events can be expected to cause increased property damage and interruption to business operations.

Well-drafted infrastructure finance documentation includes provisions that govern the obligations of parties if a catastrophic event occurs. These provisions typically excuse performance for the traditionally defined force majeure events, including political and weather events (Hoffman 2001).

An important question is whether these risks will be insurable at a commercially acceptable price in the future. As described in more detail in Chapter 5 and the insurance case study in Chapter 6, force majeure events may trigger a curtailment, withdrawal or increase in the price of insurance coverage. For example, in response to the 2004 and 2005 storm seasons, some insurers have curtailed coverage in the Gulf of Mexico, while others have increased prices as much as 300-400% (Marsh 2005).

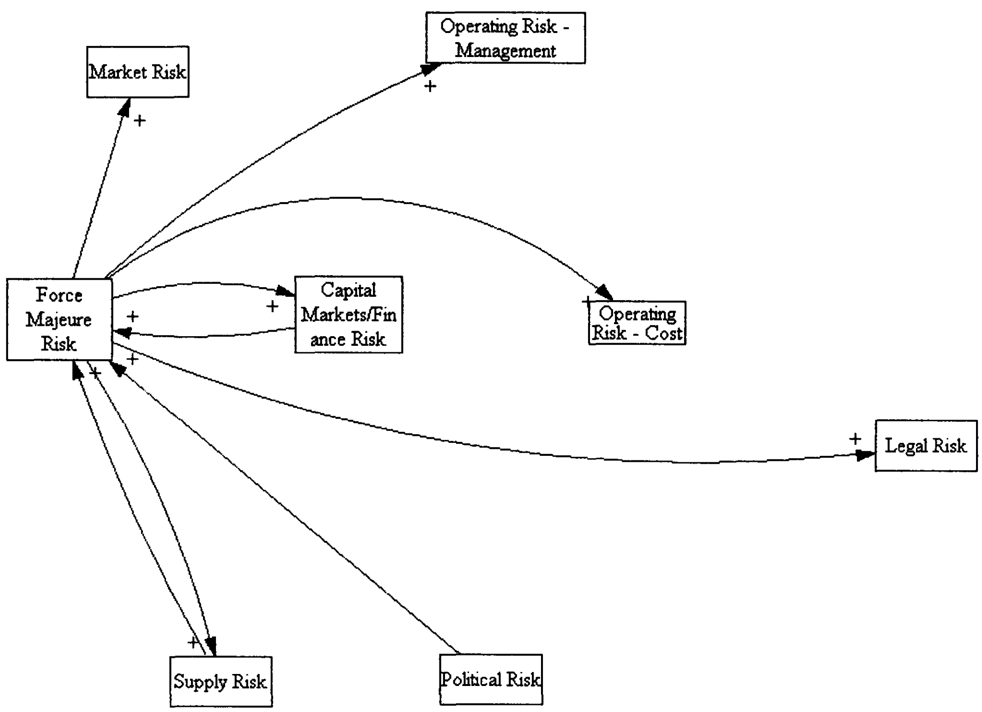
Significantly, all insurance companies that submitted responses to the Carbon Disclosure Project survey recognized climate change as a potential risk to their property and casualty businesses. In addition, twenty-one banks identified the potential for increased climate events as a risk posed by climate change, and sixteen banks expressed concern that climate change could cause inadequate insurance coverage.

Force majeure risk interacts dynamically with market, supply, legal, political, operating cost, management capacity and capital markets risks. A force majeure event would directly affect market and supply risks, disrupting markets in the affected area. For strategically sensitive areas, such as major oil or gas producing regions, the disruption could affect global markets and supplies, as occurred as a result of the 2005 Gulf of Mexico hurricanes. Supply risk also increases force majeure risk because increases in the cost of materials increase losses from catastrophic events, thereby forming a feedback loop. Political risks of fragmented regulation or failure to approve rate increases to consumers may increase force majeure risk by causing further curtailment of insurance. Force majeure affects legal risks because catastrophic events are often a contractual or common law grounds for release from legal obligations. Force majeure also directly affects operating risks both in terms of cost and management capacity, as such events will increase demands on financial and management resources.

Finally, force majeure events affect capital markets risk. The stock of a company that suffers a force majeure event that is not fully covered by insurance may potentially decrease in value and the company's credit rating could potentially be downgraded or placed on negative credit watch. Importantly, these effects may vary by industry and company. Following Hurricane Katrina, for example, oil and gas companies that were affected by Katrina generally did not suffer any credit downgrades directly due to Katrina because of strong commodity prices and financial results for oil and gas companies, which partly offset the damage to production facilities, refineries, and other infrastructure (Standard and Poor's 2006a). In contrast, approximately twenty insurers that were affected by Hurricane Katrina suffered downgrades or were placed on negative credit watch (A.M. Best 2005a) and other insurance companies were subject to further credit review (A.M. Best 2005b). Significantly, increasing capital markets risk may also increase force majeure risk because an increase in catastrophic losses increases the cost of capital for insurance companies, which in turn reduces the amount of risk coverage available or purchased, thereby exposing firms to greater force majeure risks.

Diagram 4.8 below shows potential force majeure risk interactions.

Diagram 4.8: Force Majeure Risk Interactions



Source: Author's review of literature. See main text for description.

4.4.8 Operating Risk – Cost

Operations of energy companies, utilities and transportation can be disrupted by climate events, requiring repair and rebuilding at costs exceeding operating and maintenance budgets many times over.

For the utilities industry, severe weather events are the largest single cause of disruption and damage to transmission and distribution equipment. Weather accounts for 67% of utility service disruptions (Edison Electric Institute 1999). In addition, fluctuations in energy demand caused by weather volatility impose substantial costs by adding and removing plants in service. In recent years in areas affected by hurricanes, the losses have sometimes exceeded the entire annual net profit of companies (Edison Electric Institute 2005).

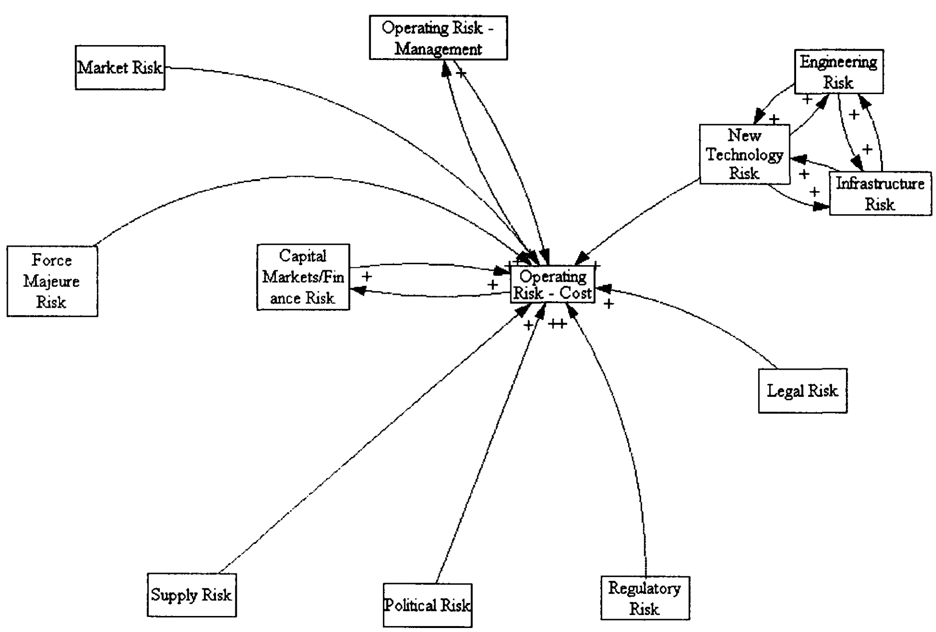
Another aspect of operating risk is reflected in the cost of more complex technologies. Carbon neutral infrastructure will require more complex energy generation plants that will be more costly. More complex plants will also entail increased operating costs. Environmental improvements to electricity generation historically have accounted for most of the increases in plant capital costs and operation and maintenance costs (Joskow and Rose 1985). A study of coal plants showed that supercritical coal-fired electricity generation technology fell into disuse during the 1980's, probably due to the increased cost of maintenance (Joskow and Rose 1985). IGCC technology has not been implemented widely partly due to higher levels of capital and operating costs (Foster 2005a and 2005b). This shows that increasing capital and operating costs may discourage the use of the most efficient or environmental technologies.

Operating cost risk was identified by fifteen banks in the Carbon Disclosure Project as a potential result of climate change. Many of the responses specifically mentioned increased cost of energy as a source of operating cost risk.

Operating cost risk interacts dynamically with every risk within the framework. Operating cost risk directly increases capital markets risk and management capacity risk. These risks in turn increase operating cost risk, forming a positive feedback loop. Significantly, increases in all of the other risks also increase operating cost risk. Therefore, operating cost is a critical risk for private sector risk analysis.

Diagram 4.9 below shows potential operating cost risk interactions.

Diagram 4.9: Operating Cost Risk Interactions



Source: Author's review of literature. See main text for description.

4.4.9 Operating Risk – Management Capacity

The management component of operating risk concerns management capacity and performance. Climate change can be expected to increase demands on the capacity of management in several areas: capacity to take preventive action or respond to disaster, ability to evaluate risk and plan, and demands on management capacity that compete with attention to ordinary business functions.

Management capacity is a limited resource, even within large companies. The demands of implementing carbon neutral infrastructure on the scale and timeframe contemplated in Chapter 2 can be expected to strain management resources. For example, Chevron, the world's fourth largest energy company by net income, at any given time considers projects from a pool of a several dozen well studied opportunities, but focuses its management attention on developing five projects around the world (Steele 2006). Thus, in the absence of catastrophic events, the selection and development of five projects largely define the extent of Chevron's management capacity for large infrastructure and strategic projects.

If climate change causes catastrophic events, management's ability to prepare in advance and respond effectively will be a critical factor in the amount of losses suffered by a firm and its customers. Utilities in the Gulf states have developed special expertise in dealing with catastrophic events, including information and communications capabilities, disaster management plans, and mutual assistance arrangements. However, recurring severe storms have stretched the ability of management to respond to crises (Oldack 2006). Following Hurricane Katrina, utilities and energy companies operating in the Gulf of Mexico mounted relief and repair efforts that have consumed large portions of management's attention and resources. For example, initial relief efforts at Shell involved over 5,000 employees, the relocation of over 1,000 employees in the exploration and production division, and the full-time effort of these employees plus over 500 additional employees and contract workers from other Shell locations to repair equipment (Fleming 2006; Shell 2006).

In the area of risk assessment and planning, climate change poses challenges to the ability of management to forecast, budget, and plan. As described further in the utilities and insurance case studies in Chapter 6, utilities and insurance companies suffered large losses in the Gulf States that temporarily impaired their financial and management capacity to continue their regular course of business. In the case of insurance, a number of companies are curtailing or withdrawing insurance coverage in the Gulf as a result of their losses (Marsh 2005). Further, the insurance industry is reexamining its models to assess risk. Changes to these models are expected to increase the level of reserves required to be set aside to cover catastrophes, further contracting the industry's capacity to underwrite risk (Mosher 2006; Muir-Wood 2006; Martucci 2006; Standard & Poor's 2005b).

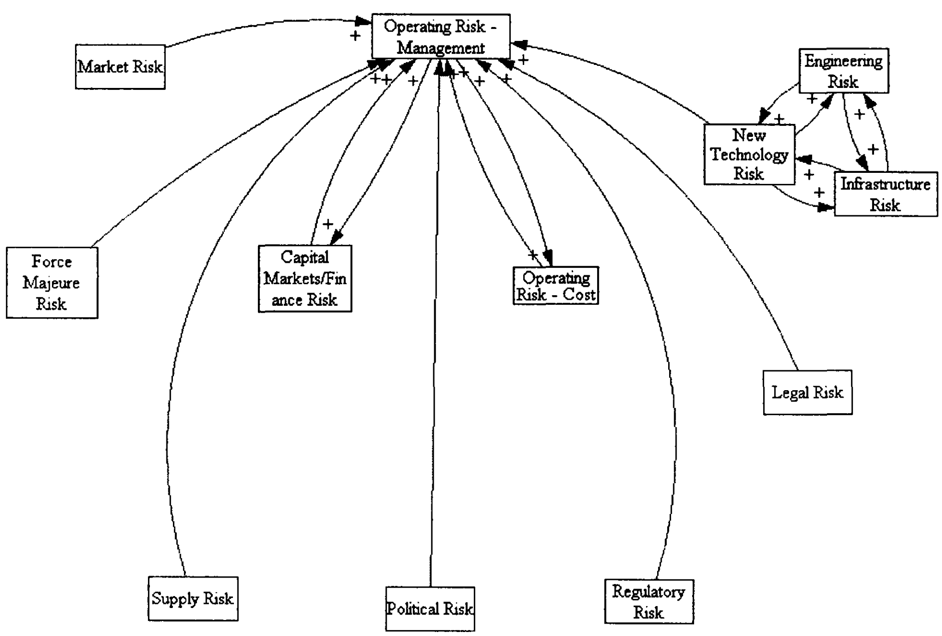
Another area where climate could pose risks for management's ability to take preventive action is in the area of protecting infrastructure. A recent study of the Boston metropolitan area recommends that highly developed urban infrastructure be protected with storm and water barriers. Such a program would involve a large commitment of personnel and financial resources over an extended period of time (Kirshen et al. 2004). Boston's recent renovation of its transportation infrastructure known as the "Big Dig" suggests that large-scale re-engineering of highly developed city infrastructure can be challenging from an engineering, management, and cost point of view. In 2006, the project is five years behind schedule and has cost in excess of $14.6 billion, over $12 billion more than originally planned (Buffa 2006; NPR 2003).

Management capacity risk was identified by twelve banks in the Carbon Disclosure Project as a potential area of increased risk as a result of climate change. The most common comment concerned the decreased capacity for management to properly assess risk and to plan.

Management capacity risk interacts dynamically with every risk within the framework. Management capacity risk directly increases capital markets risk and operating cost risk. These risks in turn increase management capacity risk, forming a positive feedback loop. Like operating risk, increases in all of the other risks also increase management capacity risk. Therefore, management capacity is a critical risk for private sector risk analysis.

Diagram 4.10 below shows potential management capacity risk interactions.

Diagram 4.10: Management Capacity Risk Interactions



Source: Author's review of literature. See main text for description.

4.4.10 Capital Markets/Finance Risk

Capital markets risk as used in the Climate Risk Assessment Matrix includes risk associated with raising debt and equity capital in both private and public capital markets. The traditional infrastructure finance risk framework includes a category called "syndication risk", which relates to the risk that the lead lenders to a project will be unable to sell interests in the loan to a syndicate of banks. The syndication risk category reflects the traditional reliance on lending institutions for raising debt. However, infrastructure finance increasingly raises capital in the public debt markets as well as traditional lending arrangements. As climate risk increases, we can expect that project sponsors will increasingly seek to spread risk to public markets, especially if lenders are less willing to accept risk. This will be further discussed in Chapter 6's discussion of the use of capital markets and catastrophe bonds. Accordingly, the Climate Risk Assessment Matrix uses the term "capital markets/finance risk" to describe the risk associated with raising capital through both public and private markets.

Capital markets risks are influenced by a number of conventional factors, some of which may be exacerbated by climate change. One of the principal capital markets risks that climate may affect relates to accounting and earnings issues. Capital markets respond well to predictable earnings patterns. Many companies therefore seek to diversify their earning streams and use derivatives products (including weather derivates) in an effort to smooth earnings and report stable growth to the markets (Graham et al. 2005). Accounting and financial disclosure issues are therefore paramount to capital markets risks.

Importantly, the influence of short-term financial reporting and accounting considerations in funding technology development is pervasive. A recent survey of over 400 corporate executives revealed that meeting public earnings expectations was perhaps the most important priority for management. Over 80% of those surveyed reported that they would cut R&D expenses in order to meet quarterly earnings targets. Further, 78% of those surveyed said they would pass up projects with a positive net present value in order to achieve smooth earnings numbers (Graham et al. 2005).

Climate change may also increase capital markets risk by increasing loan defaults and collateral impairment. Disruption to operations impairs the ability of companies to generate revenues to repay debt. Damage to physical assets impairs the value of collateral that banks depend upon in lending. Climate change may also increase the risk of collateral impairment by requiring or encouraging the introduction of new technologies that cause older assets to become obsolete.

The risk posed by climate change for lending institutions due to default and collateral impairment is illustrated by the tenure of debt. As described further in Chapter 5, the term of infrastructure loans are often measured in decades. For infrastructure financings closed in 2005, 55% of infrastructure debt tranches have tenors of ten years or more, and 16% of the tranches have tenors of twenty years or more. The longest tenor was over fifty years

(Dealogic 2006b). The longer duration debt has a payment period within the time frame when increased risk due to climate change is expected to occur.

Credit rating agencies play an important role in monitoring risks associated with infrastructure project and companies. An adverse credit rating or being placed on credit rating watch with negative implications can increase the cost of capital for projects and can trigger a default under lending agreements (Bank of America 2002). A number of insurance companies were downgraded or placed on credit watch following Katrina, which may have contributed to the contraction of the insurance market in the Gulf of Mexico (A.M. Best 2005a).

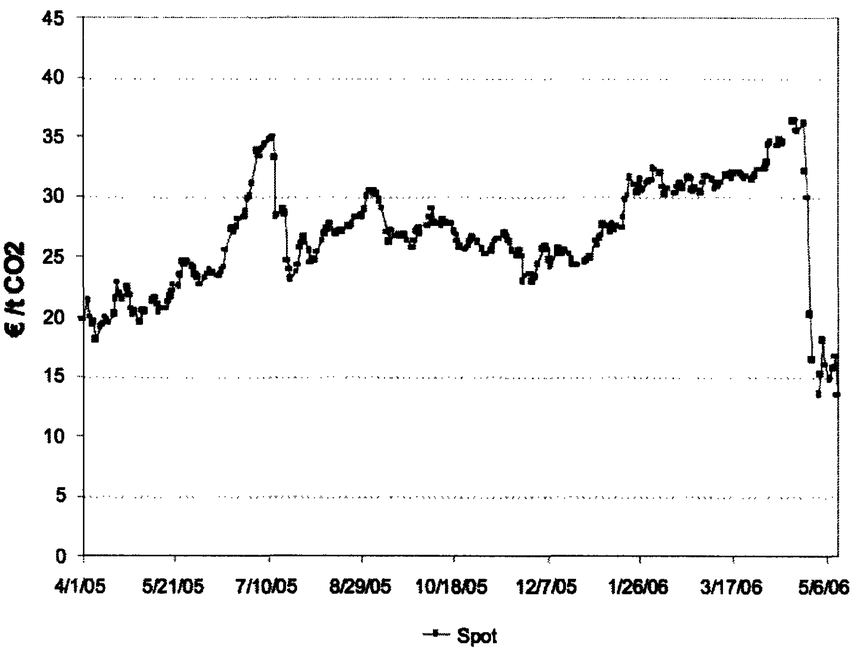
In addition to climate-related risks, the structure of capital markets poses several risks to financing carbon neutral technology. Renewable technologies and distributed generation often involve higher transaction costs than traditional energy infrastructure projects when averaged over total energy capacity (Johnson 2006). The transaction costs and expertise required to structure a tax-optimal financing arrangement have largely precluded these projects from obtaining adequate funding until recently. The increase in interest from large investment banks in renewable technology and the creation of investment funds dedicated to these technologies is encouraging. Efforts to reduce costs through standardized agreements and commoditization of projects are methods to address this problem. However, even with these approaches, renewable technology companies still face the challenge of locating projects that can be developed on a scale sufficiently large to demonstrate adequate financial returns. These considerations can be expected to slow the implementation of sustainable technologies (Colston 2006a; Johnson 2006).

Market volatility and the short-term nature of public debt and equity markets present potential risks for the development of long-term clean energy technology infrastructure. This risk will fall most heavily on companies that are new entrants and do not have a revenue stream from more established technologies. Technology can require decades to develop and commercialize, and infrastructure can have a lifetime and debt structure in excess of 40 years. In contrast, financial and accounting cycles operate on much shorter time frames, which subjects new technologies to the volatility of financial markets. For example, most investment partnerships are designed to operate for a period of 10 to 12 years, and expect to produce profits from their investments and begin liquidating assets starting in the 5 to 7 year range (VC Experts 2006a). Executive vesting schedules for most companies typically operate on a four-year basis (VC Experts 2006b). Corporate profits and losses are measured and reported quarterly. Mutual funds typically sell 85% of their holdings each year (Motley Fool 2006). Traders typically seek to close out their positions at the end of each day or by the weekend at the latest (Page, W. 2006; Miller 2006). The market as a whole has an annual turnover rate of approximately 150%, over seven times that of the 20% turnover rate of the 1960's and 1970's, and in excess of the high 112% turnover rate of 1929 (Bogle 2001, 2006).

Market volatility also poses risk for firms and new technologies that rely in part upon the sale of emissions reduction credits under the Clean Development Mechanism or Joint Implementation programs to finance infrastructure. As discussed in more detail in Chapter 5, fluctuations in the greenhouse gas emissions allowance market can adversely affect firms attempting to implement clean energy technologies. In May 2006, the value of European

Union emissions credit prices collapsed, losing over 66% of their value, following the release of 2005 emissions data confirming that original emissions allocations were too generous (Reuters 2006). The fact that the carbon market will be subject to the same kinds of fluctuations as equity markets means that even the Kyoto Protocol's primary mechanism for promoting greenhouse gas emissions reduction policy is vulnerable to the short-term volatility of markets.

Figure 4.2: European Union Emissions Allowance Prices, April-May 2006



Source: Point Carbon (2006a).

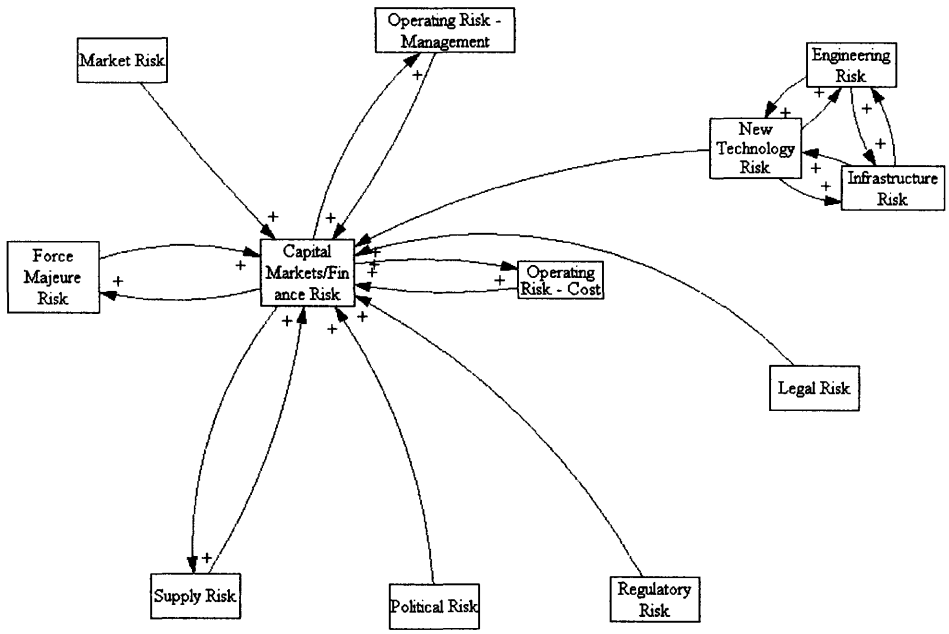
Short-term financial considerations mismatch the practical realities of science and technical development. Scientific progress is not a continuous, linear or predictable process (Kuhn 1972). Science does not accommodate the predictable revenue streams demanded by public financial markets. In the technology sector, companies that fail typically have little residual value because most of the value resides in employees, who are dispersed when a firm closes its doors. As a result, new technology companies often have limited access to debt financing for operations, and rely primarily on equity financing. These financial factors can impair the ability of the private sector to implement long-term carbon neutral infrastructure goals.

In the Carbon Disclosure Project, twenty-seven banks identified capital markets risk as a potential risk magnified by climate change. Capital markets risk was the most frequently cited risk of climate change, followed by regulatory risk. Within the capital market risk category, twenty-four banks identified credit risk, default risk and impairment of collateral as important capital markets risks.

Capital markets risk interacts dynamically with every risk within the framework. Capital markets risk directly increases operating cost and management capacity risks. These risks in turn increase capital market risks, forming a positive feedback loop. Significantly, increases in all of the other risks also increase capital markets risk. Therefore, like operating cost and management capacity risks, capital markets risk is a critical risk for climate risk analysis.

Diagram 4.11 below shows potential capital markets risk interactions.

Diagram 4.11: Capital Markets Risk Interactions



Source: Author's review of literature. See main text for description.

4.4.11 Participant Risk

Participant risk relates to the financial, management and technical capacity of project parties to meet their obligations under project documents.

All of the other risks described in this chapter potentially place increased demands on the financial and management capacity of project parties. In the case studies on utilities and insurance, there is strong evidence that climate risk can cause loss of profits, more volatile earnings streams, downgrades in credit, and in some cases, bankruptcy. In addition, storms can cause municipalities to lose substantial investment in infrastructure and tax revenues as a result of natural catastrophes. All of these events contribute to participant risk.

As described above in the section on "Operational Risk – Management", climate change can be expected to increase demands on the capacity of private sector management. For example, if climate events or the financial effects of climate events require increasing management and financial resources, management's capacity to conduct ordinary businesses will be reduced.

Similarly, the technical capacity of firms could be challenged by climate events. The introduction of new technologies may create shortages of qualified personnel within firms. This will slow the adoption of technology and stretch the management and technical capacity of firms. As described in the "Engineering Risk" section, the magnitude of protecting urban areas from climate risk could potentially overwhelm the technical and management capacity of even the largest engineering firms.

If climate risk increases significantly over this century, the private sector may experience increasing demands on the financial and managerial capacity of participants in infrastructure projects. Participant risk may become an increasing issue for private sector development of infrastructure.

In the Carbon Disclosure Project, no banks specifically identified participant risk as a risk that would be magnified by climate change. However, twenty-four banks identified operating risks (including both cost and management capacity) as potentially increasing as a result of climate change.

Participant risk interacts with all other risks. All risks that are specific to a particular firm increase participant risk for that firm. Importantly, because of the multiple contributors to participant risk, private contractual methods such as insurance may not be adequate to address this risk. For example, in the infrastructure finance field, performance bonds provide some risk coverage against contractor default. However, performance bonds are only available for proven technologies for which a replacement contractor can be engaged (Weissbrodt 2006) and would not fully compensate parties for all damages resulting from the failure of a party to perform. Ultimately, participant risk reduces the number of parties that are willing or qualified to undertake infrastructure projects. Because participant risk interacts with all other risk, the relationships are not presented in a diagram.

4.4.12 Governance Risk

Governance risk is not one of the traditional infrastructure finance risk categories. It is defined here as the risk that the institutional structure negotiated by the project participants will not be adequate to manage the project successfully. This is closely related to participant risk, although the focus is on the capacity of the intuitional framework governing the participants, as opposed to the participants themselves.

The concept of governance risk is similar to the concerns considered in the new institutionalism school concerning the design of institutions to manage public or commons resources (Ostrom 1990; Dolsak and Ostrom 2003). In a study of the financing of large engineering projects, Miller and Lessard (2000) recognized the importance of the legal documentation and relationships necessary for the successful completion of infrastructure finance projects. The formal legal and informal relationships developed over time among project participants are essential to the completion of a project, its operation, and if threatened by financial difficulty, restructuring (Miller and Lessard 2000).

Climate change poses a fundamental problem for infrastructure finance that no party may be best positioned to accept and mitigate the risks associated with climate. The necessity to identify, allocate, and manage risk is the essence of modern infrastructure finance. Thus, by challenging a fundamental tenet of infrastructure finance, climate change may hinder the ability of the parties to successfully complete negotiations, or to manage unallocated risks when unanticipated problems occur. Such a situation can lead to aborted or failed projects and can undermine the effectiveness of the private sector in infrastructure development.

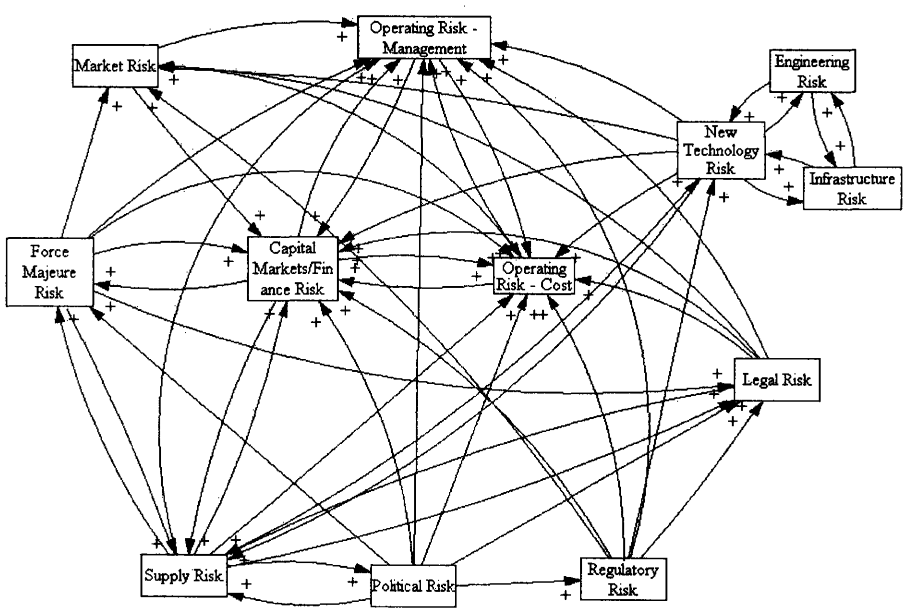
In the Carbon Disclosure Project, no banks specifically identified governance risk as a risk that would be magnified by climate change. It is not a traditional risk category.

Governance risk interacts with all other risks, particularly force majeure risk. An increase in the likelihood of force majeure events increases the unwillingness of any particular party to accept risk. Climate change potentially increases the complex interactions among risks, frustrating the clear definition and allocation of risks in contracts among project parties. Because governance risk interacts with all other risks, the relationships are not presented in a diagram.

4.5 Dynamic Interactions Among Climate Risks and Critical Risks

The interactions among risks are important. Diagram 4.12 below presents the cumulative interactions among the risks described in this chapter. Participant risk and governance risk are omitted because all other risks contribute to them.

Diagram 4.12: Potential Climate Risk Interactions



Source: Author's review of literature. See main text for description.

The diagram suggests that the various types of risks increase with climate change. Multiple interactions occur between many of the risks, with secondary and tertiary effects, and the patterns become complex.

The Carbon Disclosure Project does not ask respondents to rank climate risks or to assess the relative consequences of these risks. Although a strict ranking of the importance of individual risks is beyond the scope of this dissertation, several risks can be isolated as representing critical nodes or system pressure points. Capital markets, operating costs, and management capacity risks interact with every other risk. Regulatory, supply, market, and technology cluster risks also interact with a large number of other risks and each other.

The banks responding to the Carbon Disclosure Survey validated these risks as critical nodes based on the frequency of banks citing these risks. The banks focused primarily on capital markets, regulatory, force majeure, operating, supply, and market risks. Summary results of how frequently the banks identified specific risks is set forth below in Table 4.7.

Table 4.7: Carbon Disclosure Project Banks Frequency of Identification of Climate Risks

Risk	Number of Responses	Percentage Total Responses
Capital Markets Risk	27	57%
Environmental Regulation Risk	25	53%
Force Majeure	25	53%
Operating Risk – Cost and Management Capacity	24	51%
Operating Risk – Cost	15	32%
Market Risk	13	28%
Operating Risk – Management Capacity	12	26%
Supply Risk	12	26%
Infrastructure Risk	4	9%
Political Risk	3	6%
Technology Risk	3	6%
Legal Risk	2	4%
Engineering Risk	0	0%
Participant Risk	0	0%
Governance Risk	0	0%

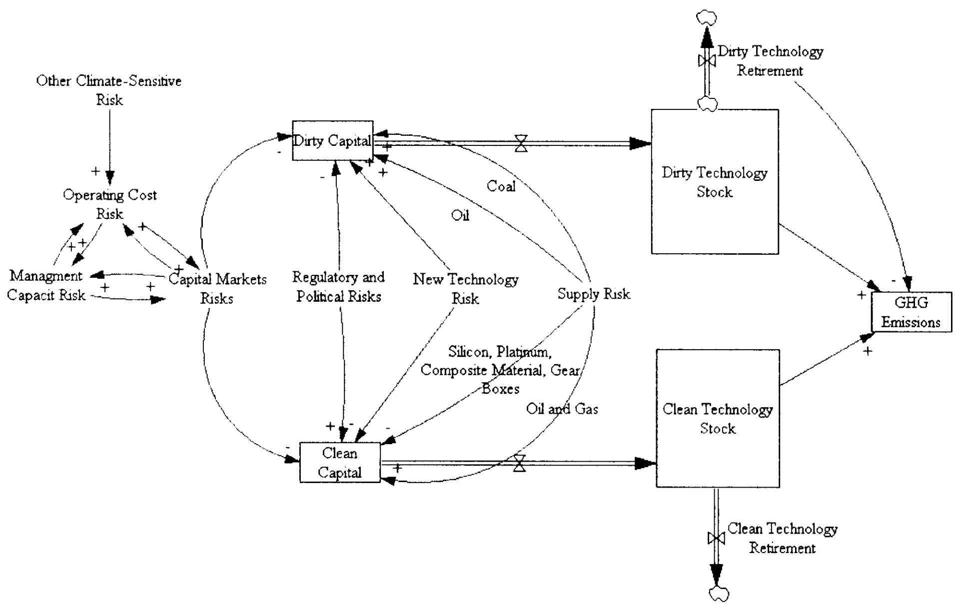
Source: Author's tabulation of banks' responses to first three years of Carbon Disclosure Project.

4.6 Implications for Financing Carbon Neutral Infrastructure

The cumulative increase in risk reflected in the financial aspects of infrastructure development can be expected to cause cost increases, delay and greater uncertainty in the planning and development of carbon neutral infrastructure.

To illustrate this, Climate Risk Assessment Matrix risks are grouped and presented below as follows: capital markets risks, regulatory and political risks, operating risks (management capacity and operating cost), supply risk, new technology risk, and the remaining risks as "other climate-sensitive risks". No effort is made to assign a relative weight to these risks in this dissertation, although this could be a worthwhile area of research with respect to particular technologies. Diagram 4.13 below illustrates how these risks potentially affect the finance and development of infrastructure.

Diagram 4.13: Risks and Carbon Neutral Technology and Infrastructure



Source: Author's review of literature. See main text for description.

Capital markets risks and operating risks generally decrease the availability of capital to both clean and dirty technologies. Thus, increases in these risks are depicted as having a negative influence on both clean and dirty technologies. However, because new technologies do not have as well developed operating and cost structures compared to established infrastructure, capital markets risks might affect new technology more profoundly than established technology.

Regulatory risk generally favors development and adoption of comparatively cleaner technologies, and decreases the adoption of older less environmental technologies. Until policy makers provide guidance as to the details of a policy, however, uncertainty may chill investment in clean technology, slowing its adoption. Similarly, political risk generally favors new technologies because political risk issues are closely associated with dependence upon petroleum. Accordingly, these risks are depicted as increasing the stock of capital for clean technology and decreasing the stock of capital for dirty technology.

New technology risks favor established technology and discourage adoption of comparatively cleaner technologies that do not yet possess a proven commercial record.

Accordingly, new technology risks are depicted as increasing the stock of capital for dirty technology and decreasing the stock of capital for clean technology.

Supply risks are complex and do not consistently favor either clean or dirty technology. Supply risks are therefore presented in Diagram 4.13 with specific technologies or commodities. With respect to supply of silicon, platinum or wind turbine components (composite materials and gear boxes), supply risk acts as a potential constraint on clean technology, limiting the sector's ability to absorb new capital. With respect to the supply of oil and gas, supply risk increases the supply of capital to new technologies.

However, supply risks associated with oil and gas also increase the supply of capital to oil and gas industries. This is because these are essential commodities to operate existing infrastructure. Substitution in the near term is not a practicable option. In addition, supply risk of oil and gas also increase capital to coal-based infrastructure. Because coal is abundant and cheap, energy supply risks in general will increase capital to coal technology. Therefore, supply risk has an ambiguous effect on technology adoption and emissions.

The remaining risks are consolidated as "Other Climate-Sensitive Risks". This includes force majeure, governance, participant, and legal risk. These risks are consolidated because they contribute to the overall level of risk. Thus, the general category "Other Climate-Sensitive Risks" is depicted as increasing the critical capital market risks, operating cost risk, and management capacity risk, which may delay capital flows generally.

While the presentation of risks is clearly a simplification of reality, these risks suggest that specific risks will influence technology adoption differently. For example, market risks associated with changes in demand for energy or increases in efficiency could affect the relative competitiveness of, and investment in, clean or dirty technologies, with the final result depending upon how specific technologies benefit from these changes. The dynamic analysis of these risks suggest that the financing process will be subject to various risks during the next several decades that can be expected to slowdown the adoption of clean technologies. As demonstrated in this chapter, climate change will increase various disparate risks, which will affect the development, finance and operation of infrastructure. The primary effects are greater uncertainty, delay in technology implementation, and increasing regulatory, capital markets, supply, and operating risks. If there is a significant perceived increase in uninsured catastrophic risk (force majeure risk as defined in the Climate Risk Assessment Matrix), the analysis suggests there will be increasing difficulty in allocating this risk, increasing participant and governance risks. The aggregate effect of the increase in risks due to climate change is to create friction impeding the efficient operation of markets for purposes of achieving sustainability goals.

If these risks cannot be managed, and the delays caused to carbon neutral technology and infrastructure adoption are significant, then these risks could potentially reduce capital to infrastructure development in general, including carbon neutral infrastructure. This could impair the private sector's efforts to develop carbon neutral infrastructure on a meaningful scale within this century.

4.7 Summary of Analysis and Results

This chapter developed a Climate Risk Assessment Matrix that is based on the traditional categorization of risk used in the infrastructure finance and development field. The Climate Risk Assessment Matrix modifies the traditional conceptualization and categorization of risks in order to show how climate can affect infrastructure investment decisions. Several traditional categories were divided and redefined, and additional categories of risk were identified to give greater visibility to climate-sensitive risks. Responses of banks and insurance companies to the Carbon Disclosure Project show that the Climate Risk Assessment Matrix is a robust representation of the perceived risks posed by climate change to infrastructure development.

The Climate Risk Assessment Matrix has applications for practitioners in the infrastructure development field and for policy analysis. For financial planning and investment, the Climate Risk Assessment Matrix is intended to give greater visibility to the effects of climate on business risk in order to better identify, and where possible, mitigate these risks. Chapter 5 further develops the Climate Risk Assessment Matrix in its analysis of the private sector's capacity to manage these risks through private contractual methods.

For purposes of policy analysis, the Climate Risk Assessment Matrix suggests various transmission mechanisms through which climate risks may potentially impair the capacity of the private sector to adapt infrastructure. These risks should be studied further and considered in policy analysis.

5 Private Contractual Methods to Mitigate Climate Risks

This chapter addresses the question: "To what extent can private contractual methods mitigate risks posed by climate change?"

Private contractual methods provide the private sector with important tools to manage risk, thereby reducing the potential for market failure, without the need for assistance from government. This chapter evaluates the ability of several important contractual methods to manage risks that will be exacerbated by climate change, principally supply risk, market risk, regulatory risk and force majeure risk.

This chapter evaluates the following kinds of risk management methods:

1. Private Insurance
2. Commodities Derivatives
3. Weather Derivatives
4. Carbon Offsets
5. Catastrophe Bonds

These methods were selected for analysis because they are among the most commonly used risk management instruments and are available in standard form. As a result, these instruments involve lower transaction costs and are more widely available to firms, in comparison to highly negotiated agreements.

Each type of contract is evaluated based on the following six criteria: (a) scope of risk covered, (b) geographic coverage, (c) contract duration, (d) availability, (e) price, and (f) market capacity. Based on these criteria, each instrument is then assessed with respect to its potential for addressing risks associated with climate change.

It is important to note that these risk management methods are perhaps the most important segments of a larger risk management market. While each instrument is distinct and mitigates risk differently,[12] there is also growing convergence among the instruments described in this chapter (Banks and Bortniker 2002). Increasingly, these instruments are used as substitutes for each other or in combination with each other. Further, in the cases of insurance, weather derivatives, and catastrophe bonds, they are priced in relation to each other for similar risks, and using similar models. Importantly, the convergence should yield deeper, more transparent, and more competitive markets for risk coverage.

[12] Private insurance and catastrophe bonds shift the risk of loss from one party to another party in exchange for a premium. Derivatives shift the risk of an event occurring, but often with the purpose of providing both parties with smoother, more predictable earnings patterns, and sometimes without the exchange of money until the end of the contract. Carbon offsets are created by reducing emissions of pollutants and are traded or used to meet regulatory obligations.

The evidence presented in this chapter shows that these risk management methods are currently subject to significant limitations in their ability to address the risks of long-term climate change. In each of the categories described above (scope of risks covered, geographic coverage, contract duration, availability, price, and market capacity), these instruments are shown to fall short in a number of respects that could limit the capacity of these instruments to address risks presented by climate change.

The evaluation of these contractual methods completes the analysis conceptualized in the Climate Risk Assessment Matrix presented in simplified form in Appendix A to this dissertation. This analysis involved the identification of specifics risks, the selection of instruments or methods to mitigate these risks, and the evaluation of these methods based on criteria designed to ascertain their ability to address long-term climate risk.

This chapter first explains the importance of these risk management techniques for infrastructure finance, provides an overview of the results of this chapter's evaluation of the capacity of these instruments to address climate change risks, and introduces the risk management survey conducted for this dissertation and explains its methodology. Next, the chapter analyzes each of the risk management methods based on the six criteria identified above. The chapter concludes by assessing the ability of these risk management methods to address the risks associated with long-term climate change. This chapter further develops the Climate Risk Assessment Matrix and uses the matrix to graphically show the results of the evaluation of risk management instruments.

5.1 Importance of Risk Management in Infrastructure Finance

Infrastructure projects involve long-term risk. Infrastructure projects are capital intensive and typically require several decades to recover costs. Over these long time periods, project sponsors and lenders will be exposed to changing market, supply, and regulatory conditions. Lenders will typically require project sponsors to hedge project risks in return for a lower cost of funding (Tinsley 2000; Ali and Yano 2004).

The tenor of debt in infrastructure projects illustrates the risk exposure of lenders. Table 5.1 below summarizes the tenors of the 487 infrastructure financings completed in 2005. These 487 projects were financed with 808 separate tranches of debt totaling almost $175 billion. These debt tranches included bridge loans, term loans, construction loans, revolving credit, and bonds.

Table 5.1: Debt Tenor for Infrastructure Finance Projects Completed in 2005

Debt Tenor (years)	0-2	3-4	5-9	10-14	15-19	20-29	30-39	40-49	50+
Number of Tranches	53	100	212	181	133	109	15	4	1

Source: Dealogic (2006b).

For 2005, 55% of infrastructure debt tranches have tenors of 10 years or more, and 16% of the tranches have tenors of 20 years or more. The shortest tenor was 3 months and the longest tenor was 50 years 11 months. The median tranche tenor was 10 years 6 months. The average project debt was $359 million. The largest tranche was $8.1 billion and the smallest was $4 million (Dealogic 2006b).

Each project typically combines several debt tranches. For example, a project financing may involve a short-term construction loan combined with a longer tenor term loan or credit facility. Thus, a high percentage of the 487 projects potentially involve a tranche with tenor of greater than 10 years. With debt tenor commonly exceeding a decade and the average amount of debt over $350 million, lenders and project sponsors are exposed to substantial risk for prolonged periods of time. In light of the amounts and tenors of capital at risk, the use of risk management instruments by project sponsors and lenders has become increasingly important.

5.2 Evaluation of Risk Management Instruments in Light of Climate Change

As discussed in Chapter 4, climate change increases the magnitude of infrastructure finance risks in such areas as market risk, supply risk, regulatory risk, and capital markets risks. Significantly, climate change could adversely affect infrastructure now being built within the "payback" period required to recover debt and return on investment. Thus, lenders and project sponsors that are currently building projects that require several decades to recover debt and equity and have a useful life of over half a century should consider risks posed by climate change in their investment and risk management decisions.

It is not clear that current risk management instruments will be available or adequate to address future climate change risks. Accordingly, this chapter evaluates several common risk management instruments based on criteria designed to asses the ability of these methods to provide a practical solution to the problem of mitigating climate change risks.

These contracts are commonly used to address market, supply, operating, regulatory, and force majeure risks, as set forth in the table below.

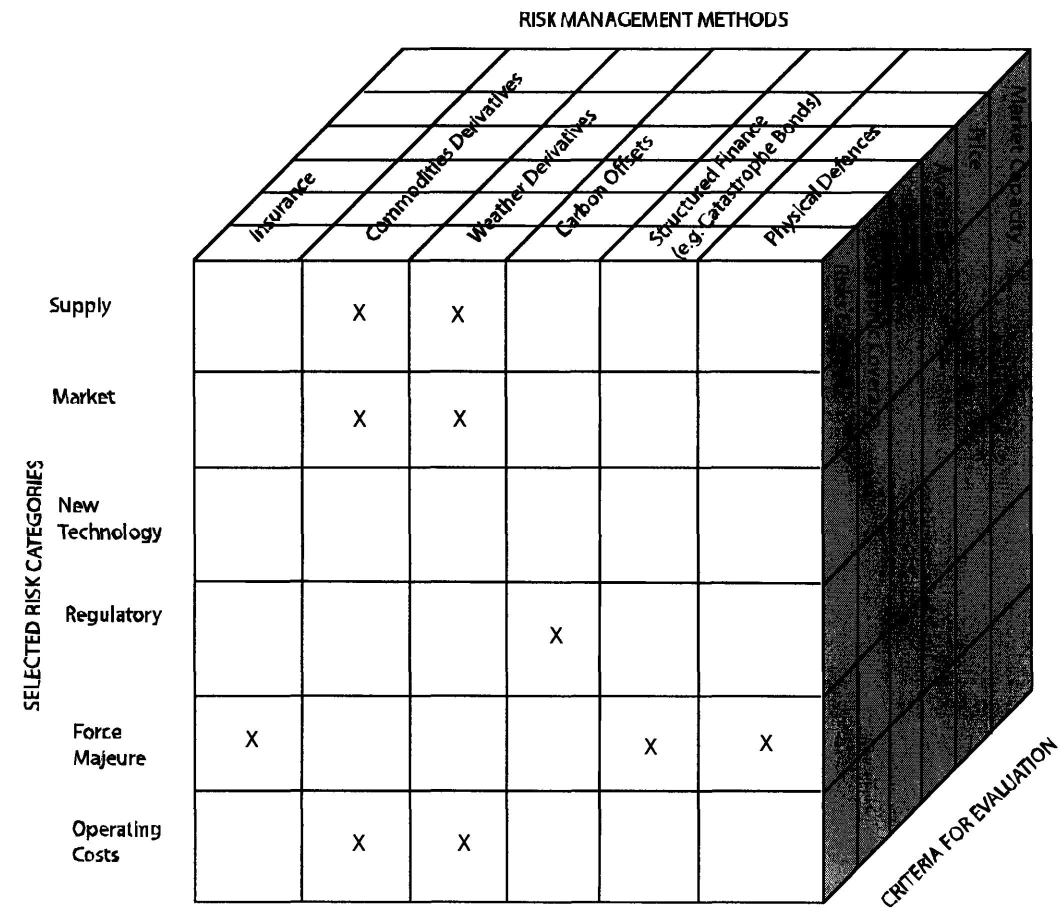
Table 5.2: Third Party Contractual Methods to Address Project Risk

Risk	**Risk Mitigation Contract**
Force Majeure Risk	Private Insurance
Supply Risk	Commodities or Weather Derivatives
Market Risk	Commodities or Weather Derivatives
Operating Risk – Cost	Commodities or Weather Derivatives
Environmental – Regulatory Risk	Carbon Offsets
Force Majeure Risk	Catastrophe Bonds

Source: Adapted from Tinsley (2000); Element Re (2002); European Climate Exchange (2006).

The Climate Risk Assessment Matrix illustrates graphically the relationship between specific risks and climate risk management instruments. Figure 5.1 shows that several major risk categories are covered by one or two kinds of risk management instruments surveyed in this chapter. However, no risk category is covered by more than two types of risk management instrument, and all of the risk management instruments are limited to covering a few categories of risks.

Figure 5.1: Climate Risk Assessment Matrix – Risks Covered



Importantly, these contractual methods do not address all of the infrastructure project risks identified in Chapter 4. For example, as reflected in Figure 5.1, none of these instruments address new technology risk. Table 5.3 presents a summary of other important risks that are not addressed by the risk management methods covered in this chapter.

In many cases, where no standardized risk management contract is available to cover a particular risk, project risks are typically allocated to the project parties in the project documents. As noted, risks that are usually allocated to a project party in project documents are not considered here because the allocation of these risks will be specific to the parties and the transaction. This chapter examines risks that are often allocated to a third party using standard contracts because none of the project parties are well positioned to accept and mitigate these risks.

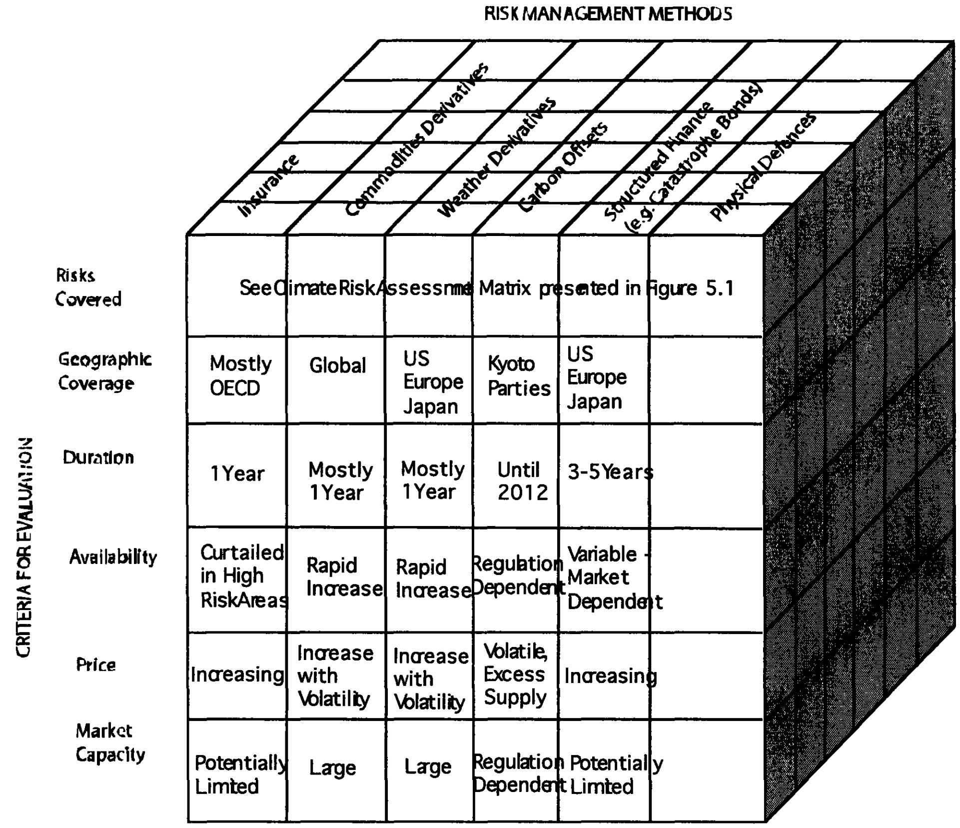
Table 5.3: Other Risks Not Covered by Risk Management Instruments

Risk	**Risk Mitigation Methods**
Technology Risk Engineering Risk	Project Documentation Technology Selection Contractor Selection
Operating Risk – Management	Project Documentation
Infrastructure Risk	Project Documentation
Political Risk	Public Insurance
Participant Risk	Project Documents Performance Bonds
Capital Markets Risks	Derivatives Diversification Structured Finance
Legal Risk	Project Documents
Governance Risk	Project Documents

Sources: Adapted from Tinsley (2000); Hoffman (2001).

Figure 5.2 below summarizes the results of the evaluation of these risk management instruments based on the remaining criteria of geographic coverage, contract duration, availability, price and market capacity. With respect to all of these evaluation criteria, these instruments are subject to limitations in addressing the longer term risks associated with climate change. Notably, evidence of the short duration and increasing prices for risk coverage instruments suggest that traditional risk management methods as presently structured have limited capacity to address climate change risks.

Figure 5.2: Climate Risk Assessment Matrix – Other Evaluation Criteria



The basis for the evaluations summarized in Figure 5.2 is an analysis of public and private data sets, the models used to design and price these contractual instruments, and a survey of industry participants in the insurance, derivatives, carbon offsets, and catastrophe bond markets. We now turn to a summary of the survey methodology and results, and then to the evaluation of each specific risk management instrument.

5.3 Summary of Risk Management Survey Methodology and Results

In connection with this dissertation, the author conducted surveys of professionals in the insurance, derivatives, carbon offsets, and insurance-linked securities markets. Appendix B of this dissertation sets forth a list of firms and other market participants that were contacted in connection with the survey, and those that responded. Separate surveys were used for insurance markets and derivatives markets.

The insurance survey requested information about primary property and business interruption insurance, reinsurance, and catastrophe bonds. The survey focused on insurance and reinsurance companies, and brokerage firms, but also included other market participants including credit rating agencies, state insurance regulators, insurance industry associations, insurance risk analysis firms, and consultants to the insurance industry. A total of twenty-nine organizations were contacted, twenty of which participated in the survey for a response rate of 69%. The form of insurance survey is set forth in Appendix C of this dissertation.

The derivatives survey requested information for several commodities important to the energy sector (oil, gas, coal, electricity, platinum), weather derivatives, European Union greenhouse gas emissions allowances, and Clean Development Mechanism certified emissions reductions certificates. The survey was designed to elicit information about general market conditions and over-the-counter market transactions ("OTC") that may not be captured in data provided by the exchanges.[13] The survey focused on brokers, but also included several utilities and energy companies that trade for their own account, exchange officials, and risk analysis companies that provide services to the derivatives industry. Twenty-six organizations were contacted, eighteen of which participated in the survey for a response rate of 69%. Of the eighteen survey participants, sixteen conduct derivatives brokerage or trading operations. Of the sixteen brokerage and trading organizations, nine firms described their commodities derivatives activities, six firms described their weather derivatives activities, and seven firms described their greenhouse gas emissions trading and Clean Development Mechanism activities. The form of derivatives survey is set forth in Appendix D of this dissertation.

The most striking survey result is the short-term nature of risk markets. Most risk markets focus on risk coverage for a period of one year or less. In the insurance market, insurance coverage is arranged almost exclusively on a one-year basis. The derivatives survey confirms that although longer-term contracts are available, most trades are for contracts that expire within one year. The carbon offsets market similarly focuses primarily on short-term timeframes, although transactions may extend to the full duration of the Kyoto Protocol arrangement. Catastrophe bond markets, the notable exception, extend risk coverage to a little over three years on average.

The short-term focus of the risk markets contrast to infrastructure lending markets, which commonly feature tenors of ten to thirty years or more. The gaps in risk coverage in each of the risk management methods are examined in the sections below.

5.4 Private Insurance

Insurance is an essential component of financing infrastructure. Lenders and customers entering into long-term agreements with project companies will require that insurance be procured and maintained by the project company, construction company, and

[13] The OTC market comprises transactions that are privately negotiated, typically using an International Swaps and Derivatives Association form agreement modified to the requirements of the parties. The OTC market represents a substantial portion of the derivatives market. OTC transactions are often cleared through an exchange. Contracts that are cleared though an exchange may or may not be reflected in data provided by the exchange; contracts that are not cleared though an exchange will not be reflected in exchange data.

project operator (Hoffman 2001; Tinsley 2000). Inability to obtain insurance would be a significant impediment to infrastructure finance and development (Safran 2006).

This section covers both primary insurance and reinsurance, focusing primarily on the U.S. market. Particular attention is devoted to the Gulf of Mexico following the 2004 and 2005 hurricane seasons because this market features highly climate-sensitive insurance risks.

This section evaluates property and casualty insurance and reinsurance based on the six criteria relating to the scope of risk coverage, geographic coverage, contract duration, availability, price, and market capacity. The section concludes by assessing the prospects for insurance to address risks posed by climate change.

Additional information about the property and casualty insurance and reinsurance industry is located in Chapter 6 in the insurance case study.

The research in this section includes results of a survey of twenty insurance industry participants, primarily comprising insurance and reinsurance companies, and brokerage firms, but also credit rating agencies, state insurance regulators, insurance industry associations, and insurance risk analysis firms.

5.4.1 Scope of Risk Coverage

Property and casualty insurance typically covers losses due to natural catastrophic events such as flood, wind, earthquake, and fire. Coverage may compensate policyholders for damage to property, loss of revenues due to business interruption, and loss of life or injury. Private insurance in the United States typically excludes flood coverage, which is available through the U.S. government's National Flood Insurance Program.

In response to storms and other catastrophic events in the North Atlantic Basin, the scope of insurance coverage has been curtailed, particularly in coastal communities along the East Coast and Gulf Coast of the United States. Following the 2005 hurricane season, Marsh (2005) reported that insurers are considering the following contractual provisions to limit their exposure to hurricane and storm risk in the Gulf of Mexico:

- Sub-limits for Gulf of Mexico exposure;
- Exclude Gulf of Mexico from coverage;
- Exclude Gulf of Mexico oil and gas platforms built prior to certain date;
- Exclude business interruption coverage for Gulf of Mexico properties;
- Increase record retention period and waiting period for business interruption coverage;
- Require complete schedule of all covered Gulf of Mexico property; and
- Exclude "windstorm" coverage in Gulf of Mexico region.

5.4.2 Geographic Coverage

Insurance is the most common and widely available risk management instrument in terms of geographic coverage. Global insurers underwrite policies on every continent of the world. However, insurance coverage is uneven and markets concentrate on developed and emerging economies. In many developing countries, insurance and reinsurance markets are underdeveloped (Varangis et al. 2002).

Importantly, insurance coverage may be curtailed or prohibitively priced in locations where insurance companies are seeking to reduce their exposure. As described in section 5.4.4, hurricane activity in the Gulf of Mexico in 1992, 2004 and 2005 has led to successive curtailment of insurance in this region. In addition, the survey revealed that some foreign insurers are reducing their risk to the United States in general due to risks associated with terrorism.

5.4.3 Contract Duration

Based upon a survey of twenty insurance industry participants, 100% of respondents reported that primary property and business interruption insurance and reinsurance are generally underwritten on a one-year basis. Where policies are written for longer contract durations, these policies typically include a one-year price reset and provisions allowing the insurer to withdraw coverage. Thus, insurance coverage is only available one year at a time.

The survey further revealed that increasing risk associated with insurance underwriting, regulatory issues, and increasing demand for insurance have contributed to the short-term nature of insurance markets.

5.4.4 Availability

Insurance is one of the most commonly available risk management instruments. However, catastrophic losses have caused insurance companies to withdraw insurance coverage altogether for certain areas and kinds of risks.

Concerns that hurricanes could become more commonplace farther north along the U.S. East Coast have caused insurance companies to withdraw coverage in coastal communities from the Gulf of Mexico as far north as Cape Cod and Long Island (Adams 2006). Since 2004, private insurers have generally eliminated coverage on Cape Cod for homes over $1 million and many insurers have discontinued coverage altogether. Insurers that remained in the market increased prices by as much as 200% in 2006. Massachusetts's state-sponsored insurance plan, which provides insurance as a last resort where private insurance is unavailable, reports that it now serves approximately one-third of the market, increasing its coverage from 6,000 Cape Cod homes in 2000 to 43,000 homes in 2006 (Smythe 2006).

Following Hurricane Andrew in 1992, private insurers in the State of Florida withdrew coverage or increased prices, forcing many homeowners to seek coverage from Florida's state-sponsored insurance program. Further, onshore insurance has been largely unavailable for utilities in the State of Florida since Hurricane Andrew (Edison Electric Institute 2005). In December 1995, Florida's public property and casualty underwriting association had 849,271 policyholders following the 1992 hurricane season; by February 2002, the number had significantly dropped to 116,027 as private insurers reentered the market for non-wind risks (Hartwig 2002). However, the Florida Windstorm Underwriting Association still provided wind coverage to 500,000 policyholders as of 2002, due to the continuing difficulty of obtaining private windstorm coverage in the state (Hartwig 2002).

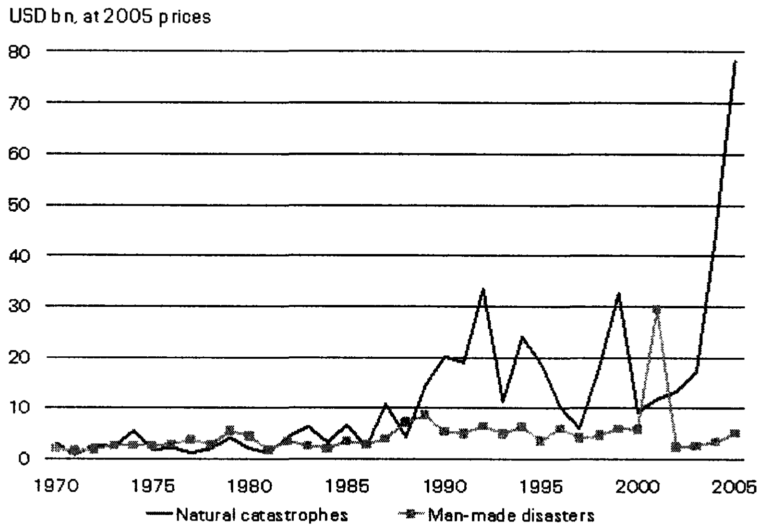
5.4.5 Price

The price of insurance coverage is influenced by a variety of factors, including assessment of risks, market conditions (supply and demand), and general price levels.

Insurance companies employ actuarial models to statistically quantify their risks over a large number of policies based on an assessment of the probability of perils. The risk of loss due to catastrophic events are estimated using detailed historic weather data, demographic data, building codes, and engineering data specific to a particular zip code (Muir-Wood 2006; Siner 2006). Models incorporate future expectations using demographic and engineering trends, and recently, scientific trends concerning changes in climate (Siner 2006). These models produce a loss exceedance curve, which shows the expected amount of insured losses from a particular risk and its estimated probability of occurrence. The exceedance probability is the estimated likelihood that a loss will occur at or greater than a specified level of loss.

During the past thirty-five years, higher population density and inflation in the cost of building materials and repair services have significantly increased the magnitude of insured losses resulting from catastrophic events. According to AIR Worldwide, a leading catastrophe modeling firm, the costs of building materials have increased 40% in the United States over the past decade. AIR Worldwide predicts that catastrophe losses will "double about every 10 years due to increases in the numbers and values of properties at risk" (ISO 2006a).

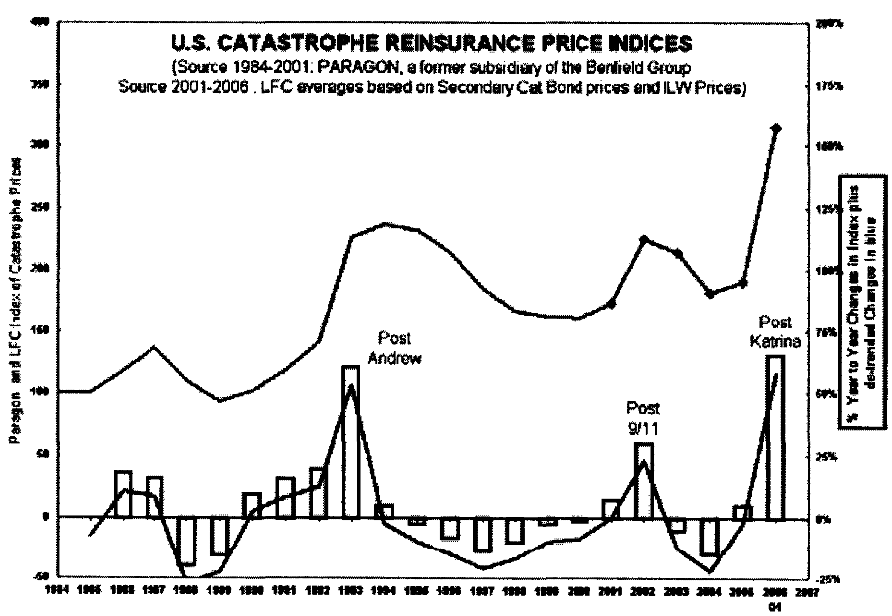
Figure 5.3: Global Catastrophic Losses, 1970-2005



Source: Swiss Re (2006a).

The increasing magnitude of insurance losses has caused increases in the cost of U.S. property and casualty insurance and reinsurance. Since 1990, the cost of reinsurance has increased following major catastrophic events. Figure 5.4 below shows large increases occurring following Hurricane Andrew in 1992, the September 11, 2001 terrorist attacks, and the 2005 hurricane season. Since 1990, U.S. catastrophe reinsurance rates have more than tripled.

Figure 5.4: U.S. Catastrophe Reinsurance Price Indices, 1984-Q1 2006



Source: Lane and Beckwith (2006).

Following the 2005 hurricane season, reinsurance rates in the Gulf of Mexico for offshore energy risks are expected to increase by as much as 300% to 400%; while reinsurance rates for onshore energy facilities are expected to increase from 10% to 30% (Frank Crystal 2006). Reinsurance prices for onshore property and casualty, primarily for homeowners, are expected to increase 30% to 100% (Binnun 2006). A number of survey respondents confirmed that these estimated cost increases are consistent with their observations of the market.

Significantly, as a result of hurricane activity during the past fifteen years, offshore energy companies have large retention rates and thus self-insure a large percentage of their Gulf of Mexico facilities due partly to insurance prices and unwillingness of insurance companies to underwrite these risks (Hartwig 2006). Similar to the latest premium increases following Hurricane Katrina, insurance companies increased premiums and withdrew coverage for onshore utilities following Hurricane Andrew in 1992 (Edison Electric Institute 2005).

Analysis of pre- and post-Katrina reinsurance rates reveals that reinsurance prices increased initially following Hurricane Katrina, and then continued to increase in subsequent months. Prices for reinsurance in Florida and the U.S. increased on average by 120% and 126%, respectively, by April 2006. Some layers of risk have experienced price increases as high as 178% for these reinsurance markets (Lane and Beckwith 2006).

Table 5.4: Pre- and Post-Katrina Reinsurance Price Changes

% Changes in ILW Premiums				1/1/06 and 4/1/06 over Pre Katrina 2005						
	Florida Wind		US All Natural Perils		California Earth Quake		Nationwide Quake		Average by Layer	
ILW Strike	1/1/0E over pre-K 05	4/1/06 over pre-K 05	1/1/06 over pre-K 05	4/1/06 over pre-K 05	1/1/06 over pre-K 05	4/1/06 over pre-K 05	1/1/06 over pre-K 05	4/1/06 over pre-K 05	1/1/06 over pre-K 05	4/1/06 over pre-K 05
$5.0	19%	54%	33%		9%	43%	3%	24%	16%	
$10.0	27%	83%	26%	85%	13%	75%	8%	59%	18%	76%
$12.5	33%	87%	23%	105%	18%	76%	5%	57%	20%	81%
$15.0	38%	92%	24%	111%	25%	81%	3%	52%	23%	84%
$20.0	32%	132%	0%	133%	23%	100%	12%	85%	16%	112%
$25.0	39%	164%	-4%	124%	22%	89%	20%	80%	19%	114%
$30.0	42%	176%	-15%	130%	28%	49%	22%	40%	19%	99%
$40.0	56%	178%	0%	157%	29%	44%	29%	43%	28%	105%
$50.0	38%	113%	0%	160%	25%	42%	42%	50%	26%	91%
Average	**36%**	**120%**	**10%**	**126%**	**21%**	**66%**	**16%**	**54%**	**21%**	**92%**

Source: Lane and Beckwith (2006).

Reinsurance rates are expected to further increase in response to revisions in catastrophe models used to price insurance. The revised models incorporate expectations regarding future hurricane activity in the Gulf Coast and Caribbean, European windstorm, and California earthquake activity (Siner 2006; Muir-Wood 2006). The revised models reflect increased probability of catastrophic events occurring in high-risk areas by as much as 30% to 60% (Martucci 2006).

5.4.6 Market Capacity

The capacity of insurance markets to continue to absorb increasing amounts of catastrophic risk is unclear. The survey conducted in connection with this dissertation revealed that it is subject to debate within the industry.

The capacity of insurance companies to underwrite risk is influenced by a number of factors, including premium levels, underwriting losses, investment returns, surplus, reinsurance markets, regulations, and the ability of the insurance industry to raise capital.

Insurance company earnings are derived from underwriting premiums and investment profits. Both U.S. primary insurance and reinsurance companies have generally incurred losses on account of underwriting activity; thus, investment profits account for most insurance company profits. Since 1975 to 2005, U.S. insurance companies incurred losses due to underwriting activities every year except in 1977, 1978 and 2004. From 1991 to 2005, U.S. property and casualty insurers incurred underwriting losses of approximately $298 billion, while net income after taxes during the same period was $313 billion, resulting from investment activity (Insurance Information Institute 2006a).

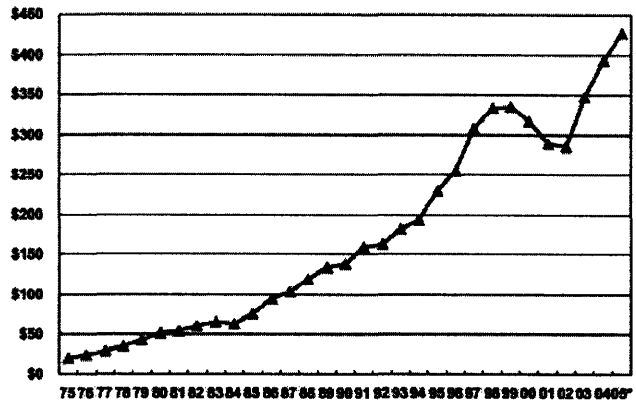
The important role of investment returns in supporting the property and casualty industry suggests that future industry capacity to underwrite risk depends in part upon investment returns in debt and equity markets.

In 2005, the U.S. property and casualty industry suffered $57.7 billion of onshore insured catastrophic losses. Foreign reinsurance and other arrangements absorbed $27-32 billion of these losses or about 57-67% (Insurance Information Institute 2006a).

Despite these record losses, policyholder surplus, a measure of the net worth of the industry, reached a record $427 billion at the end of 2005 (Insurance Information Institute 2006a). In addition, existing and start-up insurance companies have announced plans to raise an additional $19 billion in capital (Insurance Information Institute 2006a). The record policyholder surplus, the ability of the insurance industry to pay all claims for U.S. catastrophic losses, and its ability to attract new capital following the 2005 hurricane losses suggest that the industry is adequately capitalized.

At the same time that the industry is experiencing high surplus levels, U.S. insurance and reinsurance companies are curtailing coverage and raising prices for catastrophic events in high-risk areas. The survey revealed differences of opinion concerning whether market conditions reflect inadequate capacity or unwillingness to pay a fair price for providing risk coverage.

Figure 5.5: U.S. P&C Policyholder Surplus (US$ billions), 1975-2005



Source: Insurance Information Institute (2006a). Note: 2005 figures are estimated.

According to one view, the insurance industry occasionally experiences periods of inadequate capacity. Prior to September 11, 2001, the reinsurance market was estimated to lack approximately $30-55 billion of capacity to meet demand for events that causes $60 to $80 billion in losses (Ganapati, et al. 1999). The survey revealed that following the 2005 hurricane season, some believed that a global shortage of reinsurance developed for certain risks in certain areas. For example, in North America, earthquake reinsurance for California and hurricane cover for the Gulf of Mexico region experienced significant shortages (Loughlin 2006).

The Reinsurance Association of America and the Association of Bermuda Insurers and Reinsurers conducted a survey of their members regarding supply and demand of property reinsurance following the January 2006 reinsurance negotiations, during which approximately 50% of reinsurance contracts were renegotiated. The 2006 survey received nine responses representing a 32% response rate. The results suggest a potential gap of approximately $5 billion in reinsurance supply and demand for U.S. catastrophic risks based on a comparison of the mean response of reinsurance sought and purchased. The dollar value of reinsurance coverage sought versus actually purchased was broad, which might further suggest that less insurance was available at acceptable prices than would otherwise be demanded. Survey respondents estimated that approximately $42 billion (mean response) of reinsurance coverage would attach in the event of a major U.S. catastrophe. This coverage is augmented by other forms of reinsurance such as catastrophe bonds (RAA/ABIR 2006).

Table 5.5: RAA/ABIR Property Reinsurance Survey Results (US$ billions), 2006

	Median	Mean	Range
Reinsurance Sought	38.5	36	15-62.5
Reinsurance Purchased	35	31.5	12.5-47.5
Maximum excess of loss reinsurance coverage that would attach	40	42	27-75

Source: RAA/ABIR (2006).

Others expressed the view that adequate reinsurance capacity almost always exists and that pricing is the primary issue. Following a major catastrophe, catastrophe reinsurance coverage can be extremely expensive, and in the highly regulated U.S. retail insurance market, there is no certainty that insurers will be able to pass the increased cost of reinsurance on to customers (Hartwig 2006). As a result, insurance companies may be unwilling to pay the price demanded by reinsurance companies for reinsurance coverage. In turn, insurance companies have less capacity to underwrite primary insurance policies.

This dissertation's survey confirmed that a number of insurance and reinsurance companies are curtailing coverage in the Gulf of Mexico in order to reduce their exposure to the region. Some survey respondents noted that revised catastrophic loss models and concern over credit rating agency reviews may be partly responsible for the curtailment. According to Standard & Poor's, revised models estimate that the probability of catastrophic events occurring in high-risk areas has increased by 30% to 60% (Martucci 2006). Various survey respondents identified the lack of support by regulators to approve premium increases as a significant cause of insurance curtailment. A number of European industry participants further noted that the fragmented nature of state insurance regulation in the United States and the local political pressures that prevent pricing risk fairly have caused them to reduce exposure to the U.S. market.

According to the Florida State Office of Insurance Regulation, demand for reinsurance has increased by 120% from 2005, yet supply of reinsurance has contracted to 80% of 2005 levels, resulting in a substantial gap (Binnun 2006). Approximately fifteen primary insurance companies have withdrawn or curtailed insurance coverage in Florida following the 2005 season (Binnun 2006; Spudeck 2006). Although smaller regional companies have entered the state, regulators expressed concern that they may be forced to limit the underwriting activity of these smaller insurers due to concerns over their ability to pay claims, thereby leading to a further shortage in primary coverage (Binnun 2006).

The Gulf of Mexico insurance market has experienced shortage before the 2004 and 2005 hurricane seasons. Following Hurricane Andrew in 1992, eleven insurance companies became insolvent as a result of insured losses in the region (Hartwig 2005). Companies that remained in the region formed separately incorporated regional companies to limit their exposure to the region (Binnun 2006). Insurance companies withdrew insurance from utility transmission and distribution assets in the Gulf Coast area altogether (Edison Electric Institute 2005).

Significantly, the contraction of the insurance market in the Gulf of Mexico is occurring at a time when public insurance funds have exhausted their reserves. As a result of the 2005 hurricane season, the Florida Hurricane Catastrophe Fund, a state-sponsored reserve fund for large catastrophic events, has exhausted its reserves, and the Citizens Property Insurance, a state-sponsored company that provides insurance to areas that the private sector will not cover, has incurred a deficit. Both Florida entities are raising capital through public bond issuances (Binnun 2006; Bushouse 2006). The National Flood Insurance Program has similarly exhausted funds allocated to it by Congress (Insurance Journal 2006). State catastrophe insurance funds in Louisiana and Mississippi are similarly facing financial difficulties (CERES 2006).

U.S. property and casualty markets are experiencing a period of record policyholder surplus, increasing prices, and curtailment of insurance in high-risk areas. The survey revealed that curtailment is likely occurring because insurers are seeking to reduce their exposure to high-risk areas motivated by concerns over futures losses and credit ratings. These factors explain why even in an industry where policy surplus is increasing and insurers are raising substantial amounts of new capital, market capacity may be limited for high-risk areas and events.

5.4.7 Prospects for Addressing Climate Change

The short-term nature of insurance markets and the inability to predict weather events suggest that these markets will not accept climate risk beyond one year in the future. As such, insurance instruments as currently available have limited ability to address risks posed by climate change.

To the extent that climate change increases the unpredictability of weather, and makes weather more destructive by the severity and frequency of catastrophic events, we can expect insurance companies to continue to respond by increasing prices and limiting exposure to high-risk areas and perils. For some geographic areas, this may result in local shortages of insurance, as have already been observed in U.S. coastal areas from the Gulf of Mexico to as far north as Cape Cod.

The implications of climate change for the insurance market are described in further detail in Chapter 6 in the case study on the effects of catastrophic events on the insurance industry.

The summary of survey results for private insurance is set forth in Table 5.6 below.

Table 5.6: Private Property & Casualty Insurance Summary

Criteria	Direct Insurance	Reinsurance
Scope of Risk Covered	Exclusions of flood and some coastal areas.	Exclusions of flood and some coastal areas.
Geographic Coverage	Worldwide, except undersupply in developing countries.	Worldwide, except undersupply in developing countries.
Contract Duration	1 year	1 year
Availability	Curtailment in high-risk areas.	Curtailment in high-risk areas.
Price	Increases in high-risk areas.	Increases of 30% to 400% in high-risk areas.
Market Capacity	Reduced capacity for high risk areas.	Reduced capacity for high risk areas.

5.5 Commodities Derivatives

This section evaluates commodities derivatives based on the six criteria relating to the scope of risk coverage, geographic coverage, contract duration, availability, price, and market capacity. The section concludes by assessing the prospects for commodities derivatives to address risks posed by climate change. This section focuses on oil, gas, electricity, and platinum futures contracts. Gold futures contracts are also included in the survey for comparative purposes. Although gold is not a metal used in energy applications, it is the most widely traded metal and illustrates the potential capacity of commodities futures markets.

This section presents results of the derivatives survey relating to commodities derivatives. Of the sixteen derivatives brokers and dealers surveyed, nine respondents described their commodities derivatives operations.

5.5.1 Scope of Risk Coverage

Hull (2003) defines a derivative as "a financial instrument whose value depends on (or derives from) the values of other, more basic underlying variables. Very often the variables underlying derivates are the prices of traded assets."

Derivatives are therefore intended to hedge the risk of price movements in the underlying asset. Derivatives are useful for addressing market and supply risks, as well as operating cost risk more generally.

For example, electricity generators commonly use commodities derivatives to reduce market and supply risk by entering into contracts to sell electricity and/or buy fuel. A common trade for an electricity generator is to match a sale of electricity with a purchase of gas, at prices that provide a profit margin for a portion of their generation. A utility might seek to execute matched trades in electricity and gas futures to lock in 70-90% of its generation profit margin for the next year, 60-80% of its profit margin for two years in the future, and 30-40% of its profit margin for three years or more in the future (Collins 2006).

5.5.2 Geographic Coverage

Derivatives markets can be accessed globally. Because the vast majority of derivatives contracts are settled financially and do not result in physical delivery of the underlying commodity, they can be employed by parties anywhere in the world (Tippee 1993). For example, only about 1% of NYMEX metals contracts result in physical delivery (Karr 2006).

However, to obtain an effective hedge, firms must use a derivative product whose price changes in a manner that correlates strongly with the risk the party is attempting to hedge. Some contracts cover only certain geographic areas. For example, the great variety of crude oil contracts makes this market a truly global market. In contrast, New York

Mercantile Exchange (NYMEX) natural gas futures contracts are settled based on continental U.S. prices at Henry Hub in Texas and may be unsuitable for firms in other places. Similarly, electricity futures contracts are presently only available for the United States and Europe. Thus, firms are subject to constraints based on the availability of contacts; if there is no contract for the desired asset, the firm must construct an approximate hedge based on substitute assets, which may provide less risk coverage or require more cost and effort to maintain the hedge.

5.5.3 Contract Duration

The contract durations for commodities derivatives contracts are relatively short-term. Crude oil, natural gas, and gold futures contracts have expiration dates four to six years in the future. Heating oil and platinum futures contracts have expiration dates a year to a year and a half in the future.

The table below shows the open interest in selected commodities futures contracts traded over the NYMEX at the close of business on April 19, 2006. Open interest is an important measure of liquidity in a market. Open interest is the total number of long positions outstanding in a futures contract, which is equal to the number of short positions. Outstanding contracts are those that have not expired, been exercised, or fulfilled by delivery (Hull 2003).

Table 5.7: Selected NYMEX Futures Contracts Open Interest, April 2006

Commodity	Total Open Interest	Longest Duration	**Open Interest** (as a percentage of total open interest)				
			90 days May to July 2006	**90 days - 1 year** August 2006 to April 2007	**1-2 year** May 2007 to April 2008	**2-3 year** May 2008 to April 2009	**3+ years** May 2009 to end
Light Sweet Crude Oil	1,002,719	Dec 2012	44.6%	28.1%	13.7%	5.2%	8.4%
Heating Oil	174,402	Oct 2007	67.4%	30.9%	1.7%	N/A	N/A
Natural Gas	710,064	Dec 2011	23.0%	39.9%	19.2%	8.2%	9.6%
Platinum	9,559	Jan 2007	1%	99%	N/A	N/A	N/A
Gold	353,757	Dec 2010	71.7%	19.1%	6.6%	1.7%	0.8%

Source: New York Mercantile Exchange, as of close of market on April 19, 2006.

Despite the availability of multi-year contracts for some of these contracts, the majority of open interest occurs within 90 days or the upcoming season in the case of heating oil, and over 90% of open interest is within three years or less for all these commodities. Thus, exchange-traded futures markets are liquid primarily in short-term time frames.

The volume of open interest in these contracts also affects their overall liquidity. The crude oil and natural gas markets are many times larger than all other markets. The market for platinum, a metal important for the production of catalytic converters and fuel cells, is small by comparison.

The survey conducted in connection with this dissertation surveyed derivatives traders and brokers at sixteen firms; nine firms described their trades in commodities derivatives. The survey captured OTC trades that would not be reflected in the above exchange-traded data. Because OTC contracts are privately negotiated, these contracts may extend beyond the duration of the standardized exchange-traded contracts.

The survey results show that longer duration trades do occur in the OTC market. However, the survey confirms that the OTC markets follow the same short-term patterns that occur in the exchange-traded market. Like the exchange-traded futures market, the vast majority of OTC trades are for contracts with durations within one year. The notable exception is coal, which has tended to be a longer-term market. However, deregulation and the expiration of longer-term supply contracts is causing coal to move towards a shorter-term market (Gottlieb 1998). The table below summarizes the results of the surveys.

Table 5.8: Commodities Derivative Survey Results

Commodity	Longest Known Duration (years)	% Trade 90 days or Less	% Trade 90 days-1 Year	% Trade 1-3 years	% Trade 3-10 years	% Trade 10+ years
Oil	10	50-90	10-50	0-30	0-20	0
Gas	20	40	30	30	Few	Few
Coal	20+	0	40-50	30-55	0-20	Few
Electricity	10+	50-60	20-25	10-20	5	0
Platinum	3	60-75	15-40	0-10	0	0

Source: Author's survey.
Note: % trades are ranges of all survey responses for each duration period.

In addition to exchange data and survey data, surveys of national banks conducted by the U.S. Comptroller of the Currency also show that a majority of derivatives held by banks are short-term in nature, mostly less than one year in duration, and the vast majority less than three years in duration (U.S. Comptroller of the Currency 2005).

An interview with the Chicago Mercantile Exchange provides an explanation for why the exchange-traded and OTC markets follow the same short-term trend. The exchange typically offers standardized contracts for whatever duration the market is interested in trading. Thus, the dominance of short-term durations in standardized exchange-traded contracts reflects demand and supply in the overall market including the OTC market (Smith 2006).

Survey responses revealed several explanations for the market's preference for short-term agreements. Several survey respondents noted that greater price visibility for the underlying commodities in the near-term reduces the risk of trading in short-term agreements. Survey respondents also cited constraints upon a trader or trading firm's ability to accept long-term risks. Few traders are authorized to take long-term risks that may exceed their tenure at their firm and could potentially become a long-term financial burden if trades result in continuing losses over an extended period. From the perspective of the clearinghouse and its member trading firms, short-term trades are preferable because they reduce their exposure to their client's credit risk. Exchange members act as primary guarantors to the clearinghouse for trades it places on behalf of its clients. If a client defaults, the clearinghouse would make payment and then seek indemnification from the member trading firm, which would in turn seek payment from its client. If a member of an exchange defaults, all member firms would then share in the loss pro rata (Lichtenstein 2006; Yeres and Little 2000). Bankruptcies of prominent derivatives trading firms such as Drexel Burnham, Barings, and Enron have served to reinforce conservative practice among members of exchanges to avoid long-term credit exposure, thereby reinforcing the trend towards shorter-term trades (Lichtenstein 2006; Miller 2006; Zhang 1995).

Credit rating agencies also reinforce the short-term nature of markets because their ability to assess future credit risk is limited. According to one credit rating agency, it is difficult to assess the credit risk of a company beyond 3-5 years in the future (Furey 2006). Because ratings are unavailable beyond this short time frame, private sector firms are generally unwilling to extend credit for long-term trades.

Finally, the liquidity of the short-term markets reinforces the preference for short-term contracts. Survey respondents noted that liquidity is essential for speculators. Even for firms that are engaged in derivatives trading to hedge their positions, liquidity is highly desirable as hedged positions need to be continuously monitored and changed as necessary.

The survey responses are consistent with the findings of other researchers who have interviewed officials of oil exporting countries who are potentially positioned to enter into long-term contracts in commodities derivatives markets. These officials have expressed reluctance to enter into long-term contracts because these contracts could encumber their successors and open them to criticism if markets change (Verleger 1993; Daniel 2001).

5.5.4 Availability

Derivatives are traded in standardized contracts on over forty exchanges around the world (Hull 2003). Derivatives contracts include futures, options (calls and puts), and swap agreements. Assets underlying these contracts include crude, refined petroleum products (heating oil and gasoline), natural gas, electricity, and precious metals (gold, silver, copper, aluminum, platinum and palladium). Weather indexes are also increasingly the underlying variables of derivatives contracts.

Because most derivatives are settled financially and do not result in physical delivery of the underlying asset (Tippee 1993), they are available to a broad group of end-users.

5.5.5 Price

This section explains the pricing of futures and options and models the price of a hypothetical option on a futures contract using Derivagem, a version of the Black-Scholes model that accompanies Hull (2003). The pricing experiment provides insight regarding the short-term nature of commodities derivatives markets. It also provides insight into the potential effects that climate change could have on derivatives markets, depending upon climate change's effects on the underlying commodities.

Futures are priced based on the current spot price *S(t)* of the underlying commodity, discounted into the future at the prevailing risk free interest rate *r*. The risk free interest rate reflects the financing cost of the underlying commodity. In practice, futures contract pricing also reflects future expectations of the price of the commodity, which is reflected in its current spot price *S(t)*. The value of a futures contract *F(t)* purchased at time *t* with maturity at time *T* is expressed as:

$$F(t) = S(t) \cdot e^{r(T-t)}$$

In contrast to options pricing, a futures contract price does not include a premium for the risk associated with uncertainty in price movements in the underlying commodity because both parties remain subject to the risk of commodity movements under these contracts.

Options pricing is based on the Black-Scholes options model. Under the Black-Scholes model, five factors determine the price of an option: time to contract expiration *T* in years, the right to buy or sell the underlying asset in the future at price *K*, the current price of the underlying asset *S*, the constant risk-free interest rate *r*, and the historic or implied (expected) volatility of the underlying asset σ (Hull 2003). The equations below are the Black-Scholes equations for call and put options, respectively:

$$C(S,T) = SN(d_1) - Ke^{-rT}N(d_2)$$

$$P(S,T) = Ke^{-rT}N(-d_2) - SN(-d_1)$$

where

$$d_1 = \frac{\ln(S/K) + (r + \sigma^2/2)T}{\sigma\sqrt{T}}$$

$$d_2 = d_1 - \sigma\sqrt{T}$$

and *N(x)* is the cumulative distribution function for a variable that is normally distributed with a mean of zero and a standard deviation of 1.0 (Hull 2003).

Options provide the holder with the right but not the obligation to purchase (a call) or sell (a put) an asset at a predetermined price. An option contract therefore provides certainty to the party holding the option and resembles an insurance contract. The party selling the option is paid a premium in exchange for accepting the risk associated with changes in the price of the underlying assets. The premium is determined by the duration of the contract and the volatility of the underlying asset. A longer duration contract offers greater insurance value. Similarly, greater volatility of the underlying asset also increases the value of the insurance provided by the option. Finally, the greater the price of the underlying asset, the greater the potential magnitude of price changes in the underlying asset, which also increases the value of the insurance feature of an option. Thus, the price of an option increases as duration, volatility and the price of the underlying asset increases.

Because options contracts are priced based on the expected price movements of an underlying asset, as opposed to the purchase price of an asset, they are less expensive compared to futures contracts and they allow the trader to leverage cash assets much more effectively (Kline 2001). Importantly, because options and futures contracts can be used to construct a portfolio having the characteristics of either kind of instrument, these instruments present arbitrage opportunities and their prices move in relation to each other (Hull 2003).

To illustrate how the price of an option is affected by the time to maturity and volatility, eight scenarios are presented in Table 5.9 below comparing the price of a European call option on a generic futures contract. Four time frames are compared: 180 days, 1 year, 2 years, and 3 years. These time frames are tested at both 20% and 40% volatility levels for the underlying asset. All other variables were identical (strike price = 100, current underlying price = 100, risk-free rate = 5%).

Table 5.9: Options Pricing Comparison – Effects of Duration and Volatility

	20% Volatility	40% Volatility
180 Days	$5.5	$10.97
1 Year	$7.58	$15.08
2 Years	$10.18	$20.15
3 Years	$11.84	$23.32

Source: Author's calculations using Derivagem software from Hull (2003).

The increase in duration from 180 days to 3 years at 20% volatility produces a 115% increase in the price of the call option. The differences in the price of the option between different maturities increases at a similar rate for the option priced at 40% volatility. When volatility increases from 20% to 40%, the price of the same option doubles in cost for each time to maturity.

Increases in duration and volatility together can dramatically increase the price of options. For example, an increase from 180 days to 3 years combined with an increase in volatility from 20% to 40% results in a 324% increase in the cost of the option. The increased cost of longer-term derivatives, especially in periods of high volatility, will tend to limit the use of longer-term duration instruments.

In addition to duration and volatility, an increase in the price of the asset underlying the derivative also increases the cost of the derivatives contract. To illustrate this relationship, Table 5.10 below compares the price of a European call option on a generic futures contract at two different asset price levels. In the first four scenarios, the asset price and strike price are both set at 100. In the second set of scenarios, the asset price and strike price are both set at 200. Comparisons are made for maturities at 180 days, 1 year, 2 years, and 3 years. In all cases, the difference between the strike price and the underlying asset value is zero; thus there is no difference in the intrinsic value of the option. The risk-free rate is constant (5%) and volatility is 20% for all scenarios below.

Table 5.10: Options Pricing Comparison – Effects of Inflation of Asset Prices

	Asset Price = 100 Strike Price = 100 Volatility = 20%	Asset Price = 200 Strike Price = 200 Volatility = 20%
180 Days	$5.5	$11.00
1 Year	$7.58	$15.15
2 Years	$10.18	$20.35
3 Years	$11.84	$23.67

Source: Author's calculations using Derivagem software from Hull (2003).

The increase in underlying asset price causes a significant increase in the price of the option. For all scenarios, doubling the asset price and strike price results in a 100% increase in the cost of the option. This price increase reflects the model's assumptions that at higher asset valuations, the same stochastic change in asset value on a percentage basis results in a larger change in the absolute price of the asset, and thus more risk associated with the underling asset. In turn, this increases the insurance value of the option contract.

Again, if duration, volatility and price levels increase, the cost of options will increase dramatically. Table 5.11 below compares the price of options for which the asset price and strike price have increased from 100 to 200 and volatility has increased from 20% to 40%, for 180 days, 1 year, 2 years and 3 years. The risk-free rate is 5% for both scenarios. Comparing the 180 day, 20% volatility, price level = 100 instrument to the 3 year, 40% volatility, price level = 200 instrument, the aggregate increase in the price of the option is approximately 748%.

Table 5.11: Options Pricing Comparison – Duration, Volatility, and Inflation

	Asset Price = 100 Strike Price = 100 Volatility = 20%	Asset Price = 200 Strike Price = 200 Volatility = 40%
180 Days	$5.5	$21.94
1 Year	$7.58	$30.16
2 Years	$10.18	$40.30
3 Years	$11.84	$46.64

Source: Author's calculations using Derivagem software from Hull (2003).

These experiments with the Black-Scholes options pricing model suggest how climate change could potentially affect the prices of commodities derivatives. As discussed in Chapter 4, climate change is expected to increase the demand for certain commodities, such as electricity during the summer (Kirshen et al. 2004), and platinum for fuel cell technology, potentially leading to periodic or perennial supply shortages. In turn, climate change could result in an increase in the volatility of commodities prices and/or a general increase in the price level of commodities.

If climate change results in increasing commodity prices or increasing volatility of commodity prices, the cost of options and hedging in general will increase. As a result, hedging on a long-term basis will be increasingly expensive. This should result in contract durations in the derivatives markets remaining short-term under climate change conditions.

5.5.6 Market Capacity

The capacity for future growth of the commodities derivatives markets is a complex issue and is therefore presented from several perspectives: demand and supply for derivatives, credit and regulatory constraints, and the structure of underlying commodities markets.

One perspective expressed by several survey participants is that although further increases in risk should increase demand for these products, the number of credit-worthy counterparties willing to engage in transactions will likely limit market capacity.

Credit risk is a significant factor that may affect the growth capacity of derivatives markets. Credit risk is reflected in the availability of credit available from banks to its customers to purchase derivatives or the amount of credit exposure a counterparty or exchange member is willing to take on behalf of a client. Two factors may result in less bank credit being available for derivatives trades. First, continuing consolidation in the banking sector often produces reductions in overall credit availability to any given company. A larger consolidated bank may have less flexibility to extend credit under its internal credit policies or external regulatory capital requirements than would be available in the aggregate by two independent banks (Hyman 2006). Second, the introduction of risk-based regulatory capital requirements under the Basel Capital Accords sponsored by the Bank for International Settlements requires more frequent reporting and mark-to-market for derivatives, and increases regulatory reserves with respect to derivatives products purchased by clients (Hyman 2006; Gutierrez 2005; Bank for International Settlements 2005).

Regulators have also expressed concern regarding the high concentration of derivatives financing by a few U.S. banks. According to the U.S. Comptroller of the Currency, five U.S. banks account for 96% of the total notional amount of derivatives in the U.S. commercial banking system. The notional amount of derivatives held by these banks exceeded their assets by a factor of seven to forty-seven times. At end of December 2005, JP Morgan had a net value of just over $1 trillion and held derivatives with notional value of over $48 trillion on its books (U.S. Comptroller of the Currency 2005). Regulators have expressed concern that at these concentrations, the withdrawal of a single large dealer could destabilize the entire derivatives market (Hyman 2006).

The Bank for International Settlements, which monitors over-the-counter derivatives contracts held by banks, reports that notional amounts of all types of OTC contracts excluding credit derivatives stood at $285 trillion at the end of December 2005 (Bank for International Settlements 2006a).

While the magnitude of these numbers are staggering, is important to note that the actual amount of value at risk is only a percentage of the notional amount. Of the $285 trillion notional amount held by banks and other financial institutions potential liability at the end of 2005 was only $9 trillion (Bank for International Settlements 2006a).[14] Further, the Comptroller of the Currency estimates that as much as 85% of the credit risk associated with these contracts is reduced through bilateral netting procedures among banks (U.S. Comptroller of the Currency 2005). In addition, credit risk can be further reduced by collateral arrangements between the underwriting bank and the derivatives customer (Ross 2006; Upper 2006). Further, the risk in any single bank's portfolio will be diversified and no single event should threaten the value of their entire position (Upper 2006).

Even with these reductions in credit exposure, the amount of potential credit risk is still considerable. Distress in financial markets have resulted in spikes in derivatives losses in 1997-1999 as a result of the Asian currency crisis and devaluation of the Russian ruble, and in 2001-2002 following the stock market drop and the September 11, 2001 terrorist attacks (U.S. Comptroller of the Currency 2005). To place these losses in perspective, they amounted to less than 1% of bad loans losses during the respective periods (Wilhelm 2006).

Notwithstanding these concerns, to the extent derivatives are used to hedge a firm's risk, they also decrease the overall credit risk associated with lending to that borrower. Thus, depending upon how brokers and banks manage their credit exposure to clients, derivatives should reduce overall credit risk. The present large volume of derivatives does not present any evidence of a limit having been reached. Significantly, the market continues to grow rapidly (Bank for International Settlements 2006a).

Another view is the physical assets upon which they trade limit the capacity of commodities derivatives markets. Under this view, the degree to which futures and options contracts are currently used as a percentage of trade in a commodity may provide some perspective on the potential future growth capacity of commodities derivatives.

Table 5.12 below sets forth the open interest in standard exchange traded futures contracts for oil, gas, platinum and gold on the major world commodities exchanges, and data on the annual global production or demand for these commodities. Options are not included in the table because options are typically written on futures contracts, and thus would cause double counting. These numbers also do not include the OTC markets due to incomplete information. However, it should be noted that the OTC market for some of these instruments may be several times larger than the open-interest in the exchange-traded market (Daniel 2001).

---

[14] Notional amount is the nominal face value of a derivatives contract and is not the amount at risk. For example, in the case of an interest rate derivative, the actual obligation is calculated as a percentage of the notional amount. Thus, the actual risk is lower than reported notional amounts.

Table 5.12: Selected Futures Contracts as Percentage of Global Commodities Trade

Commodity	One Year Futures Contract Open Interest	Size of Each Contract, as Quoted by Exchanges (conversion)	Annual Global Production or Demand	Production Traded as Exchange-Traded Futures Contracts
Oil	NYMEX 728,976 ICE 401,916 Tokyo 270,630	1,000 bbl 1,000 bbl 50 kl (307.6 bbl)	29,072,250,000 bbl	3.97%
Gas	NYMEX 446,630	10,000 million btu	92 tcf	4.85%
Platinum	NYMEX 9,559 Tokyo 26,892	50 toz 500 g (16.1 toz)	6,700,000 toz	13.59%
Gold	NYMEX 321,211 Tokyo 14,762 CBOT 4,916 CBOT Mini 4,949	100 toz 1 kg (32.2 toz) 100 toz 33.2 toz	83,400,000 toz	39.87%

Sources: Dailyfutures.com (May 16, 2006); Tokyo Commodities Exchange (May 17, 2006); Chicago Board of Trade (CBOT) (May 17, 2006); International Commodities Exchange (ICE) (May 17, 2006); New York Mercantile Exchange (NYMEX) (April 19, 2006); EIA (2005b); CIA Factbook (2006); Flood and Morrison (2006).

With the exception of gold, only 4% to 14% of global production in these commodities are traded on a futures basis over exchanges. In contrast, 40% of global annual gold production trades over futures exchanges.

The differences between gold and the other commodities might be explained by the different structure of these commodities markets and the unique role gold has played in international finance. Unlike the other commodities, gold is held by many governments and central banks as a store of value and is traded widely to settle financial obligations. In contrast, petroleum, gas, and platinum are primarily consumed immediately.

Another explanation for the low trading volumes of the other commodities is that the production of these commodities is highly concentrated. In general, the greater concentration of production of a commodity, the stronger the position of producers of the commodity. Further, the greater influence a producer has over price, there is less need for the producer to use derivatives products to protect revenues (Daniel 2006; Verleger 2006).

Market concentration appears to provide a plausible explanation for the relative volumes of trade occurring in exchange-traded commodities futures. In the case of platinum, approximately 90% of all platinum production is located in South Africa and Russia, and there are only ten significant platinum mining companies in the world (UNCTAD 2006). In the case of oil, OPEC countries in general, and Saudi Arabia in particular, do not enter into exchange-traded futures agreements (Daniel 2006). Significantly, the number of oil exporting countries is finite and expected to decrease as countries such as the United Kingdom, Yemen and other countries switch from being oil-exporting countries to oil-importing countries during the first several decades of the 21st century.

If market concentration and the volume of trade in commodities over derivatives markets are negatively correlated, the reluctance of producers to enter into long-term contracts should intensify for commodities that producers expect to enjoy increasing market power. This conclusion is consistent with the results of the survey conducted in connection with this dissertation and the work of other researchers who have interviewed oil producers. Other researchers have found that oil producers are generally unwilling to enter into long-term contracts for fear of failing to capture potential profits if market conditions change (Verleger 1993; Daniel 2001).

5.5.7 Prospects for Addressing Climate Change

The commodities derivatives market is short-term in nature. The short-term nature is reinforced by credit risk, the desire for liquidity, and the unwillingness of producers, brokers, and exchanges to accept long-term risks that can encumber their organizations.

Options pricing is highly sensitive to the contract's duration, and the volatility and price level of underlying assets. If climate change is accompanied by increases in the volatility or price level of commodities, long-term price insurance through options contracts would become prohibitively expensive.

There is no clear limit to the capacity of these markets to grow. However, continued growth of these markets will not likely produce long-term derivatives arrangements. If concentration of production of commodities affects the capacity of futures markets, one would expect that the scarcer a commodity becomes, the more difficult it will be to enter into long-term contracts. This is the opposite of what firms might desire from the perspective of managing longer-term risks of climate change with respect to commodities supply risk.

Climate change does potentially present concerns about the stability of these markets. Given the volume of trading in these markets and the potential for disruption due to global financial crisis, climate change could potentially disrupt these markets. I could not locate any research on the potential effects of climate change on derivatives markets. This could be an important area of inquiry.

The short-term nature of commodities derivatives markets limits their usefulness in mitigating long-term trends influenced by climate change. As discussed in Chapter 4, climate change and the need to transition infrastructure could increase supply and market risks. If a firm were to seek to mitigate these risks through the use of derivatives, most firms would be limited to short-term contracts, with the greatest liquidity for contracts of less than one year in duration under current market conditions.

Table 5.13 below summarizes the findings of this section for commodities derivatives.

Table 5.13: Commodities Derivatives Summary

Scope of Risk Coverage	Price movements in commodities, which affect supply, market, and operating cost risks.
Geographic Coverage	Oil and platinum are global. Gas is U.S. Electricity is U.S. and Europe.
Contract Duration	Most liquidity within 1 year.
Availability	Broad range of energy, precious metals, and Agricultural commodities.
Price	Increases with market volatility, duration, and price level of underlying asset.
Market Capacity	Exchanges handle 4-14% trade in most commodities. OTC market is even larger.

5.6 Weather Derivatives

This section evaluates weather derivatives based on the six criteria relating to the scope of risks covered, geographic coverage, contract duration, availability, price, and market capacity. The section concludes by assessing the prospects for weather derivatives to address risks posed by climate change.

This section presents the results of the derivatives survey with respect to weather derivatives. Of the sixteen derivatives brokers and dealers surveyed, six respondents described their weather derivatives operations. In addition, interviews were conducted with firms and universities engaged in developing models for weather derivatives.

5.6.1 Scope of Risk Coverage

Weather derivatives are used by companies to maintain smooth earnings that would otherwise be subject to fluctuations due to weather events that affect the revenues or expenditures of a company. Derivatives are traded for temperature, snowfall, rainfall, sun, and wind. Their use is growing as stock market analysts increasingly expect management to protect company earnings against weather-related fluctuations.

Weather derivatives are used predominantly by the utilities industry. According to a 2005/2006 survey of the industry, energy and utilities accounted for 46% of weather derivatives transactions, agriculture 12%, retail 7%, construction 5%, transportation 4%, and various industries accounted for the remaining 26% of weather derivatives transactions (Pricewaterhouse Coopers 2006).

The buyer of a weather derivative pays a premium to the seller in return for an agreement by the seller to pay the buyer an amount determined by reference to a weather index on a specific date or dates if the index is above or below specified levels. Indexes may be based on average temperature, precipitation or other weather event in a single or multiple locations over a specified period.

A contract for "heating degree days" (HDD) or "cooling degree days" (CDD) provides an illustration of the scope of risk coverage of a weather derivative contract. Obligations under HDD and CDD contracts are calculated as the cumulative difference over a calendar month of the daily average of the high and low temperatures of each day measured on a midnight to midnight basis at a designated weather station against the contract temperature of 65°F (18°C in Europe and Japan). Thus, the daily calculation for these contracts is based on the following formulas:

HDD = Max {0, 65°F - daily average temperature}
CDD = Max {0, daily average temperature - 65°F}

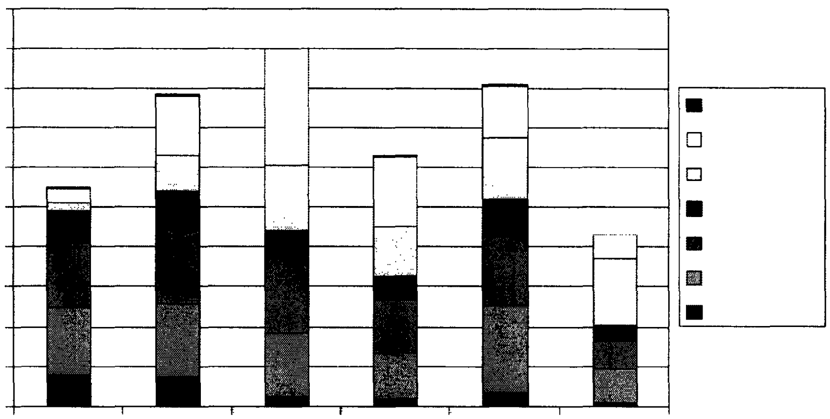
For example, if the average of a particular day's maximum and minimum temperature is 35°F, the day's HDD is 30 and the CDD is 0. HDD and CDD are then cumulated for each day in the calendar month and then multiplied by $100 to determine the contract payout (Arditti et al. 1999).

5.6.2 Geographic Coverage

Geographic coverage of exchange-traded instruments is limited to major cities in the U.S., Europe and Asia. At the time of writing, most weather derivative contracts have been traded in the United States. The survey revealed that some firms have been able to obtain satisfactory weather data for other regions. For example, OTC weather derivatives have included transactions in Africa (Lacey 2006).

The Chicago Mercantile Exchange develops exchange-traded instruments based on demand and the availability of weather data for specific locations. The geographic focus of the weather derivatives market on the United States, Europe and Asia is partly influenced by the availability of reliable weather data. Weather derivatives underwriters look for a long history of continuous weather data collection in the same locations using well-maintained equipment operated by a trained staff. A historical record of data is highly desirable because it assists underwriters in identifying where data is missing, changes in collection methods or locations, and erroneous data points. Using the historical record, underwriters may create a complete data set by interpolating data temporally or spatially (Boissonnade et al. 2002; Henderson et al. 2002).

Figure 5.6: Number of OTC Weather Contracts by Region, 2000/1-2005/6



Source: Pricewaterhouse Coopers (2006).

5.6.3 Contract Duration

An analysis of exchange-traded and OTC weather derivatives reveal that these contracts are short-term in nature.

The Chicago Mercantile Exchange (CME) introduced exchange-traded weather futures and options on futures in 1999. The table below shows the various standardized exchange-traded weather derivatives offered by CME.

Table 5.14: Chicago Mercantile Exchange Standard Weather Futures

Weather Type	Number of Cities	Periods	Longest Duration Available	Year of Introduction
HDD CDD	US: 18 Europe: 9 Asia: 2	Seasonal Monthly	1 Year	1999
Frost	Amsterdam only	Seasonal Monthly	1 Year	2005
Snow	New York Boston	Monthly	1 Year	2006

Source: Chicago Mercantile Exchange (2006).

The longest duration of each type of CME weather derivative contract is one year. The greatest liquidity for these contracts is in the first month or season of these contracts. Approximately 70% of volume in CME weather derivatives is options on futures. These are predominantly traded as 5-month seasonal contracts and 90-95% are traded for the immediate season. Of the futures contracts, over 80% of trades are for monthly contracts. Of the monthly futures contracts, 90-95% of trades are for the upcoming month, until the latter part of a month, at which point the volume of trades shift to the next month (Smith, D. 2006).

The survey of derivatives brokerage firms confirmed that short-term trends also dominate the OTC market. The six firms that traded in weather derivatives reported that the vast majority of OTC trades are for durations within one year. Table 5.15 below summarizes the results of the surveys.

Table 5.15: Weather Derivative Survey Results

Weather Risk	Longest Known Duration (years)	Trades 1 Year or Less	Trades 1-3 years	3+ Years	Geographic Coverage
HDD/CDD	3-10	80-95%	5-20%	0-1%	US, Europe, Asia
Frost	3-5				
Wind	3-5				
Precipitation	3-5				
Snow	3-5				
River Flow	3				

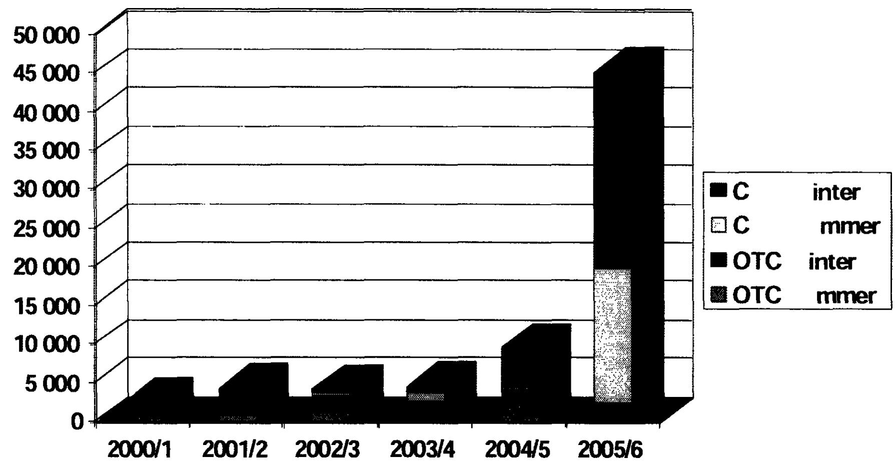
Source: Author's survey.

Five of the six weather derivatives firms surveyed indicated that 80-95% of trades are for contracts with durations of one year or less. The one exception is a firm that specializes in long-term contracts that reported 50% of its trades involve contracts of one to three years in duration. Another firm commented that the most liquidity is within the first season up to a year; beyond eighteen months the OTC market is generally illiquid.

5.6.4 Availability

Weather derivatives are traded over exchanges and the OTC market. The use of weather derivatives has increased steadily. According to an annual survey conducted by Pricewaterhouse Coopers, the notional value of weather derivatives contracts in the 2005/6 survey exceeded $45 billion. This is a growth rate of 500% since the previous record-breaking year (Pricewaterhouse Coopers 2006; O'Hearne 2006).

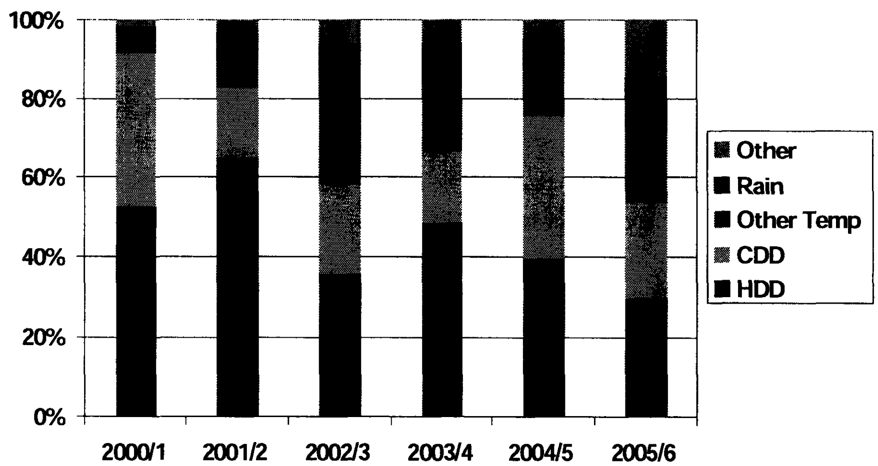
Figure 5.7: Notional Value Weather Risk Contracts (US$ millions), 2000/1-2005/6



Source: Pricewaterhouse Coopers (2006).

The majority of weather derivatives are temperature contracts, primarily "heating degree day" (HDD) for winter months, and "cooling degree day" (CDD) for summer months. The focus on temperature contracts is partly due to difficulties in accurately measuring other types of weather events such as wind, rain and snow, which tend to vary greatly by location (Ruck 2002; Smith, S. 2002). For example, the Chicago Mercantile Exchange does not offer an exchange-traded precipitation agreement because there is less demand for these contracts, which is partly due to difficulties in measuring precipitation (Smith S. 2006).

Figure 5.8: OTC Weather Risk Contracts by Type, 2000/1-2005/6



Source: Pricewaterhouse Coopers (2006).

The survey revealed that the OTC market for non-temperature contracts are thinly traded and the number of non-temperature trades varies greatly depending upon the specialization of the particular trader or brokerage firm.

Weather derivatives have several advantages and disadvantages compared to insurance that also bear on their availability. While insurance is more familiar and offers the ability to tailor contracts to the specific insured's assets, insurance requires proof of damage or loss to an insurable interest. In contrast, weather derivatives do not require any loss event or even ownership of an insured asset, which makes them available to anyone and easier to settle. Because weather derivatives contracts are highly standardized and their payout does not depend on the characteristics of the purchaser, they do not pose problems of asymmetric information or moral hazard that are associated with insurance and can be easily transferred or assigned with greater ease than insurance contracts. In addition to these considerations, tax and accounting rules may favor one form of risk management over the other (Roberts 2002).

5.6.5 Price

This section illustrates the pricing of weather derivatives using Risk Management Solutions' Climetrix weather derivatives model. The model is used to show how data selection and adjustment, weather volatility, and contract duration affect the price of weather derivatives contracts. The pricing experiment provides insight regarding the short-term nature of weather derivatives markets and how climate change could affect these markets.

Weather derivatives are priced based on three factors: actuarial weather probabilities, a subjective opinion of anticipated weather in the relevant period, and supply and demand for weather derivatives and other weather risk management contracts (Dischel 2002). However, the relatively thin market for weather derivatives has resulted in trades being priced based primarily on actuarial pricing methods, as opposed to supply and demand (Henderson 2002). Accordingly, this section focuses on actuarial methods for pricing derivatives.

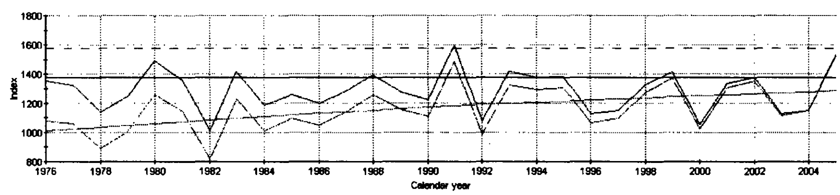
Weather derivatives are priced using models that incorporate aspects of actuarial models used to price insurance. Similar to commodities derivatives, the cost structure of weather derivatives reinforces the short-term nature of this market.

Pricing a weather derivative using the Climetrix model involves four distinct steps. The first step is selecting the number of years of weather data to be used in pricing the data. The selection of the number of years affects the pricing of the derivative (Jewson 2004). Interviews revealed that firms typically price derivatives using ten or thirty-year data sets as these periods reflect a notable increase in warming (Siner 2006). Years that are deemed anomalous may be omitted from the model data.

The second step is to adjust ("detrend") the data to correct for the gradual increase in temperature that has been observed during the last half century. Detrending may be required both as a result of global warming and local heat island effects for urban areas that have developed over the data period. Detrending changes the average temperature for the selected data set, by adjusting the observed temperature over the entire period upward as if the recently observed increase in temperature had prevailed during the entire data period. By changing the mean of the data, the choice of detrending methodology has a significant effect on the price of the derivative, more significant than the choice of the probability distribution.

For example, if fifty years of data are selected, detrending would adjust the average temperature upward for the entire data set based on the increase in average temperature observed during the last five years of the set. Although the average moves up, the observed weather pattern during the selected period remains the same. The Climetrix model provides various standard statistical methods to "detrend" the data. The loess (linear) method estimates trends over the period by placing the most weight on the data points that are closest in time to the point being estimated (Brix et al. 2002). Thus, it has the desirable characteristic of weighting the most recent years most heavily. It is a method frequently used in the industry and was selected in the examples below (Hamlin 2006; Siner 2006).

Figure 5.9: Example of Detrended Data versus Original Data



Source: RMS Climetrix model provided by Hamlin (2006). Note: The bottom line is original data; the top line is detrended data.

A complement to detrending data is to combine historical weather data with forecasts using the same information obtained through the detrending exercise. This can be done by modeling future periods by extrapolating recent observed trends into the future and then combining the historical data with extrapolated data based on weightings that reflect the degree of skill and confidence in the extrapolated data (Shorter et al. 2002). Back-testing shows that extrapolating trends over the past twenty years have rendered superior results to pricing based only on historical data (Jewson et al. 2002). These extrapolations work best over longer periods, such as five to ten years, as opposed to shorter time frames (Hamlin 2006).

The third step involves simulating data to fit a standard probability distribution function selected from a range of options. One option includes fitting simulated data to a non-parametric "kernel" distribution (Hamlin 2006). If a blended historical and forecast method is used, an overall probability distribution function is achieved by combining both historical and forecast components that are blended based on the weightings assigned to them by the modeler (Shorter et al. 2002). The selection of the probability distribution function plays a central role in the pricing of the derivative because the selection affects the standard deviation of the data (Hamlin 2006). In turn, a larger standard deviation increases the volatility of the underlying variable.

In the final step, the type of contract is specified. Based on the above input, the model produces an ensemble of model runs, which provides a representation of the range of market values for the underlying derivative.

The decision to detrend the data changes the mean of the data set. The selection of the probability distribution function affects the standard deviation of the data. These are analogous to changing the asset/strike price and the volatility in the Black-Scholes options pricing model described in the commodities derivatives section. Similar to the variables in the Black-Scholes model, changing these variables affects the price of the weather derivative.

To illustrate how these variables affect the price of weather protection, Table 5.16 below shows the pricing for a call option on a cooling degree-days contract for the city of New York (La Guardia) for the period May 1, 2006 to September 30, 2006 with strike of 1,380 cooling degree days, which pays out $5,000 per degree above 1,380, with a $1 million payout limit. Ten, thirty and fifty years of data were used without any omission of years.

Table 5.16: Call on CDD, New York City/La Guardia, May 1 to September 30, 2006

Model	Index			Profit	
	Mean	Standard Deviation	Daily Volume	Mean Price	Standard Deviation
Unadjusted 10 Year Historical (Burn)	1,228.550	163.073	13.184	73,500	232,427
Unadjusted 30 Year Historical (Burn)	1,165.883	164.632	13.310	42,167	162,712
Unadjusted 50 Year Historical (Burn)	1,120.930	170.660	13.797	25,300	126,904
Index 10 Year Loess (lin), Detrend, Kernel, No Forecast	1,343.433	174.739	14.127	267,752	360,247
Index 10 Year Loess (lin), Detrend, Normal, No Forecast	1,343.294	166.296	13.444	220,393	339,670
Index 30 Year Loess (lin), Detrend, Kernel, No Forecast	1,288.684	157.701	12.749	130,700	262,356
Index 30 Year Loess (lin), Detrend, Normal, No Forecast	1,288.588	145.884	11.794	112,476	243,788
Index 50 Year Loess (lin), Detrend, Kernel, No Forecast	1,293.339	164.191	13.274	151,587	290,753
Index 50 Year Loess (lin), Detrend, Normal, No Forecast	1,293.269	150.910	12.200	125,197	258,603
Index 50 Year, No detrend, Kernel, No Forecast	1,122.028	184.453	14.912	35,928	146,236
Index 50 Year, No detrend, Normal, No Forecast	1,121.937	169.595	13.711	22,418	111,104
Index 30 Year, Loess(lin), Detrend, Kernel, Trend Forward 2 Years	1,303.107	157.701	12.749	150,873	279,770

Source: RMS Climetrix model.

Comparing the model results shows that selecting a data set containing fewer years renders a higher number of CDDs due to recent warming and urbanization trends. Based on ten years of unadjusted (not detrended) historical data, the mean number of CDD was 1,228.55. Based on fifty years of unadjusted (not detrended) historical data, the mean number of CDD is 1,120.93. The historic data suggest approximately 2-degree day warming per year. Based on the ten-year data, the option would price at $73,500, compared to only $25,300 based on the fifty-year data.

As noted above, the detrending adjusts the entire data set as if the recently observed increase in temperature had been observed over the entire data set. As a result of detrending the data, the average temperature increases, thereby increasing the likelihood that the mean cooling degree-days will be higher and more demand for cooling will exist. In turn, this causes an increase in the price of the derivative because the increase in the mean expected number of cooling degree-days increases the expected payout to the purchaser of the instrument, as compared to an analysis done without detrending the data.

Comparing historical unadjusted data to detrended data of the same periods shows the effects of detrending. Ten-year detrended data using loess(lin) renders 1,343.433 CDDs, and fifty-year detrended data renders 1,293.269 CDDs, in each case using a non-parametric (kernel) probability distribution. The fifty-year distribution reflects the strong effects of detrending over a longer period. Here, the number of CDD increased by 173 CDD from the fifty-year unadjusted data to the fifty-year detrended data. Detrending increases the price to $151,587 based on fifty years of detrended data (kernel distribution), compared to $35,928 based on fifty years of undetrended simulated historical data (kernel distribution), or compared to $25,300 based on fifty years of undetrended actual historical data.

Selection of the probability distribution function also has a significant effect on the pricing of weather derivatives because the distribution function affects the observed volatility of the weather data. For example, compare the thirty-year detrended non-parametric (kernel) distribution with a standard deviation of 157.701 and the thirty-year detrended normal distribution with a standard deviation of 146.884, a difference of approximately 12 CDD in standard deviation. The only difference between the two runs is the choice of probability distribution function: a non-parametric kernel distribution fitted to the data versus the normal distribution. As a result of the increase in standard deviation, volatility increases, which causes the price of the call under the kernel distribution with the larger standard deviation to be $130,700 versus $112,476 under the normal distribution, a difference in price of over $18,000.

All of the prior examples are weather derivatives for the immediate future. Pricing longer-term risk increases the price of the derivative. In order to price a long-term call option, the model extrapolates the prior observed increases in temperature forward for the life of the option. This increases the option price because the expected average number of CDD would change based on the projected increase in warming. Also, increasing the duration of the option would increase the cost.

Pricing the same call option for the same period two years in the future demonstrates the increased cost of attempting to use options for periods beyond the immediate future. Based on thirty years of detrended data, an option two years in the future would cost \$157,873 compared to \$130,700 for the same option for the present year. The increase in cost is due both to the increase in mean CDD and the increase in volatility (standard deviation).

The above analysis demonstrates the potential effects of climate change for a call, put, or an instrument based on a call or a put. The same effect can be demonstrated for a swap contract. Swaps are the most common form of weather derivative. In a typical swap contract, no money is exchanged at the time of entering into the contract, but rather two parties exchange promises and then the contract is settled at the time of expiration (Hull 2003).

Swaps are structured using the mean and standard deviation of the underlying index or asset that is the subject of the swap. For example, consider a temperature swap in which the parties agree to compensate each other based on an index of weather temperatures for a particular location. The historical ten-year mean temperature in the location is 39.3°F and the bid-ask spread is 0.4°F with a \$10,000 payoff per degree away from the relevant strike price. The long strike will be 39.3+0.2 = 39.5°F and the short strike will be 39.3-0.2 = 39.1°F (Shorter et al. 2002). If the average temperature for the contract period was observed at 40°F, then the holder of the long position would be paid by the holder of the short position an amount equal to (40-39.5) * \$10,000 = \$5,000.

If the parties were aware that temperatures are increasing, the mean of the contract must be increased (e.g., through extrapolation of trends) so that the expected value of the swap at the time it is entered into is zero and the contract is priced fairly. Thus, as climate change is factored in, swaps will migrate upward in range along with average temperatures. As greater volatility is observed in historical temperatures, traders may also adjust the bid-ask spreads to reflect the changing variability of temperature. Without these adjustments, the contract would favor the holder of the long position, who would be more likely to receive the payoff from the contract. With these adjustments, the contract is priced fairly if the expected value of the contract is estimated accurately. However, on the whole, a fairly priced swap still offers less protection to firms that lose revenues under climate change conditions because swaps become unavailable (without paying a premium) at lower temperature ranges as average temperature increases.

The results described here are consistent with the calculations performed by Stern (1992, 2005) who demonstrated the effect of increases in temperature on the price of weather derivatives. Stern priced a hypothetical set of one hundred year call options on a global mean temperature futures contract using the Black-Scholes pricing model in order to demonstrate the cost of climate change to the private sector. The price of the derivative represents the cost of insurance to protect a firm against losses in revenue resulting from diminishing economy-wide industrial output due to increases in temperature. Temperature and volatility were based upon recent United Kingdom Metrological Office data. The 1992 run used temperature and volatility data based on then observed temperatures, and the 2003 run used updated temperature observations, which reflected an increase in global mean temperature of approximately 0.15°C and a similar level of temperature volatility compared to the 1992 temperature and volatility data. All other variables remained the same in both model runs. Comparison of the two runs shows that the price of the hedge increased from $12 for every $100 of future revenue to $14.79 for every $100 of future revenue. Stern runs the same calculations over the period circa 1860 to 2003 to show that the cost of protection gradually and then rapidly increased as temperatures increase over the period. From 1860 to 1960, the option increases in price from approximately $1 to $2 per $100 of future revenue. From 1960 to 2003, the price increases from $2 to almost $15 per $100 of future revenue. Since all other variables were the same in all model runs, the increase in the cost of the insurance provided by the option reflects the increase in global mean temperature.

The survey indicates that when faced with uncertainty or inadequate data, weather derivatives underwriters will further increase the price of derivatives contracts, sometimes by a large margin. In some cases, traders indicated that these price increases ruin the economics of hedging (Ricker 2006). Thin trading markets also mean that there may be inadequate competition to exert downward pressure on prices (Henderson 2002). Thus, high risk premiums may lead to wide bid-ask spreads rendering it uneconomical to hedge in light of the probable payoff versus the probable revenue decline (Dischel 2002; Brix et al. 2002).

While excessive risk loading may result in pricing beyond the ability of end-users to afford, it is important to balance the cost of the instrument against the certainty it provides that a minimum level of capital will be available in future periods (Dischel 2002). The additional cost of climate insurance will likely be passed on to consumers by firms that are able to do so (Forrest 2002). Firms that cannot pass on costs could experience reduced profit margins or forgo insurance. The cost of climate risk, or alternatively the cost of insurance against climate risk, will become increasingly expensive to society (Stern 1992, 2005).

Test runs of the Climetrix model confirm that increases in volatility, average temperature, and contract duration result in increasing cost of hedging using weather derivatives. This is consistent with Stern (1992, 2005) who shows that increasing temperature increases the cost of a hypothetical derivative designed to address the economic effects of global warming.

5.6.6 Market Capacity

As noted above, the 2005/6 Pricewaterhouse Coopers survey results indicate that the notional value of weather derivatives contracts exceeded $45.2 billion, a growth rate of approximately 500% since the previous 2004/5 survey (Pricewaterhouse Coopers 2006). To place the weather risk market in perspective, the notional value of annual weather derivatives trades is compared with the estimated portion of annual GDP that is subject to weather risk.

According to the U.S. Department of Commerce, approximately 70% of U.S. companies are subject to weather risk and $1 to $2 trillion of the approximately $9 trillion U.S. GDP is weather sensitive (US NAS 1998; Chicago Mercantile Exchange 1999; Nicholls 2004).

At $45 billion notional value, the weather derivatives market protects up to 0.5% of U.S. GDP, or put another way, up to 2.25% of U.S. GDP that is weather sensitive. However, the actual level of protection provided by these instruments may be different than indicated by the notional amount. There is not enough data to determine the precise level of protection as a percentage of economic activity.

Comparing the weather derivatives market to the broader derivatives market also provides a useful perspective. The Bank for International Settlements reports that all types of OTC derivatives contracts excluding credit derivatives held by banks exceeded $285 trillion in notional amounts at the end of 2005 (Bank for International Settlements 2006a). This figure is only a portion of derivatives as it excludes exchange-traded derivatives and credit derivatives. Yet, it shows that the present weather derivatives market is merely 0.016% of this segment of the derivatives market.

The small size of the weather derivatives market compared to non-weather derivatives markets and its rapid growth over the past five years suggest that the weather derivatives market has tremendous growth potential. A larger market should increase competition and may lead to the development of new derivatives instruments. However, as demonstrated by other markets, larger volume does not necessarily produce long-term hedging arrangements capable of addressing climate change risk.

5.6.7 Prospects for Addressing Climate Change

Because weather derivatives are intended to manage weather risk, these instruments could potentially play an important role in addressing risks associated with a changing climate for agriculture and industry (Hess et al. 2002).

The dramatic increase in trading in weather derivatives makes these products a substantial new market for mitigating risks. The notional value of these contracts have increased to provide short-term protection to approximately 0.5% of U.S. GDP or 2.25% of U.S. GDP that is climate sensitive. In evaluating the capacity of the weather derivatives market to absorb weather risk, it appears that these markets have great growth potential.

Balanced against the growth of the weather derivatives market, one must also consider that climate risk is also increasing and poses great challenges for weather risk management firms to estimate and underwrite contracts to provide protection against climate change risk.

While climate change may increase the demand for weather derivative products, there are several factors that may limit the ability of these products to address the long-term risks posed by climate change. These factors are the short-term nature of the market, price considerations, credit exposure, difficulties in modeling long-term climate trends, and difficulty determining whether a specific weather event is related to climate change. There is evidence that contracts will become more expensive for buyers and might shorten in duration due to price or credit exposure considerations or difficulties in modeling longer durations.

As demonstrated by exchange data and the survey responses, the market for weather derivatives is predominantly short-term, under one year in most cases. The short-term nature of the market limits the usefulness of weather derivatives contracts for climate change. As contracts expire, new climate conditions will be priced into replacement contracts due to their short-term nature. Further, if climate is expected to change in a non-linear manner (as has been observed in recent temperature patterns), there is no evidence to suggest that the duration of contracts would increase beyond those currently available in the market.

The price of hedging risk using weather derivatives is a critical limiting factor in their practical application for addressing climate change. Climate change is expected to continue to cause increases in global mean temperature and may increase the variability of weather patterns. As demonstrated using the RMS Climetrix weather derivatives pricing model, increasing the mean and volatility of temperature increases the cost of weather derivatives. In the short term, the arrangement is simply a transfer of wealth between buyer and seller of the contract or results in less protection being provided due to the inability of a buyer to afford the cost of insurance. Stern (1992, 2005) demonstrates how the cost of hedging is increasing at an increasing rate over time as a result of increases in global mean temperature. In the long term, the cost to society increases substantially.

The inability to model future climate conditions beyond several years into the future will likely limit the duration of weather derivatives contracts. Present weather models are generally used to forecast one year ahead, and sometimes two to three years in the future at the most. Similarly, when data is unavailable or there is little confidence in the ability to forecast future conditions based on available data, the cost of derivatives likewise becomes prohibitively expensive, potentially ruining the economics of putting a hedge in place (Ricker 2006).

The shortcomings of models can be addressed through contract terms that limit the scope of a derivative's coverage. Contracts can use moving averages and caps on payouts. However, all of these measures to address model risk ultimately shifts risk back to the purchaser of the derivative and reduces the scope of risk covered.

Alternatively, when an event becomes a near certainty to occur, the price of insuring against the event through a third party becomes prohibitively expensive and firms are forced to self-insure or go out of business. Several survey respondents acknowledged that a derivative cannot protect a company whose business is fundamentally unviable due to climate (Lichtenstein 2006; Ricker 2006). This is entirely consistent with the view that the purpose of weather derivatives is to protect revenue streams from volatility for the duration of the contract, not to offer insurance against long-term trends in the weather.

Several examples illustrate this point and demonstrate that weather derivatives are intended to protect against volatility, not against a general climate trends. A ski resort that has purchased HDD contracts to offset losses in revenues due to warm weather will eventually be unable to afford the insurance policy offered by a derivative if there is inadequate snow to operate the business. Similarly, consider a hydropower plant that enters into a river flow contract to compensate for decreases in river flow that adversely affect business operations. If climate change severely threatened water resources in the area, such a contract would eventually serve little purpose if the river flow is reduced to a level that consistently impairs the cash flows of the hydropower plant.

Long before these climate events occur, however, it is likely that no counterparty would enter into, and no broker would exchange-clear, a long-term contract with a party whose business is severely threatened by climate change. The reasons are that the cost of the derivative would become prohibitively expensive for these companies as weather changes. A company without a viable line of business would present too great a credit risk to a counterparty or brokerage house. Eventually the hypothetical ski resort and the power plant would be unable to afford insurance or stay in business.

Another important reason why weather derivatives may be unable to address long-term climate risk is that no firm is well positioned to accept such risks. Even if a firm is willing to accept these risks, the creditworthiness of the seller would become an important consideration. Even if such a long-term contract were entered into, the volume of such contracts would likely be small. Significantly, the survey revealed that the present market could not support a long-term contract intended to address climate change. In the few cases where respondents believed the market might develop a long-term contract, no survey respondent could identify a potential private party that would be sufficiently creditworthy to supply a long-term contract against climate change risk.

In summary, evidence suggests that the ability of weather derivatives to address long-term risks associated with climate change is limited due to the short-term nature of these markets, increasing costs, credit risk of counterparties, and inherent difficulties in forecasting future weather patterns. Balanced against this, these markets are in their infancy and it remains to be seen whether an innovative structure can be developed that provides protection against long-term climate change.

Table 5.17 below summarizes the findings of this section with respect to weather derivatives.

Table 5.17: Weather Derivatives Summary

Scope of Risk Coverage	Supply, market, operating cost. Protects against volatility not general climate trends.
Geographic Coverage	Mostly U.S., Europe, some Asia.
Contract Duration	1 Year; mostly upcoming season.
Availability	Temperature derivatives are most commonly available contract.
Price	Increases with weather volatility, contract duration, and global mean temperature.
Market Capacity	Increasing but still a small percentage of overall GDP at risk. Large growth potential.

5.7 Carbon Offsets

Carbon offsets are market-based instruments that provide financial incentives to support the adoption of technology to reduce carbon dioxide and other greenhouse gas emissions through the creation and trading of emissions allowances. Offsets programs have been developed for various other pollutants, including nitrogen oxides, sulphur oxides, volatile organic compounds, and hydrochlorofluorocarbons (Haites 2005; Wilder 2005; Ali and Yano 2004).

This section examines the carbon offsets programs developed under the Kyoto Protocol from the point of view of their ability to reduce regulatory risk. Specifically, it looks at the European Union's Emissions Trading Scheme (EU ETS) and the Clean Development Mechanism (CDM). It evaluates EU ETS and CDM based on the six criteria relating to the scope of risks covered, geographic coverage, contract duration, availability, price, and market capacity.

Brokers or traders at sixteen firms were surveyed in connection with this dissertation; seven firms described their business in the EU ETS and/or CDM markets. In addition to the survey of brokers and traders, interviews were conducted with six additional firms engaged in advising or verifying the results of CDM projects.

5.7.1 European Union Emissions Trading Scheme

The Kyoto Protocol created three flexible mechanisms for emissions reductions using carbon offsets: emissions trading, CDM, and Joint Implementation (JI) projects.

The European Union Emissions Trading Scheme (EU ETS) is a system for trading assigned amount units (AAUs) and other permitted emissions reductions credits. These other reductions credits are certified emissions reductions certificates (CERs) issued pursuant to CDM projects, emissions reductions units (ERUs) issued pursuant to JI projects, and removal units (RMUs) issued to countries participating in the development of domestic sinks. Currently, only participating European Union countries may conduct trades through the EU ETS. Starting in 2008, the EU ETS is expected to be available to all Kyoto Protocol countries (European Union 2003).

The EU's emissions trading scheme supports both a spot market and futures market for European Union Allowances (EUAs), which are the European Union equivalent of AAUs. AAUs, CERs, ERUs and RMUs entitle the holder to emit one tonne of carbon dioxide equivalent and are fungible with each other for meeting emissions reductions limits, subject to restrictions on banking emissions.

Developed countries that ratified the Kyoto Protocol accepted binding commitments to reduce their emissions of greenhouse gases during the 2008 through 2012 period to meet an aggregate reduction of 5% below 1990 emissions. Developed countries subject to emissions limits are obligated to set a maximum amount of emissions per compliance period, and then allocate allowances to regulated emitters within their territory for each compliance period. At the end of a compliance period, each emitter must surrender allowances equal to their allowances. If total emissions during a period exceed their AAUs, the emitter must purchase additional allowances (AAUs, CERs, ERUs or RMUs) and may be subject to a penalty. If total emissions are lower, the emitter may sell excess AAUs.

5.7.1.1 Scope of Risk Coverage

Market-based instruments such as cap-and-trade are intended to provide firms with greater flexibility in, and reduce the cost of, meeting regulatory obligations to reduce emissions of pollutants. From a policy point of view, these programs are intended to achieve the desired level of emissions reductions at reduced cost to society because reductions can be achieved by firms that have the lowest marginal cost of abatement. For emitters that have a low marginal cost of reducing emissions, they provide an economic incentive to reduce emissions below the mandatory level than would otherwise occur under a traditional command-and-control regulatory regime and to resell these credits to other emitters. From the point of view of an emitter purchasing emissions allowances, they provide a method to mitigate regulatory risk. Thus, EUAs traded under the EU ETS only address regulatory risk under the Kyoto Protocol.

5.7.1.2 Geographic Coverage

The European Union developed the EU ETS to implement its obligations under the Kyoto Protocol. The trading system operates on a trial phase from January 1, 2005 to December 31, 2007 among European Union member states. From 2008, the EU ETS is expected to be available to all Kyoto Protocol countries (European Union 2003). However the arrangements for the inclusion of other Kyoto Protocol countries have not been settled at the time of writing (Mosher 2006; Reilly and Paltsev 2006).

5.7.1.3 Contract Duration

An analysis of the European Climate Exchange's Carbon Financial Instruments (ECX CFI) futures contracts reveals that liquidity in this market is mostly short-term. As of April 2006, 100 metric tonnes of carbon contracts were available for quarterly delivery through March 2008, and then annual delivery from 2008 through 2012 (European Climate Exchange 2006).

Open interest in ECX CFI futures contracts is most liquid in the first year. At the time of analysis, 79% of open interest in exchange-traded EUAs was for delivery by December 2007, the time period during which regulatory certainty is greatest. Survey responses confirm the OTC EUA market follows the same short-term pattern as the exchange-traded futures markets.

Table 5.18: Open Interest in European Climate Exchange CFI Contracts, April 2006

Period	Open Interest Percentage
June, September, December 2006	46%
March, June, September, December 2007	32%
March, June, September, December 2008	17%
December 2009	3%
December 2010	1%
December 2011	1%
December 2012	1%

Source: European Climate Exchange, April 13, 2006.

These statistics reflect the short-term nature common to most trading markets as well as the fact that supply and demand in EUA markets is strongly influenced by regulatory considerations.

The significant volume of trades for the 2008 to 2012 period may be influenced by European Union rules that impose a penalty of €100 per tonne for failure to meet obligations in the first commitment period from January 1, 2008 through December 31, 2012 (European Union 2003; Parsons 2006).

5.7.1.4 Availability

From 2008, the European Union trading scheme is expected to be available to all Kyoto Protocol countries. Currently, only carbon dioxide emissions from large point sources in energy generation and energy-intensive industries, such as oil refineries, cement, iron and steel production, are subject to emissions limits and participate in the EU ETS (European Union 2003). Other countries are presently developing trading systems for greenhouse gases pursuant to the Kyoto Protocol but these systems are not in operation at the time of writing (Haites 2005; Wilder 2005; Ali and Yano 2004). The arrangements for the inclusion of other Kyoto Parties, additional greenhouse gases, broader industrial sectors, and for linking among national trading systems have not been settled at the time of writing (Mosher 2006; Reilly and Paltsev 2006).

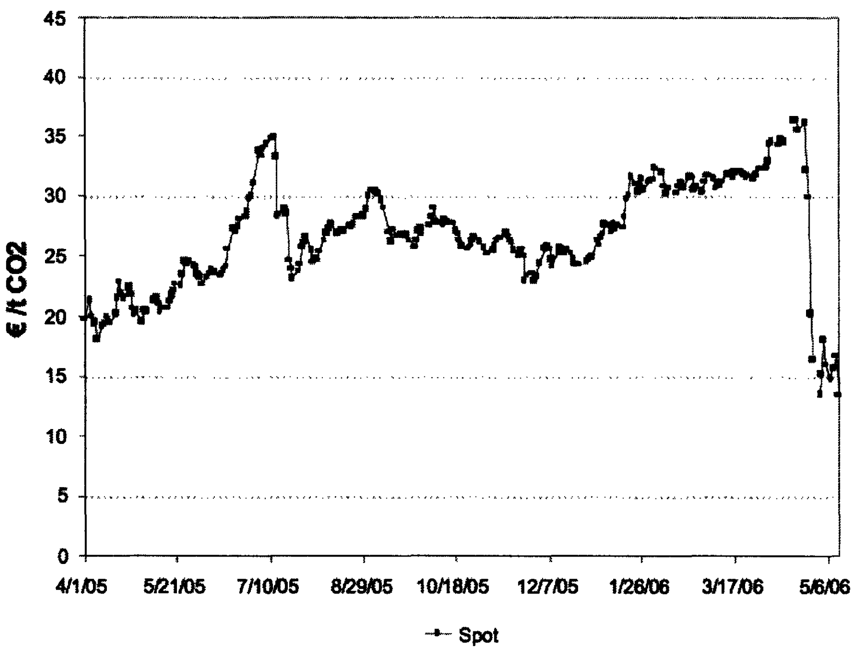
Trading EUAs is primarily conducted through brokered transactions over the OTC market. In 2005, OTC trades accounted for an estimated 80% of combined OTC and exchange trades (Point Carbon 2006b).

Several organized exchanges also trade EUAs. The European Climate Exchange is the largest exchange, representing 63% of exchange-traded emissions contracts. This exchange trades standardized futures contracts for delivery of EUA (Point Carbon 2006b).

5.7.1.5 Price

Prices for EUAs fluctuate based on supply and demand. The announcement of the first verification of European Union national emissions levels in May 2006 caused the EU ETS market price of carbon to drop by over 67% because verified emissions were 41 million metric tonnes of carbon dioxide, or approximately 2 ½% lower than expected (European Commission 2006; Timmons 2006).

Figure 5.10: European Union Emissions Allowance Prices, April-May 2006



Source: Point Carbon (2006a).

This first emissions report represents a transition from the top-down system of emissions estimation to verified plant-level data. Subsequent plant-level assessments should presumably report carbon emissions levels that are more consistent with expectations in future assessments.

However, in the near future, the structure of this market will continue to evolve, which will subject prices to uncertainty. Eventually, trading will include other greenhouse gases regulated by the Kyoto Protocol. Their introduction will involve uncertainty as allocations and emissions reporting will be tested in a live trading market. The change from top-down to bottom-up emissions assessments and technical difficulties in assessment could potentially disrupt markets if assessments are out of line with expectations.

In addition, in 2008 the European Union plans to open its trading system to other Kyoto Protocol countries' emissions. Consistency and integrity among countries in reporting emissions could pose potential issues for these markets. Institutional arrangements for ensuring the quality of emissions monitoring and reporting are still under development and remain untested (IETA 2005; Kruger and Pizer 2004; Mullins 2005).

To the extent excess emissions allowances held by Eastern European countries enter the market, these excess allowances will affect prices and the operation of the EUA market, the Clean Development Mechanism and Joint Implementation programs. The Kyoto Protocol did not place explicit limits on the entry of excess allowances, however, parties are required to limit their use of tradable allowances to levels that are "supplemental" to "significant" domestic measures to reduce greenhouse gas emissions (Marrakech Accords 2001).

The European Union has been particularly active in seeking to promote domestic reductions through the supplementarity provision. However, there are differences of opinion among European officials whether a quantitative limit on trading allowances (Woerdman 2002, 2004). Economic analysis suggests that restrictions on trading reduce efficiency because it prevents reductions from taking place at the lowest marginal cost among a broader set of trading countries (Eyckmans and Cornillie 2002; Zhang 2000). Restricting the trading of permits could also reduce the demand for tradable allowances, which could significantly reduce the price of carbon, thereby creating disincentives for firms to implement cleaner technology (Ellerman and Wing 2000).

While it is not clear how the supplementarity restriction will be implemented by Kyoto Parties, it will influence how Eastern European excess allowances compete with EUAs and other forms of AAUs, CERs, ERUs and RMUs. The EIA projects that approximately two-fifths of the required Kyoto Protocol emissions reductions could be met by Eastern European excess allowances (Lashof and Fiedler 2006). Others have estimated that the Russian Federation alone could supply as much as 70% of emissions allowances (Gusbin et al. 1999; Ciorba et al. 2001).

If Eastern European countries that were not part of the Soviet Union are permitted to trade their excess allowances, an estimated 172 million metric tonnes of carbon dioxide equivalent per year would enter the market (Blanchard 2005). Eastern European countries that are now part of the European Union have already been subject to restrictions on their ability to trade excess allowances (European Commission 2006).

Most excess emissions allowances are held by Russia and Ukraine. Russian and Ukrainian excess emissions are expected to exceed 791.5 million metric tonnes of carbon dioxide per year by 2010 from fossil fuel emissions alone. Table 5.19 below sets forth EIA's estimate of projected Russian and Ukrainian carbon dioxide emissions from fossil fuel consumption, and the resulting estimated excess carbon dioxide allowances.

Table 5.19: Russia and Ukraine Projected CO_2 Allowances (metric tonnes)

Year	Russia Emissions	Ukraine Emissions	Total Emissions	Projected Excess Allowances
1990	2,347,000,000	674,400,002	3,021,400,002	
2002	1,522,000,000	426,024,926	1,948,024,926	1,073,375,075
2010	1,732,000,000	497,898,263	2,229,898,263	791,501,738
2015	1,857,000,000	539,804,109	2,396,804,109	624,595,893
2020	1,971,000,000	568,392,418	2,539,392,418	482,007,583
2025	2,063,000,000	599,999,369	2,662,999,369	358,400,632

Source: Adapted from EIA (2005b). Note: Ukraine is 17.76% of former Soviet Union projections. These projections only take account of excess allowances from carbon dioxide emissions from fossil fuel consumption. Other greenhouse gas sources may increase the allowances.

These projections are only for carbon dioxide emissions from energy production and consumption. Other greenhouse gases are expected to produce additional allowances for Eastern European countries in excess of 100 million metric tonnes of carbon dioxide equivalent per year. Again, a majority of these excess allowances will belong to Russia and Ukraine (Rolfe 2000).

If Russian and Ukrainian excess allowances enter the market in 2008, they would exert significant downward pressure on EUA prices. To place this in perspective, if the 791.5 million tonnes of Russian and Ukrainian fossil-fuel excess carbon dioxide allowances enter the market, this additional supply would be approximately twenty times larger in volume than the May 2006 41 million tonne over-allocation of carbon dioxide that caused the price of EUAs to drop by over 67%.

The May 2006 EUA price collapse exposed a number of shortcomings of the current trading scheme that directly affects prices of EUAs. As of May 2006, national emissions reporting was conducted annually and there was no coordination among reporting countries. Further, there is little monitoring of individual country emissions reporting efforts. The drop in carbon prices has prompted some analysts to suggest that information disclosures should be more frequent, standardized and coordinated in order to improve the quality of information provided to the market (Parsons 2006). Finally, although EUAs are not presently regulated as either a security or a commodity, the large capital flows into EUA markets and the potential for manipulation of emissions data and markets suggest that regulation of these instruments may be demanded by investors.

5.7.1.6 Market Capacity

The potential market capacity of the EU ETS will be a determined by regulation. As described in the prior section on price, if the emissions allowances held by Eastern European countries, Russia and the Ukraine are permitted to enter the market, these allowances could represent a very large increase over the existing number of EAUs currently trading in the EU

ETS. This would adversely affect the ability of the EU ETS to accomplish its primary goal of reducing overall greenhouse gas emissions.

5.7.2 Clean Development Mechanism

The Clean Development Mechanism provides another means for emitters to meet greenhouse gas emissions targets under the Kyoto Protocol. Under the CDM, project sponsors earn tradable certified emissions reductions certificates (CERs) by developing projects in non-industrialized Kyoto Protocol countries that reduce greenhouse gas emissions.[15] CERs, like AAUs, ERUs and RMUs, entitle the holder to emit one tonne of carbon dioxide equivalent and are fungible with each other for meeting emissions reductions limits, subject to restrictions on banking emissions.

The CDM project cycle is a multi-step process. First, project parties prepare a project proposal, which sets out the design of the project in a document called the Project Design Document. The Project Design Document is then evaluated by a Designated Operational Entity (DOE), a private third party certified by the CDM Executive Board, that validates the project's design and estimates the project's expected contribution to emissions reductions. During this phase, the project parties procure an environmental impact assessment, obtain the approval of the host government, and circulate the Project Design Document for public comment. The Project Design Document is then submitted to the CDM Executive Board who reviews it for compliance with CDM requirements. Projects involving new methodologies will also be required to obtain approval of the specific methodology. If approved, the project is registered with the CDM. Registered projects then implement a monitoring plan approved by the CDM Executive Board. Under the plan, a DOE periodically verifies the actual emissions reductions of the project. Based on the DOE's written certification of the emissions reductions, the CDM Executive Board instructs the CDM Registry Administrator to issue the appropriate number of CERs to the project for each particular verification period (Yamin 2005).

This section analyzes CDM CERs based on the six criteria relating to the scope of risks covered, geographic coverage, contract duration, availability, price, and market capacity.

5.7.2.1 Scope of Risk Coverage

CDM CERs entitle the holder to emit one metric tonne of carbon dioxide equivalent for meeting emissions reductions limits under the Kyoto Protocol. CDM CERs can be traded to other emitters to their meet Kyoto Protocol emissions limits. Thus, CERs only address regulatory risk under the Kyoto Protocol.

---

[15] In contrast, JI allows industrialized country emitters to earn tradable emissions reductions units (ERUs) by participating in projects in other industrialized countries. At the time of writing, standards for JI programs were in the early development stage.

5.7.2.2 Geographic Coverage

The CDM allows project sponsors to earn CERs by developing projects in non-industrialized Kyoto Protocol countries that reduce greenhouse gas emissions. The CERs are used in industrialized Kyoto Protocol countries that are subject to an emissions limit. Thus, the scope of geographic coverage of CERs are those countries that have ratified the Kyoto Protocol and are subject to emissions limits.

5.7.2.3 Contract Duration

Interviews conducted by the author and industry reports (Point Carbon 2006b) confirm that CDM projects have generally sold CERs for delivery though 2012, reflecting the duration of the regulatory regime rather than the potential duration of CER contracts. Although there is little activity beyond 2012, some survey respondents and other commentators have confirmed that purchasers of CERs have entered into options agreements for CERs to be produced in the post-2012 period (Michaelowa 2005a).

The survey revealed that because CDM projects require a minimum of approximately eighteen to twenty-four months to register and verify the CERs, most activity in the CDM market is for future delivery of CERs starting approximately two years ahead of time.

5.7.2.4 Availability

The availability of CERs depends directly upon the performance of CDM projects and the price of other emissions allowances. This section discusses the availability of CERs and project performance. The next section discusses how price affects the availability of CERs.

At the time of writing, CERs have not been exchange-traded due to lack of supply and uncertainty concerning the legal arrangements required to support these instruments. CERs have been traded in limited amounts on the OTC market. Based on survey responses, acquirers obtain CDM CERs primarily through investing in or developing their own projects.

In order for CERs to be issued, the emissions reductions are first "validated", which is an estimate made at the design stage for purposes of approving the project methodology. The emissions reduction estimate forms expectations regarding the project, including the expectations of investors and those who are considering purchasing the CDM CERs produced by the project. After the project has begun operation, a DOE periodically verifies the project's actual emissions. The verification determines the actual number of CERs to be issued for each verification period.

As of August 9, 2006, thirty-five CDM projects had produced verified CERs. Comparing validation estimates against verified CERs provides useful information for evaluating the accuracy of validation estimates and project performance. Because sales of CERs have already commenced and verified CERs affect the cash flows and legal obligations of CDM projects, the ability to accurately predict a project's CERs is important to the success of the CDM.

Table 5.20 below compares validation estimates and verification results for the thirty-five CDM projects that had issued CERs as of August 9, 2006. The comparison suggests that validation procedures tend to overestimate the number of CERS that will ultimately be issued by a project. Significantly, these results reflect a broad range of CDM projects.

Table 5.20: CDM Validated versus Verified Emissions Reductions, August 2006

Country	Project Type	Validation $ktCO_2/yr$	Validation Date	Verified $ktCO_2/yr$	Verification Until	Error (%)
Brazil	Landfill gas	701.7	1/1/04	46.0	12/31/04	-93.45%
Brazil	Hydro	42.0	1/27/03	43.1	3/31/06	2.50%
Brazil	Biomass	9.0	4/23/01	7.9	10/30/05	-11.89%
Brazil	Biomass	34.7	7/1/02	18.0	12/31/05	-48.07%
Brazil	Biomass	17.2	5/7/03	15.1	11/30/05	-11.95%
Brazil	Biomass	10.2	5/5/02	10.4	11/30/05	1.94%
Brazil	Biomass	57.3	7/1/01	46.0	12/31/05	-19.74%
Brazil	Agriculture	5.1	7/1/04	0.8	10/31/06	-84.02%
Chile	Agriculture	78.7	1/1/01	71.3	12/31/04	-9.35%
Chile	Agriculture	84.0	5/1/02	81.2	4/30/05	-3.30%
Chile	Agriculture	247.4	1/1/03	194.8	4/30/05	-21.29%
China	Landfill gas	214.5	5/1/05	25.0	5/29/06	-88.34%
Guatemala	Hydro	36.9	6/29/02	31.7	12/31/05	-13.91%
Guatemala	Hydro	12.7	6/29/02	14.6	12/31/05	14.43%
Honduras	Hydro	17.8	8/1/04	17.5	12/31/04	-1.47%
Honduras	Hydro	37.0	6/1/03	1.1	5/31/05	-97.02%
India	Hydro	23.0	7/1/04	6.0	3/31/06	-73.84%
India	Hydro	27.0	11/20/04	12.8	3/31/06	-52.43%
India	Hydro	21.0	4/26/03	18.6	3/31/06	-11.46%
India	Hydro	19.1	4/1/02	17.8	3/31/06	-7.14%
India	HFC	3393.0	10/1/05	1674.0	4/30/06	-50.66%
India	HFC	3834.4	7/1/04	2519.6	4/30/06	-34.29%
India	Efficiency	24.4	8/1/03	25.4	12/31/05	3.93%
India	Efficiency	19.8	9/1/02	20.0	12/31/05	0.64%
India	Biomass	31.4	8/1/03	25.2	6/30/05	-19.73%
India	Biomass	22.0	9/15/03	24.9	3/19/04	13.10%
India	Biomass	17.4	6/1/04	11.6	12/31/05	-33.45%
India	Biomass	63.9	1/1/04	27.9	12/31/05	-56.43%
India	Biomass	14.7	12/1/01	14.4	12/31/05	-2.64%
India	Biomass	43.9	5/1/05	46.3	3/31/06	5.50%
India	Biogas	36.0	8/1/03	35.0	12/31/05	-2.71%
Mexico	Agriculture	121.7	6/1/05	10.3	12/31/05	-91.57%
Mexico	Agriculture	210.5	6/1/05	2.6	1/31/06	-98.78%
Mexico	Agriculture	127.9	9/1/05	6.9	1/31/06	-94.63%
South Korea	HFC	1400.0	1/1/03	893.7	3/31/06	-36.16%
TOTALS		**11,057.5**		**6,017.3**		**-45.58**

Source: Adapted from UNEP Risoe Centre (2006b).

The data shows that validation estimates overestimated the number of CERs produced by the first thirty-five projects by approximately 46% on average, with almost a quarter of these projects overestimating the number of CERs actually produced by 75% or more. The standard deviation of estimation error for the population of thirty-five projects is 36.87%.[16]

It should be noted that some of the early projects were validated after operation. In some cases, these projects did not invest in monitoring equipment until after the CDM Executive Board approved their registration. The first Chilean methane plant that produced a project error of approximately 10% was validated after the plant began operation under a special accommodation for early CDM projects that is no longer available. Although the validation occurred during operation, it was based on an estimate of emissions reductions and was subject to error (Esparta 2006). Omitting this plant from the data increases the -45.58% average error by less than a percent. Similarly, the first Honduran hydroelectric plant is a phased plant, and thus the validation and verification figures fail to take into account the time delay to complete subsequent phases (Colston 2006a). Omitting this project reduces the average error by less than a percent. Omitting both of these projects, the total error for the thirty-three remaining projects remains substantially unchanged at -45.67%.

The large error rate for estimating the issuance of CERs greatly increases the supply risks associated with sourcing CERs and increases the risk of investing in CDM projects generally. One major Canadian electric generator that has committed itself to meeting its requirements for allowances through CDM and JI projects expressed concern that the availability of CDM CERs will be inadequate to meet the company's needs. This company has adopted a 25-year plan to achieve zero net emissions by 2024 and has developed considerable experience assessing approximately a dozen CDM projects. Due to financial and other risks associated with CDM, the company has undertaken only one CDM project. Given Canada's role as an energy-exporter in such carbon intensive areas as tar sands, the company expects that CDM may not provide a realistic method for meeting its supply requirements for emissions allowances (Page, B. 2006).

The CDM validation/verification error has significant implications for CDM. As of August 9, 2006, there were 961 CDM projects that had estimated their emissions reductions through the validation process and will eventually verify their CERs. The other 961 projects may show error rates of similar magnitude to the first thirty-five projects that are analyzed here.

Interviews were conducted with firms involved in the CDM process in order to ascertain the reasons for the high error rate produced by validation/verification procedures. Interviews were conducted with three firms that are approved by the CDM Executive Board as DOEs. Collectively, these firms are involved in the validation or verification of 83% of the approximately 740 CDM projects that were registered as of May 1, 2006, when the interviews were conducted (UNEP RISOE 2006a). In addition, interviews were conducted

[16] The standard deviation was calculated based on the ratio of annual verified emissions reductions over annual estimated emissions reductions, using all thirty-five data points.

with four firms that invest in and/or act as project consultants to approximately 30% of all CDM projects then listed with the CDM Executive Board.

Surveys of these CDM participants revealed that a variety of factors potentially contribute to the validation/verification error for CDM projects. These firms identified the following factors as contributing to the high error rate:

Inadequate Technology or Measurement Methodology
Environmental Fluctuations
Supply and Demand Fluctuations
Delays in Project Completion or Operation
Use of Conservative Assumptions in Verification Procedures
Inadequate Guidance or Changes in Validation or Verification Procedures

The leading explanation of validation/verification error was inadequate technology or methodology to measure emissions reductions. For example, with respect to methane landfill projects, several respondents identified the primary cause of error to be lack of adequate technology to measure low concentrations of gases over large areas. Survey respondents noted that measurements are typically not conducted under ideal conditions (as assumed in the standard methodologies) and very little is known about the quality of waste in landfill sites, which affects decomposition rates and the selection of appropriate methods for analyzing data. Further, models and assumptions used for estimation are often not reliable or appropriate for local conditions (Betzenbichler 2006; Van Der Linden 2006; Eddy 2006).

With respect to environmental conditions, the performance of projects that depend upon wind, precipitation, river flow, or heat (as in the case of decomposition of waste) will be affected by fluctuation in weather conditions. These factors will significantly influence the outcome of verification results (Telners 2006; Van Der Linden 2006).

Supply and demand conditions will influence the verified results of projects whose performance is linked to market conditions. For example, electricity generation projects are verified based on the actual amount of electricity supplied to the grid. Similarly, HFC plants are typically swing production plants so their verification results are directly affected by demand for their products (Van Der Linden 2006).

Delay of project completion or operation can significantly affect the economic feasibility of a project and its verification results (Betzenbichler 2006). In particular, hydroelectric plants are highly sensitive to construction delays (Colston 2006a; Van Der Linden 2006).

Several firms identified the use of inappropriate assumptions in the validation stage and conservative assumptions in the verification stage as potential factors influencing validation/verification error. Several respondents noted that CDM methodologies often use generalized IPPC estimates that do not take local conditions into account. For example, the use of IPCC estimates for methane projects fails to take into account local agricultural conditions (Telners 2006). Several respondents noted that because the validation stage involves estimation, it is inherently subject to error, and one respondent noted that project sponsors are often optimistic in the validation stage (Esparta 2006). Others suggested that firms conducting the verification may use conservative assumptions in accordance with best practices recommended by ISO and other organizations, thereby further increasing the difference between validation estimates and verification results (Hardy 2006).

With respect to the adequacy of guidance and procedures, several respondents noted that the CDM Executive Board has not provided adequate guidance for validation and verification procedures. CDM methodologies have been frequently revised, which has contributed greatly to uncertainty. One respondent noted that some of these methodologies have been revised five or six times already since their inception and that CDM guidelines do not specify exactly what steps need to be taken to validate or verify emissions (Van Der Linden 2006). Another respondent indicated that CDM rules which prohibit direct contact between project sponsors and reviewing personnel has slowed approvals and prevented project sponsors from receiving timely or detailed guidance (Esparta 2006).

There were some differences in opinion whether seasonal patterns and the timing of the verification could influence validation/verification error. One firm that focuses on agriculture projects believes that the seasonal nature of agriculture and the timing of verification could contribute to validation/verification error (Eddy 2006). Another believed that the CDM methodologies adequately allow for adjustments for seasonal variation, and the use of continuous or frequent monitoring should correct for seasonality (Van Der Linden 2006).

Finally, CDM participants were asked their opinion as to whether they expected estimates would improve in the future. Respondents generally believed that results should improve, while at the same time acknowledged that estimation error is likely to continue due to the inherent nature of prediction. One respondent stated that we would continue to see estimation error especially for projects that are influenced heavily by outside factors, such as supply and demand, as in the case of HFC projects. In general, respondents believed that the variability is inherent in the design of the CDM validation and verification arrangement: validation estimates are made based on theoretical engineering estimates, whereas the verification is based on actual plant operations.

Some respondents suggested specific aspects of CDM that can be improved to reduce validation/verification error. One respondent suggested more detailed methodology regarding monitoring requirements should improve data collection and the consistency in assumptions used at the validation and verification stages (Betzenbichler 2006).[17] Several respondents emphasized that proven technologies should exhibit less variability between

[17] The World Resources Institute, the World Business Council for Sustainable Development, the International Organization of Standardization (see First Environment 2006), the American Petroleum Institute, and the California Climate Action Registry are developing guidance for estimation and measurement of emissions reductions. All of these standards are voluntary methods intended to help define best practices.

validation estimates and verification results (Telners 2006; Hardy 2006; TransAlta 2006).[18] Finally, one respondent indicated that training and assistance locating qualified people to carry out estimates for each methodology would help reduce error (Eddy 2006).

5.7.2.5 Price

Interviews with industry participants revealed that CDM CERs are priced based on the spot and futures prices of EUAs, the rules regarding their use, the risks of the particular project producing the CERs, expectations regarding supply and demand for CERs, and competition from other sources of carbon offsets.

The starting point for pricing a CER is the spot and futures prices of EUAs as this market is the most highly liquid and provides near-term price visibility. The recent drop in EUA prices in May 2005 placed downward pressure on CER prices and has slowed CDM activity considerably. As a result, many CDM projects are no longer financially competitive (Colston 2006a).

The rules regarding CERs also affect their price. Under the Kyoto Protocol, CDM CERs and JI ERUs may be used in future compliance periods up to a maximum of 2.5% of a party's assigned amount of emissions (Kyoto Protocol Decision 19, 1997). However, Article 12(10) of the Kyoto Protocol ensures that CERs and ERUs obtained prior to 2008 can be fully banked for use in the 2008-2012 compliance period. In contrast, AAUs are fully bankable without limitation starting during the 2008-2012 compliance period (Kyoto Protocol Decision 19, 1997). The European Union has allowed its member states to decide whether unused EUAs acquired during the 2005-2007 trial phase can be carried over and used to meet emissions limits in the first commitment period in 2008-2012 (European Commission 2003). Potential temporary restrictions on the ability to bank EUAs for the 2008-2012 period enhance the value of CERs relative to EUAs during the trial phase.

The imposition of penalties by the European Union provides some level of price support for EUAs and CERs (Parsons 2006). The European Union imposes penalties for failure to deliver adequate EUAs of €40 per tonne of carbon dioxide in the trial phase which runs from January 1, 2005 until December 21, 2007, and €100 per tonne in the first commitment period from January 1, 2008 through December 31, 2012 (European Union 2003).

CDM CER prices are also influenced by the perceived quality of the project and project sponsors. As described above, there is a great deal of uncertainty regarding the delivery of verified CERs, which increases supply risk for the purchaser of CERs. One way to address this risk is to price CERs differently based on the stage of the project; sales early in the process prior to final approval receive a much lower price than those sold post-

[18] Greater reliance on proven technology in CDM reflects the same bias toward proven technology that is identified in Chapter 4 in the technology risk analysis. This may result in CDM playing less of a role in developing innovative new technology.

verification. The creditworthiness of the seller also significantly affects the price of CERs (Milborrow 2006).

Finally, CDM CERs are priced based on expected supply and demand for carbon offsets. CERs must compete against supply from various other sources, including JI ERUs, RMUs, and excess AAUs. Over-allocation presents one of the most serious threats to the viability of the CDM. Over-allocation has occurred in both the European Union and Eastern Europe.

The May 2005 verification of emissions showed that the over-allocation of carbon dioxide emissions allowances to European Union countries was approximately 41 million metric tonnes (European Commission 2006; Timmons 2006). The announcement of these excess emissions allowances reduced the price of carbon by over 67%, thereby making CDM projects less competitive.

To place the European Union over-allocation in perspective, CDM projects that had filed with the CDM Executive Board as of August 9, 2006 represented 169,934,000 metric tonnes of validated carbon dioxide emissions reductions per year (UNEP Risoe Centre 2006b). The European Union carbon over-allocation displaces one quarter of the total amount of these estimated CDM emissions reductions. However, if the verification process results in a lower issuance of CERs, as has been observed in projects verified to date, the displacement could be considerably higher. If the validation/verification error of the first thirty-five projects is representative of the other 961validated and unverified CDM projects filed as of August 9, 2006, the expected number of CDM CERs to be issued would be approximately 92.4 million metric tonnes of carbon dioxide per year. The May 2006 over-allocation would displace 44% of the expected CERs from the CDM projects validated as of August 9, 2006.

If Russian and Ukrainian excess allowances enter the market in 2008, they would exert even greater downward pressure on CERs and AAU prices. To place this in perspective, if the 791.5 million tonnes of Russian and Ukrainian annual excess allowances produced from fossil fuel carbon dioxide emissions enter the market, this additional supply would be approximately twenty times larger in volume than the May 2006 41 million tonne over-allocation of carbon dioxide that caused the price of EUAs to drop by over 67%. The same 791.5 million metric tonnes of carbon dioxide per year would be almost five times greater than the validated annual emissions reductions of the 996 CDM projects filed as of August 9, 2006, and almost nine times greater than the expected annual volume of CERs to be issued by these CDM projects assuming that validations continue to overestimate actual issuances of CERs by a 46% error margin.

In addition, other greenhouse gases are expected to produce additional allowances for Eastern European countries in excess of 100 million metric tonnes of carbon dioxide equivalent per year, a majority of which will belong to Russia and Ukraine (Rolfe 2000). These excess emissions allowances are approximately 60% of validated CDM emissions reductions as of August 9, 2006, and slightly more than the number of CERs expected to be issued assuming validation estimates continue to exhibit an error rate of 46%. To the extent these other gases are permitted to enter the market, the resulting excess AAUs from Eastern Europe will place additional downward pressure on the price of CDM CERs.

A number of studies have estimated future carbon prices, with the results varying widely based on differing assumptions and models. These assumptions include different estimates of future economic growth, oil prices, cost of emissions abatement, the rules concerning the availability of Eastern European excess emissions allowances, the rules concerning trading across emissions sectors and countries, and banking of emissions. One 1999 study that compared the results of eleven leading models predicted prices would range below €20 to €100 per tonne of carbon dioxide in order to achieve 5% emissions reductions from 1990 levels. Seven of the eleven models surveyed predicted the price would range from €20 to €35 per tonne of carbon dioxide for a 5% reduction of 1990 levels in a market in which the United States participated (Weyant and Hill 1999; Reilly and Paltsev 2006). More recent studies have predicted median prices to range from under €1 to under €6 per tonne of carbon dioxide if trading across sectors and countries is permitted under the EU ETS (Reilly and Paltsev 2006; Pew Center 2005; See 2005). The study which predicted that carbon dioxide prices should be under €1 per tonne was based on analysis of the current EU ETS regime and assumed that emitters will find relatively inexpensive methods to meet target reductions in the 2005-2007 period (Reilly and Paltsev 2006).

These estimates are well below observed trading prices in the €15-40 range. Again, the imposition of a €40/tonne penalty for failure to meet targets during the 2005-2007 period may have supported the price at the observed levels (Parsons 2006). Alternatively, these studies may underestimate the cost of reducing emissions (Reilly and Paltsev 2006).

The availability of a large number of low-cost allowances will lower the price of carbon and potentially increase the volatility of the price of carbon dioxide emissions allowances. In turn, this will make more costly CDM projects unattractive financially and will increase the risks of CDM projects in general. Overall, the oversupply and low price of emissions allowances coupled with higher CDM risks will likely reduce the use of CDM.

5.7.2.6 Market Capacity

Market capacity for CDM CERs will depend in large part upon price levels as described in the prior section, and how risks and barriers to the development of CDM projects are addressed. This section addresses risks and barriers.

The survey conducted in connection with this dissertation revealed that CDM project risks, the additionality requirement, and regulatory uncertainty are critical areas that must be addressed successfully in order for CDM CERs to become an important source of emissions allowances. In turn, this will determine whether CDM will achieve its goals of reducing greenhouse gas emissions and promoting sustainable development in developing countries.

5.7.2.6.1 CDM Project Risks

This section summarizes various risks associated with the issuance of CERs in CDM projects. If CERs are part of a project's financing, a number of special risks need to be addressed by project parties and reflected in project documents. The risks associated with the issuance of CERs are in addition to other risks that are associated with infrastructure projects generally, as described in Chapter 4.

The CER portion of a project entails substantial risk for project sponsors, investors and project customers that rely on the issuance of CERs either as a source of project revenues or as a source of emissions allowances. As described above, the actual number of CERs that a CDM project produces depends upon the verified performance of the project.

Issuance of CERs requires approvals of the host government and the CDM Executive Board, and the successful completion and operation of the project. Purchasers of CERs should be concerned about the financial stability and performance of the project and the ability to take legal title to the CERs. These considerations favor project sponsors with established records, countries with legal systems that will enforce CER and other project contracts, national regulatory systems that will provide the necessary project approvals in a timely manner, and technologies that are reliable.

As with the risks discussed in Chapter 4, CDM risks should be separately identified, allocated, and mitigated. In addition to allocation and mitigation in the project documents, some private contractual methods may be available to address CDM risk. Swiss Re currently offers products that insure against the risks of a CDM project's failure to deliver promised CERs (CERES 2006), and other insurers are considering providing similar products (Gooch 2006).

Table 5.21 below summarizes various risks associated with the CDM aspects of projects.

Table 5.21: CDM Project Risks

Risk	Examples
Market and Supply Risks	Immature market; affected by AAU prices, energy prices, and weather conditions.
Technology Risk	Clean technologies still developing; uncertain costs and benefits.
Certification/Verification Risk	Variation in validation and verification procedures. Proving additionality requirement. Difficulty in monitoring emissions reductions. Failure to deliver promised CERs due to validation/verification estimation error.
Regulatory Risk	CDM methodologies still developing and untested. Kyoto Protocol only extends to 2012. Potential for commodities or securities regulation.
Political Risk	Host government must approve the project under domestic laws for sustainability.
Accounting/Disclosure Risk	No standard or oversight for reporting national emissions or CDM results. Conflicts of interest among project parties.
Credit Risk	Counterparty credit risk (no exchange clears CERs).
Default Risk	Failure to deliver CERs due to financial or technical failure.
Legal Risk	No legal standards for CDM. No case law in any country. Complex national and international law issues.
Capital Markets/Finance Risk	Significant volume needed for economies of scale.

Source: Adapted from AgCert (2006); TransAlta (2006); Hoyte (2006); Fussell (2006); Colston (2006b); Wilder et al. (2005).

Two of the risks associated with CDM, the additionality requirement and regulatory uncertainty, are addressed in greater detail in the next two sections. These risks were identified in a majority of interviews as significant shortcomings of CDM.

5.7.2.6.2 Additionality

The additionality provision of the Kyoto Protocol requires that project sponsors prove that the project would not have occurred in the absence of the financial incentives created by the CDM. The additionality requirement was introduced to encourage actual emissions reductions to take place by preventing a windfall to projects that would have been implemented in any case. Additionality is also a means of limiting the supply of CERs, which is intended to maintain their price, and thus the viability of the CDM (Michaelowa 2005b).

Brokers, investors and advisors to CDM projects interviewed in connection with this dissertation were in general agreement that the requirement of "additionality" is cumbersome and possibly counterproductive.[19] Various respondents observed that the additionality requirement introduces a degree of uncertainty into the process that increases costs and time to complete projects. Others noted that is could lead to manipulation of data in order to demonstrate the desired result.

Importantly, the additionality requirement does not address project quality. Several CDM participants commented that the quality of some of the projects undertaken were dubious. For example, HFC projects have been criticized as giving credit for shifting emissions away from ozone depleting HFCs that are banned under the Montreal Protocol towards a milder greenhouse gas that is to be phased out by 2040.

If projects reduce greenhouse gas emissions, there seems to be little purpose in a requirement that adversely affects the development of CDM projects by increasing uncertainty, delays and costs. Interview results suggested that more emphasis on projects that reduce greenhouse gas emissions in lieu of the additionality criteria would be appropriate.

5.7.2.6.3 Regulatory Uncertainty

Regulatory uncertainty has adversely affected the CDM at several levels. Because the Kyoto Protocol is only in force until 2012, there is uncertainty regarding the future of CDM. The short time horizon for CDM through 2012 reduces incentives to invest in developing CDM methodologies (Eddy 2006; Page, B. 2006). One project sponsor noted that if there was greater commitment to the Kyoto Protocol by his own government, he believes his firm would be much more aggressive in developing CDM and JI projects (Page, B. 2006).

Uncertainty regarding CDM standards and methodologies is another source of regulatory uncertainty. All firms surveyed identified that uncertainty in standards and methodology were causing significant delays and additional cost. For example, the cost of a new methodology is typically recovered by its application in multiple projects. Interviewees stated that the cost of developing a methodology is approximately $150,000 (Colston 2006a; Eddy 2006; Hardy 2006). Further, the time required to develop new methodologies is substantial. Methodologies have required an average of 280 days for approval, based on a total of fifty-six approved methodologies as of May 1, 2006 (UNEP Risoe Centre 2006a). Yet, a number of methodologies are under revision and review, some of which have been revised multiple times (Van Der Linden 2006). Several firms expressed concern that these problems could undermine the viability of CDM.

Significantly, because CDM projects require a minimum of approximately eighteen to twenty-four months to register and verify the CERs, CDM regulatory requirements need to be clarified well in advance of the upcoming compliance period to ensure a large volume of CDM activity (Milborrow 2006).

---

[19] Michaelowa (2005b) describes the additionality and baseline determination methods.

Finally, the price of CDM CERs will also be affected by the rules concerning trading emissions between countries. In addition to the European Union, a number of countries are developing emissions trading regimes in anticipation of the 2008-2012 compliance period (Haites 2005; Wilder 2005). The regulatory arrangements for linking these national trading systems, the rules concerning the supply of gases, and the excess AAUs that will enter the market will affect the viability of CDM (Haites 2005).

5.7.3 Prospects for EU ETS and CDM to Address Climate Risk

AAUs traded in the EU ETS and CDM CERs are intended to address twin goals of promoting carbon emissions reductions and providing flexible instruments for firms to manage regulatory risk associated with carbon emissions limits. CDM is particularly important because it is intended to achieve emissions reductions in developing countries that are among the most populous and have some of the fastest growing economies in the world, such as Brazil, China, and India.

Both EU ETS and CDM are in the development stage and both must overcome several significant hurdles before they are viable mechanisms. Specifically, policymakers must address the issue of regulatory uncertainty concerning the future of the Kyoto Protocol arrangements after 2012.

With respect to CDM CERs, the potential low cost of competing excess emissions allowances and the cost and time required to produce CERs could undermine the CDM as both a policy instrument and a means for managing regulatory risk. Significantly, the failure of the CDM to supply a reliable stream of CERs can be expected to increase reliance on excess emissions allowances. Finally, the CDM Executive Board must provide clear standards and methodologies for CDM projects if CDM is to be successful.

AAUs and CDM CERs in their current state have limited potential to address climate change unless the issues described in this section are successfully addressed. Table 5.22 summarizes the conclusions of this section regarding AAUs and CDM CERs.

Table 5.22: EUA and CDM Summary

Carbon Offsets	**AAUs**	**CDM CERs**
Scope of Risk Coverage	Regulatory	Regulatory
Geographic Coverage	EU countries until 2008, then all Kyoto Parties	Annex I parties invest in non-Annex I countries.
Contract Duration	46% for 2006 AAUs; 49% for 2007; 6% for 2008- 2012.	Mostly for 2008-2012 compliance period.
Availability	Abundant, excess allowances.	Limited; supply risk.
Price	Volatile. Subject to supply, reporting, regulatory issues.	Volatile. Depends on project, sponsor, AAU prices.
Market Capacity	Abundant, excess allowances.	Limited, unless barriers removed.

5.8 Catastrophe Bonds

This section examines catastrophe-linked debt securities, commonly known as catastrophe bonds. Because of the recent introduction of these instruments, the section first provides an overview of the fundamentals of catastrophe bonds. Next, it evaluates these instruments based on the six criteria relating to scope of risks covered, geographic coverage, contract duration, availability, price, and market capacity. Finally, the section concludes by evaluating the prospects for catastrophe bonds to address risks associated with climate change.

The research in this section presents the results of a survey of twenty insurance industry participants. Survey respondents were primarily insurance and reinsurance companies, and brokerage firms, but also included credit rating agencies, state insurance regulators, insurance industry associations, and insurance risk analysis firms.

5.8.1 Catastrophe Bond Fundamentals

Catastrophe bonds are an alternative method of accomplishing the objectives of raising capital and shifting underwriting risk to a third party. Thus, catastrophe bonds are a substitute for reinsurance because they shift the risk of loss of a specified catastrophic event in whole or in part to purchasers of the bonds. Insurers are increasingly issuing catastrophe bonds to supplement reinsurance because of the limited capacity in the reinsurance markets for high-loss events in densely populated regions at an acceptable price range.

Catastrophe bonds are typically floating-rate bonds with higher than normal returns for bonds of their rating. The principal repayment obligation is waived in whole or part if one or more natural catastrophes occur as specified in the bond documents.

From an investor's perspective, catastrophe bonds may be a desirable component of a portfolio because their returns are not correlated with general economic conditions, the returns on other fixed income securities, or the insurer's claim adjustment practices. The correlation of catastrophe losses and annual percentage changes in the S&P 500 equity index have been demonstrated to be close to zero ($r=-0.05$, $t=-0.33$) between 1949 and 1996 (Canter, Cole and Sandor 1997).

Catastrophe bonds are structured using a special purpose vehicle that holds the bond proceeds and a premium paid by the insurance company for the reinsurance aspect of the bond. These assets are invested and the proceeds pay interest on the bonds. This structure shields the bondholders from the credit risk associated with the insurance company. At the maturity date of the bond, the principal is repaid to the bondholders unless a triggering event occurs, in which case all or a portion of the assets are paid to the ceding insurance company to cover the cost of the losses.

5.8.2 Scope of Risk Coverage

The catastrophe bond market typically focuses on high-loss, low-probability risks, such as for a 1-in-100 year event (Schupp 2005: Lane and Beckwith 2006; Khater 2006). The only exception is the Spring 2006 launch of Successor by Swiss Re, a three year catastrophe bond that includes approximately $30 million of risk coverage in the 1-in-10 and 1-in-15 year event layers, which commands a generous 30-40% yield (Khater 2006). The Successor transaction is an experiment and the acceptance of this practice may depend upon whether losses are sustained by the bondholders in the upcoming hurricane season (Khater 2006).

Catastrophe bonds have been offered predominantly for United States, European and Japanese risks, primarily for earthquake and hurricanes. Catastrophe bonds can be structured to diversify risk based on multiple locations, seasons and perils. Bonds may also combine put and call options within the structure to limit the risk of the loss to all or certain layers of bondholders as a means of further reducing risk. For example, a bond typically features multiple tranches, each of which represents different levels of risk. A more secure tranche could guarantee the entire return of principal and a portion of interest even if a trigger event occurs, whereas a less secure tranche that commands a higher yield could be subject to forfeiture of all principal and interest (Caifa 2002; Martucci 2006; Ali and Yanos 2004).

In general, bondholders are not willing to accept more frequently occurring risks because investors are only interested in the return on the bond and are not accustomed to accepting the risks associated with underwriting insurance. Further, unlike reinsurance companies, bondholders have no incentive to accept greater risks in order to maintain relationships with clients (Schupp 2006; Roberts 2002). The acceptance of remote risks may account for the fact that only one catastrophe bond has ever been fully triggered (Hoffman 2006). Because investors are unwilling to accept more frequent risks common in an insurer's portfolio, catastrophe bonds presently have a limited ability to mitigate insurers' more regular risks.

Catastrophe bonds are typically structured to forgive all or a portion of principal based on one of the following kinds of triggers: (a) the insurer's actual losses, (b) an index of industry losses, usually determined by a third party, (c) anticipated losses based on model calculations derived from inputting parameters of actual catastrophic events that occur during a specified period into a computer model specified by the bond, or (d) the occurrence of a natural event meeting specified parameters, such as windspeed (for a hurricane bond) or ground acceleration (for an earthquake bond). With respect to parametric bonds described in (c) and (d), confirmation of the occurrence of the trigger typically requires multiple observation stations to provide weather data, which is used as input for a specified algorithm that determines whether the trigger is activated (Standard & Poor's 2004).

Recent trends in catastrophe bond terms have moved away from indemnifying the insurer's actual losses and towards an index or parametric risk trigger. As described above, indemnity-based catastrophe bonds forgive bond principal based on the actual losses of the insurer, which in turn depends upon the insurer's underwriting and loss adjustment practices. Indemnification bonds tend to be more expensive because these provide more certainty to insurance company and less certainty to investors.

In contrast, index bonds are based on an index of industry loss, as opposed to the insurance company's actual practices and obligations. This method limits the exposure of bondholders to the insurance company's particular portfolio of risks, which simplifies the risk analysis.

The table below shows the trends in catastrophe bond terms through 2005.

Table 5.23: Catastrophe Bond Triggers, 1997-2005

	Indemnity		Parametric		PCS (Index)		Modeled	
Year	Principal Amount (US$ millions) and Number of Transactions							
1997	$431.0	3	$90.0	1	$112.0	1	$0.0	0
1998	$846.1	8	$0.0	0	$0.0	0	$0.0	0
1999	$602.7	7	$100.0	1	$0.0	0	$282.1	2
2000	$507.0	4	$303.0	2	$150.0	1	$179.0	2
2001	$150.0	1	$270.0	2	$265.0	2	$281.9	2
2002	$355.0	2	$631.5	3	$200.0	1	$33.0	1
2003	$260.0	2	$1,119.8	4	$350.8	1	$0.0	0
2004	$227.5	1	$267.8	2	$547.5	2	$100.0	1
2005	$859.4	4	$491.7	3	$0	0	$640.0	3
TOTAL	$4,238.7	32	$3,273.8	18	$1,624.5	8	$1,516.0	11

Source: Guy Carpenter (2006).

As the risk of loss associated with catastrophic events increases and credit rating considerations require larger reserves and more reinsurance, demand for catastrophe bonds are expected to increase (Schupp 2006; Standard & Poor's 2006). This can be expected to favor bondholders who desire to accept less risk, thus reinforcing the move towards catastrophe bonds featuring index or parametric triggers (Schupp 2006). Insurers also expect to see an increasing number of bonds feature multiple triggers, which reduces the risk substantially for bondholders (Challoner 2006; Mistry 2006).

5.8.3 Geographic Coverage

Catastrophe bonds have been offered predominantly for United States, European and Japanese risks, primarily for earthquake and hurricane perils. Table 5.24 below summarizes catastrophe bond risk capital coverage by geography and risk. Note that because some catastrophe bonds cover multiple perils, the table below double counts the capital available for multiple perils in each applicable risk category.

Table 5.24: Catastrophe Bonds Principal Amounts by Risk (US$ millions), 1997-2005

Year	U.S. Earthquake	U.S. Hurricane	European Windstorm	Japanese Earthquake	Japanese Typhoon	Other
1997	112.0	395.0	0.0	90.0	0	36.0
1998	145.0	721.1	0.0	0.0	80.0	45.0
1999	327.8	507.8	167.0	217.0	17.0	10.0
2000	486.5	506.5	482.5	217.0	17.0	129.0
2001	696.9	551.9	431.9	150.0	0.0	120.0
2002	799.5	476.5	334.0	383.6	0.0	0.0
2003	803.8	416.1	474.1	691.2	277.5	100.0
2004	803.3	660.8	220.3	310.8	0.0	0.0
2005	1,269.0	994.0	830.1	138.0	0.0	405.0
TOTAL	$5,443.7	$5,229.7	$2,939.9	$2,197.5	$391.5	$845.0

Source: Guy Carpenter (2006). Note: for catastrophe bonds covering multiple perils, the table double counts the capital available for multiple perils in each applicable risk category.

The placement of catastrophe bonds for U.S., European and Japanese risks probably reflects the fact that these regions possess the most developed insurance markets and bond markets (Bank for International Settlements 2006b).

5.8.4 Contract Duration

Catastrophe bonds first appeared in 1997. From 1999 to April 2006, approximately 122 catastrophe bond tranches have been issued representing approximately $8.5 billion principal amount (Standard & Poor's 2006c). Of these transactions, the shortest tenor was 1 year and the longest tenor was 5 years. The average tenor was 3.1 years and the average tranche was approximately $70 million. The table below summarizes the tenors for the 122 catastrophe bond tranches issued from 1999 through April 2006.

Table 5.25: Catastrophe Bond Tenors, 1999-April 2006

Tenor (months)	**12**	**13-24**	**25-36**	**37-48**	**49-62**
Number of Transactions	7	22	18	55	20
Percentage	5.74%	18.03%	14.75%	45.08%	16.39%

Source: Standard & Poor's (2006c).

Catastrophe bonds offer the longest tenor of any risk product surveyed in this dissertation. Yet, even with catastrophe bonds, there is a clear mismatch between the risks assumed by lenders and the risks covered by the risk markets. To illustrate, 100% of catastrophe bond transactions have tenors of less than 5 ½ years. In comparison, 55% of infrastructure finance debt tranches in 2005 had tenors of greater than 5 ½ years; and 25%

had tenors in excess of 10 years. Some debt tranches had tenors in excess of 50 years (Dealogic 2006b).

5.8.5 Availability

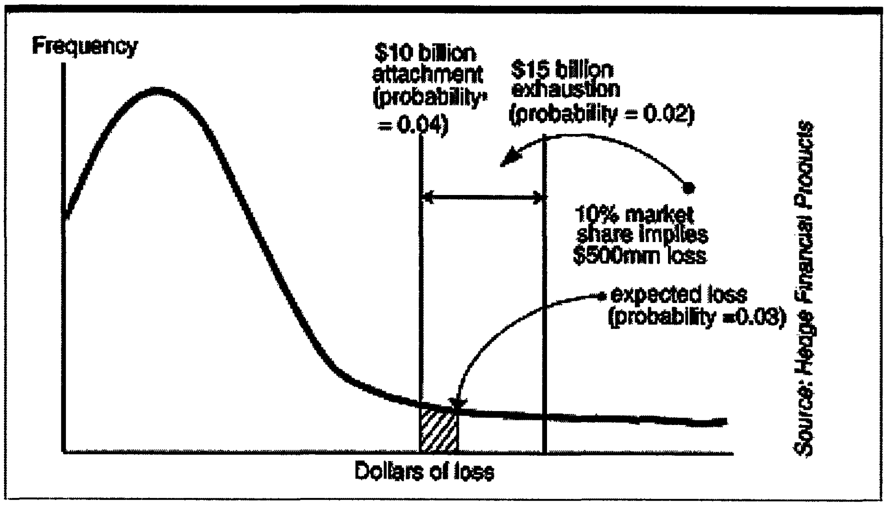
The transaction costs of issuing catastrophe bonds and the recent record of catastrophe events potentially limit the availability of catastrophe bonds. As noted in the prior section, catastrophe bonds may be structured to indemnify the insurer's actual losses or to compensate the insurer based on an index or parametric risk trigger. In the survey of insurance companies, several insurers noted that they expect that indemnity bonds will be difficult to obtain following Hurricane Katrina (Schupp 2006). Several interviewees noted that the only catastrophe bond that has been fully triggered is an indemnity-based bond, which was triggered by Hurricane Katrina (Hoffman 2006; Schupp 2006). As a result of the large payout on this bond, the industry is expected to move towards index or parametric triggers. These bonds offer lower transaction costs and shield bondholders from risk exposure to the issuer's underwriting and loss adjustment practices.

5.8.6 Price

Catastrophe bonds are priced based on actuarial risk models, expectation of future weather patterns, and supply and demand conditions. The risk of loss associated with catastrophic events are typically modeled using historic weather data, demographic data, building codes, engineering data specific to a particular zip-code, and expected trends based on scientific and demographic data (Standard & Poor's 1999; Muir-Wood 2006; Siner 2006). These models produce a loss exceedance curve, which shows the expected amount of insured losses from a particular risk and its estimated probability. The exceedance probability is the probability that a loss will occur at or greater than a specified level of loss.

Consider an example of a hypothetical catastrophe bond having a principal amount of $500 million. The bond principal is forgiven if a catastrophic event occurs that causes in excess of $10 billion of industry loss based on the issuer's percentage of industry market share until losses reach $15 billion. Assume further that the issuer has 10% market share and thus the entire $500 million principal amount is forgiven when $15 billion of industry losses are reached. The probability of a $10 billion loss event is 4% and the probability of a $15 billion loss event is 2%. The expected loss probability for this particular catastrophe bond is deemed to be 3%, which is the average loss for the $10-15 billion range according to the model. The bond is priced by comparing the 3% event probability to historic default rates of corporate bonds of similar tenor, and the corresponding corporate default rating is assigned to the catastrophe bond. For example, one-year corporate bonds having a default rate ranging from 1.35% to 7.25% are assigned a Ba to B rating. Because the 3% event probability triggering non-payment on the catastrophe bond falls within this range, the catastrophe bond could be assigned a similar rating of Ba to B. The prevailing yields in the corporate bond market for the particular rating would then be used as the basis for pricing the catastrophe bond (Cole and Chiarenza 1999).

Figure 5.11: Catastrophe Bond Exceedance Curve



Source: Cole and Chiarenza (1999).

Credit rating agencies rate catastrophe bonds based solely on the probability of the occurrence of the natural catastrophic event that triggers the loss of principal. Catastrophe bonds are generally rated BBB+, which is just below investment grade, except for bonds that feature triple-event triggers, which may receive an investment grade rating (Standard & Poor's 2004).

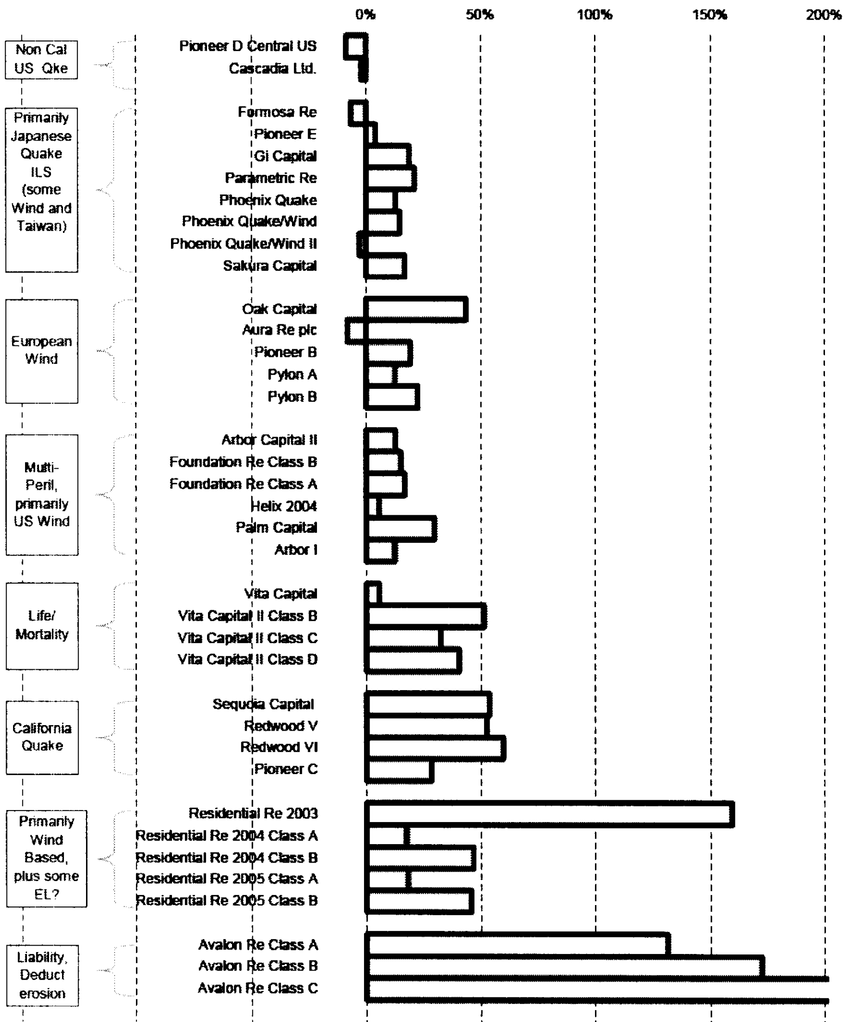
Table 5.26: Catastrophe Bond Ratings by Principal Amount (US$ millions) and Number of Transactions, 1997-2005

B		BB		BBB		A		AA		AAA	
$1,068.6	12	$7,198.7	78	$1,371.3	15	$211.5	3	$0	0	$105.9	5

Source: Guy Carpenter (2006).

Significantly, catastrophe bonds are one of the first risk transfer instruments used by the insurance industry that provide price visibility for property and casualty risk. Analysis of the catastrophe bond secondary market prior to and following Hurricane Katrina reveals that yields demanded by bondholders have increased rapidly immediately following the 2005 hurricane season. The yields on bonds that are linked to wind or hurricane events have increased by as much as 150% to 200% over LIBOR. Yields on bonds that feature multiple triggers have increased as hurricanes during the 2004 and 2005 seasons have reduced or removed the additional triggers (Lane and Beckwith 2006).

Figure 5.12: Post-Katrina Catastrophe Bonds Yields in Secondary Market



Source: Lane and Beckwith (2006).

Following Hurricane Katrina, revised catastrophe bond models estimate that the probability of occurrence some catastrophic events had increased by 30% to 60% (Martucci 2006). As a result, eighteen outstanding catastrophe bonds that were rated using old models were placed on credit watch with negative implications (Standard & Poor's 2006b; Martucci 2006). These revised models are expected to cause further increases in prices and/or potentially reduce demand for catastrophe risk bonds (Martucci 2006).

Anecdotal evidence from the dissertation survey further suggested that prices have increased dramatically. Swiss Re's $950 million Successor catastrophe bond launched in Spring 2006 covered a portfolio of perils including U.S. hurricane, European wind, California earthquake, and Japan earthquake. The catastrophe bond provided approximately $200 million in coverage for Florida, including a working layer for 1-in-15 year events with a yield of 30% to 40%. The respondent believed a 40% yield is the extent of what the market can absorb (Khater 2006). Considering that a 100% yield would equate to the issuer suffering the entire loss of principal, there appears to be little likelihood that catastrophe bond yields can continue to increase beyond those offered in the Successor transaction for working risk layers.

5.8.7 Market Capacity

In 2005, eighteen catastrophe bond transactions were completed for a total of $1.7 billion principal amount raised, at an average transaction size of $96 million per tranche or approximately $200 million per bond (Standard & Poor's 2006c; Clarke 2006). In 2005, approximately $4.9 billion principal in catastrophe bonds was outstanding. Of this, $3.08 billion was available for U.S. hurricane and earthquake risk (Clarke 2006).

To place these figures in context, it is useful to compare the size of the catastrophe bond market to the overall insurance markets, recent catastrophic losses, and to the infrastructure lending markets.

At the end of 2005, the U.S. property and casualty insurance industry possessed a policyholder surplus of $427 billion (Insurance Information Institute 2006a). In 2005, outstanding U.S. catastrophe bonds were 0.7% of the net value of the industry. In other words, this market is presently very small in size relative to the U.S. property and casualty insurance industry.

In 2005, U.S. onshore insured catastrophe losses exceeded $57.7 billion (Insurance Information Institute 2006a). Outstanding U.S. catastrophe bond principal at the end of 2005 was equal to approximately 5.3% of insured losses (Insurance Information Institute 2006a). In 2005, foreign reinsurance and other arrangements covered $27-32 billion of U.S. catastrophe losses (Insurance Information Institute 2006a), representing capacity approximately ten times larger than the U.S. catastrophe bond market (Insurance Information Institute 2006a).

Prior to September 11, 2001, the reinsurance market was estimated to lack approximately $30-55 billion of capacity to meet demand for events that causes $60 to $80 billion in losses (Ganapati et al. 1999). The $4.9 billion principal in outstanding catastrophe bonds in 2005 would have met 9% to 16% of the estimated shortfall.

One of the arguments in favor of catastrophe bonds is that it allows the insurance industry to diffuse risk beyond the industry, thereby expanding the capacity of the insurance industry to underwrite risk. It is difficult to evaluate the role of catastrophe bonds versus reinsurance because insurance companies do not release details of their reinsurance and retrocession practices. However, the insurance industry survey revealed that the reinsurance companies purchase many of the catastrophe bonds (Schupp 2006; Mistry 2006; Challoner 2006). In addition, the issuers of catastrophe bonds are expected to retain a portion of the bonds in their own portfolios to align their interests with those of the purchasing bondholders

(Mistry 2006; Challoner 2006). It is therefore unclear what percentage of catastrophe bond risk is actually transferred out of the insurance industry.

In comparison to the infrastructure lending market, the catastrophe bond market is approximately 1% of the size of the infrastructure lending market in 2005. In comparison to the $1.7 billion raised in catastrophe bonds in 2005, 487 infrastructure projects were financed with $175 billion of debt the same year.

Other factors suggest that the catastrophe bond market is unlikely to increase to the size of the reinsurance market. Bondholders have little incentive or expertise to accept the risks typically accepted by reinsurance companies (Schupp 2006; Roberts 2002). Further, catastrophe bonds are expensive to issue with high transaction costs. Recent market conditions suggest that their success will depend greatly upon offering high yields to bondholders, making them expensive alternatives (Martucci 2006).

At the same time, the capital markets have tremendous capacity to accommodate new securities products. At the end of 2005, the global value of all debt securities outstanding was estimated to be $58.6 trillion (Bank for International Settlements 2006b). The $4.9 billion principal in catastrophe bonds outstanding in 2004 represents 0.0084% of the broader global bond market. If pricing is adequate and innovative transparent structures can be developed that lead to wider acceptance of these instruments by investors, there is practically unlimited capacity in capital markets for catastrophe-linked securities.

5.8.8 Prospects for Addressing Climate Change

Survey respondents were asked to comment on how climate change might affect the catastrophe bond market. Responses varied but there was general agreement that demand for reinsurance will increase so there will be more demand for catastrophe bonds. However, a key issue will be the price and the terms of these bonds.

One survey respondent noted that it is an open question how fragile the catastrophe risk market is because of perceptions that global warming could increase the severity of storms and the magnitude of losses. The respondent noted that although Hurricane Katrina increased the demand for catastrophe bonds, he believed a series of major events would not be salutary for this market, resulting in either more expensive pricing or less capacity (Schupp 2006). Based on discussions with catastrophe bond investors during Spring 2006 investment road shows, one modeling firm which handles approximately 60-70% of catastrophe bond issuances expressed the view that a high loss year in 2006 would likely close the market entirely and an low loss year would cause dramatic growth. This respondent believed that catastrophe bond yields as high as 40% on recent transactions for working layers had reached the maximum return that is economically feasible for issuers, and thus the market could not continue to increase prices to attract further investment (Khater 2006).

In summary, evidence from the reinsurance market suggests that climate change would potentially reduce capacity, increase cost, and/or cause more strict terms in the catastrophe bond market. Catastrophe bonds use reinsurance underwriting models for setting price and bond terms. Because these markets are substitutes for each other, these markets influence each other (Standard & Poor's 2005b). Thus, increases in cost or curtailment in coverage in the reinsurance market will favor bondholders in the catastrophe bond markets. As described above, the survey revealed that the 2005 hurricane season has already caused prices to increase and catastrophe bond terms to become more restrictive.

Table 5.27 below summarizes the findings of this section with respect to catastrophe bonds.

Table 5.27: Catastrophe Bonds Summary

Scope of Risk Coverage	Force Majeure
Geographic Coverage	Primarily United States, Europe, and Japan.
Contract Duration	3.1 year average; 5 year longest duration in market.
Availability	Typically remote risk (e.g., 1-in-100 year event). Primarily for earthquake, hurricane, windstorm.
Price	Mostly sub-investment grade. Increases with reinsurance prices.
Market Capacity	Uncertain due to current high yields and future loss patterns.

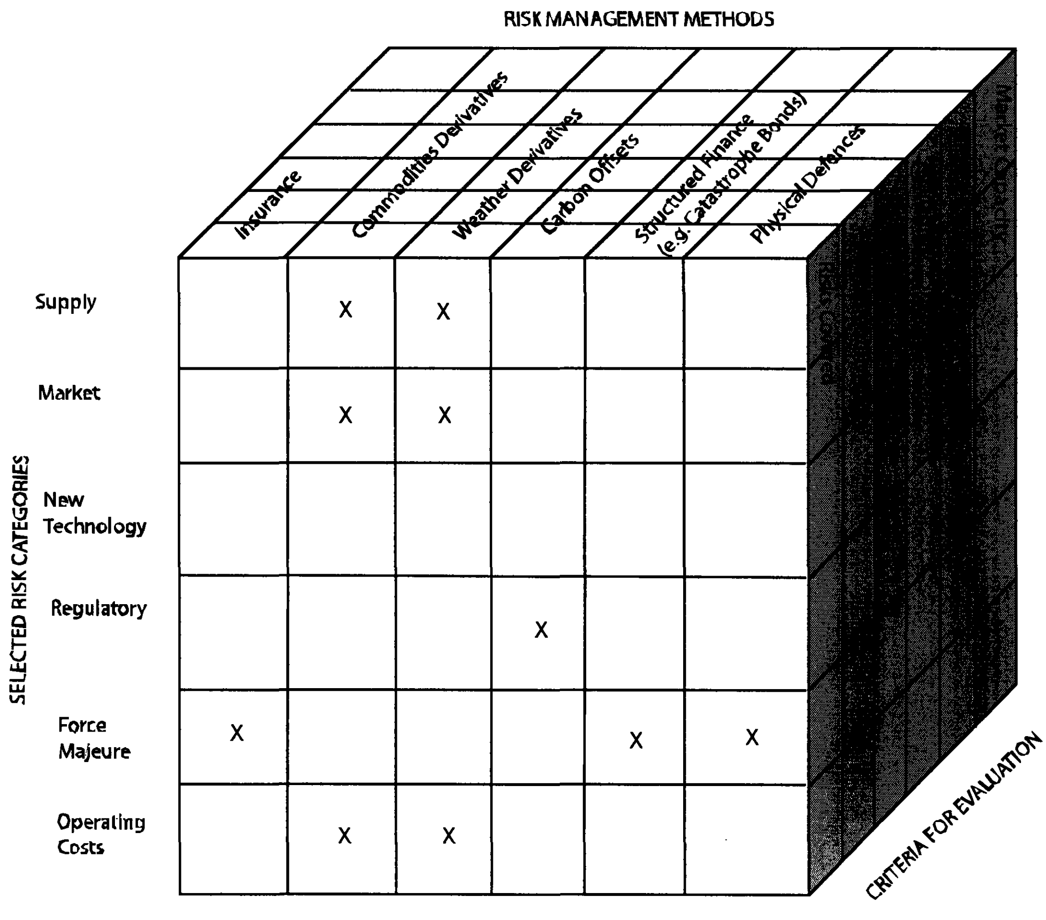
5.9 Limits of Private Contractual Methods for Addressing Climate Change

This chapter has evaluated the use of insurance, commodities and weather derivatives, carbon offsets, and catastrophe bonds for mitigating climate-sensitive risks. Each private contractual method was evaluated based on the following six criteria: (a) scope of risk covered, (b) geographic coverage, (c) contract duration, (d) availability, (e) price, and (f) and market capacity.

Based on this evaluation, the evidence suggests that the ability of these private contractual instruments to address climate risk is currently limited, and that climate change could potentially widen gaps in risk management. Using the Climate Risk Assessment Matrix, we can summarize the results.

Figure 5.13 shows the scope of risks covered by each kind of risk management instrument for selected climate-sensitive risks. No risk category is covered by more than two types of risk management instrument, and all of the risk management instruments are limited to covering a few risks.

Figure 5.13: Climate Risk Assessment Matrix – Risks Covered



	Insurance	Commodities Derivatives	Weather Derivatives	Carbon Offsets	Structured Finance (e.g. Catastrophe Bonds)	Physical Defences
Supply		X	X			
Market		X	X			
New Technology						
Regulatory				X		
Force Majeure	X				X	X
Operating Costs		X	X			

Figure 5.14 summarizes the evaluation of these risk management instruments based on the remaining criteria of geographic coverage, contract duration, availability, price, and market capacity. With respect to all of these evaluation criteria, these instruments possess limitations in addressing the longer term risks associated with climate change.

Figure 5.14: Climate Risk Assessment Matrix – All Other Evaluation Criteria

RISK MANAGEMENT METHODS

CRITERIA FOR EVALUATION	Insurance	Commodities Derivatives	Weather Derivatives	Carbon Offsets	Structured Finance (e.g. Catastrophe Bonds)	Physical Defences
Risks Covered	See Climate Risk Assessment Matrix presented in Figure 5.13					
Geographic Coverage	Mostly OECD	Global	US Europe Japan	Kyoto Parties	US Europe Japan	
Duration	1 Year	Mostly 1 Year	Mostly 1 Year	Until 2012	3-5 Years	
Availability	Curtailed in High Risk Areas	Rapid Increase	Rapid Increase	Regulation Dependent	Variable - Market Dependent	
Price	Increasing	Increase with Volatility	Increase with Volatility	Volatile, Excess Supply	Increasing	
Market Capacity	Potentially Limited	Large	Large	Regulation Dependent	Potentially Limited	

Importantly, these contractual methods do not address all of the infrastructure project risks identified in Chapter 4. For example, as reflected in Figure 5.13, none of these instruments address new technology risk. Other risks not covered by these instruments are not shown in Figure 5.13 and Figure 5.14. Table 5.28 presents a summary of other important risks that are not covered or are incompletely covered by the risk management methods described in this chapter.

Table 5.28: Other Important Risks Not Covered by Risk Management Instruments

Risk	Mitigation Methods
Technology Risk Engineering Risk	Project documentation Technology selection Contractor selection
Operating Risk – Management	Project documentation
Operating Risk – Cost	Project documentation Derivatives for supply or weather-related operating costs
Environmental Risk	Emissions allowances for emissions cap-and-trade programs Structured finance for cost recovery
Infrastructure Risk	Project documentation
Political Risk	Public insurance
Participant Risk	Project documents Performance bonds
Capital Markets Risk	Derivatives (for certain risks) Structured finance (for certain risks)
Legal Risk	Project documentation
Governance Risk	Project documentation

Source: Adapted from Tinsley (2000); Hoffman (2001).

Climate change will likely increase the demand for risk products. However, despite this growth potential, there is evidence that increases in climate risk will further limit the ability or willingness of risk underwriters to cover the long-term risks posed by climate change. This could potentially result in private contractual methods for addressing climate change risks becoming practically unavailable at an affordable price. The research presented in this chapter suggests that the following issues are likely to limit the availability or effectiveness of risk management methods in the future: short-term nature of risk markets, price considerations, difficulties in modeling long-term climate trends, and credit risk.

The short-term nature of risk markets is critical in assessing the ability of these markets to provide protection against climate change. Property and business interruption insurance and reinsurance are almost exclusively contracted for a period of one year. For most derivatives, a majority of the open interest is for contracts within one year. Catastrophe bond tenors average 3.1 years.

The short-term nature of risk markets limits the usefulness of risk management instruments for climate change. Changes in climate will be priced into short-term contracts as old contracts expire and new contracts are entered into, resulting in changed terms to reflect the change in conditions. There is no evidence to suggest that the duration of contracts would extend beyond those currently available in order to accommodate increasing climate change risks. There is evidence, however, that contracts would become more restrictive in their terms or unavailable altogether if climate risks increase in the future.

Pricing is another critical factor that will limit the potential application of risk management instruments to addressing climate change. For insurance markets, increasing volatility and severity of weather events will increase the cost of insurance and will likely lead to further curtailment of coverage in terms of scope of risks covered and geographic coverage. With respect to weather derivatives, increases in weather volatility and average temperature will increase the cost of the most widely traded temperature derivatives. To the extent that climate change causes or is accompanied by increasing commodities prices or greater volatility in commodities prices, commodities derivatives will become increasingly expensive. For catastrophe bonds, increasing frequency or severity of catastrophic events will likewise cause increases in premiums or potentially reduce demand for catastrophe bonds as these markets migrate towards even more remote levels of risk.

Importantly, prices among these markets move together because these products are substitutes for each other, present arbitrage opportunities, and are priced using models that contain similar components. Insurance, derivatives, and catastrophe bonds are substitute products for risk coverage and are often used together to create back-to-back hedges for the same underlying risk. Further, the models underlying insurance, weather derivatives and catastrophe bonds are similar in nature. As a result of their substitutability and the commonality of the models used to price them, price increases in one market are likely to trigger price increases across the entire spectrum of products.

Ultimately, if adverse climate events become a near certainty to occur, the price of insuring against such events using third party contracts becomes prohibitively expensive and firms could be forced to self-insure or go out of business.

Limitations in models used to price risk contracts reinforce the short-term duration and high cost of risk coverage. All models possess a limited ability to estimate future risks. For example, insurance and weather derivatives models are generally not used beyond three years, and most are used to price products no more than one year into the future (Muir-Wood 2006). The inability to model future climate conditions beyond several years into the future will likely limit the duration of weather risk contracts. Further, longer durations are prohibitively expensive, as demonstrated in this chapter using commodities and weather derivatives pricing models. When data are unavailable or there is little confidence in the ability to forecast future risks based on available data, the cost of risk instruments becomes prohibitively expensive, potentially ruining the economics of putting a hedge in place (Ricker 2006).

To an extent, the shortcomings of models can be addressed through contract terms that limit the scope of coverage. Contracts can use moving averages and caps on payouts. However, all of these measures to address model risk ultimately shift risk back to the purchaser of the instrument by reducing the scope of covered risks.

Finally, credit risk places limits on the abilities of parties to underwrite climate risk. Even if a firm is willing to underwrite these risks, the creditworthiness of the seller would be an important consideration for the brokerage house (in an exchange-cleared contract) or the purchaser (in an OTC trade). Even if such a contract were entered into, the volume of such contracts would likely be small unless the seller can demonstrate its ability to meet potential claims. Ultimately, credit risk reflects the fact that no party is well positioned to accept the risks posed by climate change. Significantly, nobody interviewed could identify a potential seller of long-term climate risk instruments that would be sufficiently creditworthy. It remains to be seen whether an innovative structure can be developed that provides protection against climate change backed by a creditworthy seller.

The gap in coverage for climate-sensitive risks is already apparent in infrastructure lending markets. Loan tenors for infrastructure projects typically range from 10 to 30 years, and some as long as 50 years. In contrast, most risk markets operate on a seasonal or year-to-year basis, except for catastrophe bonds, which have an average tenor of 3.1 years. Along coastal areas, private insurance coverage is becoming increasingly expensive or unavailable. If the gap in risk coverage widens, infrastructure could become more difficult to finance, including infrastructure intended to support the goals of carbon neutrality.

Importantly, if private insurers are unwilling or unable to insure long-term climate risks, there will be a need for government insurance programs to provide risk coverage. While an evaluation of government insurance programs are outside the scope of this dissertation, it is important to recognize that these programs often fail to adequately price risk, which several survey respondents noted can adversely affect private sector insurance markets.[20] Significantly, government programs in Florida, other Gulf Coast states, and the U.S. National Flood Insurance Program have experienced significant financial difficulties as a result of under pricing risk coverage followed by larger than expected catastrophic losses (Binnun 2006; Bushouse 2006; Insurance Journal 2006; CERES 2006). Expanding government insurance programs that compete with private sector insurers and place a burden on the tax base would represent a failure of both the private sector and the government to provide a long-term solution. At the same time, the absence of insurance coverage could adversely affect economic growth and, when a natural catastrophe occurs in an area without insurance, potentially produce severe economic and humanitarian crises. Efforts by both the private sector and government should focus on innovation of risk management solutions to be offered by the private sector. Any expansion of government insurance should be carefully designed to minimize potential adverse consequences for private markets.

With respect to EUAs traded on the EU ETS and CDM CERs, the viability of these instruments to address regulatory risk and to promote carbon reductions will require policymakers to successfully address several design flaws in these programs, including the problem of excess allowances. If we are going to succeed in addressing climate change, we will need highly effective mechanisms to mobilize private sector resources to build carbon neutral infrastructure. It is therefore essential that programs such as CDM and JI are highly effective in attracting and deploying resources for high quality infrastructure projects.

The development of new risk management methods for addressing climate change will be an important area of future research. Chapter 7 of this dissertation makes several recommendations for enhancing the capacity of the risk markets and the Clean Development Mechanism to support development of carbon neutral technologies and infrastructure.

---

[20] At the time of writing, the U.S. National Flood Insurance Program is in the process of revising its flood risk maps for the entire country. The revised maps are expected to expand the areas deemed at risk for floods and to change the statistical designations of areas to reflect increased risk.

6 Case Studies

This chapter presents three case studies that provide an empirical basis for further analysis of the private sector's capacity to finance and develop carbon neutral energy infrastructure. The three case studies are (i) the capacity of capital markets to supply adequate investment capital to develop a portfolio of carbon neutral electricity infrastructure providing 10-15 TW of power within a 50-year period, (ii) the effects on the electric utility industry of increasingly intense storms and hurricanes in the Eastern United States from 1990 to 2005, and (iii) the effects on the insurance industry of the increasing losses caused by natural catastrophic events from the 1970's to 2005, especially in connection with underwriting risks for energy infrastructure.

These case studies were selected because they represent three segments of the economy that are critical to developing carbon neutral infrastructure. The private sector's ability to address climate change will depend upon the capacity of the energy and insurance industries, and capital markets to support the development of carbon neutral infrastructure. At the same time, these parts of the economy are each expected to be adversely affected by the risks associated with climate change.

Each case presents a distinct financial aspect of climate change. Accordingly, these cases are evaluated based on the particular financial implications of climate change for each industry, and not on a standard set of criteria. This approach was selected in order to provide a representation of important financial aspects of climate change, without attempting to impose a rigid set of standard criteria. Table 6.1 sets forth the variables examined in evaluating each of the case studies.

Table 6.1: Case Study Variables

Capital Markets	Effect of Storms and Hurricanes on Utilities	Catastrophic Events/Insurance
Projected Capital Costs of Carbon Neutral Electricity	Recent Storm History of U.S. Atlantic Coast	Recent Catastrophic Events and Insured Losses
Historic U.S. Electricity & Energy Capital Expenditure	Economic Damage	Financial Effects on Insurance Industry
Projected Global Electricity Expenditure	Financial Effects on Utilities and Energy	Effect on Insuring Energy Sector
Required Growth of Renewable Energy		
Size of U.S. and Global Capital Markets		
Internal Funds		
International Disparities		
Capital Market Volatility		
Capital Markets Growth		
Potential Cost of Waiting		

6.1 Capital Markets Capacity to Finance Carbon Neutral Electricity Infrastructure

This case study compares a set of cost estimates for developing 10-15 TW of carbon neutral electricity infrastructure over a fifty-year period to the capacity of capital markets to finance this infrastructure. The estimates presented in Chapter 2 for 10 TW of carbon neutral electricity generation are expanded to include supporting carbon sequestration, energy storage and replacement infrastructure. This chapter also presents a 15 TW carbon neutral electricity infrastructure estimate as a high-consumption scenario, roughly the electricity portion of the projected amount of energy required to stabilize atmospheric carbon dioxide levels within the 350 ppm to 550 ppm range by 2050 (Hoffert et al. 2002). The cost estimates for 10 TW and 15 TW of carbon neutral electricity generation represent an approximate range of projected electricity demand over the next 50-year period.

The electricity sector's contribution to global warming and the capital-intensive nature of electricity infrastructure make the finance and development of carbon neutral electricity infrastructure an important and potentially difficult financial challenge. Electricity generation accounts for 40% of global carbon dioxide emissions (International Energy Agency 2003). According to the International Energy Agency's 2001-2030 projections for conventional energy investment, electricity infrastructure investment should account for at least 60% of all energy and utilities capital expenditure, and could be as high as 70% if investment in fuel infrastructure for power generation is included (International Energy Agency 2003). Further, electricity generation, transmission and distribution are the most capital intensive economic segments of the economy, requiring two to three times more capital expenditure compared to manufacturing industries (International Energy Agency 2003).

This case study compares the estimated costs of 10 TW to 15 TW of carbon neutral electricity infrastructure to historic utility and energy industry capital expenditure levels; the International Energy Agency's (IEA) projected conventional electricity infrastructure capital expenditure levels; required increases in capital investment in renewable energy technologies; the capacity of capital markets in the public debt and equity, venture finance, and bank lending segments; and savings and GDP projections. Following these comparisons, the case study examines several important issues affecting the capacity of capital markets to supply the required capital on a global scale over such a time period. These issues are the disparities among capital market capacity of different countries, the volatility of capital markets, the financial effects on utilities firms, the potential growth of capital markets, and the timing of introducing an aggressive carbon neutral energy program.

This case study contributes to the dissertation's analysis of the private sector's capacity to finance and develop carbon neutral energy infrastructure. It provides a preliminary assessment of the capacity of the private sector generally, and capital markets specifically, to provide the capital and resources to implement carbon neutral electricity infrastructure. Finally, it also provides a foundation for further research on the finance of carbon neutral infrastructure.

This is the first study known to the author that considers the capacity of the capital markets to finance renewable energy infrastructure on a global scale. In 2003, the IEA completed the first study estimating the cost of conventional global energy infrastructure requirements from 2001 to 2030. The study included electricity, oil, gas, coal, and an alternative scenario featuring limited investment in renewable technologies.

The IEA estimated that from 2001 to 2030 global energy consumption will increase by two thirds, and that projected electricity demand will increase to approximately 7.2 TW, requiring the addition of 4.7 TW of electricity generation capacity (International Energy Agency 2003). Their estimates roughly correspond to the fifty-year 10 TW carbon neutral electricity infrastructure goal adopted in this case study.

The IEA study differs from the present case study in several important respects. The IEA focused almost exclusively on conventional energy infrastructure. Also, the IEA study assumed that investment risks in the 2001 to 2030 period remain similar to past risks, although it acknowledged that environmental regulation could substantially change the risks posed to energy investment (International Energy Agency 2003). Accordingly, the IEA study did not address the issue of climate change or estimate the cost of carbon neutral energy infrastructure.

The IEA used a predictive model integrating conventional energy infrastructure demand, costs, and macroeconomic factors. In contrast, the present case study examines the technology and costs necessary to develop carbon neutral infrastructure and compares its costs to capital markets activity. Unlike the IEA model, this case study is not intended to predict future investment levels. Rather, it is designed to assess the private sector's capacity to finance carbon neutral electricity infrastructure. Because long-term projections are extremely difficult to make with confidence, this case study focuses on the costs of starting a carbon neutral infrastructure program and current levels of capital investment, rather than attempting to predict future levels of economic and capital markets activity. The case study's focus on years 1-20 of a 50-year carbon neutral infrastructure program is described more fully below.

The IEA study compared projected investment to global savings and GDP. In contrast, this case study focuses on comparison of hypothetical investment in carbon neutral electricity infrastructure to historic and projected levels of utility industry infrastructure investment and capital markets capacity. Comparison to historic and projected levels of investment in the utility sector and capital markets activity is appropriate because it provides important perspective on the feasibility of raising the investment capital necessary to develop carbon neutral infrastructure from the perspective of firms and capital markets. As noted above, this case study also examines the IEA's savings and GDP projections to supplement the capital markets analysis.

This case study makes a number of assumptions with respect to cost estimates, capital markets data, and supply chains that should be noted.

The cost estimates for 10 TW to 15 TW of carbon neutral electricity infrastructure are subject to the detailed assumptions set forth in Chapter 2 in the section describing these cost estimates.

Most of the analysis in this case study compares capital markets capacity to the financial requirements to develop 10 TW of carbon neutral electricity infrastructure within a 50-year period. The choice of 10 TW for global electricity infrastructure is a reasonable, perhaps conservative, projection of electricity growth within 50 years based upon the International Energy Agency's estimate of 7 TW of conventional electricity generation by 2030 (International Energy Agency 2003). The 15 TW estimate for carbon neutral electricity generation provides a high-consumption estimate of potential electricity demand by 2050 for purposes of comparison.

The cost estimates for carbon neutral electricity infrastructure are based on electricity generation only, and do not account for additional costs associated with other energy sectors, such as transportation. Approximately 10 TW of carbon neutral energy by 2050 is required to stabilize carbon dioxide levels at the 550 ppm level (Hoffert et al. 2002). In order to stabilize carbon dioxide levels at 450 ppm to 350 ppm, we would be required to develop an estimated 20 TW to 30+ TW of carbon neutral energy during the same period (Hoffert et al. 2002). This would require increasing the estimated infrastructure investment levels and would involve the other sectors of the energy industry, such as transportation and liquid fuels. Also, these estimates do not include the costs associated with climate change itself.

The future capacity of debt and equity markets to raise the necessary capital depends upon a number of macroeconomic factors beyond the scope of this case study. In addition, the capital markets data used here may not capture all transactions, notably private transactions, transactions structured in forms that are not easily classified as either debt or equity (such as certain forms of leases), and may include transactions that overestimate capital raising activity such as exchanges or conversions of debt and equity to the extent these transactions do not raise additional capital. In addition, the use of this data is subject to further assumptions that are noted below in the specific section presenting the particular capital markets data.

The analysis assumes that supply chains are capable of providing the labor and material required to build 10 TW to 15 TW of carbon neutral electricity infrastructure within 50 years. Meeting this goal would require society to mobilize large numbers of people and material, an assumption that may not be realistic and is worthy of further study. The IEA study specifically identified supply chains as a potential barrier to meeting future energy demand in its study of conventional energy (International Energy Agency 2003).

As a result of these assumptions, the analysis presented in this case study should be regarded as a rough comparison of the relative magnitudes of estimated future capital needs and historical capital markets activity levels.

Several points concerning the comparisons made in this case study should be explicitly stated.

Because the case study focuses on capital markets for electricity infrastructure, comparisons are made to projected and historical utility industry infrastructure investment. However, the case study also compares investment levels to the broader energy sector and, in some cases, economy-wide statistics. These broader economic sectors do not typically invest in electricity infrastructure and have different characteristics and risks. Therefore, comparisons to the broader energy markets and economy-wide statistics are intended to provide additional perspective on the capacity of the capital markets only.

Capital markets data is presented for both U.S. and global markets. Comparisons to this data should be matched to the proportionate share of energy infrastructure investment typically raised in the U.S. or global capital markets. Accordingly, where U.S. capital markets data is used, comparison is made with the costs of energy infrastructure financed in U.S. capital markets. Because the U.S. capital markets support investment in energy infrastructure in the United States and other countries, U.S. capital markets' share of energy infrastructure investment should be greater than the U.S. share of global energy consumption, which is approximately 25% (Tester et al. 2005). In this case study, U.S. capital markets are assumed to account for 35% of global capital raising activity. This assumption is based on equity and debt market capitalization data. The New York Stock Exchange, American Stock Exchange and NASDAQ together accounted for 34.7% to 52.0% of global public equity market capitalization during the 1990 to 2005 period, with an annual average of 43.6% over that period, and their year-end 2005 capitalization accounting for 38.2% of global public equity market capitalization (World Federation of Exchanges 2006). Similarly, global bond market data for 2005 shows that approximately 40.5% of domestic and international bonds outstanding were issued by U.S. resident issuers (Bank for International Settlements 2006c). Significantly, these figures do not capture government investments that are not reflected in exchange or banking data. The 35% figure was selected to account for such omissions in data and to provide a conservative estimate of the U.S. capital markets share of global capital markets activity. Significantly, the 35% figure is identical to a McKinsey estimate for the U.S. share of global financial capital as of 2004, which included banking and government financial stock (McKinsey Global Institute 2006). Accordingly, this case study compares U.S. capital markets activity to 35% of global carbon neutral electricity infrastructure investment requirements where U.S. market data is used.

Finally, most of the analysis in this case study focuses on the required investment during years 1-20 to develop carbon neutral electricity infrastructure. The focus on the first twenty years is justified for two reasons. First, any fifty-year cost estimate for infrastructure is highly speculative. Learning effects could reduce the cost estimate. Conversely, changes in the cost of materials or other economic factors could increase the estimate. Further, capital markets capacity becomes difficult to estimate, making the comparisons less meaningful over longer time frames. Second, the initial levels of capital investment required in years 1-20 is adequate to illustrate the degree to which capital markets can support starting a carbon neutral electricity infrastructure program. Significantly, the high initial costs of starting such a program may be the leading reason why an effort to build carbon neutral electricity infrastructure has not yet been undertaken on a large scale.

6.1.1 Projected Capital Requirements for Carbon Neutral Electricity

To develop 10 TW of carbon neutral electricity infrastructure using the portfolio of technologies described in Chapter 2, global investment for electricity generation infrastructure during years 1-20 starts at $1.5 to $2.8 billion per day. Replacement costs would increase capital investment starting in year 21 from $2.2 to $3.5 billion per day, in year 31 from $2.3 to $4.5 billion per day, and in year 41 from $2.9 to $5.0 billion per day. If reserves are not set aside for future carbon sequestration costs, carbon sequestration capital costs associated with coal-fired generation start at approximately $40 million per day and increase to $2.0 billion per day by year 50. Additional investment for storage to supplement intermittent wind and solar generation would add an estimated $63 million per day.

Table 6.2: 10 TW Years 1-50 Global Daily Investment with CCS, Energy Storage, and Solar and Wind Equipment Replacement (US$ millions)

Year	Generation Investment	Storage Capacity Investment	Average Carbon Sequestration Investment	Total Investment
1-20	1,475.7 – 2,770.5	62.9	416.8	1,955.4 – 3,250.2
21-30	2,194.3 – 3,489.1		1,012.2	3,269.4 – 4,564.2
31-40	2,341.4 – 4,498.7		1,409.1	3,813.4 – 5,970.7
41-50	2,864.0 – 5,021.3		1,806.1	4,733.0 – 6,890.3

Source: Author's calculations. Note: Estimates are for actual capacity. See Table 2.10 and its notes for costs and assumptions used in estimates.

Hoffert et al. (2002) estimate that 10 TW of energy by 2050 would stabilize carbon dioxide levels at the 550 ppm level. Achieving 450 ppm or 350 ppm stabilization levels would require approximately 25 TW and 30+ TW of energy. Using 10 TW to 15 TW as a rough approximation of the electricity component of these latter two stabilization scenarios, we derive the cost for 15 TW of carbon neutral electricity infrastructure by increasing the 10 TW cost estimate presented in Table 6.2 by 50%. As explained above, 10-15 TW of carbon neutral electricity infrastructure within 50 years is comparable to the IEA's 7 TW projection for electricity demand by 2030. The results are presented for years 1-20 in Table 6.3 below.

Table 6.3: 10-15 TW Years 1-20 Global Daily Investment with CCS and Energy Storage (US$ millions)

Actual Capacity	Generation Investment	Storage Capacity Investment	Average Carbon Sequestration Investment	Total Investment
10 TW	1,475.7 – 2,770.5	62.9	416.8	1,955.4 – 3,250.2
15 TW	2,213.6 – 4,155.8	94.4	625.2	2,933.1 – 4,875.3

Source: Author's calculations. See Table 2.10 and its notes for costs and assumptions used in estimates.

For purposes of comparison to global capital markets data, Table 6.4 presents annualized global required investment estimates for 10 TW and 15 TW of carbon neutral electricity infrastructure.

Table 6.4: 10-15 TW Years 1-20 Global Annual Investment with CCS and Energy Storage

Actual Capacity	Total Investment (US$ billions)
10 TW	713.7 – 1,186.3
15 TW	1,070.6 – 1,779.5

Source: Author's calculations. See Table 2.10 and its notes for costs and assumptions used in estimates.

Where carbon neutral investment levels are compared to U.S. capital markets data, only 35% of estimated global required investment is used for purposes of evaluating the capacity of United States capital markets. Table 6.5 below adjusts the annual global required investment estimate to match the share expected to be raised in U.S. capital markets. For purposes of comparison with U.S. capital markets activity, the U.S. capital markets share of 10 TW year 1-20 estimated annual required investment is $249.8 billion to $415.2 billion, and the U.S. capital markets portion of the 15 TW year 1-20 estimated annual required investment is $374.7 billion to $622.8 billion.

Table 6.5: U.S. Capital Markets Share of 10-15 TW Years 1-20 Global Annual Investment with CCS and Energy Storage

Actual Capacity	Estimated Annual Investment (US$ billions)
10 TW	249.8 – 415.2
15 TW	374.7 – 622.8

Source: Author's calculations. See Table 2.10 and its notes for costs and assumptions used in estimates.

Note that Table 6.4 and Table 6.5 do not include replacement costs for wind and solar equipment because replacement costs for these technologies are assumed to start in year 21 and year 31, respectively.

6.1.2 Capital Expenditures in the U.S. Utilities and Energy Sectors

To assess the capacity of capital markets to supply the investment capital necessary to develop 10 TW to 15 TW of carbon neutral electricity infrastructure within a fifty-year period, this case study first compares the required investment to past capital expenditures in the utilities and energy sectors.

Table 6.6 below shows capital expenditures by utilities and energy companies in the S&P 500 Index, a leading indicator of the U.S. equities markets. The five-year annual average capital investment during the 2001 to 2005 period is $52.9 billion for the utilities sector, $20.3 billion for the energy sector, and $73.2 billion for the combined utilities and energy sectors.

Table 6.6: S&P 500 Utilities and Energy Sector Capital Expenditures, 1994-2005

Year	S&P 500 Sectors (US$ billions)		
	Utilities	Energy	Combined Utilities & Energy
1994	14.8	10.3	25.1
1995	18.4	12.0	30.4
1996	21.2	18.1	39.3
1997	28.7	21.1	49.8
1998	36.9	16.1	53.1
1999	47.7	14.7	62.3
2000	73.0	13.1	86.1
2001	91.2	18.4	109.6
2002	73.7	18.2	92.0
2003	34.3	18.0	52.3
2004	28.6	20.6	49.2
2005	36.6	26.4	63.1

Source: Factset (2006).

Compared to the approximately $250 to $415 billion annual capital expenditures that would be required in years 1-20 to be raised in the U.S. capital markets to develop 10 TW of carbon neutral electricity infrastructure, the U.S. utilities sector would need to increase annual capital expenditures by a factor of approximately 5 to almost 9 times based on the most recent 5-year average. Achieving a goal of 15 TW of carbon neutral electricity infrastructure would increase the investment figure by 50%. Further, in years 21 to 50, required investment must increase further due to increasing costs of carbon sequestration and replacement of infrastructure.

Comparing required investment for 10 TW of carbon neutral electricity infrastructure to the combined U.S. utilities and energy sector average annual capital investment of $73.2 billion for the 2001 to 2005 period only slightly improves these figures. With the inclusion of energy sector capital expenditures, the years 1-20 annual capital investment must increase by a factor of over 3 to 6 times to develop 10 TW of carbon neutral electricity. However, as required investment estimates are for electricity infrastructure, it is more accurate to make comparisons with utilities industry expenditures.

6.1.3 Projected Global Capital Expenditures for Conventional Electricity Sector

This section compares the estimated global investment required for 10 TW of carbon neutral electricity infrastructure to the IEA's projected investment in conventional electricity infrastructure for the 2001 to 2030 period.

The IEA projects that global conventional energy investment during the 2001 to 2030 period should be $16 trillion. Of this amount, approximately $10 trillion to $11 trillion is for electricity infrastructure (International Energy Agency 2003).

The IEA's 30-year conventional electricity infrastructure investment figure is most appropriately compared to thirty years of carbon neutral electricity infrastructure investment. Table 6.7 sets forth the 30-year carbon neutral electricity infrastructure estimates for 10 TW and 15 TW of power.

Table 6.7: 10-15 TW Years 1-30 Global Annual Investment with CCS, Energy Storage, and Wind Equipment Replacement (US$ billions)

Actual Capacity	Year 1-20 Annual Investment	Year 21-30 Annual Investment	Total 30 Year Investment
10 TW	713.7 – 1,186.3	1,193.3 – 1,665.9	26,207.7 – 40,385.0
15 TW	1,070.6 – 1,779.5	1,789.9 – 2,498.9	39,311.5 – 60,579.0

Source: Author's calculations. See Table 2.10 and its notes for costs and assumptions used in estimates. Note: solar equipment replacement is assumed to start in year 31; these costs are therefore omitted in this table.

For 10 TW of carbon neutral electricity, the 30-year global estimated capital investment would be from $26.2 to $40.4 trillion. This is an increase of approximately 162% to 304% over the IEA's $10 trillion conventional electricity infrastructure estimate.

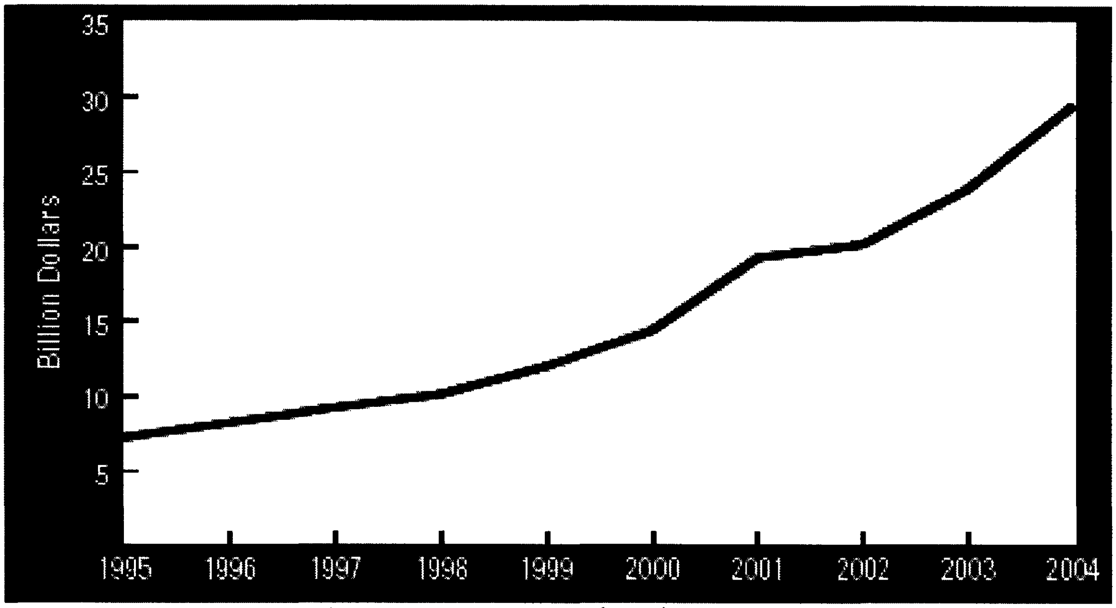
The IEA estimates that its 30-year $10 trillion conventional electricity sector infrastructure investment target represents an increase of almost three times in real terms investment in the electricity sector during the past thirty years (International Energy Agency 2003). The cost of carbon neutral electricity infrastructure is therefore a substantial increase in real terms over both historical and projected conventional energy investment levels.

6.1.4 Required Growth of Renewable Energy Technology Sector

This section compares global required investment to develop 10 TW of carbon neutral electricity infrastructure over a 50-year period to current levels of investment in renewable energy technology. This comparison provides a perspective on the growth required in the renewable energy technology sector to develop carbon neutral electricity infrastructure.

For 2004, annual global investment in wind, solar, geothermal, small hydropower and biomass energy technology was approximately $30 billion (REN21 Renewable Energy Policy Network 2005). This figure does not include investment in large hydropower, nuclear, carbon sequestration, and IGCC technology. Annual investment in hydropower and nuclear is estimated to be approximately $20-25 billion and $7 billion, respectively (see Table 2.7 and Table 2.8). Investment in carbon sequestration and IGCC is currently insignificant. Aggregate annual renewable energy technology investment, including large hydropower and nuclear energy, is approximately $62 billion.

Figure 6.1: Global Annual Investment in Renewable Energy, 1995-2004



Source: REN21 Renewable Energy Policy Network (2005). Note: Note: includes wind, solar PV, solar thermal, geothermal, small hydropower, biomass power and heat.

The global annual investment required to develop 10 TW of carbon neutral electricity infrastructure during years 1-20 of a 50-year build-out is approximately $714 to $1,186 billion per year. Thus, current carbon neutral energy investment must increase by a factor of approximately 12 to 20 times in order to meet required annual investment levels during the first twenty years of such a program.

6.1.5 U.S. Public Debt and Equity Capital Markets Activity

This section compares the estimated required investment in carbon neutral electricity infrastructure to the level of public debt and equity transactions in the U.S. capital markets. Comparisons are made to the following capital markets segments: (a) utility and energy sector, (b) oil and gas sector, (c) combined oil and gas, utility and energy sectors ("all energy"), and (d) all industry sectors.[21]

Table 6.8 presents data for U.S. public debt and equity transactions for the years 1993 to 2005 for the utility and energy, oil and gas, and all energy sectors.

[21] The utility and energy sector figures includes all energy capital markets transactions except oil and gas industry transactions. All industry sectors include all economic sectors (including service industries) that raise public debt and equity in U.S. capital markets.

Table 6.8: U.S. Public Debt and Equity Transactions – Energy (US$ millions), 1993-2005

Year	Oil & Gas			Utility & Energy			All Energy
	Debt	Equity	Total	Debt	Equity	Total	Total
1993	9,421.3	8,207.1	17,628.4	52,126.5	3,140.5	55,267.0	72,895.4
1994	5,249.0	5,239.2	10,488.3	12,957.2	2,485.7	15,442.8	25,931.1
1995	6,199.4	4,661.0	10,860.3	11,828.2	2,544.3	14,372.5	25,232.8
1996	10,542.7	7,361.3	17,903.9	13,002.7	3,694.5	16,697.2	34,601.1
1997	14,495.5	7,966.8	22,462.3	21,046.1	5,952.6	26,998.7	49,461.0
1998	22,799.7	7,267.0	30,066.7	33,914.2	9,787.2	43,701.4	73,768.1
1999	22,441.2	5,201.7	27,642.9	39,226.7	8,871.2	48,097.9	75,740.8
2000	14,037.9	10,047.8	24,085.6	38,130.0	11,611.9	49,741.9	73,827.6
2001	31,993.8	8,050.1	40,043.9	72,088.0	21,007.5	93,095.5	133,139.4
2002	23,568.9	5,446.7	29,015.6	48,926.5	20,243.4	69,170.0	98,185.5
2003	15,749.6	13,960.8	29,710.4	60,639.5	12,777.7	73,417.2	103,127.6
2004	15,467.3	13,636.0	29,103.3	42,141.0	9,596.4	51,737.4	80,840.7
2005	12,313.3	19,882.1	32,195.4	34,250.4	7,511.2	41,761.6	73,957.0

Source: Bernstein Research (2006).

Table 6.9 presents data for U.S. public debt and equity transactions for all industrial sectors during the 1993 to 2005 period.

Table 6.9: U.S. Public Debt and Equity Transactions – All Industries (US$ millions), 1993-2005

Year	All Industry Sectors		
	Debt	Equity	Total
1993	294,175.66	111,832.80	406,008.46
1994	164,838.68	68,854.56	233,693.24
1995	209,592.68	96,889.28	306,481.96
1996	299,816.42	139,715.04	439,531.46
1997	430,857.92	146,061.58	576,919.50
1998	577,757.80	147,432.30	725,190.10
1999	546,737.49	196,370.79	743,108.28
2000	504,329.62	230,808.81	735,138.43
2001	784,797.56	214,449.36	999,246.92
2002	592,229.74	142,591.38	734,821.12
2003	703,920.94	166,265.07	870,186.01
2004	733,962.93	176,269.98	910,232.91
2005	682,124.58	160,965.98	843,090.56

Source: Bernstein Research (2006).

For purposes of comparison, Table 6.10 presents 3-year, 5-year, and 10-year averages for U.S. public debt and equity transactions for the four economic segments.

Table 6.10: U.S. Public Debt and Equity Transactions – Averages (US$ millions), 1996-2005

Period	Utility & Energy	Oil & Gas	All Energy	All Industry Sectors
3 years (2003-2005)	55,638.74	30,336.37	85,975.10	874,503.16
5 years (2001-2005)	65,836.33	32,013.72	97,850.04	871,515.50
10 Years (1996-2005)	51,441.88	28,223.00	79,664.88	757,746.53

Source: Author's calculations based on Bernstein Research (2006).

Table 6.11 compares the 5-year average for the four U.S. capital markets segments to the U.S. capital markets share of required annual investment in carbon neutral electricity infrastructure for years 1-20.

Table 6.11: U.S. Public Debt and Equity Average (2001-2005) versus U.S. Capital Markets Share of 10-15 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure

Actual Capacity Target	Utility & Energy	Oil & Gas	All Energy	All Industry Sectors
10 TW	3.8 to 6.3	7.8 to 13	2.5 to 4.25	0.29 to 0.48
15 TW	5.7 to 9.5	11.7 to 19.5	3.8 to 6.4	0.44 to 0.72

Source: Author's calculations. See Table 6.5 and Table 6.10 for data used in this table. Note: The table presents the results of the comparison as a multiple indicating how many times investment in the particular capital markets segment must increase (if greater than 1) over the 5-year average in order to supply the annual investment target for carbon neutral electricity infrastructure. A multiplier of less than 1 indicates that the volume of investment for the particular capital markets segment is greater than the target investment.

Combined annual capital markets activity for all energy segments are presently inadequate to supply the capital necessary to develop 10 TW of carbon neutral electricity infrastructure; public debt and equity transactions must increase by at least a factor of 2.5 to 4.25 times over current levels to achieve the target investment amount during years 1-20. The utility and energy segment alone must increase by 3.8 to 6.3 times over current levels to achieve the target investment during years 1-20.

Importantly, the proceeds of public debt and equity transactions are used for more than capital investment. For example, they may be used for recapitalization of existing debt, transaction costs, operating expenses, and compensation. As a result, these estimates likely underestimate the magnitude of the required increase in capital markets activity.

Only the capital resources of the entire U.S. capital markets are adequate to supply the capital required to meet the investment targets required for 10 TW of carbon neutral electricity infrastructure. If the proceeds of all U.S. public debt and equity transactions were available to develop 10 TW of carbon neutral electricity during years 1-20 of the build-out, it would require approximately a third to a half of all capital currently raised in U.S. capital markets. However, in years 21-50, assuming that the proceeds of all U.S. public debt and equity transactions are available to develop carbon neutral electricity infrastructure, the entire proceeds of U.S. public debt and equity transactions would be inadequate and would have to increase by a factor of up to 2.9 times over their 5-year average (2001-2005) in order to supply the required investment capital. Such demand for capital would likely have deleterious effects on interest rates and draw resources from other essential industries.

6.1.6 U.S. Private Equity Transactions – Venture Finance

Venture finance provides funding to start-up companies, typically focusing on new technologies or innovative ideas that have large growth potential. The U.S. venture capital market is the largest and most developed. However, the level of venture finance activity in the energy industry has typically been low. Table 6.12 below shows that investment levels reached $1.1 billion in 2005, less than 0.26% to 0.44% of the U.S. capital markets share of required annual year 1-20 investment to develop 10 TW of carbon neutral electricity capacity.

Table 6.12: U.S. Energy/Industrial Venture Capital Fund Capital, 2004-2005

Year	Number of Funds	Total Capital Raised (US$ millions)
2004	12	241.20
2005	16	1,096.3

Source: Thomson Venture Economics (2006).

Importantly, the explosive growth of venture finance activity in the energy industry reflects its relative inexperience in this sector. From 2004 to 2005, venture finance investment levels in energy technology increased 355%. Prior to 2004, activity was insignificant (Thomson Venture Economics 2006). Historically, very few venture firms are involved in the energy field (see Gompers et al. 2006).

Table 6.13 presents U.S. venture finance activity from 1996 to 2004 for all sectors of the economy. The five-year annual average (2000-2004) is $41 billion. Even if all venture finance capital was raised for the purpose of supporting the electricity sector, it would amount to only 10% to 17% of the U.S. capital markets share of required annual year 1-20 investment to develop 10 TW of carbon neutral electricity infrastructure.

Table 6.13: U.S. Venture Finance Transactions (US$ millions), 1996-2004

Year	Number of Transactions	Total Investment
1996	2,613	11,513.5
1997	3,184	14,907.2
1998	3,689	21,346.7
1999	5,613	54,603.6
2000	8,073	105,892.1
2001	4,619	41,015.3
2002	3,050	21,580.3
2003	2,847	18,946.2
2004	2,876	20,940.6

Source: VC Experts (2006c).

It is important to note that venture capital is subject to several important limitations that make it unsuitable for sustained investment in infrastructure. First, venture finance investment is not usually employed for established technologies. Venture capital is based on a strategy of high risk and large returns, not the approximately 10% return on investment typically earned in the U.S. electricity sector (International Energy Agency 2003). Further, venture funds seek rapid returns; the target investment return period for venture capital is typically less than seven years (VC Experts 2006a). This makes venture capital more appropriate for new inventions, rather than for supporting sustained investment in long-term infrastructure.

Second, venture finance investment and portfolio companies are highly volatile. From a peak in 2000, venture finance investment dropped by almost 80% in 2004 (VC Experts 2006c). Another important aspect of volatility is the high failure rate of start-up companies. Gompers et al. (2006) estimate that venture companies have a success rate of approximately 50% to 60%.[22] A recent survey of new companies based on U.S. government economy-wide employment data suggests that the figure is slightly lower, below 50% after four years of operation (Knaup 2005).

Finally, while the skill set of venture capital funds and their portfolio companies are critical to developing new technology, including in the renewable energy area, these firms typically lack the skills and resources required to finance and develop large-scale infrastructure. Only large firms with strong balance sheets, established customer bases, and stable revenues have been able to attract the capital necessary to finance electricity generation infrastructure (International Energy Agency 2003).

6.1.7 U.S. Private Equity Transactions – Energy and All Sectors

In addition to venture finance transactions for start-up firms in new technologies, established energy firms also engage in private equity transactions. Unlike venture capital firms, established energy firms possess the expertise and resources necessary to develop energy infrastructure.

The five-year annual average (2001-2005) for energy-related private transactions is $2.7 billion, almost three times higher than investment levels for energy investment by venture finance firms. However, this is still only 0.65% to 1.08% of the U.S. capital markets share of required annual year 1-20 investment to develop 10 TW of carbon neutral electricity infrastructure.

[22] The estimate may overstate success rates if the study omits start-ups that fail before they are reflected in the data.

Table 6.14: U.S. Private Equity Transactions – Utilities, Energy, Oil and Gas, 1996-2005

Year	Number of Transactions	Average Transaction Size (US$ millions)	Total Investment (US$ millions)
1996	53	7.54	399.58
1997	64	10.23	654.57
1998	110	15.95	1,754.06
1999	68	20.41	1,387.81
2000	142	14.71	2,089.17
2001	140	8.38	1,173.62
2002	99	13.29	1,315.89
2003	137	24.48	3,353.86
2004	187	24.27	4,539.29
2005	173	18.16	3,141.15

Source: Thomson Investment Analytics (2006).

Even considering all U.S. private equity transactions for all sectors combined, the five-year annual average (2001-2005) of $55.45 billion is only 13% to 22% of the $250 to $415 billion annual capital expenditure that would be required to be raised in the U.S. capital markets to develop 10 TW of carbon neutral electricity infrastructure in years 1-20.

Table 6.15: U.S. Private Equity Transactions – All Sectors, 1996-2005

Year	Number of Transactions	Average Transaction Size (US$ millions)	Total Investment (US$ millions)
1996	3,730	6.50	24,257.49
1997	4,376	6.43	28,131.83
1998	5,443	8.12	44,175.68
1999	6,562	13.53	88,812.49
2000	9,509	15.21	144,667.48
2001	6,086	10.37	63,099.68
2002	4,104	11.46	47,047.08
2003	3,942	15.80	62,278.92
2004	4,186	12.79	53,533.86
2005	4,462	11.49	51,288.68

Source: Thomson Investment Analytics (2006).

6.1.8 U.S. and Global Bank Lending

This section compares bank lending activity to investment levels required to develop carbon neutral electricity infrastructure.

Table 6.16 below presents lending by U.S. domestic banks, foreign bank branches, and Edge Act banks located in the fifty U.S. states and the District of Columbia that report to the Federal Reserve Bank. The table presents lending by these banks to domestic and international borrowers for all sectors of the economy, which is comprised of the following categories: commercial and industrial, real estate, consumer loans, loans to purchase securities, and other loans and leasing. The commercial and industrial and other loans and leasing categories include loans and leasing arrangements to the electricity sector and are therefore presented separately.

Table 6.16: U.S. Bank Lending (US$ billions), 2001-2005

Year (as of December)	All Sectors	Commercial and Industrial	Other Lending and Leasing
2001	3,934.2	1,026.0	425.4
2002	4,166.7	962.4	403.6
2003	4,404.1	902.3	425.3
2004	4,858.7	927.8	471.1
2005	5,449.4	1,044.1	524.6
3 Year Average Annual Growth (2003-2005)	348.4	47.3	33.1

Source: Federal Reserve Board of Governors (2006).

The three-year average annual increase (2003-2005) in loans to all sectors of the economy is $348.4 billion, of which $80.4 billion is commercial and industrial and other lending and leasing combined.

Comparing the 3-year average annual increase in lending by the U.S. bank lending sector to the U.S. portion of required annual investment for years 1-20 to produce 10 TW of carbon neutral electricity infrastructure demonstrates that lending markets are not currently large enough to provide the required capital. Over the 2003-2005 period, lending to the combined commercial and industrial and other lending and leasing categories grew by only $80.4 billion each year, only 19% to 32% of the U.S. capital markets share of the required $250 to $415 billion annual investment for 10 TW of electricity infrastructure in years 1-20. Even the $384 billion average annual growth in lending for all sectors of the economy might be inadequate to supply the U.S. capital markets share of the required capital, depending upon actual costs given the estimated range of $250 to $415 billion per year.

Importantly, comparisons based on U.S. bank lending data overestimate the amount of credit available to the electricity sector due to the composition of the data. The "all sectors" category and the "industrial and commercial" and "other lending and leasing" subcategories supply capital to many other segments of the economy. These loans also provide capital for more than just capital investment. In addition, this data does not make any distinction between short and long-term lending.

Global debt issued by power projects from 1991 to 2002 confirm that current levels of lending to the global electricity sector would also be inadequate to provide the capital necessary to develop carbon neutral electricity infrastructure. Electricity project debt peaked in 2001 at approximately $130 billion, and then dropped by 40% in 2002 (International Energy Agency 2003). Global lending levels for electricity are far short of the estimated years 1-20 global annual investment of $714 to $1,186 billion required to develop 10 TW of carbon neutral electricity over a 50-year period. At the peak of lending in 2002, global lending only provides approximately 11% to 18% of required global carbon neutral electricity investment.

6.1.9 Global Bond Markets

This section examines the capacity of global bond markets to supply the required capital to develop carbon neutral electricity infrastructure. Because this section considers global bond markets, it uses global investment levels for carbon neutral electricity. Table 6.4 above presents the global annual investment required for years 1-20 to develop 10-15 TW of carbon neutral electricity infrastructure. To develop 10 TW of carbon neutral electricity capacity, the required global annual capital investment is estimated to be $713.7 billion to almost $1.2 trillion during years 1-20.

Global bonds outstanding reached approximately $58.9 trillion in 2005 for government, financial institution, and corporate issuances combined. However, 2-year average annual growth (2004-2005) in global bond issuances was only $4.1 trillion for all issuers.

Table 6.17: Global Bonds Outstanding and 2-Year Average Growth (US$ billions), 2004-2005

	December 2003	December 2004	December 2005	Annual Average Growth
International	11,705.7	13,945.7	14,634.5	1,464.4
Domestic	39,042.6	43,787.8	44,314.6	2,636.0
Total	50,748.3	57,733.5	58,949.1	4,100.4

Source: Bank for International Settlements (2006c).

Comparing the $4.1 trillion annual average increase in global bond issuances to the required global annual investment to develop 10 TW of carbon neutral electricity infrastructure shows that carbon neutral energy investment would consume 17.4% to 28.9% of annual growth in global bond issuances during years 1-20 of a 50-year build-out.

Table 6.18: Global Bonds Annual Average Growth in All Issuances (2003-2005) versus 10-15 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure

Generation	Required Annual Investment (US$ billions)	Annual Average Growth Bonds (US$ billions)	Minimum Percentage of New Issuances	Maximum Percentage of New Issuances
10 TW	713.7 – 1,186.3	4,100.4	17.4%	28.9%
15 TW	1,070.6 – 1,779.5		26.1%	43.4%

Source: Author's calculations. . See Table 6.4 and Table 6.17 for data used in this table.

Up to now, no distinction has been made between bond issuances by governments, financial institutions, and corporations. Table 6.19 below shows the total principal amount of bonds outstanding of each of these types of issuers as of December 2005.

Table 6.19: Global Bonds Outstanding by Issuer (US$ billions), December 2005

	International	Domestic	Total	Percentage
Government	1,437.0	21,618.5	23,055.5	39.1%
Financial	11,105.9	17,546.4	28,652.3	48.6%
Corporate	1,547.2	5,149.7	6,696.9	11.4%
Int. Organizations	544.4	N/A	544.4	0.9%
Total	14,634.5	44,314.6	58,949.1	100%

Source: Bank for International Settlements (2006c).

Government and international organization issuances accounted for 40% of global bonds outstanding at the end of 2005. If the government and international organization issuances are excluded from the analysis, approximately 26.8% to 44.6% of average annual increases in private sector bond issuances would be consumed by developing 10 TW of carbon neutral electricity infrastructure during years 1-20 if bonds were the only source of capital. If only corporate issuances are considered, further excluding financial institution bond issuances, the approximately $228.8 billion average annual increase (2004-2005) in corporate issuances must increase by a factor of 3 to 5 times in order to provide the required investment capital to develop 10 TW of carbon neutral electricity infrastructure in years 1-20.

Table 6.20: Global Bonds Annual Average Growth in Corporate and Financial Issuances (2004-2005) versus 10-15 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure

Actual Capacity	Required Investment (US$ billions)	Average Annual Corporate/Financial Bond Growth (US$ billions)	Minimum Percentage of New Issuances	Maximum Percentage of New Issuances
10 TW	713.7 – 1,186.3	2,660.1	26.8%	44.6%
15 TW	1,070.6 – 1,779.5		40.2%	66.9%

Source: Bank for International Settlements (2006c); Table 6.4, Table 6.17, and Table 6.19.

The above analysis does not take into consideration the tenor of bonds. Short-term tenors are not appropriate for financing long-term infrastructure projects. Data is not available for the tenor of new bond issuances. However, data is available for bonds outstanding that mature within a year or less. As of December 2005, $10,625.6 billion of domestic bonds and $2,422.5 billion of international bonds had maturities of one year or less (Bank for International Settlements 2006c). Thus, approximately 22% of outstanding bonds mature within one year. To the extent that new bond issuances possess short tenors, they reduce the capacity of the global bond market to finance carbon neutral electricity infrastructure.

6.1.10 Internal Funds

In addition to capital markets, the availability of funds generated by utility firms from operations will be essential to their ability to develop carbon neutral electricity infrastructure. Banks may require as much as 50% of the required investment to be provided by the project sponsors in the form of equity and will require firms to show adequate assets and revenues to support loan repayment.

Currently, the financial condition of utilities on a global basis suggests that they would experience difficulty raising the required amount of investment capital from profits to develop carbon neutral electricity infrastructure on the scale contemplated here. According to the IEA, utilities in OECD countries that have liberalized electricity markets face increasing competition, less certain revenue streams, lower profit margins, and in many cases, large operating losses and debt (International Energy Agency 2003). Utilities in developing countries, especially state-owned utilities, similarly face severe financial difficulties (International Energy Agency 2003).

Further, utilities would also face limits on their ability to obtain loans due to adequacy of assets. According to the IEA, electricity generation and downstream gas are the only two industries in which debt/equity ratios exceed 50%, meaning that debt exceeds equity (International Energy Agency 2003).

Significantly, the financial condition of utilities may already be limiting their ability to raise the capital necessary to support conventional infrastructure development. Electricity reserve margins have declined in liberalized electricity markets, reflecting underinvestment in electricity infrastructure (International Energy Agency 2003).

To place into perspective the degree to which electricity utilities can finance carbon neutral infrastructure from internally generated funds, we compare the required investment to develop 10 TW of carbon neutral electricity infrastructure to earnings figures for utilities. The Edison Electric Institute tracks the combined financial results for sixty-five U.S. shareholder-owned electric utilities and six additional regulated utilities that serve the United States market, together representing approximately 60% of U.S. power generation. During the 2004-2005 period, the annual average earnings, after adding back depreciation and amortization expenses, totaled $56.9 billion (Edison Electric Institute 2006b).

Table 6.21: U.S. Shareholder-Owned Electric Utility Earnings (US$ millions), 2004-2005

Earnings Item	2004	2005
Earnings Excluding Non-Recurring and Extraordinary Items	23,264	27,667
Depreciation & Amortization	30,460	32,482
Total	53,724	60,149

Source: Edison Electric Institute (2006b).

In order to compare the annual earnings of these U.S. shareholder-owned utilities to required investment levels to develop 10 TW of carbon neutral electricity infrastructure, it is necessary to match the earnings figure with the proportionate level of carbon neutral electricity infrastructure investment that corresponds to 60% of the U.S. electricity utility sector. Assuming U.S. electricity consumption is approximately 25% of global demand (Tester et al. 2005), the U.S. portion of global annual investment to develop 10 TW of carbon neutral electricity infrastructure is 25% of $713.7-1,186.3 billion during years 1-20, or $178.4-296.6 billion per year during years 1-20. Further taking into consideration that the $56.9 billion average annual income figure represents only 60% of U.S. power generation, the annual investment to develop 10 TW of carbon neutral electricity infrastructure for 60% of the U.S. electricity industry is $107.1-177.9 billion.

Comparing $56.9 billion of earnings before depreciation and amortization to the $107.1-177.9 billion annual investment target suggests that internal funds are available to support carbon neutral infrastructure development. However, the entirety of profits would not be available to reinvest in operations because management must provide a competitive return to shareholders in order to maintain the share value of these firms and to attract additional capital.

6.1.11 International Disparities

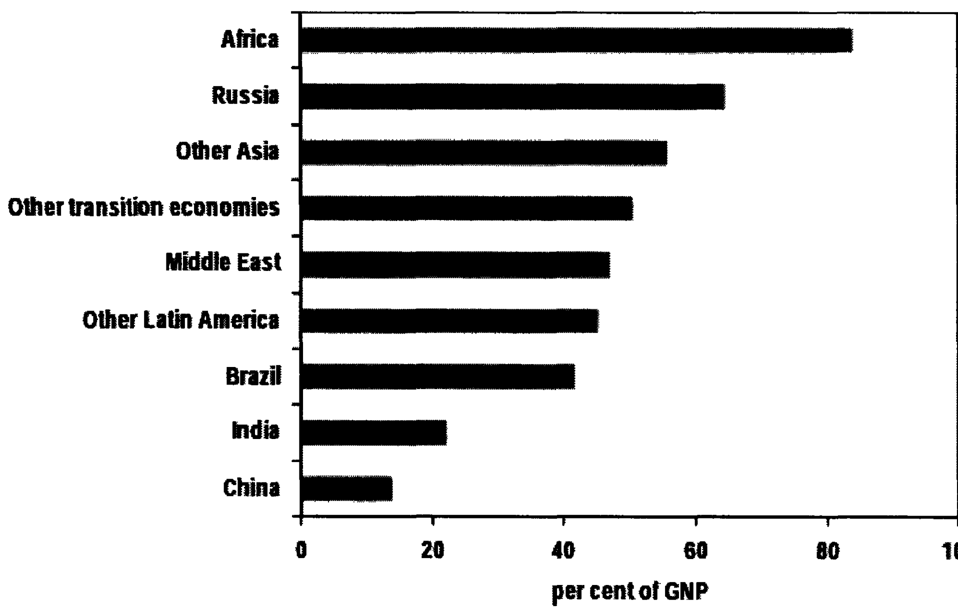
Up to now, the case study has examined the capacity of capital markets from a global and U.S. capital markets perspective. No distinction has been made among countries or regions with respect to the ability to access capital markets due to different risk profiles, and economic and investment conditions.

Different nations have different risk profiles. Countries that have deregulated electricity markets or are considering deregulation provide firms with less certainty in regulatory frameworks and revenues. Similarly, disparate national environmental regulations can create significant differences in the competitive positions of utilities (International Energy Agency 2003). For example, in the United States, environmental regulations introduced in the 1960's and 1970's have been one of the most important sources of capital cost increases in electricity generation (Joskow and Rose 1985).

The greatest difference among countries, however, is between developed and developing countries. The IEA predicts that approximately 60% of projected conventional energy investment during the 2001-2030 period will occur in non-OECD countries (International Energy Agency 2003). Yet, developing countries possess fewer financial resources and poor conditions to raise the required investment for either conventional energy infrastructure or carbon neutral energy infrastructure.

Developing countries that are politically or economically unstable face higher risks associated with exchange rates, inflation, and political conditions. These countries typically have underdeveloped private sectors. Countries with high external debt levels will face limits on their ability to attract the necessary capital to finance carbon neutral infrastructure. With the exception of China and India, total external debt of non-OECD countries typically exceeds 40% of GDP, with transition economies in Asia approaching 60%, and African countries exceeding 80% of GDP (International Energy Agency 2003).

Figure 6.2: External Debt by Region, 2001

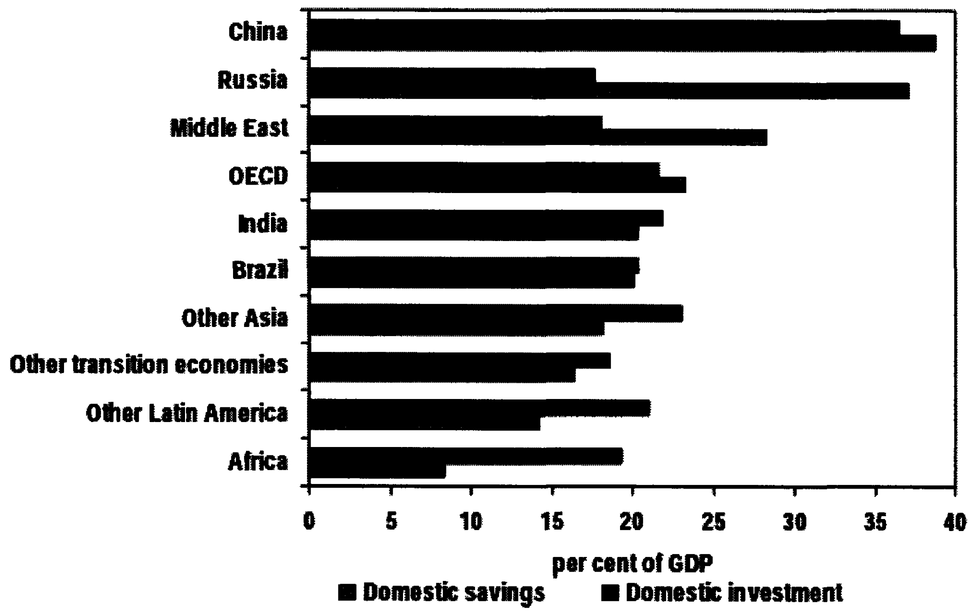


Source: World Bank (2003), as presented in International Energy Agency (2003).

Domestic savings is the single most important source of funds for infrastructure finance in industrial countries (International Energy Agency 2003). In contrast, domestic savings rates are also among the lowest in developing countries. For example, Africa's savings rate is under 10% of GDP, and the savings rates of Latin American and most transition economies on average range from 15% to 20% of GDP (International Energy Agency 2003). Oil producing countries of the Middle East, Russia and China have exceptionally high savings rates, exceeding 30% of GDP on average in Middle East countries, and approaching 40% of GDP in Russia and China. In addition, China's government sector has been the largest supplier of capital in that country for infrastructure projects (International Energy Agency 2003).

A comparison of domestic savings to domestic investment in Figure 6.3 shows that developing countries generally spend more than they save as a percentage of their GDP. With the exception of OECD countries, China, Russia, and some countries in the Middle East, most countries spend more on domestic investment than they save (International Energy Agency 2003). Countries that do not have adequate savings face potential difficulties financing energy infrastructure on a conventional or carbon neutral basis.

Figure 6.3: Domestic Savings and Investment by Region, 2000



Source: World Bank (2003), as presented in International Energy Agency (2003).

Capital markets development also differs greatly among countries. A recent McKinsey study estimates that 80% of the world's financial capital is located in North America, Japan, and Europe (McKinsey Global Institute 2006). Debt markets in these three areas are the most developed, accounting for 89% of all international bond issuances by nationality of issuer, and 94% of domestic bond issuances (Bank for International Settlements 2006b). Further, debt markets in developing countries typically are dominated by short-term debt, which is poorly suited for long-term energy projects (International Energy Agency 2003). Similarly, equity markets in non-OECD countries are much smaller than in OECD countries. As measured by the value of listed shares divided by GDP, non-OECD equity markets are 20-40% of the size of OECD equity markets (International Energy Agency 2003).

As a result of the relative weaknesses in the economies and capital markets of developing countries, developing countries have experienced difficulty attracting the level of investment achieved in OECD countries for infrastructure investment in general, and the capital-intensive power sector in particular. In 2002, non-OECD countries attracted only 25% of foreign direct investment (International Energy Agency 2003). Private investment in developing countries peaked at $52 billion before the Asian currency crisis in 1997, and then dropped to $17 billion in 2002. Similarly, private investment for power projects in developing countries reached over $40 billion in 1997, and then dropped to approximately $5 billion in 2002. These levels fall far short of the IEA's projections for conventional energy investment in non-OECD countries.

The burden of energy infrastructure investment is expected to differ greatly among countries. According to IEA projections for the 2001 to 2030 period, conventional energy investment in OECD countries will average 0.5% of GDP and 2.5% of total domestic investment. In contrast, in Africa, Russia and other transitions economies, conventional energy investment will range from 3.5% to 5.5% of GDP and from 20% to over 30% of total domestic investment (International Energy Agency 2003).

6.1.12 Capital Market Volatility and Effects on Firms

The magnitude and duration of capital investment required to develop carbon neutral energy infrastructure raises important issues concerning the volatility of capital markets and the capacity of firms to attract and absorb these levels of investment for sustained periods.

Capital markets are volatile and are subject to dramatic swings between periods of investment, speculative activity, and recession. The technology and broadband build-out of the late 1990's to early 2000's provides the most recent example of the potential effects of rapid growth in investment activity over a short time period. At the peak of investment in 2000, the computer, electronics and telecommunications sectors raised over $201 billion in U.S. public capital markets. From 1994 to 2000, annual capital raised in U.S. public debt and equity markets for these sectors increased by 702%. Table 6.22 below shows public debt and equity transactions in the United States for these sectors from 1993 to 2005.

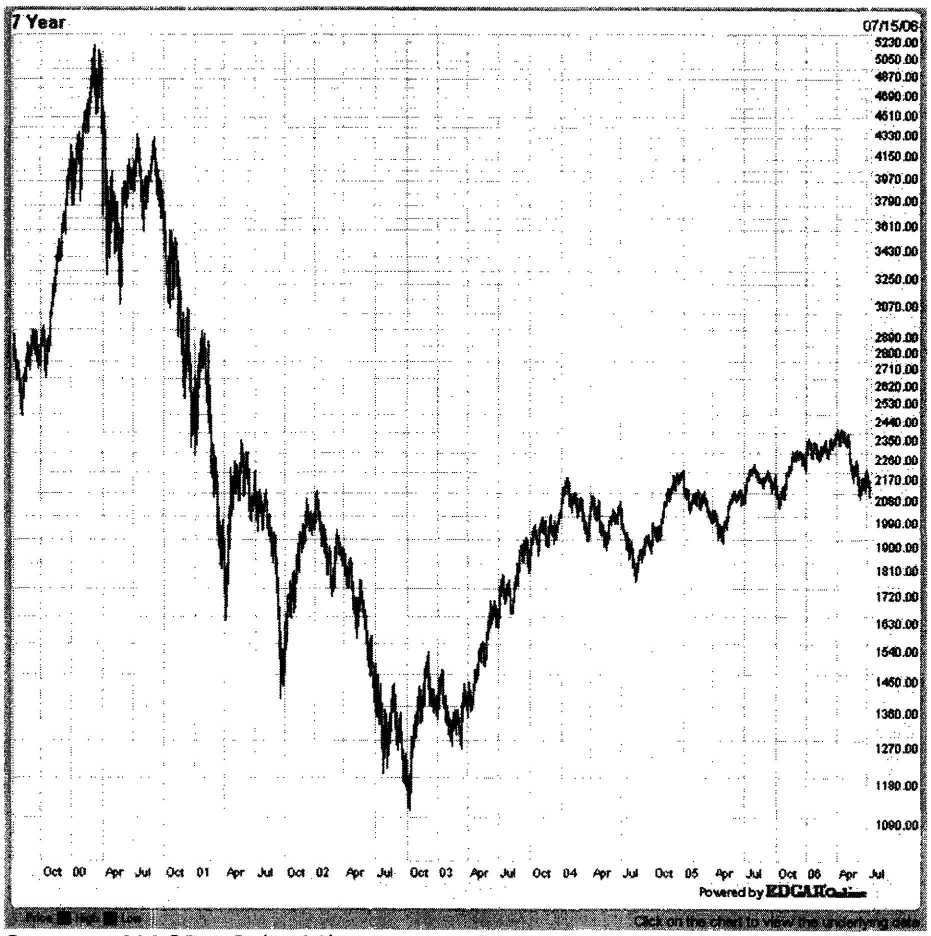
Table 6.22: U.S. Public Debt and Equity Transactions – Computer, Electronics and Telecommunications Industries (US$ millions), 1993-2005

Year	Computer & Electronics		Telecommunications		Total Capital	Number of Transactions
	Debt	Equity	Debt	Equity		
1993	4,672.05	10,629.00	35,617.47	9,562.50	60,481.02	442
1994	2,276.45	6,627.31	12,706.21	3,585.35	25,195.32	299
1995	2,810.72	22,592.61	22,469.96	11,514.79	59,388.08	536
1996	8,205.36	20,771.45	22,898.79	14,883.23	66,758.83	701
1997	10,688.73	19,451.26	38,992.73	10,234.30	79,367.02	613
1998	15,840.39	17,972.58	68,746.53	28,554.88	131,114.38	537
1999	14,184.82	57,876.62	50,610.17	47,178.56	169,850.17	659
2000	16,234.91	89,659.68	49,713.98	46,218.24	201,826.81	552
2001	16,357.99	32,222.07	94,223.35	33,222.99	176,026.40	274
2002	17,233.78	10,573.16	29,978.10	13,433.50	71,218.54	153
2003	13,864.37	24,251.12	39,562.72	12,074.21	89,752.42	275
2004	9,227.10	17,855.47	37,997.32	10,141.58	75,221.47	247
2005	14,481.01	19,275.29	18,257.20	8,415.84	60,429.34	168

Source: Bernstein Research (2006).

The large dollar volume and number of transactions in these sectors resulted in speculative investment activities and stretched the capacity of regulators to monitor financial markets. The results were a dramatic drop in stock market levels following the 2001 peak and a series of accounting and financial scandals. The NASDAQ Composite lost 78% of its value, falling from 5,046.86 points on March 11, 2000, to 1,114.11 points on October 9th, 2002 (Investopedia.com 2006).

Figure 6.4: NASDAQ, September 2000-July 2006



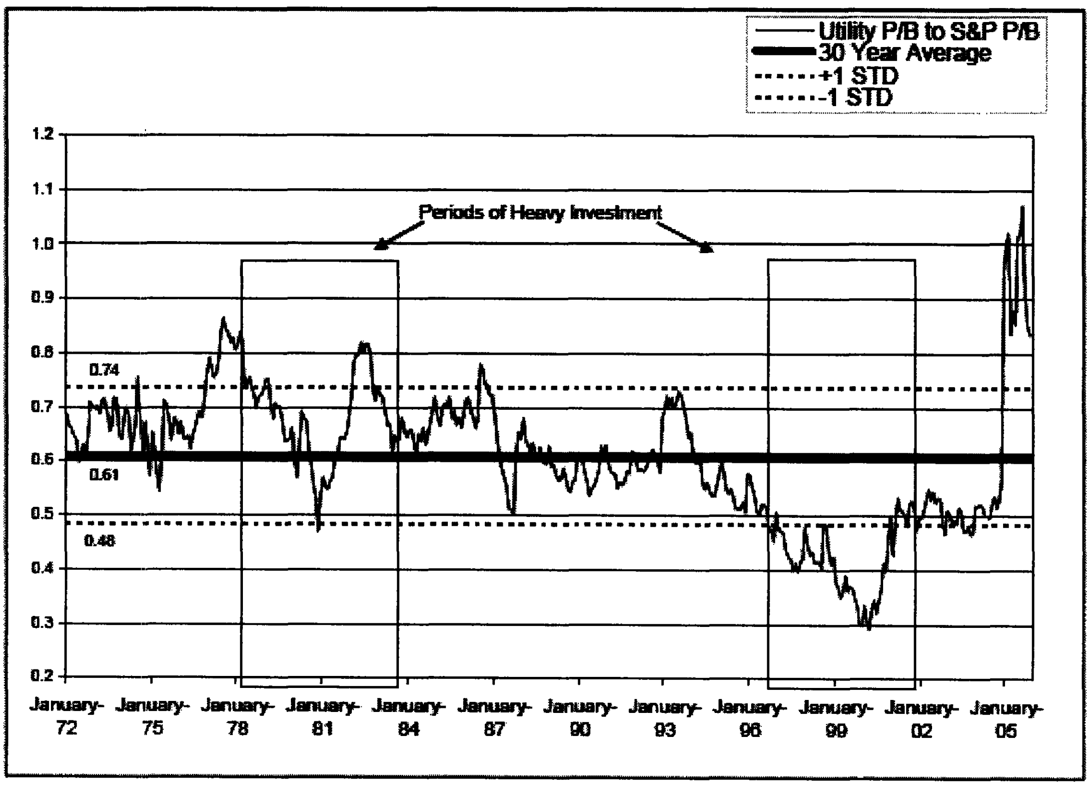
Source: NASDAQ (2006).

Based on the relative volume of investment, the potential for boom-bust cycles to threaten the stability of capital markets supporting carbon neutral electricity infrastructure is even greater than in the technology and broadband build-out. Compared to the almost $202 billion of public debt and equity raised in the computer, electronics, and telecommunications sectors at the peak of investment in 2000, the U.S. capital markets share of annual investment required to develop 10 TW of carbon neutral electricity infrastructure is much higher, ranging from $249.8 to $415.2 billion annually during years 1-20, and then increasing through years 21-50.

It is important to consider the effect of these investment levels in relation to the ability of individual firms to attract and invest capital. For electricity infrastructure, the appropriate analysis focuses on utilities as these firms will be primarily responsible for the investment necessary to develop carbon neutral electricity infrastructure and must recover the costs of this investment from their customer base.

Compared to the investment levels required for carbon neutral electricity infrastructure, relatively small increases in capital expenditures adversely affect the financial performance of utilities. According to a study of the financial performance of forty-one regulated utilities conducted by Lehman Brothers, periods of high capital expenditure depress stock prices, making it more difficult for utilities to raise financing through equity offerings. Potential delays in obtaining regulatory approval to recover capital expenditures further exacerbate the negative effects of heavy investment in the utilities sector (Lehman Brothers 2006).

Figure 6.5: Price-to-Book Ratios – Utilities versus S&P 500, 1972-January 2005

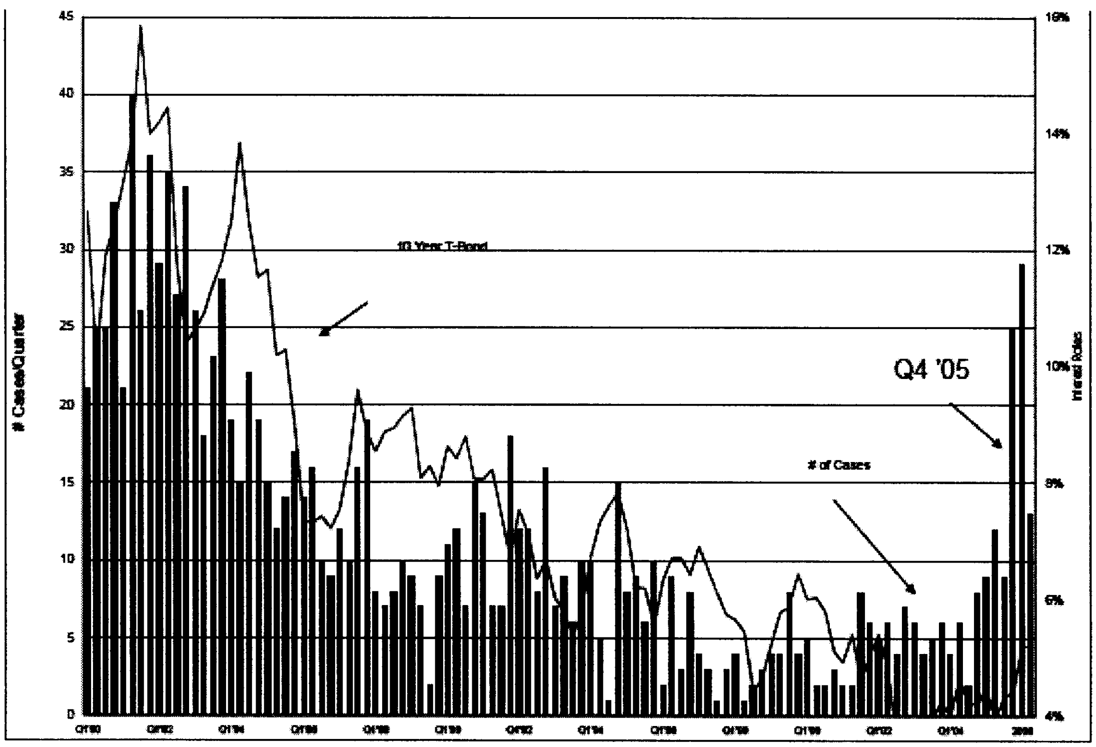


Source: Factset, as presented in Lehman Brothers (2006).

Significantly, based on this analysis, Lehman Brothers concluded that a $15 billion increase in capital expenditure over a two year period would be sufficient to depress the financial performance of the U.S. utilities sector (Lehman Brothers 2006). The five-year average (2001-2005) of annual utility and energy capital expenditures for firms in the S&P 500 Index is $52.9 billion (Factset 2006). Current investment levels are therefore much smaller than the $250 to $415 billion required to be raised annually by utilities in U.S. capital markets to develop 10 TW of carbon neutral electricity infrastructure within a 50-year period.

Increased investment levels will also subject firms to greater financial risk associated with interest rates. Because the utilities industry is one of the most capital intensive industries (International Energy Agency 2003), capital expenditures in the utilities industry closely track interest rates and are highly cyclical. Figure 6.6 below shows the relationship between interest rate cycles and utility investment activity as reflected by the number of filings by utilities to recover the cost of capital investment (Lehman Brothers 2006).

Figure 6.6: Interest Rates Cycles and Utility Rate Cases, Q1 1980-2006



Source: Lehman Brothers (2006).

The volatility and cyclicality of investment suggests that investment in carbon neutral infrastructure will be difficult to maintain over a 50-year period on a consistent basis. This will undoubtedly slow the introduction of carbon neutral energy infrastructure.

Significantly, to the extent that the development of carbon neutral infrastructure involves the replacement of capital equipment, the early retirement of this equipment will further adversely affect the financial condition of utilities. These effects are not reflected in the prior analysis, which is of past financial performance data on a business-as-usual basis. Stranded cost recovery and accounting treatment for equipment that is deemed prematurely obsolete would be important for managing the financial consequences of a carbon neutral energy infrastructure policy.

6.1.13 Relative Contributions of Capital Markets Segments

Each segment of the capital markets would potentially contribute to the development of carbon neutral electricity infrastructure, but no single segment is capable of financing carbon neutral electricity infrastructure alone. This section tabulates the potential contribution of each segment of the capital markets in order to provide an overall picture of the capacity of capital markets to finance carbon neutral electricity infrastructure. This section conducts this analysis in terms of the utilities segment of the U.S. capital markets, all sectors of the U.S. capital markets, and global bond markets.

Table 6.23 compares the utilities segment of the U.S. capital markets to the U.S. capital markets share of global annual investment required to develop 10 TW of carbon neutral electricity infrastructure during years 1-20, which is $250 to $415 billion per year.

We compare required investment to the aggregate of capital expenditures levels among U.S. utilities, increases in utility sector public debt and equity transactions in U.S. capital markets, venture finance and private equity investment in energy, and increases in U.S. bank lending to the industrial and commercial sectors.

Internally generated funds of U.S. shareholder-owned utilities averaged $56.9 billion per year during the 2004-2005 period, after adding back depreciation and amortization expenses (Edison Electric Institute 2006b). However, because profits are essential to attracting further investment, these will not be counted as available for reinvestment for carbon neutral electricity infrastructure. In fact, utilities must generate additional profits to maintain profit levels in order to successfully develop carbon neutral infrastructure.

Table 6.23: U.S. Capital Markets Utilities Sector versus U.S. Capital Markets Share of 10 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure (US$ billions)

U.S. Capital Markets – Sources of Funds Potentially Available to Utilities Industry	Average Annual New Capital	U.S. Capital Markets Share of Global 10 TW Investment Years 1-20	Percentage of Required Investment	
			Minimum Investment	Maximum Investment
U.S. Utility Capital Expenditures (2001-2005)	52.9	249.8 – 415.2	21.2%	12.7%
Public Debt & Equity – Utilities (2001-2005)	65.8		26.3%	15.8%
Venture Capital (2005)	1.1		0.4%	0.3%
Private Equity (2001-2005)	2.7		1.1%	0.7%
Bank Lending (2003-2005)	80.4		32.2%	19.4%
TOTAL	202.9		81.2%	48.9%

Source: Factset (2006); Bernstein Research (2006); Thomson Venture Economics (2006); Thomson Investment Analytics (2006); Federal Reserve Board of Governors (2006); Author's calculations.

To meet required investment levels during years 1-20 to develop 10 TW of carbon neutral electricity infrastructure, the total capital potentially available to the utilities sector as presented in Table 6.23 will be consumed and must increase by at least $47 billion to $213 billion, an increase of 25% to 100%, depending upon the actual costs of development.

These are substantial increases given Lehman Brother's assessment that that a mere $15 billion increase in capital expenditure over two years could adversely affect the financial performance of the U.S. utilities sector (Lehman Brothers 2006). The five-year average (2001-2005) of annual utility and energy capital expenditures for firms in the S&P 500 Index is $52.9 billion (Factset 2006). Current investment levels represent only 12.7% to 21.2% of required investment to develop 10 TW of carbon neutral electricity infrastructure during years 1-20. The required increase in investment represents an increase in capital expenditures by a factor of 5 to almost 9 times.

Importantly, these figures likely overstate the total capital available to the utilities sector for capital improvements. For example, the bank lending data includes all U.S. commercial and industrial lending, not only lending to the utilities sector. Further, utilities use the proceeds of capital markets transactions for a wider variety of purposes than capital expansion.

Nevertheless, the overall utilities sector tabulation suggests that while challenging, the amount of investment capital required to develop carbon neutral infrastructure may be feasible.

To further explore the potential feasibility of raising the required capital, Table 6.24 compares the U.S. capital markets share of required global investment to develop 10 TW of carbon neutral electricity infrastructure to U.S. capital markets activity for all industrial sectors.

Table 6.24: U.S. Capital Markets All Sectors Activity versus U.S. Capital Markets Share of 10 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure (US$ billions)

U.S. Capital Markets – All Industries	Average Annual New Capital	U.S. Capital Markets Share of Global 10 TW Investment Years 1-20	Percentage of Required Investment	
			Minimum Investment	Maximum Investment
Public Debt & Equity (2001-2005)	871.5	249.8 – 415.2	348.9%	209.9%
Private Equity (2001-2005)	55.45		22.2%	13.3%
Bank Lending (2003-2005)	348.4		139.5%	83.9%
TOTAL	1,275.3		510.5%	307.2%

Source: Bernstein Research (2006); Thomson Investment Analytics (2006); Federal Reserve Board of Governors (2006); Author's calculations.

Comparison of required investment levels to all U.S. capital markets suggests that carbon neutral electricity infrastructure investment would become a very large portion of U.S. capital markets activity, consuming almost one-fifth to one-third of increases in U.S. capital markets activity by dollar volume. To place this in perspective, from 1990 to 2005, the utility sector accounted for 5.9% of U.S. public equity transactions and 7.4% of U.S. public debt transactions (author's calculations based on Bernstein Research 2006). Such a large increase in the volume of capital devoted to carbon neutral electricity infrastructure would draw resources from other industries, raising concerns about the stability of such capital flows and the effects on other sectors of the economy.

Finally, Table 6.25 compares global bond markets capacity to the global investment required to develop 10 TW of carbon neutral electricity infrastructure during years 1-20.

Table 6.25: Average Annual Growth in All Global Bond Issuances (2004-2005) versus 10 TW Years 1-20 Global Annual Investment in Carbon Neutral Electricity Infrastructure (US$ billions)

Global Bonds By Issuer	Annual Average Growth in Issuances (2004-2005)	Global Required Investment 10 TW Years 1-20	Percentage of Required Investment	
			Minimum Investment	Maximum Investment
Corporate and Financial	2,660.1	713.7 - 1,186.3	26.8%	44.6%
Government, Corporate and Financial	4,100.4		17.4%	28.9%

Source: Bank for International Settlements (2006c); Author's calculations.

The global debt securities market comparison confirms that carbon neutral electricity infrastructure would consume a large portion of growth in global capital markets activity. Global investment levels required to develop 10 TW of carbon neutral electricity infrastructure during years 1-20 would consume from 27% to 45% of growth in corporate and financial debt issuances. Including the government sector, required investment would consume 17% to 29% of growth in all global debt securities issuances.

6.1.14 Growth Potential of Capital Markets

The foregoing analysis raises the question whether the capital markets can grow to supply the levels of investment required to develop carbon neutral electricity infrastructure.

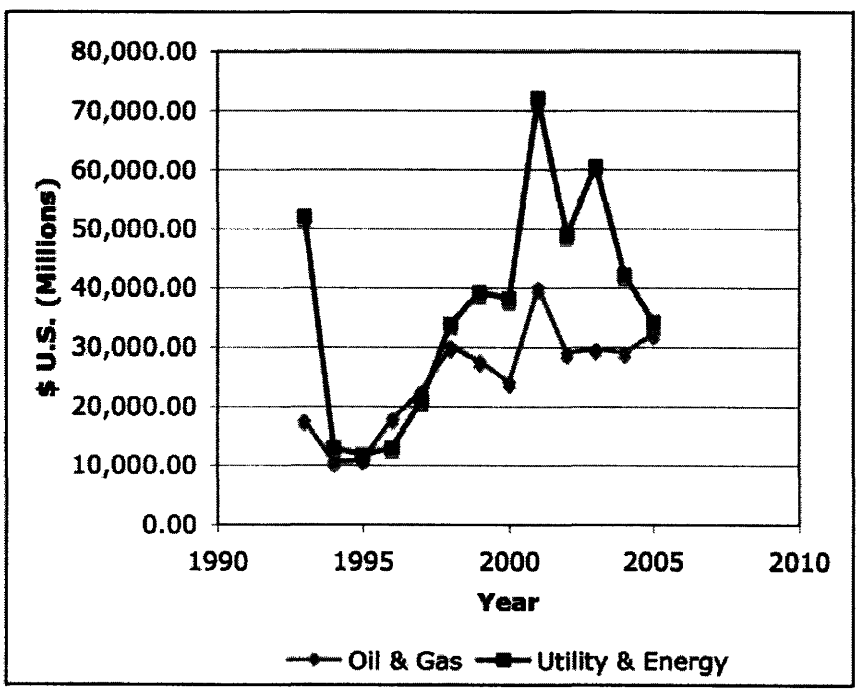
Historically, the capital markets have demonstrated their capacity for tremendous growth. A recent McKinsey study estimates that the total value of the world's financial assets (including bank deposits, government debt securities, corporate-debt securities, and equity securities) have grown from $12 trillion in 1993 to $136 trillion at the end of 2004, an average increase of $11.3 trillion per year during this period (McKinsey Global Institute 2006). Extrapolating the 11-year historic growth rate, the study predicts that global financial assets will exceed $228 trillion by 2010 (McKinsey Global Institute 2006).

The estimated global annual investment required to develop 10 TW of carbon neutral electricity infrastructure is $714 billion to $1,186 billion per year during years 1-20 of a 50-year build-out, or approximately 6.3% to 10.5% of historic annual increases in global wealth.

Carbon neutral electricity infrastructure investment levels would be higher than EIA projections for conventional electricity investment during the period 2001 to 2030. IEA estimates that OECD investment in conventional electricity infrastructure will average 0.5% of GDP and 2.5% of total domestic investment, and that Africa, Russia and other transitional economies will invest from 3.5% to 5.5% of GDP and from 20% to over 30% of total domestic investment (International Energy Agency 2003). IEA acknowledges that these conventional investment targets would be difficult for many countries to meet. Meeting carbon neutral electricity infrastructure investment targets would be even more difficult.

In addition to the growth of capital markets generally, it is important to consider the development of capital markets in the utilities and energy sector in particular. The data in Table 6.8, reproduced as Figure 6.7, sets out U.S. public debt and equity transactions in the utilities and energy, and oil and gas sectors. Capital markets activity in the utilities sector has not followed a stable upward trajectory during the past decade. In contrast, capital markets activity in the oil and gas sector has increased in a comparatively more stable manner.

Figure 6.7: U.S. Public Debt and Equity Transactions, 1993-2005



Source: Bernstein Research (2006).

The volatility of U.S. public debt and equity transactions in the utilities sector reflects uncertainty during the past decade due to regulatory changes, the Enron collapse, instability of California's electricity sector, and overall economic conditions associated with the decline of the technology sector in 2001. Significantly, electricity utility industries in many other countries also face uncertainty from deregulation, tightening profit margins, and difficult competitive environments (International Energy Agency 2003).

Recent U.S. capital markets data suggests that capital markets activity in the utilities sector is inadequate to sustain the required levels of investment on a consistent basis to develop carbon neutral electricity infrastructure.

6.1.15 Waiting and Its Potential Costs

This section considers the timing to implement a carbon neutral electricity infrastructure program on the scale contemplated by this case study. It considers the issues of the time required for technology adoption, the ability of the capital markets to provide the investment in the near term, and the potential cost of waiting to implement carbon neutral energy infrastructure.

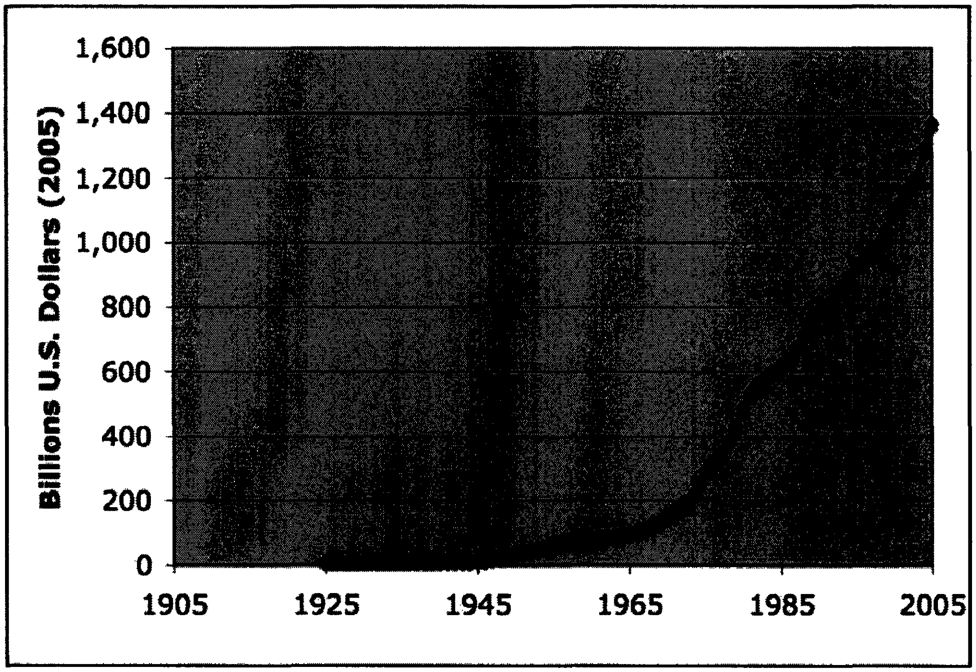
The ability of the capital markets to provide the level of investment required to develop carbon neutral electricity infrastructure and the ability of firms to absorb these levels of investment will partly depend upon the maturity of the technologies. Because several of these technologies such as solar photovoltaic and carbon sequestration have yet to be perfected, the time period for their adoption will take decades. A recent study of hybrid vehicles illustrates the delays in technology adoption. According to the study, hybrid vehicles will require approximately thirty-five years from their introduction into commercial production before they become economically competitive with other technologies, and gain the market position required to significantly reduce U.S. energy consumption (MIT Laboratory for Energy and the Environment 2005). Studies of solar PV technology similarly estimate that this technology should become cost competitive with other technologies starting at approximately mid-century (Nemet 2006b).

Economists and technologists have emphasized that waiting to implement a program of carbon neutral infrastructure and technology allows society to benefit from advances in technology, which potentially reduce the costs of addressing climate change (Webster 2000). But waiting to transition our infrastructure also involves potential costs that are difficult to estimate. In addition to the damage to the environment that will occur, the scale of transforming infrastructure also increases as we delay.

The amount of physical infrastructure has been increasing over the past fifty years and, if this trend continues, will increase the magnitude of the challenge society faces when it does eventually attempt to develop carbon neutral infrastructure. Figure 6.8 shows the net stock of U.S. private power generation, transmission and distribution assets in the United States, on a replacement cost basis. As demonstrated by these figures, the net stock of electricity infrastructure steadily increased throughout the second half of the last century.

Given the increasing rate of infrastructure development, waiting to develop carbon neutral infrastructure could substantially magnify the challenge we face as a society.

Figure 6.8: Real Value of U.S. Electricity Industry Fixed Assets, 1925-2005



Source: Bureau of Economic Analysis (2006)

Finally, the issue of petroleum resource scarcity must be considered given the time frame required to develop carbon neutral energy infrastructure. As described in Chapter 2, a number of studies have predicted that the time until global conventional petroleum production peaks is likely within this century, depending upon global economic growth rates, conventional petroleum resources, petroleum consumption rates, and advances in petroleum exploration and production technology (Wood et al. 2004; Campbell and Laherrere 1998; Deffeyes 2001). The timing of peak petroleum production is important because it could potentially disrupt the economy and preclude a smooth transition to carbon neutral infrastructure.

6.1.16 Capital Markets Case Study Main Findings

The capital markets case study compared estimates for the cost of developing 10 TW to 15 TW of carbon neutral electricity infrastructure during years 1-20 of a 50-year development program with historical capital expenditures in the utility industry, projected conventional electricity investment levels, and recent U.S. and global capital markets activity levels.

Based on these comparisons, the capital markets case study presents four primary findings. First, it reveals that the magnitude of required investment to achieve carbon neutral electricity infrastructure within a 50-year time frame will potentially exceed the capacity of capital markets. Second, while private sector resources are essential to develop carbon neutral electricity infrastructure, private sector resources are limited and likely to be inadequate to successfully develop carbon neutral infrastructure without government support. Third, the stability of capital markets and firms are important conditions for the development of carbon neutral energy infrastructure. Finally, the magnitude of the task of implementing carbon neutral infrastructure is likely to increase in the future, and policymakers should consider the early initiation of such a program.

The investment levels required to develop 10 TW of carbon neutral electricity infrastructure may be difficult to raise in capital markets. The required investment levels during years 1-20 of a 50-year program exceed current capital expenditures in the utilities and energy sector by a factor of 5 to almost 9 times. If all growth in U.S. capital markets activity in the utilities sector were devoted to the development of carbon neutral electricity infrastructure, the available capital would still fall short by as much as one-half of the required level of investment to be raised in U.S. capital markets. If all capital currently raised in U.S. capital markets were devoted to this effort, the U.S. capital markets share of investment for developing 10 TW of carbon neutral electricity would consume an estimated one-fifth to one-third of growth in U.S. capital markets activity.

While the private sector's resources are essential to developing carbon neutral energy infrastructure, they are also likely to be inadequate. This is evident in the analysis of the global bond markets, where the government sector accounts for approximately 40% of all issuances. Further, in developing countries where private capital markets are underdeveloped, government financing for carbon neutral energy infrastructure will be essential. The private sector will require both government policy support and financial resources in order to develop carbon neutral energy infrastructure.

Given the magnitude of required investment, the financial stability of firms and capital markets become important issues if addressing climate change requires the private sector to develop carbon neutral energy infrastructure. Evidence suggests that periods of high capital expenditure depress stock prices, making it more difficult for utilities to raise financing through equity offerings. Increased exposure to interest rate risk and potential delays in obtaining regulatory approval to recover capital expenditures further exacerbate the negative effects of utilities sector capital expansions (Lehman Brothers 2006).

Under these conditions, the stability of firms is especially important because higher than normal levels of investment must be sustained for many decades to successfully develop carbon neutral electricity infrastructure. Market volatility and the short-term nature of public debt and equity markets present potential risks and delay for the development of carbon neutral infrastructure.

Finally, delaying the implementation of carbon neutral electricity infrastructure will likely increase the magnitude of the challenge and may eventually place it beyond society's capacity to implement at some point in the future. The scale of the challenge increases with the further development of conventional energy infrastructure. The long-time frame and inevitable delays involved in implementing a large-scale change in infrastructure suggest that commencing early and gradually increasing our capacity to develop carbon neutral energy infrastructure is preferable to indefinitely delaying starting such a program.

6.2 Storm Effects on Utilities and Energy Sector

The second case study examines the financial effects of storms and hurricanes on energy infrastructure, especially utilities located on the East Coast of the United States during the past fifteen years. Storms and hurricanes have caused tremendous physical damage to energy infrastructure, disrupting service, causing economic losses, and harming the financial stability of utilities in the region.

The financial well-being of utilities following these events is central to the issue of how climate risk may affect the capacity of private sector institutions to develop carbon neutral energy infrastructure. Because utilities make investment decisions regarding choice of generation technology, and must recover capital costs from consumers, utilities play a critical role in transforming energy infrastructure. To the extent that storms or hurricanes weaken the financial position of utility companies, these events adversely affect their ability to adapt our energy infrastructure because catastrophic losses make it more difficult to finance energy infrastructure in storm-prone areas of the United States.

The case study is organized in the following sections: (a) an overview of storm and hurricane history on the East Coast of the United States from 1990 to 2005, (b) economic damage caused by storms and hurricanes, and (c) the financial effects of storms and hurricanes on utilities and other energy infrastructure in the Gulf of Mexico region.

6.2.1 Storm and Hurricane History of the United States Atlantic Coast 1990-2005

The North Atlantic Basin is one of the most active storm and hurricane regions of the world. Because storms are particularly strong over warm water, storms and hurricanes commonly affect the states along the U.S. Gulf Coast, the Carolinas, and on rare occasions reach New England states. The Atlantic storm season typically begins in June and ends in November.

Storms with winds in excess of 38 mph are given names to raise public awareness, and in excess of 73 mph are deemed hurricanes. Hurricanes are rated on the Saffir-Simpson hurricane scale, which ranks hurricanes from 1 to 5 based on wind speed. Importantly, because the scale does not take into account rainfall or location, lower category hurricanes can be more damaging than higher category hurricanes depending upon precipitation and location.

Table 6.26: Saffir-Simpson Hurricane Scale

Category	Central Pressure (Millibars)	Central Pressure (Inches)	Wind Speed (Mph)	Storm Surge (Feet)	Damage
1	>979	>28.91	74-95	4-5	Minimal
2	965-979	28.50-28.91	96-110	6-8	Moderate
3	945-964	27.91-28.47	111-130	9-12	Extensive
4	920-944	27.17-27.88	131-155	13-18	Extreme
5	<920	<27.17	156+	19+	Catastrophic

Source: Simpson (1974).

Historical data shows that storms and hurricanes have been increasing in frequency during the past 150 years, with a marked increase since 1985. The increase in major hurricanes also suggests that they have been increasing in severity during the same period.

Table 6.27: Average Annual Number of Storms by Period, 1851-2004

Period	Total Years	Average Annual Number of Tropical Storms	Average Annual Number of Hurricanes	Average Annual Number of Major Hurricanes
1851-2004	154	8.5	5.2	1.8
1944-2004	61	10.3	6.0	2.6
1955-2004	50	10.3	5.9	2.4
1965-2004	40	10.6	5.9	2.2
1975-2004	30	10.8	6.0	2.3
1985-2004	20	11.5	6.4	2.6
1990-2004	15	12.2	6.7	2.9
1995-2004	10	13.9	7.8	3.8

Source: Blake, Jarrell, Rappaport and Landsea (2005).

Storm and hurricane activity is concentrated along the Gulf Coast and southern states. Florida, Texas, Louisiana, Mississippi, North Carolina, and South Carolina experience the highest incidence of storms and hurricanes.

Table 6.28: Hurricane Direct Hits on U.S. Coastline Texas to Maine, 1851-2004

Area	Category Number						Major Hurricanes
	1	2	3	4	5	All	
U.S.	109	72	71	18	3	273	92
Texas	23	17	12	7	0	59	19
Louisiana	17	14	13	4	1	49	18
Mississippi	2	5	7	0	1	15	8
Alabama	11	5	6	0	0	22	6
Florida	43	32	27	6	2	110	35
Georgia	12	5	2	1	0	20	3
South Carolina	19	6	4	2	0	31	6
North Carolina	21	13	11	1	0	46	12
Virginia	9	2	1	0	0	12	1
Maryland	1	1	0	0	0	2	0
Delaware	1	1	0	0	0	2	0
New Jersey	2	0	0	0	0	2	0
Pennsylvania	1	0	0	0	0	1	0
New York	6	1	5	0	0	12	5
Connecticut	4	3	3	0	0	10	3
Rhode Island	3	2	4	0	0	9	4
Massachusetts	5	2	3	0	0	10	3
New Hampshire	1	1	0	0	0	2	0
Maine	5	1	0	0	0	6	0

Source: Blake, Jarrell, Rappaport and Landsea (2005).

Improvements in communication, building codes, and other mitigation measures have reduced the number of deaths from storms and hurricanes. The deadliest hurricanes have occurred in the early part of the last century with the single exception of Hurricane Katrina in 2005.

Table 6.29: Ten Deadliest U.S. Hurricanes, 1900-2005

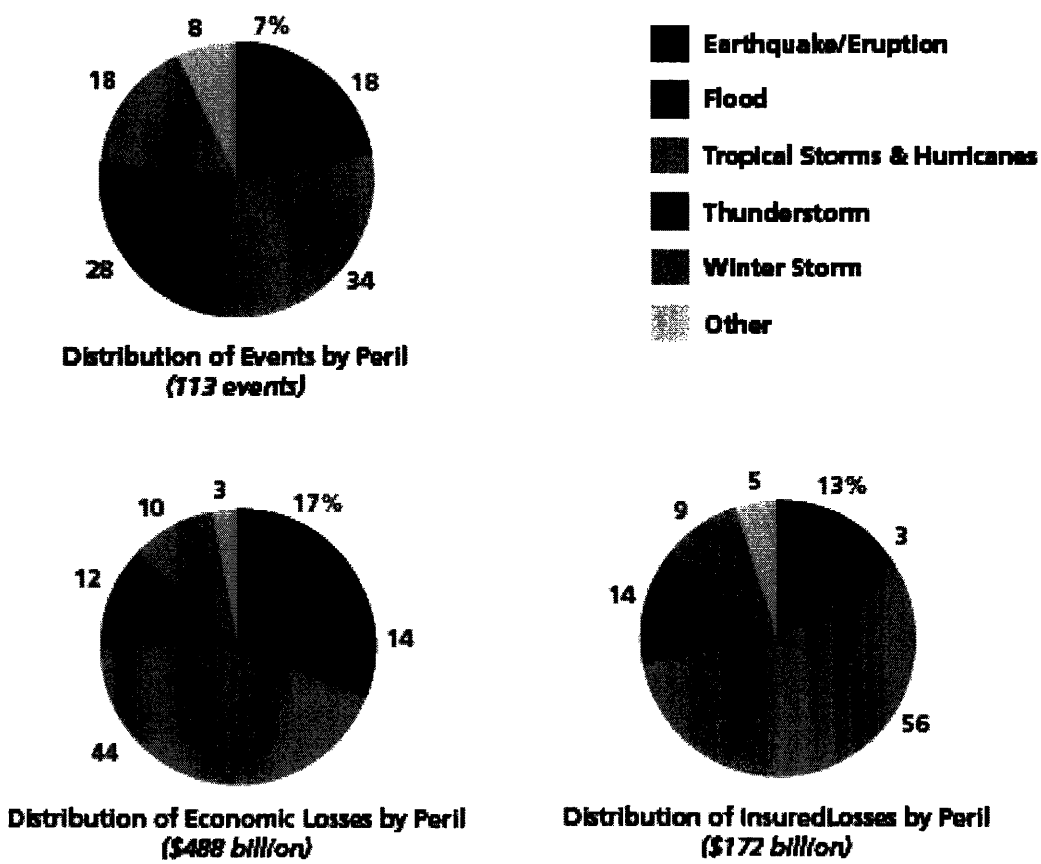
Rank	Hurricane	Year	Category	Deaths
1	Texas (Galveston)	1900	4	8000-12,000
2	FL (Lake Okeechobee)	1928	4	2500-3000
3	Hurricane Katrina	2005	4	1300+
4	Florida Keys	1935	5	408
5	Hurricane Audrey (LA, TX)	1957	4	390
6	Florida	1926	4	372
7	LA (Grand Isle)	1909	3	350
8	Florida Keys/Texas	1919	4	287
9	LA (New Orleans)	1915	4	275
10	TX (Galveston)	1915	4	275

Source: Blake, Jarrell, Rappaport and Landsea (2005), as updated for 2005 based on NCDC (2006).

6.2.2 Economic Damage Caused by Storms and Hurricanes

Storms and Hurricanes are among the most economically costly natural catastrophes. They cause approximately 66% of economic losses and 79% of insured losses for all natural catastrophe events.

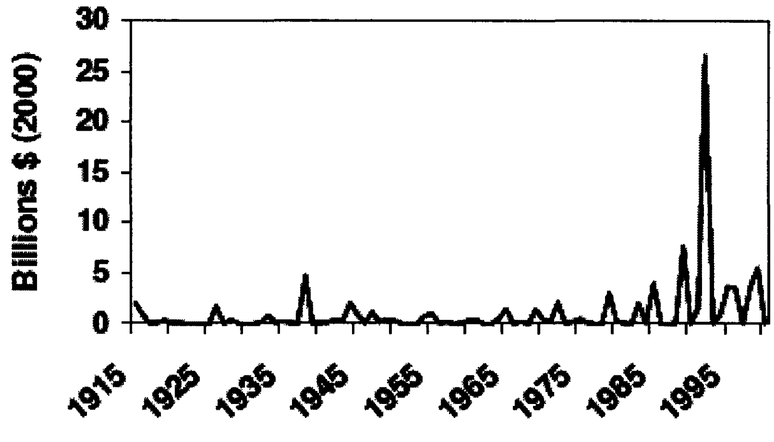
Figure 6.9: Natural Perils and Losses by Type, 1950-2004



Source: American Re (2005), in CERES (2005a). Includes only events causing $1 billion and more in insured losses.

Storms and hurricanes are inflicting increasing economic losses both because of their increasing severity and the increasing density of infrastructure. As shown in Table 6.30 below, of the twenty costliest U.S. storms since 1900, ten have occurred since 2000, and all of them since 1970.

Figure 6.10: U.S. Hurricane Losses, 1915-2000



Source: Meade (2004).

Table 6.30: Twenty Costliest Mainland U.S. Tropical Cyclones, 1900-2005

Rank	Name	States Affected	Year	Category	Damage (U.S.)	2004 Dollars for 2003 and Before
1	Katrina	AL, FL, LA, MS	2005	4	$100,000,000,000	
2	Andrew	FL, LA	1992	5	$26,500,000,000	$43,672,000,000
3	Charley	FL	2004	4	$15,000,000,000	
4	Ivan	AL, FL	2004	3	$14,200,000,000	
5	Wilma		2005	3	$10,000,000,000	
6	Frances	FL	2004	2	$8,900,000,000	
7	Rita		2005	3	$8,000,000,000	
8	Hugo	SC	1989	4	$7,000,000,000	$12,250,000,000
9	Jeanne	FL	2004	3	$6,900,000,000	
10	Allison	TX	2001	Storm	$5,000,000,000	$5,829,000,000
11	Floyd	Mid-Atlantic NE US	1999	2	$4,500,000,000	$5,764,000,000
12	Isabel	Mid-Atlantic	2003	2	$3,370,000,000	$3,643,000,000
13	Fran	NC	1996	3	$3,200,000,000	$4,525,000,000
14	Opal	FL, AL	1995	3	$3,000,000,000	$4,324,000,000
15	Frederic	AL, MS	1979	3	$2,300,000,000	$6,291,000,000
16	Agnes	FL, NE U.S.	1972	1	$2,100,000,000	$11,290,000,000
17	Alicia	TX	1983	3	$2,000,000,000	$4,384,000,000
18	Dennis		2005	3	$2,000,000,000	
19	Bob	NC, NE U.S.	1991	2	$1,500,000,000	$2,593,000,000
20	Juan	LA	1985	1	$1,500,000,000	$3,105,000,000

Source: Blake, Jarrell, Rappaport and Landsea (2005), updated for 2005 hurricane season based on NCDC (2006). Note: 2004 US$ based on U.S. Department of Commerce implicit price deflator for construction.

The 2005 hurricane season illustrates the potential economic damage caused by storms and hurricanes. Risk Management Solutions estimated that total losses from Hurricanes Katrina and Rita totaled approximately $140 billion. Of that amount, approximately $40 to $67 billion was insured. The Congressional Budget Office estimated that damage to physical infrastructure totaled $70 to $130 billion (U.S. Congressional Budget Office 2005).

Table 6.31: Estimated Capital Stock Destroyed by Hurricanes Katrina and Rita

Type	Range (2005 US$ billions)	Percentage
Housing	$17 to $33	24%-25%
Energy Sector	$18 to $31	24%-25%
Other Private Sector	$16 to $32	24%-25%
Government	$13 to $25	19%
Consumer Durable Goods	$5 to $9	7%
TOTAL	$70 to $130	

Source: U.S. Congressional Budget Office (2005).

In addition to the immediate loss of physical assets, storms inflict ongoing economic losses to local jobs and state and municipal tax revenues, and have adverse national and regional macroeconomic effects. As a result of Hurricanes Katrina and Rita, an estimated 293,000 to 480,000 jobs were lost. In Louisiana, two thirds of the population, representing 70% of the tax base, lived in the federal disaster zone, which caused a loss of state tax revenues of approximately $1 to $3 billion (U.S. Congressional Budget Office 2005).

The Congressional Budget Office estimated that Hurricane Rita would continue to affect the national economy through 2007. Table 6.32 shows the estimated economic effect of Hurricane Katrina on GDP.

Table 6.32: Estimated Net Effect of Hurricane Katrina on Real GDP (2005 US$ billions)

	2005	2006		2007	
	2nd Half	1st Half	2nd Half	1st Half	2nd Half
Energy Production	-18 to -28	-8 to -10	-5 to -7	-5 to -7	-5 to -7
Housing	-1 to -2	-2 to -4	-1 to -3	0 to -2	0 to -2
Agricultural Production	-1 to -2	0	0	0	0
Replacement Investment	6 to 12	16 to 34	16 to 35	16 to 35	12 to 25
Government Spending	6 to 10	12 to 18	14 to 20	10 to 16	7 to 11
Energy Prices Effect on Consumption	-6 to -10	-5 to -7	-2 to -5	-1 to -3	0 to -2
Other Consumption	-8 to -12	-2 to -4	-1 to -3	-1 to -3	0 to -2
Real GDP	-22 to -32	11 to 27	21 to 37	19 to 36	14 to 23

Source: U.S. Congressional Budget Office (2005).

Federal disaster relief payments have been rising steadily during the past thirty years. While there is some debate whether the increases in payments are influenced by political considerations, the increasing economic effects of natural disasters are clearly a primary factor. The U.S. federal government allocated approximately $62 billion for relief efforts following Hurricanes Katrina and Rita (U.S. Congressional Budget Office 2005). One analyst estimated that total federal relief spending could reach as high as $150 billion, which would incur additional interest expense of $80 billion, for a total increase in government spending of $230 billion over the next ten years (Horney et al. 2005).

Table 6.33: Federal Disaster Relief Payments (2005 US$ millions), 1974-2007

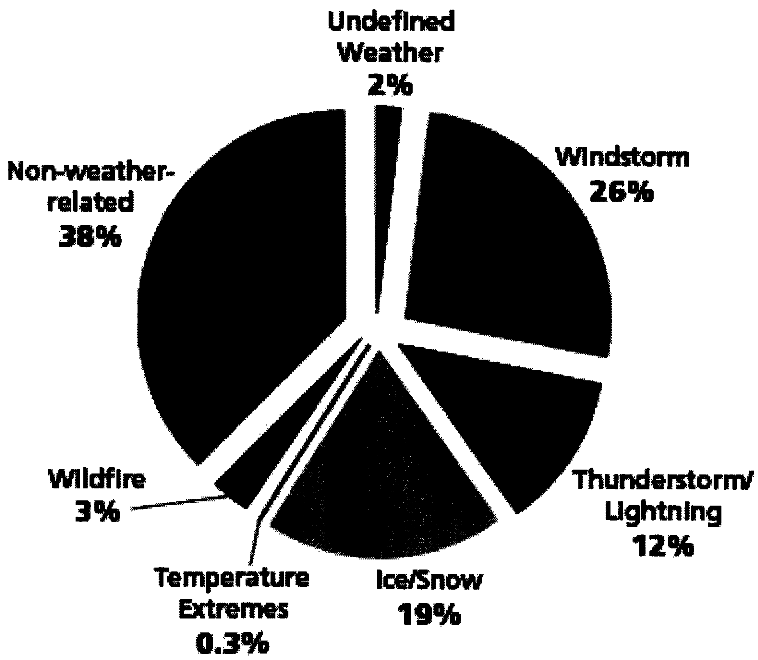
	Total Appropriations					Outlays	
FY	[a]Request	Original	Supple-mental	Nominal	Constant	Nominal	Constant
1974	100	200	233	433	1,412	250	816
1975	100	150	50	200	591	206	609
1976	187	187	0	187	517	362	999
1977	100	100	200	300	770	294	754
1978	150	115	300	415	997	461	1,108
1979	200	200	194	394	876	277	616
1980	194	194	870	1,064	2,175	574	1,173
1981	375	358	0	358	668	401	746
1982	400	302	0	302	526	115	201
1983	325	130	0	130	217	202	337
1984	0	0	0	0	0	243	391
1985	100	100	0	100	156	192	299
1986	194	100	250	350	533	335	511
1987	100	120	[b]0	120	178	219	325
1988	125	120	0	[c]120	173	187	269
1989	200	100	[d]1,108	1,208	1,674	140	194
1990	270	98	[e]1,150	1,248	1,668	1,333	1,781
1991	270	0	0	0	0	552	711
1992	[f]184	185	4,136	[g]4,321	5,429	902	1,134
1993	292	292	2,000	[h]2,292	2,816	2,276	2,796
1994	[i]1,154	226	[j]4,709	4,935	5,935	3,743	4,502
1995	320	320	[k]3,275	3,595	4,235	2,116	2,492
1996	320	222	[k]3,275	[k]3,497	4,042	2,233	2,581
1997	320	[l]1,320	[l]3,300	4,620	5,248	2,551	2,898
1998	[m]2,708	320	[n]1,600	1,920	2,155	1,998	2,242
1999	[o]2,566	[p]1,214	[q]1,130	2,344	2,597	3,746	4,149
2000	2,780	[r]2,780	0	2,780	3,019	2,628	2,853
2001	2,909	300	[s, t]	[t]5,890	6,249	3,217	3,413
2002	[u]1,369	664	[v]7,008	[v]12,160	12,677	3,947	4,114
2003	1,843	800	[w]1,426	[w]2,199	2,255	8,541	8,761
2004	1,956	1,800	[x]2,275	[x]2,042	[y]2,068	[y]3,044	[y]3,082
2005	2,151	2,042	[z]8,500	10,542	10,542	[y]3,363	[y]3,363
Total	**24,240**	**16,360**	**48,988**	**72,099**	**84,455**	**50,648**	**60,224**

Sources: Congressional Research Service (2005b). Note: 2005-2007 are estimates based on federal government allocation of $62 billion for disaster relief resulting from Hurricanes Katrina and Rita. Estimates do not include interest payments, possible further allocations, or other catastrophic events that may occur in 2006 and 2007.

6.2.3 Financial Effects of Storms and Hurricanes on Utilities and Energy Sectors

Storms and hurricanes presently pose the single most significant climate risk to utilities. Damages include loss of revenues due to service disruption and destruction of capital assets, particularly transmission and distribution equipment. Weather-related incidents account for almost two-thirds of utilities service disruptions in North America.

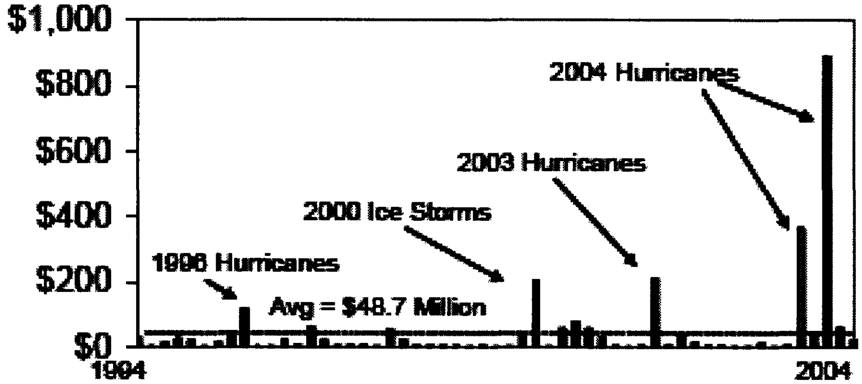
Figure 6.11: Causes of North American Electricity Service Disruption, 1982-2002



Source: North American Electric Reliability Counsel, in CERES (2005a).

A recent survey of fourteen utilities covering eighty-one major storms from 1994 to 2004 shows that the financial effects of storms on electric utilities is substantial and increasing. Figure 6.12 below shows that the costs of these eighty-one storms have increased throughout the period surveyed.

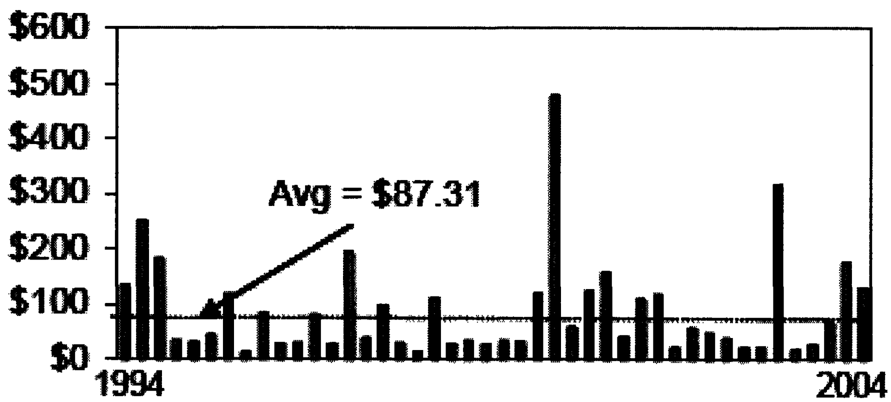
Figure 6.12: Major Storm Costs (2003 millions US$), 1994-2004



Source: Edison Electric Institute (2005). Note: figure shows eighty-one storms surveyed. Some storms have been grouped for a total of fifty-five data points.

The cost of these storms averaged $87.31 per customer per year from 1994 to 2004 (Edison Electric Institute 2005). Figure 6.13 shows that annual costs were highly variable, making estimation for planning and rate case purposes difficult.

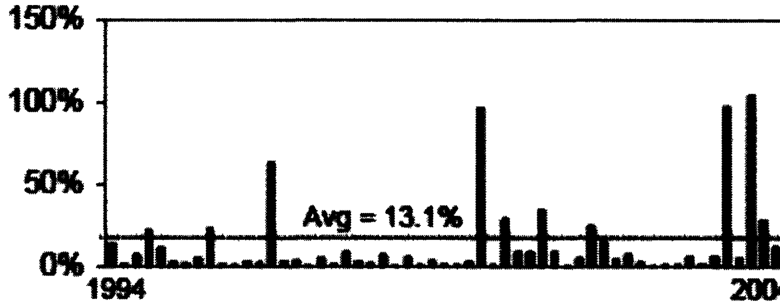
Figure 6.13: Major Storm Costs per Customer (2003 US$), 1994-2004



Source: Edison Electric Institute (2005). Note: figure shows eighty-one storms surveyed. Some storms have been grouped for a total of forty-four data points. Costs per customer are calculated using peak number of customers per year.

Importantly, the cost of storms may significantly affect earnings. Figure 6.14 shows that storms costs for the eighty-one storms surveyed from 1994 to 2004 have cost an average of 13% of net income for the fourteen utilities surveyed. In some years, storm costs approached or exceeded net income for several of the utilities.

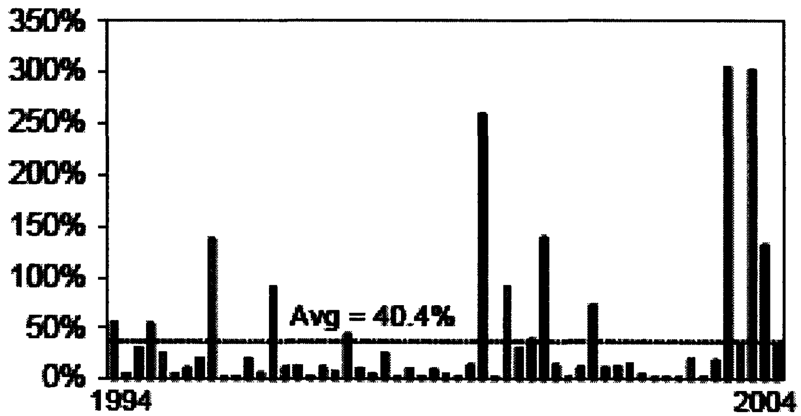
Figure 6.14: Ratio of Storm Cost/Net Operating Income (2003 US$), 1994-2004



Source: Edison Electric Institute (2005). Note: figure shows eighty-one storms surveyed. Some storms have been grouped for a total of fifty-five data points.

Utility transmission and distribution systems are especially vulnerable to storms. Figure 6.15 shows that costs of the eighty-one storms included in the Edison Electric Institute study exceeded the annual transmission and distribution budget of the utilities surveyed by as much as 300%.

Figure 6.15: Storm Costs as % of T&D Expenses (2003 US$), 1994-2004



Source: Edison Electric Institute (2005). Note: figure shows eighty-one storms. Some storms have been grouped for a total of fifty-five data points.

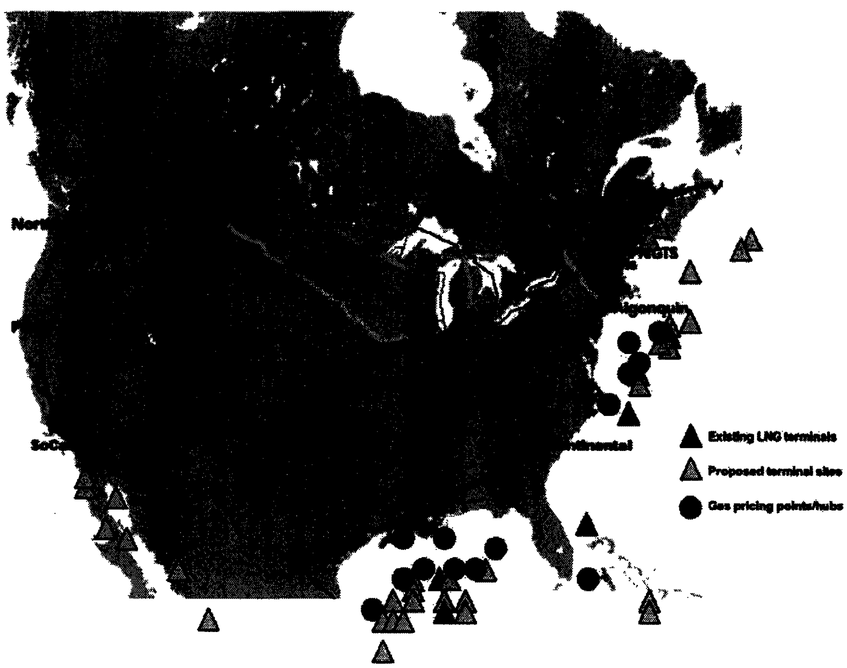
Importantly, among the fourteen utilities surveyed, only one maintained cash reserves to cover the costs of storm damage; the other companies maintained unfunded accounting reserves (Edison Electric Institute 2005).

The 2005 hurricane season caused record damage to utility infrastructure in the Gulf Coast region. Utilities estimate that lost revenues and the cost of repairing transmission and distribution equipment totaled approximately $2.5 billion (U.S. Congressional Budget Office 2005). The 2005 storms forced one utility, Entergy New Orleans, a wholly owned subsidiary of Entergy, to file for protection under Chapter 11 (reorganization) of the federal bankruptcy laws.

In addition to the loss of capital assets and reserves, storms may also damage the credit rating of energy companies. For example, as a result of the 2004 storms, credit rating agencies placed Progress Energy on negative credit watch for concern that the storms could hamper its ability to pay debt obligations in a timely manner and potential delays in obtaining regulatory approval to recover the cost of repairing storm damage (Edison Electric Institute 2005).

In addition to utilities, other energy infrastructure was also affected by the 2005 storms. A large percentage of United States oil and gas infrastructure lies in the Gulf of Mexico and southern United States, and was heavily damaged during the 2005 hurricane season.

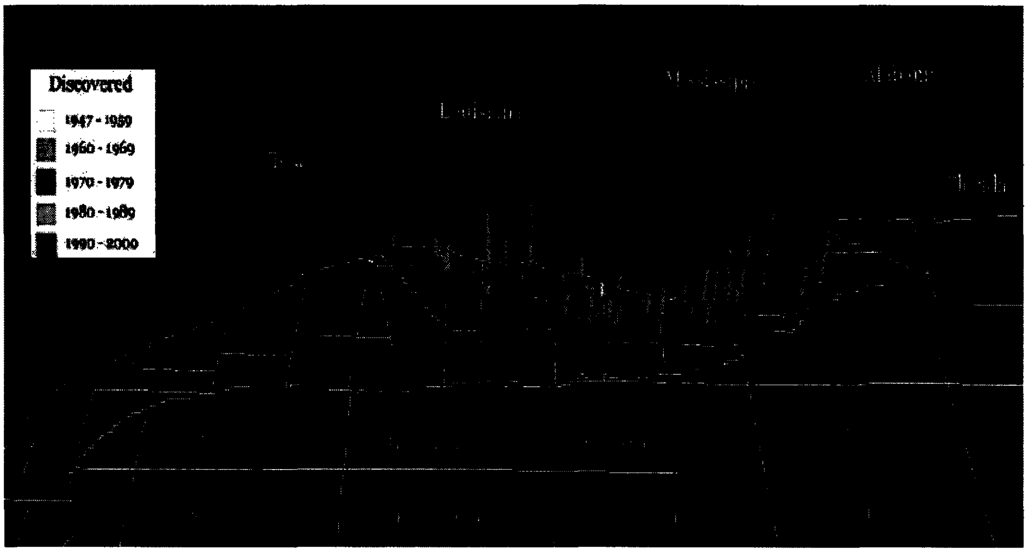
Figure 6.16: Existing and Projected U.S. Liquid Natural Gas Infrastructure, 2005



Source: Kiley (2006).

Hurricanes Katrina and Rita caused an estimated $17 to $31 billion in losses to capital stock in the energy sector, approximately 25% of all capital stock losses (U.S. Congressional Budget Office 2005) (See Table 6.31). In the oil and gas production sector, these hurricanes destroyed or damaged 167 offshore platforms and 183 pipelines in the Gulf of Mexico. The hurricanes shut down approximately 70% of gas production, and 90% of crude oil production in the Gulf of Mexico. This caused the loss of about 2% of global oil production, and about 20% of U.S. oil refining capacity (U.S. Congressional Budget Office 2005). As of March 2006, 87 platforms were still evacuated (Minerals Management Service 2006). By late June 2006, ten months after Hurricane Katrina, approximately 15% of oil production and 11% of gas production remained unrestored (Financial Times 2006e).

Figure 6.17: Gulf of Mexico Oil and Gas Fields, 1947-2005



Source: Mineral Management Service as presented by Kiley (2006).

Further, the energy sector is expected to bear the largest portion of continuing losses resulting from Hurricanes Katrina and Rita. Year 2006 revenue losses are expected to be approximately $13 to 17 billion, and year 2007 losses $10 to 14 billion (U.S. Congressional Budget Office 2005) (See Table 6.32).

In addition to these financial effects, storms and hurricanes also adversely affect the ability of the utilities and energy industries to obtain insurance, an important requirement of banks to finance infrastructure. The effect of storms and hurricanes on the ability of utility and energy companies to obtain insurance is addressed in the next case study.

6.2.4 Utility and Energy Storm Damage Case Study Main Findings

This case study examined the increase in storm and hurricane activity in the Eastern United States and Gulf of Mexico during the past fifteen years and the losses they have caused to the utilities and energy industries.

The case study analysis demonstrates that storm damage has various negative financial effects on the utilities and energy industries. These negative effects include the immediate loss of revenues due to disruption, damage to capital stock, increasing demands on cash or accounting reserves, large increases in future capital expenditure, potential delays in recovering lost revenues or capital expenditures through the regulatory approval process, and potential downgrade by credit rating agencies. In turn, these factors adversely affect the ability of these firms to raise debt and equity in capital markets.

Climate change is believed by some in the scientific community to have contributed to the observed recent increase in the number of storms and hurricanes and the resulting losses. If changing climate increases the frequency or intensity of storms, and the resulting losses to these firms, it could significantly increase operating costs for utilities and energy companies in affected areas. Importantly, the increasing costs and other negative effects on financial performance could potentially undermine the capacity of utilities and energy companies to finance carbon neutral energy infrastructure.

6.3 Natural Catastrophic Events Effects on Insurance Industry

The third case study examines the effects of natural catastrophic events on the willingness or ability of insurers to provide property and casualty insurance.

Insurance is critical for financing and developing infrastructure. Lenders require insurance as a condition to financing infrastructure. Lenders typically require that a physical asset be insured at a level adequate to repay debt or replace the asset. The inability to obtain insurance for a particular geographic area or type of activity could adversely affect society's ability to finance capital-intensive infrastructure.

The case study is organized in the following sections: (a) insurance industry fundamentals, (b) overview of natural catastrophes and insured losses during the past several decades, (c) financial effects of natural catastrophic events on the insurance industry, (d) natural catastrophes' effects on insuring utilities and other energy infrastructure in the Gulf of Mexico.

6.3.1 Insurance Industry Fundamentals

Primary insurance is offered by insurance companies to businesses and consumers. With respect to primary insurance, the dissertation surveyed property insurance, which includes weather risks such as fire, flood, and earthquake, and business interruption insurance.

The availability of primary insurance is directly affected by conditions in the reinsurance market. Reinsurance is a method by which insurance companies transfer a portion of their primary underwriting risks to other insurance companies. Reinsurance allows the ceding insurance company to underwrite larger risks than would otherwise be allowed due to regulatory or credit rating requirements concerning adequacy of reserves. Reinsurance may be structured to transfer a pro-rata share of premiums and liabilities for all or a specified subset of policies or risks unwritten by a ceding insurer, transfer liabilities in excess of the amount of risk retained by the ceding insurer for a fee, or require single or multiple events to trigger the reinsurance obligation. Unlike primary insurance, reinsurance is not regulated, however the reinsurance market is analyzed by credit rating agencies, which effectively places limits on reinsurance companies' capacity to underwrite risk.

Assessing risk in connection with underwriting activities is a critical function of insurance companies. For a risk to be insurable, several criteria must be satisfied: (a) the timing or occurrence of losses must be uncertain; (b) the amount and rate of losses must be capable of being estimated accurately on a macro scale: and (c) the event must be catastrophic, meaning that it is far from the mean based on historical observed weather patterns by some measure, usually by several standard deviations.

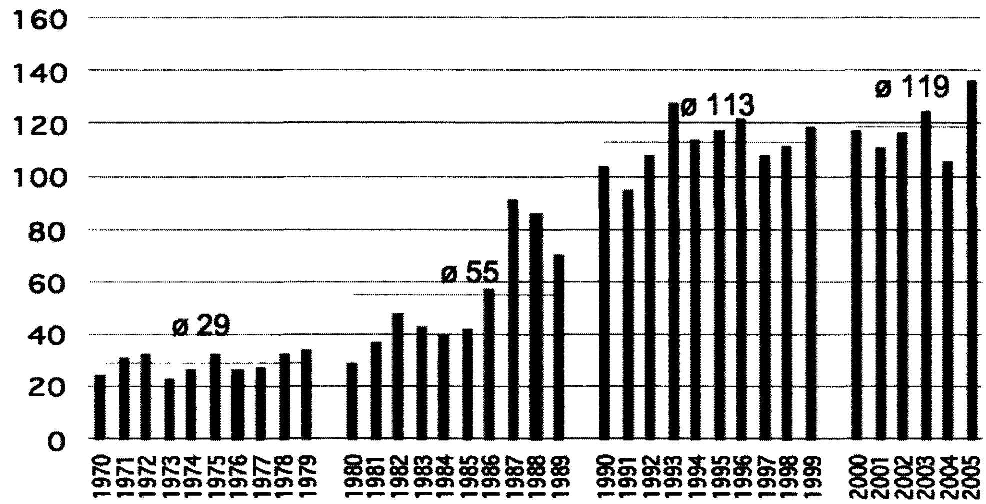
Insurance companies use actuarial models to statistically quantify their risks over a large number of policies based on an assessment of the probability of perils. The risks of loss of catastrophic events are estimated using detailed historic weather data, demographic data, building code and engineering data specific to a particular zip code (Muir-Wood 2006; Siner 2006). Models incorporate future expectations using demographic and engineering trends, and recently, scientific trends concerning changes in climate (Siner 2006). These models produce a loss exceedance curve, which shows the expected amount of insured losses for a particular risk and the estimated probability of occurrence. The exceedance probability is the probability that a loss will occur at or greater than a specified level of loss.

Actuarial models are used to set premiums, to determine appropriate levels for reserves, to purchase reinsurance, to demonstrate compliance with regulatory requirements, and to demonstrate adequate capitalization to regulators and credit rating agencies. These models also provide guidance for setting contractual terms to limit potential underwriting losses.

6.3.2 Recent History of Natural Catastrophic Events and Insurance Losses

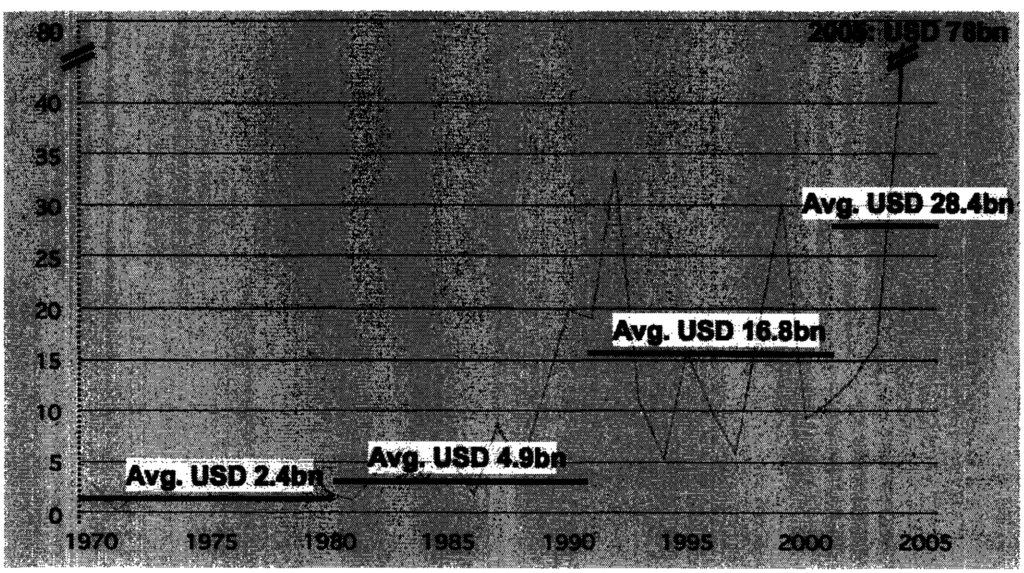
During the past thirty-five years, the number of catastrophic events and the magnitude of damage caused by them have increased dramatically, causing record losses for insurance companies. The increase in damages is influenced by the increased number and severity of events, but also by increasing price levels (inflation), population, levels of wealth, and reliance on physical infrastructure.

Figure 6.18: Number of Natural Catastrophic Events, 1970-2005



Source: Swiss Re (2006b). Note: Includes floods, storms, droughts, forest fires, cold waves, frost, and hail.

Figure 6.19: Natural Catastrophe Insured Losses (2005 US$ billions), 1970-2005

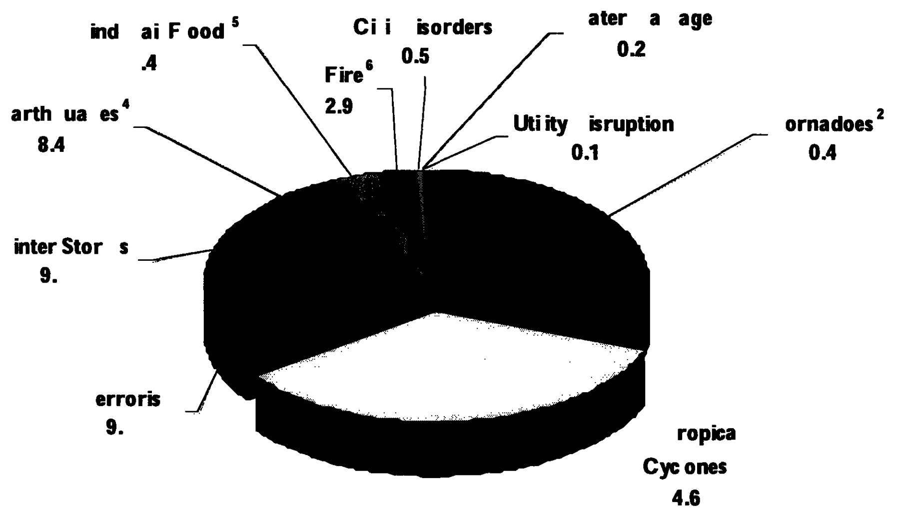


Source: Swiss Re (2006b).

Annual average damage from natural catastrophes has risen by 475% from the period 1995 to 2004, as compared with the period 1974 to 1983 (Frank Crystal 2006). While absolute monetary losses resulting from natural catastrophes have been much higher in industrialized countries, loss of life and economic effects as a percentage of GDP are higher in developing countries (Gurenko 2004).

Storms and hurricanes are an important segment of natural catastrophe losses, accounting for approximately 78% of all insured losses due to natural catastrophes (Insurance Information Institute 2006a).

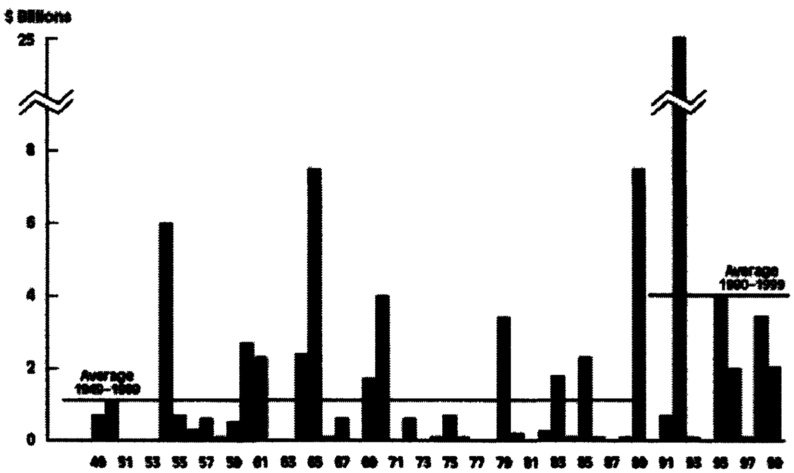
Figure 6.20: U.S. Insured Catastrophic Losses by Category, 1985-2004



Source: Insurance Information Institute (2006a). Note: inflation adjusted.

Damages from storms and hurricanes have been increasing, following the same upward trend for natural catastrophes. From 1949 to 1999, hurricanes caused U.S. insured property losses totaling \$37.9 billion, or \$87.8 billion adjusted for inflation, population and wealth levels. Of that amount, 52% of losses, or \$45.7 billion on an adjusted basis, occurred during the eleven-year period from 1989 to 1999. From 1989 to 1999, U.S. insured losses from hurricanes averaged \$4.2 billion per annum on an adjusted basis, in contrast to average adjusted losses of \$1.1 billion per annum from 1949 to 1988 (ISO 2006b). From 2000 to 2005, U.S. insured losses due to hurricanes have averaged in excess of \$21 billion per year (Insurance Information Institute 2006b).

Figure 6.21: Adjusted Annual Insured Losses due to Hurricanes, 1949-1999



Source: ISO (2006b).

6.3.3 Financial Effects of Natural Catastrophes on Insurance Industry

Natural catastrophes adversely affect the insurance industry's profitability, capacity to underwrite risk, rate of insolvencies, and credit ratings. This section examines each of these aspects of the insurance industry's financial position.

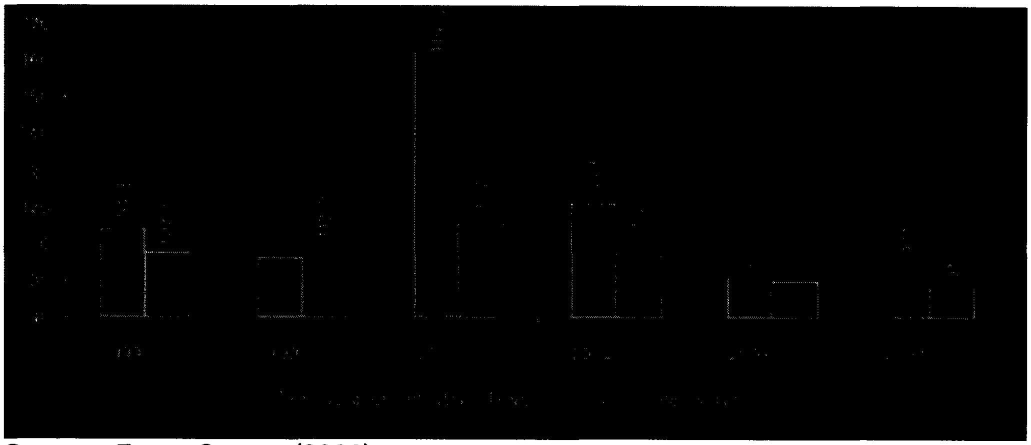
The combined ratio is an important measure of insurance company performance and profitability with respect to underwriting operations. The combined ratio is the ratio of losses plus expenses over earned premiums for a particular period:

$$Combined\,Ratio = \frac{(Losses + Expenses)}{Earned\,Premiums} * 100$$

A combined ratio of 100 or more indicates an underwriting loss; a ratio of less than 100 indicates a gain; and a ratio of 100 is the breakeven point for underwriting business. The combined ratio only measures underwriting performance and does not take into account other aspects of insurance company profits, such as investment of assets (Frank Crystal 2006).

Figure 6.22 below shows the aggregate combined ratios of reinsurance companies and property and casualty insurers. The relatively higher combined ratios of reinsurance companies reflect that reinsurers bear most of the cost of catastrophic events. In 2001, the attacks on the World Trade Center increased the combined ratio of the reinsurance segment of the industry to a peak of 162.5 (Frank Crystal 2006).

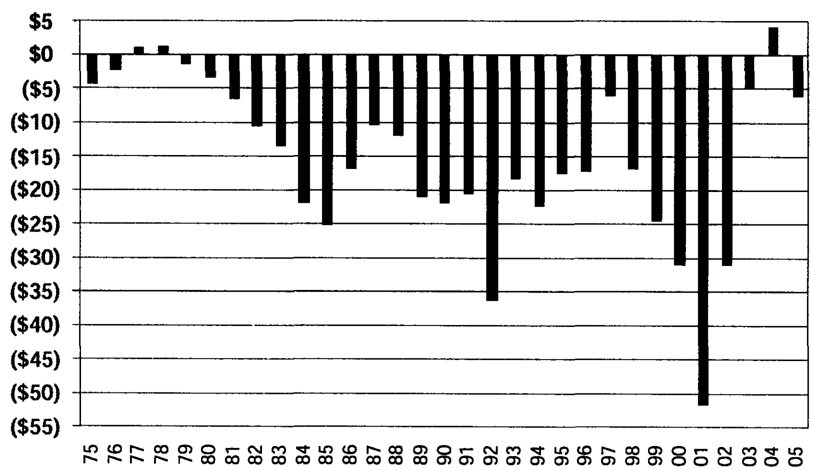
Figure 6.22: Combined Ratio of P&C Reinsurers v. P&C Insurers and Reinsurers, 1999-2004



Source: Frank Crystal (2006).

The U.S. property and casualty insurance industry has incurred underwriting losses each year from 1975 to 2005, except in 1977, 1978, and 2004 (Insurance Information Institute 2006a).

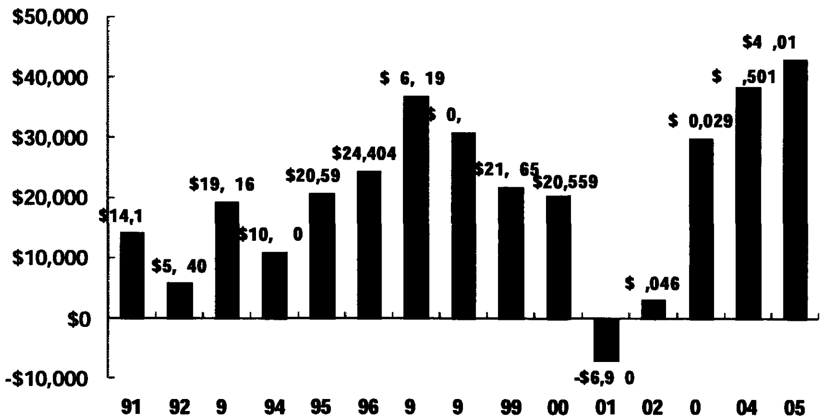
Figure 6.23: U.S. P&C Underwriting Gain/Loss (US$ millions), 1975-2005



Source: Insurance Information Institute (2006a).

Despite persistent underwriting losses, the U.S. property and casualty insurance industry has remained profitable due primarily to investment income. From 1991 to 2005, U.S. property and casualty insurers incurred underwriting losses of approximately $298 billion, while net income after taxes during the same period was $313 billion, as a result of investment activity (Insurance Information Institute 2006a).

Figure 6.24: U.S. P&C Net Income After Taxes (US$ millions), 1991-2005



Source: Insurance Information Institute (2006a).

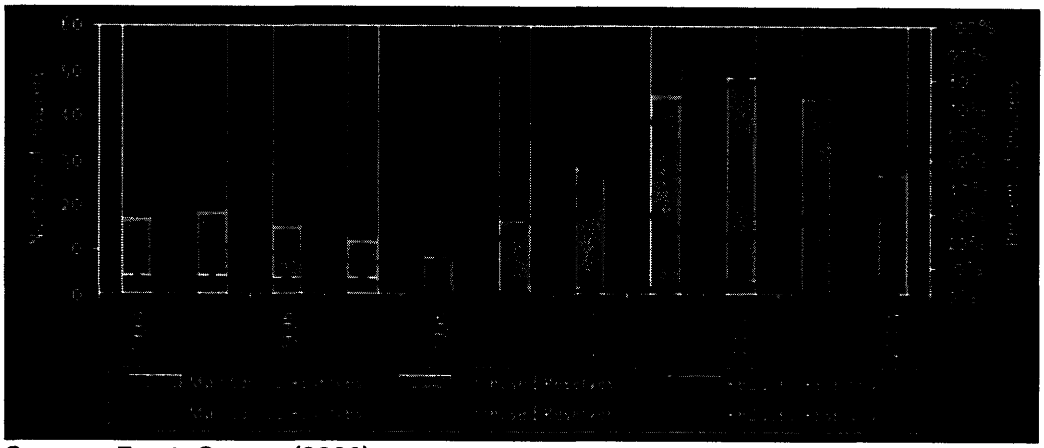
U.S. insurance companies typically invest up to 7% in equities, 70% to 90% in fixed income instruments, and the remainder in cash (Frank Crystal 2006). Some insurance companies and reinsurance companies, however, invest 20% to 35% of their assets in equities, with one company planning to invest as much as 50% of its assets in equities (Credit Suisse First Boston 2005).

The capacity of insurance companies to meet policy obligations and to continue to underwrite risk is measured by their reserves and surplus accounts. Reserves are funds expensed from the surplus general funds of an insurance company to pay for actual or anticipated claims. When reserves are inadequate to meet claims or drop below levels required by applicable insurance regulations, surplus must be further reduced to increase reserves. Thus, surplus serves as the measure of the insurance industry's capacity to underwrite additional risk. Surplus funds may be increased by policy premiums, investments, and new capital (Frank Crystal 2006).

Insurance companies are highly vulnerable to stock market performance for funding reserves and maintaining surplus capacity (Frank Crystal 2006). If climate change adversely affects the macro economy, it could potentially threaten the insurance industry's practice of funding reserves from investment returns. With the drop in stock prices since first quarter 2000, insurance companies have had to increase premiums and focus on improving underwriting performance (Frank Crystal 2006).

Figure 6.25 below shows recent reserve trends for the insurance industry. It is important to note that industry reserves are not an indication of any particular company's ability to meet obligations and that reserves for individual companies must be examined. The September 11, 2001 attacks on the World Trade Center reduced aggregate industry surplus by 7% (Frank Crystal 2005a). Following September 11, insurance companies sought to increase surplus (Frank Crystal 2005b). To place losses in perspective, Hurricane Katrina reduced industry surplus by 15% (Frank Crystal 2005a).

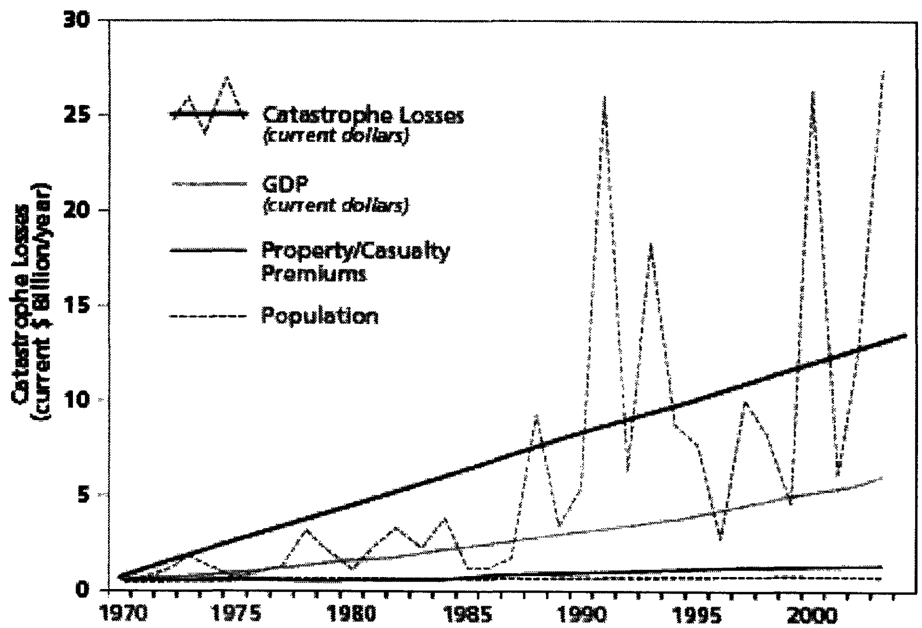
Figure 6.25: Insurance Company Reserve Trends, 1994-2004



Source: Frank Crystal (2006).

Significantly, since the 1970's, U.S. catastrophic losses have grown ten times faster than property/casualty premiums (CERES 2005a). GDP and population growth also lag catastrophe losses (CERES 2005a), making it increasingly difficult to spread the risk of growing catastrophe losses across the economy and population.

Figure 6.26: U.S. Catastrophe Loss Growth v. GDP, Premiums, Population, 1970-2004

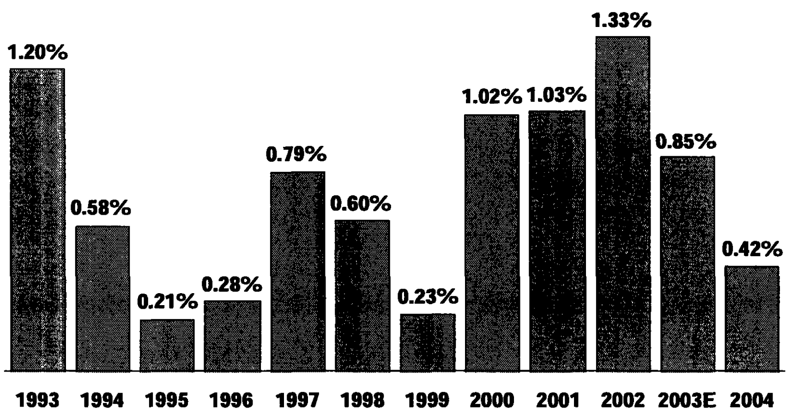


Source: CERES (2005a). Note: GDP, population and premiums are indexed to 1971 losses. Loss cost, premium, and GDP data reflect values in year incurred.

Insolvencies among insurance companies are not common, but are influenced by catastrophic events. Following Hurricane Andrew in 1992, approximately a dozen insurance companies became insolvent due to losses incurred in Florida (Binnun 2006). Insurance company insolvencies in general, including those resulting from Hurricane Andrew and other catastrophic events, have typically been limited to smaller, less diversified companies that provide only a single kind of insurance and/or operate in a single state or region (Hartwig 2006).

From 1993 to 2004, the twelve-year property and casualty insurance industry average insolvency rate was 0.71% of the total number of companies (Insurance Information Institute 2006a). Because these insolvencies are almost exclusively smaller insurance companies (Hartwig 2006), they represent a much smaller portion of the industry on a policy surplus basis.

6.27 . . 1993 2004



Source: Insurance Information Institute (2006a).

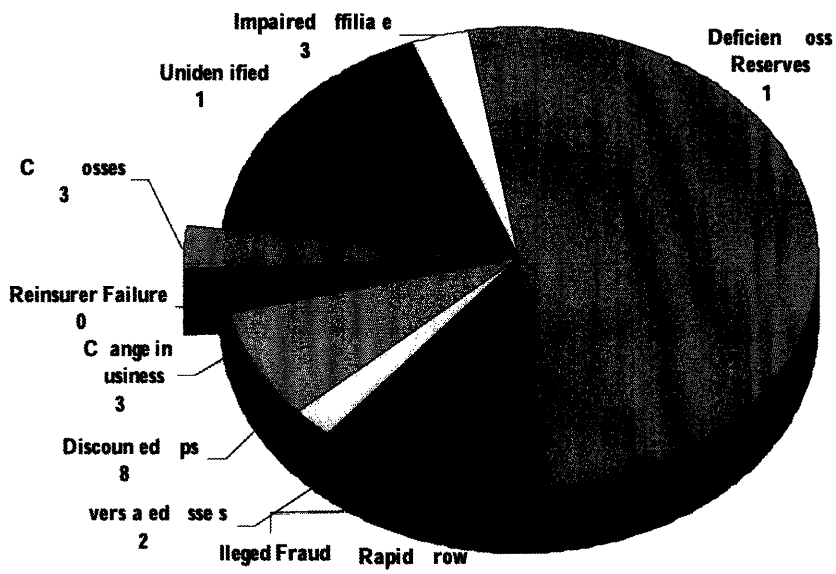
6.34 . . 2000 2004

2000	2001	2002	2003	2004
30	30	38	21	10

Source: Insurance Information Institute (2006a)

While only 3% of insurance company insolvencies are attributed to natural catastrophes, over 50% are attributed to inadequate reserves. As described above, adequacy of reserves are strongly influenced by loss history and capital markets performance. A.M. Best estimated that at year-end 2004 the property casualty industry was inadequately reserved by $59 billion (Credit Suisse First Boston 2006). Explanations for the under reserving include optimistic evaluations of potential liabilities and short-term management incentives to maintain the stock prices of their companies (Credit Suisse First Boston 2006).

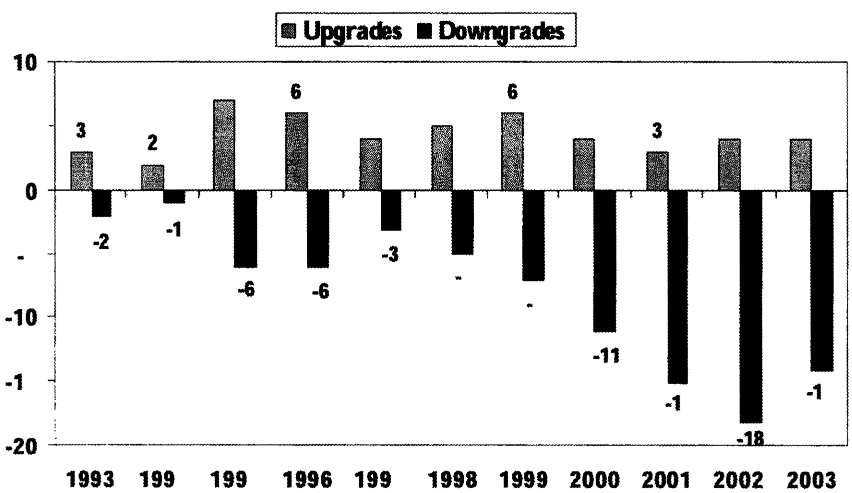
Figure 6.28: Reasons for P&C Insolvencies, 1993-2002



Source: Insurance Information Institute (2003). Note: data comprises 218 insolvencies

Credit rating agencies play an important role in monitoring the financial health of the insurance industry. Credit rating agency monitoring is especially important for reinsurance companies, which are not regulated by any government authority. Lower credit ratings affect the ability of insurance and reinsurance companies to attract capital, to compete for business, and influence the cost of capital. Importantly, crediting ratings should also provide an early indication of insolvency.

Figure 6.29: Insurance Company Upgrades and Downgrades, 1993-2000



Source: Insurance Information Institute (2006a).

Catastrophic events may increase the chances of insurance company downgrades. Following Hurricane Katrina, Standard & Poor's placed ten insurance and reinsurance companies on negative credit watch as a result of loss estimates (Insurance Journal 2005).

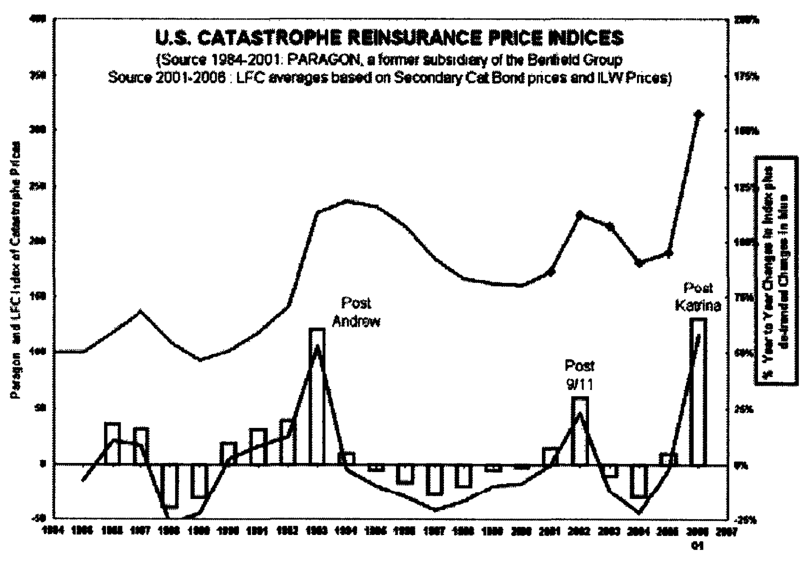
6.3.4 Natural Catastrophe Effects on Insuring Energy Sector

In recent years, insurance and reinsurance companies have responded to the financial effects of storms and hurricanes by increasing premiums, tightening contractual terms, or withdrawing insurance from high-risk areas altogether.

The increasing magnitude of insurance losses has caused increases in the cost of both U.S. property and casualty insurance and reinsurance. Since 1990, the cost of reinsurance has been gradually increasing, with large increases occurring following major catastrophic events. Figure 6.30 below shows large increases occurring following Hurricane Andrew in 1992, the September 11, 2001 terrorist attacks, and the 2005 hurricane season.

Following the 2005 hurricane season, the cost of insurance for offshore energy infrastructure reportedly increased 300% to 400%, while onshore rates increased 10% to 30% (Frank Crystal 2006). Since 1990, U.S. catastrophe reinsurance rates have more than tripled (Lane and Beckwith 2006).

Figure 6.30: U.S. Catastrophe Reinsurance Price Indices, 1984-Q1 2006



Source: Lane and Beckwith (2006).

In addition to increased rates, insurers also have curtailed coverage of insurance in high-risk areas following natural catastrophes. In 1992, following Hurricane Andrew, insurance companies withdrew insurance from utility transmission and distribution assets in the Gulf Coast area (Binnun 2006). Following the 2005 hurricane season, insurers are considering a number of contractual provisions to limit their exposure to hurricane and storm risk in the North Atlantic Basin, including:

- Sub-limits for Gulf of Mexico exposure;
- Exclude Gulf of Mexico from coverage;
- Exclude Gulf of Mexico platforms built prior to certain date;
- Exclude business interruption coverage for Gulf of Mexico properties;
- Increase record retention period and waiting period for business interruption coverage;
- Require complete schedule of all covered Gulf of Mexico property; and
- Exclude "windstorm" coverage in Gulf of Mexico region (Marsh 2005).

The withdrawal of insurance coverage for the energy sector in the Gulf Coast is part of a larger trend of curtailing insurance coverage in coastal areas along the East Coast. Insurance coverage is increasingly difficult to obtain in Florida (Binnun 2006; Spudeck 2006), Cape Cod and Long Island (Adams 2006), Rhode Island, Louisiana, Mississippi, and South Carolina (CERES 2006). Some large insurers have curtailed coverage or stopped underwriting coastal insurance along the entire East Coast (CERES 2006). As a result, state-sponsored insurance programs are serving an increasing portion of the consumer market in these coastal areas (Smythe 2006; Hartwig 2002).

Hurricanes and other catastrophic events may also affect other lines of insurance coverage. Hurricane Katrina released over seven million gallons of petroleum into the Gulf of Mexico, approximately two-thirds the amount of oil spilled by the Exxon Valdez in Prince William Sound, Alaska in 1989 (Marsh 2005). The large volume of environmental debris and drinking water contamination will increase insurance losses and possibly result in curtailment or price increases for other lines of infrastructure insurance (Marsh 2005).

6.3.5 Insurance Case Study Main Findings

The insurance case study examined how catastrophic losses have affected the insurance industry during the past several decades. The insurance case study shows that the insurance industry has experienced increasing losses due to natural catastrophes, which in the case of storms has resulted in curtailment of coverage and increases in premiums. Unavailability of insurance coverage could potentially adversely affect lending activity in certain regions, and thereby reduce the resources available for the development of carbon neutral energy infrastructure in affected areas.

During the last several decades, the insurance industry has experienced continuing losses on account of underwriting activities for property and casualty insurance. These losses are the result of increasing frequency and severity of natural catastrophic events as well as increases in the density of infrastructure in high-population areas and the cost of replacing such structures. Storm activity accounts for approximately 78% of insured catastrophic losses (Insurance Information Institute 2006a). With respect to storm activity in particular, increasing losses have already caused curtailment of, and increasing prices for, insurance coverage along coastal areas in the United States.

If climate change causes further increases in the severity or frequency of storms, resulting in increasing losses, it could potentially lead to inability to obtain property and casualty insurance for highly vulnerable areas. In turn, if insurance coverage is unavailable in certain regions or coastal areas, private lenders may decline to lend to infrastructure projects in these areas. Because a majority of the population lives in coastal areas (Changnon 1999), the inability to obtain insurance could lead to difficulties in financing infrastructure in critical high-population areas.

6.4 Case Studies Conclusions

This chapter has presented three case studies, each focusing on a particular aspect of financing energy infrastructure in light of risks associated with a changing climate.

The capital markets case study examined the magnitude of investment required to develop 10-15 TW of carbon neutral electricity infrastructure within a 50-year time frame. Comparing the required investment levels based on estimates developed for the case study to historical, projected, and current capital markets activity in the energy and utilities sector, reveals that efforts to develop carbon neutral electricity infrastructure will potentially exceed the capacity of capital markets. Given the magnitude of required investment, the financial stability of firms and capital markets become important issues if society addresses climate change by developing carbon neutral energy infrastructure.

The utility case study examined the increase in hurricanes and storms in the Eastern United States and Gulf of Mexico during the past fifteen years and the losses they have caused to the utilities industry and energy infrastructure. Climate change is believed by some in the scientific community to have contributed to the observed increase in the number of hurricanes and storms and the resulting losses. If changing climate does increase the losses caused by storms, climate change could significantly increase the costs for utilities and energy companies in affected areas. If the affected infrastructure is a critical energy supply node, as in the case of the Gulf of Mexico, catastrophic storms associated with climate change could affect global energy markets. Importantly, the increasing costs associated with these storms could potentially adversely affect the financial condition of utilities and energy firms in storm-prone areas, and undermine their capacity to finance carbon neutral infrastructure.

The insurance case study examined how this essential industry to financing infrastructure may be affected by catastrophic losses. The insurance case study suggests that if climate change is accompanied by increasing catastrophic losses, the insurance industry will likely be characterized by increasing costs of coverage, curtailment in coverage based on location or activity, and continuing losses by insurance companies on underwriting activities, especially in regulated markets. The insurance case study results are significant because they suggest that businesses and households face increased costs for insurance and the potential to be inadequately insured for catastrophic events. Importantly, if insurance coverage for energy infrastructure projects is unavailable in certain regions or coastal areas, private lenders may decline to provide insurance coverage to these projects.

The results of these case studies suggest that the utilities and energy industries face increasing risks that may become uninsurable, and that the capital requirements for the sector as a whole will increase dramatically in order to develop carbon neutral infrastructure. The conflict between increasing risk and increasing need for capital creates the potential for failure by the private sector to develop carbon neutral infrastructure within a time frame calculated to prevent long-term damage to the earth's atmosphere and other natural systems due to climate change. Potential policy measures to prevent market failure are further discussed in Chapter 7.

7 Results and Policy Recommendations

This final chapter summarizes the dissertation's primary findings, makes several recommendations for policy based on the research, and suggests areas for further study.

7.1 Primary Findings

The main findings of the dissertation are as follows:

Private Sector Role Critical. Increasingly, the private sector is responsible for financing and developing infrastructure. Further, financial and other demands on the government sector are expected to increase during this century. Thus, the private sector will be an essential partner in addressing climate change.

Magnitude of Transition is Large. The magnitude of the transition to carbon neutral infrastructure is of such a scale that achieving it within half or even an entire century will be difficult. This is in contrast to prior research (e.g., US NAS 1992) that had assumed that infrastructure could be changed within one-lifetime of infrastructure (e.g., 50 years for power plants). Based on the analysis presented in Chapter 6, developing 10 TW of carbon neutral electricity over a 50-year period would require global annual investment of $714 billion to $1,186 billion during the first twenty years, and then would further increase during the next thirty years as capital equipment is replaced. To meet this goal, over 562 MW of actual generation capacity must be added each day, which would require construction of 1,287 MW of new nameplate capacity per day taking capacity factors into account, based on the technology wedge portfolio described in Chapter 2. Such large-scale development presents challenges from the point of view of construction times, supply chains, risk, and financial requirements.

Time To Prevent Potentially Dangerous Greenhouse Gas Concentrations is Limited. The timeframe for developing carbon neutral energy infrastructure will require decades and will be influenced by a number of factors, including economic conditions, technology development, and public policy. Given these long development periods, the timeframe to initiate a program to develop long-term solutions to climate change becomes urgent. According to most IPCC SRES scenarios, we are likely to reach carbon dioxide concentrations of approximately 550 ppm by mid-century, which the IPCC assigns a likely or very likely chance of causing potentially dangerous conditions, including health effects, increased potential for famine, and potentially significant sea level rise (IPCC 2001). Further, if the potential adverse economic effects that could accompany peak production of conventional oil are considered in the timing of the transition to carbon neutral energy infrastructure, then the timeframe for this transition is likely within this century and potentially within the first half of this century (Wood. et al. 2004).

Long-Term Sustained Effort Required. Sustained financial and policy commitment is essential for supporting carbon neutral energy infrastructure. Technology requires decades to develop and commercialize, and infrastructure often has lifetimes and debt structures in excess of thirty years or more. In contrast, business and government operate on much shorter time frames. For example, in the case of financial markets, investment partnerships operate for less than a decade before liquidating investments (VC Experts 2006a), executives are typically compensated with stock options on a four-year vesting schedule (VC Experts 2006b), corporate profits and losses are measured and reported quarterly, and traders typically close out their positions at the end of each day or by the weekend (Page, W. 2006; Miller 2006). Political cycles are only slightly more stable, with the U.S. Senate, President, and Congress running for re-election on six, four, and two year terms, respectively.

Any successful effort to address climate change through the development of carbon neutral energy infrastructure will require sustained, long-term effort spanning decades. In turn, this will place increased emphasis on the financial and public policy commitment required to support transformation to carbon neutral energy infrastructure.

<u>Climate Change Risks to Infrastructure Increasing and Complex</u>. The risks associated with climate change will likely increase during this century. In turn, the changing nature of risk could have profound effects on the risk profile of large engineering infrastructure projects, especially in the capital-intensive electric and energy sectors. As demonstrated by the analysis in Chapter 4, there are substantial positive correlations among different kinds of risks. Multiple interactions can occur between many of the risks, with secondary and tertiary effects. These risks potentially adversely affect both individual firms and the systemic risks of financial markets. Ultimately, these risks could increase both the capital and financing costs of, and adversely affect the private sector's ability to undertake, infrastructure development, including carbon neutral energy infrastructure.

<u>Risk Management Markets and Methods Inadequate</u>. Current private sector risk management methods are currently inadequate to address the risks associated with climate change. The study of private contractual methods in Chapter 5 evaluated insurance, commodity and weather derivatives, carbon offsets, and catastrophe bonds based on six criteria: (a) scope of risk covered, (b) geographic coverage, (c) contract duration, (d) availability, (e) price, and (f) market capacity. It found that all of these risk management instruments do not provide full protection against common risks that will likely increase due to climate change. Significantly, their short-term durations of generally one-year or less, but in no cases greater than five years, limit their ability to address long-term climate risk. Risks beyond this timeframe are generally considered too uncertain or costly to underwrite. In the case of insurance products, there is already evidence that increased risks associated with climate have caused curtailment of coverage and increased cost of risk coverage in certain coastal areas. As a result, risk management markets and methods are presently inadequate to address the risks posed by climate change.

<u>Capital Markets Capacity Limited and Volatile</u>. Development of carbon neutral energy infrastructure within a time-frame intended to prevent potentially dangerous levels of atmospheric greenhouse gas concentrations will challenge the capacity of capital markets to provide the required investment capital and the ability of firms to raise and absorb such investment levels. As demonstrated in the case study in Chapter 6, the level of required capital investment to develop 10 TW of carbon neutral electricity infrastructure within a 50-

year period would require from $714 billion to $1,186 billion annually during the first twenty years, which would then further increase over the 50-year period. Compared to capital expenditures by utilities included in the S&P 500, the U.S. share of carbon neutral electricity would require increasing capital expenditures by a factor of approximately 5 to 9 times during the first twenty years of investment, and further increasing thereafter. The U.S. capital markets portion of the required investment for carbon neutral electricity infrastructure during the first twenty years would consume approximately 30% to 50% of all capital raised from U.S. public debt and equity transactions for all economic sectors of the U.S. economy. The financial stability of capital markets and the ability of firms to recover capital investment through operations become major issues for private sector efforts to develop carbon neutral energy infrastructure within the time frames contemplated by this dissertation.

The next section examines the issue of what government policies are necessary or desirable in order to support the private sector playing a dynamic role in addressing climate change through developing carbon neutral infrastructure.

7.2 Policy Recommendations

This section recommends several policies based on the research presented in the dissertation. The policy recommendations focus on government policy that is essential to promoting private sector solutions to climate change. As these recommendations are limited both by the scope of the research presented in the dissertation and by their focus on promoting private sector solutions, they are not intended to provide an exhaustive treatment of all potential approaches to addressing climate change.

Recovery Risk. The most significant policy recommendation is that government must address recovery risk associated with capital expenditures for utilities and other firms engaged in developing carbon neutral energy infrastructure. Recovery risk is a prominent risk in both the utilities and insurance case studies. In the case of utilities, the risk that regulators will not permit recovery of capital expenditures and catastrophic losses, or that such recoveries will be delayed, may significantly depress capital investment in carbon neutral electricity technologies. In the case of insurance firms, the risk that regulators will not allow recovery for the cost of providing risk coverage could lead to curtailment of insurance in high-risk areas. For areas where catastrophic insurance is unavailable, lenders and other investors may be unwilling to provide financing, as insurance is a standard condition of infrastructure financings.

With respect to developing carbon neutral electricity infrastructure, the German Renewable Energy Sources Act adopted in 2000 provides an example of one policy approach for addressing recovery risk. The law provides that electricity generated on a renewable basis will be sold to the regional transmission organization at a guaranteed price for a period of years set by a government committee to insure repayment of capital expenditures, debt, and a market return on investment. Electricity from different technologies is sold at different guaranteed prices based on the economics of the particular technology at the time of construction. The committee periodically adjusts guaranteed prices downward for new projects based on improvements in technologies in order to capture cost reductions for the benefit of consumers. The costs of renewable electricity are spread among the consumer base by the regional transmission utility, which charges a uniform price for all electricity (United Nations Development Programme et al. 2004).

In contrast, the Clean Development Mechanism (CDM) provides an example of an arrangement that is intended to increase the implementation of renewable technologies but raises its own set of recovery risks. As described in Chapter 5, the CDM requires that project sponsors prove that projects would not have been implemented but for the CDM arrangements, and comply with standards that are often changing and unclear. Further, the certified emissions reductions certificates (CERs) issued pursuant to the CDM are subject to dilution in value due to over-allocation of emissions allowances under the Kyoto Protocol. These various issues have created uncertainty for the ability of investors to recover their investment through the sale of CERs. If CDM is to play a role in directing much needed resources towards renewable technologies in developing countries, the process must be streamlined and greater certainty needs to be provided to investors so that their investment and a market return will be recovered.

In summary, adequate recovery of costs is the single most important element for the private sector to supply the levels of investment required to transition society to carbon neutral energy infrastructure.

Government Policy. If we are to succeed in developing carbon neutral energy infrastructure, government policy must provide strong incentives for the private sector to develop carbon neutral energy infrastructure and to minimize risks. This includes providing signals as to what infrastructure government intends to support, certainty in cost recovery for large investments made in approved technologies, market-based programs such as cap-and-trade that feature aggressive mandatory caps on emissions,[23] and commercially competitive returns for developing carbon neutral infrastructure. In addition to addressing recovery cost, government regulation and tax mechanisms must be an important part of supporting the development of carbon neutral infrastructure. Regulation coupled with strong financial rewards for developing carbon neutral infrastructure are essential if we are to accomplish societal goals of sustainable development through the private sector.

Financial Market Stability. The capital markets must play an essential role in any private sector effort to develop carbon neutral energy infrastructure. Governments must tailor fiscal and regulatory regimes to accommodate a rapid expansion of capital markets activity in carbon neutral energy infrastructure. As demonstrated in the capital markets case study presented in Chapter 6, the level of required capital investment to develop 10 TW of carbon neutral electricity infrastructure within a 50-year period would require from $713 billion to $1,186 billion annually for the first twenty years alone, requiring utilities to increase capital expenditures by approximately 400% to 700% compared to current levels.

---

[23] The problems of excess inventories of emissions allowances are discussed in Chapter 5 in the section on carbon offsets. See also Kosobud et al. (2004) for a description of how regulations have been primarily responsible for reductions in VOCs while excess emissions allowances have resulted in the Chicago-area VOC cap-and-trade system being ineffectual thus far.

Such an increase in capital investment activity within one sector of the economy would potentially adversely affect the financial condition of utilities and could destabilize financial markets.

Higher levels of investment will place greater emphasis on the efforts of government regulators and self-regulatory organization (e.g., exchanges and professional accreditation organizations) to insure transparent and properly functioning capital markets. The recurrence of accountability and transparency issues in financial markets during periods of increased investment activity underscores the importance of these issues. The development of carbon neutral energy infrastructure will require sustained investment over a long period, and financial and accounting scandals of the kind experienced in the past could potentially set society back many years in this undertaking.

Aggressive Government and Corporate Planning. The nature and magnitude of the problems presented by climate change requires aggressive government and corporate planning. Government can and should respond to the risks presented by climate change by developing infrastructure guidelines for changing conditions and planning purposes. With respect to the development of carbon neutral energy infrastructure, the magnitude of the transformation is of such a scale that coordinated leadership and planning between the private and public sector is essential to its successful completion.

Attention to Areas of Potential Market Failure. Government policymakers should focus on the potential for markets to fail as a result of, or in addressing, climate change. The dissertation's research suggests two specific areas where market failure might occur: insurance and capital markets.

As discussed in chapters 4 and 5, the private sector currently lacks risk management instruments that are designed to address potential risks associated with climate change. As climate risks increase, we should expect increasing costs associated with risk coverage and curtailment of coverage in areas where insurance is not adequately priced to cover this risk. The insurance markets have already shown evidence of a potential gap in the amount of risk coverage available at a price that businesses and households are willing or able to pay.

The other potential area of market failure is the capital markets capacity to provide the required levels of investment for infrastructure intended to address climate change. The level of investment required over a multi-decadal period is so great that the potential failure of capital markets to provide adequate capital should be anticipated and planned for if the development of carbon neutral energy infrastructure is pursued. Importantly, any expansion of the government's role that may adversely affect the operation of the market should be undertaken carefully.

Barriers to the goal of encouraging investment in renewable technology should be removed wherever possible, and polices that would promote introduction of carbon neutral energy infrastructure should be given the highest priority in government circles for consideration and adoption.

7.3 Areas for Further Research

The research presented in the dissertation could be advanced and expanded in several areas. Four areas are emphasized here.

First, further efforts to develop the specific details of technology-oriented approaches to climate change are particularly valuable in assessing the viability of these approaches. This dissertation developed a portfolio of carbon neutral electricity infrastructure technologies. The portfolio of carbon neutral electricity infrastructure and the comparison to capital markets activities presented in Chapter 6 could be expanded to include the transportation and other energy sectors. Proven technologies such as biofuels, coal-to-liquids, and gas-to-liquids are now ripe subjects for this kind of analysis. Further research examining some of the assumptions made in constructing the portfolio, such as the capacity of supply chains to meet the challenges posed by developing carbon neutral infrastructure, would make a substantial contribution to assessment of the private sector's capacity to address climate change.

Second, to the knowledge of the author, the financial risks identified in Chapter 4 have yet to be reflected in any climate modeling efforts. These risks potentially influence the speed at which technology will be adopted in the future. Accordingly, further study of risk by climate modelers, particularly in relation to adoption of technology, could potentially increase the realism of these models in their assumptions about the ability and willingness of the private sector to adopt carbon neutral technology.

Third, as suggested by the financial risks analysis in Chapter 4, the financial instruments assessment in Chapter 5, and the insurance case study in Chapter 6, climate change poses a number of risks that are not presently addressed by risk management instruments. The absence of risk management instruments for addressing risks posed by climate change exposes the private sector to potentially significant risks that could adversely affect firms and their capacity for adjusting to climate change. Accordingly, the study of risk management tools for mitigating climate risk is a critical area for further research.

Finally, further research in the area of conservation could provide important insights into measures that can be taken to decrease the future magnitude of the transformation of energy infrastructure. Similarly, research in the area of distributed generation could assist our understanding of ways to more widely disperse the burden of transforming energy infrastructure. The dissertation research suggests that the challenges of developing carbon neutral energy infrastructure eventually may grow beyond the financial, engineering, and management capacity of the private sector to develop within the time required to prevent potentially dangerous levels of greenhouse gas concentrations.

The carbon neutral electricity portfolio presented in Chapter 2 and the capital markets case study presented in Chapter 6 puts into perspective the magnitude of the challenges society faces in pursuing a solution to addressing climate change for the electricity sector. Importantly, the case study contemplates that only limited conservation efforts will be undertaken in the form of one technology wedge of greater efficiency, and shows that attempts to build our way out of the climate change problem by developing infrastructure that is both capable of meeting future projected energy demand and is carbon neutral is a costly and uncertain task.

Importantly, as carbon-intensive infrastructure increases, the size of the transition increases, requiring more capital investment and longer transformation periods. Weighing expected future technology learning curves against demographic and economic trends suggests that the potential complexity of this challenge could very well increase. Given the magnitude and risks of this task, we should acknowledge the limits of, and actively reconsider, approaches to solving energy and environmental problems that are exclusively based on mega-engineering projects.

Conservation could increase the time, material and financial resources we have for transforming infrastructure and ultimately addressing climate change. At the same time, conservation has potential economic costs, raises difficult equity and distribution issues, and requires a society-wide shift in values. These are challenging issues that should become a part of mainstream research if we are to employ conservation as a policy measure in connection with engineering approaches to address energy and environmental challenges.

7.4 Conclusion

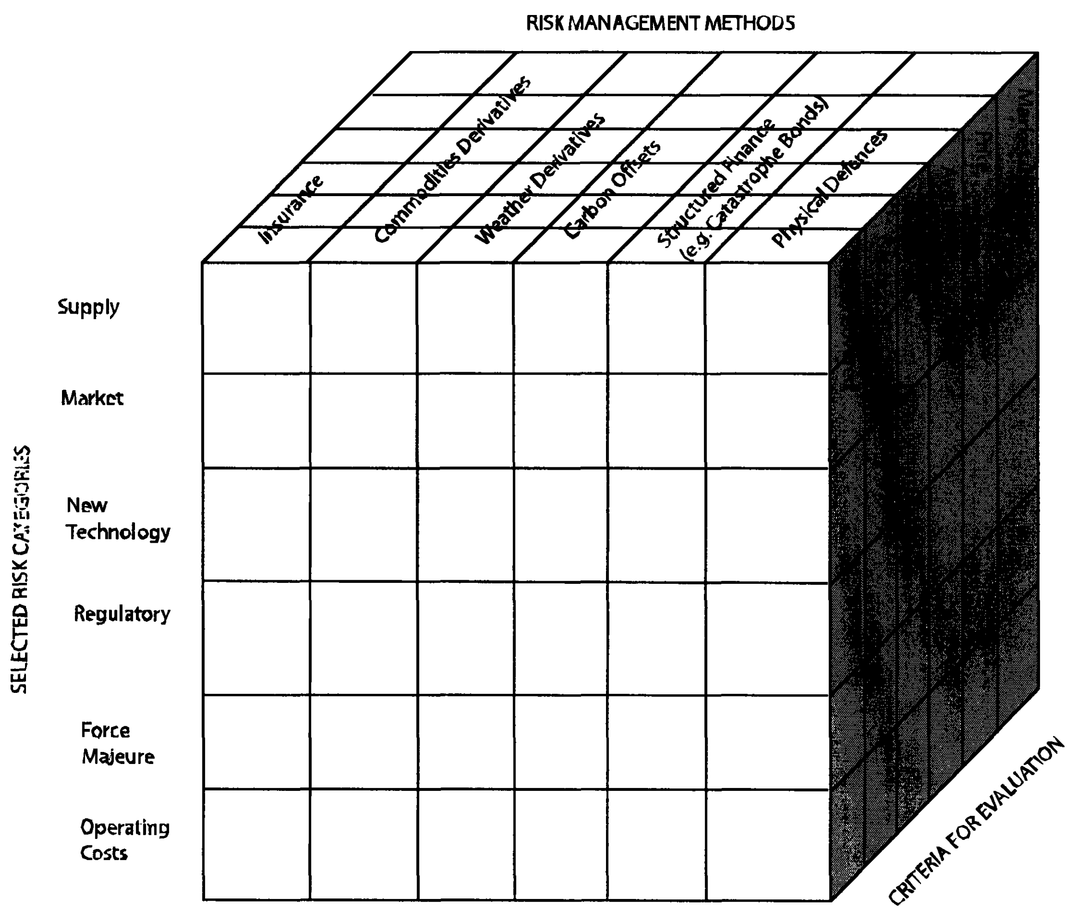
This dissertation has examined the capacity of the private sector to finance and develop carbon neutral energy infrastructure in order to provide a long-term solution to one important cause of climate change. The dissertation has identified the financial risks associated with climate change and evaluated private sector risk management methods for mitigating risks associated with climate change. The dissertation has developed a portfolio of carbon neutral electricity infrastructure technologies and assessed the financial costs associated with implementing this infrastructure. The dissertation has examined the capital markets, utilities and insurance sectors to assess the extent to which these critical segments of the economy can support the transformation to carbon neutral electricity infrastructure and withstand the risks associated with climate change.

Based on the research presented in the dissertation, the financial risks and costs of developing carbon neutral electricity infrastructure within a time period intended to prevent potentially dangerous levels of greenhouse gas concentrations are of such a magnitude that there is substantial risk that the private sector could fail in this undertaking. At the same time, private sector financial and management resources are essential to successfully transforming energy infrastructure to a carbon neutral basis. If society is to pursue carbon neutral infrastructure, government policy must support the financial recovery of firms engaged in developing carbon neutral infrastructure, the financial stability of capital markets, and the mitigation of risks associated with climate change.

APPENDIX A

CLIMATE RISK ASSESSMENT MATRIX

The Climate Risk Assessment Matrix is developed in Chapter 4 this dissertation. Appendix A contains the basic matrix without any evaluative data for the risks or risk management methods. Chapter 5 evaluates the risk management methods based on the evaluation criteria identified in the matrix. Revised Climate Risk Assessment Matrices that show the results of the evaluation are presented in Chapter 5.



APPENDIX B

RISK MANAGEMENT SURVEY PARTICIPANTS

Organizations listed below were contacted in connection with the insurance and derivatives survey described in Chapter 5 of this dissertation. Organizations marked with an asterisk (*) provided information in response to the applicable survey questionnaire. Some firms provided information for more than one line of risk management product.

I. INSURANCE SURVEY (Insurance and Catastrophe Bonds)

Insurance and Reinsurance Companies

AIG
Allianz
Allstate
American Re (a division of Munich Re)*
Aviva*
AXA Re*
Benfield
GE Insurance
Swiss Re*
Lloyds*
Millea Tokio Marine
XL Group*
Zurich Financial Services*

Insurance Brokers

Aon*
Arthur Gallagher*
Frank Crystal & Co.*
JW Bond Consultants*
Guy Carpenter*
Marsh

Insurance Regulators

Florida*

Credit Rating Agencies

Fitch*
Moodys
S&P*
A&M Best*

Modeling Firms

AIR
Eqecat*
Risk Management Solutions*

Other

Association of British Insurers*
Insurance Information Institute*

II. DERIVATIVES SURVEY (Commodities and Weather Derivatives, Carbon Offsets)

Derivatives Brokers and Underwriters

ABN AMRO
Accord Energy
AXA Re
Carbon Credit Capital*
Constellation Energy*
Coriolis Capital*
CTA Miller*
DE Shaw*
Ecosecurities*
DTE Energy
Evolution Markets*
GuaranteedWeather
Goldman Sachs*
Hess Energy Trading Company
Merrill Lynch
Morgan Stanley*
Optiver*
NatSource*
Sempra
Societe Generale (Fimat)*
Swiss Re*
TFS*
Transalta*
XL Group*

Other

Chicago Mercantile Exchange*
Risk Management Solutions*

APPENDIX C

FORM OF INSURANCE SURVEY

This form was used to conduct surveys of insurance organizations described in Chapter 5.

Date: ____________________________

Name:____________________________ **Title:**____________________________
Email:____________________________ **Phone:**____________________________
Firm: ____________________________ **Division:**__________________________

INSTRUCTIONS

The survey of insurance companies has been prepared in connection with a Ph.D. dissertation at the Massachusetts Institute of Technology concerning the private sector's role in infrastructure development in light of potential risks due to weather and commodities.

Survey Format

The Survey consists of two parts. The first part asks about your firm's risk assessment practices. The second part asks about insurance products that your firm provides or brokers.

Survey Responses Confidential and Reporting

Your submissions will be held in confidence and survey results will be reported in summary format only without attribution to source. Participants will receive summary results.

Part I: Climate Risk Programs

Has your firm developed a climate risk program? ______ (Y/N)

Does your firm presently consider climate risks in future investment or operational decisions? _______ (Y/N) If yes, please describe:

____

____

Has your firm withdrawn insurance or other risk management products coverage due to climate risks? If so, please describe where and why?

____

____

How far into the future does your firm typically forecast?

For general business purposes:	For climate risk assessment:
___ 30 days	___ 30 days
___ 60 days	___ 60 days
___ 1 year – 2 years	___ 1 year – 2 years
___ 2 years – 5 years	___ 2 years – 5 years
___ 5 years – 10 years	___ 5 years – 10 years
___ 11 years – 20 years	___ 11 years – 20 years
If over 20 years: ____	If over 20 years: ____

Describe how climate affects your company's ability to implement its strategic plan or costs?

____

____

How does your firm deal with the inherent uncertainties posed by climate risk?

____

____

How have you reflected climate risks in your modeling efforts?

____

____

____

With respect to catastrophic losses due to climate, how have your models performed during the past 10-year period, 5-year and 1-year periods compared to prior periods?

____

____

How do extreme market conditions impact your models (do they work within certain ranges), your risks (can you cover)?

____

____

What methods do you use to cover your own firm's Climate risks?

Diversification____
Reinsurance ____
Special Purpose Vehicles/Corporate Structures ____
Securitization/Capital Market Transactions ____
Other:____

How far out into the future can you hedge your firm's climate risk?

____

PART II: INSURANCE PRODUCTS BROKERED, OFFERED OR USED BY YOUR FIRM

	Climate Events Covered	Geographic Coverage	Longest Duration Available	Longest Lock-In on Price	% of coverage sold 1 year	% of coverage sold 1-3 years	% of coverage sold 3-10 years	% of coverage sold 10+ years
Business Interruption								
Property								
Reinsurance For Property								

APPENDIX D

FORM OF DERIVATIVES SURVEY

This form was used to conduct surveys of derivatives organizations described in Chapter 5.

Date: ______________________________

Name:______________________________ **Title:**______________________________
Email:______________________________ **Phone:**______________________________
Firm: ______________________________ **Division:**____________________________

Bushiness: ____ **Bank** ____ **Insurance Company**
____ **Risk Management Company** _____ **Broker**
____ **Utility** ____ **Oil/Gas** _____ **Renewable**

INSTRUCTIONS

The survey has been prepared in connection with a Ph.D. dissertation at the Massachusetts Institute of Technology concerning the private sector's role in infrastructure development in light of potential risks due to weather and commodities.

Respondents

Please direct survey to officer or employees familiar with your firm's risk management practices.

Survey Format

The Survey consists of two parts. The first part asks about risk management products that your firm buys or sells for its own account, and brokers or arranges for third parties. Leave sections that do not apply to your firm blank.

The second part asks how you might design a risk management program for three hypothetical situations. If no hedge is possible, please indicate.

Survey Responses Confidential and Reporting

Your submissions will be held in confidence and survey results will be reported in summary format only without attribution to source. Participants will receive summary results.

Derivatives (Fill out all that apply)									
RISK	Longest Known Duration	Geographic Coverage (Weather only) Good Reasonable Inadequate	Longest Duration Plausible Liquid	% buy/sell at 90 days or less	% buy/sell 90 days – 1 year	% buy/sell 1-3 years	% buy/sell 3-10 years	% buy/sell 10+ years	Primary Trading Purpose Speculative Hedging
Supply									
Oil									
Gas									
Coal									
Electricity									
Platinum									
Weather									
Heat									
Cold									
Precipitation									
Snow									
Wind									
Regulatory									
SO_x									
NO_x									
RECs									
GHG Allowance									
CDM CERs									
Credit (Counter party risk)									

References

Adams, M. (2006). "Strapped Insurers Flee Coastal Areas." USA Today, April 26, 2004. http://www.usatoday.com/money/industries/insurance/2006-04-25-hurricane-usat_x.htm (accessed June 3, 2006).

Adelman, M.A. (1995). The Genie out of the Bottle: World Oil since 1970. Cambridge, MA: MIT Press.

Ad Hoc Study Group on Carbon Dioxide and Climate (1979). "Report of an Ad Hoc Study Group on Carbon Dioxide and Climate, Woods Hole, MA, July 23-27, 1979." Carbon Dioxide and Climate: Scientific Assessment. Washington, D.C.: National Academy Press.

AgCert (2006). "AgCert Presentation" (Powerpoint presentation at the Engineering Institute of Canada Climate Change Technology Conference, Ottawa, Canada, May 10-12, 2006).

AGU (2002). "Scientists Debate Wisdom of Plan to Save Venice From Flooding." American Geophysical Union News, 8 May 2002.

Ali, P. and Yano, K. (2004). Eco-Finance: The Legal Design and Regulation of Market-Based Environmental Instruments. The Hague, Netherlands: Kluwer Law International.

Alley, R., Clark, P., Huybrechts, P. and Joughin, I. (2005). "Ice Sheet and Sea-Level Changes." Science 310, 456-460.

A.M. Best (2005a). "A.M. Best Takes Various Rating Actions Resulting from Impact of Hurricane Katrina." Press Release, September 15, 2005.

A.M. Best (2005b). "A.M. Best Comments on Potential Exposure to Hurricane Katrina." Press Release, September 22, 2005.

American Law Institute (1992). Restatement of the Law Third, Trusts. St. Paul, Minnesota: American Law Institute. Paragraph 227.

American Law Institute (1994). The Principles of Corporate Governance: Analysis and Recommendations. St. Paul, Minnesota: American Law Institute. Paragraphs 2.01 and 4.01.

American Re (2005). Annual Review of North American Catastrophes 2004. Princeton, NJ: American Reinsurance Company.

Arctic Climate Impact Assessment (2004). Impacts of a Warming Arctic. Cambridge, UK: Cambridge University Press.

Arditti, F., Lan, C., Cao., M. and McDonald, R. (1999). "Whether to Hedge." Weather Risk, August 1999.

Arisz, H., and Burrell, B. (2005). "Planning and design of urban drainage infrastructure considering climate change." Canadian Civil Engineer, Summer 2005, 10-13.

Arnell, N.W., (1999). "Climate change and global water resources." Global Environmental Change, 9, S51-S67.

Auld, H. and MacIver, D. (2005). "Cities and Communities: The Changing Climate and Increasing Vulnerability of Infrastructure." Occasional Paper 3. Ontario, Canada: Environment Canada.

Auld, H. and MacIver, D. (2006). "Changing Weather Patterns, Uncertainty and Infrastructure Risks: Emerging Adaptation Requirements." Occasional Paper. Ontario, Canada: Environment Canada.

Auld, H., MacIver, D. and Klaassen, J. (2006). "Adaptation Options for Infrastructure under Changing Climate Conditions." (Paper presented at the Engineering Institute of Canada Climate Change Technology Conference, Ottawa, Canada, May 10-12, 2006).

Auld, H. (2006). Associate Director, Adaptation and Impact Research Division, Atmospheric Science and Technology Directorate, Environment Canada. Personal communications, May 12, 2006.

Bank for International Settlements (2005). International Convergence of Capital Measurement and Capital Standards: a Revised Framework. Basel, Switzerland: Bank for International Settlements.

Bank for International Settlements (2006a). OTC derivatives market activity in the second half of 2005, May 2006. Basel, Switzerland: Bank for International Settlements.

Bank for International Settlements (2006b). BIS Quarterly Review, March, 2006. Basel, Switzerland: Bank for International Settlements.

Bank for International Settlements (2006c). BIS Quarterly Review, June, 2006. Basel, Switzerland: Bank for International Settlements.

Bank of America (2002). "Bank of America Model Syndicated Credit Agreement." Unpublished document.

Banks, E. and Bortniker, J. (2002). "Product and Market Convergence." In Element Re (2002), Weather Risk Management: Markets, Products and Applications. Basingstoke, United Kingdom: Palgrave.

Bartsch, U. and Muller, B. (2000). Fossil Fuels in a Changing Climate. New York, New York: Oxford University Press.

Baue, W. (2003). "Climate Change Litigation Could Affect Companies' Market Value." http://www.socialfunds.com/news/article.cgi/article1180.html (accessed April 26, 2006).

Baumert, K., ed. (2002). Building on the Kyoto Protocol. Washington, D.C.: World Resources Institute.

Bell, A. (2005). "Two aids for addressing climate change." Canadian Civil Engineer, Summer 2005, 18-22.

Bernanke, B., Gertler, M. and Watson, M. (1997). "Systematic Monetary Policy and the Effects of Oil Price Shocks." Brookings Papers on Economic Activity. Washington, D.C.: Brooking Institution.

Bernstein Research (2006). Proprietary database.

Betzenbichler, W. (2006). Head of the Certification Climate & Energy, TUV-SUD. Personal Communications, May 16, 2006.

Binnun, S. (2006). Deputy Insurance Commissioner, Florida Office of Insurance Regulation, State of Florida. Personal communications, May 2, 2006.

Blake, E., Jarrell, J.D., Rappaport, E. and Landsea, C. (2005). "The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2004 (and Other Frequently Requested Hurricane Facts)." NOAA Tech. Memo, NWS TPC-4. Coral Gables, Florida: National Hurricane Center.

Blanchard, O. (2005). "Trading through flexibility mechanisms: quantifying the size of the Kyoto markets." In Yamin, F., ed. (2005), Climate Change and Carbon Markets: A Handbook of Emissions Reduction Mechanisms. London, United Kingdom: Earthscan.

Blanco (2005). "Presentation of Carlos Blanco." (Presentation at the 2005 EPIIC Symposium, Tufts University, February 26, 2005).

Blasing, T.J. and Smith, K. "Recent Greenhouse Gas Concentrations." http://cdiac.ornl.gov/pns/current_ghg.html (accessed September 2, 2006).

Bogle, J. (2001). John Bogle on Investing: The First 50 Years. New York, NY: McGrawHill.

Bogle, J. (2005). The Battle for the Soul of Capitalism. New Have, CT: Yale University Press.

Boissonnade, A., Heitkemper, L., and Whitehead, D. (2002). "Weather Data: Cleaning and Enhancement." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Bowota v. Chevron Texaco Corp. (2004). 312 F. Supp. 2d 1229 (N.D. Cal. 2004).

Bradsher, K. (2002). "Taiwan: Water Rationing for Capital." New York Times, May 8, 2002. http://query.nytimes.com/gst/fullpage.html?res=9A05E2DE1230F93BA35756C0A9649C8B63&n=Top%2fReference%2fTimes%20Topics%2fSubjects%2fS%2fShortages (accessed June 8, 2006).

Bras, R. (2006). Professor of Engineering, Massachusetts Institute of Technology. Personal communications, May 4 , 2006.

Brix, A., Jewson, S., Ziehmann, C. (2002). "Weather Derivative Modeling and Valuation: A Statistical Perspective." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Brown, T.J., Hall, B.L. and Westerling, A.L. (2004). "The Impacts of 21st century climate change on wildland fire danger in the western United States: an application perspective." Climatic Change 62, 365-388.

Buffa, A. (2006). "Highway Robbery in Boston: Bechtel." http://urbanhabitat.org/node/315 (accessed April 27, 2006).

Bunn, M. (2006). Director, Project on Managing the Atom, John F. Kennedy School of Government, Harvard University. Personal Communications, June 15, 2006.

Bureau of Economic Analysis (2006). "Table 2.1. Current-Cost Net Stock of Private Fixed Assets, Equipment and Software, and Structures by Type." Standard Fixed Asset Tables. Washington, D.C.: Bureau of Economic Analysis. http://www.bea.gov/bea/dn/FA2004/SelectTable.asp (accessed August 23, 2006).

Bushouse, K. (2006). "Florida homeowners face another charge for propping up state's hurricane fund." South Florida Sun-Sentinel, March 26, 2006. http://www.sun-sentinel.com/news/weather/hurricane/sfl-zcatfund16mar16,0,1372026.story?coll=sfla-news-hurricane (accessed May 7, 2006).

Caifa, F. (2002). "Weather Note Securitization." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Campbell, C. and Laherrere, J. (1998). "The End of Cheap Oil." Scientific American, March 1998.

Canadian Council of Professional Engineers (2006). "Climate Change." Position Statement. www.ccpe.ca (accessed May 11, 2006).

Canadian Institute of Chartered Accountants (2004). Financial Reporting Disclosures About Social, Environmental and Ethical (SEE) Issues. Ontario, Canada: Canadian Institute of Chartered Accountants.

Canter M., Cole, J.B. and Sandor, R.L. (1997). "Insurance derivatives: A new asset class for the capital markets and a new hedging tool for the insurance industry." Journal of Applied Corporate Finance, Autumn, 1997.

CERES (2005a). Availability and Affordability of Insurance Under Climate Change: A Growing Challenge for the U.S. Boston, Massachusetts: CERES.

CERES (2005b). Institutional Investor Summit on Climate Risk: Final Report. New York, New York: CERES.

CERES (2006). From Risk to Opportunity: How Insurers Can Proactively and Profitably Manage Climate Change. Boston, Massachusetts: CERES.

Challoner, A. (2006). Head of General Insurance Risk Management, Aviva. Personal communications, May 18, 2006.

Changnon, S.A. (1999) "Factors affecting temporal fluctuations in damaging storm activity in the United States based on insurance loss data." Meteorological Applications 6, 1-10.

Chicago Mercantile Exchange (1999). "Weather Futures & Options" Press release, August 23, 1999.

Chicago Mercantile Exchange (2006). "Weather product specifications." http://www.cme.com/clearing/clr/spec/contract_specifications.html?type=wea (accessed April 19, 2006).

Choucri, N. (1976). International Politics of Energy Interdependence. Lexington, MA: Lexington Books.

CIA Factbook (2006). http://www.cia.gov/cia/publications/factbook/rankorder/2173rank.html (accessed May 16, 2006).

Ciorba, U., Lanza, A., and Pauli, F. (2001). "Kyoto Protocol and Emission Trading: Does the US Make a Difference?" Nota di Lavoro 90.2001. Milan, Italy: Fondazione Eni Enrico Mattei.

Clarke, L. and Weyant, J. (2002). "Modeling Induced Technological Change: An Overview." In Grubler, A., Nakicenovic, N., and Nordhaus, W., eds. (2002), Technological Change and the Environment. Washington, D.C.: Resources for the Future.

Clarke, R. (2006). Guy Carpenter. Personal communications, May 30, 2006.

Climate Law (2006a). "Worldwide litigation highlighted at UN talks." http://www.climatelaw.org/media/litigation.UN.talks. (accessed April 26, 2006).

Climate Law (2006b). "Judge orders Shell Nigeria MD and Petroleum Minister to appear in court." http://www.climatelaw.org/media/Nigeria.shell.april06 (accessed April 26, 2006).

Cogan, D., ed. (1989). The Greenhouse Effect: Investment Implications and Opportunities. Washington, D.C.: Investor Responsibility Research Center.

Cole, J. and Chiarenza, A. (1999). "Insurance Risk – Securitization: The best of both worlds." Risk, July 1999.

Coleman, T. (2002). The Impact of Climate Change on Insurance Against Catastrophes. Melbourne, Australia: Insurance Australia Group.

Collins, R. (2006). Vice President, Commodities, Swiss Re. Personal communications, May 8, 2006.

Colston, A. (2006a). U.S. Country Manager, Ecosecurities. Personal Communications, April 4 and May 19, 2006.

Colston, A. (2006b). "Ecosecurities plc Presentation on Green Project Design for CDM." (Powerpoint presentation at the Green Trading Summit, New York, New York, April 5, 2006).

Commonwealth of Massachusetts et al. v. United States Environmental Protection Agency (2006). Petition for Writ of Certiorari in the Supreme Court of the United States, March 2, 2006.

Congressional Research Service (2005a). "Global Warming: The Litigation Heats Up." CRS Report for Congress. Washington, D.C.: Congressional Research Service.

Congressional Research Service (2005b). "Federal Stafford Act Disaster Assistance: Presidential Declarations, Eligible Activities and Funding." CRS Report for Congress. Washington, D.C.: Congressional Research Service.

Connecticut et al. v. American Electric Power Company, Inc. et al. (2004). Complaint, Southern District of New York, July 21, 2004.

State of Connecticut et al. v. American Electric Power Company, Inc. et al. (2005). Brief submitted to the Court of Appeals for the Second Circuit, December 15, 2005.

Connors, S. (2006). Research Scientist, Laboratory for Energy and the Environment, Massachusetts Institute of Technology. Personal communications, June 19, 2006.

Cosimo, J. (2004). "Observation of a Decreasing Sea Ice Cover from Satellites." (Powerpoint presentation to Artic Forum, Washington, D.C., May 13-14, 2004).

Credit Suisse First Boston (2005). 2005 Property-Casualty Insurance Primer: 20th Edition. New York, New York: Credit Suisse First Boston.

Daniel, J. (2001). "Hedging Government Oil Price Risk." IMF Working Paper. Washington, D.C.: International Monetary Fund.

Daniel, J. (2006). Deputy Division Chief, Fiscal Affairs Department, International Monetary Fund. Personal Communications, May 18, 2006.

Davis, J.M., Ossowski, R. and Fedelino, A. (2003). Fiscal Policy Formulation and Implementation in Oil-Producing Countries. Washington, D.C.: International Monetary Fund.

Dealogic (2006a). "Dealogic Project Finance Review: Full Year 2005." Press Release, January 20, 2006. London, United Kingdom: Dealogic.

Dealogic (2006b). Proprietary database. Courtesy of Dealogic, February 21, 2006.

de Figueiredo, M. (2003). "The Hawaii Carbon Dioxide Ocean Sequestration Field Experiment: A Case Study in Public Perceptions and Institutional Effectiveness." Master's Thesis, Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA.

Deffeyes (2001). Hubbert's Peak: The Impending World Oil Shortage. Princeton, New Jersey: Princeton University Press.

Deutch and Lester (2004). Making Technology Work: Applications in Energy and the Environment. New York, New York: Cambridge University Press.

Dischel, R., ed. (2002). "Introduction To The Weather Market: Dawn to Mid-Morning." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Doe v. Unocal (2003). 395 F.3d. 978 (9th Cir. 2003) .

Dolsak, N. and Ostrom, E. (2003). The Commons in The New Millennium: Challenges and Adaptation. Cambridge, MA: MIT Press.

Drumbl (1998). "Waging War Against the World: The Need to Move From War Crimes to Environmental Crimes." 22 Fordham Int'l L.J. 122.

Dyurgerov, M.B. and Maier, M.F. (1997). "Mass balance of mountain and sub-polar glaciers: a new global assessment for 1961-1990." Arctic and Alpine Research, 29(4), 379-391.

Edison Electric Institute (1999). Reliability Report. Washington, D.C.: Edison Electric Institute.

Edison Electric Institute (2005). After the Disaster: Utility Restoration Cost Recovery. Washington, D.C.: Edison Electric Institute.

Edison Electric Institute (2006a). Peggy Suggs, Business Information Group. Personal Communications, April 26, 2006.

Edison Electric Institute (2006b). 2005 Financial Review Plus 2006 Developments: Annual Report of the U.S. Shareholder-Owned Electric Utility Industry. Washington, D.C.: Edison Electric Institute.

Eddy, L. (2006). Managing Director, AgCert. Personal Communications, May 15, 2006.

EIA (1997). World Oil Market and Oil Price Chronologies: 1970-1996. Washington, D.C.: Energy Information Administration. http://www.converger.com/eiacab/chron.htm (accessed April 29, 2006).

EIA (2005a). Annual Energy Outlook 2006. Washington, D.C.: Energy Information Administration.

EIA (2005b). International Energy Outlook 2005. Washington, D.C.: Energy Information Administration.

Element Re (2002). Weather Risk Management: Markets, Products and Applications. Basingstoke, United Kingdom: Palgrave.

Ellerman, D. and Wing, I. (2000). "Supplementarity: an invitation to monopsony?" The Energy Journal 21, 29-59.

Emanuel, K. (2005a). "Increasing destructiveness of tropical cyclones over the past 30 years." Nature 436, 686-688.

Emanuel, K. (2005b). "Emanuel Replies." Nature 438, E13.

Enos, J. (2000). Technical Progress and Profits: Process Improvements in Petroleum Refining. Oxford, United Kingdom: Oxford University Press.

EPRI (2004). "Economic Assessment Methodology for Offshore Wave Power Plants." EPRI Global E21 Guideline. Palo Alto, CA: Electric Power Research Institute.

Esparta, R. (2006). Technical Director, Ecoinvest. Personal communications, May 22, 2006.

European Climate Exchange (2006). www.europeanclimateexchange.com (accessed April 17, 2006).

European Commission (2006). "EU emissions trading scheme delivers first verified emissions data for installations." Press Release, May 15, 2006. Brussels: European Commission.

European Union (2003). Directive 2003/97/EC of the European Parliament and for the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. Official Journal of the European Union L 275/32.

ExxonMobil (2004). A Report on Energy Trends, Greenhouse Gas Emissions and Alternative Energy. Irving, Texas: ExxonMobil.

Eyckmans, J. and Cornillie, J. (2002). "Supplementarity in the European carbon emissions market." In Albrecht, J., ed. (2002), Instruments for Climate Policy. Cheltenham, United Kingdom: Edward Elgar Publishing Ltd.

Factset (2006). Proprietary database.

Federal Reserve Bank of San Francisco (2005). "Why Hasn't the Jump in Oil Prices Led to a Recession?" FRBSF Economic Letter, 2005-21, November 18, 2005. San Francisco, California: Federal Reserve Bank of San Francisco.

Federal Reserve Board of Governors (2006). Federal Reserve Statistical Release H.8: Assets and Liabilities of Commercial Banks in the United States. http://www.federalreserve.gov/releases/h8/Current/ (accessed July 19, 2006).

Fenning, L. and Hart, C. (1996). "Measuring Chapter 11: The Real World of 500 Cases." American Bankruptcy Institute Law Review, Vol. 4. No.1.

Financial Times (2006a). "Ecuador declares state of emergency." Financial Times, February 23, 2006. Ft.com (accessed May 1, 2006).

Financial Times (2006b). "Oil prices jump as bombers strike at Saudi refinery." Financial Times, February 24 2006. Ft.com (accessed May 1, 2006).

Financial Times (2006c). "Oil nervous ahead of IAEA and OPEC." Financial Times, March 6, 2006. Ft.com (accessed May 1, 2006).

Financial Times (2006d). "Chad demands $100m from US-led oil consortium." Financial Times, April 15, 2006. Ft.com (accessed May 1, 2006).

Financial Times (2006e). "Oil groups still struggling to repair Katrina damage." Financial Times, June 26, 2006. Asia edition, part 1, p. 1.

First Environment (2006). "ISO 14064: The New Climate Change Standard." http://www.firstenvironment.com/html/climate_change_faq_1-iso_14064.html (accessed May 20, 2006).

Fleming, L. (2006). Project Manager, Shell International Exploration and Production, Inc. Personal communications, May 1, 2006.

Flood, C. and Morrison, K. (2006). "Refiner reckons platinum demand is sustainable." Financial Times, May 15 2006. Ft.com (accessed May 16, 2006).

Forest, C. (2006). Research Scientist, Laboratory for Energy and Environment, Massachusetts Institute of Technology. Personal communications, April 26, 2006.

Forest, C., Stone, P., and Sokolov, A. (2006). "Estimated PDFs of climate system properties including natural and anthropogenic forcings." Geophysical Research Letters, Vol. 33, L01705.

Forrest, P. (2002). "A Case Study of Heating Oil Partners' Weather Hedging Experience." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Foster (2005a). "S&P Report Concludes That Coal-Gasification Technology Holds Potential Financial Risks, as Well as Environmental Rewards." Foster Electric Report, 403.

Foster (2005b). "S&P Outlines Challenges IGCC Technology Will Have to Overcome to Be a Viable Power Supply Option." Foster Electric Report, 422.

Francis, D., and Hengeveld, H. (1998). Extreme Weather and Climate Change. Downsview, Ontario: Environment Canada.

Frank Crystal (2006). Insurance Market Overview: Winter/Spring 2006. New York, New York: Frank Crystal & Company.

Frank Crystal (2005a). "Insurance Market: Hurricane Katrina Impact." Client Update, October 6, 2005. New York, New York: Frank Crystal & Company.

Frank Crystal (2005b). "Hurricanes & Typhoons: Can The Soft Market Continue?" Industry Issues. New York, New York: Frank Crystal & Company.

Frankhauser, S. and Tol, R.S.J. (2002). "On Climate Change and Economic Growth." http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/tol.html (accessed August 5, 2006).

Freestone, D. and Streck, C., eds. (2005). Legal Aspects of Implementing the Kyoto Protocol Mechanisms. Oxford, UK: Oxford University Press.

Freshfields Bruckhaus Deringer (2005). A legal framework for the integration of environmental, social and governance issues into institutional investment. Geneva, Switzerland: UNEP Finance Initiative.

Fried, J., Torn, M., and Mills (2004). "The Impact of Climate Change on Wildfire Severity: A Regional Forecast for Northern California." Climatic Change 64: 169-191.

Fuller, L. and Eisenberg, M.A. (1999). Basic Contract Law. Minneapolis, MN: West Publishing Company.

Furey, D. (2006). Senior Director, Global Power, Fitch Ratings. Personal communications, April 21, 2006.

Fussell, Oliva (2006). "Carbon Credit Capital Presentation on How to Create & Trade Carbon Credits." (Powerpoint presentation at the Green Trading Summit, New York, New York, April 5, 2006).

Gallon, G. (2002). "Global Warming: What's the Price?" www.evworld.com/view.cfm?section=article&storyid=443 (accessed July 2, 2006).

Ganapati, S., Retik, M., Puleo, P. and Starr, B. (1999). "Catastrophe-Linked Securities." In Babbel, D.F. and Fabozzi, F.J., eds. (1999), Investment Management for Insurers. New Hope, Pennsylvania: Frank J. Fabozzi Associates.

Geothermal Energy Association (2005). Guide to Geothermal Energy and the Environment. Washington, D.C.: Geothermal Energy Association.

Gibbas, M. (2002). "The Nature of Climate Uncertainty and Considerations for Weather Risk Managers." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

GISS (2006). Goddard Institute for Space Studies Datasets & Images. http://data.giss.nasa.gov/ (accessed September 17, 2006).

Golay, M. (2006). Professor of Nuclear Engineering, Massachusetts Institute of Technology. Personal communications, March 10, 2006.

Gompers, P., Kovner, A., Lerner, J., and Scharfstein, D. (2006). "Specialization and Success: Evidence from Venture Capital." Unpublished Manuscript.

Gooch, C. (2006). Associate Director, Enterprise Risk Management, AON. Personal communications, May 10, 2006.

Gordon, R.B., Bertram, M. and Graedel, T.E. (2006). "Metal stocks and sustainability." PNAS, Vol. 103, No. 5, 1209-14.

Gottlieb, J. (1998). "The Development of Coal Futures." In Fusaro, P., ed. (1998), Energy Risk Management. New York, New York: McGraw-Hill.

Graham, J.R., Harvey, C.R. and Rajgopal, S. (2005). "The Economic Implications of Corporate Financial Reporting." Social Science Research Network.

Gramling, R. (1996). Oil on the Edge: Offshore Development, Conflict, Gridlock. Albany, NY: SUNY Press.

Green, P. M., Legler, D. M., Miranda V, C. J., O'Brien, J. J. (1997). "The North American climate patterns associated with El Niño-Southern Oscillation." Report 97-1. Tallahassee, Florida: Center for Ocean-Atmospheric Prediction Studies.

Grossman, D. (2003). "Warming Up to a Not-So-Radical Idea: Tort-Based Climate Change Litigation." 28 Columbia Journal of Environmental Law 1.

Grubler, A. (1990). The Rise and Fall of Infrastructures. Heidelberg, Germany: Physica-Verlag.

Grubler, A. (1998). Technology and Global Change. Cambridge, UK: Cambridge University Press.

Grubler, A., Nakicenovic, N., and Nordhaus, W., eds. (2002). Technological Change and the Environment. Washington, D.C.: Resources for the Future.

Gurenko, E. and Lester, R. (2004). Rapid Onset of Natural Disasters: The Role of Financing in Effective Risk Management. Washington, D.C.: The World Bank.

Gusbin, D., Klaassen, G. and Kouvaritakis, N. (1999). "Costs of a ceiling on Kyoto flexibility." Energy Policy 27(14): 833-844.

Gutierrez, E. (2005). "A Framework for the Surveillance of Derivatives Activities." IMF Working Paper. Washington, D.C.: International Monetary Fund.

Guy Carpenter (2006). The Catastrophe Bond Market at Year-End 2005: The Ripple Effects from Record Storms. New York, New York: MMC Securities.

Haeberli, W. and Beniston, M. (1998). "Climate change and its impacts on glaciers and permafrost in the Alps." Ambio 27(4): 258-265.

Haites, E. (2005). "Conclusion: Mechanisms, linkages and the direction of the future climate regime." In Yamin, F., ed. (2005), Climate Change and Carbon Markets: A Handbook of Emissions Reduction Mechanisms. London, United Kingdom: EarthScan.

Hamilton, J. (1983). "Oil and the Macroeconomy since World War II." Journal of Political Economy 91(2), 228-248.

Hamilton, J. (1996). "This Is What Happened to the Oil Price-Macroeconomy Relationship." Journal of Monetary Economics 38(2), 215-220.

Hamilton, J. (2003). "What Is an Oil Shock?" Journal of Econometrics 113, 363-398.

Hamlin, J. (2006). Manager, Weather Risk Group, Risk Management Solutions. Personal Communications, May 8 and 19, June 16, 2006.

Hancock, J. (2003). Environmental Human Rights: Power Ethics and Law. Hants, UK: Ashgate Publishing Ltd.

Hardy, P. (2006). Manager, Climate Change Services Canada, Det Norske Veritas. Personal communications, May 10-11, 2006.

Harleman, D., Bras, R., Rinaldo, A, and Malanotte, P. (2000). "Blocking the Tide." Civil Engineering, October 2000.

Hart, C. (2004). "Carbon Cycle Stabilization Scenario using toy MIT EPPA model." Unpublished manuscript.

Hartwig, R. (2002). "Florida Case Study: Economic Impacts of Business Closures in Hurricane Prone Counties." Unpublished manuscript. New York, New York: Insurance Information Institute.

Hartwig, R. (2005). "Overview of Florida Hurricane Insurance Markets." (Testimony of Robert Hartwig before the Florida Joint Select Committee on Hurricane Insurance, May 28, 2006).

Hartwig, R. (2006). Chief Economist, Insurance Information Institute. Personal communications, May 28, September 1, 2006.

Hayhoe et al. (2004a). Choosing Our Future: Climate Change in California, Solutions for the Golden State. Berkeley, CA: Union of Concerned Scientists.

Hayhoe et al. (2004b). Choosing Our Future: Climate Change in California, Declining Snowpack and Risks to Water Supplies. Berkeley, CA: Union of Concerned Scientists.

Hayhoe et al. (2004c). Choosing Our Future: Climate Change in California, Rising Heat to Human Health. Berkeley, CA: Union of Concerned Scientists.

Hayhoe et al. (2004d). Choosing Our Future: Climate Change in California, Declining Snowpack and Risks to Water Supplies. Berkeley, CA: Union of Concerned Scientists.

Heddle, G., Herzog, H., and Klett, M. (2003). "The Economics of CO_2 Storage." LFEE Publication, No. 2003-003 RP. Cambridge, MA: Massachusetts Institute of Technology.

Henderson, R., Li, Y., and Sinha, N. (2002). "Data." In Element Re (2002), Weather Risk Management: Markets, Products and Applications. Basingstoke, United Kingdom: Palgrave.

Henderson, R. (2002). "Pricing Weather Risk." In Element Re (2002), Weather Risk Management: Markets, Products and Applications. Basingstoke, United Kingdom: Palgrave.

Hennessy, K., Lucas, C., Nicholls, N., Bathois, J., Suppiah, R., and Ricketts, J. (2005). Climate Change Impacts on Fire-Weather in South-East Australia. Victoria, Australia: Commonwealth Scientific and Industrial Research Organization.

Herzog, H. (2006). Principal Research Engineer, Laboratory for Energy and the Environment, Massachusetts Institute of Technology. Personal communications, March 20, June 27, 2006.

Hess, U. , Richter, K., and Stoppa, A. (2002). "Weather Risk Management for Agriculture and Agri-Business in Developing Countries." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Hesseldahl, A. (2002). "Taiwan's Dry Chips." Forbes, May 12, 2002. http://www.forbes.com/2002/05/13/0513drought.html (accessed June 8, 2006).

Hill et al. (2004). "Human Rights and the Environment: A Synopsis and Some Predictions." 16 Geo. Int'l Envtl. L. Rev. 359.

Hoffert et al. (1998), "Energy implications of future stabilization of atmospheric CO_2 content." Nature 395, 881-884.

Hoffert et al. (2002). "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet." Science 298, 981-987.

Hoffert, M. (2006). "An Energy Revolution for the 21st Century." (Presentation at the Engineering Institute of Canada Climate Change Technology Conference, Ottawa, Canada, May 10, 2006).

Hoffman, S. (2001). The Law and Business of International Project Finance. Ardsley, NY: Transnational Publishers, Inc. and Kluwer Law.

Hoffman, D. (2006). Chief Economist, Zurich Financial Services. Personal Communications, May 5, 2006.

Hoover's Online (2006). www.hoovers.com (accessed June 8, 2006).

Horney, Greenstein and Kogan (2005). "Katrina Relief and Federal Spending Deficits." Unpublished document. Washington, D.C.: Center on Budget and Policy Priorities.

Hoyte, P. (2006). "Caiteur Group Presentation on CDM." (Powerpoint presentation at Engineering Institute of Canada Climate Change Technology Conference, Ottawa, Canada, May 12, 2006).

Hull, J. (2003). Options, Futures & Other Derivatives. Upper Saddle River, NJ: Prentice Hall.

Hulme, M. (1997). "The climate in the UK from November 1994 to October 1995." Weather 52, 242-257.

Human Rights Watch (2004). "Some Transparency, No Accountability: The Use of Oil revenue in Angola and Its Impact on Human Rights." Human Rights Watch, Vol. 16, No. 1 (A), 33. New York, New York: Human Rights Watch.

Hyman, J. (2006). New Ways for Managing Global Financial Risk. West Sussex, United Kingdom: John Wiley & Sons.

IETA (2005). Verification Protocol v. 2.0: Verification of Annual Emission Reports of Installations Engaged in EU Emissions Trading. Toronto, Canada: International Emissions Trading Association.

Innovest Strategic Value Advisors (2005). Carbon Disclosure Project 2005. London, UK: Carbon Disclosure Project. http://www.cdproject.net/ (accessed May 10, 2006).

Institute of International Finance (2006). "External Financing of Emerging Economies." Proprietary data. Washington D.C.: Institute of International Finance.

Insurance Information Institute (2003). "Trends & Challenges in the Property Insurance Business Today." (Powerpoint presentation, November 12, 2003). http://www.iii.org/media/presentations/ (accessed August 22, 2006).

Insurance Information Institute (2004). State Regulation of Rates, December 2004. New York, New York: Insurance Information Institute. http://www.iii.org/media/hottopics/insurance/ratereg/ (accessed May 15, 2006).

Insurance Information Institute (2006a). "Property/Casualty Insurance Financial & Hurricane Update." (Powerpoint presentation, April 25, 2006). http://www.iii.org/media/presentations/ (accessed August 22, 2006).

Insurance Information Institute (2006b). "Facts and Statistics: Hurricanes." http://www.iii.org/media/facts/statsbyissue/hurricanes/?table_sort_755573=4 (accessed August 22, 2006).

Insurance Journal (2005). "S&P Puts 10 Insurers on "Katrina" Credit Watch/Negative." Insurance Journal, September 12, 2005. http://www.insurancejournal.com/news/international/2005/09/12/59361.htm (accessed May 7, 2006).

Insurance Journal (2006). "NFIP Seeks $5.6B Loan; Sen. Shelby Vows Rating Overhaul." Insurance Journal, January 27, 2006. http://www.insurancejournal.com/news/national/2006/01/27/64695.htm (accessed May 7, 2006).

International Energy Agency (2003). World Energy Investment Outlook. Paris, France: Organization for Economic Co-Operation and Development.

International Energy Agency (2004). World Energy Outlook 2004. Paris, France: Organization for Economic Co-Operation and Development.

International Energy Agency (2006). IEA Energy Statistics - Government R&D Database. Paris, France: Organization for Economic Co-Operation and Development. http://www.iea.org/Textbase/stats/rd.asp (accessed April 10, 2006).

Investopedia.com (2006). "The Dot Com Crash." http://www.investopedia.com/features/crashes/crashes8.asp (accessed July 15, 2006).

Iowa Energy Center (2006). "Wind Energy Systems." www.energy.iastate.edu/renewable/wind/wem/wem-07_systems.html (accessed June 19, 2006).

IPCC (1995). "Second Assessment Synthesis of Scientific-Technical Information relevant to interpreting Article 2 of the UN Framework Convention on Climate Change." IPCC Second Assessment Report. Cambridge, UK: Cambridge University Press.

IPCC (2001). "Summary for Policymakers, Climate Change 2001: Synthesis Report", "Summary for Policymakers, Climate Change 2001: The Scientific Basis", and "Summary for Policymakers, Climate Change 2001: Impacts, Adaptation and Vulnerability". IPCC Third Assessment Report. Cambridge, UK: Cambridge University Press.

IPCC (2005). Carbon Dioxide Capture and Storage. Cambridge, UK: Cambridge University Press.

ISO (2006a). "Catastrophe Losses Will Double Almost Every 10 Years, Says leading Catastrophe Modeling Expert at PCS Conference". Press Release, April 29, 2006. Jersey City, NJ: ISO. Website: http://www.iso.com/press_releases/2006/04_25_06.html (accessed May 7, 2006).

ISO (2006b). "A Half Century of Hurricane Experience." Studies and Analyses. Jersey City, NJ: ISO. http://www.iso.com/studies_analyses/hurricane_experience/historical.html (accessed September 17, 2006).

Jewson, S., Ziehmann, C., and Brix, A. (2002). "Use of Meteorological Forecasts in Weather Derivative Pricing." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Jewson, S. (2004). "The relative importance of trends, distributions and the number of years of data in the pricing of weather options." Unpublished Manuscript. http://ssrn.com/abstract=516503 (accessed May 10, 2006).

Johnson, Claire Broido (2006). President, Sun Edison. Personal Communications, April 4, 2006.

Jordan, R.L., and Warren. W. (1991). Bankruptcy. Westbury, NY: The Foundation Press.

Joskow, P. and Rose, N. (1985). "The Effects of Technological Change, Experience, and Environmental Regulation on the Construction Cost of Coal-Burning Generating Units." Rand Journal of Economics 16:1.

Karl, T. R, Knight, R.W., Easterling, D.R., and Quayle, R.G. (1996). "Indices of climate change for the United States". Bulletin of the American Meteorological Society 77(2), 279-292.

Karr, A. (2006). "Metals' Direction Uncertain After Recent Price Rises." Managing Global Energy Risk. New York, New York: New York Mercantile Exchange.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G.A., Mitchell, J.F.B., Stouffer, R.J., Tokioka, T. Weaver, A.J. and Wigley, T.M.L. (1996). "Climate models - projections of future climate." In Houghton, J.T, Filho, L.G.M., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (1996), Climate Change 1995: The Science of Climate Change. Cambridge, U.K.: Cambridge University Press.

Keith, D. (2002). "Geoengineering the Climate: History and Prospect." In Watts, R.G., ed. (2002), Innovative Energy Strategies for CO_2 Stabilization. Cambridge, UK: Cambridge University Press.

Kel Kim Corp. v. Central Markets, Inc. (1987). 70 N.Y.2d 900, 524 N.Y.S.2d 384, 519 N.E.2d 295 (Court of Appeals of New York, 1987).

Kerr (2006). "A Worrying Trend of Less Ice, Higher Seas." Science 311, 1698-1701.

Kharin, V. and Zwiers, F. (2005). "Estimating Extremes in Transient Climate Change Simulations." Journal of Climate 18: 1156-1173.

Khater, M. (2006). Senior Vice President, Chief Science and Technology Officer, Eqecat. Personal Communications, June 20, 2006.

Kiley, S. (2006). "Trends in Natural Gas Markets." (Powerpoint Presentation at the NYMEX Commodities and Metals Day, New York, New York, May 23, 2006).

King, David (2005). "Global Warming: A Clear and Present Danger." http://www.opendemocracy.net/debates/article-6-129-2488.jsp (accessed August 23, 2006).

Kirshen, P., Ruth, M., Anderson, W., Lakshmanan, T.R. et al. (2004). "Infrastructure Systems, Services and Climate Change: Integrated Impacts and Response

Strategies for the Boston Metropolitan Area." http://www.tufts.edu/tie/climb/CLIMBFV1-8_10pdf.pdf (accessed April 5, 2006).

Kirshen, P. (2006). Professor of Engineering, Tufts University. Personal communications, May 8, 2006.

Klare, M. T. (2001). Resource Wars: The New Landscape of Global Conflict. New York, New York: Holt.

Kline, D. (2001). Fundamentals of the Futures Market. New York, New York: McGraw-Hill.

Knaup, A. (2005). "Research Summary: Survival and longevity in the Business Employment Dynamics data." Monthly Labor Review, May 2005.

Knutson, T. and Tuleya, R. (2004). "Impact of CO_2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Parameterization." The Journal of Climate 17(18).

Kruger, J. and Pizer, B. (2004). "The EU Emissions Trading Directive: Opportunities and Potential Pitfalls." Discussion Paper 04-24. Washington, D.C.: Resources for the Future.

Kosobud, R.F., Stokes, H.H., Tallarico, C.D., and Scott, B.L. (2004). "The Chicago VOC Trading System: The Consequences of Market Design for Performance." Working Paper 04-019. Cambridge, MA: MIT Center for Energy and Environmental Policy Research.

Kovacs, P. (2006). "Building resilient communities – adapting to the growing threat of high impact weather." (Powerpoint presentation at the Engineering Institute of Canada Climate Change Technology Conference, Ottawa, Canada, May 10, 2006).

Kristiansen, Kjell (2006). "Carbon Point Presentation on Emissions Trading Throughout the World." (Presentation at the Green Trading Summit, New York, New York, April 4, 2006).

Kuhn, T. (1972). The Structure of Scientific Revolutions. Chicago, Illinois: The University of Chicago Press.

Kutting, G. (2004). Globalization and the Environment. Albany, NY: State University of New York Press.

Kyoto Protocol Decision 19 (1997). Decision 19/CP.7, -/CMP.1, Annex, Article 15. http://unfccc.int/national_reports/annex_i_national_communications/fourth_national_communications/items/3360.php (accessed June 10, 2006).

Lacey, M. (2006). "Food Aid Program Takes Out Insurance on Ethiopian Weather." New York Times, March 8, 2006.

Landsea, C. (2005). "Increasing destructiveness of tropical cyclones over the past 30 years." Nature 438, E11-3.

Landsea, C. and Knaff, J.A. (2000). "How Much Skill Was There in Forecasting the Very Strong 1997-1998 El Nino?" Bulletin of the American Meteorological Society 81, 2107-19.

Lane and Beckwith (2006). "How High is Up?: The 2006 Review of the Insurance Securitization Market." Trade Notes. Wilmette, IL: Lane Financial L.L.C.

Lapp, D. (2006). "Adapting to Climate Change: An Engineering Perspective." (Presentation at the Engineering Institute of Canada Climate Change Technology Conference, Ottawa, Canada, May 10, 2006).

Lashof and Fiedler (2006). "Hot Air-Controlling the Flow." http://www.climatenetwork.org/eco/cops/cop5/4_cop5_hot.html (accessed May 20, 2006).

Leake, S.A. (2006). "Land Subsidence from Ground-Water Pumping." http://geochange.er.usgs.gov/sw/changes/anthropogenic/subside/ (accessed April 23, 2006).

Lehman Brothers (2006). "Capital Lessons: Another Capex Cycle Looms." Global Equity Research Report. New York, New York: Lehman Brothers.

Lewis, N. (2005). "Chemical Challenges in Renewable Energy." Unpublished manuscript. http://www.localenergy.org/pdfs/Document%20Library/Energy_Notes.pdf (accessed June 22, 2006).

Lichtenstein, H. (2006). Managing Director, Institutional Sales – Energy, Fimat (a subsidiary of Societe Generale). Personal communications, April 4 and 17, 2006.

Linderer, K.P. (1988). "Regional and national effects of climate change on demands for electricity." In The Climate Institute (1988), Second North American Conference on Preparing for Climate Change. Washington, D.C: The Climate Institute.

London Assembly (2005). London under Threat: Flooding Risk in the Great Thames Gateway. London, United Kingdom: Greater London Authority.

Loughlin, M. (2006). AON. Personal communications, May 22, 2006.

Lyons, J. (2006). Chief Engineer – EE Technologies, GE Global Research. Personal communications, April 28, 2006.

Makkonnen, Y. (2002). Natural Resource Based Violent Intra-State Conflict: Towards the Development of Social Responsibility Guidelines for Non-State Actors in Conflict Prevention and Peace-Building. New York, New York: United Nations.

Marland, G., T.A. Boden, and R. J. Andres (2003). "Global, Regional, and National CO_2 Emissions." Trends: A Compendium of Data on Global Change. Oak Ridge, Tenn.: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

Marrakech Accords (2001). The Marrakech Accords, Decision 15/CP.7, -/CMP.1. http://unfccc.int/documentation/decisions/items/3597.php?dec=j&such=j&volltext=+%2FCP&anf=80&sorted=&dirc=&anf=80&seite=3 (accessed June 22, 2006).

Marsh (2005). The Impact of Nature: The Aftermath of Hurricanes Katrina and Rita. New York, New York: Marsh.

Martucci, G. (2006). Director, Financial Group Services, Standard and Poor's. Personal communications, April 24 and June 2, 2006.

Maynard, B. (2006). "The Oil & Gas Industry's role in a Climate Change Strategy for Canada." (Presentation at the Engineering Institute of Canada Climate Change Technology Conference, Ottawa, Canada, May 10, 2006).

Martinot (2006). "Renewable Energy Information." www.martinot.info (accessed April, 2006).

McCabe, P.J. (1998). "Energy resources – cornucopia or empty barrel?" AAPG Bulletin 82, 2110-2134.

McCulley, P. and Wong, S. (2004). "Powering a Sustainable Future: The Role of Large Hydropower in Sustainable Development." (Paper presented at the UN Symposium on Hydropower and Sustainable Development, Beijing, China, October 27-29, 2004).

McKinsey Global Institute (2006). "Mapping the Global Capital Market 2006: Second Annual Report." The McKinsey Quarterly, January 2006. http://www.mckinsey.com/mgi/publications/gcm/ (accessed September 3, 2006).

Meade, C. (2004). "Strengthening Research & Development for Wind Hazard Mitigation." (Testimony before the Committee on Science of the U.S. House of Representatives, February 9, 2004).

Mehta, M. (2005). Nuclear Power and Public Protest In Canada. Lanham, Maryland: Lexington Books.

Meyer, W. (2003). "Activism and Research on TNCs and Human Rights: Building a New International Normative Regime." In Frynas, J. and Pegg, S., eds. (2003), Transnational Corporations and Human Rights. Basingstoke, UK: Palgrave Macmillan.

Michaelowa, A. (2005a). "Creating the foundations for host country participation in the CDM: experiences and challenges in CDM capacity building." In Yamin, F., ed. (2005), Climate Change and Carbon Markets: A Handbook of Emissions Reduction Mechanisms. London, United Kingdom: Earthscan.

Michaelowa, A. (2005b). "Determination of baselines and additionality for the CDM: A crucial element of credibility of the climate regime." In Yamin, F., ed. (2005), Climate Change and Carbon Markets: A Handbook of Emissions Reduction Mechanisms. London, United Kingdom: Earthscan.

Michaels, P., Knappenberger, P., Landsea, C. (2005). "Comments on Impact of CO_2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Scheme." The Journal of Climate 8, 5179-5182.

Milborrow, D. (2004). "Impacts of Wind on Electricity Systems with Particular Reference to Alberta." Unpublished manuscript. http://www.canwea.ca/ (accessed April 26, 2006).

Milborrow, I. (2006). Assistant Director, Corporate Finance – Emissions Trading, Pricewaterhouse Coopers. Personal communications, May 30, 2006.

Miller, N. (2006). Principal, Miller CTA. Personal communications, April 4-5, 2006.

Miller, R. and Lessard, D.R. (2000). The Strategic Management of Large Engineering Projects. Cambridge, MA, MIT Press.

Millerd, F. (2005). "The Economic Impact of Climate Change on Canadian Commercial Navigation on the Great Lakes." Canadian Water Resources Journal, Vol. 30(4), 269-280.

Mills, E., Lecomte, E. and Peara, A. (2001). U.S. Insurance Industry Perspectives on Climate Change. Berkeley, California: U.S. Department of Energy.

Mimura, N., Tsutsui, J., Ichinose, T., Kato, H., and Sakaki, K. (1998). "Impacts on infrastructure and socio-economic system." In Nishioka, S. and Harasawa, H., eds. (1998), Global Warming: The Potential Impact on Japan. Tokyo, Japan: Springer-Verlag.

Mirza, M., Gaudreau, K, Morrison, T. and Munroe, E. (2005). "Climate Change and Canada's infrastructure." Canadian Civil Engineer, Summer 2005, 24-29.

Mirza, M. (2006a). Environment Canada. Personal communications, May 12, 2006 (summarizing the statements of Ian Noble, Advisor (Adaptation), World Bank).

Mirza, M. (2006b). Environment Canada. Personal communications, May 12, 2006.

Mistry, V. (2006). Development Manager, Aviva. Personal communications, May 18, 2006.

MIT (2003). The Future of Nuclear Power: An Interdisciplinary MIT Study. Cambridge, MA: Massachusetts Institute of Technology.

MIT (2006). "Chapter 3: Coal-Based Electricity Generation." Unpublished Manuscript, to be published as part of the MIT Future of Coal Study. Cambridge, MA: Massachusetts Institute of Technology.

MIT Laboratory for Energy and the Environment (2005). "New Vehicle Technologies: How Soon Can They Make a Difference?" Energy & Environment. Cambridge, MA: Massachusetts Institute of Technology.

Mitchell, T. and Hulme, M. (2000). "A country-by-country analysis of past and future warming rates." Tyndall Center Working Paper No. 1. Norwich, UK: Tyndall Center, University of East Anglia.

Morehouse, D. (2006). Staff, U.S. Energy Information Administration. Personal communications, April 26, 2005.

Moritz, H. (2006). Vice President of Sales and Marketing, GT Solar Technologies. Personal communications, April 28, 2006.

Morton, W. (2003). "Corporate Responsibility for Preventing Human Rights Abuses in Conflict Areas." In Frynas, J. and Pegg, S., eds. (2003), Transnational Corporations and Human Rights. Basingstoke, UK: Palgrave Macmillan.

Mosher, M. (2006). Insurance Industry Analyst, A.M. Best. Personal communications, April 24, 2006.

Motley Fool (2006). "Investing Basics: Mutual Funds." http://www.fool.com/school/basics/basics04.htm (accessed May 7, 2006).

Mowery (2002). "Earth Rights, Human Rights: Can International Environmental Human Rights Affect Corporate Accountability?" 12 Fordham Envtl. Law J. 343.

Muir-Wood, R. (2006). Chief Research Officer, Risk Management Solutions. Personal Communications, April 24, 2006.

Mullins, F. (2005). "Implementation Challenges: Insights from the EU Emission Allowance Trading Scheme." In Yamin, F., ed. (2005), Climate Change and Carbon Markets: A Handbook of Emissions Reduction Mechanisms. London, United Kingdom: EarthScan.

Nakicenovic, N. and Grubler, A., eds. (1989). Diffusion of Technologies and Social Behavior. Berlin, Germany: Springer-Verlag.

Namovicz, C. (2006). Analyst, Energy Information Administration. Personal communications, April 26, 2006.

NASDAQ (2006). Nasdaq.com (accessed July 30, 2006).

NCDC (2006). "Billion Dollar U.S. Weather Disasters." http://www.ncdc.noaa.gov/oa/reports/billionz.html (accessed May 16, 2006).

Nelson, J. (2002). The Business of Peace: The Private Sector as a Partner in Conflict Prevention and Resolution. London, U.K.: Prince of Wales International Business Leaders Forum, International Alert, and Council on Economic Priorities.

Nemet, G.F. (2006a). "Behind the Learning Curve: Factors Influencing Cost Reductions in Photovoltaics." Energy Policy 34(17): 3218-3232.

Nemet, G.F. (2006b). "Behind the Learning Curve: Quantifying the Sources of Cost Reductions in Photovoltaics." Working Paper. Berkeley, California: University of California at Berkeley.

Nevitt, P. and Fabozzi, F. (2000). Project Financing, 7th Ed.. London, UK: Euromoney Books.

Nicholls, M. (2004). "Confounding the Forecasts." Environmental Finance, October 2004. http://www.environmental-finance.com/2004/0410oct/weather.htm (accessed May 18, 2006).

Nicholls, R.J. and Mimura, N. (1998). "Regional issues raised by sea level rise and their policy implications." Climate Research 11, 5-18.

Nicholls, N., Gruza, G.V., Jouzel, J., Karl, T.R., Ogallo, L.A., and Parker, D.E. (1996). "Observed climate variability and change." In Houghton, J.T, Filho, L.G.M., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (1996), Climate Change 1995: The Science of Climate Change. Cambridge, U.K.: Cambridge University Press.

Nijhawan, S.A. (2003). "A Human Right to a Clean Environment?" Unpublished manuscript.

NOAA (2006). "What is El Nino?" http://www.pmel.noaa.gov/tao/elnino/el-nino-story.html (accessed April 23, 2006).

NOAA Mauna Loa Observatory (2006). http://www.cmdl.noaa.gov/gallery/ccgg_figures (accessed June 29, 2006).

Noreng, O. (2002). Crude Power: Politics and the Oil Market. London, UK: I.B. Taurus Publishers.

Northern Territory University (2006). "Climate Change Fact Sheets." http://www.cs.ntu.edu.au/homepages/jmitroy/sid101/uncc/fs-index.html (September 17, 2006).

NPR (2003). "Cost Overruns Plague Boston's Big Dig." National Public Radio, April 10, 2003. http://www.npr.org/templates/story/story.php?storyId=1227895 (accessed April 25, 2006).

OECD (2006). "Projecting OECD Health and Long-Term Care Expenditures: What are the Main Drivers?" Economics Department Working Papers, No. 477. Paris, France: Organization for Economic Co-Operation and Development.

O'Hearne, B. (2006). Managing Director, Environmental and Commodity Markets, Swiss Re; President, Weather Risk Management Association. Personal communications, May 17, 2006.

Oldack, M. (2006). Senior Director, State Competitive and Regulatory Policies, Edison Electric Institute. Personal communications, April 10, 2006.

Olivera, O. (2005). Unpublished transcript of interview. (Presented at EPIIC Symposium, Tufts University, February 23-27, 2005).

Olivier, E. (2003). "Survey of Contingent Financing & Risk Mitigation Instruments for Clean Infrastructure Projects." http://carbonfinance.org/Router.cfm?Page=DocLib&CatalogID=6179 (accessed August 22, 2006).

O'Neill, B. and Oppenheimer, M. (2002). "Dangerous Climate Impacts and the Kyoto Protocol." Science 296: 1971-1972.

Oppenheimer, P. (2004). "The West Antarctic Ice Sheet and Long Term Climate Policy." Climatic Change (draft version).

Oreskes, N. (2004). "The Scientific Consensus on Climate Change." Science 306, 1686.

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action. New York, Cambridge University Press.

Pacala and Socolow (2004). "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." Science 305, 969-972.

Pacific Islands Regional Assessment Group (2001). Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change. Washington, D.C.: East-West Center.

Page, B. (2006). Vice President Sustainable Development, TransAlta. Personal communications, May 16, 2006.

Page, W. (2006). Principal, State Street Global Advisors. Personal communications, May 3, 2006.

Parmesan and Galbraith (2004). Observed Impacts of Global Climate Change in the U.S. Washington, D.C.: The Pew Research Center.

Parry, M. (1990). Climate Change and World Agriculture. London, United Kingdom: Earthscan.

Parsons, J. (2006). "European Trading Scheme." (Presentation to the MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA, May 19, 2006).

Perry (1987). "Tort Reform and the Market-Share Rule." Cato Journal, Vol. 7, No. 2.

Pew Center (2005). "The European Union Emissions Trading Scheme (EU-ETS): Insights and Opportunities." Alexandria, VA: Pew Center on Global Climate Change.

Pielke , R. (2005). "Are there trends in hurricane destruction?" Nature 438, E11.

Point Carbon (2006a). www.pointcarbon.com (accessed May 20, 2006).

Point Carbon (2006b). Carbon 2006: Towards A Truly Global Market. Oslo, Norway: Point Carbon.

Prentice, M.L. and Karlen, W. (2003). "Changes in African Glaciers Since 1900." Report to the World Wildlife Fund. Washington, D.C.: World Wildlife Fund.

Pricewaterhouse Coopers (2006). "Results of the PwC Survey." (Powerpoint presentation to the Weather Risk Management Association, June, 2006). http://www.wrma.org/wrma/index.php?option=com_content&task=view&id=36&Itemid=34 (accessed August 22, 2006).

RAA/ABIR (2006). "Private Sector Risk Bearing Capacity." Letter of Franklin Nutter, President of Reinsurance Association of America, and Bradley Kading, President of Association of Bermuda Insurers and Reinsurers, dated May 8, 2006.

Rand (2005). Oil Shale Development in the United States: Prospects and Policy Issues. Santa Monica, CA: Rand Corporation.

Reilly, J.M., and Paltsev, S. (2006). "European Greenhouse Gas Emissions Trading: A System in Transition." In De Miguel, C., Labandeira, X. and Manzano, B., eds. (2006), Economic Modeling of Climate Change and Energy Policies. Cheltenham, UK: Edward Elgar Press, Cheltenham, UK.

Reilly, J.M., Baethgen, W., Chege, F.E., van de Geijn, S.C., Lin, E., Igesias, A., Kenny, G., Patterson, D., Rogasik, J., Roetter, R., Rosenzweig, C., Sombroek, W., and Westbrook, J. (1996). "Agriculture in a Changing Climate: Impacts and Adaptation." In Watson, R.T., Zinyowera, M.C., and Moss, R.H., eds. (1996), Climate Change 1995: Impacts Adaptation and Mitigation of Climate change – Scientific-Technical Analyses – Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press.

REN21 Renewable Energy Policy Network (2005). Renewables 2005 Global Status Report. Washington, D.C.: Worldwatch Institute.

Reuters (2006). "European carbon market rattled as prices dive." Reuters.com (accessed May 1, 2006).

Revelle, R.R. (1983). "Probable Future Changes in Sea Level Resulting from Increased Atmospheric Carbon Dioxide." Changing Climate. Washington, D.C.: National Academy Press.

Ricker, R. (2006). Trader, D.E. Shaw. Personal communications, May 26, 2006.

Riesenfeld, Stefan (1993). Professor of Law, University of California at Berkeley. Personal Communications, 1993.

Rignot, E., Rivera, A., Casassa, G. (2003). "Contributions of the Patagonian Icefields of South America to Sea Level Rise." Science 302, 434-7.

Rind, D. and Lebedeff, S. (1984). Potential Climate Impacts of Increasing Atmospheric CO_2 With Emphasis on Water Availability and Hydrology in the United States. Washington, D.C.: Govt. Printing Office.

Roberts, J. (2002). "Weather Risk Management in the Alternative Risk Transfer Market." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Rodi, M. (2005). "Legal Aspects of the European Trading Scheme." In Hansjurgens, B., ed. (2005), Emissions Trading for Climate Policy: US and European Perspectives. Cambridge, United Kingdom: Cambridge University Press.

Rolfe (2000). "Note 4: Hot Air." The Earth in the Balance: Briefing Notes for the November 2000 Climate Summit. weel.org (accessed September 3, 2006).

Rosenberg (2004). "Financing IGCC for Near-Term Deployment." http://www.climatevision.gov/pdfs/coal_roundtable/rosenberg.pdf (accessed September 1, 2006).

Rosencranz (2003). "20th Annual Symposium: Lex & The Lorax: Enforcing Environmental Norms Under International Law: The Origin and Emergence of International Environmental Norms." 26 Hastings Int'l. & Comp. L. Rev. 309.

Ross, M. (2001). "Does Oil Hinder Democracy?" World Politics 53, 325-61.

Ross, S. (2006). Senior Counsel, White & Case LLP. Personal communications, May 25, 2006.

Ruck, T. (2002). "Hedging Precipitation Risk." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Safran, Andrew (2006). Managing Director & Global Head, Energy, Utilities & Chemicals Investment Banking, Citigroup. Personal Communications, May 24, 2006.

Samii, S. (2005). Lecture, International Construction Finance, Massachusetts Institute of Technology, May 7, 2005.

Sarofim, M., Forest, C., Reiner, D., and Reilly, J. (2004). "Stabilization and Global Climate Policy." MIT Joint Program on the Science and Policy of Global Change, Report No. 110. Cambridge, MA: Massachusetts Institute of Technology.

Schindler, D.W. and Donahue, W.F. (2006). "Potential freshwater crisis in western Canada." PNAS Early Online Edition, April 6, 2006. http://foodsafetynetwork.ca/fsnet/2006/4-2006/fsnet_april_3-2.htm#story1. (accessed June 26, 2006).

Schmidheiny, S. and Business Council for Sustainable Development (1992). Changing Course: A Global Business Perspective on Development and the Environment. Cambridge, MA: MIT Press.

Schmidheiny, S. , Zorraquin, F., and Business Council for Sustainable Development (1996). Financing Change: The Financial Community, Eco-Efficiency, and Sustainable Development. Cambridge, MA: MIT Press.

Scholte, J.A. and Schnabel, A. (2002). Civil Society and Global Finance. London, United Kingdom: Routledge.

Schrattenholzer, L., Miketa, A., Riahi, K., Roehrl, R. (2005). Achieving a Sustainable Global Energy System: Identifying Possibilities Using Long-Term Energy Scenarios. Cheltenham, United Kingdom: Edward Elgar.

Schwartz, S.E. (2004). "Uncertainty requirements in radiative forcing of climate change." J. Air Waste Management Assoc. 54, No. 11.

Schupp, J. (2006). Zurich Financial Services. Personal Communications, May 8, 2006.

See, C.S. (2005). "Carbon Permit Prices in the European Emissions Trading System: A Stochastic Analysis." Master's Thesis, Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA.

Sell, C. (2006). "Statement of Clay Sell, Deputy Secretary U.S. Department of Energy, FY 2007 Appropriations Hearing." appropriations.senate.gov/hearmarkups/FINALGNEP3-2-06SEWD.html (accessed May 1, 2006).

Shell (2006). "The Impact of the 2005 Hurricanes on the US Gulf Coast." Unpublished document. Houston, Texas: Shell International Exploration and Production Inc.

Shorter, J., Crawford, T., and Boucher, R. (2002). "The Accuracy and Value of Operation Seasonal Weather Forecasts in the Weather Risk Market." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Simpson, R.H. (1974). "The hurricane disaster potential scale." Weatherwise 27, 169-186.

Siner, R. (2006). AON Consulting. Personal communications, May 26, 2006.

Smil, V. (2003). Energy at the Crossroads: Global Perspectives and Uncertainties. Cambridge, MA: MIT Press.

Smith, D. (2006). Weather Derivatives Marketing Manager, Chicago Mercantile Exchange. Personal communications, May 3, 2006.

Smith, E. (2002). Energy, The Environment, and Public Opinion. Oxford, UK: Rowman & Littlefield Publishers.

Smith, J. et al. (1995). Adapting to Climate Change: Assessment and Issues. New York, New York: Springer-Verlag.

Smith, S. (2002). "Weather and Climate – Measurements and Variability." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

Smythe, C. (2006). "Insurance Costs Soar on Cape Homes." Cape Cod Times, June 2, 2006. http://www.capecodonline.com/cctimes/insurancecosts2.htm (accessed June 3, 2006).

Spudeck, R. (2006). Chief Economist, Florida Office of Insurance Regulation, State of Florida. Personal communications, April 25, 2006.

Standard & Poor's (1999). "Modeling Catastrophe Reinsurance Risk: Implications for the CAT Bond Market." Ratings Direct. New York: NY: Standard & Poor's.

Standard & Poor's (2004). "Property/Casualty Insurance: Rating Catastrophe Bonds." Ratings Direct. New York: NY: Standard & Poor's.

Standard & Poor's (2005a). "The Economic and Financial Outlook: An Energetic Economy." (Powerpoint presentation of David Wyss, Chief Economist, Standard & Poor's, presented at the EIA Energy Modeling Conference, Washington, D.C., April 12, 2005).

Standard & Poor's (2005b). "Insurance Criteria: Catastrophe-Specific Capital Charges To Be Extended To Primary Insurers, But Reinsurance Criteria Unchanged." Ratings Direct. New York: NY: Standard & Poor's.

Standard & Poor's (2006a). "U.S. Oil and Gas in the Gulf: Still Recovering." Ratings Direct. New York: NY: Standard & Poor's.

Standard & Poor's (2006b). "Standard & Poor's Updates U.S. Catastrophe Bond Hurricane Ratings Criteria." Ratings Direct. New York: NY: Standard & Poor's.

Standard & Poor's (2006c). Catastrophe Bond Database, 1/1/1999 to 4/1/2006. New York, New York: Standard & Poor's.

Steele, M. (2006). Director, Treasury Department, Chevron. Personal communications, April 11, 2006.

Sterman, J.D. (1980). "The effect of energy depletion on economic growth." Series Working paper (Sloan School of Management), 1130-80A. Alfred P. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA.

Sterman, J.D. (1981). "The Energy transition and the economy: a system dynamics approach." Ph.D. Dissertation. Alfred P. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA.

Sterman, J.D. (1982). "Economic vulnerability and the energy transition." Series Working paper (Sloan School of Management), 1325-82. Alfred P. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA.

Stern, H. (1992). "The likelihood of climate change: A methodology to assess the risk and the appropriate defence." (Paper presented at the 5th International Meeting on Statistical Climatology, Toronto, Canada, June 24-26, 1992). http://www.weather-climate.com/climatechangerisk.html (accessed June 29, 2006).

Stern, H. (2005). "Evaluating the Cost of Protecting Against Global Climate Change: Options Pricing Theory and Weather Derivatives." (Paper presented at the 16th Conference on Climate Variability and Change, San Diego, California, January 9-13, 2005). http://www.weather-climate.com/ams2005cc.html (accessed June 29, 2006).

Stigler, G.J. (1971). "Theory of Economic Regulation." Bell Journal of Economics and Management Science, Spring 1971, 114-141.

Stocks, B.J., Fosberg, M.A., Lynhm, T.J. Mearns, L. Wotton, B.M., Yang, Q., Jin, J-Z, Lawrence, K., Hartley, G.R., Mason, J.A., and McKenney, D.W. (1998). "Climate Change and forest fire potential in Russian and Canadian boreal forests." Climatic Change 38, 1-13.

Stott, P.A., Stone, D.A. and Allen, M.R. (2004). "Human Contribution to the European heat wave of 2003." Nature 432, 610-614.

Swiss Re (2006a). "Natural catastrophes and man-made disasters 2005: high earthquake casualties, new dimension in windstorm losses." Sigma, No. 2/2006. Zurich, Switzerland: Swiss Re.

Swiss Re (2006b). "Managing Risk in an Uncertain Climate." (Powerpoint presentation of John R. Coomber at Columbia University, March 26, 2006). http://www.swissre.com/INTERNET/pwswpspr.nsf/fmBookMarkFrameSet?ReadForm&BM=../vwAllbyIDKeyLu/rscd-6nebls?OpenDocument (accessed August 22, 2006).

Tang, K., ed. (2005). The Finance of Climate Change. London, United Kingdom: Risk Books.

Telners, E. (2006). Manager, Climate Change Services, Det Norske Veritas. Personal communications, May 15, 2006.

Tester, J., Drake, E., Driscoll, M., Golay, M., and Peters, W. (2005). Sustainable Energy: Choosing Among Options, Cambridge, MA, MIT Press.

Tester, J. (2006). H.P. Meissner Professor of Chemical Engineering, Massachusetts Institute of Technology. Personal communications, April 3, August 30, 2006.

Thomas, S. (2005). The Economics of Nuclear Power: Analysis of Recent Studies. Greenwich, United Kingdom: Public Services International Research Unit.

Thomson Financial (2006a). Syndicated Loans Database, 1/1/1962 to 2/14/2006. New York, New York: Thomson Financial.

Thomson Financial (2006b). Global Project Finance Review, Fourth Quarter 2005. New York, New York: Thomson Financial.

Thomson Investment Analytics (2006). Private Equity Database. New York, New York: Thomson Financial.

Thomson Venture Economics (2006). Venture Finance Database. New York, New York: Thomson Financial.

Tibet Environmental Watch (2006). http://www.tew.org/tibet2000/t2.ch2.water.html. (accessed April 23, 2006).

Tinsley, R. (2000). Advancing Project Financing, 1st ed. London, UK: Euromoney Books.

Tippee, B. (1993). Where's the Shortage?: A Nontechnical Guide to Petroleum Economics. Tulsa, Okalahoma: PennWell Books.

Timmons, H. (2006). "Data Leaks Shake Up Carbon Trade." New York Times, May 26, 2006.

Titus, J., Park, R., Leatherman, S., Weggel, J., Greene, M., Mausel, P., Brown, S., Gaunt, G., Trehan, M., Yohe, G. (1987). "Greenhouse Effect, Sea Level Rise, and Coastal Drainage Systems." Journal of Water Resources Planning and Management 113(2).

Tol, R.S.J. (2002). "Estimates of the Damage Costs of Climate Change: Part 1: Benchmark Estimates." Environmental and Resource Economics 21: 47-73. The Netherlands: Kluwer Academic Publishers.

TransAlta (2006). "Emissions Trading for Technology Change: Integrated Strategy." (Powerpoint presentation at Engineering Institute of Canada Climate Change Technology Conference, Ottawa, Canada, May 12, 2006).

Trenberth (2005). "Uncertainty in Hurricanes and Global Warming." Science 308, 1753 -1754.

UNCTAD (2006). "INFO COMM: Market Information in the Commodities Area." http://r0.unctad.org/infocomm/anglais/platinum/chain.htm (accessed May 16, 2006).

UNEP Grid Arendal (2006). http://www.grida.no/climate/vital/13.htm (accessed June 29, 2006).

UNEP Risoe Centre (2006a). CDM Pipeline: excel spreadsheet, as of May 1, 2006. http://www.cd4cdm.org/publications.htm (accessed May 5, 2006).

UNEP Risoe Centre (2006b). CDM Pipeline: excel spreadsheet, as of August 9, 2006. http://www.cd4cdm.org/publications.htm (accessed August 15, 2006).

United Nations (1972). Declaration of the United Nations Conference on Human Environment, Stockholm.

United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy Council (2004). World Energy Assessment: Overview 2004 Update. New York, New York: United Nations Development Programme.

University of Washington (2002). "Climate and Climate Change Course Notes, Fall Quarter 2002." http://www.atmos.washington.edu/2002Q4/211/notes_humancarbon.html (accessed May 5, 2006).

Unruh, G. C. (2000). "Understanding carbon lock-in." Energy Policy 28: 817-830.

Unruh, G. C. (2002). "Escaping carbon lock-in." Energy Policy 30: 317-325.

Unruh, G. C. and Carrillo-Hermosilla, J. (2006). "Globalizing carbon lock-in." Energy Policy 34: 1185-1197.

Upper, C. (2006). Research Staff, Bank for International Settlements. Personal communications, June 8, 2006.

U.S. Congressional Budget Office (1997). "Should the Federal Government Sell Electricity?" A CBO Paper. Congressional Budget Office, Washington, D.C.

U.S. Congressional Budget Office (1999). "Trends in Public Infrastructure Spending." A CBO Paper. Congressional Budget Office, Washington, D.C.

U.S. Congressional Budget Office (2002). "A 125-Year Picture of the Federal Government's Share of the Economy, 1950 to 2075." Long Range Fiscal Policy Brief. Congressional Budget Office, Washington, D.C.

U.S. Congressional Budget Office (2005). "Statement of Douglas Holtz-Eakin, Director." CBO Testimony. Congressional Budget Office, Washington, D.C.

U.S. Comptroller of the Currency (2005). OCC Bank Derivatives Report, Fourth Quarter 2005. Washington, D.C.: U.S. Comptroller of the Currency.

US EPA (2006a). "Global Warming – News and Events." Science and Policy News. http://yosemite.epa.gov/oar/globalwarming.nsf/content/newsandeventsScienceandPolicyNews.html (accessed April 23, 2006).

US EPA (2006b). "Hydropower." Global Warming Impacts. http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ImpactsWaterResourcesHydropower.html (accessed April 26, 2006).

USGS (2006). "The water cycle: snowmelt runoff to streams." http://ga.water.usgs.gov/edu/watercyclesnowmelt.html (accessed April 23, 2006).

U.S. Minerals Management Service (2006). "Hurricane Katrina/Hurricane Rita Evacuation and Production Shut-in Statistics Report as of Wednesday, March 22, 2006." Washington, D.C.: U.S. Department of Interior.

US NAS (1979). U.S. National Academy of Sciences, Committee on Nuclear and Alternative Energy Systems. Energy in Transition 1985-2000. Washington, D.C.: National Academy Press. Pp. 179-203, Chapter 9.

US NAS (1992). U.S. National Academy of Sciences, Panel on Policy Implications of Greenhouse Warming, Committee on Science, Engineering, and Public Policy. Policy Implications of Greenhouse Warming: Mitigation, Adaptation and the Science Base. Washington, D.C.: National Academy Press. Pp. 531, 601.

US NAS (1998). U.S. National Academy of Sciences, National Research Council. The Atmospheric Sciences: Entering the Twenty-First Century. Washington, D.C.: National Academy Press.

US NAS (2002). U.S. National Academy of Sciences, National Research Council Committee on Abrupt Climate Change. Abrupt Climate Change: Inevitable Surprises. Washington, D.C.: National Academy Press.

US Office of Technology Assessment (1993). Preparing for an Uncertain Climate, Vol. I, OTA-O-567. Washington, D.C.: U.S. Government Printing Office.

Utilipoint (2004). "Underground Lines: Panacea or Too Pricey?" Issue Alert, 9/29/2004.

Van Der Linden, M. (2006). CDM/JI Program Director, SGS. Personal Communications, May 16, 2006.

Varangis, P., Skees, J., Barnett, B. (2002). "Weather Indexes for Developing Countries." In Dischel, R., ed. (2002), Climate Risk and the Weather Market. London, United Kingdom: Risk Books.

VC Experts (2006a). Encyclopedia of Venture Capital. http://vcexperts.com (accessed April 29, 2006).

VC Experts (2006b). Employment and Stock Purchase Agreement (Model). http://vcexperts.com (accessed April 29, 2006).

VC Experts (2006c). Proprietary database. http://vcexperts.com (accessed April 29, 2006).

Velicogna, I. and Wahr, J. (2006). "Measurements of Time-Variable Gravity Show Mass Loss in Antarctica." Science 311, 1754-6.

Verleger, P. K. (1993). Adjusting to Volatile Energy Prices. Washington, D.C.: Institute of International Economics.

Vicuna (1998). "Focus Issue: Resolution on Responsibility and Liability: Responsibility and Liability for Environmental Damage Under International Law: Issues and Trends." 10 Geo. Int'l. L. Rev. 27.

Vincent, D. (2006). "Presentation of The Carbon Trust." (Presentation at the Engineering Institute of Canada Climate Change Technology Conference, Ottawa, Canada, May 10, 2006).

Watson, R. T. (2001). "Climate Change 2001." (Presentation to the Intergovernmental Panel on Climate Change at the resumed Sixth Conference of Parties to the United Nations Framework Convention on Climate Change, July 19, 2001). http://www.ipcc.ch/present/COP65/COP-6-bis.htm (accessed April 23, 2006).

Wawryk, A. (2003). "Regulating Transnational Corporations Through Corporate Codes of Conduct." In Frynas, J. and Pegg, S., eds. (2003), Transnational Corporations and Human Rights. Basingstoke, UK: Palgrave Macmillan.

WBCSD (2005). Facts and Trends to 2050: Energy and Climate Change. Conches-Geneva, Switzerland: World Business Council for Sustainable Development.

Webster, M. (2000). "The Curious Role of Learning in Climate Policy: Should We Wait for More Data?" MIT Joint Program on the Science and Policy of Global Change, Report No. 67. Cambridge, MA: Massachusetts Institute of Technology.

Webster, M., Forest, C., Reilly, J.M., Babiker, M.H., Kicklighter, D.W., Mayer, M., Prinn, R.G., Sarofim, M., Sokolov, A.P., Stone, P.H., and Wang, C. (2003). "Uncertainty Analysis of Climate Change and Policy Response." Climatic Change, 61(3), 295-320.

Webster's (2002). Webster's Third New International Dictionary of the English Language Unabridged. Springfield, MA: Merriam-Webster Inc.

Weissbrodt, J. (2006). Principal, JW Bond Consultants. Personal communications, May 5, 2005.

Weyant, J., ed. (1999). Energy and Environmental Policy Modeling. Boston, Massachusetts: Kluwer Academic Press.

Weyant, J. and Hill, J. (1999). "Introduction and Overview." In The Energy Journal Special Issue: The cost of the Kyoto Protocol: A Multi-Model Evaluation, 1999.

Wheeler, D. and Woodward, T. (2004). Comparative Study of U.K. and Canadian Pension Fund Transparency Practices. York, United Kingdom: York University.

Whittaker, M. (2003). "Carbon Finance and the Global Equity Markets." In Fusaro, P. and Yuen, M., eds. (2003), GreenTrading: Commercial Opportunities for the Environment. Brooklyn, NY: GreenTrading, Inc.

Wicke, L. (2005). Beyond Kyoto – A New Global Certificate System. Berlin, Germany: Springer-Verlag.

Wilder, M., Willis, M., and Guli, M. (2005). "Carbon Contracts, Structuring Transactions: Practical Experiences." In Freestone, D. and Streck, C., eds. (2005), Legal Aspects of Implementing the Kyoto Protocol Mechanisms. Oxford, UK: Oxford University Press.

Wilder, M. (2005). "Implementing the Clean Development Mechanism and emissions trading beyond Europe." In Yamin, F., ed., (2005), Climate Change and Carbon

Markets: A Handbook of Emissions Reduction Mechanisms. London, United Kingdom: EarthScan.

Wilhelm, K. (2006). Director, Commercial Credit Risk, Chief National Bank Examiner, Comptroller of the Currency. Personal communications, May 30, 2006.

Williamson, H. (2005). "Climate Change: The Challenge to Canadian Municipalities and InfraGuide." Municipal World, March 2005.

Wiwa v. Royal Dutch Petroleum Company and Shell Transport and Trading Company PLC (2000). 226 F.3d 88 (2nd Cir. 2000), cert denied.

Woerdman, E. (2002). "Why did the EU propose to limit emissions trading? A theoretical and empirical analysis." In Albrecht, J., ed. (2002), Instruments for Climate Policy. Cheltenham, United Kingdom: Edward Elgar Publishing Ltd.

Woerdman, E. (2004). The Institutional Economics of Market-Based Climate Policy. Amsterdam, The Netherlands: Elsevier.

Wood, Sir Alan Muir (1999). "Future Energy Supply and demand – steps toward their reconciliation." In McVeigh, J.C. and Mordue, eds. (1999), Energy Demand and Planning. London, United Kingdom: E & FN Spon.

Wood, J.H., Long, G.R. and Morehouse, D.F. (2004). "Long-Term World Oil Supply Scenarios: The Future Is Neither as Bleak or Rosy as Some Assert." Washington, D.C.: Energy Information Administration. http://www.eia.doe.gov/pub/oil_gas/petroleum/feature_articles/2004/worldoilsupply/oilsupply04.html (accessed September 5, 2006).

Wood MacKenzie (2004). "New Thinking Needed for Exploration?" Horizons, Energy Issue 15. London, United Kingdom: Wood MacKenzie.

World Bank (2003). Global Development Indicators. Washington, D.C.: The World Bank.

World Bank (2006a). Clean Energy and Development: Towards an Investment Framework. Washington, D.C.: The World Bank.

World Bank (2006b). Private Participation in Infrastructure Project Database. Washington, D.C.: The World Bank. http://ppi.worldbank.org/resources/ppi_aboutDb.aspx (accessed April 2006).

World Federation of Exchanges (2006). Stock Exchange Market Capitalization Database, 1990-2005. Paris, France: World Federation of Exchanges.

Wotton, B.M., Martell, D.L. and Logan, K.A. (2004). "Climate change and people-caused fire occurrence in Ontario." Climatic Change, 60, 275-295.

Woynillowicz, D., Severson-Baker, C. and Raynolds, M. (2005). Oil Sands Fever: The Environmental Implications of Canada's Oil Sands Rush. Drayton Valley, Alberta, Canada: The Pembina Institute.

WWF (2005). An Overview of Glaciers, Glacier Retreat, and Subsequent Impacts in Nepal, India and China. WWF Nepal Program.

Yamin, F. (2005). "Part I: The International Rules on the Kyoto Mechanisms." In Yamin, F., ed. (2005), Climate Change and Carbon Markets: A Handbook of Emissions Reduction Mechanisms. London, United Kingdom: EarthScan.

Yeres, D. and Little, B. (2000). "Regulation of Energy Futures and Options Trading." In Treat, J., ed. (2000), Energy Futures: Trading Opportunities. Tulsa, Okalahoma: PennWell.

Yergin, D. (1991). The Prize: The Epic Quest for Oil, Money and Power. New York, New York: Free Press.

Yu Bing (2006). General Manager, Shanxi Sinochem Wonder Industries Co., Ltd., Shanxi, China. Personal communications, January, 2006.

Zhang, P.G. (1995). Barings Bankruptcy and Financial Derivatives. Singapore: World Scientific Publishing Co.

Zhang, Z.X. (2000). "Estimating the size of the potential market for the Kyoto flexibility mechanisms." Review of World Economics, 136(3), 491-521.

Zuazo, A. (2006). "Update 8: Bolivia Military Told to Occupy Gas Fields." www.Forbes.com (accessed May 1, 2006).