



### AGEDI | THE ABU DHABI GLOBAL ENVIRONMENTAL DATA INITIATIVE CLIMATE CHANGE PROGRAMME



Full Technical Report



an initiative of



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# About this Final Technical Report

In October 2013, the Abu Dhabi Global Environmental Data Initiative (AGEDI) launched the "Local, National, and Regional Climate Change (LNRCC) Programme to build upon, expand, and deepen understanding of vulnerability to the impacts of climate change as well as to identify practical adaptive responses at local (Abu Dhabi), national (UAE), and regional (Arabian Peninsula) levels. The design of the Programme was stakeholder-driven, incorporating the perspectives of over 100 local, national, and regional stakeholders in shaping 12 research sub-projects across 5 strategic themes.<sup>1</sup> The "National Water-Energy Nexus & Climate Change" sub-project within this Programme aims to assess the vulnerability of the UAE's water resources relative to long-term climatic changes in the context of its interactions with energy use and socio-economic conditions.

The purpose of this "Final Technical Report" is to offer a comprehensive discussion of what has been learned in carrying out the research activities involved in the study. In short, this report seeks to provide the reader with a comprehensive overview of the results of the assessment, supported by a discussion of the input data, methodology, modelling tools and other issues that can support future research and policymaking regarding water and energy planning in the UAE under climate change.

<sup>&</sup>lt;sup>1</sup> For more information on the LNRCC programme, please contact Marco Vinaccia (Inrclimatechange@ead.ae).





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# List of Acronyms

AGEDI	Abu Dhabi Global Environmental Data Initiative
BAU	Business-As-Usual
BCM	Billion Cubic Meters
CCRG	Climate Change Research Group
CO2	Carbon Dioxide
DSS	Decision Support System
EAD	Environment Agency - Abu Dhabi
EU	European Union
FAO	Food and Agricultural Organization of the United Nations
GCC	Gulf Cooperation Council
GCM	Global Climate Model
GW	Groundwater
GWh	Gigawatt-hour (billion watt-hours)
IPCC	Intergovernmental Panel on Climate Change
LEAP	Long-Range Energy Alternatives Planning
LEDS	Low Emission Development Strategies
LNRCCP	Local, National, Regional Climate Change Programme
m3	Cubic Meters
MED	Multi Effect Distillation
MGD	Million Gallons per Day
Mm3	Million cubic meters
MODFLOW	MODular Three-Dimensional Finite-Difference Groundwater FLOW model
MSF	Multi Stage Flash
MWh	Megawatt-hour (million watt-hours)
NCAR	National Center for Atmospheric Research
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RO	Reverse Osmosis
SEI-US	Stockholm Environment Institute – US Center
UAE	United Arab Emirates
UN-ESCWA	United National Economic and Social Commission for Western Asia
US	United States
WEAP	Water Evaluation and Planning
WWTP	Wastewater Treatment Plant
Yr	Year





## **Executive summary**

The "Water-Energy Nexus" is a concept that recognizes the many inter-connections between water and energy and seeks to account for these in planning and policymaking. Until recently, energy and water have been viewed as separate planning challenges. Any interactions between energy and water have typically been considered on a case-by-case basis. However, water is used in all phases of the fuel cycle, from extraction of energy resources like natural gas and oil, to energy production and electricity generation. Energy is required to extract, convey, purify, and deliver water to various types of end users in the economy. It is also used to treat municipal and industrial wastewater. Changing demographics, large-scale development initiatives and increased reliance on desalination have recently drawn attention to the connections between water and energy use, and the fuels and infrastructure used in their generation.

Using a water-energy nexus approach is a particularly relevant planning framework for the UAE. This is because the UAE relies on desalinated water to account for an increasing share of water supply. The energy inputs for desalination are order of magnitude greater than the energy required for either groundwater pumping or transmitting water from surface rivers or reservoirs. Hence, water and energy are linked to a much greater degree in the UAE than in other countries where the climatic context reflects more annual rainfall and water resources are more plentiful. In the future, individual municipalities are expected to increase their desalination capacity to meet the demands of growing population and economic development, suggesting that reliance on desalination is as much of an energy challenge as it is a water challenge.

The overall goal of the sub-project was to better understand the water-energy nexus challenge in the UAE in the face of climate change and socioeconomic development. The major research questions underlying the methodological approach were twofold. First, what would be the future benefits - as measured in water savings, energy savings, greenhouse gas emission reductions – associated with various potential development scenarios that aim to promote efficiency and conserve natural resources under climate change? Second, what would be the costs associated with shifting to such scenarios and away the current baseline development trajectories?

To conduct an analysis of the UAE's water-energy nexus under climate change, an analytical framework was applied capable of accounting for water, energy and climate interactions in an integrated way. On the water side, the Water Evaluation And Planning (WEAP) system was used; on the energy side, the Long Range Energy Alternatives and Planning (LEAP) system was used. WEAP and LEAP are integrated modeling tools that can track water and energy resources associated with extraction, production, and consumption, throughout the economy, including seawater desalination, groundwater pumping, and the transmission of water. The models were validated against historical conditions and have been coupled (i.e.,





outputs of one model are used as the inputs to the other) to enable an analysis of the interplay between water management and energy management policies under changing future conditions. A planning period of 2015 through 2060 was considered in the analysis.

The validated water-energy system coupled model was used to analyze the impact of heuristic policy scenarios intended to promote resilience of water and energy systems in the UAE in the face of climate change. The scenario framework consisted of five (5) scenarios. Two scenarios focused on Business-as-Usual Scenario; one scenario with climate change; the other without climate change. These scenarios simply extend past energy/water use patterns into the future. The remaining three policy scenarios focused on alternative development paths. One policy scenario focused on improving efficiency in resource use "High Efficiency &

Table ES-1: Policy scenarios analyzed						
Sector	Energy Efficiency & Conservation Scenario	Natural Resource Protection Scenario				
	<ol> <li>Indoor water use efficiency and conservation programme</li> </ol>	1. Fossil groundwater phase-out				
Water policies	2. Introduction of outdoor garden and amenity caps	2. Increased use of treated sewage effluent				
	3. Improved irrigation efficiency	3. Sustainable desalination				
	4. Water loss reduction programme					
Electricity	<ol> <li>Demand side electric efficiency and conservation programme</li> </ol>	4. Carbon dioxide cap				
policies	6. Peak load management of space cooling load	<ol> <li>Renewable portfolio standard</li> <li>Clean coal capacity cap</li> </ol>				

Conservation"; another focused on preserving natural resources such as groundwater and fossil fuels ("Natural Resource Protection"); the third focused on the integration of these scenarios to capture synergies. A list of the policies analyzed within the High Efficiency & Conservation scenario is provided on the left side of Table ES-1, with the policies analyzed within the Natural Resource Protection shown on the right side of the Table.

**A summary of the results is presented in Table ES-2.** This Table synthesizes the essential findings of the study. Brief descriptions of the key outcomes are provided in the bullets that follow:

- In a future in which past policies continue without any additional efforts to improve the efficiency of water/energy use and introduce renewable energy, climatic changes would lead to a total increase of CO2e emissions of about 138 million tonnes and an additional 5 billion cubic meters of water consumption.
- Introducing a set of targeted efficiency and conservation measures across the water and energy sectors in the UAE would cumulatively avoid CO2e emissions of about 283 million tonnes and a cumulative reduction of about 28 billion cubic meters of water consumption. There would also be net economic benefits to the UAE from this investment, relative to the reduction of greenhouse gas emissions; each tonne of CO2e avoided would be achieved while *saving* \$10.2.





- Introducing a set of targeted measures to protect groundwater resources for future generations and limiting the use of fossil energy resources (oil and natural gas) would cumulatively avoid CO2e emissions of about 933 million tonnes and a cumulative reduction of about 2,100 TWh is fossil fuel consumption. These reductions would be achieved at a modest cost of about \$13.2 per tonne of CO2e avoided.
- Combining targeted efficiency/conservation and natural resource protection measures across the water and energy sectors in the UAE would cumulatively avoid CO2e emissions of about 845 million tonnes and leads to reduction of about 28 billion cubic meters of water consumption and about 2500 TWh is fossil fuel consumption, respectively. These reductions would be achieved at a low cost of about \$13.2 per tonne of CO2e avoided.

The results of the study confirm that green growth objectives that will increase the resilience of the water-energy nexus in the UAE under climate change can be achieved cost-effectively. Some key implications for green growth in the UAE include the following:

- Assessing regional green growth scenarios in the context of climate requires a broader analytical framework which the W-E Nexus approach provides
- Pursuing an economic diversification agenda (as has been prominently reported recently by some countries in the region) employing a green growth framework poses numerous W-E Nexus modeling challenges, but this analysis has shown that diversification of the energy portfolio will be necessary to achieve environmental targets, such as GHG stabilization or even reduction.
- Quantitative, data intensive models can be used to meaningfully explore the kind of necessary adaptation that would be needed to achieve green growth objectives such as GHG emission targets and the costs associated of these measures.





			Cumulative benefits (2015-2060)				Avoided CO2e
Impact	Alternative Scenario	Starting Scenario	Water savings (BCM)	Fossil fuel savings (GWh)	CO2e reductions (million tonnes)	Total Incremental cost (billion 2015\$)	emissions from policies (\$ per tonne
From climate change, only	BAU-RCP8.5	BAU	-5	-470	-138	4	NA
From introduction of improved efficiency & conservation measures	High Efficiency & Conservation	BAU- RCP8.5	28	1600	283	-3	-\$10.2
From introduction of renewable energy and reductions in groundwater withdrawals	Natural Resource Protection	BAU- RCP8.5	0	4200	933	12	\$13.2
From introduction of all sustainable development measures	Integrated Policy	BAU- RCP8.5	28	4400	845	3	\$3.4

#### Table ES-2: Costs and benefits associated with the implementation of the policy scenarios





# 1. Introduction

In the UAE, water resource management has been recognized as a serious emerging challenge to long-term sustainable development. At the national level, domestic, agricultural, and industrial water consumption have increased at annual rates roughly consistent with the population growth rate, suggesting that little conservation or efficiency improvement is taking place. At the emirate level, these growth rates vary from one Emirate to another due to differences in economic development, size of each Emirate and population growth rates. Nevertheless, it has been increasingly recognized that improvement of water-resource management across all the emirates is urgently needed to achieve water conservation, maintenance of better quality water, and restoration of deteriorating aquifer systems (Rizk and Alsharhan, 2003). High efficiency irrigation technologies, groundwater-recharge dams, salt-tolerant crops, increased public awareness, and strengthen institutional capacity have been cited as urgent national priorities to help ensure that water demand growth rates decline in the future.

**Desalinated water accounts for an increasing share of water supply.** In the UAE, large desalination plants are combined with power plants for electricity generation to meet on-site requirements and to satisfy national electricity needs. All three major types of desalination technology currently used for desalination – Reverse Osmosis (RO), Multi-Stage Flash (MSF), and Multi-Effect Distillation (MED) – consume significant levels of electricity and lead to corresponding levels of greenhouse gas emissions. Currently, there are 35 desalination plants in the UAE with a total capacity of 700 million m<sup>3</sup>/year. Individual municipalities, with the aid of the Federal Government, are expected to increase their desalination capacity soon for some urban centers, mainly in Abu Dhabi, Dubai and Sharjah, to meet the demands of growing population and economic development. This suggests that reliance on desalination is as much of an energy challenge as it is a water challenge.

The challenge of effective water and energy resource management at the national level, already difficult, will be exacerbated by climate change. The Emirates lie within an arid-semiarid zone with high climatic variability typical of arid regions, and it is expected that climate change will directly increase this variability. Rainfall is erratic and irregular in time and space and clearly insufficient to supply the needs of agriculture, industrial development, and a growing population. The average annual rainfall in the UAE varies from less than 60 mm around the Liwa area in the interior of southern desert to about 160 mm in the mountainous areas of northern and eastern parts of the country where surface runoff is captured in small dams to support groundwater recharge (Murad et al., 2007). Climate change is likely to alter patterns and cycles of water supply, with profound implications for water resource management.

To capture the interactions between water, energy, and climate change, a "water-energy nexus" framework has been applied. The "Water-Energy Nexus" (W-E nexus) is a framework that views water as part of an integrated water and energy system, rather than as an





independent resource. Water is used in all phases of the fuel cycle, from extraction of energy resources like natural gas and oil, to energy production and electricity generation. Energy is required to extract, convey, purify, and deliver water to various types of end users in the economy. It is also used to treat municipal and industrial wastewater. Until recently, energy and water have been viewed as separate planning challenges. Any interactions between energy and water have typically been considered on a case-by-case basis. However, changing demographics, large-scale development initiatives and increased reliance on desalination have recently motivated attention on the connections between water and energy use, and the fuels and infrastructure used in their generation.

In the UAE, several trends suggest the importance of addressing the W-E Nexus in an integrated and proactive way. First, climate change has already begun to affect rainfall and temperature patterns across the region, and while the country is characterized as a typically warm, arid region, future warming and changing rainfall, wind, humidity, and cloud cover could change patterns of water and energy use and production (Xue and Elthair, 2014). These changes are expected to intensify in the coming years, as the outputs of LNRCCP sub-project #1 (Regional Atmospheric Modeling) have confirmed.<sup>2</sup> Second, socioeconomic growth trends indicate that the population in the country's arid environment is likely to continue to increase and will require additional desalination capacity to satisfy increasing water demands. This will further affect the management of electricity and water systems. Finally, a W-E Nexus strategic approach could help to inform the technology research, development, demonstration, and deployment currently underway at several centers of excellence in the country.

The rest of this Final Technical report is organized around several core sections that build upon the context described above. The report also builds on the methodological discussion addressed in the Preliminary Findings and the draft outputs presented in Draft Visualizations and Draft Technical reports previously developed and distributed to partners and stakeholders for feedback. For additional details, the reader is kindly referred to those documents. The next section starts with a review of keys background issues, followed by a discussion of technical results regarding data inputs and model structure for the water system model (Section 3) and the energy system model (Section 4). Section 5 describes the policy scenario framework used to analyze the impact of alternative development strategies. The policy scenario framework is presented and discussed in Section 5, followed by a discussion of results of the analysis of the two Business-as-Usual Scenarios (Section 6) and the three policy scenario (Section 7). Conclusions and recommendation for further research are offered in Section 8.

<sup>&</sup>lt;sup>2</sup> For location-specific information about climate change in the UAE, please see the Regional Atmospheric Modeling Inspector available at <u>www.ccr-group.org/atmospheric</u>





# 2. Analytical framework

The overall goal of the sub-project is to better understand the water-energy nexus challenge in the UAE in the face of climate change and socioeconomic development. The major research questions underlying the methodological approach were twofold. First, what would be the future benefits - as measured in water savings, energy savings, and greenhouse gas emission reductions – associated with various scenarios that aim to promote efficiency and conserve natural resources under climate change? Second, what would be the costs associated with shifting to such scenarios and away the current baseline development trajectories?

Addressing the goal and research questions required an analytical framework capable of accounting for water, energy and climate interactions in an integrated way. On the water side, the Water Evaluation And Planning (WEAP)<sup>3</sup> system was used; on the energy side, the Long Range Energy Alternatives and Planning (LEAP) system was used.<sup>4</sup> WEAP and LEAP are integrated modeling tools that can track water and energy resources associated with extraction, production, and consumption, throughout the UAE's economy, including seawater desalination, groundwater pumping, and the transmission of water. Moreover, the models have been coupled (i.e., outputs of one model are used as the inputs to the other) to enable an analysis of the interplay between water management and energy management policies under changing future conditions. A planning period of 2010 through 2060 was considered in the analysis.

# 2.1. Regional atmospheric modeling

As part of a separate LNRCCP sub-project<sup>5</sup> regional atmospheric modeling for the Arabian Peninsula region was undertaken under conditions of climate change. Some of the outputs of this research were incorporated into the analytical framework to capture the impact of climate change on the supply and demand for water and energy resources. Two greenhouse emission scenarios were modeled. One scenario assumed the IPCC's Representative Concentration Pathway 8.5 (RCP8.5), analogous to business-as-usual emissions; the other assumed RCP4.5, analogous to global greenhouse gas mitigation activities significantly limit the increase in greenhouse gas concentrations in the atmosphere. Average temperature impacts in the region from climate change are illustrated in Figure 2-1 for RCP8.5.



<sup>&</sup>lt;sup>3</sup> Information about the WEAP model can be found at <a href="http://www.weap21.org">http://www.weap21.org</a>

<sup>&</sup>lt;sup>4</sup> Information about the LEAP model can be found at

http://www.energycommunity.org/default.asp?action=47

<sup>&</sup>lt;sup>5</sup> Sub-project #1; Yates, et al., 2015. "Regional Atmospheric Modeling: Final Technical Report from AGEDI's Local, National, and Regional Climate Change Programme"



The results of regional atmospheric modeling were incorporated into the analytical framework of the national waterenergy nexus study. This was important an consideration as an already hot region will become even hotter. leading additional to energy for end uses like conditioning air and additional water for end uses like irrigation to account for higher evaporation rates. An algorithm was developed for, and incorporated

Figure 2-1: Future temperature around the UAE for the historical period (left maps), 2060-2079 under RCP 8.5 (center maps), and percent difference (right maps), averaged over winter (top) and summer (bottom) months.



into, the modelling framework that addresses the projected seasonal change in average temperatures. Other modelled climatic variables such as rainfall, humidity, wind, and extreme events were not incorporated in the analytical framework due to their negligible impact on water and energy.

## 2.2. Regional ocean modeling

As part of a separate LNRCCP sub-project<sup>6</sup> regional ocean modeling in the Arabian Gulf was undertaken under conditions of climate change and increased desalination activity. The Arabian Gulf has historically been one of the most stressed marine environments on earth. It is a semi-enclosed, highly saline sea between latitudes 24°N and 30°N surrounded by a hyperarid environment and limited freshwater inflow via the Tigris, Euphrates, and Karun rivers at the delta of the Shatt al Arab in Iraq. Under climate change alone, the Arabian Gulf will become even more highly stressed, with significant increases in temperature throughout coupled with zones of large salinity increases (Edson, *et. al.*, 2015).

The results of LNRCCP sub-project #10 regarding average salinity impacts from climate change and desalination were incorporated into the analytical framework of the national water-energy nexus study. This was considered necessary due to the relationship between feedstock salinity and the energy required for desalination (i.e., the higher the salinity, the

<sup>&</sup>lt;sup>6</sup> i.e., Sub-project #10 of the LNRCCP focused on desalination and climate change in the Arabian Gulf. It was led by Ze Edson from the Oceanography Institute at the University of Sao Paulo.





more energy is needed to remove the salt). Average salinity impacts on the Arabian Gulf from climate change and desalination are illustrated in Figure 2-2. In shallow areas throughout the Southern Gulf, desalination activity represents a significant impact on average salinity. Depending on the brine discharge rate scenario, average salinity is projected to rise between 1.1 and 2.6 psu in the Southern Gulf. An algorithm was developed for, and incorporated into, the energy system model that addresses this change in Gulf salinity. The other modelled

ocean variable - sea surface temperature – was not incorporated into the analytical framework due to its comparatively negligible impact on the energy needed for desalination.

## 2.3. Water system model

WEAP software was used to build a water system model for the UAE. WEAP provides an sector-specific integrated approach to water resources planning by linking quantification of water availability and water allocation routines, hydrologic



processes, system operations and end-use quantifications within a single analytical platform (Yates et al. 2005). The modeling software incorporates the multiple dimensions critical to water resources management, including surface water and ground water hydrology, water quality, water demands, population growth, reuse, system losses and consumption. WEAP represents water supply and demand centers in a spatial way because the focus is the flow of water from abstraction sites to consumption sites.

The UAE water system model was built for the whole of the country, broken into five general regions (western region, coastal Abu Dhabi, interior Abu Dhabi, Dubai-Sharjah, and Fujairah). The model captures system characteristics like agricultural areas, populations, water demand for human consumption and irrigated amenity areas, wastewater treatment plant capacities, desalinated water production capacities, irrigation demands, and groundwater availability/recharge. The model was developed using a monthly time step to examine water quantity availability in the UAE to balance supplies and demands in the country. An illustrative, schematic view of the model is shown in Figure 2-3. The schematic demonstrates the aggregated nature of the national representation of water supply (green lines) and demand (red dots) and their linkages. A final version of the UAE water system model, after receiving and incorporating all stakeholder feedback, will be available for download at www.ccr-group.org/nat-water-energy-inspector-full in the coming days.







In the UAE, groundwater mainly supplies irrigated agriculture and to a lesser extent, amenity plantings. Most of the groundwater comes from fossil water sources deposited on geological time scales with negligible recharge on human timescales. The boundary of the WEAP model encompass all the UAE and the shared aquifer between the Al Ain Region

and Oman, where there is some renewable fresh groundwater. Abu Dhabi, as the largest emirate by area, is divided into three sections: Western Region, Abu Dhabi, and Al Ain Region. These three regions are distinct except for sharing desalinated water sources.

**Finally, the representation of water supply and demand characteristics within the water system model was as "granular" as possible.**<sup>7</sup> While there was ample local data to construct a modestly granular water system model, there was not enough detailed data to develop a highly granular water system model. This poses implications for the level of detail that can be analyzed during the policy scenario analysis. That is, the water system model can analyze high-level (i.e., sectoral level) policy scenarios and offer first-order indications of the costs and benefits of a transition to alternative development pathways. However, it is not capable of analyzing the interactions between water supply/demand policies at lower levels of disaggregation (e.g., level of enterprises, households, precincts). Additional details for the water system model are discussed in Section 3.

## 2.4. Energy system model

**LEAP software was used to build an energy system model for the UAE.** LEAP provides a sector-specific decision support system (DSS) within an integrated modeling framework that can be used to track energy consumption, production and resource extraction in different sectors of the economy. This can include the energy associated with providing water, such as pumping, desalination, treating, delivering, etc. The LEAP DSS can structure complex energy inputs for analysis in a transparent and intuitive way. It offers a wide range of flexibility, to produce specific results and enable tailored policy examinations.



<sup>&</sup>lt;sup>7</sup> "Granularity" refers to the level of physical detail that has been reflected in the model. A highly granular water system model typically incorporates highly disaggregated supply sources and detailed water consumption breakdowns, typical of bottom-up models.



Unlike WEAP, LEAP software does not represent energy supply and demand centers in a spatial way because the focus is on energy-related processes and activities rather than the flow of electrons. At the supply level, this corresponds to transforming energy from one form into another (e.g., natural gas to electricity; crude oil to gasoline). At the demand level, this corresponds to accounting for energy consumed by sector (e.g., households), activity (e.g., space cooling), and technology (e.g., efficient air conditioners).

The UAE energy system model was built for the whole of the country, focusing on all energy supply sources and all energy demand sectors. Specifically, the power/water supply, residential, services, industry, and transport sectors were considered, with a special emphasis on energy uses associated with water resource use. The model represents UAE electric generating and desalination stations together with their associated fuel and energy transformation methods used to create electricity and freshwater. The model was developed using a monthly time step to examine energy supply and demand in the UAE. A small excerpt of the model structure is illustrated in Figure 2-4 showing the desalination technologies

considered in the analysis (e.g, reverse osmosis for municipal and industrial applications or "RO\_MandI"). A final version of the UAE energy system model, after receiving and incorporating all stakeholder feedback, will eventually be available for download at <u>www.ccr-</u> <u>group.org/nat-water-energy-inspector-full</u>.

The model explicitly accounts for how electricity is produced (i.e. oil, natural gas, nuclear, solar, wind, etc.) and how it is used (i.e. people and their use of electricity for cooling, commercial and industrial activity). The energy system model is particularly focused on water supply (i.e., human consumption, irrigation, amenity watering of green spaces, and water treatment) and electricity use [i.e., groundwater abstraction from the hundreds of wells is overwhelmingly through electric (as opposed to diesel



pumps); desalination is dominated by electricity-intensive Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED) technologies]. There is considerably less detail is the energy system model for non-water and non-electric applications (e.g., transport sector). Finally, the model tracks carbon dioxide equivalent emissions associated with the combustion of fossil fuels for meeting water/energy demand, thereby enabling direct comparisons of potential development scenarios.





**Finally, the representation of energy supply and demand characteristics within the energy system model was also as "granular" as possible.**<sup>8</sup> There was enough data to construct a lowgranularity energy system model (i.e., basically a top-down model). However, there was not enough detailed data to develop even a modestly granular energy system model. This poses implications for the level of detail at which the policy scenarios can be analyzed. That is, the energy system model can analyze high-level (i.e., sectoral level) policy scenarios and offer first-order indications of the costs and benefits of a transition to alternative energy development pathways. However, it is not capable of analyzing the interactions between energy supply/demand policies at lower levels of disaggregation (e.g., technologies, transmission networks, dispatch considerations). Additional details for the energy system model are discussed in Section 4.

## 2.5. Coupled water-energy system model

The development of a coupled water-energy system model for the UAE is the final component of the analytical approach. This task involved the coupling of the calibrated water and energy systems models via a software link, which was exclusively a one-way pass of energy used in water production, as determined within the water system model, which was then added to the energy demand component of the energy system model in LEAP. Since the volume of water used in energy production is negligible for the UAE, no information is passed from the energy system model back to the water system model, hence only the one-way pass of outputs from the water system model to the energy system model to the energy needed. There were four (4) major steps involved in analyzing the water-energy nexus under climate change as illustrated in Figure 2-5 and briefly explained in the bullets that follow.

• Step 1: The use of WEAP to develop the water system model required a comprehensive estimate of the water supply/demand characteristics of the UAE and all energy associated with that water supply/demand excluding desalinization. Once the baseline data were established, such as the regional population, the per-capita indoor water demand, the extent of outdoor irrigation for amenity, garden, and agricultural uses, the water supply sources including fresh and brackish groundwater, desalinization and technologies used, etc., the electric energy demand for the water supply was passed to the energy system model (LEAP) via a built-in software link within WEAP.



<sup>&</sup>lt;sup>8</sup> In reference to energy system modeling "granularity" refers to the level of physical, process, and technology detail that has been reflected in the model. A highly granular energy system model typically represents a highly disaggregated power system at the plant/unit/stack level; unit dispatch rules/protocols, together a detailed breakdown of end use by sector, customer class, and technology, all of which is typical of bottom-up models.





- Step 2: The use of LEAP to develop the energy system model accounted for the electric energy associated with water treatment, processing, and distribution, as well as energy associated with all sectors of the economy (e.g., electricity for air conditioning in the residential and commercial sectors; gasoline for cars in the transport sector; natural gas and liquefied petroleum gas, oil in the industry sector, etc.). Energy demand for desalination was accounted for in the energy model based on the volume of water needed by each technology type (e.g MSF and MED use heat and electricity; RO just electricity).
- Step 3: The separate water and energy system model outputs represent the "waterenergy nexus". It is important to note that there is no "coupled water-energy system model" per se, but rather a "coupled water-energy system modeling framework". Modeling the water-energy nexus consists of running the WEAP and LEAP models sequentially, as opposed to a single integrated model that seeks to balance water-energy supply/demand simultaneously.
- *Step 4:* Estimates of the costs and benefits associated with each policy scenario were developed by saving the outputs of the water-energy nexus into a spreadsheet format. Offline analyses were then conducted in Excel to compute the incremental costs and benefits for each Policy scenario.

# 3. Water system model

This section provides an overview of the data sources, key underlying assumptions, structure, and validation of the water system model. The water system model uses a host of data assumptions that influence water supply and demand, including costs associated with water production and transmission activities. These data assumptions have been carefully assessed and incorporated into a working version of the water system model which adequately simulates historical conditions. After a review and vetting process by stakeholders





of the current version of the model, a final version will be developed that incorporates all feedback.

## 3.1. Data input sources

The water system model built in WEAP is fundamentally data-driven. Hence, there is a large amount of data that was needed to build the model. The data collection effort has benefitted from collaboration across relevant UAE institutions which have granted access to necessary data. As of this writing, this process has been satisfactorily completed. Annex A provides a detailed accounting of all the national and international datasets that were accessed in building the water system model, together with a detailed accounting of key variables and their assumed values that were incorporated into the model.

### 3.2. Model structure

The structure of the water system model accounts for the locations of all water supply sources and the magnitude of current and future demand for water. The spatial coverage encompasses all the UAE and the shared aquifer between the Al Ain Region and Oman, where there is some renewable fresh groundwater. The nomenclature of water system components, as illustrated in the figures that follow, is outlined below:

- Green squares represent national aquifers;
- Red dots <a><br/>
  erepresent indoor water consumption per capita;</a>
- Maroon dots epresent wastewater treatment facilities;
- Green dots represent catchment water demands associated with different types of land covers that require irrigation;
- Green diamonds 🔷 represent desalination plants;
- Green lines ---- represent water transmission flow
- Red lines represent water return flow

**Abu Dhabi, as the largest emirate by area, is divided into three regions.** This includes the Western Region, Abu Dhabi, and the Al Ain Region. These three regions are distinct except for sharing desalinated water sources. Figure 3-1a shows the model structure for the Western Region, Abu Dhabi, and Al Ain Region regions and the various corresponding elements representing water supply and demand.

**The rest of the UAE is represented by 3 additional regions.** This includes Dubai, the Eastern Region and the Fujairah Region, with shared groundwater access between these three demand regions (see Figure 3-1b). Dubai and the Eastern Region emirates share wastewater treatment capacity and desalinated water sources, but have distinct urban indoor, outdoor, amenity and agricultural demand sites. The Fujairah Region has its own wastewater





treatment capacity, desalinated water and urban indoor, outdoor, amenity and agricultural demand sites.

# 3.3. Major modeling assumptions

There several were differing types of modeling assumptions that were incorporated into the water system model. Background for each of the major assumptions is provided in the subsections below regarding water supply, water demand, and wastewater treatment.

# 3.3.1. Groundwater supply

The Western and Al Ain regions of Abu Dhabi emirate are divided into five (5) aquifers for modeling purposes. These Figure 3-1 Schematic representation of the UAE water system model

a) Western Region, Abu Dhabi, and Al Ain Region



b) Dubai, Eastern and Fujairah Regions



are shown in Figure 3-1a as the "West Fresh" aquifer, denoting fresh groundwater supply that is fossil (i.e., non-renewable) in nature; the "West Brackish" aquifer, denoting saline groundwater supply that is fossil in nature; the "Abu Dhabi Brackish" aquifer, denoting brackish groundwater supply that is fossil in nature; the "East Fresh" aquifer, denoting fresh groundwater supply that is renewable in nature; and the "East Brackish" aquifer, denoting brackish groundwater supply that is renewable in nature. The supply of groundwater from these aquifers have been subdivided in this way because in the UAE, salt tolerant cops can use brackish water that would not be suitable for human consumption. While there are saline groundwater sources throughout the Western and Al Ain regions of Abu Dhabi emirate, that have been excluded them as a source of supply in the analysis. The three eastern regions of the UAE contain a single aquifer for modeling purposes. This is shown in Figure 3-1b as the "EasternReg\_GW" aquifer, denoting brackish groundwater supply that is fossil (i.e., non-





renewable) in nature. The representation of this entire region with a single groundwater aquifer was deemed adequate for modeling purposes because most of the water consumed is from desalination.

The presence of renewable, fresh groundwater is limited in the UAE. As noted above, a single catchment object (i.e., the "East Fresh" aquifer), is used to represent the eastern region of the UAE that includes the region bordered by Oman and which encompasses about 6,000 km<sup>2</sup> of the Al Hajar Mountain range in Oman. This is the one region where natural groundwater recharge is generated through rainfall via near-surface alluvial aquifers that extend westward from near the Oman Mountains into the eastern deserts of the UAE. These fresh groundwater resources are found in the eastern area of the Abu Dhabi Emirate, the region near and around Al Ain, which was once a much more active fluvial system. In many locations, aerial photographs reveal evidence of strong outflow through the wadi gaps onto the western plains. During this period, the region was climatically 'wet' with several perennially flowing surface wadis.

The contributions from this paleo rainfall and paleo wadi flow likely played a major role in creating secondary permeability, flushing out soluble matter from the soil matrix. This allows for a relative increase in groundwater storage in certain locations west of the Al Hajar Mountains (Source to be added.). In this arid climate, annual potential evapotranspiration is significantly greater than rainfall, and most rain that infiltrates is evaporated or transpired from the shallow subsurface. However, during infrequent but more intense storm events, infiltration rates can exceed evaporation rates so that some recharge to the aquifer occurs in the piedmont plain to the west of the mountains (Ostercamp et al. 1995; Silva 1999).



Figure 3-2: Wadis of eastern Abu Dhabi Emirate, near Al Ain, where groundwater recharge occurs on a limited basis





**Figure 3-2 shows the regional wadis and a time series of rainfall over the period 2020 to 2060.** The historical annual rainfall in this region averages only about 125 mm per year, while the annual potential evapotranspiration is nearly 3,000 mm. Our WEAP simulations suggest annual recharge from these wadi aquifers of about 58 MM3 per year during the historic period, which is a small percentage of overall water demand for the country.

**Groundwater was assumed to have different pumping lifts or depth to the groundwater.** This variable has been used to evaluate the sustainability of the aquifers, and estimate when aquifers could be depleted. Fresh aquifers located inland such as the eastern alluvial aquifer near Al Ain are nearer the surface than the deeper brackish sources. For fresh aquifers, we have developed a linear interpolation function that defines the pump lift in function of initial storage volume and initial pump lift and the corresponding available volume in the aquifer in each time step. That is:

Meters Lift = f { Initial Storage and Pump Lift, and Available Groundwater Volume in corresponding time step }

**Figure 3-3 illustrates the approach implemented for the Upper Fresh West Aquifer.** We use this available groundwater and forecast estimate of future available groundwater volumes to make a quantitative determination, through scenario analysis, regarding the sustainability of the aquifers, and when aquifers could be depleted. The associated energy demand in KWH

per cubic meter of groundwater pumped and the monetary costs is also evaluated. Groundwater extraction to satisfy water demands is not subject to any physical constraints in the model, nor constraints in energy demands. Hence, inland groundwater systems have an estimated, exhaustible capacity, which can be mined to meet demand until exhausted.

# 3.3.2. Desalinated water supply



### The UAE is divided into

three (3) desalination zones for modeling purposes. One is in the Abu Dhabi emirate, shown as "WesternReg\_Desal" in the previously shown Figure 3-1a. The potable water produced at this node is assumed to meet demand through the Abu Dhabi emirate. Another desalination





zone is in the Dubai emirate, shown as "EasternReg\_Desal" in the previously shown Figure 3-1b. The potable water produced at this node is assumed to serve demand through the northern emirates. The remaining modeled desalination zone is in the Fujairah emirate, shown as "FujairahReg\_Desal" in the previously shown Figure 3-1b. The potable water produced at this node is assumed to serve demand through the northern emirates. The total number of desalination plants using seawater as a feedstock was assumed based on Edson, et al (2015).

It was assumed that a desalination plant typically uses three kilograms of seawater to produce one kilogram of fresh water, with the extracted salt dissolving back into the excess sea water in the form of highly saline brine. The brine is returned to the Arabian Gulf, where seawater can dilute it, but there is evidence for enhanced salinity along the coast due to these desalinization activities. In theory, about 1 kWh is required to produce one ton of fresh water from seawater, but in practical terms, a desalination system was assumed to require 7 to 18 kWh/m<sup>3</sup> depending on the technology and equipment used.

**Desalinization processes were modeled as being of two technology types: reverse osmosis (RO) and thermal desalination.** Osmosis is a natural phenomenon that occurs when two solutions with different salt concentrations are separated by a semi-permeable membrane. Normally, fresh water will migrate through the membrane from the lower concentration side to the higher concentration one. Reverse Osmosis upends this process by subjecting one side of the membrane to hydrostatic pressure greater than the osmotic pressure. This forces the water to move from high concentration to lower concentration, and enables desalination. The second method, thermal desalination or distillation, reproduces the natural cycle of rain within an evaporator.

There are two main types of seawater distillation processes: Multi Stage Flash (MSF) and Multiple Effect Distillation (MED). The latter has two alternate configurations: MED with thermal vapor compression (MED-TVC) and MED with mechanical vapor compression (MED-MVC). All desalination processes require large amount of energy. Most desalination capacity in the UAE uses Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED), while the less common Reverse Osmosis (RO) technology is currently growing in importance. For future capacity, it was assumed that desalination capacity is unconstrained. Additional capacity is endogenously added in the water system model consistent with growing water demand.

### 3.3.3. Water demand

**Municipal water demand (i.e., drinking water) estimates were developed for the 6 individual regions represented in the water system model.** These regions include 1) Abu Dhabi, 2) Al Ain, 3) the Western Region, 4) Dubai, 5) the Eastern Region, and 6) the Fujairah emirates. Municipal water demand was calculated as a function of population which was assumed to grow over time consistent with the central estimate from UNDESA (UNDESA, 2015) and a water use per capita value of 115 m<sup>3</sup>/year. Each demand site in the UAE assumes





that the indoor per-capita water demand is constant throughout the year and over the entire planning horizon in the absence of water efficiency and conservation measures.

**Catchment water demand (i.e., non-drinking water) estimates were developed for three individual catchment that were represented in the water system model.** Catchments represent water demands associated with different types of land covers that require irrigation. The three catchment types are shown in Figures 3-1a and 3-1b as having its own catchment element representing the area it occupies in the respective regions. "Outdoor water use" corresponds to irrigation for private outdoor household demand. "Amenity water use" corresponds to irrigation for public forests and amenity use (i.e., recreational or green areas such as public parks, green areas along road ways and freeways, turfs mainly representing golf courses, and trees in urban areas). "Agricultural water use" corresponds to land area used for crop cultivation (i.e., date palm plantations, fodder, agricultural vegetables crops, and other agricultural crops). An example of the catchment disaggregation by outdoor use category is illustrated in the enlarged section at left in Figure 3-4, with associated quantities shown on the right side of the Figure.

Figure 3-4: Example of the catchment disaggregation by outdoor use category, showing Amenity, Outdoor and Agriculture use objects.



### 3.3.4. Wastewater treatment

**The UAE is divided into five (5) wastewater treatment zones for modeling purposes.** These serve the six municipal water demand sites discussed in the previous subsection. Three are in the Abu Dhabi emirate and the other two are in the northern emirates (see previous Figure 3-1a and 3-1b). It was assumed that 50% of the treated waste water in the country is reused as a non-potable supply for outdoor irrigation. It was further assumed that of the total water supplied to the indoor demand sites, 15% is consumed and or lost from the system. The remaining 85% is returned to waste water treatment systems. Some of this water is treated in wastewater treatment plants which have been assumed to have daily treatment capacities





to treat wastewater coming from the different demand sites with a corresponding cost for this treatment. Any wastewater quantity above the treatment capacity threshold flows untreated into wadis in the model.

### 3.3.5. Water-related costs

Water-related costs are limited to the costs of electricity and process heat to deliver water to consuming sectors. That is, there is no inherent value ascribed to water in the modeling framework as it is considered a "free" natural resource with the only cost to consumers related to the energy needed to extract, desalinate, and deliver it. This energy is associated with groundwater pumping, wastewater treatment, wastewater reuse, improved water conservation/efficiency technologies, as well as the process heat needed for desalination using thermal technologies. Hence, all costs water supply and demand are accounted for in the energy system model (see Section 4.3.5).

### 3.4. Model calibration

**Calibrating the water system model consisted of several key steps, as illustrated in Figure 3-5.** First, as outlined in the previous section, the calibration process begins with a schematic representation of the water supply-demand system (i.e., "Study Definition" in Figure 3-5). This is intended to visually indicate all the system's physical determinant components: demand sites, wastewater treatment plants, groundwater access sites and links to transport the water between these areas. Secondly, once the components have been represented physically, they have been populated with some of the acquired local UAE data for the period 2010-2012 (i.e., "Current Accounts" in Figure 3-5) and structured with the remaining local UAE data to ensure that system constraints are adequately represented (i.e., "Historical UAE data" in Figure 3-5). Lastly, the water system model was compared to historical conditions to asses if it could reproduce the physical reality as closely as possible.



Figure 3-5 Observed and modeled estimates of water demand (left) and water supply right in MM3. \*The observed desalinization is estimated from electricity and water agency reports from Abu Dhabi (ADWEA), Dubai (DEWA), Sharjah (SEWA), and Fujairah (FEWA).





The results of the calibration indicate that the water system model adequately reproduces historical conditions for water supply and demand. Figure 3-6 shows the estimate of observed water use and water supply in the UAE for the period 2010 to 2012 and the corresponding modeled estimate. The total observed annual water demand for this period was about 3,900 MM3, with agricultural water use about 60% and municipal and industrial use about 40% of total demand. The water system model tends to overestimate Agricultural water use slightly (or 5.1% more) and underestimate municipal and industrial (M&I) water use (or 13.5% less). The M&I estimate includes both indoor and outdoor uses, where indoor water use is about 75% of total water use.

Regarding groundwater supply, about 2,200 MM3 of groundwater was abstracted annually to meet water demand during the 2010-2012 period, per local observed data. The water system model slightly overestimates groundwater supply at about 2,396 MM3 (or 7.6% more). Of this supply, 1700 MM3 or 70% were derived from brackish sources, with the remainder, or 800 MM3, from freshwater sources. The model estimates about 700 MM3 of these fresh groundwater sources are taken from the eastern aquifers around the Al Ain region, which is the only region in the UAE with renewable groundwater resources, with annual recharge estimates of between 50 MM3 to 100 MM3. Thus, our annual use rate estimate for these eastern fresh groundwater aquifers suggests that current abstraction rates exceed recharge rates between 10 and 20 times.

#### Regarding desalinated water supply, we estimate



**about 1,500 MM3 of seawater was produced during the 2010-2012 period, per local observed data.** The water system model estimates desalinated water use of about 1,100 MM3 (or 29.0% less) than the historically observed produced amount. A few notes on this difference. One, because water is co-produced with energy, it is known that water production often outpaces water use in the country (Dr. Mohammad Dawood, EAD communication). Second, the water system model estimates about 200 MM3 of reuse water. We assume that the reuse supply is primarily derived through the desalination process and so is additive in terms of the total water produced through desalinization. Hence, the model estimate of desalinated water is 1,300 MM3 (i.e., 1,100 + 200) which represents an underestimate of about 15% of total observed desalinated water production during the 2010-2012 period. While this seems like a large deviation, it was considered acceptable for modeling purposes, given that the modeled total of all supply sources (i.e., 3,695 MM3) compares well to the





observed total of all supply sources, i.e., 3,763 MM3), or about a 2% underestimate. Of the desalination water produced, it is assumed that 80% is through thermal distillation using either MSF or MED process, while 20% is produced through reverse osmosis during this period.

**Regarding treated wastewater effluent, the data sources accessed were not able to offer an observed estimate of reuse volume.** Alternatively, the FAO-Aquastat database was used for this estimate. This source suggests that about 35% of treated waste water is reused as a non-potable source for outdoor irrigation. This assumption was used in the model.

In conclusion, comparing the water system model to historical conditions shows that the model can reproduce the physical reality of water supply and demand adequately. For this reason, it was considered a valid modeling framework to use in the exploration of future development scenarios.

# 4. Energy system model

This section provides an overview of the data sources, key underlying assumptions, structure, and validation of the energy system model. The energy system model uses a host of data assumptions that influence energy supply and demand, including costs associated with electricity generation, transmission and distribution. These data assumptions have been carefully assessed and incorporated into a working version of the energy system model which adequately simulates historical conditions. After a review and vetting process by stakeholders of the current version of the model, a final version will be developed that incorporates all feedback.

### 4.1. Data input sources

Like its water counterpart, the energy system model built in LEAP is fundamentally datadriven. Hence, there is a large amount of data that was needed to build the model. The data collection effort has benefitted from collaboration across relevant UAE institutions which have granted access to necessary energy-related data. As of this writing, this process has been satisfactorily completed. Annex B provides a detailed accounting of all the national and international datasets that were accessed in building the water system model, together with a detailed accounting of key variables and their assumed values that were incorporated into the model.





## 4.2. Model structure

The structure of the energy system model is based on a model developed for the UAE during an LEAP training workshop at the UAE Ministry of Energy.<sup>9</sup> This energy system model was built using LEAP and relied on a detailed dataset from the International Energy Agency (IEA). During the current water-energy nexus sub-project, this starting point was further enhanced and built upon with local data sources provide by the Abu Dhabi Water and Electricity Company (ADWEC); the Abu Dhabi Water and Energy Authority (ADWEA); the Dubai Electrify and Water Authority (DEWA); the Sharjah Energy and Water Authority (SEWA); and the Environment Agency of Abu Dhabi (EAD). The energy system model is broad but comprehensive in terms of its representation of the energy sector of the UAE.

The structure of the energy system model accounts for all processes, sectors, resources, technologies, and policies implicated in the fuel cycle from resource extraction to end use. An excerpt of the model structure developed within LEAP is shown in Figure 4-1a (demand side) and 4-1b (supply side). The nomenclature for energy system components is outlined below:

- Sub-categories of energy demand and energy supply are denoted by a <sup>P</sup> symbol. Many of these subcategories are not shown so that the model structure can fit into one figure for illustration purposes
- Red wheels <sup>\$\$</sup> represent demand side technologies;
- Yellow folders <sup>(a)</sup> represent major repositories of demand and supply side data
- Green folders 🚞 indicate baseline databases for the demand and supply side (not shown).
- Yellow dots 🥮 represent supply side fuels.

On the energy demand side, ten (10) major energy demand sectors are included (see Figure 4-1a). Within each of these subsectors, the model accounts for the usage of various fuel such

<sup>&</sup>lt;sup>9</sup> The energy system model was built by Dr. Charlie Heaps, the lead developer of LEAP, in close collaboration with stakeholders participating in the workshop.





# Figure 4-1: Representation in LEAP of the UAE energy system model



as, LPG, coal, natural gas, and fuel oil, as well as electricity. Other energy demand sectors have a similar structure - the residential demand sector is a single user of two primary energy sources - electricity and liquefied petroleum gas (LPG); the services sector only uses electricity, while the transport sector includes two sub-sectors domestic aviation and roads, which makes use of kerosene jet fuel, diesel, gasoline, and electricity. The non-energy uses include natural gas, ethane, LPG, and other oil products.

On the energy supply side, the model includes transformation of primary fuels that include all possible energy sources (see Figure 4-1b). This includes fossil-based resources such as natural gas, crude oil, coal. It also includes renewable resources such as solar thermal, solar photovoltaics, wind and biomass. Finally, nuclear power is also included in the model to account for the Baraka power

station that is due online soon. These primary fuels are then used to generate secondary (useful) energy sources for each of the demand sectors, and include Kerosene, Heat, Gasoline, Kerosene, Electricity, Diesel, Charcoal, Fuel oil, and LPG. The structure of the energy system model gives special attention is given to the electricity sector. This is because it figures so prominently in the production of desalinated water. Generation and capacity expansion planning, including which fuel energy sources, are prioritized (e.g. Natural Gas, Oil, Nuclear, and/or Renewables).

## 4.3. Major modeling assumptions

There were several differing types of modeling assumptions that were incorporated into the water system model. Background for each of the major assumptions is provided in the subsections below regarding water supply, water demand, and wastewater treatment.





### 4.3.1. Reliability and quality of input data

As noted earlier, the energy system model relies primarily on energy statistics from the International Energy Agency. The IEA publishes comprehensive annual energy statistics of Non-OECD Countries, covering both energy supply and consumption. <sup>10</sup> These datasets include detailed UAE energy supply data regarding all energy sources – coal, gas, oil, electricity, renewables and waste that are available and/or consumed in the country. The IEA builds their datasets based on energy statistics maintained and provided by the Non-OECD countries. The most recent data have been used to populate the energy system model. These data were considered of sufficient quality for use in the study as the basis for historical energy



Figure 4-2: Total energy annual LEAP simulated energy flows given as a Sankey diagram in GWh.

supply in the UAE and for calibration of the energy system model. For 2013, the data are illustrated in the Sankey diagram shown in Figure 4-2. Some of the general trends of this diagram are that energy demand is dominated by industrial use, while desalinization energy use is about 9% of total use. All other energy use for water-related activities is less than 1% of total use. Fuel sources for power and water production are currently dominated by natural gas, with other sources (i.e., crude oil, heavy fuel oil, diesel oil) only making up about 1% of total electric generation.

<sup>&</sup>lt;sup>10</sup> IEA statistics are available here <u>http://www.iea.org/statistics/</u>





### 4.3.2. Representation of non-water activities

Consistent with the goal of developing a comprehensive energy system model for the UAE, water-related as well as non-water-related demand sectors are included together with water-related demand sectors. An example is the industrial sector includes three sub-sectors, "Chemical and Petrochemical"; "Non Metallic Minerals"; and "Other Industry". The energy system model tracks the energy use and corresponding emissions associated with industrial production and does not address water consumption. Another example is transport demand sector in which the model accounts for the increasing amounts of diesel and gasoline used in road transport and domestic aviation as the UAE's population and economy grow without any consideration of water consumption.

### 4.3.3. Representation of water activities

Water-related aspects are represented in greater detail in the energy system model than non-water related activities. Desalinization has been sub-divided those by source technology (RO, MSF, and MED) and the fuel needed for each of those technologies. MSF and MED are thermal process and need heat, but also need some electricity for operation of pumps and other needs, while RO is purely an electricity process. Normally, agricultural water supplies do not use desalinated water for irrigation, but since our approach to scenarios assumes a substation of service, when groundwater supplies are short to meet agricultural demand requirements, we substitute groundwater for desalinized water. We have assumed that the first source of desalinized water will be from RO plants, where water would be treated to a quality that is suitable to meet irrigation requirements at a treatment of 1/3 of a potable water supply standard. On the demand side, we have subdivided each of the sectors that use water to help identify which are the most energy intensive, water related activities (e.g. Municipal and Industrial, Amenity, or Agricultural uses).

### 4.3.4. Algorithms for calculating energy use, emissions and costs

**LEAP's built-in algorithms were used to calculate all energy, emissions and cost-benefit outputs.** This refers to the use of LEAP's expressions to specify time-varying data of the local electricity, energy, and transport systems to create a multi-variable energy simulation model, thus enabling an energy supply and demand analysis. For example, energy demand is derived from estimates of per-capita energy use for the residential sector (tonnes of oil equivalent per person, or TOE per person), while all other sectors use the estimate of historic total energy and the fractional contribution of the Gross Domestic Product (GDP) for that sector and its value added to the economy to estimate the energy activity for that sector (e.g. TOE per unit \$ output for industry, services).

**In parallel, two supplementary algorithms were developed for calculating energy demand.** First, an algorithm regarding electricity consumption under climate change was developed to represent the incremental air conditioning load expected in the future in response to the increase in average annual temperatures in the UAE projected by the regional atmospheric





modeling sub-project. Second, an algorithm regarding seawater salinity under the combination of climate change and increased desalination activity was developed to account for the incremental energy required to desalinate seawater, based on the increase in average surface/bottom salinity in the UAE's coastal region projected by the desalination and climate change sub-project. Both algorithms were embedded in LEAP's internal calculation sequences for the energy system model.

### 4.3.5. Energy-related Costs

Costing was carried out in the energy system model for activities to explore the impact of water-related efficient and conservation policies, as well as energy-related efficiency and renewable policies. Cost inputs were assembled on a levelised basis. Levelised costs are defined as a constant annual cost that is equivalent on a present value basis to the actual annual costs. That is, if one calculates the present value of levelised costs over a certain period, its value would be equal to the present value of the actual costs of the same period. Levelised cost estimates are included in Annex B. It is important to note that these are representative levelised costs used in energy planning in industrialized countries and do not account for market, regulatory, and other local factors in the UAE that could lead to higher or lower levelised cost estimates. Levelised costs are expressed in units of 2015 \$/MWh.

**Energy-related costs correspond only to those costs associated with the energy used for water-related activities.** On the water side, this includes the costs of electricity for desalination, groundwater pumping, wastewater treatment, water reuse transmission, as well as the costs of process heat for desalination using thermal technologies. On the energy side, this includes costing to account for the impact of new demand-side electricity efficiency programmes and new supply-side renewable energy investments. All other costs such as those associated with fuel use (e.g., transport sector gasoline/diesel use, industrial sector natural gas use) or electricity/fuel use in other sectors (e.g., agriculture and fishing sector) are ignored as they were beyond the scope of this water-energy nexus study.

**Finally, costing has been carried out from a "societal" perspective.** Societal costs are typically understood as the private costs of resources plus externalities. In this study externalities, including the intrinsic value of fossil fuels or the costs of fossil fuel depletion, have been assumed to be zero and subject to subsequent sensitivity analysis. Societal costs represent the costs to society rather than the costs from the perspective of any private entity.




## 4.4. Model calibration

Calibrating the energy system model consisted of several key steps, as illustrated in Figure 4-3. First, as outlined in the previous section, the calibration process begins with a process-



based representation of the energy supplydemand system (i.e., "Study Definition" in Figure 4-3). This is intended to explicitly identify all components that produce, deliver, and consume energy: demand sectors, power plants, industrial facilities, and the power transmission and distribution (T&D) network. Secondly, once the components have been represented, they were populated with some of the acquired IEA data and other local data for the base year of 2013 (i.e., "Current Accounts" in Figure 4-3) and structured with the IEA data to ensure that system characteristics are adequately represented in the historical period (i.e., "Historical UAE data (from IEA)" in Figure 4-3). Lastly, the energy system model was compared to historical conditions to asses if it could reproduce the physical reality as closely as possible.

### The results of the calibration indicate that the energy system model adequately reproduces historical conditions for total electricity demand.

Figure 4-4a shows the estimate of observed sectoral electricity demand in the UAE, where annual EIA data and WEAP-LEAP simulated estimates of energy consumption were averaged over the period 2010 to 2014. The two highest electricity-consuming sectors are the residential sector and the commercial/public sector which each account for about 35% of total electricity demand. The energy system model tends to underestimate the 'other' electric energy uses, which includes the electricity associated with water use (about 11% less) and tends to overestimate commercial/public electricity use (about 5% more). Overall, total observed electricity demand for the period 2010 to 2014 as reported by the EIA was about 87.2 TWh and compares well with the modeled estimate of 86.9 TWh (or 0.5% less). Electricity consumption on a per capita basis was around 9,000 kWh per capita per year in 2013. Figure 4-4b shows the natural gas energy balance based on EIA data and the LEAP simulated estimate that includes the production, net import, total domestic supply, and electric transformation averaged over the period 2010 to 2014. The imported natural gas estimate from LEAP is an exogenous estimate from EIA and based on historically observed amounts and suggests a discrepancy in data sources, as the historical estimate from LEAP is slightly less. The estimate of historic national production of natural gas is about 550 GWh or 48 Mtoe.





### Figure 4-4a: Observed and modeled electricity





Figure 4-4b: Estimated observed and modeled energy balance of natural gas from 2010 - 2013 (TWh)



The results of the calibration also indicate that the energy system model adequately reproduces historical conditions for electricity demand directly associated with water use. The category of "Other" electricity use includes the power associated with water production and use (i.e., groundwater pumping, treatment and the electricity transport) and for desalination. The total observed "other" electricity demand was about 13 TWh, with the energy system model overestimating this total at 13.5 TWh (or 3.7% more).

In conclusion, comparing the energy system model to historical conditions shows that the model can reproduce the physical reality of energy demand adequately. For this reason, it was considered a valid modeling framework to use in the exploration of future development scenarios.

## 5. Policy scenario framework

The validated water-energy system coupled model was used to analyze the impact of potential policy scenario that could promote resilience of water and energy systems in the UAE in the face of climate change. Establishing a plausible policy scenario framework is fundamental for using the coupled model to explore challenges and opportunities for transitioning to more climate-resilient development paths. As described in the sub-sections that follow, this scenario framework is based on a set of underlying premises and consists of five (5) scenarios: Two (2) Business-as-Usual Scenarios (one scenario with climate change; the other without climate change) that simply extend past energy/water use patterns into the future; and three policy scenarios (i.e., demand-side focused; supply-side focused; and demand-supply together) whose core aim is to yield substantial resource and environmental benefits at least cost. A brief overview of each scenario is provided in Figure 5-1.

Two BAU scenarios were developed to better understand the impacts of climate change on the water-energy nexus. Comparing the BAU-RCP8.5 and BAU scenarios reveals the impact of climate relative to resource (e.g., natural gas consumed in power stations; water used in irrigation) and environmental indicators (e.g., greenhouse gas emissions). In contrast,





### Figure 5-1: Brief overview of the BAU and Policy scenario



comparing the individual policy scenarios to the BAU-RCP8.5 scenario reveals policy-only impacts relative to the same resource and environmental indicators where the climate change role has been eliminated.

### 5.1. Underlying issues

There are five (5) key underlying premises to the scenario framework. First, it considers the same planning period as used in the validated waterenergy system coupled model, namely 2015 to 2060. Second, the scenarios themselves are not intended to be predictions of the

future but rather exploratory narratives that describe potential futures that are considered plausible/desirable relative to the UAE's culture and hyper-arid environment. Third, each policy scenario is quantifiable relative to its costs and benefits and can be directly compared to the BAU scenario as well as to the other policy scenarios. Fourth, the three policies scenarios all assumed a changing climate consistent with the findings of the regional atmospheric modeling sub-project. Lastly, each policy scenario considers specific policies that are capable of being implemented in the UAE context.

There are three (3) key principles governing the scenario framework. First, all non-waterenergy specific indicators are kept constant across the BAU and policy scenarios. This includes the UAE's growth in population, GDP and other socioeconomic characteristics. This enables a direct comparison of changes in water and energy use across the scenarios, all else being equal. Second, all services provided by water resources (e.g., irrigation, drinking water, etc) and energy resources (e.g., space cooling, refrigeration, etc) are kept constant across the BAU and policy scenarios. This means that the same level of service is provided, though at lower water/energy intensities due to the introduction of more efficient technologies, or by means of alternative (i.e., renewable) technologies, all else equal. Lastly, the policy scenario framework is meant to be illustrative and was developed to illustrate the merits of pursing demand policies only, supply policies only, and demand and supply policies simultaneously.

There are two (2) key modeling issues governing the analysis of the policy scenarios. First, all policies in each scenario were evaluated as a collective whole, as opposed to each





individual policy.<sup>11</sup> It was assumed that real-world policy development in the UAE would tend to favor pursuit of demand-side and supply-side policies together, as evidenced by the Draft Climate Change Strategy for the Abu Dhabi emirate (EAD, 2014). Second, electric capacity expansion planning protocols were set up within the coupled modeling framework to ensure consistency with conservative assumptions regarding the electric system reserve margin (i.e., 20% in the BAU scenarios; 40% in the scenarios where intermittent renewable energy capacity is added).

Finally, the coupled water-energy modeling framework has been used to quantify and report four (4) key outputs for each of the policy scenarios. First, annual reductions in CO<sub>2</sub>equivalent emissions are reported for the years 2040 and 2060, with cumulative emission reductions reported over the entire planning period. Second, annual water savings abstracted from groundwater sources or produced in desalination plants are reported for the years 2040 and 2060, with cumulative water savings reported over the entire planning period. Third, the incremental present value cost associated with the implementation of the policies are reported for the entire planning period. The incremental costs for each of the three policy scenarios are reported relative to the BAU scenario which incorporates climate change. Finally, an indicator is reported for each scenario that shows the cost of transitioning to a policy scenario relative to the amount of CO2e reductions achieved. This indicator is calculated as the incremental present value cost divided by the cumulative (undiscounted) CO2e reductions, and has units of \$/tCO2e avoided (2015\$). In summary, the reporting framework outlined above can help provide a basis to better understand the costs and benefits associated with transitioning to water-energy development paths that will be more resilient to climate change.

### 5.2. The Business-As-Usual Scenarios

The Business-As-Usual scenarios includes population and climatic assumptions that also apply to all policy scenarios. The future population forecasts were taken from projections made by the United Nations (2015) and include a single population growth rate projection for the country over time. The UAE's population was estimated at about 9,300,000 in 2015 and is projected to grow to 13,500,000 by 2060 (1.8% per year). Two future climate forecasts (i.e., total precipitation, average annual temperature) were taken from the outputs of LNRCCP subproject #1 (Yates, et al., 2015): extension of climatic trends for the 1985-2004 period through 2060 and the IPCC's RCP8.5 projection which assumes a global business-as-usual trajectory of greenhouse gas emissions and their resulting concentrations in the atmosphere.

On the other hand, the two (2) Business-As-Usual scenarios are characterized by resource use trends that are distinct from the policy scenarios. Both the Business-as-usual (hereafter: "BAU") scenario and the Business-as-usual under climate change (hereafter: "BAU-RCP8.5)

<sup>&</sup>lt;sup>11</sup> All overlaps and synergies between the policies have been accounted for within the coupled waterenergy system modeling framework to avoid any double-counting.





scenario continue past resource use with respect to water and energy consumption on a percapita basis, and the technologies associated with their production and delivery. Specifically, this refers to the range of indicators evident in the historical period; e.g., water use per capita, energy use per capita, desalination capacity shares, penetration of fossil fuel based energy production. These are all assumed to continue at their historical growth levels, with no new policies that would influence water and energy use trends to 2060. For the BAU scenario, some of the key assumptions are as follows:

- *Climate change.* Not considered.
- *Power supply fuel mix.* The fuel mix for power supply remains fossil based, although the share of fuel oil use declines relative to natural gas, consistent with current trends.
- *Desalinization technology mix.* Capacity continues to be dominated by MSF at 60%, while MED and RO continue to make-up around 20% of the capacity; new capacity to meet future desalinated water demand is added at these ratios.
- Role of natural gas. Natural gas is endogenously added into the energy generation fuel mix, to maintain a minimum planning reserve margin<sup>12</sup> of 40%. Incremental electricity generation to meet future demand is dominated by natural gas, with other resources (i.e., nuclear, solar, clean coal) only added per current and planned projects.
- *Nuclear generation.* Nuclear capacity at the Baraka power station in the western region of the Abu Dhabi emirate peaks by 2020 at 5.6 GW.
- *Centralized solar photovoltaic technology.* New solar PV capacity is added to the electricity supply system, peaking at 5 GW by the year 2060.
- *Solid fuels.* Clean-coal is incrementally introduced from 2015 to 2030 up to a total capacity of 3.6 GW and remains constant thereafter through 2060 (DEWA 2016).
- *Energy use growth (GDP based).* For the energy related demand sectors whose future generation is based on GDP output, the assumed an annual growth of energy use is 1.8% per year.
- Energy use growth (population based). For electricity use in the municipal, industrial and commercial sectors whose future generation is based on population, the assumed growth in per-capita use stabilizes by 2020 and then holds constant to 2060. Consumption levels depend on the monthly heat index.
- *Water use growth.* For the municipal and industrial water sector, indoor per-capita use remains constant for each region of the country, while outdoor water use is assumed to grow at half the population growth rate estimated for the period 2010 to 2060.



<sup>&</sup>lt;sup>12</sup> The planning reserve margin is a measure of the amount of generation capacity available to meet expected demand in planning horizon, and is ratio of the deliverable electric capacity and the actual demand.



The BAU-RCP8.5 scenario shares all the same key assumptions as the BAU scenario except for the role of climate change. From 2015 to 2030, it was assumed that the UAE's historic climate continues. For the period 2031 through 2060, climatic outputs from the regional

atmospheric modeling sub-project were used to estimate outdoor irrigation requirements and the amount of rainfall for groundwater recharge in the Oman Mountains. These climate projections are from the regional atmospheric modeling sub-project and include monthly time series of total precipitation and monthly average temperature (see Figure 5-2 for a comparison with BAU climatic trends). Historic annual average precipitation over the Oman Mountain region is 125 mm, while the future projected annual precipitation is 185 mm per year. While the percent change is significant, the absolute precipitation in the region remains relatively small and with increased warming of more than 2°C by mid-century, the additional rainfall is mostly lost to increased evaporative loss.

## 5.3. Policy Scenario #1: High Efficiency and Conservation





Table 5-1: List of policies analyzed in Policy Scenario 1: **High Efficiency and Conservation** 

Sector	Policy # and Name				
	7. Indoor water use efficiency and				
	conservation programme				
Water	8. Introduction of outdoor garden and				
policies	amenity caps				
	9. Improved irrigation efficiency				
	10. Water loss reduction programme				
	11. Demand side electric efficiency and				
Electricity	conservation programme				
policies	12. Peak load management of space				
	cooling load				





incorporated into the water and energy system models. The effect of climate change was incorporated into the scenario.

### Water policies:

- Indoor water use efficiency and conservation programme. This policy involves a) providing residential consumers with access to information about water-efficient technologies and household/business benefits of water conservation; b) removing any barriers to the widespread dissemination of water-efficient technologies throughout the UAE. The policy target is 75 gal/capita/day by 2060, declining from BAU-RCP8.5 levels starting in 2030.
- 2. Introduction of outdoor garden and amenity caps. This policy involves a capping of the annual land area eligible for green-scaping. The policy target is a maintenance of the 2015 level of outdoor garden and amenity watering land area. This contrasts with the BAU-RCP8.5 scenario, where outdoor watering land area is assumed to grow proportionally to population.
- 3. *Improved irrigation efficiency.* This policy involves a) providing industrial, municipal, and agricultural consumers with access to information about water-efficient technologies and the national benefits of water conservation; b) removing any barriers to the widespread dissemination of water-efficient technologies throughout the UAE. The policy target is a 20% reduction in outdoor water use by 2060, relative to what it would have been in that year in the BAU-RCP8.5 scenario. The phase-in start year is 2015.
- 4. *Water loss reduction programme.* This policy involves improvements in municipal water distribution networks, leading to reduced water losses between the supply center and the end use location, and resulting in greater fraction of reuse water available for treatment. The policy target is a 25% reduction in water losses by 2060, relative to what they level would have been in that year in the BAU-RCP8.5 scenario. The phase-in start year is 2015.

### Electricity policies:

- 5. Demand side electric efficiency and conservation programme. This policy involves a) providing residential consumers with access to information about electric-efficient technologies and household/business benefits of electricity conservation; b) removing any barriers to the widespread dissemination of electric-efficient technologies throughout the UAE. The policy target is 7,000 kWh/capita/year by 2060, or about a 20% decrease in per capita usage from BAU-RCP8.5 levels, starting in 2030.
- 6. *Peak load management of space cooling load*. This policy involves additional measures on the demand side that can help to flatten peak electricity demand for space cooling. This will reduce the electric supply system's summer peak loads. The policy target is a 15% reduction in peak summer space cooling load, relative to it would have been in that year in the BAU-RCP8.5 scenario. The phase-in start year is 2030.





## 5.4. Policy Scenario #2: Natural Resource Protection

The *Natural Resource Protection* scenario assumes that the UAE will implement aggressive supply-side policies to conserve its natural resources, specifically groundwater and energy.

The overall aim of this policy scenario is to protect fossil groundwater resources from any further depletion and to reduce the use of fossil fuels. A total of six (6) specific policies were assumed for resource planning across water and energy that would be phased in through 2060, with the phase-in start year depending on the specific policy. These policies are outlined in Table 5-2 and briefly described in the bullets

Table 5-2: List of policies analyzed in Policy Scenario 2:
Natural Resource Protection

Sector	Policy # and Name				
	7. Fossil groundwater phase-out				
Water	8. Increased use of treated sewage				
policies	effluent				
	9. Sustainable desalination				
Electricity	10. Carbon dioxide cap				
Electricity	11. Renewable portfolio standard				
policies	12. Clean coal capacity cap				

below, together with the default targets that have been incorporated into the water and energy system models. The effect of climate change was incorporated into the scenario.

### Water policies:

- Fossil groundwater phase-out. This policy involves reducing fossil groundwater extraction for irrigated agriculture to stabilize groundwater levels. The policy target is a 4.5% per year reduction in the magnitude of fossil groundwater use, starting 2015, which results in a stabilization of total groundwater storage by 2060. The water use deficit is made up by RO-based desalinated water, treated at half the level of potable supply in terms of salt extraction.
- 2. *Increased use of treated sewage effluent (TSE).* This policy involves increasing the percentage of waste water that is treated and re-used for outdoor irrigation purposes. The country wide policy target is 90% of all TSE is reused by 2060, staring in 2030.
- Sustainable desalination. This policy involves increasing the share of reverse osmosis technology. The country wide policy target is 60% of total desalinization capacity for potable supply by 2060, starting 2030. Desalinated water production form other technologies are reduced to meet annual control totals in the BAU-RCP8.5 scenario (MSF declines from 60% to 30% over the same period).

### Electricity policies:

- 4. *Carbon dioxide cap.* This policy involves capping carbon dioxide-equivalent (CO2e) emissions from the electricity supply sector. The policy target is to reach the 2005 CO2e level in the UAE by 2060. The 2005 level was assumed to be about 35 mtCO2e. The phase-in start year is 2030.
- 5. *Renewable portfolio standard.* This policy involves the introduction of concentrated solar power (CSP) and centralized solar photovoltaic technology into the capacity mix. The policy target is to a) add CSP and PV solar capacity at 0.25 GW/year through 2060, starting





in 2021; b) maintain a 40% reserve margin to account for intermittency, while natural gas continues its 2020 level of capacity to maintain a 40% reserve margin through 2060.

6. *Clean coal capacity cap.* This policy involves capping any clean coal capacity additions at the current planned addition levels. The policy target is to cap clean coal technology at the 2,400 MW by 2025 that is introduced in the BAU-RCP8.5 scenario, with no additional capacity added thereafter.

# 5.5. Policy Scenario #3: Integrated Policies (Both demand- and supply-side measures)

The Integrated Policy scenario assumes that the UAE will implement all 6 demand-side and all 6 supply-side policies collectively. The overall aim of this policy scenario is to optimize efficiency and natural resource protection in the UAE. The scenario assumes a future in the UAE where there is a broad consensus among national policymakers that the implementation of all the policies and measures embedded in the *High Efficiency* and *Natural Resource Protection* Scenarios are essential. The effect of climate change was incorporated into the scenario.

## 5.6. Scenario Policy Caveats and limitations

There are several caveats associated with modeling the above policy scenarios. The degree to which these caveats apply across the water and energy system models depend on the characteristics of the corresponding policy scenario, as outlined below.

### Water system modeling caveats:

- The expansion of water system infrastructure, implied by the policy scenarios, can be achieved. For example, new water desalination infrastructure can be expanded to satisfy future water demands.
- There is enough current/future wastewater treatment infrastructure to treat wastewater outputs from demand sites, and the reuse of treated wastewater is fully subscribed to urban outdoor irrigation.
- Most the groundwater throughout the region is unrenewable 'fossil' groundwater. This caveat is important as it influences whether demand at certain locations within the domain can 'run out of water'.
- Access to available groundwater storage will continue without the introduction of any legal framework that would constrain its use.
- Access to available brackish fossil groundwater is unconstrained. The model allows full depletion, especially in those areas with limited storage capacity.





• Water savings in the agriculture sector through efficiency and conservation measures do not result in a decrease in overall agriculture productivity.

### Energy system modeling caveats:

- The expansion of electric system infrastructure, implied by the policy scenarios, can be achieved. For example, in the Natural Resource Projection scenario, there is an assumption that the land requirements associated with new solar CSP and PV capacity can be met,
- For the *Natural Resource Projection* and *Integrated Policy* scenarios, new capacity is added that prioritizes solar PV and CSP capacity, and then natural gas combined cycle capacity.
- For the *Natural Resource Projection* and *Integrated Policy* scenarios, the models were run iteratively to determine the rate of forced retirement of natural gas capacity and the substitution rate of new solar gas capacity needed to meet the 2005 GHG target of about 35 mtCO2e.

## 6. Baseline Scenario Results

**This section provides an overview of the results for the** *BAU\_RCP8.5* **scenario.** The BAU-RCP8.5 scenario incorporates the impact of climate change and is the baseline development scenario against which each of the three policy scenarios is compared. It is important to note that the results of the BAU scenario (i.e., scenario without climate change) is not beyond it providing the basis for a summary of the impact of climate change.

### 6.1. Water supply and demand

**Figures 6-1a and 6-1b show the water supply and demand results for BAU-RCP8.5 scenario.** At the outset, it is important to note that total water supply equals total water demand. By convention, the water system model allocates all losses within the demand sector themselves. Overall, the UAE water system grows by about 15% over the 2020-2060 period, or an average of about 0.4% per year.







### Figure 6-1: UAE water supply and demand characteristics in the BAU-RCP8.5 scenario, 2020-2060

**On the water supply side, several key trends are evident from a review of Figure 6-1a.** First, total groundwater supply remains considerably larger than desalinization and reuse water in absolute terms. By 2060, groundwater supply reaches 2,499 MM3 compared to 1,678 MM3 for desalinated supplies, or roughly 50% more. Second, it's clear that under business-as-usual assumptions, the share of desalinated water supply is growing, increasing from 32% of total supply in 2020 to 37% by 2060; while the share of groundwater supply is diminishing, decreasing from 62% of total supply in 2020 to 56% by 2060. Third, groundwater supply grows over the 2020-2030 period by about 0.46% per year, but declines thereafter through 2060 by around 0.05% per year, as some regional groundwater systems are depleted. Over this same 2030-2060 period, water reuse (which represent a small fraction) and desalination water supply grows by just over 0.6% per year.

**On the water demand side, several key trends are evident from a review of Figure 6-1b.** First, agricultural water demand remains considerably larger than indoor and outdoor water use combined, in absolute terms. By 2060, agricultural water demand reaches 2,517 MM3 compared to 1,980 MM3 for indoor and outdoor water use, or roughly 27% more. Second, it's clear that under business-as-usual assumptions, the share of indoor and outdoor water use is growing, increasing from 37% of total demand in 2020 to 44% by 2060; while the share of agricultural water demand is diminishing, decreasing from 63% of total demand in 2020 to 56% by 2060. Third, agricultural water demand grows over the 2020-2030 period by about 0.44% per year, but declines thereafter through 2060 by around 0.05% per year, as some regional groundwater systems are depleted which previously had met agricultural demand. Over this same 2030-2060 period, indoor and outdoor water use grows by just over 0.6% per year.





## 6.2. Electricity supply and demand

Figures 6-2a, 6-2b, and 6-2c show the electricity generation supply and demand results for BAU-RCP8.5 scenario. At the outset, it is important to note that total electricity supply does

not equal total electricity demand. By convention, the energy system model allocates all losses within the supply sector. Losses consist of the energy lost during the fuel combustion process at the power station, as well as electricity lost over the transmission and distribution network. Total losses of the UAE electricity system average about 72% over the period 2020-2060, declining from about 82% in 2020 to 60% in 2060 as nuclear power becomes a larger share of total production. Overall, UAE electric system generation increases by about 70% in term of total generation between 2020-2060, growing at an average annual rate of about 1.7% per year.

On the electricity supply side, several key trends are evident from a review of Figure 6-2b. First, natural-gas fired generation in high efficiency cogeneration units continues to dominate power supply. By 2060, natural gas-fired generation reaches 288 TWh compared to 164 TWh across all other fossil-fired and nuclear generation, or roughly two times more. Second, under the assumption that nuclear generation becomes active as planned and the business-as-usual assumptions, the share of nuclear power generation remains a small fraction over the planning period, decreasing from about 45% of total generation in 2020 to about 25% by 2060; while the share of natural gas-fired generation increases from 50% of total

## Figure 6-2: UAE electricity supply and demand characteristics in the BAU-RCP8.5 scenario, 2020-2060

a) Total Electricity Supply, Showing Losses (TWh)



b) Total Electricity Supply Inputs (TWh)



c) Electricity Demand by Sector (TWh)



generation in 2020 to 60% by 2060. Third, generation from all other sources (i.e., oil and clean coal) is a small but growing share of total generation, increasing from about 6% in 2020 to 10% by 2060.





**On the electricity demand side, several key trends are evident from a review of Figure 6-2c.** First, the combined electricity consumption from the residential and services sectors dominates electricity demand. By 2060, these two sectors account for 126 TWh compared to 62 TWh across all other sectors, or roughly two times more. Second, it's clear that under business-as-usual assumptions, electricity for desalination remains a small fraction over the entire planning period, about 3% of total use throughout. Third, electricity for groundwater pumping and other water-related activities remains a very small fraction over the entire planning period, accounting for about 1% of total use throughout the 2020-2060 period.

Figure 6-3: UAE water-related energy supply (electricity and heat) and demand characteristics in the BAU-RCP8.5 scenario, 2020-2060



**Figures 6-3a and 6-3b show additional key trends associated with water-related energy supply and demand.** As shown in Figure 6-3c, the electricity required for desalination is small in absolute terms (i.e., increasing from 5 to 6 TWh over the 2020-2060 period across all technologies. However, the process heat requirement for desalination is much higher. Desalinization energy in the UAE is primarily from thermal distillation with most of the heat obtained via heat recovery units at natural gas combined cycle plants. Expressed in units of TWh instead of TOE to enable a direction comparison, process heat requirements for water desalination grow from 80 TWh in 2020 to about 109 TWh in 2060; nearly 20 times the electricity requirement.

On the demand side, the electricity required per unit of water demand is low in comparison to the total energy (electricity plus process heat) to produce water. This is evident in Figure 6-3b which shows electricity (only) requires for all water demand growing from about 2 TWh in 2020 to nearly 2.5 TWh by 2060. The categories "WaterTreatment", AgWater, and "Reuse" represent a breakdown in the categories "Desalinization" and "EnergyinWaterUse" presented earlier in Figure 6-2b.





### 6.3. Greenhouse gas emissions

Figure 6-4 shows the trajectory of greenhouse gas emissions, separated into emissions from all energy use (top curve) and the electricity generation portion (bottom curve). The increasing trend in GHG emissions in the BAU-RCP8.5 scenario is associated socioeconomic development under business-as-usual conditions under climate change. The GHG's associated with electric generation shows emissions nearly doubling over the period.

Figure 6-4: UAE Greenhouse Gas Emissions in the BAU-RCP8.5 scenario for the period 2015 to 2060 (million metric tonnes CO2e)



It is important to note that the GHG growth declines from 2015 to 2025 as nuclear power comes online. The 2015 total simulated emissions from all fossil fuel activities are estimated at about 150 million metric tonnes, of which about 60 MMT are associated with electric generation, which grows to more than 350 MMT of which more than 100 MMT are from electric generation.



### 6.4. Water and energy costs

**Figures 6-5a and 6-5b show the discounted costs associated with water demand and energy supply for the BAU-RCP8.5 scenario.** At the outset, it is important to note that cost results reflect present value costs that incorporate a 5% real discount rate. Actual annual costs can





be reviewed by accessing the online versions of the water and energy system models and retrieving the annual costs through the appropriate menu in WEAP and LEAP, respectively. Various levels of aggregation are available for viewing cost results.

**Figure 6-5a includes an estimate of the discounted water use costs.** It is important to note that these costs are provided for information only. As discussed previously, all water-related costs are accounted for on the energy side. The annual costs of water shown on the Figure were calculated by simply multiplying an assumed value of the social cost of water in units of \$/MM3 (i.e., an attempt to reflect its inherent value, not its retail value) by the total annual quantity of water consumption across all end use activities. These annual costs were then discounted to determine the present value of water demand in the BAU-RCP8.5 scenario. The total discounted social cost of water over the 2015-2060 period is about \$10 billion (2015\$).

**Figure 6-5b shows the discounted energy production costs.** It is important to note that the costs are associated with a) total UAE electricity production for both water-related (e.g., desalination, groundwater pumping) and all other electricity consuming activities (e.g., in factories, in households, in refineries, etc) and b) total UAE process heat production for water-related activities only (i.e., process heat required for desalination using thermal technologies). The present value of total electricity and water-related process heat production over the planning period is about \$200 billion (2015\$). The fact that the costs include non-water related activities is intended to account for the fact that the policy scenarios introduce electricity-savings policies in non-water sectors. In any event, the BAU-RCP8.5 cost stream is shown for illustrative purposes only as the ultimate objective is to understand the difference in total costs between the BAU-RCP8.5 and each of the policy scenarios (i.e., the incremental cost of shifting from the BAU development scenario to alternative development scenarios).

## 6.5. Impact of climate change

The impact of climate change on the water-energy nexus has been estimated by comparing the BAU-RCP8.5 scenario (with climate change; no policies) with the BAU scenario (without climate change; no policies). Several conclusions may be offered as summarized in Table 6-1 and outlined in the bullets below. The next section discusses selected impacts of climate change; complete details of the analysis of the BAU scenarios are available by accessing the online water and energy system models

themselves.

 Water consumption: Climate change will lead to annual increases in water use, reaching about 3% by 2060, as warming conditions create slightly greater demand for water. Over the 2015-2060 period, this cumulative additional water demand amounts to about 4.4 BCM.

Table	6-1: Summary of climate change impact on the
	national water-energy nexus, 2015-2060

		Additional	
	Additional	CO2e	Additional
Additional	electricity	emissions	Costs
Water	production	(Million	(billion NPV
use (BCM)	(TWh)	tonnes)	2015\$)
4.4	425	109	4.3





- *Electricity production:* Climate change increases demand for electricity for space cooling, resulting in annual increases in electricity use, reaching about 4% by 2060 due to an increase in the number of cooling degree days. Over the 2015-2060 period, this cumulative additional electricity generation amounts to about 425 TWh.
- *Greenhouse gases:* Climate change leads to additional annual emissions of greenhouse gases associated with the additional energy production, reaching about 5% by 2060. Over the 2015-2060 period, these cumulative additional emissions amount to about 109 million tonnes of CO2e.
- *Costs:* Climate change leads to additional annual costs of meeting water and energy demands with an additional 5% annually by 2060. Over the 2015-2060 period, the cumulative present value additional cost amounts to about \$4.2 billion (2015\$) as shown in Table 6-1.

## 7. Policy Scenario Results

This section provides an overview of the results for all policy scenario relative to both BAU scenarios. The policy scenario results incorporate the impact of climate change and can be directly compared to the BAU-RCP8.5 scenario to estimate the impact of the policy scenario net of any climate change impact.





### 7.1. Water supply

**Figures 7-1a, 7-1b and 7-1c show water supply results.** Several key trends are evident from a review of annual water supply for all uses in Figure 7-1a. These are briefly highlighted in the bullets below.

- While it appears that there are only three scenarios plotted, all five scenarios are shown on the Figure, with two of the scenarios fully overlapping by visual inspection.
- The highest trend in water supply is represented by the BAU-RCP8.5 and natural resource protection scenarios which are virtually identical in all years (i.e., top dashed line). This is because no efficiency/conservation measures are included in either scenario. This leads to a total growth in water supply by about 17.7% over the 2015-2060 period, or about 0.36% per year. In absolute terms, an additional 5 BCM (or 2.7%) in water supply would be needed relative to the BAU scenario over the 2015-2060 period. This also represents the impact of climate change.
- The lowest trend in water supply is represented by the high efficiency/conservation and integrated scenarios which are also virtually identical in all years (i.e., bottom dashed line). This is because the same aggressive level of efficiency/conservation is included in both scenarios. This leads to a total

Figure 7-1: Water supply across all scenarios, 2015-2060 (BCM)

a) Annual water supply for all uses



b) Water supplied from desalinization







*reduction* in water supply by about 18.1% over the 2015-2060 period, or about -0.44% per year. In absolute terms, about 28 BCM in water supply is avoided relative to the BAU-RCP8.5 scenario over the 2015-2060 period.





**Several key trends are evident from a review of desalinated water supply in Figure 7-1b.** These are briefly highlighted in the bullets below.

- While it appears that there are only fours scenarios plotted, all five scenarios are shown on the Figure, with the two BAU scenarios virtually fully overlapping by visual inspection. There is a small difference between the two scenarios that represents the impact of climate change. Roughly 0.2 BCM more desalinated water would be supplied in the BAU-RCP8.5 scenario over the 2015-2060 period, or about 0.3% more.
- The highest trend in desalinated water supply is represented by the natural resource protection scenario (i.e., top dashed line). This is because desalinated water is substituted for groundwater to meet agricultural and other water demands served by groundwater supply. This leads to a total growth in desalinated water supply by about 152% over the 2015-2060 period, or an average annual growth of about 2.1% per year. In absolute terms, an additional 22 BCM (or 32%) in desalinated water supply would be needed relative to the BAU-RCP8.5 scenario over the 2015-2060 period.
- The lowest trend in desalinated water supply is represented by the high efficiency/conservation scenario. (i.e., bottom solid line). This reflects the impacts of the implementation of aggressive efficiency/conservation measures. This limits the growth in desalinated water supply to about 6.2% over the 2015-2060 period, or about 0.13% per year. In absolute terms, about 9.1 BCM in desalinated water supply is avoided relative to the BAU-RCP8.5 scenario over the 2015-2060 period.

Several key trends are evident from a review of total and fresh groundwater storage in Figure 7-1c. These are briefly highlighted in the bullets below.

- The small uptick in all scenarios around 2037 and 2057 is directly related to regional modeling outputs which show small perturbations in the climate system in those years.
- The greatest rate of depletion of groundwater storage capacity is shown in the BAU scenarios (bottom two solid lines). There is a negligible difference between these two scenarios, with both showing a steep decline of 40% over the 2015-2060 period, or about 1.1% per year. In absolute terms, groundwater aquifers would be depleted by about 2,415 BCM over the 2015-2060 period relative to 2015 levels.
- The lowest rate of depletion of groundwater storage capacity is represented by the high natural resource protection scenario. (i.e., top dashed line). This reflects the impact of a gradual elimination of groundwater withdrawals. The scenario shows a less steep decline over the 2015-2060 period, around 27% or about 0.7% per year. In absolute terms, groundwater aquifers would be depleted by about 1,587 BCM over the 2015-2060 period relative to 2015 levels.





### 7.2. Water demand

**Figures 7-2a, 7-2b and 7-2c show water demand results for all water-consuming sectors.** Several key trends are evident from a review of agricultural water demand in Figure 7-2a. These are briefly highlighted in the bullets below.

- While it appears that there are only three scenarios plotted, all five scenarios are shown on the Figure, with two of the scenarios fully overlapping by visual inspection. The BAU-RCP8.5 scenario overlaps the natural resource protection scenario as would be expected since the latter scenario only affects water supply. Also, the high efficiency and conservation scenario overlaps the integrated scenario as would be expected since these are the only two scenarios that reflect changes in agricultural demand.
- The highest trend in agricultural water demand is represented by the BAU-RCP8.5 and natural resource protection scenarios which are virtually identical in all years (i.e., top dashed line). This is because no efficiency/conservation measures are included in either scenario. This leads to a total growth in agricultural water demand by about 2.9% over the 2015-2060 period, or about 0.06% per year. In absolute terms, there are no water savings relative to the BAU-RCP8.5 scenario over the 2015-2060 period.

Figure 7-2: Water demand across all scenarios, 2015-2060 (BCM)













 The lowest trend in agricultural water demand is represented by the high efficiency/conservation and integrated scenarios which are also virtually identical in all years (i.e., bottom dashed line). This is because the same aggressive level of efficiency/conservation is included in both scenarios. This leads to a





total *reduction* in agricultural water demand by about 31.5% over the 2015-2060 period, or about 0.84% per year. In absolute terms, about 17 BCM in agricultural water demand is avoided relative to the BAU-RCP8.5 scenario over the 2015-2060 period.

• The impact of climate change on agricultural water demand, while small, is non-trivial. This is illustrated by the difference between the top dashed line and the middle solid line (BAU scenario). An additional 4.4 BCM is consumed in the agricultural sector due to climate change over the 2015-2060 period, about 3.9% more than what would have been consumed without climate change.

**Several key trends are evident from a review of indoor water demand in Figure 7-2b.** These are briefly highlighted in the bullets below.

- While it appears that there are only two scenarios plotted, all five scenarios are shown on the Figure, with three of the scenarios fully overlapping by visual inspection. The BAU scenario overlaps with both the BAU-RCP8.5 and natural resource protection scenarios as would be expected since the latter scenario only affects water supply. Also, the high efficiency and conservation scenario overlaps the integrated scenario as would be expected since the only two scenarios that reflect changes in indoor water demand.
- The highest trend in indoor water demand is represented by the BAU, BAU-RCP8.5 and natural resource protection scenarios which are virtually identical in all years (i.e., top dashed line). This is because no efficiency/conservation measures are included in these scenarios. This leads to a total growth in indoor water demand by about 45% over the 2015-2060 period, or about 0.8% per year. In absolute terms, there are no water savings relative to the BAU-RCP8.5 scenario over the 2015-2060 period.
- The lowest trend in indoor water demand is represented by the high efficiency/conservation and integrated scenarios which are also virtually identical in all years (i.e., bottom dashed line). This is because the same aggressive level of efficiency/conservation is included in both scenarios. This leads to a total *reduction* in indoor water demand by about 8.8% over the 2015-2060 period, or about 0.19% per year. In absolute terms, about 8.5 BCM in indoor water demand is avoided relative to the BAU-RCP8.5 scenario over the 2015-2060 period.
- The impact of climate change on indoor water demand is zero. This is because an underlying assumption of the water system model was that climate change would not impact indoor water use.

Several key trends are evident from a review of amenity and other outdoor water demand in Figure 7-2c. These are briefly highlighted in the bullets below.

• While it appears that there are only two scenarios plotted, all five scenarios are shown on the Figure, with three of the scenarios fully overlapping by visual inspection. The BAU scenario overlaps with both the BAU-RCP8.5 and natural resource protection scenarios as





would be expected since the latter scenario only affects water supply. Also, the high efficiency and conservation scenario overlaps the integrated scenario as would be expected since these are the only two scenarios that reflect changes in amenity and other outdoor water demand.

- The highest trend in amenity and other outdoor water demand is represented by the BAU, BAU-RCP8.5 and natural resource protection scenarios which are virtually identical in all years (i.e., top dashed line). This is because no efficiency/conservation measures are included in these scenarios. This leads to a total growth in amenity and other outdoor water demand by about 41% over the 2015-2060 period, or about 0.8% per year. In absolute terms, there are no water savings relative to the BAU-RCP8.5 scenario over the 2015-2060 period.
- The lowest trend in amenity and other outdoor water demand is represented by the high efficiency/conservation and integrated scenarios which are also virtually identical in all years (i.e., bottom dashed line). This is because the same aggressive level of efficiency/conservation is included in both scenarios. This leads to a total *reduction* in amenity and other outdoor water demand by about 6.2% over the 2015-2060 period, or about 0.14% per year. In absolute terms, about 2.4 BCM in amenity and other outdoor water demand is avoided relative to the BAU-RCP8.5 scenario over the 2015-2060 period.
- The impact of climate change on amenity and other outdoor water demand, while small, is non-trivial. This is illustrated by the difference between the top dashed line and the middle solid line (BAU scenario). An additional 0.7 BCM is consumed by the amenity and other outdoor sector due to climate change over the 2015-2060 period, about 4.5% more than what would have been consumed without climate change.

## 7.3. Electricity supply

**Figures 7-3a, 7-3b, and 7-3c show electricity supply results for all primary fuel types.** There are several key trends that are evident from a review of total electric supply results shown in Figure 7-3a. At the outset, it is important to note that Figure 7-3a shows only electric supply. All other non-electricity types of energy such as fuels combusted for mechanical power (e.g., gasoline for cars) or fuels required for industrial processes are discussed in the energy demand section. Major trends are briefly highlighted in the bullets below.

- The impact of climate change (only) results in the use of about 21 TWh more electricity in 2060. Over the 2015-2060 period, roughly 5.5% more electricity would be used under conditions of climate change (i.e., BAU-RCP8.5 scenario compared to the BAU scenario). The Natural Resource Protection scenario shows similar total electricity supplied.
- The High Efficiency and Integrated policy scenarios show lower total electricity generation than in the Natural Resource Protection scenario, as efficiency measures reduce overall





electricity supplied. Fossil-fuel based electricity supply is decreased, primarily due to savings in the residential sector.

- The Natural Resource Protection and Integrated scenarios shows less fossil fuel generated electricity than in the BAU-RCP85 scenario. These scenarios imply no reduction in demand, as efficiency measures are not included, but the reduction in fossil fuel use is due to the switch to solar generation and nuclear to a lesser extent.
- The Integrated scenario shows substantially less generation than in the BAU-RCP85 scenario. Over the period 2015-2060, generation requirements increase by 36.2% considerably less than the 83% increases in the BAU-RCP8.5 scenario. In absolute terms, total generation reductions reach nearly 69 TWh in 2060, roughly 74% of what they would have been in that year in the BAU-RCP85 scenario.

There are several key trends that are evident from a review of fossil-fired electric supply results shown in Figure 7-3b. These are briefly highlighted in the bullets below.

 The impact of climate change (only) results in the use of about 21 TWh more electricity in 2060, as noted above. This is related to the modeling assumption that only fossil-fired resources would track electric

#### Figure 7-3: Electricity supply across all scenarios, 2015-2060 (TWh)

a) Total electricity supply











generation impacts associated with climate change.

• The impact of the high efficiency and conservation scenario shows reductions in fossil-fired generation requirements. Over the period 2015-2060, generation requirements increase





by 25% - less than the 46% increases in the BAU-RCP8.5 scenario. In absolute terms, efficiency and conservation results in overall demands that are lower in 2060 than what they would have been in that year in the BAU-RCP85 scenario.

- The impact of the Natural Resource Protection scenario shows the lowest fossil-fired generation of all the policy scenarios. This is as expected since this scenario assumes a shift away from natural energy resources (i.e., natural gas, oil) and towards renewable resources and nuclear. Over the period 2015-2060, there is a decline of 82.3%, or roughly 3.8% per year. In absolute terms, fossil-fired generation reductions reach 197 TWh in 2060, or roughly12% of what they would have been in that year in the BAU-RCP85 scenario.
- The impact of the integrated scenario shows substantially less fossil-fired generation than in the BAU-RCP85 scenario. Over the period 2015-2060, generation requirements decline by 54.4%, or roughly 1.7% per year. In absolute terms, fossil-fired generation reductions reach nearly 157 TWh in 2060, roughly 29% of what they would have been in that year in the BAU-RCP85 scenario.

There are several key trends that are evident from a review of renewable electric supply results shown in Figure 7-3c. These are briefly highlighted in the bullets below.

- The impact of climate change (only) results in no additional renewable generation throughout the 2015-2060 period. All increased electricity demand is assumed to be supplied by fossil-fired generation.
- The impact of the High Efficiency and conservation scenario assumes no increase in renewable generation. This is as expected since this scenario is strictly focused on efficiency and conservation measures, rather than renewable energy.
- The impact of the Natural Resource Protection scenario shows the highest renewable generation of all the policy scenarios. This is as expected since this scenario assumes a shift away from natural energy resources (i.e., natural gas, oil) and towards renewable resources. Over the period 2015-2060, there is an increase of over 1,000 times, due the fact that starting levels of renewable energy in 2015 were very low. In absolute terms, renewable solar capacity reaches about 60 GW and generation reaches 140 TWh by 2060.
- Also, the lower rate of introduction of new solar generating capacity in the Integrated scenario, compared to the Natural Resource Protection is due to the fact that demands are lower in the Integrated scenario, thus less new solar capacity is added more slowly.
- The impact of the Integrated scenario shows substantially more renewable generation than in the BAU-RCP85 scenario. Over the period 2015-2060, there is an increase of about 785 times, again due the fact that starting levels of renewable energy in 2015 were very low. In absolute terms, renewable solar generation capacity is about 45 GW and reaches about 100 TWh in 2060.





### 7.4. Energy demand

**Figures 7-4a, 7-4b, and 7-4c show energy demand results for all sectors.** At the outset, it is important to note that the consumption of both electricity and non-electricity energy forms is addressed in these charts. Nonelectricity energy forms include the use of fuels combusted for mechanical power (e.g., gasoline for cars) or the use of fuels to produce process heat for industrial processes (e.g., natural gas for desalination) Also, to show both electric and non-electric consumption on the same charts, the energy content of fuels has been converted to units of TWh consistent with conventional conversion factors.

There are several key trends that are evident from a review of total energy demand results shown in Figure 7-4a. These trends are briefly highlighted in the bullets below.

- While it appears that there are only four scenarios plotted, all five scenarios are shown on the Figure, with two of the scenarios seeming to overlap by visual inspection. The BAU scenario seems to overlap with the BAU-RCP8.5 scenario. However, over the 2015-2060 period, there is about 379 TWh more energy consumed in the BAU-RCP8.5 scenario. This represents the impact of climate change (only).
- Interestingly, the high efficiency and conservation scenario shows higher total energy use than in the natural protection scenario where no demand side efficiency measures are introduced, as the total energy associated with desalinization use remains high due to the assumed continued use of fossil fuels in desalinization through co-generation.

Figure 7-4: Energy demand across all scenarios, 2015-2060 (TWh)















- The impact of the Natural Resource Protection scenario shows less total energy use than in the BAU-RCP85 scenario, attributed to a reduction in energy use associated with desalinization away from thermal source (MSF and MED) which are replaced by reverse osmosis (RO).
- The impact of the Integrated Policy Scenario shows less total energy use than in the BAU-RCP8.5 scenario, and all other scenarios.

There are several key trends that are evident from a review of total electricity demand results shown in Figure 7-4b. These trends are briefly highlighted in the bullets below.

- While it appears that there are only four scenarios plotted, all five scenarios are shown on the Figure 7-4b, with two of the scenarios seeming to overlap by visual inspection. The BAU scenario seems to overlap with the BAU-RCP8.5 scenario. However, over the 2015-2060 period, there is about 325 TWh more energy consumed in the BAU-RCP8.5 scenario. This represents the impact of climate change (only).
- The high efficiency and conservation scenario shows a decline in electricity use. The impact of the natural resource protection scenario shows less total electricity use than in the BAU-RCP85 scenario. The BAU-RCP8.5 scenario shows the climate change has led to an increase in electricity use, which is matched under the Natural Resource Protection scenario, which assumes similar patterns of electricity demand.
- In the Natural Resource Protection scenario, there is higher electricity use due to greater desalination from thermally based sources including MSF and MED. So, while there is less use of water and electricity energy overall, there is a substantial net increase in overall electricity use.

There are several key trends that are evident from a review of total electricity demand results shown in Figure 7-4c. These trends are briefly highlighted in the bullets below.

- The impact of the policy scenarios (High Efficiency and Conservation, Natural Resource Projection, and Integrated) is particularly apparent in desalinization energy used, with reductions in 2060 of about 20% and 45%, respectively.
- Over the period 2015-2060, electricity use associated with desalinization is about 55% less in the Integrated scenario than the BAU scenarios.





### 7.5. Greenhouse gas emissions

**Figures 7-5a, 7-5b, and 7-5c show CO2e emissions from all sources.** There are several key trends that are evident from a review of total emission results shown in Figure 7-5a. These trends are briefly highlighted in the bullets below.

- Under both BAU scenarios and the Efficiency and Conservation scenarios, greenhouse gases nearly double over the period 2015 to 2060. This increase outpaces population growth, mainly due to increased GDP per capita growth and thus and increase in relative resource use.
- High efficiency and conservation impact improvements related to energy use (electricity and fuels) do not have a substantial impact on emissions, as the High Efficiency scenario implies only a 4% reduction in overall GHG emissions.
- The Natural Resource Protection scenario and the Integrated scenario do suggest reductions in GHG emissions overall, as there is a substantial shift away from fossil-fuel generated energy.
- Water related emissions are reduced under all scenarios, as reduced overall water demand and reuse reduces the energy used in treating and transporting water. This energy use is independent of the energy used for desalination, and at about 5 GWh per year, is around 1% of total energy use.

Figure 7-5: CO2e emissions across all sources, 2015-2060 (million metric tonnes)



b) Total Electricity Generation



c) Water-related emissions only (Electricity and fuels)



There are several key trends that are

evident from a review of GHG emission associated with electricity use shown in Figure 7-5b. These trends are briefly highlighted in the bullets below.





- The *BAU\_RCP8.5* scenario leads to 6% greater GHG emissions when compared with the *BAU* scenario, as natural gas continues to dominate energy production and resource use increases due to warmer conditions that require more water and energy for space cooling.
- For the *High Efficiency* scenario, efficiency improvements and conservation targets reduce emissions, but regional population growth means that both water and energy use have grown overall, with emissions only being reduced by about 12% relative to the *BAU\_RCP8.5* scenario.
- The Natural Resource Protection scenario shows the greatest reduction in emissions compared with the other policy scenarios even though over the analysis period 2015 to 2060 there are higher demands for electricity. The policies under this scenario assume that electricity generation is primarily solar- and nuclear-based rather than fossil-based. The higher energy demands force the introduction of new solar capacity earlier in the simulation period, resulting in less natural gas generation and thus lower GHG emissions.
- The emissions of the *Integrated Policy* scenario are higher than those *Natural Resource Protection,* as new solar is added at a slower rate due and hence reducing the GHG reduction benefits associated with lower electricity demand.

There are several key trends that are evident from a review of total water-related emission results shown in Figure 7-5c. These trends are briefly highlighted in the bullets below.

- The GHG emissions associated with water use grow more gradually when compared to total GHG emissions (see earlier Figure 7-5a). In the BAU scenarios, we have assumed that land associated with outdoor amenity watering has grown at half the rate of population growth and thus the overall demand of water grows at a slower rate and thus desalinated water as well.
- The High efficiency and conservation scenario shows a leveling out of GHGs associated with water, as overall demand flattens (see earlier Figure 7-2). The Natural Resource Protection and Integrated Policy scenarios shows the decline in electricity use in the water sector,
- In the Integrated Policy scenario, total water-related GHG emissions decline, but are actually slightly higher than the Natural Resource Protection scenario, as endogenously added solar capacity is smaller, because energy demands are reduced due to efficiency and conservation improvement.

## 7.6. Incremental costs of the policy scenarios

Table 7-1 summarizes the costs and benefits associated with the implementation of the policy scenarios within the water-energy nexus. At the outset, it is important to note that a) costs represent the costs to society from the implementation of the policies, rather than any segment of society (see discussion in Section 4.3.5); b) benefits are presented in physical units and are limited to water savings, fossil fuel savings, and greenhouse gas emission reductions; the magnitude of other benefits (e.g., fossil-fuel use) are accessible through the water and





		Cumulative benefits (2015- 2060)				Avoided CO2e	
Impact	Alternative Scenario	Starting Scenario	Water savings (BCM)	Fossil fuel savings (GWh)	CO2e reductions (million tonnes)	Total Incremental cost (billion 2015\$)	emissions from policies (\$ per tonne
From climate change, only	BAU-RCP8.5	BAU	-5	-470	-138	4	NA
From introduction of improved efficiency & conservation measures	High Efficiency & Conservation	BAU- RCP8.5	28	1,600	283	-3	-\$10.2
From introduction of renewable energy and reductions in groundwater withdrawals	Natural Resource Protection	BAU- RCP8.5	0	4,200	933	12	\$13.2
From introduction of all sustainable development measures	Integrated Policy	BAU- RCP8.5	28	4,400	845	3	\$3.4

### Table 7-1: Summary of Costs and benefits associated with the implementation of the policy scenarios

energy models themselves; and c) the reported costs and benefits are incremental in nature; that is, they result from shifting the development pathway from the BAU to each of the other alternative development pathways. Highlight are briefly described in the bullets below relative to cumulative impacts over the 2015-2060 period.

- Under the BAU-RCP8.5 scenario (i.e., with climate change) there is a net increase in cumulative GHG emissions of 138 MMT when compared to the BAU scenario. Climate change results in increased water use and energy use, and results in an additional cost of about \$4 billion to meet water and energy demand over the period.
- Under the High Efficiency scenario, there are cumulative reductions of GHGs (i.e., 283 million tonnes of CO2e avoided) that come at a negative cost (i.e., -\$3 billion). This means that the implementation of efficiency measures *saves* money and offers a cost-effective way to reduce greenhouse gas emissions (i.e., UAE society would receive a \$10.2 benefit for every tonne of CO2e avoided). This is true even at the conservatively assumed high value of the levelized cost of achieving efficiency targets used in this study.
- Under the Natural Resource Protection scenario, there are the largest savings of GHGs but at the highest incremental costs of saved CO2e, as the shift from fossil fuel generation to solar based generating increases the incremental costs of energy by \$12 Billion and a positive cost to society of reducing CO2e emissions (i.e., \$13.2 per tonne avoided). The scenario implies that solar can be added an extraordinary level. While there are cost savings as groundwater pumping is reduced, water supply costs are shifted to the electricity generation sector, as desalinated water is the substituted source for avoided groundwater use.
- Under the Integrated Policy scenario, there is a modest increase in the incremental cost, which again is heavily dependent on the assumption of the levelized costs of efficiency and conservation, the levelized costs associated with new solar capacity, and the assumption that new solar capacity can be accommodated on the power system. Both the cost of saved CO2e and water are positive, albeit smaller than those of the Natural





Resource Protection scenario, since the demand for water and energy have been reduced from the implementation of efficiency and conservation measures.

## 8. Conclusion and Recommendations

We have developed a UAE wide study of the Water-Energy Nexus using an integrated water and energy planning framework based on the Water Evaluation and Planning (WEAP) and Long range Energy Analysis and Planning (LEAP) decision support system. These coupled models can be used to explore current and future water-energy pathways by quantifying how patterns of both water and electricity demand are impacted by climate, what level of efficiency and conservation might be needed to meet carbon emissions targets, exploring the relative costs of renewable energy technologies relative to traditional fossil-fuel based forms, the costs associated with efficiency and conservation, etc.

The water systems model divides the country into five water resource demand and supply zones, that considers municipal, industrial, and agriculture demands supplied by both desalination and groundwater. Groundwater in the region is dominated by non-renewable, fossil sources mainly serving agriculture, while the bulk of municipal and industrial water is supplied through desalinization. Historically, most seawater desalinization has been made using energy intensive, fossil fuel based technologies, although it is commonly co-generated at power plants whose priority is to first generate electricity, but the waste heat is then used to produce water.

Our models of water and energy demand within both the WEAP and LEAP models include climate dependent factors, as climate is a major determinate of outdoor water demands for amenity landscapes, gardens, etc. and agricultural, while electric energy demands are primarily for cooling. The county is generally characterized as hyper-arid, receiving very little rainfall and little of which can be used to satisfy irrigation demands. The regions proximity to the Arabian Gulf and a majority of the population centers located and developing there, means that cooling loads are particularly high as both higher temperatures and high humidity tend to exacerbate cooling needs. The future climate projection applied in this study is characterized by warmer temperatures, with regional mean temperatures more than 2.5°C warmer and mean humidity increasing by nearly 10% by 2060. Thus, the warmer and more humid conditions, which when combined can be referred to as the "heat index", suggest an even greater need for cooling in the future. Given current cooling technologies and behavioral patterns, this implies greater energy needs. Projections of future rainfall based on results from Global Climate Model output suggests increases in rainfall, but the change is small relative to the increasing temperature and does little in the way of satisfying overall irrigation requirements or serving as a source of groundwater recharge.

We have demonstrated how the integrated WEAP-LEAP modeling framework can be used to evaluate various future water and energy policies, and have done so in an incremental fashion, by first developing a policy scenario focused on demand side interventions- the





*Energy Efficiency* scenario and then a supply-oriented scenario- the Natural Resource *Protection* scenario. The *Energy Efficiency* scenario was used to explore water and energy efficiency and conservation programs, while the Natural Resource Protection scenario explored the implications of a reduced reliance on fossil-fuel based generation and the mining of fossil groundwater. These demand and supply side scenarios, along with their attending assumptions, were then combined into an *Integrated Policy* scenario.

### Highlights and Lessons Learned include the following:

- Reductions in water use are likely more attainable than energy use. Agricultural policies that recognize the unique climatic conditions and agricultural heritage of the region could lead to reductions in agricultural water use. Policy-makers will need to decide the importance of preserving fossil groundwater versus its exploitation in the short term.
- While desalinization is costly in terms of energy-use, it is often co-generated and therefore care must be taken when accounting for water's share of the energy footprint.
- The approach applied a set of assumptions regarding future population trajectories by country and the future climate projection with regional heterogeneity. These two assumptions were shown to dominate the results in terms of the baseline assumptions.
- We have developed a limited set of future policy scenarios that apply broad, region-wide assumptions to demonstrate the merits of those policies and the flexibility of the framework to rapidly explore alternative policy scenarios.
- In the *Business-as-Usual* scenario where the UAE population grows by 33% from 2020 to 2060, from about 10 to 13.3 million persons, total water use grows from about 4 BCM to 4.5 BCM or about 12.5%. If just municipal water is considered, then demand grows from 1.5 BCM to 2.0 BCM or 35%. Total energy use in all sectors is assumed to grow from about 57 Mtoe to 133 Mtoe or more than doubling over the 40 year period.
- For the BAU scenarios, total electricity use grows from about 80 TWh to 172 TWh or more than 100%; and with climate change, the warmer and more humid conditions lead to an additional 15% more electric energy use while increasing water demand by less than 2%.
- To stabilize or even reduce greenhouse gas emissions, the penetration of renewable energy sources in the country will have to be substantial. Policy makers can use the tools developed as part of this study to explore if the trajectory of these new energy technologies is at all realistic. The *Natural Resource Protection* and *Integrated Policy* scenarios imply significant increases in solar and nuclear power would be required.
- The policy scenarios were implemented using a demand side (*High Efficiency*) and supply side (*Natural Resource Protection*) approach, while a third scenario, the *Integrated Policy* represents a "balanced-approach" to achieving energy and water savings, and attending reductions in GHGs. Demand side or supply side policies, pursued in insolation, would





prove costly and perhaps even be impossible to implement. It is highly unlikely that the country can install 10's of GW of new solar by 2060, with current region capacity less than 25 GW from all sources.

- The Integrated Policy scenario, which combines both supply and demand side actions, requires the installation of roughly 2,500 MW per year starting in 2044 when the current natural gas capacity can no longer meet the minimum reserve margin requirement of 40%. This solar expansion target also achieves a GHGs levels observed between 2005 and 2010. This results in a very high, and perhaps unrealistic installation of additional solar capacity of more than 40 GW. Without both demand side actions also taken (the Natural Resource Protection scenario), an additional 65 GW of new solar would have to be added to meet the same GHG levels and reserve margin.
- By 2060 under the Integrated Policy Scenario, there is about 15 GW of Natural Gas, 3 GW of Clean Coal, 6 GW of Nuclear, and 40 GW of solar capacity.
- A balanced set of both supply-side and demand-side interventions in both the water and energy sectors will be necessary to achieve sustainable resource management goals.
- "Water Savings" are likely easier to achieve than energy savings in the country. Policies that reduce irrigated agricultural use and the pumping of fossil groundwater would need to be put in place.

### Key knowledge gaps include the following:

- While there is growing recognition of understanding the interactions and feedbacks of the W-E Nexus, there has been little work in quantifying these relationships in order to gain a better understanding of how polices in either or both of the sectors influence these systems.
- Through modeling, there is a need to better understand the relationship among the W-E Nexus components in the country in the context of climate change and other uncertain factors.
- Lack of official long-term forecasts (i.e., to 2060) of water and energy requirements which account for temperature changes with climate change.
- Lack of GCC-specific databases on cost and performance of demand-side energy saving devices
- Lack of GCC-specific databases on cost and performance of demand-side water saving devices
- Current Photo-voltaic solar panels become increasingly inefficient at higher temperatures. The level of new PV capacity that would be needed is arguably unrealistic, and even more so, when the high temperatures in the region are considered.





- It was difficult to find detailed information on local and regional groundwater systems and to know precisely the sustainable rate of abstraction.
- Municipal water and electricity use were assumed to occur on a per-capita basis. There are likely local and regional differences in water and energy use patterns.
- Most potable water generated through desalinization is done using thermal, cogeneration processes, which have a seasonal dependence in terms of generation efficiency. For example, in the winter when electricity demands are lower, there could be insufficient heat at co-generation plants to generate adequate water supplies. These dynamics were not captured in the model, and should be considered in the future.

### Key interactions across the nexus sectors include:

- The need for coordinated policies for fossil groundwater protection
- The need for policies to promote renewable-based energy-water co-production with back-up fossil energy.
- Lack of local studies to assess supply side energy-water cogeneration efficiency improvement potential
- Interactions between energy and water have not been considered on a regional or technology-by-technology basis.
- Because the majority of the potable water supply is co-generated with energy, it is more difficult to identify the true costs of the water.

The modeling tools and data used here to explore the regional W-E Nexus demonstrates that green growth objectives can be achieved with balanced and comprehensive approaches. Some key implications for green growth in the UAE include the following:

- The 2011 Report of the Arab Forum for Environment and Development on Green Economy in the Arab world lays the argument why Arab governments should want to invest in the green economy future.
- There is a strong link between green economic growth and management of water and energy resources
- Assessing regional green growth scenarios in the context of climate requires a broader analytical framework which the W-E Nexus approach provides
- Pursuing an economic diversification agenda (as has been prominently reported recently by some countries in the region) employing a green growth framework poses numerous W-E Nexus modeling challenges, but this analysis has shown that diversification of the energy portfolio will be necessary to achieve environmental targets, such as GHG stabilization or even reduction.





• We have demonstrated that quantitative, data intensive models can be used to meaningfully explore the kind of necessary adaptation that would be needed to achieve green growth objectives such as GHG emission targets and the costs associated of these measures.

Several recommendations for further research have emerged from the study. While the integrated water-energy models and policy analysis methods that we have demonstrated are powerful tools for quantifying the interactions of the W-E Nexus, the ability to explore the full range of options within the context of this published report is limited. It would be very useful to continue to develop these capabilities with a broad array of stakeholders, where the tools could be used to explore more targeted questions and regional differences. Examples include:

- Further research would seek to better quantify regional groundwater and how it is used. Since groundwater is the primary water source for irrigated agriculture, it would be useful to disaggregate the agricultural sector into multiple crops which would provide more accuracy in simulating agricultural demands.
- The regional planning objectives for each region of the country are likely to vary. For example, Dubai and Abu Dhabi Emirates development goals and pathways are likely very different.
- Alternative approaches to modeling water and energy use could be explored. These could include agent-based, econometric, or other methods that could provide additional insights and perspectives.
- More detailed multi-crop irrigation model could be developed to more accurately explore water use and crop production of specific systems (e.g. date palms, vegetables, grains, fodder, etc.).
- A more detailed examination of the energy used in thermal-based desalinization, particularly those plants that use co-generation is warranted, including the understanding of seasonal productions and efficiencies. This is important so as to not 'double-count' the energy used to make electricity and potable water at a co-generation plant and to ensure proper treatment of energy need for desalinization.
- The groundwater supply does not include some current projects in the UAE around groundwater aquifer storage and recovery. Future analysis could include this resource.





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## Annex A: Water-related data sources

The table below shows the datasets used for the various supply and demand elements in the water system model and the data sources for this information. With this table, partners can determine the type of data that is used and their corresponding source.

Node	Variable in WEAP	Numeric Value	Numeric Value	Unit	Year	Source
			Made of			
Demands:	Annual Activity Level	Interpolation	% of UAE Population	1000	[in	United Nations, Department of Economic and Social Affairs, Population Division (2015). World
Abu Dhabi,		values: (2000,671,	by regions	cap	function]	Population Prospects: The 2015 Revision, custom data acquired via website.
Western, Al		2010,1832,	(22, 3, 12, 32, 28,			
Ain, Dubai,		2020,2161,	and 3 Respectively			
Eastern, and		2030,2413, 2040 2639	by regions)			
Fujairah		2050,2814,				
Regions		2060,2922)				
Abu Dhabi	Ag - Date Palms	10,464	40% of Ag areas in	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
			Abu Dhabi			
	Ag - Foder	8,633	33% of Ag areas in	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
			Abu Dhabi			
	Ag - Vegetables	1,570	6% of Ag areas in	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
			Abu Dhabi			
ents	Ag - Other Crops	5,493	21% of Ag areas in	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
mu			Abu Dhabi			
atcl	Amenity - Amenity	2,054	74684 * 0.0275	ha	2000	2.75% of total urban land cover (Lincoln Institute of Land Policy (Table-Urban-Land-Cover-
0		(1.5% growth rate)				Data_Lincoln Institute of Land Policy.xlsx) <sup>1</sup>
	Amenity - Forest	1,867	74684 * 0.025	ha	2000	2.5% of <sup>1</sup>
	Outdoor - Household	1,867	74684 * 0.025	ha	2000	2.5% of <sup>1</sup>
nents tern ion	Ag - Date Palms	17,440	50% of Ag areas in	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
			Western Region			
tchr Ves Reg	Ag - Foder	11,510	33% of Ag areas in	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
C ai			Western Region			


	Ag - Vegetables	2,093	6% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Other Crops	3,837	11% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Amenity - Amenity	1,120	74684 * 0.015	ha	2000	1.5% of <sup>1</sup>
	Amenity - Forest	1,494	74684 * 0.02	ha	2000	2.0% of 1
	Outdoor - Household	1,120	74684 * 0.015	ha	2000	1.5% of <sup>1</sup>
Region	Ag - Date Palms	79,352	70% of Ag areas in Western Region	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
	Ag - Foder	22,672	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
Al Ain	Ag - Vegetables	6,802	6% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
ments	Ag - Other Crops	4,534	4% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
atd	Amenity - Amenity	1,120	74684 * 0.015	ha	2000	1.5% of <sup>1</sup>
0	Amenity - Forest	1,494	74684 * 0.02	ha	2000	2.0% of 1
	Outdoor - Household	1,120	74684 * 0.015	ha	2000	1.5% of <sup>1</sup>
atchments Dubai	Ag - Date Palms	2,976	60% of Ag areas in Western Region	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
	Ag - Foder	992	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Vegetables	298	6% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Other Crops	694	14% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
0	Amenity - Amenity	1,867	74684 * 0.025	ha	2000	2.5% of <sup>1</sup>
	Amenity - Forest	0	0	ha	2000	ASR UAE (CD) 2014. Ministry of Energy
	Outdoor - Household	1,867	74684 * 0.025	ha	2000	2.5% of <sup>1</sup>
astern	Ag - Date Palms	9,275	40% of Ag areas in Western Region	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
nents E. Region	Ag - Foder	4,638	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
Catchm R	Ag - Vegetables	4,638	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy



	Ag - Other Crops	4,638	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Amenity - Amenity	1,120	74684 * 0.015;	ha	2000	1.5% of <sup>1</sup>
	Amenity - Forest	0	0	ha	2000	ASR UAE (CD) 2014. Ministry of Energy
	Outdoor - Household	1,120	74684 * 0.015;	ha	2000	1.5% of <sup>1</sup>
	Ag - Date Palms	2,130	50% of Ag areas in	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
			Western Region			
gior	Ag - Foder	1,405	33% of Ag areas in	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
l Re			Western Region			
irah	Ag - Vegetables	256	6% of Ag areas in	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
-uja			Western Region			
Its F	Ag - Other Crops	468	11% of Ag areas in	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
mer			Western Region			
Itchi	Amenity - Amenity	1,867	74684 * 0.025	ha	2000	2.5% of <sup>1</sup>
Ca	Amenity - Forest	0	0	ha	2000	ASR UAE (CD) 2014. Ministry of Energy
	Outdoor - Household	1,867	74684 * 0.025	ha	2000	2.5% of 1
Desal for :	Inflow - MSF	1000	Assumption	MGD	[in	Model uses a maximum capacity for the future of 1,000 MGD per each technology to satisfy the
Western					function]	demand in each region
Region,	Inflow - MED	1000	Assumption	MGD	[in	Model uses a maximum capacity for the future of 1,000 MGD per each technology to satisfy the
Eastern					function]	demand in each region
Region, and	Inflow - RO	1000	Assumption	MGD	[in	Model uses a maximum capacity for the future of 1,000 MGD per each technology to satisfy the
Fujaira					function]	demand in each region
Regions						
WTP for: Abu	Daily capacity	N/A	Assumption	MCM	[in	WTPs have daily treatment capacities to treat all wastewater coming from the different demand
Dhabi,				/Day	function]	sites. Any untreated water flows into wadis in the model.
Western, Al						
Ain, Dubai-						
Eastern, and						
Fujairah						
Regions						
AbuDhabi Brackish GW	Initial Storage	40		BCM		AGEDI
Western	Initial Storage	2		BCM	2005	GTZ
Fresh GW						



Western	Initial Storage	27	BCM	2005	GTZ
Brackish GW					
East Fresh	Initial Storage	31	BCM	[in	AGEDI
GW				function]	
East Brackish	Initial Storage	63	BCM	[in	AGEDI
GW				function]	
Eastern	Initial Storage	100	BCM	[in	AGED
Region GW				function]	

<sup>1</sup>: Total urban land cover (Lincoln Institute of Land Policy (Table-Urban-Land-Cover-Data\_Lincoln Institute of Land Policy.xlsx)



## Annex B: Energy-related data sources

The table below shows the datasets used for the various supply and demand elements in the energy system model and the data sources for this information. With this table, partners can determine the type of data that is used and their corresponding source.

Energy intensities for key water-sector activities (Source: World Business Council for Sustainable Development).

Activity	kWh/m³	Description	
GW Pumping* 0.5		Electricity use is a function of water pumped and depth to groundwater; $\alpha(\text{depth})$ * (kwh /m³).	
Desal-MSF	16.0	Electricity use related to multi-stage flash desalinization (MSF).	
Desal-RO	6.5	Electricity use related to desalinization by reverse osmosis (RO).	
Desal-MED	14.0	Electricity use related to multi-effect distillation (MED)	
Waste Water Treatment	0.8	Electricity use associated with primary and second water and waste water treatment.	
Reuse	1.5	Electricity use associated with treatment and distribution of waste water treated to a non-potable standard for outdoor use.	

\*Electricity use associated with groundwater pumping varies by depth to Groundwater

Monthly generation fraction, with solar having a seasonal distribution based on average regional latitude of 25oN and assumed process efficiency for each generation. New Natural Gas Efficiency is assume to be combined cycle at 55% efficiency.

Fuel Type	Monthly Generation Fraction	Process Efficiency
Fuel oil	65%	38%
Clean Coal	70%	43%
Natural Gas*	60%	45%
Nuclear	90%	33%
Solar	Jan 16%; Jul 33%	100%
Wind	15%	100%



Levelised cost estimates for each fuel type used in the LEAP model. \*Energy Efficiency/Cost Savings Efficiency (EE CSE) is not a fuel, rather it is being treated as a resource cost to facilitate policy scenario analysis and used to represent cost savings of fuel-efficient technologies and conservation (EIA 2016).

Fuel Technology	Levelized cost (\$2015/MWh)
Fuel Oil	150
Natural Gas	75
Solar (PV and CSP)	125
Wind	73
Nuclear	115
Clean Coal	130
EE CSE*	30

Levelised cost of water, including the cost associated with Water Efficiency and the Cost of Saving Water (WE-CSW), which is treated as a resource cost to facilitate policy scenario analysis and used to represent cost savings of water-efficient technologies and conservation (Molina 2014; AWWA 2008).

Water Related Costs	Levelized cost (\$2015/M <sup>3</sup> )
Desalinization	(incl. in energy cost)
Groundwater	0.10
Waste Treatment	0.50
Reuse*	0.35
WE CSW	0.20





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