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Renewable Energy in Abu Dhabi: Opportunities and Challenges

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Abstract: The United Arab Emirates (UAE) is an oil-rich country located in the eastern part of the Arabian Peninsula. Abu Dhabi is the largest emirate in the country, and Abu Dhabi is the capital of the UAE. The country has the one of the highest per capita rates of CO_2 emission and water consumption in the world. Most of the water consumed is produced in desalination plants, which are energy intensive. The leadership of the country has made the bold decision to establish a renewable energy (RE) sector to diversify its energy sources and the economy as a whole. The Masdar Initiative was established to promote this objective. The government has established its first RE policy; the goal is to have 7% of power come from RE sources and technologies by 2020. This paper highlights the different RE projects of the Masdar Initiative, with particular emphasis on the power sector, and examines the new concentrated solar power (CSP) plants developed as part of the initiative. **DOI: 10.1061/(ASCE)EY.1943-7897.0000042.**

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Introduction

The emergent worldwide commitment to sustainable development places a special responsibility on technology policy. This situation creates specific challenges for any oil-rich economy in which reliance on conventional sources is generally seen as the backbone of its survival. The United Arab Emirates (UAE) has taken steps to establish a renewable energy (RE) sector to address its CO_2 emission problem and to diversify its economy.

This paper explores these conditions and their implications. In so doing, the writers seek to achieve four objectives: (1) to fill a hole in the literature, because the UAE has not been considered in recent analysis of emerging technology policies; (2) to review the current plans of the UAE, coordinated under the Masdar Initiative, to introduce renewable technologies; (3) to evaluate one of these plans, namely the introduction of concentrated solar power (CSP) facilities; and (4) to highlight the potential trajectories of these plans within the overall objectives of the country.

The UAE in a Global Context

The writers begin with a look at the UAE in the context of emerging global norms and practices. In the last several decades of the 20th century, the instability of oil prices and oil embargos were the main drivers for finding alternative sources of energy to meet the demand of economic growth around the globe. Today, a new factor—climate change—is playing a major driver toward finding alternative sources of energy. The Third (2001) and Fourth (2007) Assessment Reports of the United Nations' Intergovernmental Panel on Climate Change (IPCC) confirmed that change in the climate is attributable to human activities, especially fossil energy use (IPCC 2007). Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas (GHG). Annual emissions grew by approximately 80% between 1970 and 2004. Reduction of CO_2 emissions from energy use can be done in three ways: energy efficiency, RE, and carbon capturing and sequestration.

Renewable energy is an attractive option because it substitutes for fossil fuel and the economic feasibility of RE technologies is improving with time (Clift 2007, Sims 2004). Even though carbon capturing and trading are effective and practical solutions for reducing CO_2 emissions, they do have some uncertainties concerning GHG inventories in the context of compliance evaluation in an emission trading program (Nahorski and Horabik 2008, Bartels and Musgens 2008). In addition, CO_2 is still emitted. Fossil fuel will remain the major source of energy for decades to come, but eventually alternative sources of energy will surpass fossil fuels (Zerta et al. 2008). Deployment of RE in any country will have an effect on its sustainability and will provide a wide variety of socioeconomic benefits, contribute to the diversification of energy supply, enhance regional and rural development, and create an opportunity for a domestic industry and job creation potential (del Rio and Burguillo 2009).

The UAE is located in the Middle East and in the eastern part of the Arabian Peninsula. The land is largely hot, dry desert. The UAE consists of the seven emirates. Abu Dhabi is by far the largest and controls 90% of all oil and natural gas reserves in the UAE. The federal government of the UAE recognizes that diversification of its economy plays a key role in maintaining growth. The other main industrial activities in the country include construction, aluminum, chemicals and plastics, metals, and heavy equipment.

According the state of the environment (SOE) report of Abu Dhabi (EAAD 2007), the main source of air pollution in the country comes from the oil and gas industry, followed by electricity and

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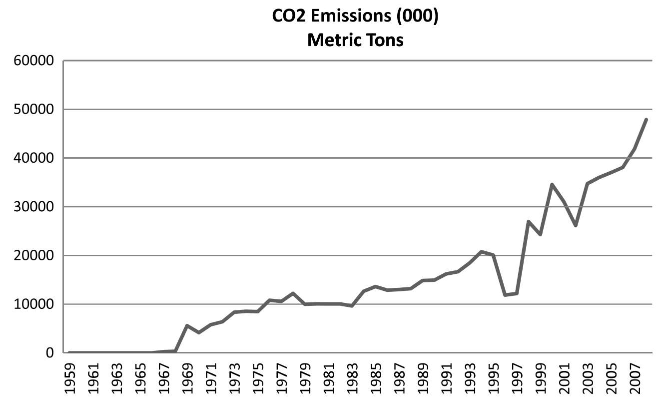

Fig. 1. Historical CO_2 emissions in the UAE (data from CDIAC 2009)

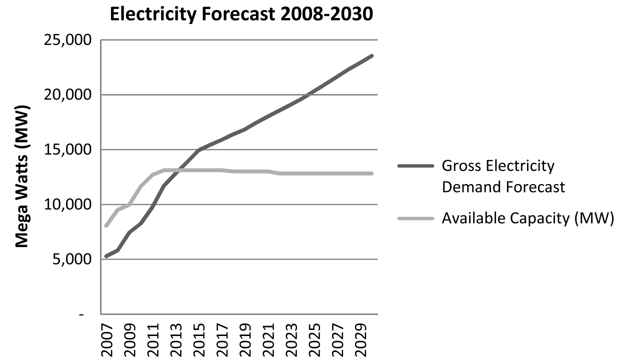

Fig. 2. Projected electricity demand for Abu Dhabi (data from ADWEC 2008)

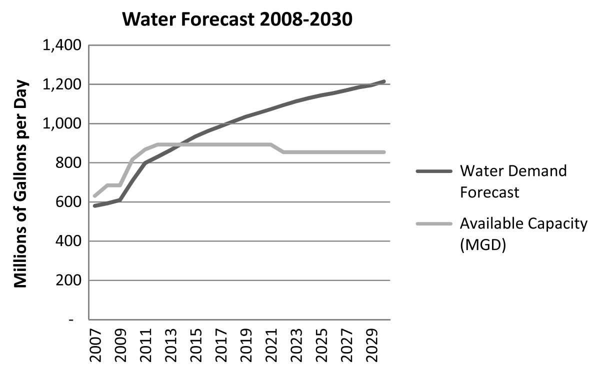

Fig. 3. Projected water demand for Abu Dhabi (data from ADWEC 2008)

water desalination production. More than 90% of the water consumed in the country comes from desalinated water, and this shows the coupling between energy and water. Natural gas fuels more than 99% of total electricity generation, with the remainder on the basis of oil (ADWEC 2008). It is noticeable that the percent internal consumption of natural gas is decreasing with time. This can only signal the gas reserve in the UAE is not enough to meet the future internal energy needs of the country. Therefore, the economy will depend in the future on more polluted sources of energy to make up for the gas deficit. Although Abu Dhabi has the petroleum resources necessary to sustain increased electricity production, CO_2 emissions will also rise. In addition, the UAE and other Gulf states have the highest CO_2 emissions per capita and the UAE has the second highest water consumption per capita after the United States (EAAD 2007). Fig. 1 shows the historical CO_2 emissions in the UAE (CDIAC 2009).

Early this year, the government of the UAE announced its first RE policy. By the year 2020, 7% of the energy for the power sector will come from RE. This means RE resources will be used along with fossil fuel to power electricity generation and water desalination plants.

The Masdar Initiative—Emerging Technology and Sustainability Planning

The UAE has developed a vision for the year 2030 that includes economic growth and diversification. Several specific activities have already been framed.

Overall Vision

The Masdar Initiative is designed to pursue this vision for diversifying the economy into RE. The Abu Dhabi Urban Planning Council (ADUPC) has developed the "Plan Abu Dhabi 2030" (ADUPC 2007). It is the most comprehensive visionary plan for the city of Abu Dhabi. This urban structure framework plan is first and foremost grounded in the cultural and environmental identity of Abu Dhabi. The city's population may grow to three million or may exceed five million by 2030. Clearly this situation will have important implications and will assert more pressures on existing infrastructure and institutions—even without drawing upon the demand for RE technology. At the same time, it is clear that even though the plan covers most aspects of urban planning, it still lacks attention to the energy required to meet the comprehensive development plan. This omission could have serious consequences. Abu Dhabi's energy demand and supply to meet electricity generation and water desalination is critical to the sustainable development of the city and must be dealt with very wisely because it could be the tipping point between success and failure of the plan.

Abu Dhabi Water & Electricity Company (ADWEC) is the government agency dealing with electricity and water needs not only for the Emirate of Abu Dhabi but for the whole country. On the basis of Plan Abu Dhabi 2,030, ADWEC developed a projection plan for electricity and water demand up to the year 2030 (ADWEC 2008). The mandate of ADWEC is to "ensure that, at all times, all reasonable demands for water and electricity in the Emirates are satisfied." Figs. 2 and 3 show the projected electricity and water demands, respectively, for the city of Abu Dhabi. As shown in both figures, the tipping point is the year 2013, when the demands will exceed available capacities. Therefore, planning for new power and desalination plants should be ongoing because the mandate of ADWEC is to supply electricity and water at all times.

Renewable Energy in the Power Sector in Abu Dhabi and the UAE

In April 2006, Abu Dhabi took a bold and historic decision to embrace renewable and sustainable energy technologies through its Masdar Initiative. The initiative is a multibillion dollar comprehensive economic development program designed to leverage Abu Dhabi's considerable financial resources and energy expertise into innovative solutions for cleaner, more sustainable energy production and resource conservation (Masdar 2008). The Masdar Initiative has four primary objectives:

1. To help drive the economic diversification of Abu Dhabi,
2. To maintain, and later expand, Abu Dhabi's position in evolving global energy markets,

J. Energy Eng., 2011, 137(4): 169-176

3. To position the country as a developer of technology, and not simply an importer, and
4. To make a meaningful contribution toward sustainable human development.

To implement the Masdar Initiative, the Abu Dhabi government has created the Abu Dhabi Future Energy Company (ADFEC). This is a private joint stock company wholly owned by the government of Abu Dhabi through Mubadala Development Company. The following is a brief description of the different business units of ADFEC.

Masdar City

Masdar City is an emerging global clean-technology cluster located in what aims to be one of the world's most sustainable urban developments powered by RE. This $22 billion free zone located approximately 17 km from downtown Abu Dhabi will eventually be home to companies, researchers, and academics from across the globe, creating an international hub for companies and organizations focused on RE and clean technologies. Masdar City will be a great place in which to live. It will be home to residents and commuters who will live the technological innovations under development in the city's laboratories, research centers, and demonstration showcases. A test bed for new approaches to the planning, design, engineering, construction, and operational challenges involved in creating environmentally sustainable cities, Masdar City itself will be helping test and solve these problems, thereby making it easier and cheaper to develop sustainable cities in the future. Masdar City will set a benchmark that will ultimately support sustainable development throughout Abu Dhabi and the region and provide a functioning blueprint for sustainable living around the world. Construction began in 2008, and just two years later, the first buildings opened in the third quarter of 2010. The city will be home to international corporations and leading minds in the field of sustainability and RE. General Electric is a strategic partner in Masdar City and will build its first ecomagination center in the city. The center will focus on promoting sustainable business solutions that will support the development and deployment of new and innovative technologies. Businesses are able to take advantage of a homegrown research and development center, the Masdar Institute, the first graduate-level academic institution dedicated to the research of alternative energy, environmental technologies, and sustainability. Masdar City will be discussed in more details in the following section.

Carbon Management

This unit creates value for Masdar by monetizing GHG emission reductions under the provisions of the United Nations–led Clean Development Mechanism (CDM) framework of the Kyoto Protocol. Masdar Carbon does this by offering project owners, primarily in oil & gas and power in the Middle East, Africa, and Asia, technical assistance, project management, carbon finance, and emissions trading expertise. The unit then buys a share of the credits it helps generate at a discount. Both the Masdar City 10-MW photovoltaic (PV) plant and the Shams 1 concentrated solar power plant in the western region of Abu Dhabi are registered CDM projects handled by Masdar Carbon. On a parallel track, Masdar Carbon is developing a multi-billion-dollar national carbon capture network capable of creating a significant reduction in Abu Dhabi's carbon footprint. The first phase of the network, one of the world's first commercial-scale carbon capturing and sequestration (CCS) projects, will sequester approximately 6.5 million tons of CO_2 from power plants and industrial facilities in Abu Dhabi by 2013. The captured CO_2 will be transported and injected into oil reservoirs to enhance oil recovery.

Masdar Power

Masdar Power invests both in RE power projects and in companies with proven clean-tech technologies—within the UAE and internationally. Through this two-pronged investment strategy, the unit helps power companies add RE to their generation mix and provides clean-tech companies with expertise and capital for growth. As an RE power project developer, Masdar Power adds RE to the electricity generation mix on a worldwide scale. The unit makes direct investments in individual utility scale projects in all areas of RE and sustainability, with a focus on CSP, PV solar energy, and onshore and offshore wind energy. Masdar Power is developing a 100-MW CSP plant in the western region of Abu Dhabi Emirate, called Shams 1. International projects include the 1 GW London. Array offshore wind farm and a wind farm in the Seychelles that will provide 25% of the island's energy needs. The unit also is developing a 500-MW hydrogen-fired power plant in Abu Dhabi that uses advanced technologies to make hydrogen power commercially viable today by feeding the CO_2 into the CCS network to be developed by Masdar Carbon.

Masdar Institute

Developed in cooperation with the Massachusetts Institute of Technology (MIT), the Masdar Institute is a postgraduate university focused on the science and engineering of advanced RE, environmental technologies, and sustainability. The Masdar Institute is the nucleus of the research and development activities in Masdar City and will play a major role in building the city. First opened to students in September 2009, the institute offers nine master of science programs and a doctorate program in renewable energies and sustainable technologies and encourages an environment to foster the next generation of scientific discoveries. Designed by Fosters + Partners, the Masdar Institute building will be the first completed building at Masdar City and a model of sustainability. It uses at least 70% less electricity and potable water than conventional buildings of its size and is wired throughout with an energy metering system that monitors energy consumption and produces data that are easily accessible to students and faculty for use as a research tool. The building incorporates a wide range of emerging green-building technologies that will be evaluated, with the building itself serving as a test bed for technologies that will help Masdar City achieve its zero carbon, zero waste, clean-power goals.

Through the Masder Initiative, a series of CSP power plants are going to be built to power the electrical sector in Abu Dhabi. The CSP technology has proven to be reliable in a country such as the UAE, and the next section will detail the proposed power plants.

Concentrated Solar Power Parabolic Trough Technology

Against this background, the writers now turn to the third objective of this paper, namely to consider their choice of a particular RE technology. No matter how much the oil prices fluctuate at the global level, there is every expectation that energy from renewables will increase in the future. Fig. 4 shows that fossil fuel will peak globally around 2020 in addition to the alternative energy outlook between 1930 and 2100. Table 1 compares the present production and economic cost of some renewables with their future potential capacity and cost between 2005 and 2030 (IEA 2006, LBST 2007, Zerta et al. 2008). This table shows that the future for renewables is promising and feasible (Abmann et al. 2006, WEA 2004). After 2030, RE will constitute major sources of energy. These projections may change and new sources will be found because of the serious commitment of the world in investing in RE research and development. The European Union (Reiche and Bechberger 2004),

J. Energy Eng., 2011, 137(4): 169-176

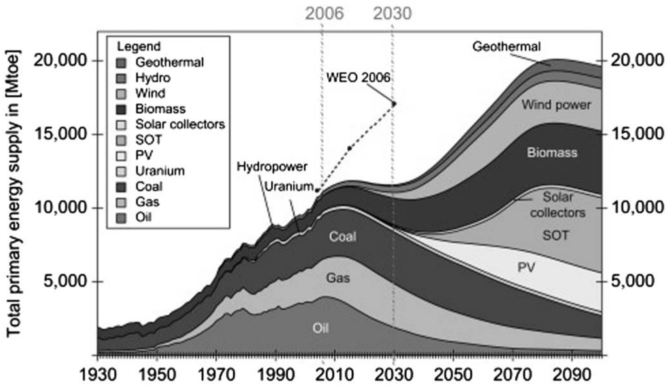

Fig. 4. Alternative world energy outlook (LBST 2007, reprinted with permission from Ludwig-Bölkow-Systemtechnik)

Unites States (Bolinger et al. 2001, IEA 2006), China (Weidoua and Johansson 2004, Tsai 2005, Hang et al. 2008, Su et al. 2008), England (Upret and van der Horst 2004, Simms et al. 2008), Japan (EIA 2005), and many other countries such as Brazil, India, and Turkey (Ramachandra and Shruthi 2007, Evrendilek and Ertekin 2003, Goldemberga et al. 2004, Shikha et al. 2004) have developed RE policies accompanied by the right legislative framework to encourage research and development, investment, and diffusion of these technologies, especially in the power sector. Table 2 shows the potential RE resources in selected regions around the globe.

Through the Masdar Initiative, a series of CSP plants are expected to be built in the middle of the desert in Zayed City in Abu Dhabi, where the land and the sun are abundant. These CSP plants should supply part of the energy needed for electricity generation and water desalination production. Why was CSP technology chosen and in particular the parabolic trough systems?

The literature review and analysis of earlier cases have shown a convergence toward CSP plants, parabolic troughs, in the power sector, especially in desertlike countries. The California experience indicates that the first and subsequent parabolic trough power plants that were installed since 1985 are performing well over their operational life of 15 to 20 years. The technology has been amply demonstrated by a 354-MW modular plant in the Mojave Desert for the past 20 years.

There are several other commercial trough projects in the planning or active project development stage, including a 64-MW plant in Nevada and several 50-MW plants in Spain. Integrated solar combined cycle systems (ISCCS) are in various stages of planning in southern California, India, Egypt, Morocco, Mexico, and Algeria. A 1-MW trough plant was recently constructed for Arizona Public Service. The CSP technology, parabolic troughs, has proven its economic, energy, and environmental benefits in California and other part of the world (Tester et al. 2005, NREL 2006).

Table 2. Renewable Energy Resources in Selected Regions for Comparison Purposes

Renewable energy sources	Middle East and North Africa	North America	Sub-Saharan Africa
Wind[a] (exajoules)	492	1512	420
Solar (exajoules)	Minimum 412, maximum 11,060	Minimum 181, maximum 7410	Minimum 371, maximum 9,528
Geothermal (Millions exajoules)	6	26	17

Source: (WEA 2004, Abmann et al. 2006).
[a]No land restriction.

The evidence suggests that CSP technology has proven to be very competitive to any new power plant, including coal power plants. Variable power requirements are a problem for the grid because consumers' demand varies during the day. Other RE technologies, such as wind and solar cells, have limitations because of their lack of storage capacity and their strong variability. The CSP plants have the ability to compensate for the variations in both demand and power inputs into the grid through thermal storage. The technology is also suitable for both electricity and water desalination in a cogeneration setup. The potential for cogeneration of desalinated water on a large scale is a major advantage of CSP technology (Shinnar and Citro 2007). All this suggests a closer look at the planned and the potential implications.

Shams 1 and Alternative Futures for Renewable Energy Power Plants in Abu Dhabi

Shams 1 is the first CSP, parabolic trough, power plant under construction in the United Arab Emirates. Construction of Shams 1 commenced in July 2010 and is expected to be completed by 2012. Table 3 shows all the key data related to the plant.

Masdar will build additional CSP plants on a yearly basis until a total capacity of 1, 500 MW_{el} is reached in the year 2020, as shown in Table 4 as current plan, Scenario 1. Also shown is the maximum potential of CSP plants that can be built technically if the country retains the political will to remain on the trajectory path that it has framed. This potential is shown as Scenario 2.

For exploratory purposes, the writers have included another scenario, Scenario 3, which is almost half the capacity of Scenario 2.

Table 1. Growth in Some Renewable Energy Sources and Their Technical and Potential Capacity

	Production[a]		Potential[b]		Current energy cost[b]	Potential energy cost[b]
Renewable energy sources	2005	2030	Technical (exajoules/year)	Theoretical (exajoules/year)	Electricity production ($/kW · h)	Electricity production ($/kW · h)
Wind	121 terawatt hours	3,742 terawatt hours	600	6,000	0.04–0.12	0.03–0.10
Photovoltaic	4.9 terawatt hours	1,147 terawatt hours	> 1, 600	3,900,000	0.25–1.60	0.05–0.25
Solar Thermal	0.7 terawatt hours	456 terawatt hours			0.12–0.34	0.04–0.20
Biomass	1,032 million tonnes of oil equivalent	1,650 million tonnes of oil equivalent	> 250	2,900	0.03–0.12	0.02–0.08
Geothermal	2.1 million tonnes of oil equivalent	31 million tonnes of oil equivalent	5,000	140,000,000	0.02–0.10	0.03–0.10

[a]Source: (LBST 2007, Zerta et al. 2008).
[b]Source: (WEA 2004, Abmann et al. 2006).

J. Energy Eng., 2011, 137(4): 169-176

Table 3. Key Data Related to Shams 1

Key indicators	Values
Peak capacity	100 MW_{el}
Area required	2 km^2
Engineering, procurement, and construction (EPC) price	Approximately \$350 million
Annual solar generation	220 million kW·h, operating hours
Annual operating hours	2,200 h
Project structure	Independent power plant (IPP)
Ownership of the plant	60% by Masdar and 40% by EPC contractor
Workforce during construction	200–300 people
Permanent jobs for operations	60–70 people
Construction period	2010–2012
Commercial operation	2013
Location of the plant	Madinat Zayed
Source of energy for electricity generation	75% from solar radiation/20% gas-fired boost burner/5% gas boiler
Thermal storage	None
Plant lifetime	30 y

Table 4. Commissioned Concentrated Solar Power Plants per Year and Different Scenarios

Year	Forecasted electricity demand (MW) (ADWEC 2008)	Current plan (MW_{el}) (Scenario 1)	Maximum potential (MW_{el}) (Scenario 2)	Half the maximum potential (MW_{el}) (Scenario 3)
2011	9,770	100	100	100
2012	11,706	100	250	150
2013	12,817	100	250	150
2014	13,868	100	500	250
2015	14,946	100	500	250
2016	15,437	200	500	250
2017	15,888	200	500	250
2018	16,399	200	500	250
2019	16,842	200	500	250
2020	17,469	200	500	250
2021	18,020		500	250
2022	18,558		1,000	500
2023	19,109		1,000	500
2024	19,687		1,000	500
2025	20,334		1,000	500
2026	20,982		1,000	500
2027	21,650		1,000	500
2028	22,331		1,000	500
2029	22,924		1,000	500
2030	23,554		1,000	500
Total		1,500	13,600	6,900

The current power generation in Abu Dhabi is approximately 40,000 GWh/year, and this could be totally satisfied by CSP plants and the cost could reach \$30 billion. The land area needed to build such capacity is 400 km^2, which is available in the desert (ADFEC 2008).

Given these various scenarios, it is useful to consider some of the critical contingencies. Although CSP plants are excellent source of energy, there are some challenges associated with operating and maintaining them in Abu Dhabi. First, the weather in the summer is hazy and will affect the solar radiation. Sand dunes exist in the desert and flat area is needed to build CSP plants, so this will increase the cost to clear the site when needed. Table 3 shows that only 220,000,000 $kW \cdot h$/per year of electricity will be generated from the Shams 1 plant operating for 2,200 h/year. All the following CSP plants will have thermal storage capacity, which will allow the plant to operate for 4,400 h/year and will double the annual solar generation like many existing CSP plants around the world (Shinnar and Citro 2007, Al-Soud and Hrayshat 2009, NREL 2003). The thermal energy storage systems technologies are becoming more feasible, technically and economically (Chen et al. 2009, Sharma et al. 2009).

Effect of Concentrated Solar Power Plants Given Climate Change

Current gas-powered electricity generation has a carbon footprint of 430 $g/kW \cdot h$ and solar thermal electric generation has an average carbon footprint of 32 (26–38) $g/kW \cdot h$. Therefore, when CSP plants are deployed, the CO_2 emission reduction will be 398 $g/kW \cdot h$ (430-32) (Akella et al. 2009). The Appendix at the end of the paper shows the calculation of CO_2 emission reductions.

All the existing power plants in Abu Dhabi are powered by natural gas (ADWEC 2008). Given the different scenarios in Table 4, there is potential for CO_2 reduction in Abu Dhabi as shown in Fig. 5. The current scenarios will have an effect on the reduction of CO_2 emissions. The three scenarios show reduction in CO_2 emissions, but none of them show a peak. Still, this is considered an important step forward in the sustainable energy deployment of the country.

Renewable Energy Policy: Opportunities and Dilemma

In conclusion, what can now be said about the role of CSP options for the future development of the country? The evaluation of the CSP options shows specific opportunities and dilemmas for the UAE. On the one hand, under any scenario, the CSP options lead to reductions in CO_2 emissions. On the other hand some scenarios show an inability to meet the country's stated objective of 7% power from RE. There is a gap between policy expectations and potentials for actual performance. This gap requires special

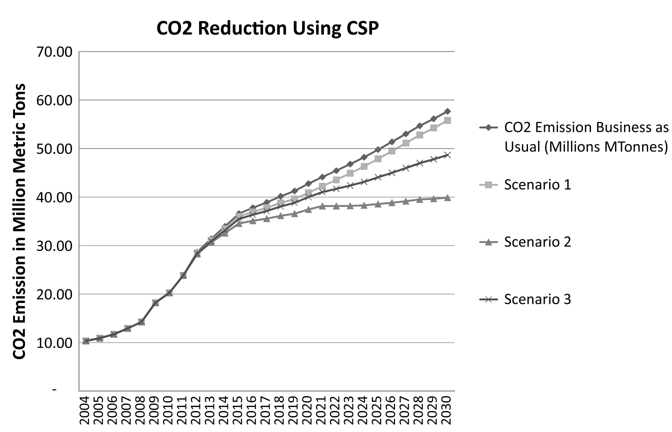

Fig. 5. CO_2 emission with and without CSP

attention. If it can be reduced, then the country will be able to meet its goals and demonstrate the energy diversification of an oil-rich economy. If it cannot close that gap, then it will reinforce the usual beliefs that oil-rich states cannot at the same time consider energy-diversification. Regarding the 7% RE policy 2020 target for UAE, the CSP scenarios that have been explored focus on the power sector in Abu Dhabi specifically and not for all the emirates in the UAE. Fig. 6 shows that 7% policy target is achievable in Scenarios 2 and 3.

Regarding the current plan of Abu Dhabi (Scenario 1), the 7% target was not achieved. If the government of Abu Dhabi decides to stay with its current plan and wants to reach the policy target, then CSP plants should be part of a well-devised RE strategy. Such a strategy should include other feasible RE sources such as PV, biomass, and geothermal. In addition, the UAE should consider implementing energy efficiency measures and carbon capturing and sequestration projects to reduce CO_2 emissions. This consideration has already started with the Masdar Initiative.

In any case, for all three scenarios, many factors must be taken into consideration when planning for strategies to reach the 2020 policy target. Fig. 7 identifies these factors and challenges facing the implementation of any RE policy. It is evident that the UAE has to make an effort, which will take time, to build its workforce, institutions, and infrastructure to be able to develop and diffuse RE technologies.

The big question is: can the UAE meet the 7% set target? The answer should be "yes." However, this can only be achieved with the close collaboration of the important players of the "Technology Triangle," which refers to strategic interaction and cooperation among (1) the scientific and research community, (2) business and industry, and (3) institutions of governance. The Technology Triangle is focused on human capital development, business development, building up the infrastructure, wealth-generating capacity, and competitiveness and sustainable development of the country (Mezher 2000).

The results from Figs. 5 and 6 show potentials and CSP technology seems to be very promising for the power sector in Abu Dhabi and the UAE. However, what is wrong here? The analysis assumes that all the factors in Fig. 7 are competitive enough to smooth the building and commissioning of the new CSP plants. In reality, the UAE and other Gulf countries lack the competitiveness because RE is new to the region and the workforce, institutions, and infrastructure are not prepared to handle this new change (Patlitzianas et al. 2006). In addition, the interrelationship between the different factors and their corresponding subfactors still needs to be taken into consideration.

To make the right policy decisions, there needs to be an understanding of the dynamics of these factors. For example, a CSP plant cannot be built in the desert without introducing the needed laws and legislations to regulate the new industry. In addition, infrastructure is needed to connect to the grid and this takes time. What about establishing a regulating agency, and what would be the best approach to tariff issues? Who will pay for the extra cost of RE? The 7% set target by 2020 will require a "leap-frog" effort that will provide the basis for a smooth introduction of RE deployment in the oil-rich economy of Abu Dhabi.

Today, policy makers need to support their decisions with the appropriate analytical quantitative tools to understand the dynamics of the different factors that are involved in the decision-making process. There are many unintended and hidden consequences. These tools will help policy makers identify and monitor the factors that they consider to be more critical to achieving any RE policy targets. The issue of building decision-making tools for energy policy in this type of economy will be the subject of another paper.

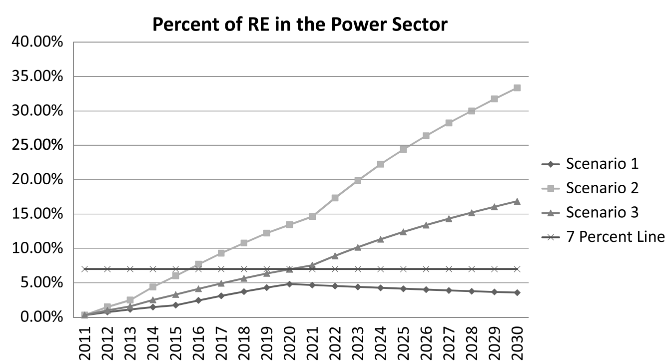

Fig. 6. Scenarios for the percent of power coming from CSP plants

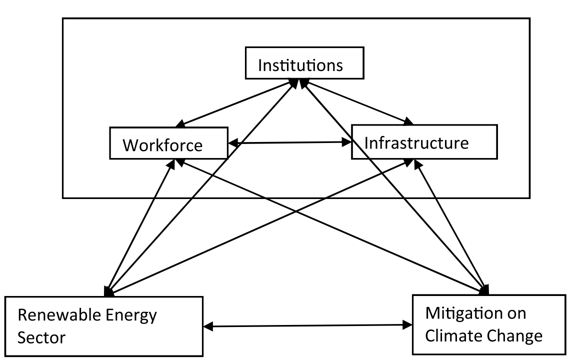

Fig. 7. The framework for renewable policy

Conclusion

This paper addressed the lack of literature and information on the UAE and the region regarding merging technologies and environmental policies. It provided an overview of the sustainability challenges. In addition, it provided the economic diversification plan of Abu Dhabi, an oil-rich emirate, into RE through the Masdar Initiative. The paper concentrated on the power sector and on building the series of CSP RE plants for electricity generation. Different trajectory scenarios were highlighted to see how CSP plants can contribute to the 2020 energy policy of Abu Dhabi and to the overall objectives of the Masdar initiative, in addition to reduction of CO_2 emissions. Building only CSP plants is not enough; to be successful, Abu Dhabi should have a portfolio of different RE technologies, especially now that many other solar technologies such as PV are becoming more economically feasible, energy efficiency measures, and carbon capturing and sequestration projects. The Technology Triangle should play a leading role in the development and diffusion of RE technologies in the UAE and the region.

Appendix

The equations used in the scenario calculations are as follows (Akella et al. 2009):

$$\text{Annual Electricity Generation}\left(\frac{\text{kW}\cdot\text{h}}{\text{year}}\right) = \text{Plant Capacity (kW)} \times \text{Plant Capacity Factor} \times 8{,}760\ \text{h} \quad (1)$$

J. Energy Eng., 2011, 137(4): 169-176

Table 5. Calculation Assumptions Made for the Three Different Scenarios

Assumption	Source
2030 electricity forecasting for total plant capacity in Fig. 4	(ADWEC 2008)
Plant capacity factors for gas-fired power plants is an average 65%	(ADWEC 2008)
Carbon footprint for gas-powered electricity generation is 430 g/kW · h	(Akella et al. 2009)
Carbon footprint for solar thermal electric generation is an average 32 (26–38) g/kW · h	(Akella et al. 2009)
CO_2 emission reduction by using a concentrated solar power plant is 398 (430-32) g/KW.h	
75% of the yearly electricity generation from concentrated solar power comes from solar radiation	

$$\text{Annual } CO_2 \text{ Emissions (tonnes } CO_2) = \text{Power Generation}\left(\frac{\text{kW}\cdot\text{h}}{\text{year}}\right)\times\text{Emission Factor}\left(\frac{\text{tonnes } CO_2}{\text{kW}\cdot\text{h}}\right) \quad (2)$$

Table 5 shows the assumptions made for the calculations. In addition, the calculations for the numbers in Figs. 6 and 7 are shown subsequently.

Calculation for Year 2011 for Scenario 1

Gross capacity demand forecast is 9,770 MW for gas-fired plants

From Eq. (1):

Annual Electricity Generation $(\text{kW}\cdot\text{h}) = 9,770,000 \times 0.65 \times 8,760 = 55,630,380,000\ \text{kW}\cdot\text{h}$

From Eq. (2):

Annual CO_2 Emission (metric tonnes of CO_2) $= (55,630,380,000\ \text{kW}\cdot\text{h} \times 430\ \text{g/kW}\cdot\text{h})/10^{12} = 23.92$ millions of metric tonnes

For the 100-MW Shams 1 CSP Plant:

Annual Electricity Generation $(\text{kW}\cdot\text{h}) = 220,000,000\ \text{kW}\cdot\text{h}$

Annual CO_2 Emission Reduction (metric tonnes of CO_2) $= (220,000,000\ \text{kW}\cdot\text{h} \times 0.75 \times 398\ \text{g/kW}\cdot\text{h})/10^1 = 0.06567$ millions of metric tonnes

Net CO_2 Emission for 2011 (as shown in Fig. 6) $= 23.92 - 0.06567 = 23.86$ millions of metric tonnes

Percent of power generated from RE (as shown in Fig. 7) from total energy generations is equal to

$220,000,000\ \text{kW}\cdot\text{h} \times 0.75/55,630,380,000\ \text{kW}\cdot\text{h} = 0.00296$ or approximately 0.30 %.

Calculation for Year 2012 for Scenario 1

Gross capacity demand forecast is 11,706 MW for gas-fired plants

From Eq. (1):

Annual Electricity Generation $(\text{kW}\cdot\text{h}) = 11,706,000 \times 0.65 \times 8760 = 66,653,964,000\ \text{kW}\cdot\text{h}$

From Eq. (2):

Annual CO_2 Emission (metric tonnes of CO_2) $= (66,653,964,000\ \text{kW}\cdot\text{h} \times 430\ \text{g/kW}\cdot\text{h})/10^{12} = 28.66$ millions of metric tonnes

For the 200-MW CSP Plants (100-MW Shams 1 without storage+100-MW Shams 2 with Storage):

Annual Electricity Generation $(\text{kW}\cdot\text{h}) = 220,000,000 + 440,000,000 = 660,000,000\ \text{kW}\cdot\text{h}$

Annual CO_2 Emission Reduction (metric tonnes of CO_2) $= (660,000,000\ \text{kW}\cdot\text{h} \times 398\ \text{g/kW}\cdot\text{h}) \times 0.75/10^{12} = 0.19701$

Net CO_2 Emission for 2012 $= 28.66 - 0.19701 = 28.46$

Percent of power generated from RE (as shown in Fig. 7) from total energy generations is equal to

$660,000,000\ \text{kW}\cdot\text{h} \times 0.75/66,653,964,000\ \text{kW}\cdot\text{h} = 0.0074$ or approximately 0.74%.

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References

Abmann, D., Lauman, U., and Uh, D. (2006). *Renewable energy: A global review of technologies, policies and markets*, Earthscan, London.

Abu Dhabi Environment Agency (EAAD). (2007). "State of the environment." ⟨http://www.soe.ae/⟩ (Apr. 2009).

Abu Dhabi Future Energy Company (ADFEC). (2008). "Shams 1." Executive briefing, Abu Dhabi Future Energy Company, Abu Dhabi, UAE.

Abu Dhabi Urban Planning Council (ADUPC). (2007). "Plan Abu Dhabi 2030." ⟨http://www.upc.gov.ae/en/MasterPlan/PlanAbuDhabi2030.aspx⟩ (Aug. 2008).

Abu Dhabi Water & Electricity Company (ADWEC). (2008). "Abu Dhabi electricity and water forecasts 2008-2030." ⟨http://www.adwec.ae/forecast/⟩ (Apr. 2009).

Akella, A. K., Saini, R. P., and Sharma, M. P. (2009). "Social, economical and environmental impacts of renewable energy systems." *Renewable Energy*, 34, 390–396.

Al-Soud, M. S., and Hrayshat, E. S. (2009). "A 50MW concentrating solar power plant for Jordan." *J. Cleaner Prod.*, 17(6), 625–635.

Bartels, M., and Müsgens, F. (2008). "Is a cap-and-trade system always efficient? The case of new entrants in the emissions trading system of the EU." *J. Energy Eng.*, 134(2), 33–39.

Bolinger, M., Wiser, R., Milford, L., Stoddard, M., and Porter K. (2001). "States emerge as clean energy investors: A review of state support for renewable energy." *Electricity J.*, 14(9), 82–95.

Carbon Dioxide Information Analysis Center (CDIAC). (2009). Carbon Dioxide Information Analysis Center. ⟨http://cdiac.ornl.gov/⟩ (Apr. 2009).

Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., and Ding, Y. (2009). "Progress in electrical energy storage system: A critical review." *Progress in Natural Science*, 19(3), 291–312.

Clift, R. (2007). "Climate change and energy policy: The importance of sustainability arguments." *Energy*, 32(4), 262–268.

del Rio, P., and Burguillo, M. (2009). "An empirical analysis of the impact of renewable energy deployment on local sustainability." *Renew. Sustain. Energ. Rev.*, 13(6-7), 1314–1325.

Energy Information Administration (EIA). (2005). "Policies to promote non-hydro renewable energy in the United States and selected countries." ⟨http://www.eia.gov/cneaf/solar.renewables/page/non_hydro/nonhydro_toc.html⟩

Evrendilek, F., and Ertekin, C. (2003). "Assessing the potential of renewable energy sources in Turkey." *Renewable Energy*, 28(15), 2303–2315.

Goldemberg, J., Coelho, S. T., and Lucon, O. (2004). "How adequate policies can push renewables." *Energy Policy*, 32(9), 1141–1146.

Hang, Q., Zhao, J., Yu, X., and Cui, J. (2008). "Prospect of concentrating solar power in China—the sustainable future." *Renew. Sustain. Energ. Rev.*, 12(9), 2505–2514.

International Energy Agency (IEA). (2006). *World energy outlook*, International Energy Agency, Paris.

Intergovernmental Panel on Climate Change (IPCC). (2007). "Intergovernmental Panel On Climate Change." ⟨www.ipcc.ch⟩ (Jun. 2008).

J. Energy Eng., 2011, 137(4): 169-176

Ludwig-Bolkow-Systemtechnik GmbH (LBST). (2007). ⟨http://www.lbst.de/publications/presentations2007/LBST_HYSYDays_6-8JUN2007_Torino.pdf⟩ (Apr. 2009).

Masdar. (2008). Masdar. ⟨http://www.masdar.ae⟩ (2008).

Mezher, T. (2000). "Strategies for industrial and technological development of Middle Eastern countries." *Int. J. Environ. Stud.*, 57(5), 543–562.

Nahorski, Z., and Horabik, J. (2008). "Greenhouse gas emission permit trading with different uncertainties in emission sources." *J. Energy Eng.*, 134(2), 47–52.

National Renewable Energy Laboratory (NREL). (2003). "Assessment of parabolic trough and power tower solar trough and power tower solar performance forecasts." National Renewable Energy Laboratory, Goldon, CO.

Natonal Renewable Energy Laboratory (NREL). (2006). "Economic, energy, and environmental benefits of concentrating solar power in California." National Renewable Energy Laboratory.

Patlitzianas, K. D., Doukas, H., and Psarras, J. (2006). "Enhancing renewable energy in the Arab States of the Gulf: Constraints & efforts." *Energy Policy*, 34(18), 3719–3726.

Ramachandra, T. V., and Shruthi, B. V. (2007). "Spatial mapping of renewable energy potential." *Renew. Sustain. Energ. Rev.*, 11(7), 1460–1480.

Reiche, D., and Bechberger, M. (2004). "Policy differences in the promotion of renewable energies in the EU member states." *Energy Policy*, 32(7), 843–849.

Sharma, A., Tyagi, V. V., Chen, C. R., and Buddhi, D. (2009). "Review on thermal energy storage with phase change materials and applications." *Renew. Sustain. Energ. Rev.*, 13(2), 318–345.

Shikha, Bhatti, T. S., and Kothari, D. P. (2004). "Wind energy in India: Shifting paradigms and challenges ahead." *J. Energy Eng.*, 130(3), 67–80.

Shinnar, R., and Citro, F. (2007). "Solar thermal energy: The forgotten energy source." *Technol. Soc.*, 29(3), 261–270.

Simms, R. W., Djokic, S. Z., and Murray, A. F. (2008). "Renewable generation in the London built environment." *J. Energy Eng.*, 134(2), 71–79.

Sims, R. E. H. (2004). "Renewable energy: a response to climate change." *Solar Energy*, 76(1-3), 9–17.

Su, M.-S., Deng, J., and Zhao, C. R. (2008). "Interaction of renewable energy policy and CO_2 emission control policy: Case study." *J. Energy Eng.*, 134(2), 63–70.

Tester, J. W., Drake, E. M., Driscoll, M. J., Golay, M. W., and Peters, W. A. (2005). *Sustainable energy: Choosing among options*, MIT Press, Cambridge, MA.

Tsai, W.-T. (2005). "Current status and development policies on renewable energy technology research in Taiwan." *Renew. Sustain. Energ. Rev.*, 9(3), 237–253.

Upret, B. R., and van der Horst, D. (2004). "National renewable energy policy and local opposition in the UK: The failed development of a biomass electricity plant." *Biomass Bioenergy*, 26(1), 61–69.

World Energy Assessment (WEA). (2004). "World energy assessment." ⟨http://www.undp.org/energy/activities/wea/index.html⟩ (Apr. 2009).

Weidou, N., and Johansson, T. B. (2004). "Energy for sustainable development in China." *Energy Policy*, 32(10), 1225–1229.

Zerta, M., Schmidt, P. R., Stiller, C., and Landinger, H. (2008). "Alternative World Energy Outlook (AWEO) and the role of hydrogen in a changing energy landscape." *Int. J. Hydrogen Energy*, 33(12), 3021–3025.

J. Energy Eng., 2011, 137(4): 169-176