Systems Analysis Methodologies

Sustainable Energy "Toolbox" Lecture

E. M. Drake

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The Systems Approach

- What is the problem? Who are stakeholders?
- What are the questions and issues?
- What are the decision options?
- How do they fit into a bigger picture?
- Are any obviously ridiculous? (Why?)
- What are the uncertainties?
- Are there feedbacks?
- Can I get more information to help make a better decision? (At what cost and delay?)
- How do I discount costs and impacts in the future?

Types of Analysis

- Scoping analysis ("back-of-envelope")
- Simulation models
- Economic models (micro- and macro)
- Life-Cycle Analysis (LCA)
- Risk Assessment Techniques
- Systems Dynamics Models
- Decision Models
  - Optimization with respect to parameter or function
  - Multi-attribute trade-off analysis
  - *Delphi* or other group consensus techniques

How to choose analysis method?

- Start with simple scoping analysis
- What is the nature of the system?
  - Complex? Linear? Feedbacks? Well-known? Single or multiple attributes of concern? Constraints?
- Who is/are decisionmaker/s? Their stakes?
- Who are other stakeholders? Vested interests?
- What are timing issues?
  - Can changes be made later? Cost of delay? Value of seeking more information?

The Energy Challenge

- **If we have to change our energy technologies over a relatively short period of time, where are the best alternatives?**
- **How should we invest in developing better alternatives?**
- **What are the drivers that will encourage timely development and market penetration of these technologies?**

- **Do we also have to change behaviors?**

Scoping Analysis- an example

- **Should China build more energy efficient housing complexes or less efficient ones and extra power plants?**
  - **What are the initial capital cost differences?**
  - **What is the annual operating cost difference?**
  - **What is the life cycle cost difference?**

BUT, if the answer is not obvious, need more work!!

  - **What are differences in GHG emissions? Materials use? Waste production? Land impacts? Customer satisfaction? etc.**

Simulation Analysis - examples

- **Development of a computer simulation model that reflects the behavior of a complex system**
  - **Model of the electricity production, transmission, and demand system to study system behaviors, costs, emissions, etc. under varying operational and use strategies**
  - **Model of a hybrid automobile to evaluate tradeoffs between engine size, performance, and electricity storage needs**
  - **etc.**
- **Results are only as good as the model!**

Economic Analysis

- Macro (top-down) and micro (bottom up) approaches
- Used to assess alternatives when the major impact of concern is economic
  - Varies from detailed cost estimation models to minimize production costs, to
  - Global trade models to study impacts of various trade policies and local economic conditions on the world economy
- If other attributes are important, they must be addressed as fixed costs or "externality costs"
  - Cost-Benefit models, Input-Output models, Optimization models, etc.

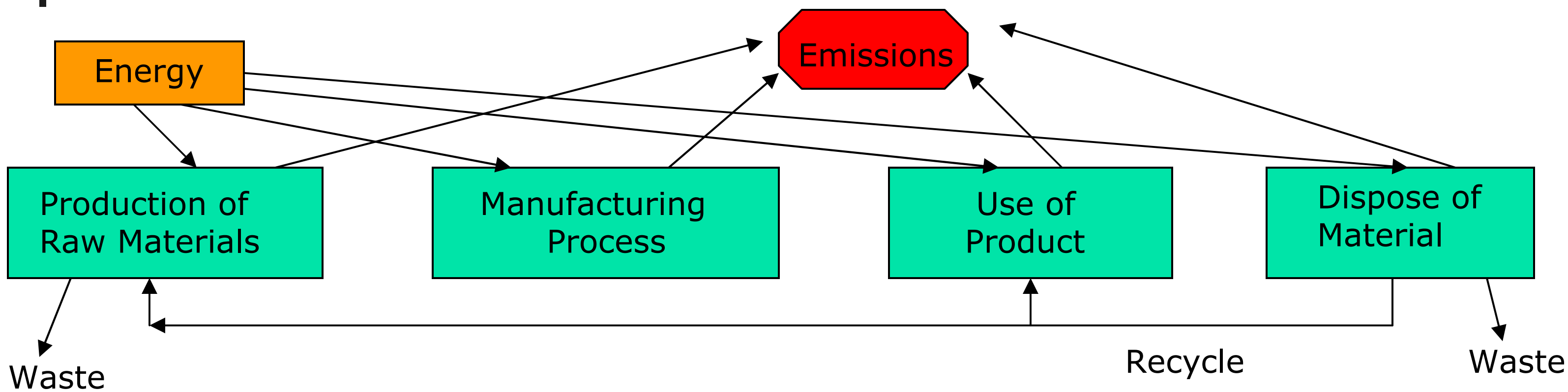
Life-Cycle Analysis - approach

- Define "cradle-to-grave" alternative systems
- Set system boundary conditions
- Set time basis (snapshot; one life cycle)
- Identify impacts of interest to decision-makers
  - Costs, air pollution, GHG emissions, wastes, resource depletion, etc.
- For each portion of the life-cycle, estimate the impacts of interest
- Assess tradeoffs, considering uncertainties

Components of LCA

- Inventory
  - Quantify energy and raw material requirements, emissions, effluents, solid waste, costs
  - Mass and energy balance of each process in system
- Improvement
  - Reduce environmental or other burden through process design changes, material substitution, recycle, etc.
- Impact Assessment
  - Assign values to each effect to achieve an overall environmental score or set of scores
- Limitation
  - Normal operations assumed – doesn't address upsets

Life Cycle Analysis – for a product



Attributes: Costs, Resource use, Emissions, Wastes, Costs, Performance, etc.

Sum cumulative attributes over total life cycle of product to compare net impacts

MacDonald's Styrofoam or paper?

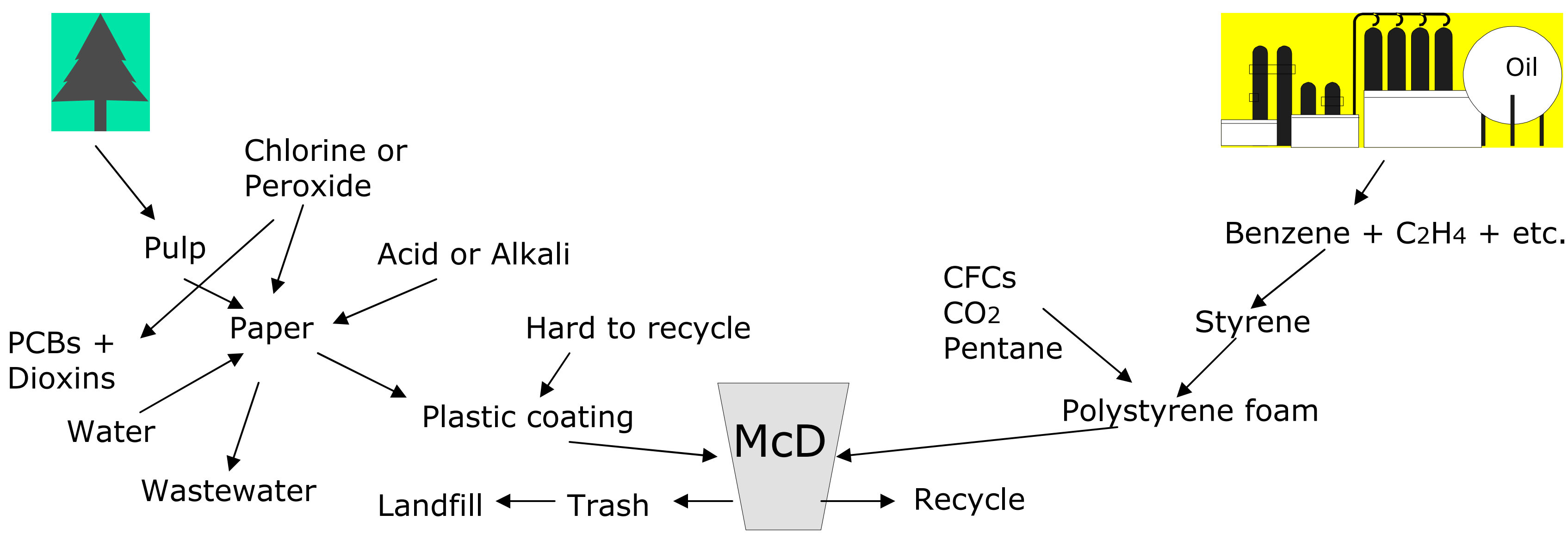
Trees (natural)

Paper (good ?)

Oil (bad)

Chemicals (worse)

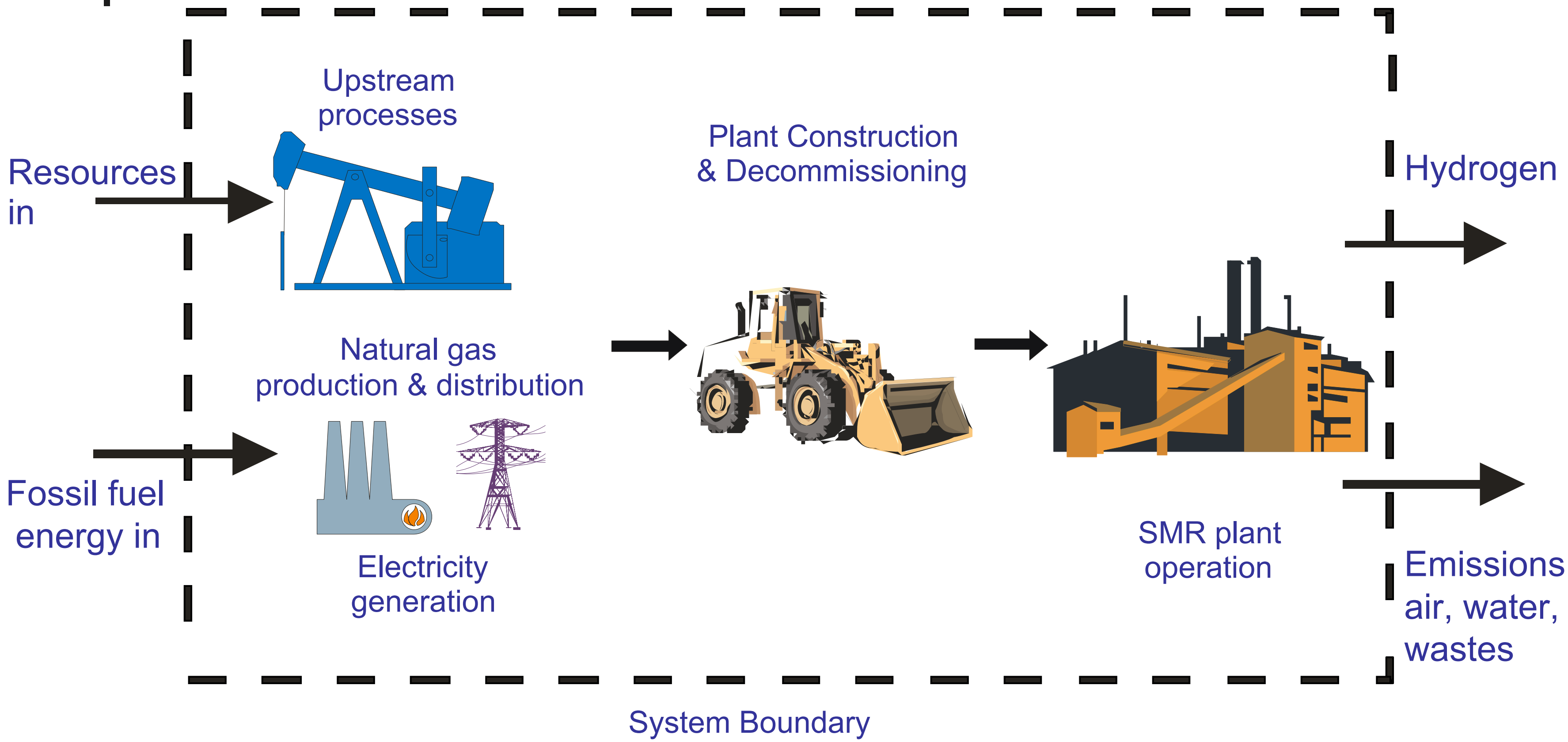
Styrofoam (??)



Hydrogen Production Example

- Make from steam methane reforming?
- Make from water electrolysis using wind power?

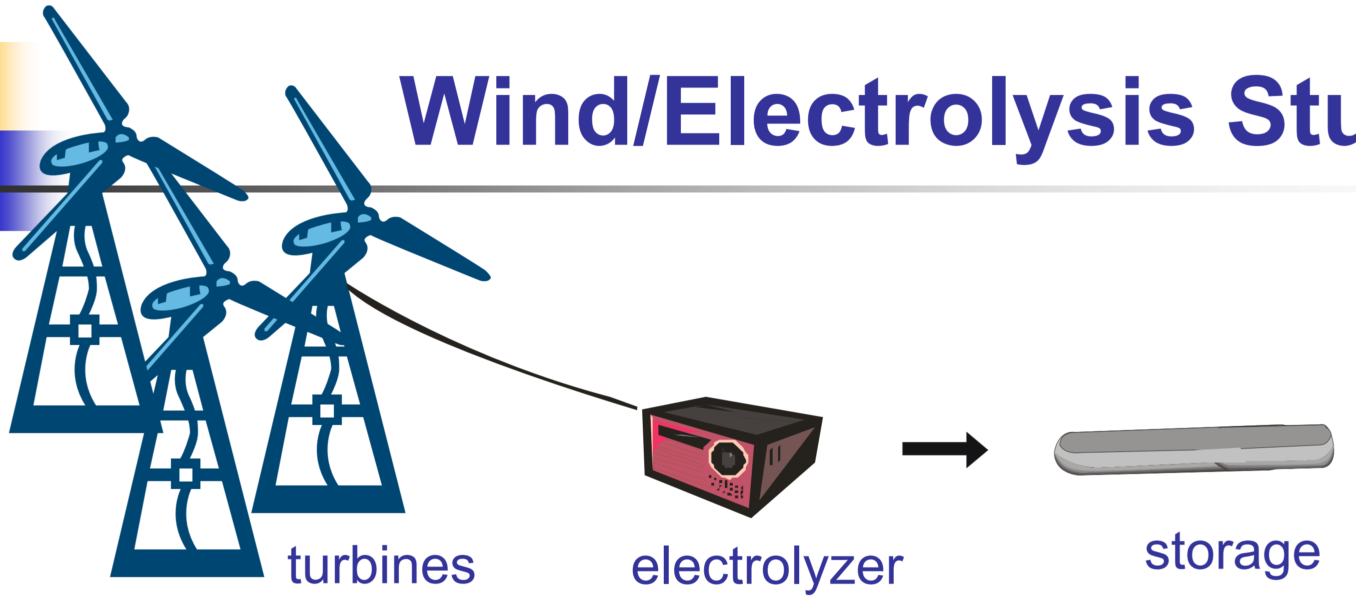
Steam Methane Reforming System Boundary Definition



SMR Results

- H_2 is a clean fuel but production has environmental consequences
- H_2 plant itself produces few emissions, except CO_2
- CO_2 is the largest air emission (98 wt%) and accounts for 77% of the GWP
- 0.64 MJ of H_2 produced for every 1 MJ of fossil energy consumed

Wind/Electrolysis Study



Wind turbine:
- Atlantic Orient Corporation (50kW x 3)
- Class 5 wind data from upper Midwest site (North Dakota)

Electrolyzer:
- Stuart Energy (30 Nm^3/hr nominal capacity)

Cars fueled: 46 per day at 3 kg/car/week

GWP and Energy Balance - Wind/Electrolysis

Preliminary results:

- **GWP = 650 g CO_2-eq/kg H_2**
  - **5% of the greenhouse gas emissions from SMR**
- **Energy balance = 20 MJ of H_2 produced for every 1 MJ of fossil energy consumed**
  - **31 times greater than the net energy balance of SMR**
- **Emissions are from equipment manufacture**
  - **Majority from concrete bases for wind turbines**
  - **Water consumption in electrolysis accounts for nearly all resources**

Hydrogen Production Choice?

- Wind power offers significant reduction in GHG emissions
- For transportation, there is a mismatch between wind turbine energy availability and fuel needed by the large concentrated populations of cars
- Costs for hydrogen from wind power are MUCH higher than those from SMR

On the Road in 2020

- An MIT Energy Lab study of alternative automotive systems projected to 2020 – updated in 2003
- LCA
- Considers evolutionary improvement of today’s typical car as a baseline
- Alternatives are comparable in performance, size, etc.

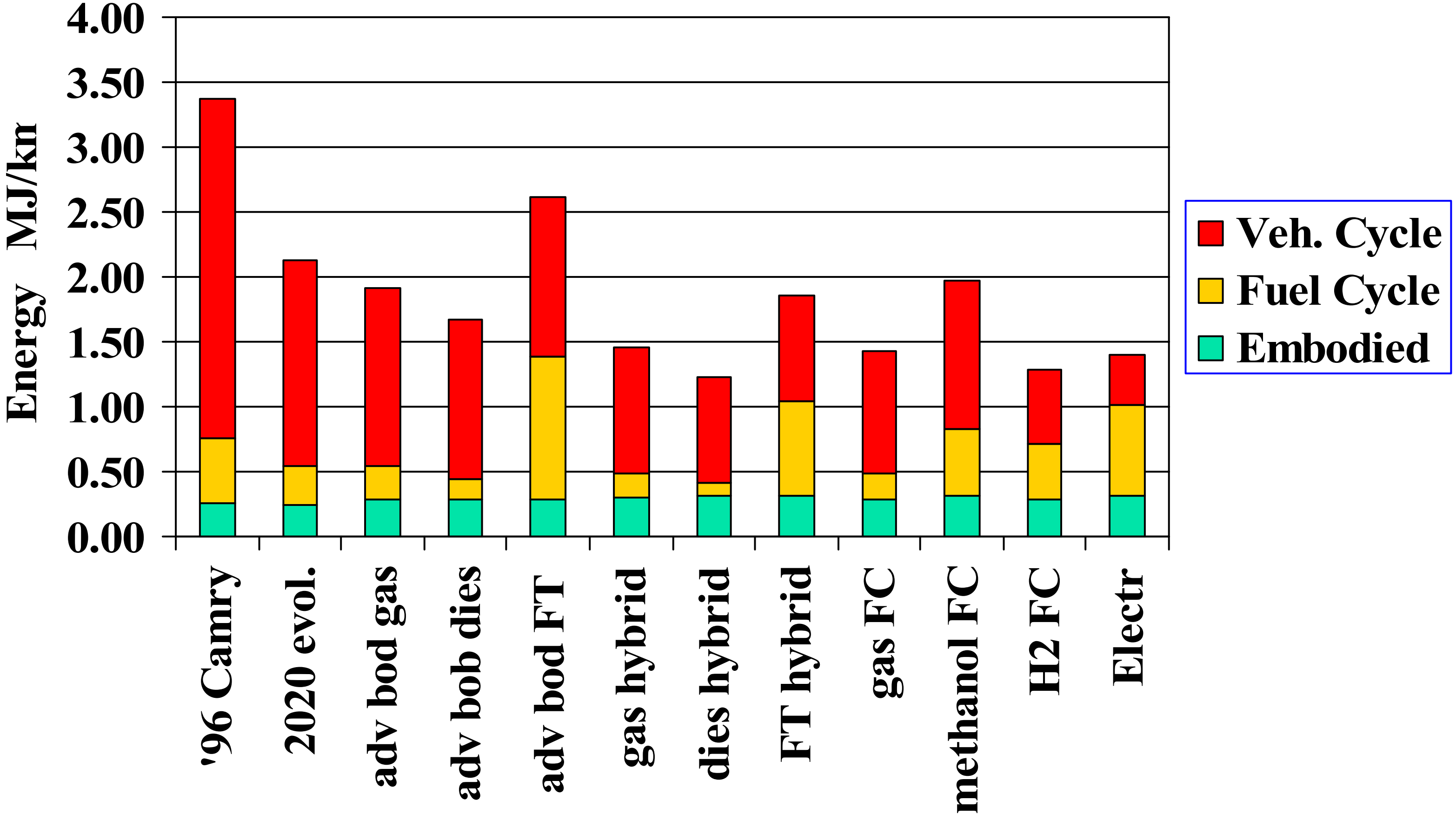
Comparison of Energy Consumption and GHG Emissions on Life Cycle and Vehicle Operation Bases

2020 Technologies	Relative Energy Consumption		Relative GHG Emissions	
	Life Cycle Basis	Vehicle Operation Only	Life Cycle Basis	Vehicle Operation Only
Baseline gasoline ICE	100	100	100	100
Advanced gasoline ICE	89	88	89	88
Advanced diesel ICE	76	77	78	82
Hybrid gasoline ICE	65	61	63	61
Hybrid petrol. diesel ICE	55	53	56	56
Hybrid CNG ICE	62	59	51	45
Hybrid F-T diesel	86	53	66	54
Hybrid gasoline FC	66	56	66	54
Hybrid methanol FC	89	66	89	66
Hybrid hydrogen FC	60	33	60	0
Battery electric	80	29	69	0

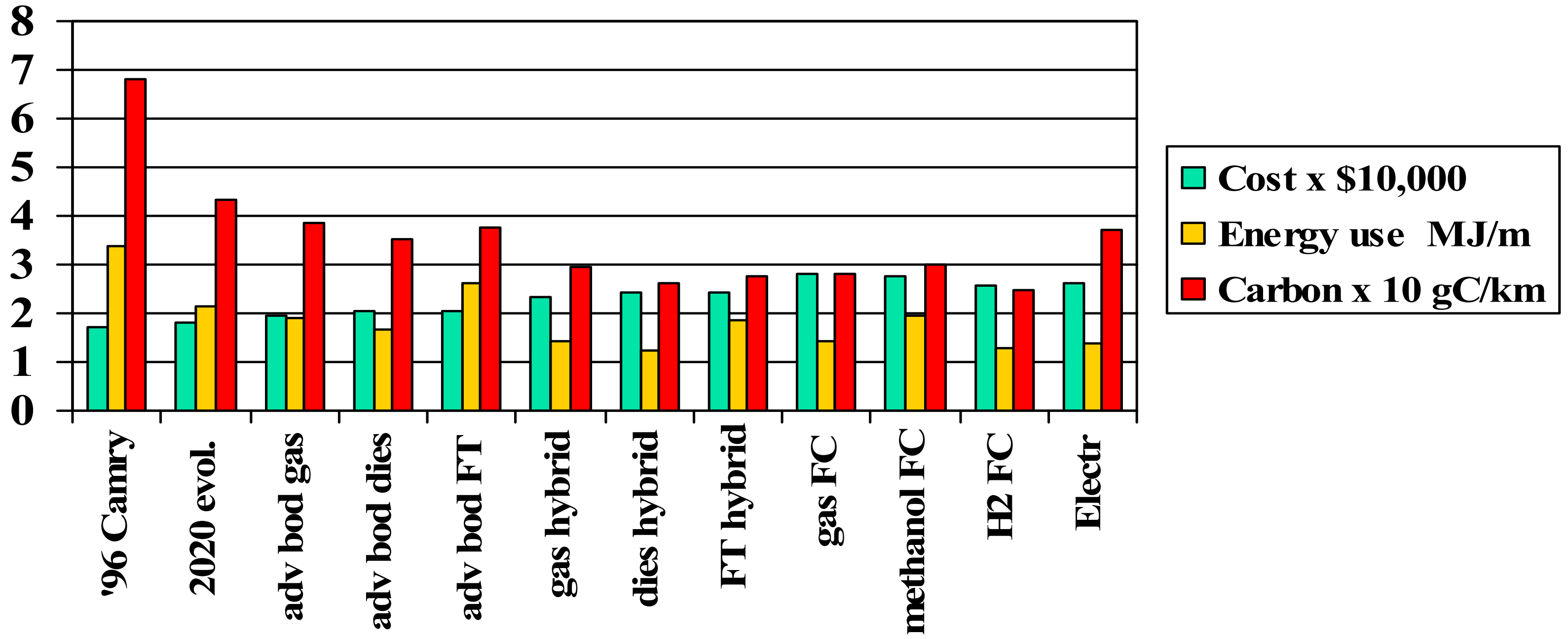
Operating Costs for New Passenger Cars in 2020, ¢ (1997)/km

2020 Technology (Vehicle Price)	Total	Fixed	Variable
Baseline gasoline ICE ($18,000)	30.6	25.0	5.6
Advanced gasoline ICE ($19,400)	32.1	26.8	5.3
Advanced diesel ICE ($20,500)	32.8	28.1	4.7
Hybrid gasoline ICE ($21,200)	34.1	29.2	4.9
Hybrid diesel ICE ($22,200)	34.8	30.4	4.4
Hybrid CNG ICE ($21,700)	34.6	29.7	4.9
Hybrid gasoline FC ($23,400)	37.3	31.7	5.6
Hybrid methanol FC ($23,200)	36.5	31.5	5.0
Hybrid hydrogen FC ($22,100)	35.7	30.3	5.4
Battery electric ($27,000)	40.8	36.3	4.5

Life Cycle Energy Use Comparisons



Life Cycle Comparisons of Cost, Energy Use, and Carbon Emissions



Risk Assessment Techniques

- **Risk assessment builds on LCA where there is potential for undesired effects outside of normal operations that may affect choices**

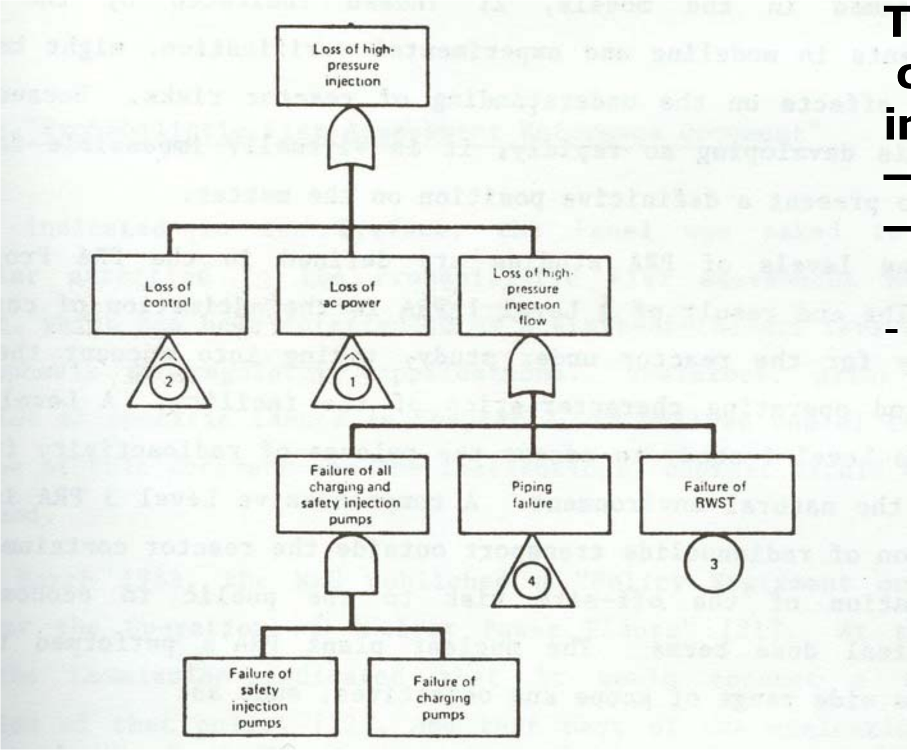
  Risk ~ Likelihood x Consequences

  - **Likelihood can be a probability of occurrence or a frequency of occurrence**
  - **Consequences can be fatalities, $ loss, health effects, etc.**
  - **Multiple risks can be assembled to give a composite "risk profile" for an operation or activity**

Risk Assessment Techniques: Sudden Events

- Use of logic trees (fault trees or event trees) to systematically describe sequence of failures or circumstances leading to an undesired event
- Employs Boolean algebra to identify and quantify different accident pathways
- Allows risk ranking and mitigation of highest impact risks first
- Used in nuclear and other high hazard industries

Example Fault Tree – PRA Status Report NUREG – 1050 (1985)



Top event is loss of emergency coolant injection capability in a reactor emergency

– note "and" and "or" gates

– triangles show top events from other sub-trees

- RWST is reactor water storage tank

Source: U.S. Nuclear Regulatory Commission, Probabilistic Risk Assessment (PRA) Reference Document, NUREG 1050, September 1984.

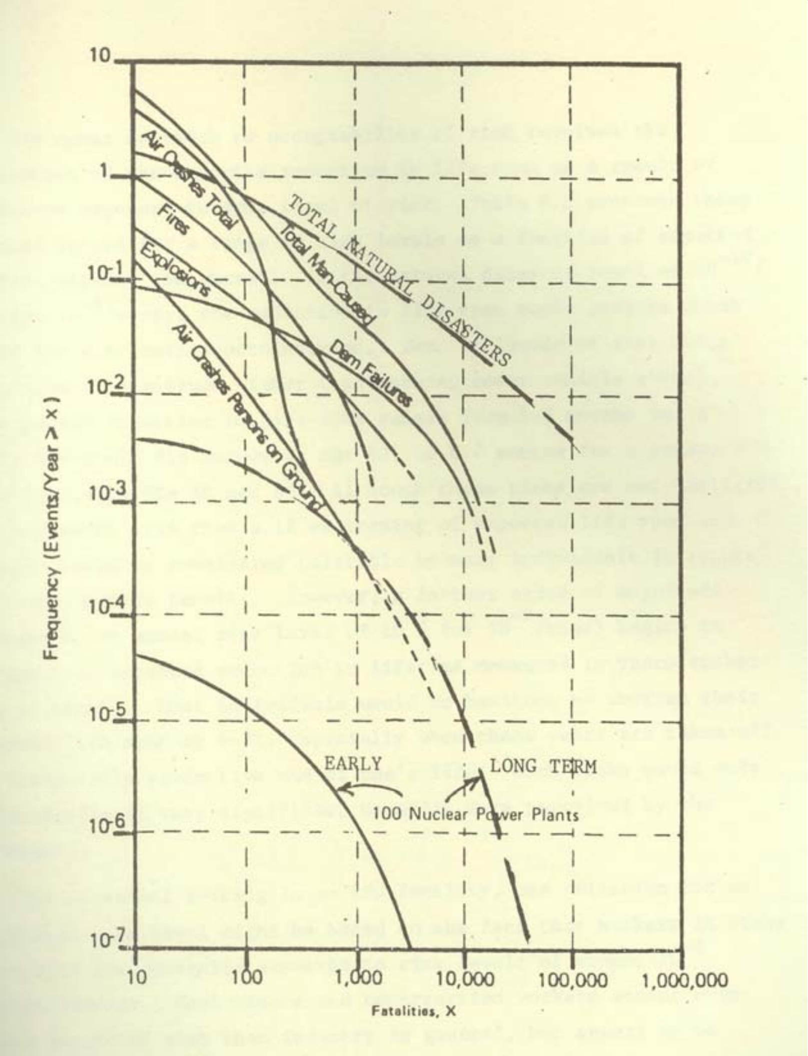
Risk Assessment Techniques: Long Term Health Effects

- Identification of Sources, Dispersion Patterns, Chemical Transformations, Ingestion modes
- Dose = Concentration X Exposure Time
- Cumulative dose estimation
- Dose response estimation based on cell, animal, or other data

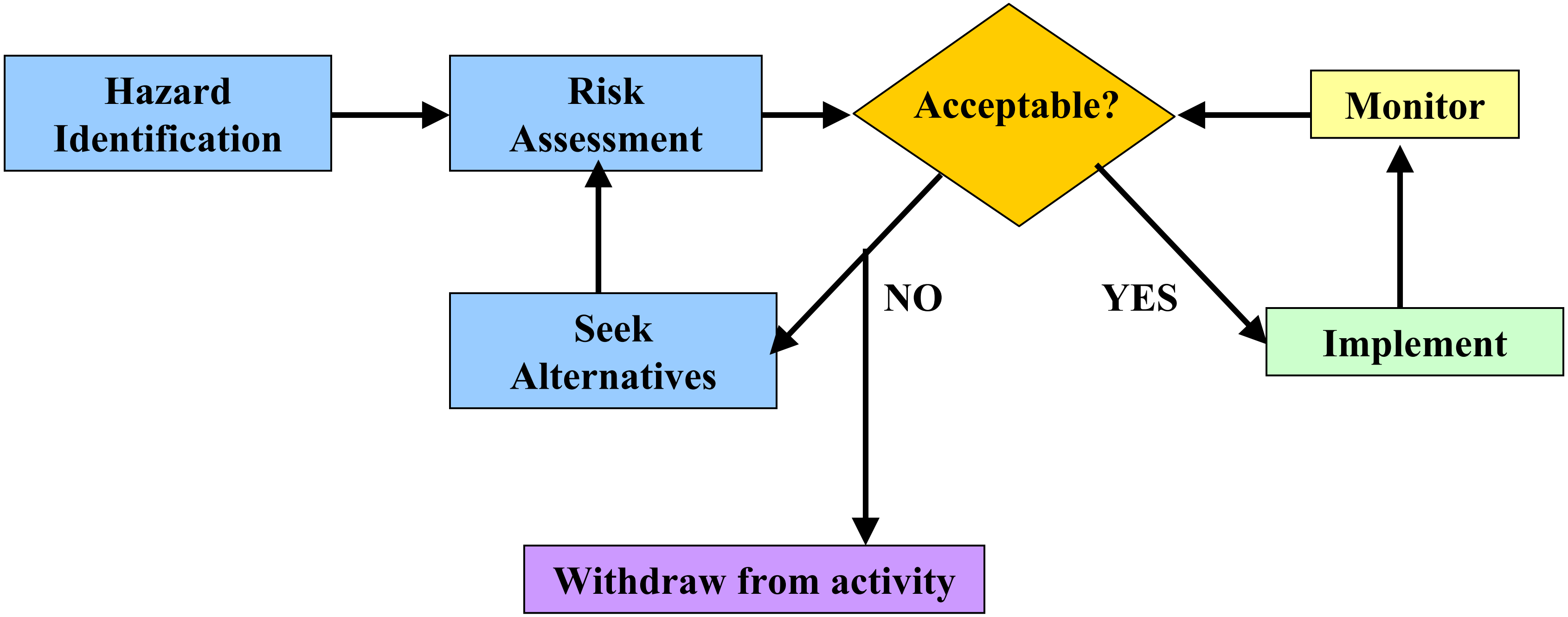
Used to predict latent cancers, mutagenicity, etc.

Source: U.S. Nuclear Regulatory Commission, Reactor Safety Study,
An Assessment of the Accident Risks in U.S. Commercial Nuclear Power Plants,
WASH-1400 (NUREG-75/014)

Example Risk Profile – Reactor Safety Study, WASH-1400 (1975)



Life Cycle Risk Management

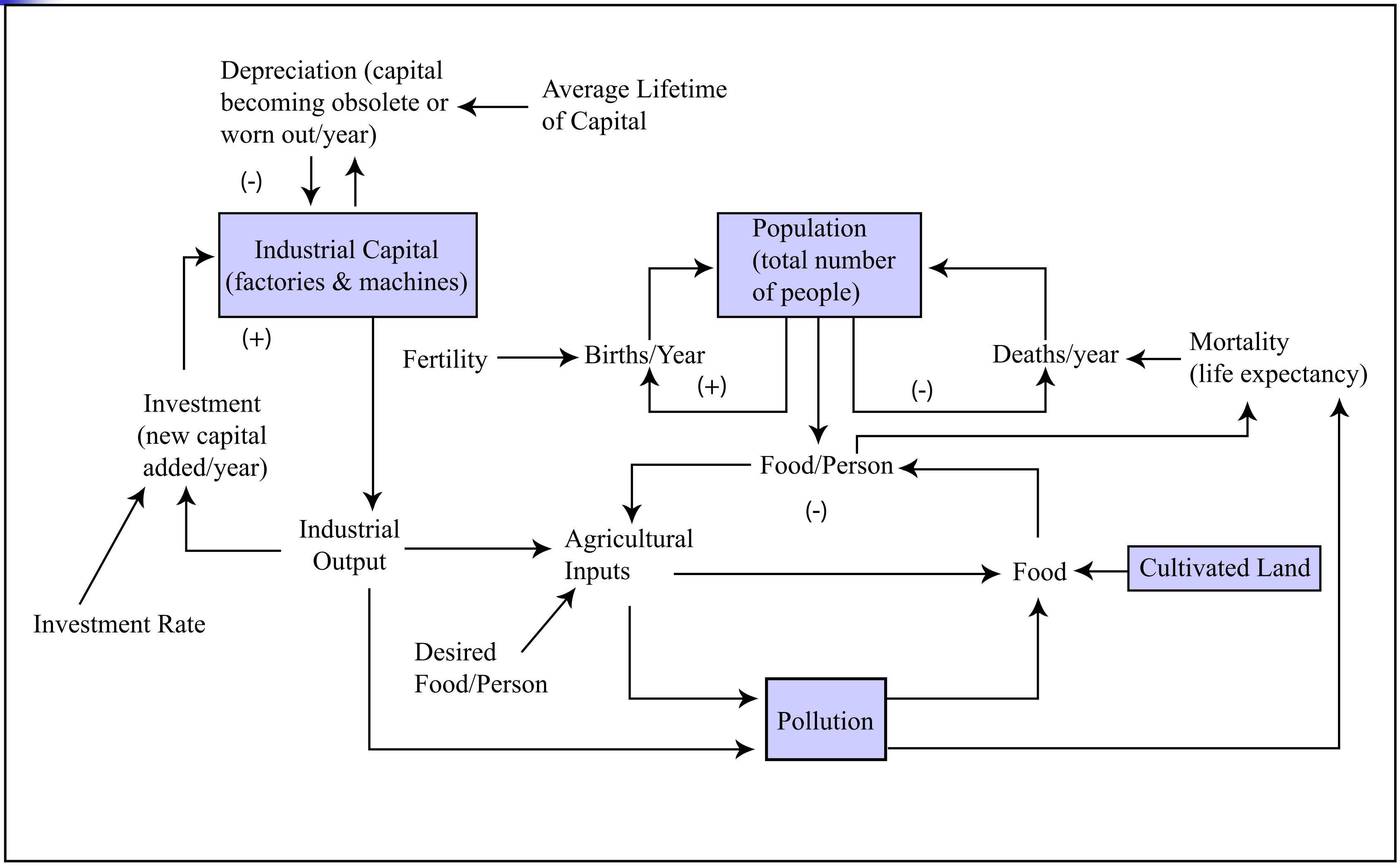


Systems Dynamics Models

- Useful for complex systems with feedback
- Identify system nodes
- Interconnect nodes by arrows showing whether node is influenced by and/or influences other nodes
- Build influence relationships matrix

Explores more interactive systems – US energy pricing, etc.

Systems Dynamics Model – Population, Land, and Capital – Meadows, 1992



After Meadows, D. H., D. L. Meadows, and J. Randers. *Beyond the Limits: Confronting Global Collapse, Envisioning A Sustainable Future*. Post Mills, VT: Chelsea Green, 1992.

Figure by MIT OCW.

Decision Models

- Single decision maker
- Group decision processes
  - Define decision characteristics, facts, uncertainties, and general goals
  - Set decision process rules (weight, sequence, etc.)
- Decision model development
  - Characterize preferences of decision makers and do composite optimization
  - Use simulation model to generate scenarios to aid decision makers understanding and final decision

Some Decision Analysis Techniques

- **Voting Methods**
- **Weighted Scoring Methods**
- **Analytic Hierarchy Process**
- **Kepner-Tregoe Method ("musts & wants")**
- **Multi-attribute Rating Techniques**
- **Outranking Methods**
- **Screening/Ranking Methods**

- **Caveats: Gaming possibilities; different results from different methods; challenges in valuing "externalities;" attitudes toward "risk;" ability to characterize preferences ("utilities") of stakeholders; dealing with feedbacks and multidimensionality; sound formulation of issues and process critical to results; etc.**

Systems Analysis Benefits

- Helps in understanding of the system and issues – forces a systematic and careful analysis
- Identifies critical areas of agreement, disagreement and uncertainty
- Can contribute to finding improvements and tracking them out in time (indicators)
- Can foster group learning on a common knowledge base
- Can explore uncertainties and identify preferred option spaces