an initiative of

AGEDI | THE ABU DHABI GLOBAL ENVIRONMENTAL DATA INITIATIVE

CLIMATE CHANGE PROGRAMME

WATER RESOURCES: REGIONAL WATER-ENERGY NEXUS AND CLIMATE CHANGE

- Atmospheric Modelling
- Arabian Gulf Modelling
- Terrestrial Ecosystems
- Marine Ecosystems
- Transboundary Groundwater
- Water Resource Management
- Al Ain Water Resources
- Coastal Vulnerability Index
- Desalinated Water Supply
- Food Security
- Public Health Benefits of GHG Mitigation
- Sea Level Rise

Full Technical Report

AGEDI.org

The authors of this report are Francisco Flores (co-Principal Investigator) and Stephanie Galaitsi from the Stockholm Environment Institute – US Center and David Yates (co-Principal Investigator) from the National Center for Atmospheric Research.

Suggested Citation:

AGEDI 2016. Technical Report: Regional Water-Energy Nexus under Climate Change. LNRCCP. CCRG/NCAR/SEI.

Acknowledgments

Many individuals provided invaluable support, guidance, and input to the Regional Water-Energy Nexus & Climate Change project.

The authors would like to express their sincere and heartfelt gratitude to them for taking time to review our reports, provide comments, feedback, data as well as for the opportunity to present multiple deliverables within the course of the project. These individuals include but are not limited to the below list:

Prof. Waleed Al Zubari, Arabian Gulf University (AGU)
Carl Nettleton, Open Oceans Global
Dr. Fred Launay, Environment Agency - Abu Dhabi (EAD)
Dr. Mohamed Dawoud, Environment Agency – Abu Dhabi (EAD)
Dr. Abdul-Majeid Haddad - United Nations Environment Programme – Regional Office for West Asia (UNEP-ROWA)
Dr. Tarek Sadek, United Nations Economic and Social Commission for Western Asia (UNESCWA)
Ziad Khayat, United Nations Economic and Social Commission for Western Asia (UNESCWA)

We had the pleasure of convening a 4 day Regional Water-Energy Nexus Training Workshop in collaboration with the UAE Ministry of Energy (MOENR) in Abu Dhabi from 10-13 October 2016. We would like to warmly thank all the participants for making it such a successful event.

We are additionally thankful the participation, time and effort that multiple stakeholders across the region who participated in the multitude of meetings and dialogue. The authors would like to especially thank the following stakeholders for their particularly involved participation: Bruce Smith - Abu Dhabi Water and Electricity Company (ADWEC) and his team, the AGU team, the EAD team, the Emirates Wildlife Society – World Wildlife Fund (EWS-WWF) team, the International Center for Biosaline Agriculture (ICBA) team, Taha Ouarda and the Masdar Institute of Science and Technology (MIST) team, Tomoo Machiba and the Ministry of Climate Change and Environment (MOCCAE) team, the UAE MOENR team as well as the Research Triangle Institute (RTI) team.

List of Acronyms

AGEDI	Abu Dhabi Global Environmental Data Initiative
BAU	Business-as-usual
BCM	billion cubic meters
CCRG	Climate Change Research Group
CO_2	carbon dioxide
CSP	Concentrating solar power
CSE	Cost saving energy
DSS	Decision Support System
EAD	Environment Agency of Abu Dhabi
EIA	US Energy Information Administration
EU	European Union
FAO	Food and Agricultural Organization of the United Nations
GCC	Gulf Cooperation Council
GCM	Global Climate Model
GPCPC	Gallons per capita per day
GW	Groundwater
GWh	Gigawatt-hour (billion watt-hours)
mtCO2e	Millions of metric Tonnes of CO2 equivalent
IPCC	Intergovernmental Panel on Climate Change
LEAP	Long-Range Energy Alternatives Planning
LEDS	Low Emission Development Strategies
LNRCCP	Local, National, and Regional Climate Change Programme
MED	Multi effect distillation
MGD	Million gallons per day
mm	Millimeters
MM3	Million Cubic Meters
MODFLOW	MODular Three-Dimensional Finite-Difference Groundwater model?
MSF	Multi-stage flash
Mt	Millions of metric tons
MWh	Megawatt-hour (million watt-hours)
NPV	Net Present Value
PV	Photovoltaic
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RO	Reverse Osmosis
SEI-US	Stockholm Environment Institute – US Center
TM3	Thousands of cubic meters
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

Table of Contents

List of Figures

page

List of Tables

Executive Summary

This report summarizes the motivation, methodology and results of the project *Water-Energy Nexus Challenges & Opportunities in the Arabian Peninsula under Climate Change* from AGEDI's *Local, National, and Regional Climate Change Programme (LNRCCP).* The study evolved from an initial directive to examine transboundary groundwater flows in the Arabian Peninsula to an exploration of the Water-Energy Nexus (W-E Nexus) in the region. The W-E Nexus is constituted by the interconnectivity of water-energy systems, such as energy needed for the desalination, treatment, and transportation of water and waste water, as well as water needed for energy extraction and production. By its nature, the W-E Nexus constitutes a set of interactions, tradeoffs, and system balances among its component pieces, which makes its analysis challenging and not necessarily straightforward. The work presented here provides a relatively high level analysis of the W-E Nexus for the Arabian Peninsula region while including considerable detail regarding sources, demands, and costs of the water and energy components.

In a context where water is scarce, fossil energy is plentiful, demands for both are high, and concerns about climate change are growing, as well as continued population growth, connections between energy and water can reveal potential opportunities for efficiency improvements or mutually beneficial tradeoffs. To examine the regional W-E Nexus, the project constructed and linked water and energy models (WEAP and LEAP, respectively) for the countries of the Arabian Peninsula with particular attention to the Arabian Gulf region- specifically Kuwait, Bahrain, Qatar, the United Arab Emirates (UAE), Eastern Saudi Arabia and Northern Oman. The coupled water-energy models required detailed data, which were obtained through literature reviews and extensive consultations with key stakeholders in the region. As part of this process the outputs of both models were validated for historic periods using existing data to ensure that the models could adequately represent the systems under investigation.

With the validation verified and the data entry complete, the project deployed the models in simulating future conditions to the year 2060 for five different scenarios. Since the future is uncertain, the models examined two baseline and three policy scenarios for different resource management futures. The baseline scenarios include an investigation of future conditions if current water and energy management practices are kept in place. These are the Business-as-Usual scenarios and include one where the historic climate repeats itself (the BAU scenario) and a second with future climate change conditions based on the United Nation Framework Convention on Climate Change (UNFCC) Representative Concentration Pathway (RCP) 8.5 trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5) in 2014. This is referred to as the BAU-RCP8.5 scenario, where climate change projection comes from the AGEDI LNRCC atmospheric modeling study, which embodies a warming trend of about 2.0°C increase in annual average temperature by 2060 and a slightly wetter climate across the region. However, the increased precipitation does little to satisfy water demands. Three policy scenarios then tier off these BAU scenarios, including a *High Efficiency* scenario, where each country gradually implements policies to reduce the consumption of water and electricity in all sectors; a *Natural Resource Protection* scenario with resource efficiencies, the phasing out of fossil groundwater extraction, and drastic reduction in fossil fuel usage for power generation; and an *Integrated Policy* scenario that combines the prior two policy scenarios. In addition, the scenarios are implemented using an assumption of input substitution for the same level of service. For example, if water is in short supply in a region, those shortages can be made up by the next available water supply, usually at a greater cost.

The main findings of the analysis show that water use for the Gulf countries can mostly be met in any scenario through combinations of groundwater, desalination and wastewater reuse, with some regional fossil groundwater basins drawn potentially to extinction by 2060 under the most intensive resource-use scenarios. The scenarios produce different water use for the countries, for example the *Integrated Policy* Scenario embeds the implementation of all policies and measures that would reduce water demand in the region, resulting in diminishing indoor water use starting in 2020. Since water provision impacts energy demand (requiring pumping, desalination, and transport), any decreases in water demand will exert similar effects on the energy sector supporting water provision. As groundwater resources are depleted, desalination becomes the main water resource in the region, followed by treated wastewater, which will be limited to amenity and agricultural sectors.

Some of the groundwater aquifers are depleted or nearly depleted in the Arabian Peninsula by the end of model period in the *Business as Usual* scenarios. This includes groundwater depletion for Central Saudi Arabia's Dammam aquifers that represents the single biggest use and supply that are considered in the model. These results are not strongly tied to climate change, since the aquifer conditions are more affected by what is taken out (pumping policies) than any recharge. Climate change does not exert a big impact on overall water demand, as the climate of the region already requires considerable irrigation to sustain agricultural and amenity demands. Thus, Irrigation demands increase only slightly due to warming.

While the analysis includes both a demand oriented scenario (*High Efficiency*) and a supply oriented scenario (*Natural Resource Protection*), the results of the analysis strongly suggest that the region will need to simultaneously pursue demand and supply side policies to achieve more sustainable uses of water and energy over the next half century (the *Integrated Policy* scenario). Figure E1 summarizes the portfolio of energy generation for the *Integrated Policy* scenario, which assumes a reduction in per capita water use driven by a target to meet an indoor standard of 75 M^3 per year by 2060, stabilization of outdoor water use through improvements of current practices, no new land under irrigation for either agriculture or amenity areas and reductions in fossil groundwater use. On the energy side, the policy objective is to meet 2005 levels of GHG emissions for the region included in the study, which we estimate at 70 mtCO2e. This is done by installing new solar capacity in favor of natural gas, with new solar capacity being added at about a 3:1 ratio to new natural gas capacity. By 2060, the *Integrated Policy* scenario requires the generation of 133,000 GWh, which would require more than 330 km^2 of PV solar. To put that into perspective, the area of Abu Dhabi is about 950 km^2.

Figure E1 shows the supply of water by source and demand type for the 2020 *BAU* scenarios and the 2060 *Integrated Policy* scenario. It shows that overall, a similar amount of water is delivered, despite a nearly 40% increase in population. This is primarily achieved through conservation and irrigation efficiency improvements for both amenity and agricultural uses. The share of agriculture water use has declined, and the share of water used for indoor use has grown. Water reuse has increased as has the share of water generated through reverse osmosis.

Figure E1. Water use by type (Agriculture, Municipal Indoor and Municipal and Amenity Outdoor) and supply source (Groundwater, Reuse Water, and Desalination technology) for 2020 and the 2060 *Integrated Policy* Scenario.

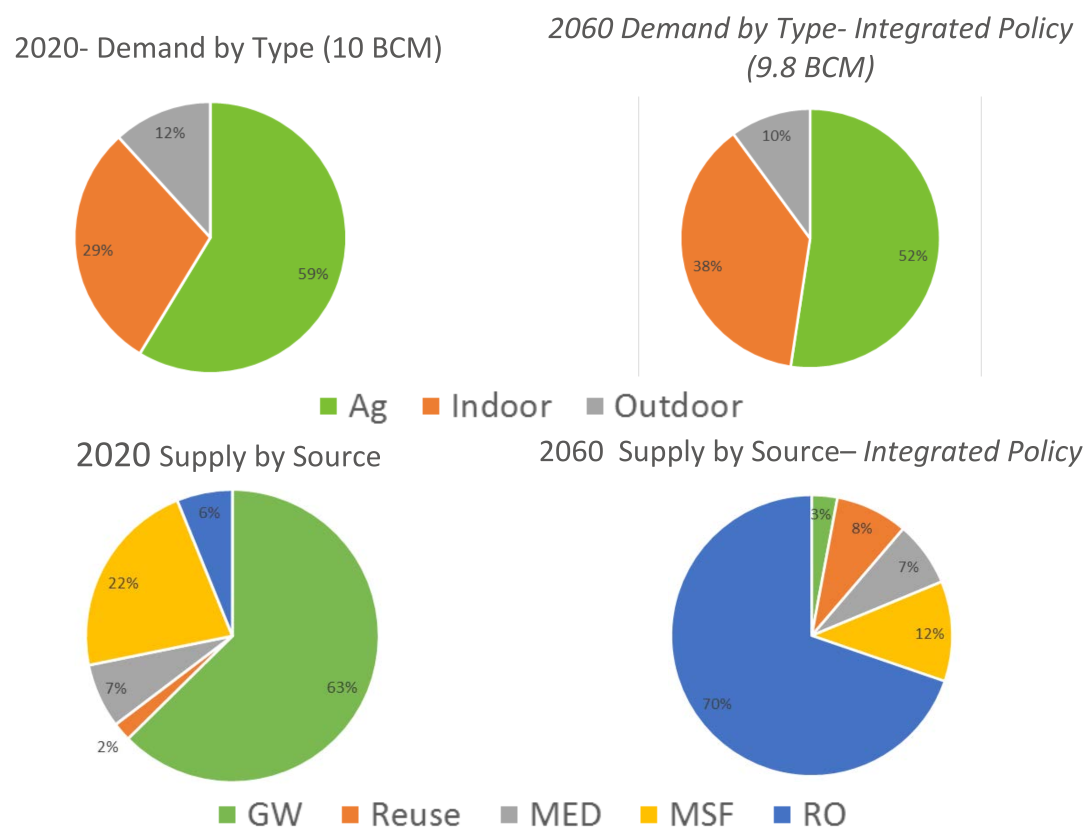
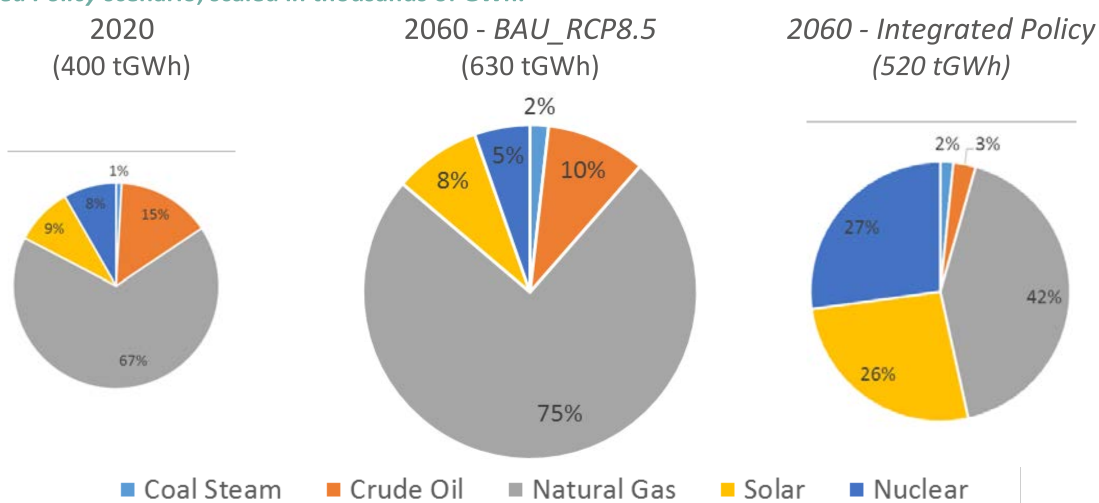


Figure E2 shows that for the *BAU_RCP8.5* scenario, energy demand has increased by about 60% from 2020 to 2060, driven by both population growth and increasing cooling demand due to warmer, more humid conditions throughout the region. These increased energy demands are met primarily through increased energy generation from natural gas sources. For the *Integrated Policy* scenario, demand increases by about 30% from 2020 to 2060, and the fuel portfolio to meet these demands is much more diversified, with solar and nuclear capacity each accounting for more than 25% of total generation. The share of natural gas generation has dropped to about 40%. The *Integrated Policy* scenario implies a modest increase in per unit cost of water from \$35/TM3 to \$38/TM3. The CO2 emissions are at 2005 levels, but the unit cost has roughly doubled, from \$61/tonne CO2 for the *BAU_RCP8.5* to \$122/tonne CO2 for *the Integrated Policy* scenario.

Figure E2. Total annual generation in 2020 and in 2060 for the *BAU_RCP8.5* scenario and in 2060 for the *Integrated Policy* scenario, scaled in thousands of GWh.



1. Introduction and Background

This section provides an overview of the core features of the sub-project. This study was originally designed as a quantitative assessment to better understand the vulnerability of the Arabian Peninsula's shared transboundary groundwater resources due to concerns surrounding socio-economic growth and sea level rise associated with long-term climate change. Based on the research team's initial research activities, several key findings emerged on the current understanding of the transboundary nature of the Dammam/Umm Er-Radhuma aquifer that underlies the Arabia Peninsula, the advantages and limitations of potential groundwater modeling approaches. These findings, detailed below, suggested that a modification to the original technical scope of the sub-project would provide more actionable information. Subsequently, discussions were held among the AGEDI project management team to identify an optimum way forward relative to AGEDI's Local, National, and Regional Climate Change Programme (LNRCCP) goals of promoting improved information systems, developing a network of networks, and strengthening institutional capacity. Four conclusions emerged from these discussions that are important to outline as context for the results presented later in this report. These conclusions are summarized in the subsections below.

2. Negligible Transboundary Groundwater Flows in the Region

The Dammam/Umm Er-Radhuma aquifer is a large groundwater system that flows from central Saudi Arabia eastward to Arabian Gulf waters. Over the past decades, groundwater abstraction had been occurring at unsustainable rates, with Gulf countries heavily depending on the aquifer for meeting agricultural and municipal sectors water demand. As a consequence, there has been increasing seawater intrusion leading to a continuous salinization and deterioration of groundwater quality. These factors suggested that, with the aggravating factor of climate change, the challenge of transboundary groundwater management would be even greater and that intervention measures should be considered at the Gulf Cooperation Council (GCC) level, or the whole aquifer could be lost. At the time the transboundary groundwater management sub-project was designed, the prevailing estimate for transboundary groundwater flows between Saudi Arabia and the other Gulf countries was between 8.3-24.9 Million Cubic Meters (MM3) per year (Murakami 1995), which is only a fraction of the total water used in the country in any one year. A focus on transboundary water risked overlooking more determinant factors in water access.

The Dammam was found to have negligible transboundary groundwater exchange between Saudi Arabia and the other countries of the region- Bahrain, Kuwait, Qatar, UAE, and Oman. This conclusion was reached after a review of a recent water inventory and projection assessments in each country commissioned by the GCC in 2014, and undertaken by United Environment in partnership with prominent research institutions in each country. According to UN-ESCWA, BGR (2013), the average annual abstraction from the transboundary Dammam/Umm Er-Radhuma aquifer system happens mainly in the northern aquifer system in Kuwait and the central aquifer systems in Bahrain, Eastern Saudi Arabia and Qatar but not in UAE. These include approximately 120 MM3/y (1993) for Kuwait, 150 MM3/year for Bahrain (2010), 850 MM3/year in Eastern Saudi Arabia (2004), and 100 MM3/year in Qatar (1983)). These abstractions total more than 1200 MM3/y, with the transboundary Dammam flow estimated at 24 MM3/y or only 2% of the annual abstraction.

Hence, the AGEDI project management team examined various possibilities for redesigning the transboundary groundwater sub-project consistent with these findings. A decision was eventually made to adapt the design of the sub-project to address other, complementary water management issues of particular interest in the region in the context of climate change. This led to a new focus on several core elements, namely an expansion of scope of the study to a) consider the “Water-Energy (W-E) Nexus” as an organizing analytical framework, b) evaluate optimal modeling framework for analyzing the W-E Nexus and seawater intrusion at the regional level, and c) introduce a role for strengthening regional networks through training in W-E Nexus analytical tools. Each of these new core research elements are briefly discussed in the subsections that follow.

2.1. Emergence of the "W-E Nexus" as an Organizing Framework

The "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 infrastructure.

In the Arabian Peninsula, 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. These changes are expected to intensify in the coming years, as the outputs of sub-project #1 (Regional Atmospheric Modeling) have confirmed.[1] Second, regional socioeconomic growth trends indicate that the population in the region's hyper-arid environment is likely to continue increasing and will require additional desalination capacity to satisfy increasing water demands. This will further affect the management of electricity and water systems. Third, new energy and water technologies can increase production efficiency for both resources, if introduced within a water-energy integrated framework. A W-E Nexus strategic approach could help inform the technology research, development, demonstration, and deployment currently underway at several centers of excellence in the region. Finally, as the cross-cutting implications of water and energy have become clearer, tackling the challenges and exploiting the opportunities of the W-E Nexus have moved steadily higher on the international agenda.[2]

Hence, a W-E Nexus approach to the transboundary groundwater management sub-project was considered by the AGEDI project management team to be a more valuable framework to consider in a redesign of the sub-project scope. The initial review of available data confirmed the close links between energy and water in the region. This is especially true due to the strong dependence of each of the Arabian Peninsula countries on the production of desalinated water,

---

[1] For location-specific information about climate change in the Arabian Peninsula, please see the Climate Inspector developed at an output of the regional atmospheric modeling sub-project, available at https://uae.rap.ucar.edu/uae.

[2] For example, see, US Department of Energy, 2014. The Water-Energy Nexus: Challenges and Opportunities", (http://energy.gov/sites/prod/files/2014/07/f17/Water Energy Nexus Full Report July 2014.pdf)

a particularly energy-intensive process. The possibility of expanding the scope of the sub-project to address the regional energy-water nexus was considered feasible, thanks to the amount of GCC water data already obtained and publicly available information for energy from the Energy Information Administration (EIA) in the United States and the International Energy Agency (IEA) in Europe. As this expansion could be carried out without budgeting or scheduling impacts, the decision was made to shift to incorporating an energy-water nexus analysis framework. Hereafter, the title of the transboundary groundwater management under climate change sub-project was formally changed to: "Regional Water-Energy Nexus and Climate Change" as this title betters captures the types of assessments underway.

2.2. Appropriate Modeling Frameworks for Water-Energy Nexus Analysis

Expanding the scope of the sub-project to address the regional W-E Nexus required a reevaluation of the overall modeling framework. At the outset, this reevaluation involved assessing the viability of the water-based modeling tools that had been originally envisioned for application in the sub-project. In addition, it also required a review of the various energy modeling options that could be used within a W-E Nexus analytical framework.

Regarding the water modeling framework, identifying the most suitable model for a W-E Nexus analysis revolved around data issues. Initial research confirmed that groundwater data availability for the region was found to be excellent, due in large part to the water inventory and projection assessments mentioned above. The datasets provided in these reports were considered adequate enough to undertake detailed groundwater supply-demand and seawater intrusion assessments under climate change at the regional scale, as originally designed. However, due to the absence of significant transboundary groundwater flows between countries, a modeling challenge emerged regarding the most appropriate approach to use for undertaking national-level analysis in each country of the region. For such an effort, the Water Evaluation And Planning (WEAP)[3] system, one of two complementary modeling frameworks originally proposed, would still be adequate under any redesign of the sub-project (Yates et al. 2005). WEAP has a built-in function for modeling groundwater impacts that can absorb limitations of data availability. The other modeling framework originally proposed made use of the MODular Three-Dimensional Finite-Difference Groundwater FLOW (MODFLOW) model, and was determined to be unsuitable at this large, regional level. MODFLOW is a data-intensive model and the granularity of the available data for this large region was insufficient to assess the physical configuration of the local groundwater drawdown, cones of depression around individual wells, and groundwater flow dynamics between wells. Hence, the decision was made to move forward using WEAP as the sole groundwater modeling framework.

[3] Information about the WEAP model can be found at http://www.weap21.org

Regarding the energy modeling framework, identifying the most suitable model for a W-E Nexus analysis revolved around the potential for integrating energy and water modeling. The Long Range Energy Alternatives and Planning (LEAP) system was introduced as the energy modeling approach (Heaps 2012).[4] LEAP is an integrated modeling tool that can be used to track energy consumption, production, as well as resource extraction in all sectors of an economy, including seawater desalination, groundwater pumping and water transmission. Moreover, the model can be directly coupled with WEAP to analyze the interplay between water and energy management under changing future conditions that include climate change. Hence, the decision was made to move forward using LEAP as the energy modeling framework.

2.3. Capacity Building Workshop

Given the substantial stakeholder interest in capacity strengthening around W-E Nexus issues, the project team set out to organise a Regional Water-Energy Nexus Training Workshop, which was held in partnership with the UAE Ministry of Energy in October 2016. Particular interest had been expressed in "hands-on" training in the use of the WEAP-LEAP coupled modeling system. The workshop addressed this regional interest and promoted a network of networks by enhancing the Gulf region's research capability and capacity in water-energy assessments under climate change. The workshop helped promote data sharing and collaborations around transboundary groundwater and energy management issues. Moreover, it was carried out with no adverse budget or schedule impacts.

2.4. Organization of the Remainder of this Report

The rest of this Technical Report is organized around several core sections related to the context described above. Section 3 & 4 discuss the data inputs and model structure for WEAP and LEAP, respectively). Section 5 discusses the representation of the costs and benefits in our analysis. Section 6 discusses the scenario analysis framework for exploring policies and measures that influence sustainable resource use within the W-E Nexus, while Section 7 provides an overview of the results for the historical period use the coupled WEAP-LEAP model developed for the Arabian Peninsula region.

[4] Information about the LEAP model can be found at http://www.energycommunity.org/default.asp?action=47

3. Methodological Approach

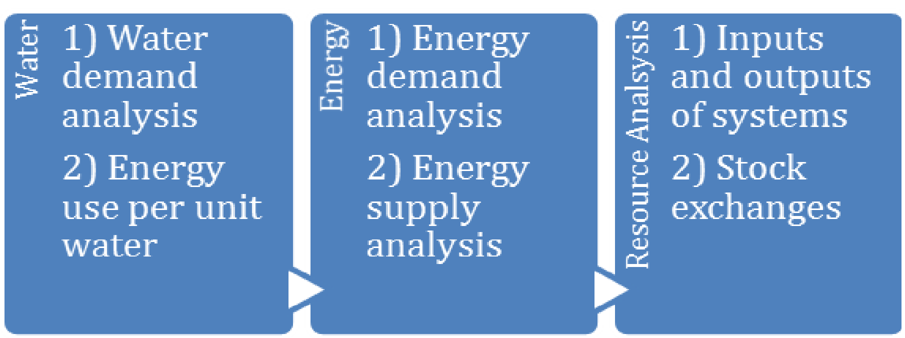
This section provides a synthesis of the conceptual approach, methodological approach and an overview of the W-E Nexus modeling framework. The discussion builds upon the previously submitted "Preliminary Findings" report and "Draft Visualizations" report.[5] For additional details on these topics, the reader is kindly referred to those documents.

3.1. Conceptual Approach

Future water and energy planning in the Arabian Peninsula will be characterized by a consideration of the nexus including the energy used in providing water. The region's growing population and growing per capita water demand for public water usage like amenities have increased the pressure on potable water resources. Water itself is not limited, since sea water is readily available for desalination. Turning sea water into potable water requires energy. Similarly, as groundwater withdrawals encourage saltwater infiltration into the aquifers, pumping will incur energy costs for treating the water to sufficiently potable levels. Wastewater produced in these systems can have the potential to be reused in the environment, following treatment which also requires energy. As natural freshwater becomes scarcer, the region's water supply and energy needs will become more tightly coupled.

The energy requirements of water usage can be calculated for the present and the future. The conceptual analytical framework can estimate the inputs and outputs of the W-E Nexus as well as changes in stocks in freshwater resources and energy. Figure 3-1 provides a conceptual overview of the process.

Figure 3-1: Conceptual approach for water-energy analysis



[5] The "Preliminary Findings" report (CCRGa, 2014) was submitted on 2 July 2015. The "Draft Visualizations" report (CCRGb) was submitted on 14 October 2015. Please contact Jane Glavan (Jane.Glavan@ead.ae) for a copy of the reports.

The approach first examines the year-by-year demand for water and the energy requirement to supply such demands. These energy requirements are then identified at the country level, where two pools of energy are identified.

A pool of electricity and diesel for water-related supplies processes such as desalination, wastewater treatment, groundwater pumping, water distribution, and re-use; and a pool of electricity for residential-commercial-industrial use. These demands are quantified to provide an overview of possible futures until 2060 using different scenarios to look into changes in water and energy supplies and demand. The process required extensive data acquisition and parsing, which benefited from local experts and stakeholders involvement.

The interactions of water and energy demands require the development of detailed models of the respective resources. This framework uses two models, the Water Evaluation and Planning (WEAP) system model and the Long-range Energy Alternatives Planning (LEAP) system for the Arabian Peninsula. Some regions are more aggregated than others, for example, due to the focus on the Arabian Gulf, the Eastern Region of Saudi Arabia is modeled in detail, while the major population centers of the west are aggregated into a single demand site, with the exception of Riyadh. A key element of the framework is the ability to readily analyze multiple scenarios that may be of particular interest or relevance to policymaking in the region. The scenarios are described in Section 6. The linked models were used to simulate a 61 year period, from 2000 to 2060. The ten year period prior to 2010 allowed for validation of the model data against observed data.

Figure 3-2: Interaction between WEAP and LEAP in the project

The models examine resource stocks and flows over 60 years. Figure 3-2 illustrates the modeling sequence where WEAP water data plays into LEAP, which includes energy usage that can subsequently inform the electricity calculations in WEAP, creating an exchange between the two systems. Both models contribute results to the project. All of the information in the databases is being processed to quantify water demands, water use, and energy demands and energy use.

A core feature of the methodological approach was a prominent role for the "socialization" of the models' data and draft technical results. The assumptions made in the model were presented to stakeholders and regional water-energy specialists for review and comment. The socialization exercises were useful for the perspectives and information to improve the WEAP and LEAP models. Though not all the data mentioned in these meetings was subsequently provided, the models benefitted from stakeholder feedback. Specifically, conversations over email took place with Tareq Sadek of the UN's Economic and Social Commission for Western Asia and Sgouris Sgouridis of the Masdar

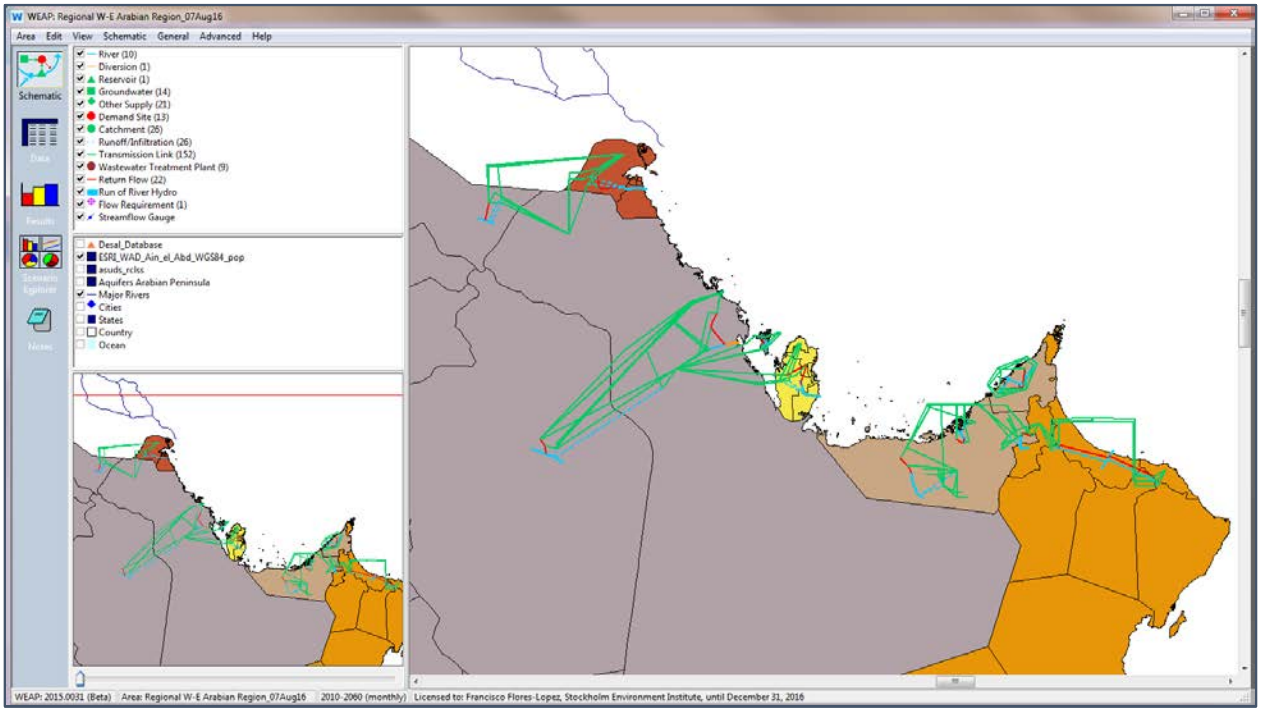
Institute. The socialization approach to data gathering and validation is intended as a way to ensure that the analysis closely mirrors stakeholder perspectives and knowledge.

3.2. Overview of WEAP – the Water System Model

The WEAP model examines water quantity availability in the Arabian Peninsula to balance supplies and demands in the different geographical areas. WEAP provides an 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 includes physically-based, hydrologic simulation capability that can be used to model watershed dynamics, irrigation demands, groundwater recharge and other components of the hydrologic cycle. WEAP can represent multiple time steps, with increments as short as daily and as long as yearly. The WEAP model has been used across the globe and provides users and viewers with clarity in data management structures and flexibility to model specific situations, like energy use from water supply.

A monthly WEAP model was developed for the Arabian Peninsula (Kuwait, Bahrain, Qatar, Saudi Arabia, Oman and the UAE). 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 and groundwater availability. The schematic view of the Arabian Peninsula WEAP model is illustrated in Figure 3-3. The schematic demonstrates the aggregated nature of the regional representation of water supply (green lines) and demand (red dots) and their linkage.

Figure 3-3. WEAP interface for the Regional Water Energy Model.



3.3. Overview of LEAP - the Energy System Model

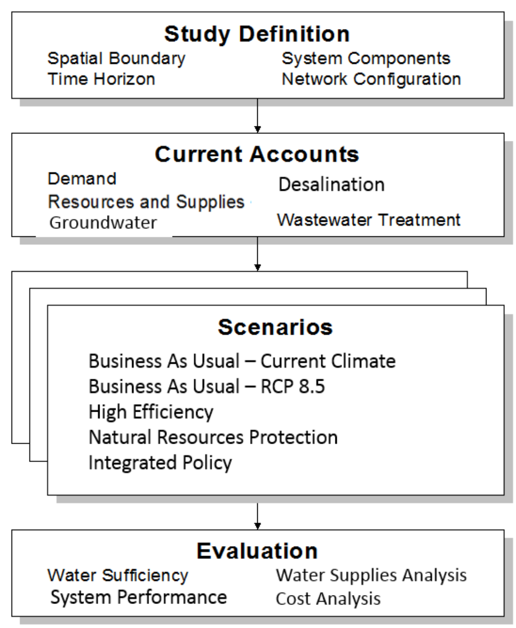
The LEAP model examines the links between energy production and water requirements in the Arabian Peninsula. The Long Range Energy Analysis and Planning (LEAP) decision support system (DSS) is an integrated modeling tool that can be used to track energy consumption, production and resource extraction 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.

The LEAP model includes a representation of the electricity generation and desalination technologies and their associated fuel and energy transformation methods used to create electricity and freshwater. This LEAP model for the Arabian Gulf region has focused on the electricity sector and the fuels and technologies used for its generation. Other energy intensive sectors, such as transportation, have not been included in our analysis. Many of the desalinization plants in the region are co-generation systems, where both electricity and water are produced concurrently. Desalinization technologies are dominated by thermal methods, such as Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED), while the less used but equally important Reverse Osmosis (RO) technology is growing in importance. The RO technology makes use of pressure generated by electrical pumps to force water through membranes. Groundwater abstraction from the hundreds of wells in the region occurs overwhelmingly through the use of electric (as opposed to diesel) pumps. The model explicitly considers how electricity is produced in the region (i.e. oil, natural gas, nuclear, solar, wind, etc.) and how it is used (i.e. people and their use of electricity for heating and cooling, commercial and industrial activity, and to supply water for human consumption, irrigation, amenity watering of green spaces, and water treatment, etc.). Since LEAP includes data on the carbon emissions associated with the use of various fossil fuels, the analysis enables one to explore how various energy policies and the portfolio of water uses translate into carbon emissions associated with electricity generation and usage. In generating desalinized water, we have assumed that the different technologies (i.e. MSF, MED, or RO) have an electricity equivalence to create freshwater.

4. Data Inputs and Historic Period Validation

Both the WEAP and LEAP models begin with a schematic representation of the water and energy supply-demand system. 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. Once the components are represented physically, users can populate them with data and then structure the model to assure that system constraints are adequately represented. For uncertain future infrastructure projects or growth trajectories, WEAP and LEAP uses scenarios that extend into the future to see impacts within the system. These scenarios can compare future results against what would have transpired in the absence of those changes. Lastly, once the WEAP and LEAP models are built, they must be validated against historic conditions to ensure that they properly represent the physical realities as closely as possible. The overall sequence of steps is illustrated in Figure 4-1.

Figure 4-1: Overall sequence of models implementation



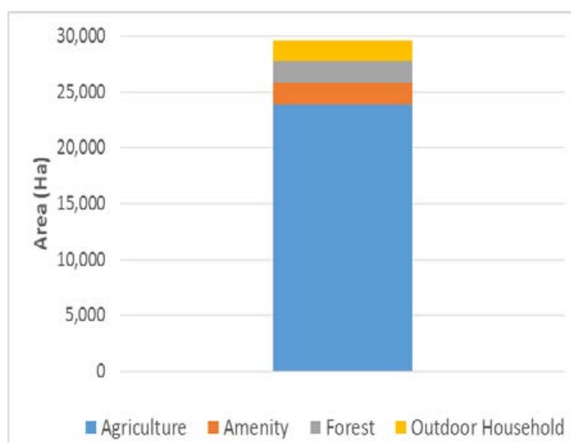
The WEAP and LEAP models are fundamentally data-driven and the project has made great efforts to obtain necessary data from credible sources. We benefited from socializing the results with local stakeholders and managers.

4.1. WEAP Water Data Sources and Assumptions

The water model uses a host of data assumptions that influence water supply and demand, including costs associated with water production and transmission activities. Thanks to publicly available data and the many supportive stakeholders and analysts in the region who provided data, all of these local data that are essential to running the model have been acquired and are detailed in Annex A. Validation or corrections of these assumptions is an essential milestone for ensuring that the research team has a valid understanding of the regional water system.

The WEAP model for the Arabian Region was developed on a country-by-country, aggregated basis. Indoor and outdoor water demand are aggregated at the regional level (e.g. for the entire UAE there are five demand sites including the Abu Dhabi Region, the Western Region, the Al Ain Region, the Dubai Region and the Eastern Region) that encompasses residential, industrial and commercial water demand on a per-capita basis. In WEAP there is an estimate of indoor per-capita water demand by liters per person per day (FAO AQUASTAT, 2008) associated with socio-economic activity in the region (aggregated municipal, industrial and commercial water use). For outdoor water demands, the WEAP model has an aggregation of irrigation demands that includes a coarse category for amenity, forest (for the case of UAE), outdoor household and agriculture. The corresponding areas under agriculture were provided by the FAO AQUASTAT reports for each country, and by previous modeling efforts developed for the UAE (EAD, 2009). Areas of amenity, forest, and outdoor household were estimated as a fraction of the total urban land cover area based on an Atlas of Urban Expansion (Angel et al., 2000). In Figure 4-2, the corresponding areas are shown as an example of data inputs in the WEAP model demanding irrigation in the Abu Dhabi Region catchment.

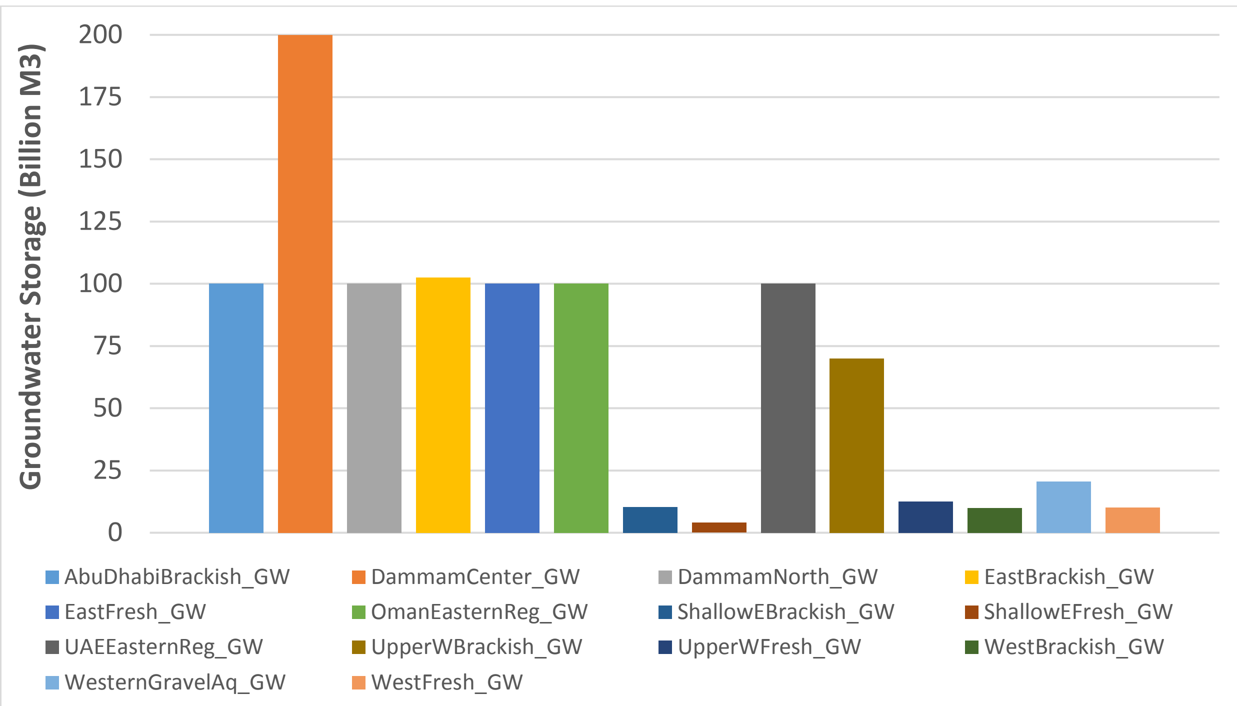
Figure 4-2: Example of outdoor irrigation demand areas in the Abu Dhabi Region



It was initially decided that, for each of the six countries included in the analysis, all regions and thus all water and energy uses would be included in the analysis. This assumption resulted in a disproportional water use for Saudi Arabia, particularly when the western and southwestern regions were included, since these are the areas with considerable amounts of irrigated agriculture. Because of the LNRCC's focus on the Arabian Gulf region and to better balance the analysis among the various countries, the western and southern region of Saudi Arabia and the Southern Oman region were dropped from this analysis. This resulted in a decrease in the represented regional population by 38% (i.e. from 45 million to 28 million in 2010) and a decrease in total water use of nearly 50% (i.e. from 19.6 BCM to 9.8 BCM in 2010).

For the WEAP model's supply side, there are three major water supply sources: groundwater, desalination, and the reuse of treated wastewater. To represent the groundwater supply in the Arabian Gulf region there are twenty aquifers implemented in the WEAP model. Figure 4-3 shows the corresponding groundwater storage volume for all 20 aquifers as they are implemented in the WEAP model. The main section of the model on the Arabian Gulf coast is divided into three unconnected sections of the massive Dammam aquifer underlying the eastern region of the peninsula (north, center and south). The divisions of the aquifer system stem from a study convened by the German Cooperation (GIZ), the Federal Institute for Geosciences and Natural Resources (BGR) and the United National Economic and Social Commission for Western Asia (UN-ESCWA 2013).

Figure 4-3: Groundwater storage volume for aquifers in the Arabian Region.



The Dammam aquifer constitutes the only groundwater source available to users in the northern and central regions of the model. The North Dammam supplies water to Kuwait and the Northern Boundary region of Saudi Arabia (see Figure 4-4). The Central Damman aquifer, shown in, supplies the Eastern region of Saudi Arabia, Bahrain and Qatar. In WEAP, the region also includes the city of Riyadh because it interacts with the urban centers in other ways, particularly by taking desalinated water from the coast.

Figure 4-4: WEAP schematic view of the North Dammam aquifer system

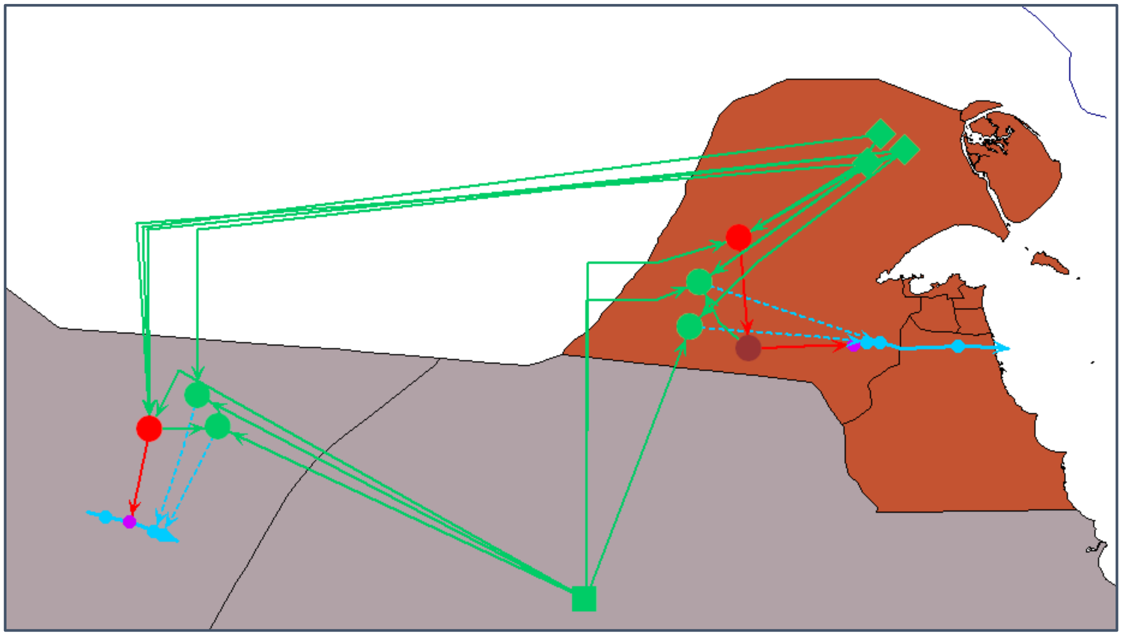
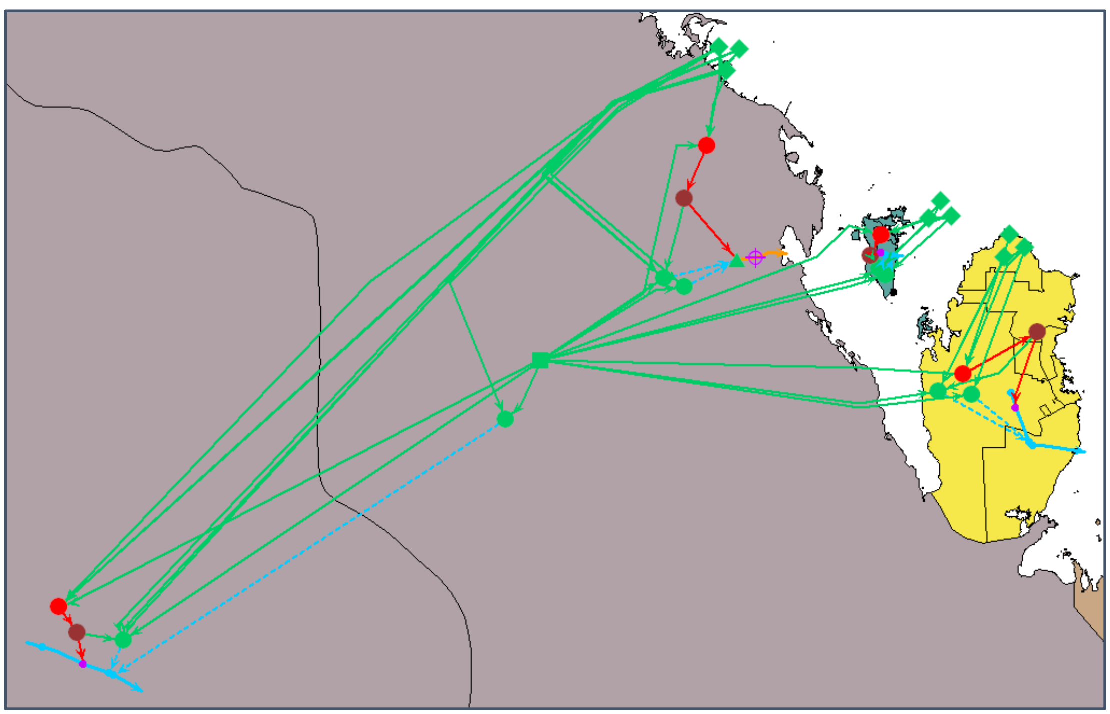


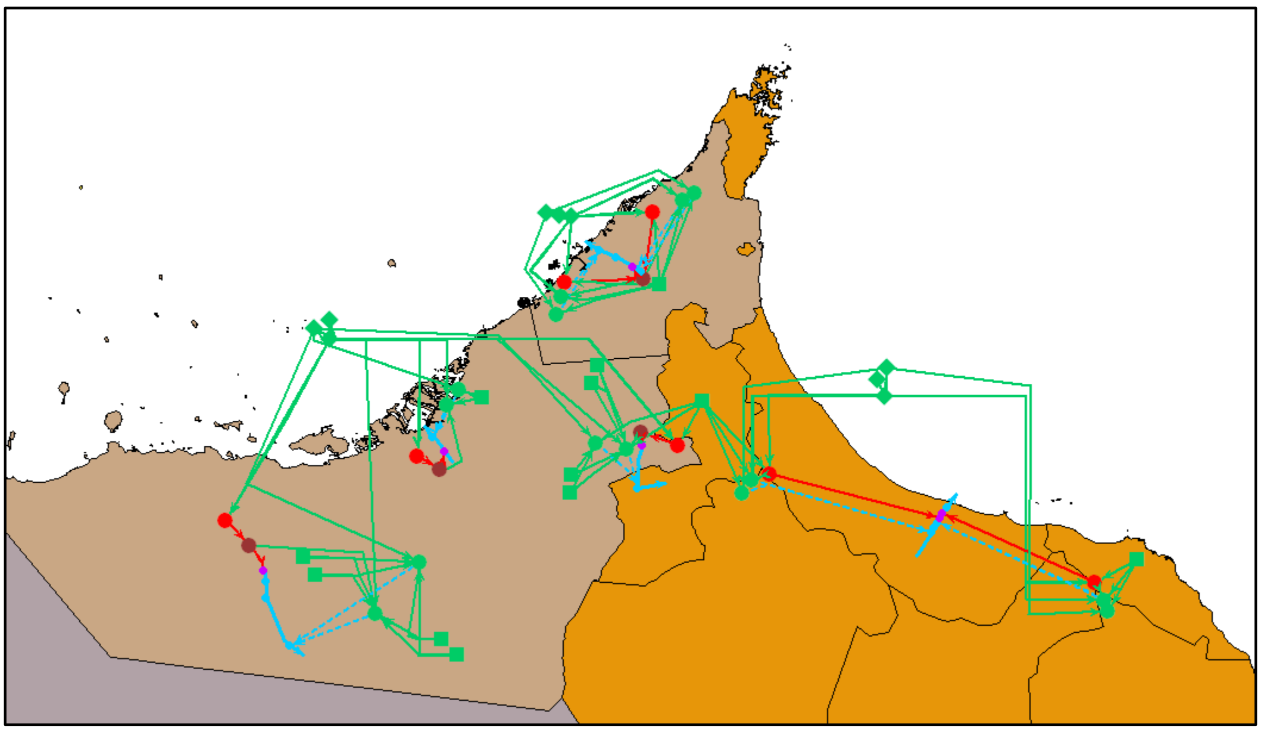
Figure 4-5 shows the population centers that interact within the central region of the Dammam aquifer.

Figure 4-5: WEAP schematic view of Central Dammam aquifer system



Finally, the southern aquifers of the UAE and Oman and Figure 4-6. In the southern region, the UAE has identified additional groundwater sources (Table B-3 in Annex B shows all initial storage volumes for each individual aquifer represented in the model). Outside the east coast, Southern Oman, and Western Saudi Arabia do not have access to the Dammam aquifer but have access to other aquifers. These regions are not crucial to the development of the model. Assumptions about groundwater storage volumes were taken from a study convened by the German Cooperation (GIZ), the Federal Institute for Geosciences and Natural Resources (BGR), the United National Economic and Social Commission for Western Asia (UN-ESCWA 2013), previous modeling efforts developed for the UAE (EAD, 2009), and some were implemented by the project team and placed in the WEAP model where information from regional experts and stakeholders provided some better estimate. It should be noted that a better identification and representation of the available fossil groundwater in the region is a recommendation for future research.

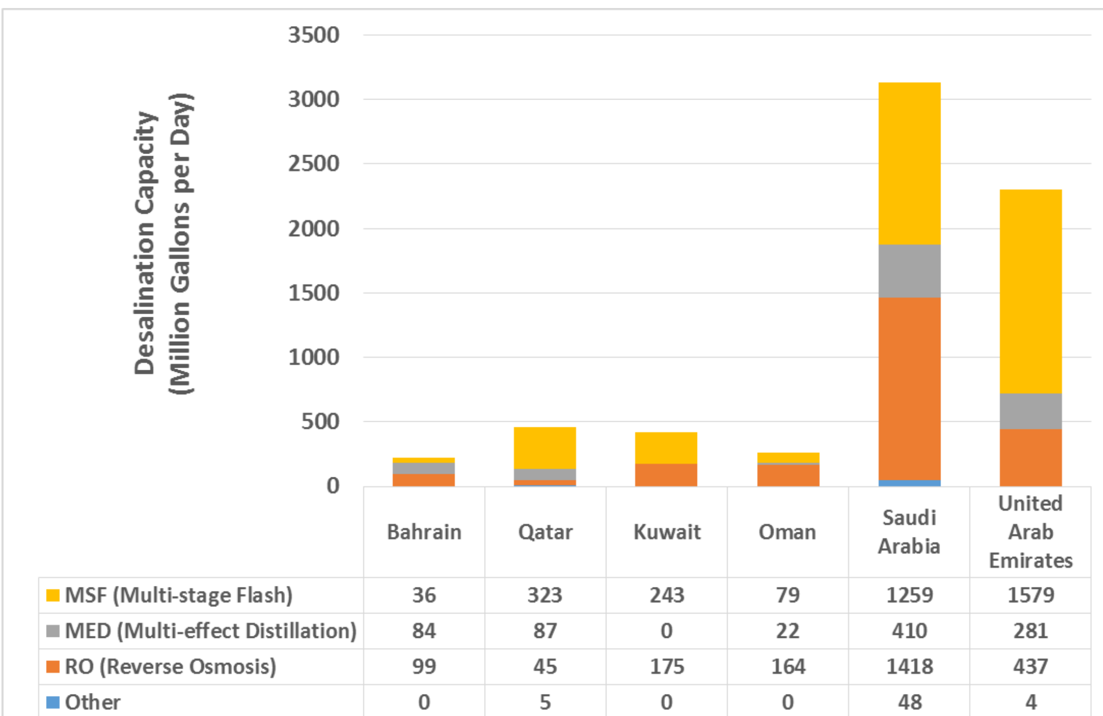
Figure 4-6: WEAP schematic view of the southern aquifers systems of the UAE and Oman.



The supply of freshwater through desalination technologies in the region are dominated by Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED), while the less used but equally important Reverse Osmosis (RO) technology is growing in importance. These three desalination technologies were implemented in the WEAP model for the Gulf countries (Bahrain, Qatar, Kuwait, Eastern Saudi Arabia, UAE, and part of Oman) in aggregated capacity and given as proportional shares of capacity, where we have assumed that MSF is 62%, MED is 20%, and RO Is 18% of installed capacity for the historic period.

For each demand site in the WEAP model representing commercial, residential and industrial water demand there is a corresponding wastewater treatment plant that treats water to a non-potable standard to be reused for outdoor irrigation in the municipal and amenity sectors. Due to the limited data available for wastewater treatment capacity, the project team assumed that currently 10% of all water that reaches the wastewater plant is treated to a reusable water quality standard for outdoor use. In WEAP the electricity associated with water returned to a wastewater treatment plant and treated to a non-potable standard is calculated based on an electricity demand in kWh per cubic meter of treated wastewater. In the same way, the electricity demand for desalination, groundwater pumping, and water distribution is calculated in LEAP based on energy demand (KWh) per cubic meter of water. More detail information about this is presented in the energy LEAP description section. Figure 4.7 shows the proportional share of desalinization capacity by technology for each country in 2010.

Figure 4-7: Current desalination capacity by technology in the Arabian Region.

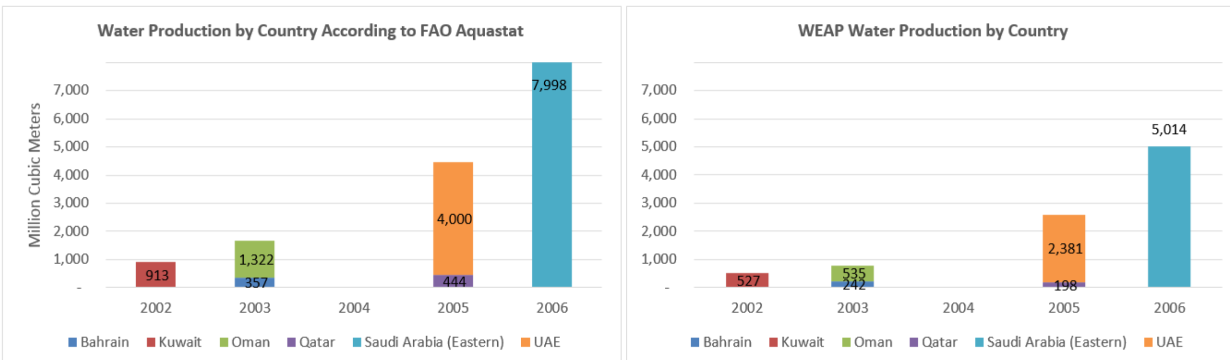


	Bahrain	Qatar	Kuwait	Oman	Saudi Arabia	United Arab Emirates
MSF (Multi-stage Flash)	36	323	243	79	1259	1579
MED (Multi-effect Distillation)	84	87	0	22	410	281
RO (Reverse Osmosis)	99	45	175	164	1418	437
Other	0	5	0	0	48	4

4.2. WEAP Historic Period Validation of Water Supply and Demand

Observational records from the Food and Agricultural Organization (FAO) AQUASTAT of the United Nations were used to validate the WEAP models estimate of water use. Validation of water supply and demands employed manual validation techniques replicating annual values of water withdrawal by sources (groundwater, desalination water and reused treated wastewater). A set of annual available water withdrawal values were developed for each country in the Arabian Peninsula to capture the regional water demands. Figure 4-8 shows the annual water production by country according to FAO AQUASTAT and the corresponding WEAP water production.

Figure 4-8: Validation of water production in the Arabian Peninsula.



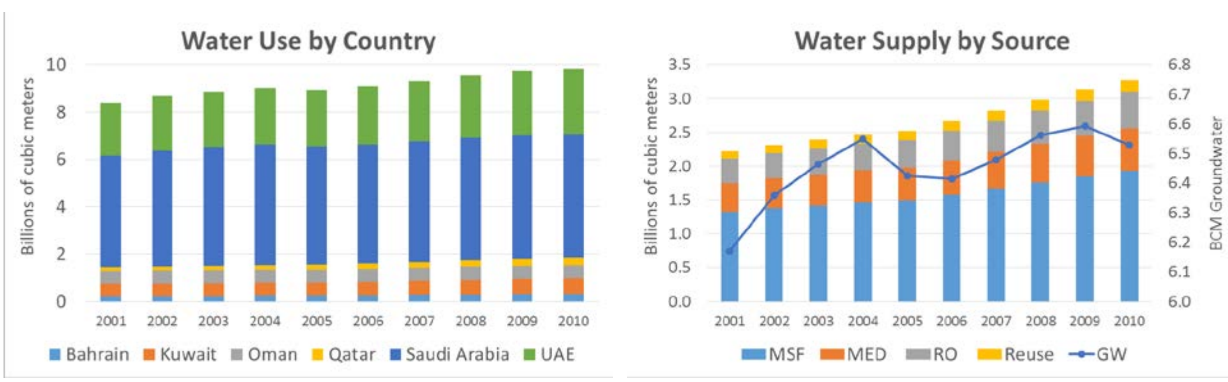
Note: FAO Aquastat reports annual volumes of water production on specific years (2002 for Kuwait, 2003 for Bahrain and Oman, 2005 for Qatar and UAE and 2006 for Saudi Arabia). The corresponding annual water production in WEAP is shown in the right hand figure.

Numbers of water production by country in the WEAP model are underestimated. This validation process was implemented based on the direct feedback to project team from regional stakeholders and regional water-energy specialists, provided during the socialization of the models' data and draft technical results webinar on 26 January 2016. The regional experts made the point that FAO AQUASTAT data was not accurate and its numbers for the annual water production in the Arabian Region were inflated. As a consequence, the estimated water production in WEAP was reduced as shown in Figure 4-8. Between 2002 and 2006, excluding non-Gulf regions from the analysis, the total annual water use in the six countries of the Arabian Peninsula were estimated to be about 10 BCM, with about 6 BCM used in the agricultural sector and 4 BCM for municipal, industrial and commercial uses.

Due to the complexity of obtaining data representing water production by both country and source in the Arabian Peninsula, the project team decided to use a conservative approach to estimate water demand based on experience gained in similar environments. The approach assumed that applied irrigation water was between 900 to 1200 mm per year for both agricultural uses and non-agricultural uses such as gardens, parks, and other outdoor amenity uses. With that in mind, the project team produced the model validation data summarized in Figure 4-8 for the water production in the Arabian Peninsula. Values of total water production vs. total water withdrawal were underestimated, within a range varying from -20% to -55% depending on the country (Table B-8).

Some model parameters were adjusted on a country-by-country basis, such as the irrigated amenity areas in the urban landscape, outdoor household use, and managed forests. The estimated fraction for these urban irrigated areas varies for each country in the region and those areas are shown in the Annex in Table B-1. One important distinction in modeling water use, particularly when validating against the historic period, is the assumption that per-capita water use remains constant. This contrasts with the energy sector, where historic data suggests there has been considerable per-capita growth over the past few decades. In the same Annex B, the groundwater, wastewater and desalinated production according to the FAO AQUASTAT data and the same data simulated in the WEAP model are shown in Table B-5 and Table B-6. The areas under irrigation in each country were those reported by FAO AQUASTAT reports. As a result of this validation process, Figure 4-9 shows the total WEAP model supply delivered in the Arabian Region from 2001 through 2010 by country and source. Values of supply delivered during this period vary from more than 8 BCM in 2001 to about 10 BCM in 2010. The water delivered to the region was supplied by the three different supply sources including groundwater, desalination, and reclaimed waste water. Groundwater is the primary supply source for agriculture and some municipal demand, representing about 65% of the water delivered followed by desalination (MSF, MED, and RO) at 31%, and 4% of treated wastewater as reuse.

Figure 4-9. WEAP model supply delivered in the Arabian Region by country (left) and source (right).

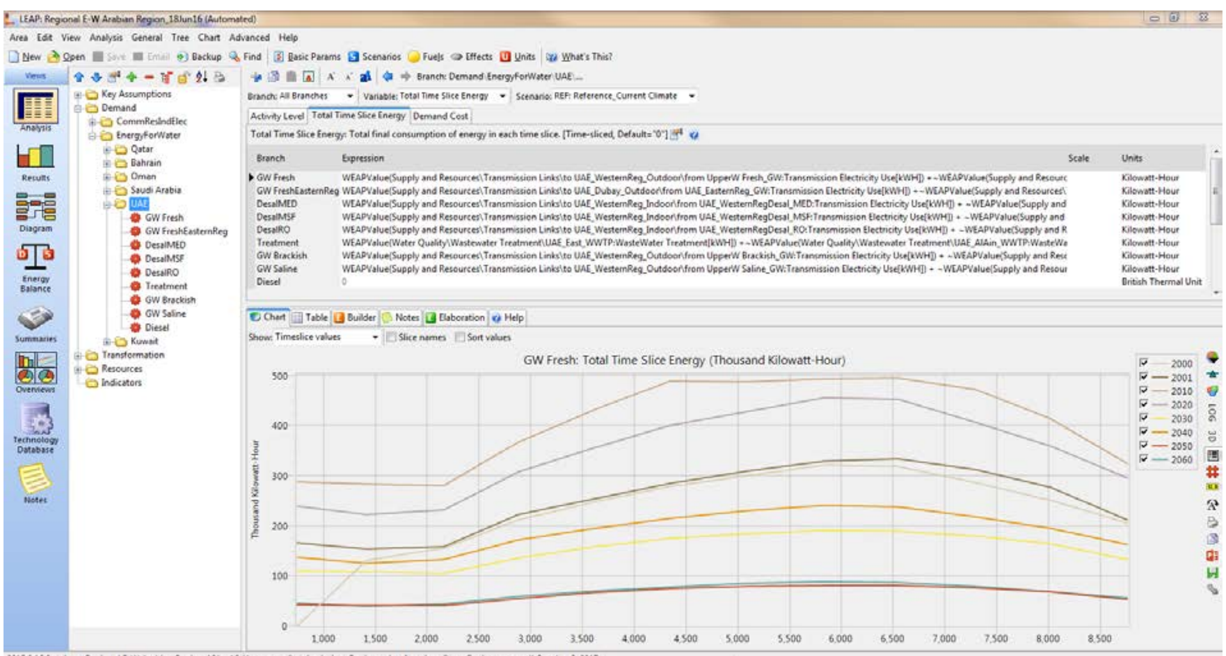


4.3. LEAP Energy Data Sources and Assumptions

The Long Range Energy Analysis and Planning (LEAP) decision support system is an integrated modeling tool that can be used to analyze energy supply and demand. The model tracks energy consumption, production and resource extraction, accounting for both energy sector and non-energy sector greenhouse gas (GHG) emission sources and sinks. In addition to tracking GHGs, LEAP can also be used to analyze emissions of local and regional air pollutants, making it wellsuited to study climate co-benefits of local air pollution reduction. LEAP is useful when conducting integrated resource planning, GHG mitigation assessments, and Low Emission Development Strategies (LEDS). LEAP is not a model of a particular energy system, but rather a tool that can be used to create models of different energy systems, where each requires its own unique data structures. LEAP supports a wide range of different modeling methodologies: on the demand side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modeling. On the supply side, LEAP provides a range of accounting and simulation methodologies for modeling electric sector generation and capacity expansion planning.

A typical LEAP application is developed through a multi-step process. As with its water analog, WEAP, the study definition sets up the time frame, spatial boundary, system components and configuration of the problem. The Current Accounts scenario provides a snapshot of historic energy demand, resources and supplies for the system for the beginning year of the simulation. LEAP also serves as a decision support system by providing data management and reporting capabilities for visualizing data and results. This sequence of analytical steps closely tracks the water analog model, namely study definition, current energy accounts, scenario construction and evaluation. The model's overall menu is illustrated in Figure 4-10.

Figure 4-10: LEAP analysis menu view showing the LEAP model's link to WEAP and its representation of electricity demand associated with water related activities.



4.4. LEAP Data Inputs for this Regional Water-Energy Study

The energy model makes use of data assumptions that influence energy supply and demand, as well as the costs of technologies and fuels. These include some of the same assumptions being used for the water side of the energy-water nexus, namely baseline population by country, population growth rate estimates and desalination plant capacities and performance characteristics. It also includes energy-specific data such as historical electricity demand statistics, power station fuel types, supply-side efficiency, and output-based emission factors. End-use consumption refers to energy consumed in industrial, business, and residential activities, such as lighting, heating and cooling, running motors and electrical devices, powering industrial processes, etc. Primary or source energy is represented where it is first accounted, (e.g. the heat associated with coal, oil and natural gas), before it is transformed into, for example, electricity.

Electricity demand has been divided into two major categories; water-related and non-water related. The non-water related electricity demand has been simplified in LEAP by assuming a population in each region and a per-capita electricity use. *Per-Capita* electric energy intensity (MWh/person) are estimated for each region for the period 2001 through 2010, computed using data from international energy statistics compiled by the US Energy Information Administration (EIA) (please see www.eia.gov), local sources such as the Abu Dhabi Water and Electricity Authority and others. The estimation of electricity demand is based on a polynomial regression model that estimates electricity use by country as a function of population, per-capita electricity demand, and a monthly heat index[6] for each country and is summarized below. The model's coefficients represent base per-capita demand, which can grow over time to reflect increasing per-capita use. Part of this growth stems from a behavioral response to a higher heat index, when there is greater need for cooling during the warm summer months. The per-capita energy demand coefficients also reflect a prosperity level, as certain regions can afford the higher cost of cooling, even with high heat index.

Water related energy demand is primarily the energy needed for desalinization and is given in electric generation equivalent, as natural gas and fuel oil have been the primary fuel sources. In many cases, desalinization is done via co-generation, where an energy facility burns fossil fuel to generate electricity and the heat generated from this combustion process is used to power the desalination process either through multi-stage flash (MSF) or multi-effect distillation (MED) processes. Reverse osmosis (RO) technology, on the other hand, uses electricity directly to generate pressure for the membrane filiation process. Other water related energy uses include the pumping of groundwater by either diesel or electric motor and the energy associated with

[6] The Heat Index is a measure of how hot it really feels when relative humidity is factored together with the actual air temperature.

the treatment of municipal waste water, which can either be treated to a non-potable standard for outdoor re-use, can be used for groundwater recharge, or can be wasted back to the ocean.

Water sector electricity demand was estimated by the WEAP model based on electricity intensity estimates by activity multiplied by monthly water use for each activity. Water related electricity demands include groundwater pumping, water transmission (lifting and conveyance), municipal water treatment (potable, waste, desalination, and reuse), and agricultural end uses. Table 4.1 shows the list of assumed energy intensities associated with water use activities.

Table 4-1: Energy intensities for key water-sector activities (Source: World Business Council for Sustainable Development).

Activity	kWh/m^3	Description
GW Pumping*	0. 5	Electricity use is a function of water pumped and depth to groundwater; α(depth) * (kwh /m^3).
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.

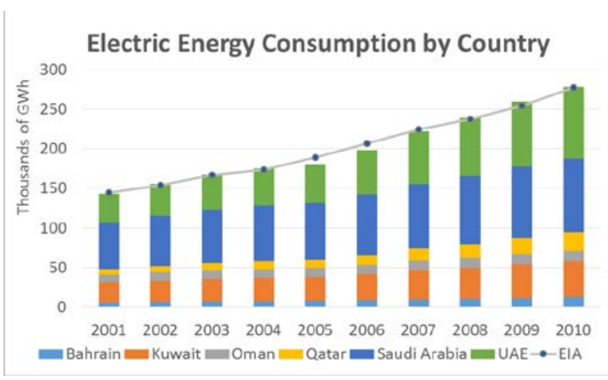
**Electricity use associated with groundwater pumping varies by depth to Groundwater*

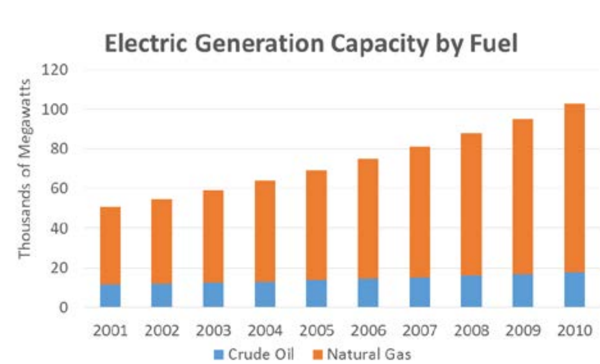
Water sector electricity demand is spatially disaggregated in WEAP throughout the Arabian Gulf region and dependent on the amount of water used, the source of water and the type of use. The resulting electricity use by the water sector is passed from WEAP to the LEAP model during the concurrent model run. When these water sector electricity demands are brought into LEAP, they are aggregated at the country level. It was assumed that water related household electricity use was primarily for water heating and was embodied within the commercial-industrial and municipal electricity use category, to avoid double-counting. With the exception of Saudi Arabia, which uses considerable amounts of diesel fuel for groundwater pumping to meet agricultural demands, it was assumed that groundwater pumping takes place through the use of electricity.

4.5. LEAP Historic Period Validation

Validation of assumptions in terms of the energy use estimates is essential to ensure that the supplies and demands of the regional electricity system are properly represented. The LEAP simulated estimates of annual electricity consumption at the national level for the Arabian Gulf countries are shown in Figure 4-11 (p.31) and shows that the model generally reflects the total electricity production and trend in energy growth over the historic period. The population represented for the six countries of the Arabian Gulf region included in this study was just over 17.5 million in 2001, growing to 28 million by 2010 for a growth rate of about 6%, while energy consumption over this same period nearly doubled from 145,000 GWh to 275,000 GWh by 2010 corresponding to an annual growth rate of more than 8%. We estimate that the portion of the population for the six countries included in the study represents about 60 percent of the total, both currently and in the future. With this assumption, the annual total LEAP simulated electric demand is very close to the EIA estimate as shown in Figure 4-11. The LEAP simulated electricity demand per-capita is estimated around 6,000 MWh/cap for Saudi Arabia and Oman and to more than 11,000 MWh/cap for Bahrain, the UAE, Qatar, and Kuwait. The biggest consumer of electricity is Saudi Arabia, also with the largest population, followed by the UAE, Kuwait, and then the three other countries.

Figure 4-11: Left: Historic electric energy consumption by country in GWh and modeled by LEAP (bars) and the estimate of the annual energy consumption for the same six countries from the Energy Information Administration (EIA). Right: Electricity capacity by fuel source in MW. Note that solar and wind are less than 0.1% of total production through this period.





Most of the fuel used to generate electricity in the Arabian Gulf region is from natural gas. Saudi Arabia is the exception, where nearly half of their generation is from fuel oil and the other half, from natural gas. The assumed total installed electric generation capacity for the six Arabian Gulf countries included in this study in 2001 is about 50 GW, of which about 75% is in natural gas and 25% in oil (Figure 4-11). Total capacity of both fuel sources grow proportionally through 2010, with a total capacity of more than 100 GW[7]. Renewable generation capacity from sources like solar and wind during this period are a trivial fraction of the total generation and they remain a fraction of total generation until 2015. Table 4-2 summarizes the assumptions regarding monthly percent availability and process efficiency for each fuel source (UEI 2003).

Table 4-2: Monthly generation fraction, with solar having a seasonal distribution based on average regional latitude of 25 degrees North and assumed process efficiency for each generation. New Natural Gas Efficiency is assumed 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%

Figure 4-12 shows regional energy consumption in the water sector by use type including desalinization technology, groundwater pumping that uses electricity (this excludes diesel pumping in the agricultural sector) and waste water treatment and distribution for the period 2001 through 2010. Electric energy use associated with multi-stage flash desalination is the greatest water related energy use, followed by MED and GW pumping. The figure also shows country level energy demand by country and shows Saudi Arabia with the greatest demand, followed by the UAE and Kuwait.

[7] The EIA International reports a total installed capacity for Saudi Arabia, Kuwait, Bahrain, Qatar, the UAE, and Oman in 2010 of about 165 GW and we have assumed that our study area represents about 60% of this capacity or 100 GW.

Figure 4-12: LEAP simulated, historic period energy consumption by the water sector for each technology type (left) and for each country in the region (right).

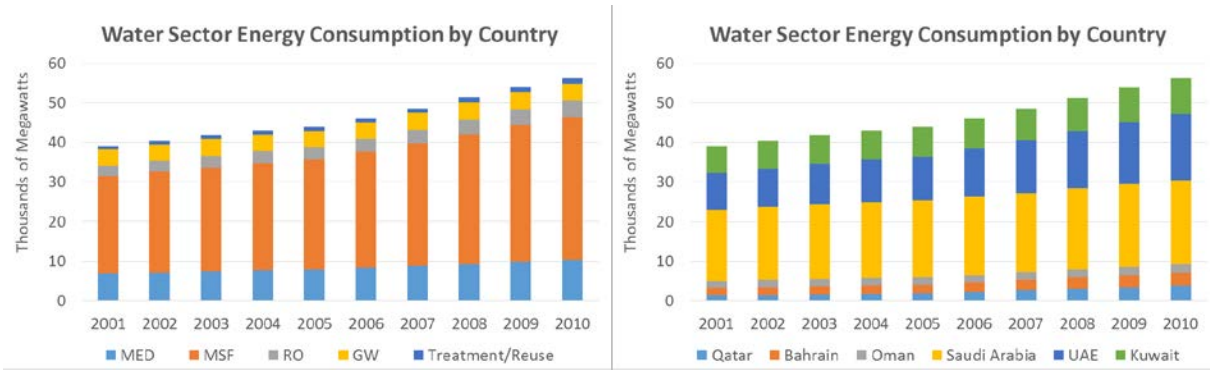
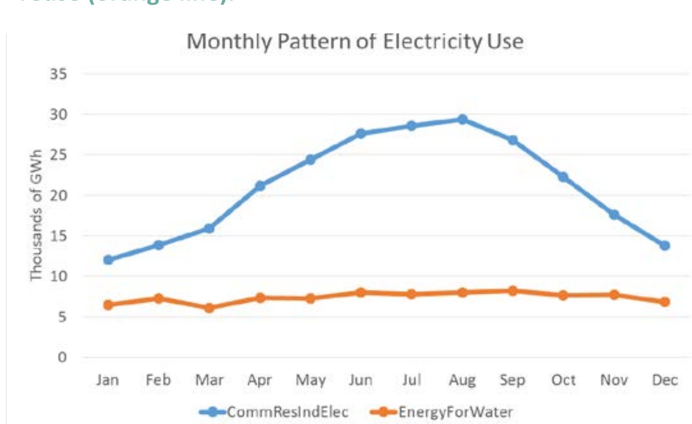


Figure 4-13 is the average pattern of monthly electricity and water use for 2001 through 2010 for all six countries in the Arabian Gulf region included in this study, disaggregated by the commercial-industrial and household sector (computed by LEAP); and the water sector, which is estimated by WEAP and passed to LEAP.

Electricity use for commercial, industrial, and household uses has a strong summer peak, driven primarily by the high summer heat index[8]. Electricity use in the water sector is nearly constant, as water use does not have a strong seasonal signal. The demand for electricity related to water use depends on the per-capita municipal use and irrigation demands which are influenced by climate patterns. When considering all electricity demands, summertime monthly peak electricity use is about 30% higher than the annual average.

Figure 4-13: Monthly average pattern of residential, commercial, and industrial electricity use (blue line) and electricity use associated with water related activities, including pumping, desalinization, water treatment, and reuse (orange line).



[8] The heat index combines relative humidity and temperature to reflect the role that higher humidity has in the perceived temperature.

4.6. Actions vs. Policies

In the previous sections, we have demonstrated the ability of the integrated WEAP and LEAP models to represent the water and electricity supply and demand of the six major countries that comprise the Arabian Gulf Region. We have demonstrated that the region has experienced rapid growth at the beginning of the 21st century, especially in terms of demographics and the use of water and electricity to meet growing demands amid rapid economic growth. We have shown that natural gas and then fuel oil are the major fuel sources that have been used to meet these growing electrical needs. This same fuel is used throughout the region, often in co-generation with electricity, to generate the potable water supply for the region using various desalinization technologies. Water use has also grown in the region and while desalinization capacity has followed suit, the use of groundwater for irrigated agricultural is still the largest water use.

We have developed an integrated modeling platform that can be used to explore the impact of various assumptions around broad water and energy policies. While we are using the term "policy", it should be noted that we are not developing and analyzing specific, place-based actions that could be taken. Rather, our scenarios are more general in nature, taking a top-down perspective to explore, for example, the level to which renewable energies would be necessary to meet greenhouse gas targets across the region. So this study is not policy analysis per-se, but rather an exploratory examination of a generic suite of command and control actions within an exploratory modeling framework that can be used to establish order of magnitude impacts and responses.

5. Representing Costs and Benefits in the Regional W-E Nexus Analysis

The cost-benefit analysis in this study focuses on a few key metrics that could be reasonably estimated and used to compare among the various policy scenarios. A full economic evaluation, that would include the benefits and costs of use values (market and non-market) and non-use values of both the water and energy systems, was beyond the scope of this project. Benefit metrics can be market-based, as when a farmer uses water to irrigate commercial crops which are sold for economic gain. In contrast, a non-market benefit, which has a societal value, could include water that is used to irrigate noncommercial forests or amenity areas on public lands. Nonmarket benefits are typically more difficult to measure than market-based benefits, because they are not directly linked to commercial transactions or economic returns. There can also be intrinsic value/benefits of water even when it is not directly used, such as society's knowledge that the resource exists (existence value) and is being protected for future generations (bequest value). Another non-use value can be benefits derived by leaving the water in place, such that environmental areas are protected or salt water intrusion in coastal aquifers is reduced. Such a comprehensive analysis is beyond the scope of this project, as it would include a 'willingness-to-pay' analysis that would explore market, nonmarket, and nonuse costs and benefits for all the services provided by water and energy.

5.1. Energy and Water Costs

The economic costs of providing a modern water and electric energy supply are made up of several components, which generally include: 1) the cost of the raw material; 2) the cost of generation; and 3) the cost of distribution and resource management. The relative costs of each component can be quite different among water and energy systems. Water, for example, typically has a low raw material costs (the raw water supply) relative to the other components at less than 10%. Typically, the storage, transmission, and treatment of water to a potable water standard (i.e. “water generation”) and its distribution to end-uses such as households and commercial entities makes up a large share of water’s total cost (roughly 40%). Municipal water use typically includes a waste management component, including the collection, treatment, and discharge and/or reuse cost, which can be more than 50% of the total cost (Whittington and Hanemann 2006). For electric energy, fossil-fuel based generation has a high raw material/fuel cost which can exceed 70% of total cost, in contrast to solar-based generation that has virtually no raw-material costs. Nearly all electricity generation is capital intensive, with conventional generation methods such as combined cycle between 20% and 30% of total costs, while for nuclear generation, the capital costs can be as much as 75% of the total, but with smaller fuel costs at about 15% of total costs. Transmission costs for electricity are typically less than 5% (IEA, 2015).

Recognizing the complexity of these various cost components, the utility sectors often use a levelised cost approach to allow for comparison among the various alternatives. Levelised cost can be 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. For electrical energy, levelised costs are often reported in $/MWh, which allows for a direct comparison of technologies in any year, something that would be more difficult to do with differing annual costs.

For this study, the cost of generating electricity and water were done on a levelised basis. For power generation technologies, there are several components that typically comprise the levelised cost estimate, including Capital costs (units of $/MW), Fixed Operations & Maintenance (O&M units of $/kW-yr), Variable O&M (in units of $/MWh) and Fuel (in units of $/ MWh of heat unit equivalent such as British Thermal Units of fuel heat content). For this analysis, we are going to make use of the literature to estimate a levelised cost for each fuel type, with those estimates provided in Table 5.1. It is important to note that actual plant investment decisions are affected by the specific technological and regional characteristics, which involve numerous other factors not reflected in Levelised Cost of electricity (LCoE) values.

Table 5-1: Levelised cost estimates for each fuel type used in the LEAP model.

Fuel Technology	Levelised cost ($2010/MWh)
Fuel Oil	150
Natural Gas	75
Solar (PV and CSP)	125
Wind	73
Nuclear	115
Clean Coal	130
EE CSE*	30

*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).

We note that the cost assumptions have a considerable degree of uncertainty. Future fuel costs, for example, may be significantly different from the costs assumed, and in fact, commodity prices such as oil and natural gas have declined significantly over the past few years. These uncertainties cannot be fully captured in the analysis done for this study. We have assumed that the levelised cost of Fuel Oil is the highest, while wind is the lowest. Nevertheless, there is very little renewable wind energy the region (IEA, 2015).

The water generation cost was also done on a levelised basis. First, however, we assume that desalination costs represent all the costs associated with the generation and distribution of the region's potable water supply, and are thus embedded in the levelised cost of the electricity supply (Table 5-1). This assures that we do not double count the cost of generating electricity in the potable water supply. The other costs associated with the water supply water, beyond the potable supply, including the cost of pumping groundwater, which is dominated by the agriculture sector, and the cost of treating, managing, and possibly reusing municipal wastewater. These costs are treated on a levelised basis and are summarized in Table 5-2.

Table 5-2: 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).

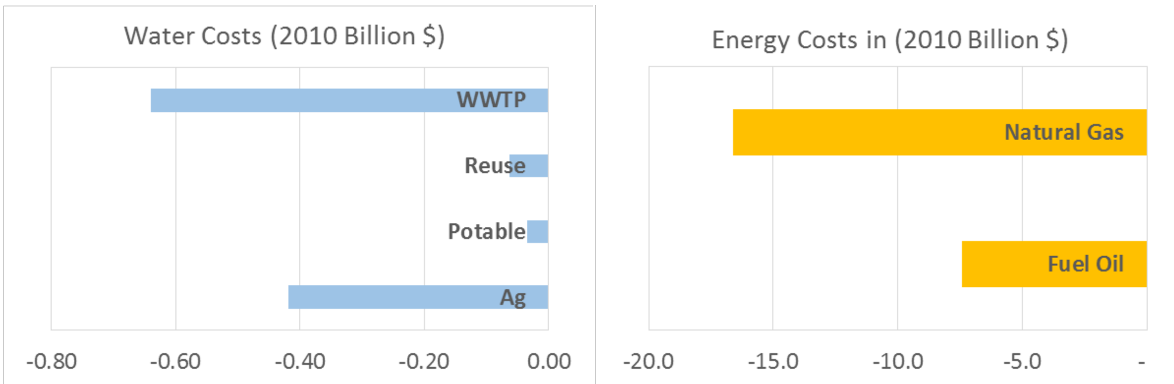
Water Related Costs	Levelised cost ($2015/M^3)
Desalinization	(incl. in energy cost)
Groundwater	0.10
Waste Treatment	0.50
Reuse	0.35
WE CSW	0.20

The analysis includes an estimate of the costs associated with achieving water and energy efficiency improvements and conservation targets. Water and energy efficiency program costs are assessed differently than other supply-side water and energy resources, and are often evaluated against the avoided costs of alternative supply options. It is important to include in the analysis the cost of procuring additional water and energy via efficiency improvements and conservation, which can be used to compare with the prevailing cost of the next marginal unit of supply that would otherwise be incurred using traditional technologies. In this case, those technologies include, for the energy sector, the use of fuel oil, natural gas, solar, nuclear and wind sources to generate electricity; and for the water sector, the use of desalinization and the pumping of groundwater to generate additional supply. Efficiency/Conservation resources that cost less than the avoided costs of the new supplies are deemed cost effective.

Because the regional LEAP and WEAP models use coarse representations of the energy and water demands at the per-capita level, energy and water efficiency and conservation were assumed to include both programmatic and end-user actions. The levelised cost estimate for Energy Efficiency and the Cost of Saving Energy (EE-CSE) was $30/MWh and for Water Efficiency and the Cost of Saving Water (WE-CSW) was $0.20 / M^3 (Molina 2014). The costs associated with energy efficiency and cost savings are considered as demand-side actions that can be taken to reduce both water and energy use.

Figure 5-1 provides a summary of the 2010 water and energy costs, where water related costs include waste water treatment, water reuse, potable supply and the costs related to groundwater for the agricultural sector, including pumping groundwater for agricultural uses. Diesel pumps are primarily used in Saudi Arabia while electrical pumps are assumed to be used in the other countries. The figure includes the cost of electric energy generation based on fuel type, which for the historic period are dominated by Natural Gas and Fuel Oil. The figure shows that the relative costs of electrical generation are considerably larger than those associated with water use, although the electric energy costs include the embedded energy associated with desalinization.

Figure 5-1: Estimated 2010 water (left) and electrical (right) energy costs.



6. Scenario Framework

The development of a valid WEAP-LEAP coupled model, as discussed in the previous sections, is fundamental to analyzing W-E Nexus Challenges & Opportunities in the Arabian Peninsula under Climate Change. However, the core of the research is the actual analysis of policy-relevant scenarii. This section offers a framework for the development of potential scenario narratives that may be of interest to regional stakeholders. It is important to note that these scenarii are exploratory in nature and not specific to local policy. Rather, they seek to address questions such as, "What level of renewable energy penetration would be required to achieve regional greenhouse gas reduction targets? Or what level of water use would be needed to meet resource conservation objectives?" Hence, they are not predictions of the future but narratives that describe potential futures in the region considered to be plausible. A comparison of each policy scenario to a *BAU* scenario through the integrated WEAP-LEAP modeling apparatus provides a mechanism to quantify the implications of potential future conditions across a range of physical and cost parameters.

Several principles underlie the development of the policy scenario framework. First, the framework makes a distinction between a set of underlying *assumptions* and the *policy scenarii* to be explored. The assumptions define the baseline and future conditions that are predominantly outside the control of the water and energy enterprises, such as the future climate conditions and the regional population growth. The second principle is that the scenarii should be plausible, policy-oriented narratives that account for the unique perspectives and characteristics of the region and its culture. For the Gulf countries, this means, at a minimum, that they need to account for the hyper-arid environment and that the countries of the Arabian Peninsula are at various stages of policy development regarding the sustainable management of their water and energy resources. The policy scenarii should recognize and build upon efforts to establish a credible storyline about the impact of such policies, whether implemented selectively at the national level or collectively at a regional level. Third, they need to be quantifiable. That is, some policy interventions can only be characterized in a qualitative sense relative to their impacts on water and energy (e.g., the greater role of environmental education in primary and secondary education). For the purposes of this sub-project, scenario storylines were developed relative to the specific (and numerous) quantifiable policy levers that have been built into the modeling framework.

Another underlying principle of the policy scenario approach used in this study is the assumption of equivalent service. For example, there are no service substitutions for "space cooling", "irrigation", “indoor water”, etc. when efficiency, conservation, or alternative supply technologies are introduced across the scenarios. The same level of service is consumed more efficiently through better technology or delivered more sustainably with alternative renewable technologies, all else equal. Thus, under this principle, per-capita outdoor water use and crop production is the same across all the policy scenarios.

Taking the above principles into account, a set of baseline, business-as-usual assumptions and specific policy scenarios were developed for the analysis. The assumptions that characterize the business-as-usual scenarios and the policy-oriented scenarios are described in the text and bullets below. These assumptions and scenarios provide a foundation for the research team to study the implication of the scenario policies on the W-E Nexus of the region. The integrated modeling framework was validated against the historic period 2001 through 2010, while the future scenarios are evaluated for the period 2020 through 2060.

6.1. The Business-As-Usual Scenario

The Business-As-Usual (BAU) scenario include a set of baseline assumptions, such as the rate of population growth in each country. The future population forecasts were developed by the United Nations (2015) and include population growth rate projections over time for each country. The regional population that is included in this study estimated at 36,000,000 in 2020 and grows to 49,000,000 by 2060[9]. Climate model output, including monthly total precipitation and average temperature are included in two different ways. For the BAU scenario, the current climate is used to define the future climate by repeating the historical climate data for the 20-year period, 1985 to 2004. The time period of analysis is from 2020 to 2060 for the RCP 8.5 scenario. The RCP8.5 represents a higher limit of global greenhouse gas emissions and thus a higher bound on future climate change conditions and thus a good delimiter of possible extreme conditions.

[9] The total UN population projection for all 6 countries is 57,000,000 in 2020 growing to 78,000,000 by 2060.

The baseline assumptions assume a levelised cost for both the water and energy sectors and apply a 5% discount rate for both the baseline and policy scenario. The scenario that are based on these assumptions include:

- ***The Business-As-Usual*** scenario continues past resource use in each country with respect to per-capita water consumption and set of assumptions regarding growth in energy and water use in those sectors. For example, 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) will continue at their historical levels, with no new policies that would influence water and energy use to 2060. This assumption will be implemented during the 2010-2060 time frame. The BAU scenario assumes that the fuel portfolio remains fossil based, although the share of fuel oil use declines relative to natural gas, consistent with the current trends. Natural gas is endogenously added into the energy generation fuel mix, to maintain a minimum planning reserve margin[10] of 20%. Nuclear capacity peaks by 2020 at 5.6 GW, while new solar capacity peaks at 5 GW at 2020. Clean-coal is incrementally introduced from 2015 to 2030 to a total capacity of 3.6 GW (DEWA 2016).

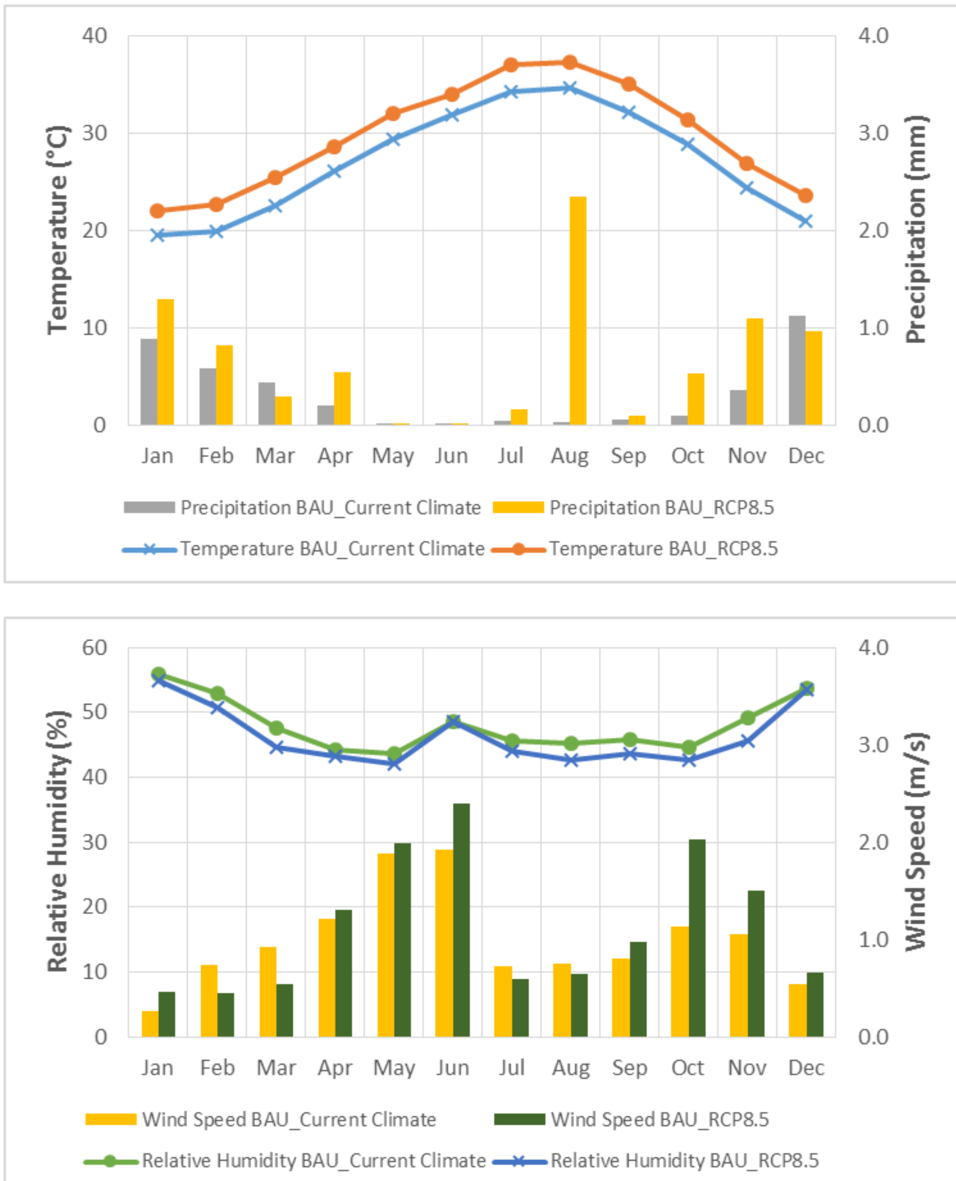
  For electricity use in the municipal, industrial and commercial sectors, the BAU scenario assumes that the growth in per-capita use stabilizes by 2020 and then holds constant to 2060. For the municipal and industrial water sector, indoor per-capita use remains constant for each country, while outdoor water use is assumed to grow at half the population growth rate estimated for the period 2010 to 2060. This BAU scenario represents the baseline by which a second BAU scenario (below) was developed that includes the impacts of a changing climate on the water resources and energy sectors. Total demand can increase due to an increase in regional population.

- ***The Business-as-Usual with Representative Concentration Pathways (RCP 8.5)*** scenario *(BAU-RCP8.5)* repeats the historic climate until the year 2030, after which the precipitation and temperature assume the values of a changing climate, which were simulated using RCP 8.5 projection adopted by the IPCC for its Fifth Assessment Report (AR5) in 2014. These climate projections were obtained from the outputs of the Regional Atmospheric Modeling sub-project as part of the LNRCCP Program, which extends to the end of the model's time period in 2060. The historical, non-climate trends follow the previous *BAU* scenario, repeating themselves in the presence of future climate change. The three policy scenarios, described below, all use the RCP8.5 climate change scenario to characterize the future climatic conditions, and so the analysis of the future policy

[10] 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.

scenarios focus on a comparison with this *BAU-RCP8.5* scenario. Figure 6-1 shows the climate characterization of average temperature, precipitation, relative humidity, and wind speed for the BAU and *BAU-RCP8.5* scenario.

Figure 6-1: Climate characterization of monthly average temperature, precipitation, relative humidity, and wind speed for Abu Dhabi



Summary of BAU Assumptions:

- Population growth rate follows the UN projection for each country.
- Indoor water use occurs on a per-capita basis, estimated for each country, and is assumed stationary for the full period of the simulation to 2060. Per-capita estimates were based on data from the FAO AQUASTAT database, with Municipal and Industrial Indoor uses assumed to be 60% of the estimate.
- Outdoor water use grows at the population growth rate for each country, represented by an increase in area.
- Municipal, Industrial, and Commercial electric energy use occurs on a per-capita basis, and includes both a base load amount and a time varying amount that depends on the monthly heat index.
- Some groundwater systems have an estimated exhaustible capacity, such as the Dammam aquifer, which we assume can be mined to meet demand until it is exhausted.
- Desalinization capacity continues to be dominated by Multi-Stage Flash (MSF) at 60%, while Multi-Effect Distillation (MED) and Reverse Osmosis (RO) continue to make-up around 20% of the capacity. Any new capacity is added at these ratios.
- New energy generation is dominated by natural gas, with new energy technologies including nuclear, solar and clean coal only added according to current and planned projects.
- The only difference between the *BAU* and *BAU-RCP8.5*, is that the latter makes use of a future climate projection, derived from a regional climate model, which assumes a changing climate driven by globally high levels of greenhouse gases continues into the future.

6.2. The Policy Scenario

Three policy scenario were developed according to the guidance and principals described earlier. The first scenario focuses on demand side activities, meant to reduce demand for water and electricity; the second scenario focuses on natural resource protection, by assuming the region can significantly increase renewable electric generation capacity, primarily solar, and strives to reduce the mining of fossil groundwater. The third policy scenario simply combines the assumptions made for the first two. The details of each policy scenario are described below.

- ***High Efficiency and Conservation Policy Scenario (Demand Side Actions):*** The *High Efficiency and Conservation* scenario assumes that each country will gradually implement policies to reduce the consumption of water and electricity on a per-capita water and electricity basis starting in 2020. The impact of these policies will be evidenced through *a*) a reduction in CO_2 emissions and relative levels of water abstracted from groundwater sources or produced in desalination and *b*) a likely increase in the incremental costs associated with the implementation of the policies. Please note the difference between energy itself and energy efficiency; energy acts more like a cost, while energy efficiency acts more like an investment. Like most investments, energy efficiency works by taking on an up-front expense to generate a stream of future economic benefits.

- Indoor water demand efficiency and conservation targets are implemented by each country to target a per-capita use of about 75 gallons/capita/day. The conservation target is unique to each country given their current level of consumption.
- Each country maintains the 2020 level of outdoor garden and amenity watering area, in contrast to the *BAU* scenarios, where outdoor water area grew proportionally to the population estimate.
- Irrigation efficiencies in both the municipal outdoor, amenity, and agricultural sectors begin in 2020, with a gradual reduction in water use for the same relative benefit by 2060 achieved through a 20% reduction.
- Indoor water use efficiencies and system improvements lead to a 25% reduction in municipal water losses, resulting in greater fraction of reuse water available for treatment, noting that per-capita water consumption reductions can result in reduced available waste water.
- Per-capita electricity demand targets are set by each country to achieve a per-capita target of about 7,000 GWh. This means that countries such as the UAE and Kuwait have a much more aggressive efficiency and conservation program in place and must achieve reductions of more than 2% per-year starting in 2020. In contrast, Saudi Arabia and Oman, who currently have a lower per-capita electricity consumption, have efficiency targets of about 1% per-year.
- The recognition of the high energy use for cooling in the summer leads to more efficient technologies, practices and behavioral responses that reduce the summer peak load. There is an assumption that technological improvements reduce peak demand for summery cooling by 15% by 2060 for the same level of current cooling requirement (e.g. cooling demand depends on the heat index, so a higher heat index counters an increase in efficiency).
- New electricity generation is assumed to be met by natural gas, where new capacity can be added at 1GW/year to maintain a 20% reserve margin. The level of Nuclear and Solar capacity is as the BAU scenarios.
- Cost of saving energy and water through efficiency and conservation is made relative to the energy and water used in the business-as-usual scenario.

- ***Natural Resource Protection Policy Scenario (Supply Side Adaptation):*** The *Natural Resource Protection* scenario assumes a future where different adaptations are implemented in the supply side where: *a*) each country implements policies to drastically reduce the use of fossil groundwater systems, protecting fossil groundwater resources from any further depletion throughout the Arabian Peninsula and

  b) each country implements policies to reduce the use of fossil fuels, with the priority of new generation being non-fossil dominated. New generation comes primarily from solar and nuclear fuels and to a lesser extent wind, biogas and other technologies which are not modeled. For the purposes of the analysis, the policies are assumed to start in 2020 and proceed through 2060, at which year they achieve full protection of natural resources.

  Specific actions for the *Integrated Policy* scenario include:

  - The policy is to reduce fossil groundwater extraction for irrigated agriculture to stabilize groundwater levels. We substitute fossil groundwater with RO-based desalinated water to serve irrigated agriculture, treated at half the level of a potable supply in terms of salt extraction and estimate the equivalent cost. Groundwater extraction is reduced by 4.5% annually, which results in a stabilization of total groundwater storage
  - The percentage of waste water that is treated and re-used for outdoor irrigation purposes is assumed to increase from 10% to 35%, region-wide.
  - Reverse osmosis grows from 18% to 50% of total desalinization capacity for the potable supply, while MSF declines from 60% to 30%, by 2060 region-wide.
  - Nuclear capacity is incrementally added by both the UAE and Saudi Arabia, with 10 GW by 2020, 15 by 2023, and 22 GW by 2040.
  - The policy targets 2060 emissions that are equivalent to the 2005 estimate of the region included in the study, of about 80 mtCO2e. Solar energy is added as the first build order and can be added at 1.0 GW/year, while natural gas is the second build order and can be added at a rate of 0.33 GW/year to maintain a 20% reserve margin.

- ***Integrated Policy Scenario (both Supply and Demand Side Measures):*** The *Integrated Policy* Scenario assumes a future in the region 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 impact of integrating this set of policies will create the lowest resource use scenario by consumers but not necessarily at the lowest cost in terms of implementation. The cost and savings are presented across the range of physical indicators for water and energy.

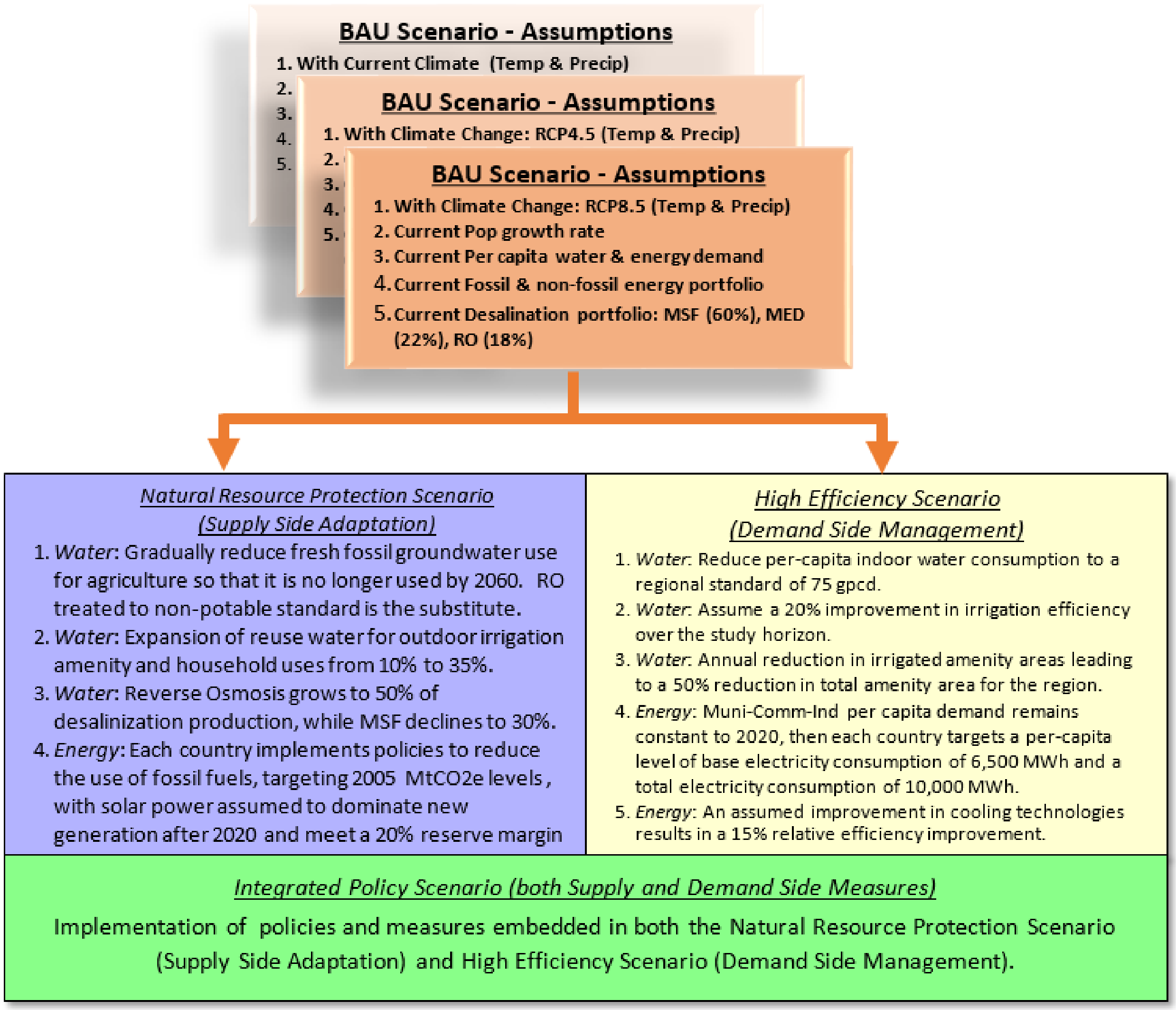
6.3. Scenario Policy Caveats and limitations

Figure 6-2 summarizes the policies as implemented in each scenario and shows the changes made to the WEAP and LEAP models that characterize then.

A few caveats and limitations of the policy scenarios include:

- These scenario policies are meant to be illustrative and were developed to demonstrate the merits of pursing demand and supply oriented policies in isolation and together. The WEAP and LEAP models are designed to allow for an interactive exploration of alternative scenarios within the tools themselves, and thus other policy scenarios could be explored.
- It is highly unlikely that either a 'demand' or a 'supply' policy would be pursued in isolation, rather sound policies that simultaneously pursue combinations of demand-side and supply-side interventions are the most likely.
- There is not sufficient detail in either the water or energy models to represent the merits of local, detailed supply or demand-side interventions or conservation programs; rather the results suggest regional policies that are assumed to be implemented homogeneously.
- There is an assumption that the expansion of infrastructure in both the water and energy sectors can be achieved. For example, in the Natural Resource Projection scenario, there is an assumption that new solar capacity will be the preferred and implemented energy alternative. New water desalination infrastructure can be expanded to satisfy the future water demands.

Figure 6-2. The summary of the scenarios, which include a set of Business-As-Usual Assumptions, which can reflect different assumptions about the current climate; and for this study, a set of 3 policy scenarios have been developed, whose narratives are summarized.



- There are enough wastewater treatment infrastructures to treat wastewater outputs from demand sites, and the reuse of treated wastewater is fully subscribed to urban outdoor irrigation.
- The majority of the groundwater throughout the region is considered 'fossil' water and is not renewable. We have made estimates of the available, extractable storage at the beginning of the simulation based on best available data. This estimate is important as it influences whether demand at certain locations within the domain can 'run out of water'.
- The degree to which these caveats and limitations apply are likely different for each of the corresponding policy scenario.

- Access to available groundwater storage will continue without any legal framework that might constraint its use.
- There is the ability to use fossil groundwater to extinction especially in those areas with limited storage capacity.
- It is assumed that water savings in the agriculture sector through water efficiency and water conservation results in a decrease in overall agriculture productivity.
- For the Natural Resource Projection and Integrated Policy scenarios, new capacity is added that first prioritizes solar and then natural gas generation, where the models were run iteratively to determine the levels of new solar and natural gas capacity that would be needed to meet the 2005 GHG target of about 80 mtCO2e.

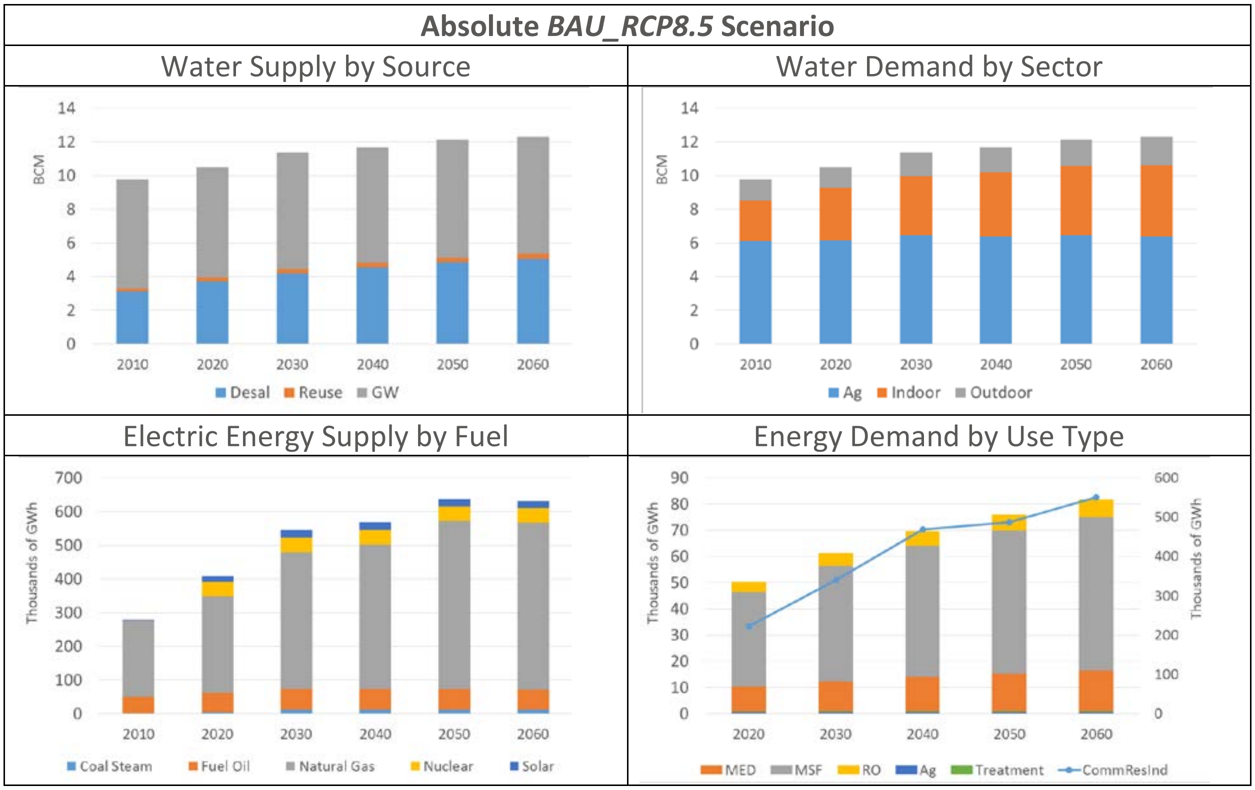
7. Scenario Results

Figure 7-1 summarizes the water and energy balances from 2020 through 2060 for *BAU_RCP8.5* scenario by decade. Water demand grows gradually, dominated by agriculture use supplied by fossil groundwater used primarily to support the agricultural sector. Municipal water use continues to grow and is supported through saltwater desalinization, still dominated by Multi-stage Flash (MSF). Total groundwater supply remains considerably larger than desalinization and reuse, and agriculture uses are larger than indoor and outdoor municipal uses. Growth in groundwater as a supply source and agricultural demand stops after about 2030 and by 2060 shows slight decline, as some regional groundwater systems are depleted. Desalinization capacity grows and while water reuse does as well, it remains a relatively small fraction of the total water supply.

7.1. BAU-RCP8.5 Summary

Natural gas continues to be the primary fuel source for new generation, while generation by fuel oil remains relatively constant and solar and nuclear generation make up a larger overall share but still relatively small compared to natural gas. Commercial-Industrial-Municipal electricity demand more than doubles between 2020 and 2060, scaled on the 2nd y-axis of Figure7-4 since its share is proportionally much larger. Water related energy demand consumes between 15% and 20% of total energy, with the majority of that for desalination.

Figure 7-1: Summary of water and electricity supply and demand given for the *BAU_RCP8.5* scenario. The total water and energy supply delivered in 2060 for the *BAU_RCP8.5* scenario was 23 BCM and 745 GWh, respectively.



7.2. Comparing the Policy Scenarios

The two *BAU* scenarios and the three policy scenarios are run through 2060, with the implementation of the policy actions starting in 2020 and are fully implemented by 2060. To gain an understanding of how the assumptions regarding regional population growth and climate change and the policy interventions affect overall water and electricity use, we present a summary of results in Figure 7.2 and Figure 7.3 for all of the scenario pathways. Because of the uniform nature of the scenarios in terms of country-level adaptations, we chose to focus our analysis on the regional results, rather than on a country-by-country basis. The overall increasing trend in water and energy demand for the *BAU* scenarios is driven primarily by the assumptions of the regional population growth. Comparing the *BAU_RCP8.5* scenario relative to the *BAU* scenario, we see that climate change increases annual water demand by about 3%, while electricity demand increases by more than 15%. This increase in electricity demand is driven by the higher heat index, leading to an increased demand for seasonal cooling; while the increase in water demand is due to increased evaporative losses due to warming.

Figure 7-2. Total annual water use for each of the five scenarios over the study horizon.

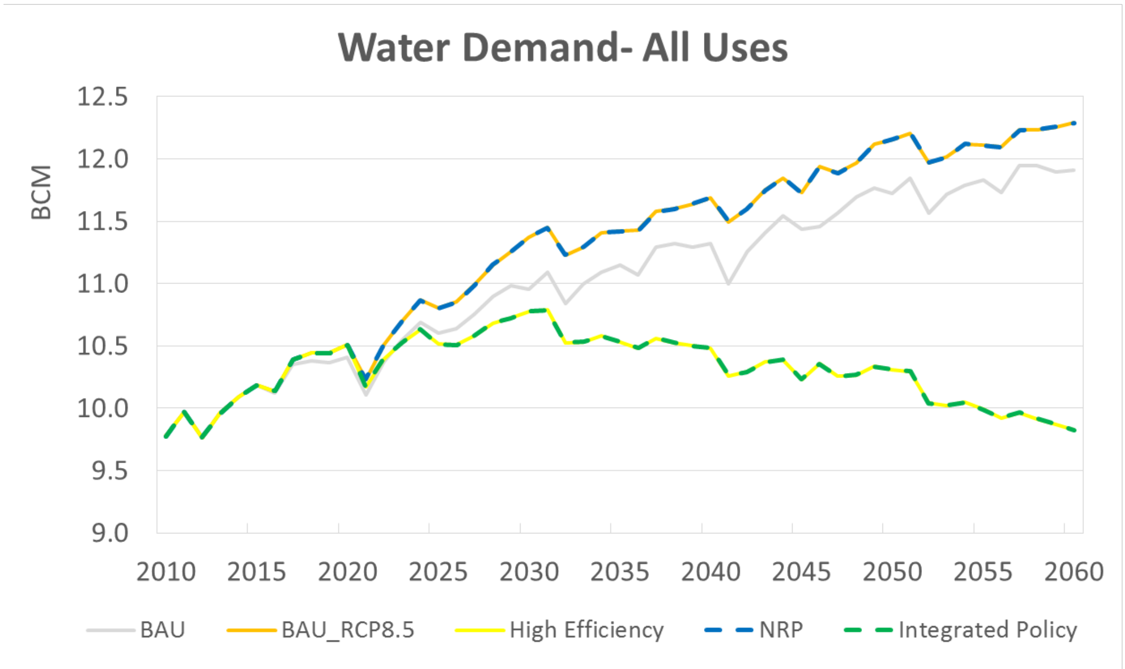
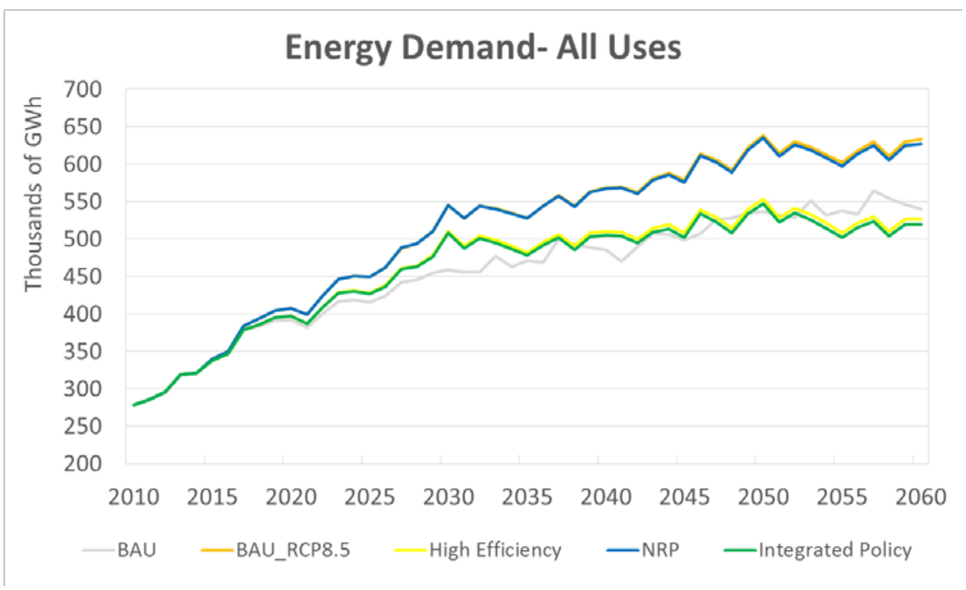


Figure 7-3: Summary of total energy use for all scenarios over the study horizon.



Note that the policy assumptions regarding reductions in resource use reflect similar savings in the water and energy sectors, where water savings are achieved by efficiencies in agriculture and outdoor irrigation and reductions in indoor, per-capita water use; and electricity savings are are also achieved through efficiency improvements and per-capita reductions. By 2060 and relative to the *BAU_RCP8.5* scenario, the *High Efficiency* or demand-side scenario reduces water use by 20% and electricity use by more than 15%, achieved primarily through efficiencies and conservation in indoor and outdoor municipal use and agricultural use; and reductions in per-capita electricity use, respectively.

Since the *Natural Resource Protection* scenario includes only supply side measures, water use remains unchanged relative to the *BAU_RCP8.5* scenario, while electricity use is reduced by a modest 1%. The small reduction in energy use is attributable to changes in the municipal water supply sources such as the shift away from MSF and MED to RO technologies, which is less energy intensive. While the *Natural Resource Projection* scenario does not substantially reduce overall electricity use relative to the *BAU_RCP8.5* scenario, the fact that it is focused on renewable electric generation technologies results in a considerable reduction in greenhouse gases (Figure 7-8). Combing both demand and supply side measures of the *Integrated Policy* scenario results in a 16% reduction in energy use relative to the *RCP_8.5* scenario and similar reductions in water use as the *High Efficiency* scenario.

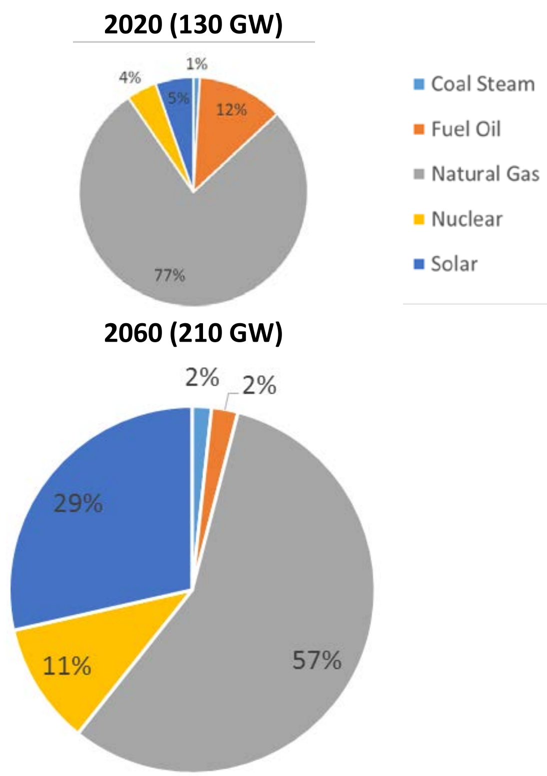
7.3. Summarizing Differences among the Policy Scenarios

Figures 7-5, 7-6, and 7-7 summarize the change in the water and energy supply and demand relative to the *BAU_RCP8.5* scenario, for the *High Efficiency, Natural Resource Protection*, and *Integrated Policy* scenarios, respectively. For the *High Efficiency* scenario, water savings in the agriculture and municipal sectors are realized through efficiency and conservation, resulting in more than a 20% reduction in use relative to the *BAU_RCP8.5* scenario. The per-capita reduction in indoor and outdoor water use led to savings in desalination production which has decreased by 1 BCM or 20%, relative to the *BAU_RCP8.5* production in 2060. Overall, natural gas use is reduced by about 100 GWh or about 20%. These energy savings are achieved through both reductions in Commercial-Industrial and Municipal uses and to a lesser extent, the water sector through reductions in groundwater pumping and reductions in energy associated with desalinization.

For the *Natural Resource Protection* scenario, water and energy use generally follow the *BAU_RCP8.5* trajectory, driven by population growth. There is an increase in water re-use with a concurrent increase in energy use. The movement away from fossil groundwater as a primary supply source is substituted with treated brackish water via reverse osmosis so energy use in the water sector is greater**.** Overall, though, there is a decrease in desalinization energy due to both the increase in re-use and the use of Reverse Osmosis in favor of more energy intensive thermal desalinization technologies (MSF and MED). Overall, there is a net decrease in energy of 30 GWh or about 4%. Note that this scenario assumes no savings in commercial, municipal, and industrial energy use, and so all energy savings are achieved through changes in the water sector and desalination technology. New energy generation capacity is dominated by solar generation, with more than 100 GW of new capacity needed to try and meet the 2060 GHG target of about 80 mMtCO2e for the region included in the study. Natural gas capacity is reduced by 38 GW or about 30% of the capacity simulated under the BAU_RCP8.5 scenario. Nuclear capacity grows by 17GW. Recall that the 2010 total installed capacity in the region was estimated at 105 GW (see Figure 4-11). Total new capacity is about 80 GW for the *Natural Resource Protection* scenario.

The *Integrated Policy* scenario shows the overall savings of water and energy due to efficiency and conservation, with water savings similar to the High Efficiency Scenario, but with municipal indoor and outdoor water savings as well (Figure 7-7). Energy is saved in both the water and non-water sectors. There is less groundwater pumping for both agriculture and municipal uses and there is more reuse of already desalinated waste water to meet outdoor, non-potable needs. Solar and nuclear technologies are substitutes for natural gas and fuel oil in electric generation. Overall reductions in energy use over the study period mean that solar-based generation capacity is more realistic in terms of capacity added, with total new capacity additions of 36 GW by 2060, of which 26 GW was endogenously added beyond the 10 GW already developed or planned. Only 3 GW of natural gas were endogenously added out of a total of 43 GW, so while natural gas still dominates overall production, the *Integrated Policy* scenario highlights the push towards solar and nuclear generation to achieve GHG reductions. There is the continued need for natural gas generation as the backbone of the energy sector, but it goes from representing 77% of generating capacity in 2020 to 57% of generation by 2060 (Figure 7-4), with generation more evenly balanced between natural gas, solar, and nuclear.

Figure 7-4: The 2020 and 2060 generation capacity for the *Integrated Policy* scenario.



The *Integrated Policy* scenario implies a more realistic entry of new solar capacity when compared with the *Natural Resource Projection* scenario, with 50 GW of new solar endogenously added, whereas 100 GW of new solar are added for the later. With the addition of new clean coal and nuclear capacity, and the retirement of natural gas, the resulting total increase in new capacity from 2020 to 2060 Total new capacity in the *Integrated Policy* scenario is 90 GW from 2020 to 2060. If we assume a 20% efficiency, 70% sunshine days per year, and 1000 watts of solar energy per square meter, then 400 kw-hours can be produced per square meter of land. By

2060, the Integrated Policy scenario requires the generation of 133,000 GWh, which would require more than 330 km^2 of PV solar. To put that into perspective, the area of Abu Dhabi is about 950 km^2.

Figure 7-5: Summary of water and electricity supply and demand given as the difference between the High Efficiency and BAU_RCP8.5 scenario, whose absolute results are presented in Fig. 7-3.

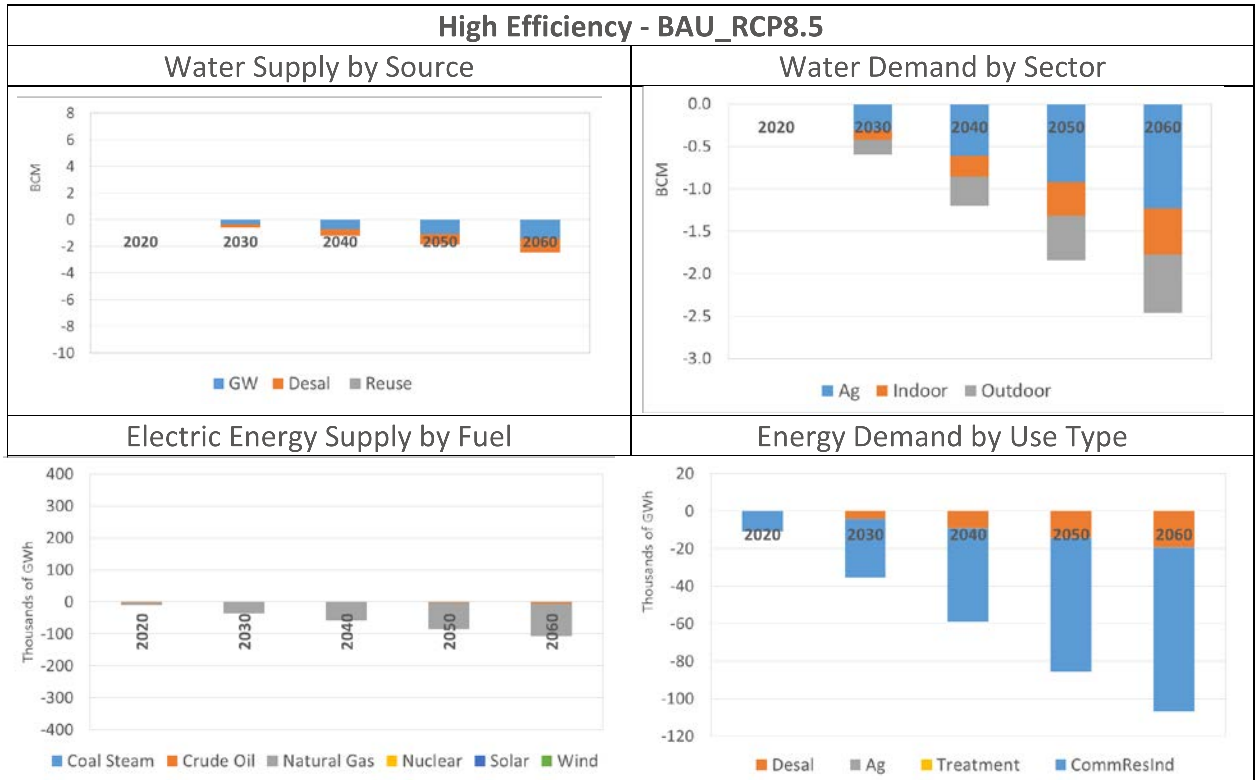


Figure 7-6: Same as 7-5, but as the difference between the ***Natural Resource Protection*** **and** ***BAU_RCP8.5*** **Scenario.**

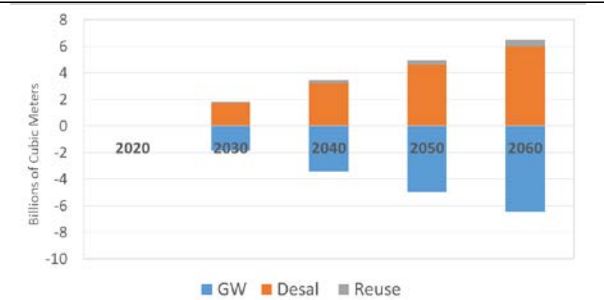
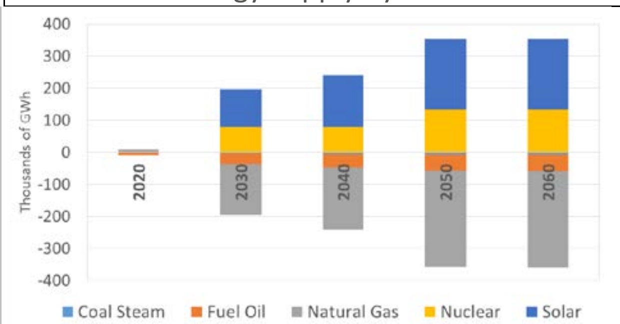
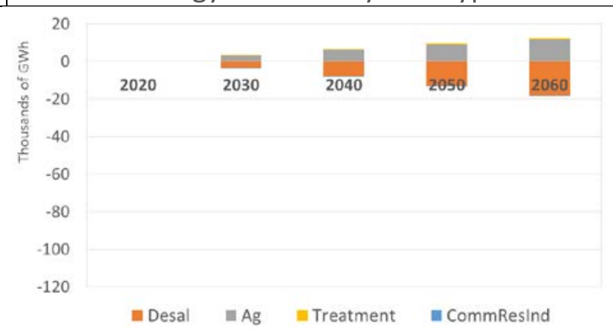
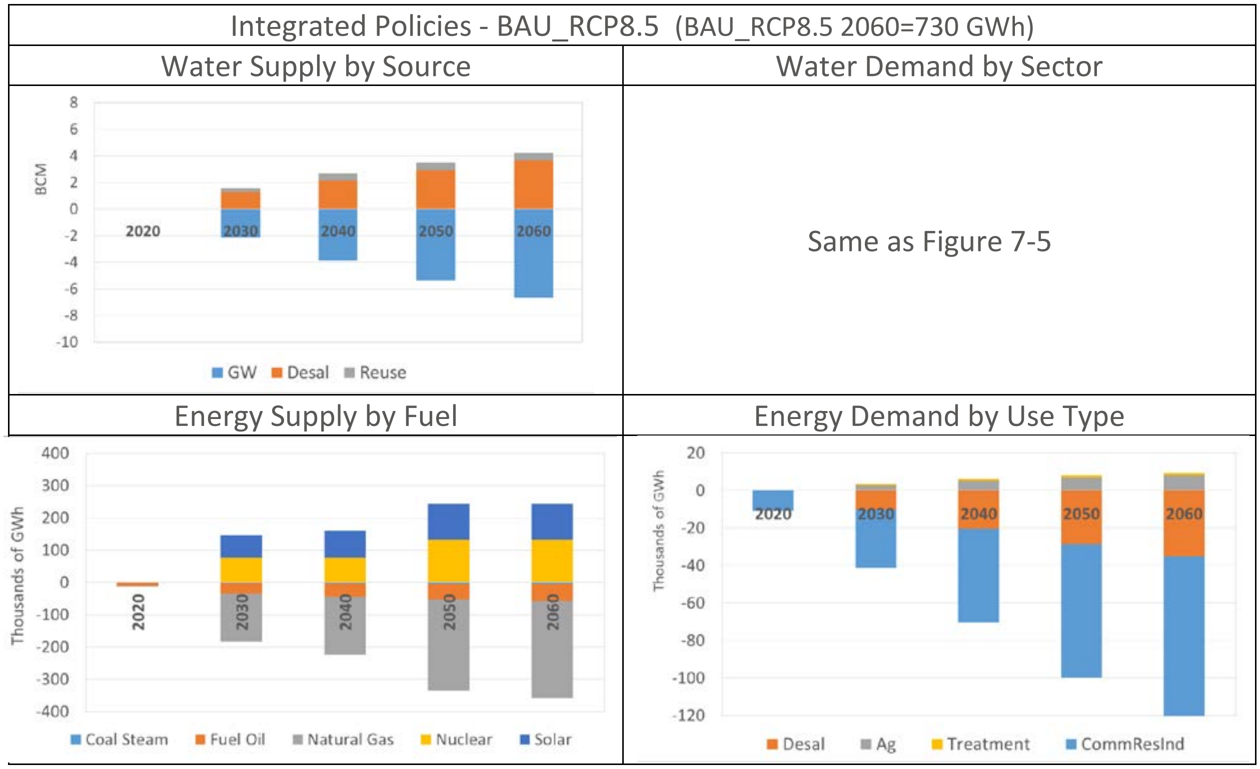
Natural Resource Protection - BAU_RCP8.5	
Water Supply by Source	Water Demand by Sector
	No Difference (Same as BAU_RCP8.5)
Energy Supply by Fuel	Energy Demand by Use Type
	

Figure 7-7: Same as 7-5, but as the difference between the *Integrated Policies* and *BAU_RCP8.5* scenario.



Greenhouse Gases and Groundwater Storage- Figure 7-8 shows the total annual carbon dioxide equivalent from 2000 through 2060. The *BAU_RCP8.5* scenario leads to more than 15% greater GHG emissions when compared with the *BAU* scenario, as natural gas continues to dominate energy production and resource use increase due to warmer conditions that require more water and energy. 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 15% relative to the *BAU_RCP8.5* scenario. The *Natural Resource Projection* and *Integrated Policy* scenarios target GHG emissions at 2005 levels, where new solar capacity is added in favor or new natural gas capacity, at a ratio of about 3:1. Interestingly, the total emissions of the *Integrated Policy* scenario are slightly higher than the *Natural Resource Protection*, primarily because natural gas remains a larger share of overall production as energy demand stays lower and is not replaced by new solar capacity.

Figure 7-9 is the total groundwater storage for the various scenarios and shows that with conservation and efficiency improvements, that their drawdown could be stabilized, assuming there is some regional recharge. Even though the analysis suggests that groundwater remains available regionally, there are local systems where groundwater is depleted to exhaustion in the BAU scenarios, such as some of the groundwater systems of the UAE. The results suggest that without significant reductions in abstraction groundwater will be continually depleted, with local systems fully depleted.

Figure 7-8: Annual Greenhouse gas emissions measured in millions of metric tonnes for all scenarios.

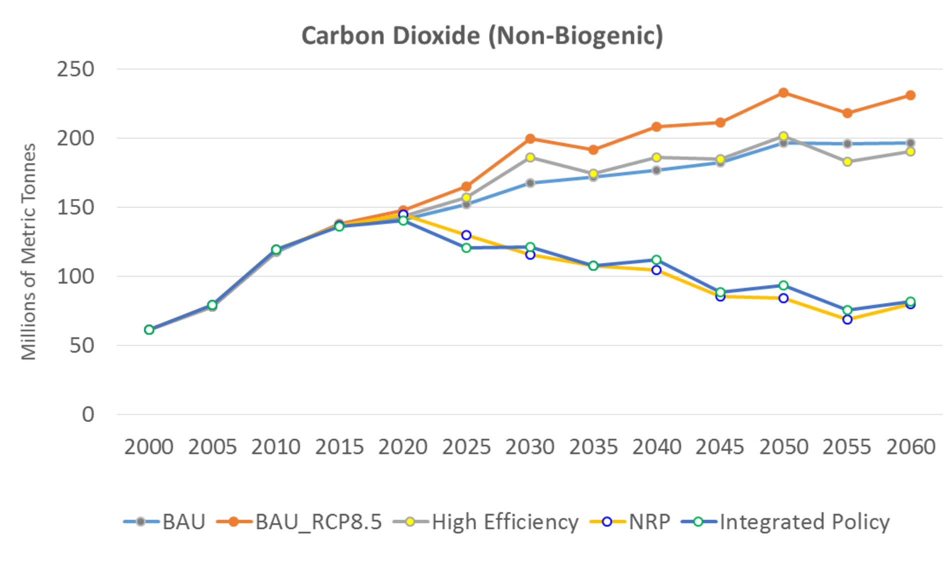
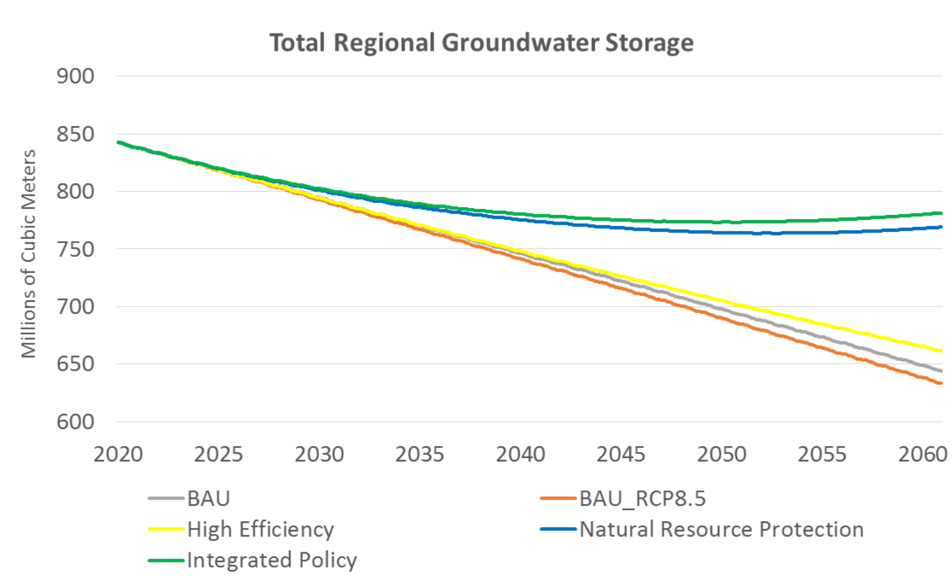


Figure 7-9 Total regional groundwater storage for the two business as usual scenarios and the three policy scenarios.



Costs and Benefits- Figure 7-9 shows the Net Present Value (NPV) for the water and energy sectors as the sum of the discounted costs for the *BAU_RCP8.5* scenario from 2020 through 2060, with an assumed discount rate of 5% for all scenarios. The net present value of the water and energy supply cost between 2020 and 2060 for the *BAU_RCP8.5* scenario is about $22 billion and $500 billion, respectively. The figure shows the costs of each component of the water supply and the cost of generating electricity by fuel source based on the levelized cost assumptions. Most of the cost of the potable water supply are embedded in the cost of generating energy, with other major costs including waste water treatment, water reuse, and the potable water supply from groundwater. The costs associated with the agricultural water supply are limited to the costs of pumping groundwater. The total NPV of electricity generation from all fuel sources is more than $500 billion USD, with 62% from natural gas and about 20% from fuel oil, while nuclear and solar make up the remainder at 16% of total generation cost, and Coal Steam at about 3%. We estimate that about 15% of the total cost of energy production is attributable to the generation of the potable water supply through desalinization or about $75 billion USD.

Figure 7-10: Sum of the Net Present Value of costs for water (left) and energy (right) for the *BAU_RCP8.5* scenario from 2020 to 2060 discounted at 5%. The water costs include waste water treatment, water reuse, and the costs associated with groundwater pumping for the potable supply. The energy costs include all fuel sources.

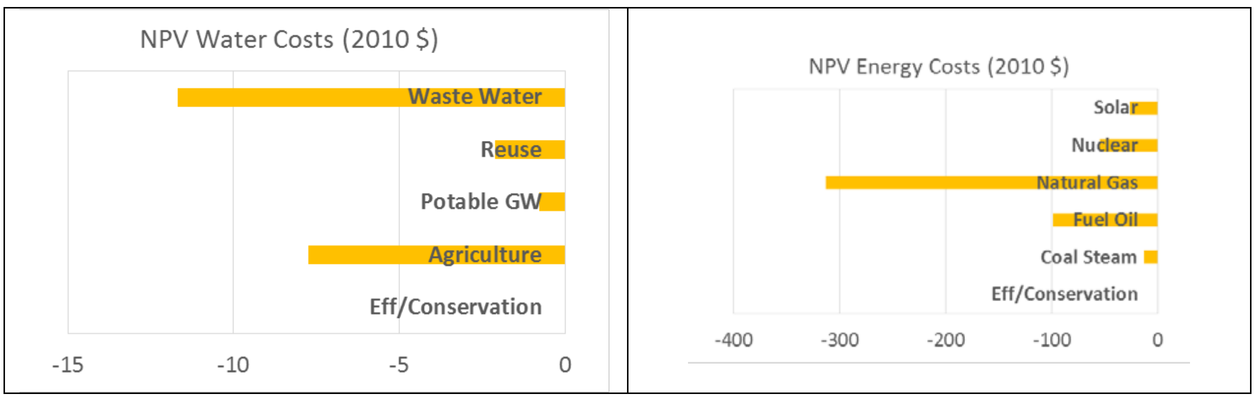
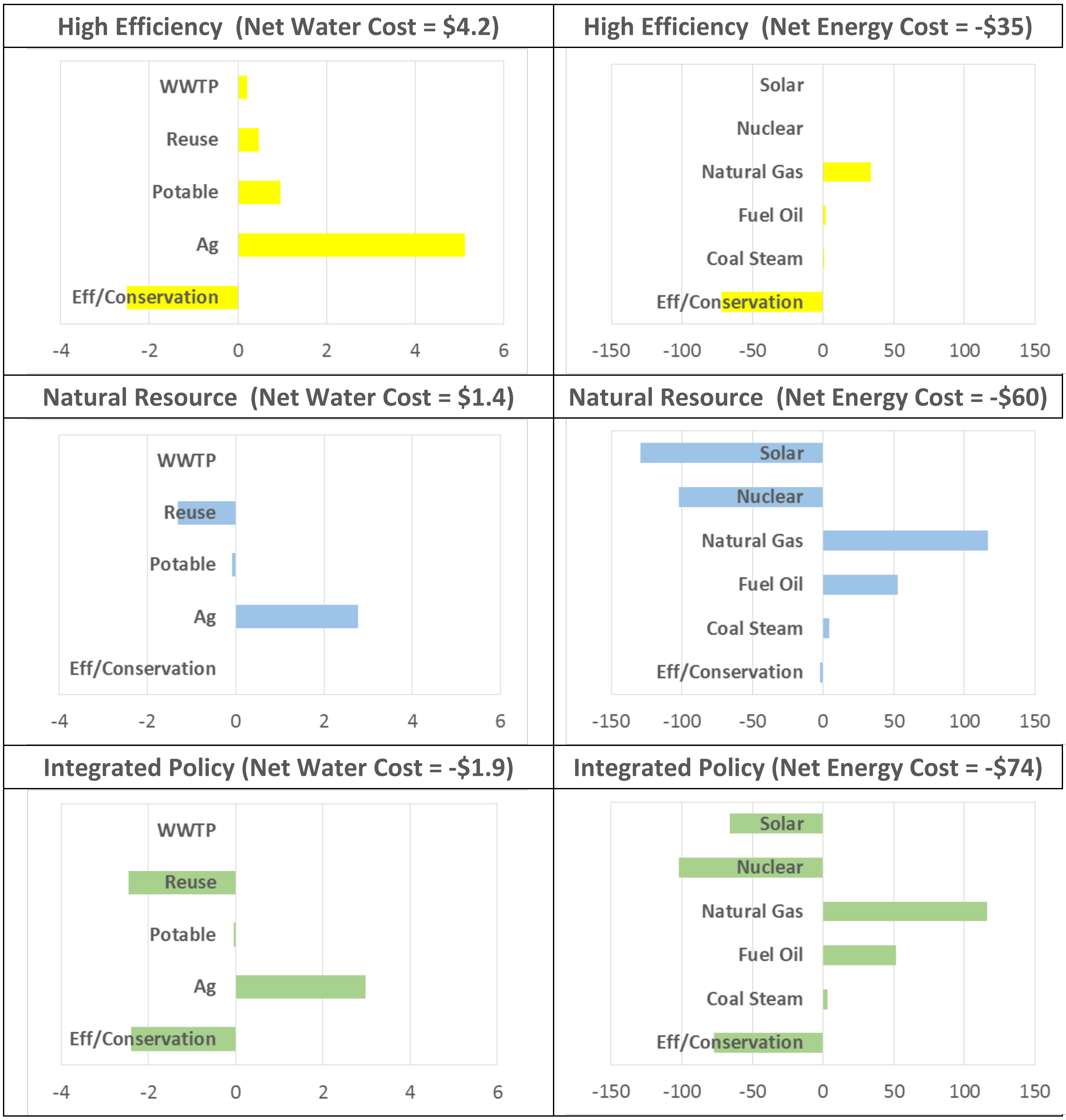


Figure 7-10 summarizes the change in the NPV of each of the policy scenarios relative to the *BAU_RCP8.5* scenario for the period 2020 to 2060. A positive value represents a cost savings while a negative value indicates additional costs. The figure includes a summary of costs reported as the overall change in the NPV for each scenario. For the *High Efficiency* scenario, the water sector savings are due to reductions in water use in general and a reduction in energy use related to water, while costs are due to conservation program implementation. On the energy side, there is an overall savings in fuel costs, while efficiency and conservation programs reduce the overall savings by about 20%. For the *Natural Resource Protection* scenario, costs come in the form of increased costs of reuse and the potable supply, while direct agriculture costs have decreased due to reductions in groundwater pumping. However, there is more energy used to meet all needs, and thus increased costs to generate energy using non-fossil energy sources such as solar as there is a move away from natural gas, replaced primarily by solar and nuclear generation. This has a positive net benefit in terms of total cost relative to the *BAU_RCP8.5* scenario.

Figure 7-11: A comparison of the change in costs relative to the components presented in Figure 7-9 for water (left) and energy (right), given as the difference in Net Present Value from the *BAU_RCP8.5* scenario of the cost in 2010 USD Billion over the period 2020 through 2060 for each scenario. Positive values represent a cost savings while negative values are additional costs.



The *Integrated Policy* scenario has the highest cost in the water sector, as costs associated with the implementation of efficiency and conservation programs are high, with an increased cost of reuse. There is some savings due to decreased costs for pumping groundwater, while re-use costs also increase. On the energy side, there is a balance among costs associated with conservation and solar and nuclear generation, and a relative savings from reduced natural gas fuel costs. Overall, the costs are higher for the *Integrated Policy* scenario relative to the *BAU_RCP8.5* scenario, although most of the additional costs are associated with the implementation of the energy efficiency and conservation programs which are highly speculative. Thus, if those costs could be reduced, then the Integrated Policy scenario could become more cost competitive, as there is a net saving of $3 Billion if just the energy costs are considered, whereas for the Energy Efficiency Scenario, the net costs are -$25 Billion; while for the Natural Resource Protection, the net costs without conservation are -$58 Billion.

Table 7-1 provides a summary of the two BAU scenarios and the three policy scenarios, where we highlight overall water use, GHG emissions, the NPV of the water and energy supply, and the unit cost of water and of CO2. For the unit cost of water, we have not included the cost of desalinization, as those costs are embedded in the energy cost. The water costs include waste water treatment, reuse, the costs associated with the potable supply from groundwater, and the costs of efficiency and conservation programs. By 2060, water use declines by almost 20% in the *Integrated Policy* scenario, while GHG emissions are reduced by almost 60%. The per-unit cost of water for the *BAU_RCP8.5* is $35 per thousand m^3, while the unit cost per tonne of CO2 is $61 based on the 2010 NPV estimate for generation through 2060. Unit costs for water increase slightly in the *High Efficiency* and *Integrated Policy* scenarios, primarily attributed to an increase in conservation program costs. While overall GHG emissions decline in all scenarios, the relative per-unit cost of per tonne of CO2 increases and in fact, more than doubles for the *Natural Resource Protection* and *Integrated Policy scenarios,* as the costs of solar and nuclear energy are considerably higher than fossil-based sources.

Table 7-1: Summary of the BAU and policy scenarios, including water use and GHG Emissions for 2040 and 2060; the Net Present Value of water and energy; and the unit cost of water and CO2. The unit cost of water only includes the cost to pump and treat water and do not included the embedded cost associated with desalinization.

Scenarios	Water Use (BCM)		GHG Emis (MMT)		NPV (2010 $B)		Unit Cost (2010$)	
	2040	2060	2040	2060	Water	Energy	Water 1000 m^3	tonne CO2
BAU	11.3	11.9	177.0	231.0	-$16.4	-$459	$ 35.5	$ 63.1
BAU_RCP8.5	11.7	12.3	208.1	196.6	-$16.6	-$506	$ 34.9	$ 61.1
High Efficiency	10.5	9.8	186.3	190.5	-$16.6	-$484	$ 39.0	$ 65.6
Nat Res Protection	11.7	12.3	104.5	80.0	-$15.5	-$565	$ 32.6	$ 137.1
Integrated Policy	10.5	9.8	111.3	81.8	-$16.3	-$518	$ 38.3	$ 122.2

Because future policies are most likely to combine objectives that improve water and energy use through improvements in efficiency and conservation and seek to further develop renewable energy sources, we focus the discussion on the *Integrated Policy* scenario, within the context of the demand oriented scenario (*High Efficiency*) and the supply oriented scenario (*Natural Resource Projection*). When these two policies are simultaneously pursed in the *Integrated Policy* scenario, water use declines by about 20% by 2060. The majority of the water savings are from reductions in the agricultural sector, made through some efficiency improvements and conservation but mainly derived through fallowing. These would represent agricultural policies that diminish agricultural output in the region and reduce the mining of fossil groundwater.

Figure 7-4 shows the increasing share of solar and nuclear power and the declining share of fuel oil and natural gas for the *Integrated Policy* scenario. The assumption regarding the higher costs of Solar PV and Nuclear Energy as alternatives to cheaper natural gas means that the unit cost of CO2 increases despite an overall reduction in use. Between 2020 and 2060, the fuel share for Natural Gas goes from nearly 70% to about 40%, Fuel oil from 13% to 2%, and Solar Power grows to nearly 30% of the total energy share. This scenario implies an aggressive implementation of new solar capacity, requiring more than 330 km^2 of PV solar. Despite a reduction in total water use in the *Integrated Policy* scenarios, the total cost increases by about 2%, but has the highest increase in unit cost among the policy scenarios at about 10%. The small increase in total cost is due to fuel costs and conservation programs.

8. Conclusions and Recommendations

We have developed a regional, integrated water and energy planning model based on the Water Evaluation and Planning (WEAP) and Long range Energy Analysis and Planning (LEAP) decision support systems. These coupled model 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 region into 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, with regional groundwater supplies, primarily in Central and Western Saudi Arabia. Historically, the majority of seawater desalinization has been made using energy intensive, fossil fuel based technologies, although it is commonly co-generated at power plants that also produce electric power.

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 region 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. Future rainfall for the region shows both increases and decreases depending on the region, 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:

- Reductions in regional water use are likely more attainable than regional energy use. Agricultural policies that recognize the unique climatic conditions and agricultural heritage of the region could lead to significant reductions in agricultural water use. This has already been demonstrated in Saudi Arabia over the past decade. 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 population grows by 37% from 2020 to 2060, total water use grows by about 15%. If just municipal water is considered, then demand growth is 35%; while total electricity use grows by nearly 40%. 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 region 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 region can install more than 60 GW of new solar by 2060, with current region capacity less than 100 GW from all sources.
- The *Integrated Policy* scenario, which combines both supply and demand side actions, requires the installation of roughly three new units of new solar for each new unit of natural gas, to achieve 2005 levels of GHGs and 20% reserve margin. This results in a very high, but perhaps realistic installation of additional solar capacity of about 50 GW. Without both demand side actions also taken (the Natural Resource Protection scenario), an additional 100 GW of new solar would have to be added to meet the same GHG levels and reserve margin.
- 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 region. This is already evidenced by Saudi Arabia, as that country has dramatically altered its irrigation policies over the past decades which have led to reductions in irrigated agricultural use and the pumping of fossil groundwater.

Knowledge gaps

- 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 region 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 by country. There are likely local and regional differences in water and energy use patterns.
- The majority of potable water generated through desalinization is done using thermal, co-generation processes. We have assumed the fraction of energy needed at a co-generation plant for desalinization, but this is a simple estimate.

Interactions across the nexus sectors

- Lack of GCC-coordinated policies for fossil groundwater protection
- Lack of 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.

Transboundary/geopolitical aspects of the Arabian W-E Nexus

- Climate change has already changed rainfall and temperature in the region which have not been accounted for an a regional basis
- Projected population/economic growth suggests further impacts on the management of energy and water systems in the region and calls for more cross-border collaboration.
- Policy developments in light of COP-21 are likely to introduce additional complexities/challenges for decision making regarding energy impacts of water production.

- A more regionally-integrated approach to address the national challenges and opportunities of the W-E Nexus is warranted.

Implications for green growth in the region- 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.

- 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.

8.1. Recommendations for further research

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 country are likely to vary considerably. For example, Saudi Arabia could pursue in the future, policies that significantly expand solar generation capacity beyond their own national needs, especially during winter-time, and thus they could become a seasonal exporter of electrical energy to the region, and

beyond. Each country's policies and targets on, for example, water and energy use or food-self-sufficiency could vary, and thus lead to different outcomes if they were to be analyzed within the WEAP-LEAP framework.

- 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 are co-generation. This is important so as to not 'double-count' the energy used to make electricity and potable water at a co-generation plant.

9. References

American Water Works Association, 2008, Water Reuse Rates and Charges, 6666 W. Quincy Ave., Denver, CO 80235 USA.

Angel, S.; J. Parent; D.L. Civco; and A. M. Blei. 2000. THE ATLAS OF URBAN EXPANSION. Lincoln Institute of Land Policy. http://www.lincolninst.edu/subcenters/atlas-urban-expansion/

Dougherty, William. 2015. Local, National and Regional Climate Change Programme. Desalination and Climate Change. Climate Change Research Group. Excel File (Desalination spreadsheet_vPWK_150807.xlsx)

Dubai Water and Electricity Authority (2016) , Annual Statistics.

Environment Agency-Abu Dhabi (EAD). 2009. Climate Change: Impacts, Vulnerability and Adaptation, Abu Dhabi, United Arab Emirates

FAO AQUASTAT. 2008. Bahrain. Irrigation in the Middle East region in figures – AQUASTAT Survey 2008. http://www.fao.org/nr/water/aquastat/countries_regions/bhr/index.stm

FAO AQUASTAT. 2008. Kuwait. Irrigation in the Middle East region in figures – AQUASTAT Survey 2008. http://www.fao.org/nr/water/aquastat/irrigationmap/kwt/index.stm

FAO AQUASTAT. 2008. Oman. Irrigation in the Middle East region in figures – AQUASTAT Survey 2008. http://www.fao.org/nr/water/aquastat/countries_regions/omn/index.stm

FAO AQUASTAT. 2008. Qatar. Irrigation in the Middle East region in figures – AQUASTAT Survey 2008. http://www.fao.org/nr/water/aquastat/countries_regions/qat/index.stm

FAO AQUASTAT. 2008. Saudi Arabia. Irrigation in the Middle East region in figures – AQUASTAT Survey 2008. http://www.fao.org/nr/water/aquastat/countries_regions/sau/index.stm

FAO AQUASTAT. 2008. United Arab Emirates. Irrigation in the Middle East region in figures – AQUASTAT Survey 2008. http://www.fao.org/nr/water/aquastat/countries_regions/are/index.stm

Heaps, C.G., 2012. Long-range Energy Alternatives Planning (LEAP) system. [Software version 2012.0049] Stockholm Environment Institute. Somerville, MA, USA. http://www.energycommunity.org/

International Energy Agency. 2015. Projected costs of generation electricity. Organisation for Economic Co-operation and Development/International Energy Agency.

IPCC, 2014 (AR5): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Molina, Maggie. "The best value for America's energy dollar: a national review of the cost of utility energy efficiency programs." American Council for an Energy-Efficient Economy. 2014.

Murakami, Masahiro. 1995. Managing Water for Peace in the Middle East; Alternative Strategies. United Nations University Press, 1995.

United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision, custom data acquired via website.

UN-ESCWA, BGR. 2013. "Inventory of Shared Water Resources in Western Asia: Chapter 6 Jordan River Basin. United Nations Economic and Social Commission for Western Asia." Federal Institute for Geosciences and Natural Resources, Beirut.

Union of the Electricity Industry (2003), Efficiency of Electricity Generation – EURELECTRIC, Boulevard de l'Impératrice, 66 – B-1000 Brussels.

US Energy Information Administration, (2016), Levelized cost and levelized avoid cost of new generation resources in the Annual Energy Outlook,

Whittington, D. and Hanemann, W. M. 2006. The Economic Costs and Benefits of Investments in Municipal Water and Sanitation Infrastructure: A Global Perspective. Department of Agricultural & Resource Economics, UC Berkeley. PP 1027.

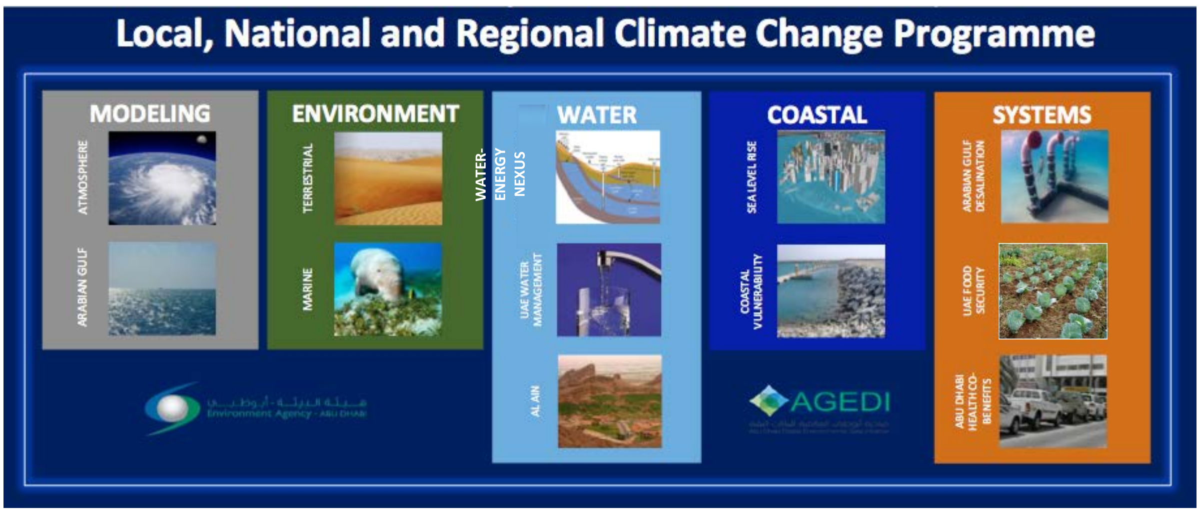
World Business Council for Sustainable Development. http://www.wbcsd.org/about/organization.aspx

Yates D, Sieber J, Purkey D, and Huber-Lee A 2005 WEAP21 - A Demand-, Priority-, and Preference-driven Water Planning Model Part 1: Model Characteristics, Water International, 30: 487–500

A. Annex W-E Nexus Visualization of Results

The results of the regional W-E Nexus sub-project will be incorporated into an LNRCCP website portal (currently under development) for all 12 sub-projects. In this way, the visualization framework of W-E Nexus will be consistent with the visualization framework of the other sub-projects within the overall LNRCCP. In brief, the LNRCCP website portal is a central website that will offer stakeholders access to all the models and visualization tools developed as part of each sub-project. The initial page seen by a user upon accessing the LNRCCP portal address is shown in Figure A-1. There are a total of twelve (12) icons, one for each sub-project in the LNRCCP. By clicking them, a user can navigate to the visualization tool or model developed specifically for that particular sub-project. The icon for the “W-E Nexus Challenges & Opportunities in the Arabian Peninsula under Climate Change” sub-project is shown as the “W-E Nexus” icon under the "Water" strategic theme at the top of the middle column.

Figure A-1. Initial page seen by a user upon accessing the Local, National, and Regional Climate Change Programme portal



Upon clicking on the “W-E Nexus” icon, the user is offered two options. The first option is oriented toward water analysts in the region who are interested in technical water-energy modeling aspects. This option offers full technical access to the LEAP and WEAP models themselves, which can be downloaded to view results within the structure of the models and/or to conduct additional policy explorations as desired using the modeling framework. Licensed versions of these models, with access to technical support, are being provide to AGEDI at no cost for a 1-year period. Following the WEAP-LEAP training programme, participants and others already familiar with WEAP or LEAP frameworks will be able to access and implement the models within this server.

The second option is oriented toward stakeholders in the region that are not water specialists but may want to explore the project's analytical results in a visual interactive way. This option offers full access to the outputs of LEAP and WEAP modeling results (though not to the models themselves) within PowerView, an interactive data exploration, visualization, and presentation tool that is oriented toward intuitive ad-hoc visualization. It is a feature of Microsoft Excel 2013, a widely used software program in the region, and of Microsoft SharePoint Server 2010 and 2013 as part of the SQL Server 2012 Service Pack 1 Reporting Services Add-in for Microsoft SharePoint Server Enterprise Edition.

The subsections that follow use PowerView to visualize the range of outputs developed with the models. Rather than including the full time-series data of detailed results available within the coupled WEAP-LEAP modeling system, this report contains a "tutorial" for using and exploring those results to demonstrate the computing power of the integrative models, the visualization options in PowerView, and the range of quantitative and spatial results that can be produced. There a list of steps to follow in order to explore and visualize the results in PowerView and a set of screen captures are included as well to show the type of visualizations available in PowerView.

A.1 Tutorial for data exploration and visualization of model's outputs in an interactive way with the use of PowerView

The LEAP and WEAP modeling results are aggregated in four files with a format of Microsoft Excel 2013. Each file has results for each policy scenario implemented (see in this report Section 5 for Scenario Framework) in the study. Those four files and corresponding scenarios' names are shown in Table A-1.

A.2 Installation of PowerView, a feature of Microsoft Excel 2013

In order to install PowerView in Microsoft Excel there are specific steps listed here:

- Turn on the Power View add-in from Excel Options
- Go to File > Options > Add-Ins.
- In the Manage box, click the drop-down arrow > COM Add-ins > Go.
- Check the Power View check box > OK.

For further information about how to create a PowerView sheet in Excel and to start using PowerView for the first time, more information can be found in this link:

https://support.office.com/en-us/article/Create-a-Power-View-sheet-in-Excel-2013-b23d768d-7586-47fe-97bd-89b80967a405

A.3 Brief description of PowerView Excel Database

The different Excel files have two main components, the database and visualizations. There are ten spreadsheets within the database from the WEAP and LEAP model results. Those data spreadsheets are identified with this format: "DATA_DatasetNumber_Results Type_Scenario". In the upper-left corner (row #1 to #4) there is a legend that came from exporting results from the WEAP and LEAP models. In general the information contained in this legend is the result variable, scenario's name, branches, and units. Followed by the corresponding output data from both models. In Column A, the years of the simulation are placed. From Column B and Row 6 forward the different names of results' branches are placed. From Column B Row 7 the actual results' branches is listed. These results are presented in a matrix format and vary depending the attributes of the variables.

Direct output from the WEAP and LEAP models is not properly configured for PowerView. The necessary PowerView format needed is the "long-format", which requires a data transformation. This transformation was done for all the results (DATA spreadsheets) and a table with the long-format is located right below the last row of the WEAP and LEAP results. Thus, there is no need to proceed with any type of transformation in order to plot results. As a reference, this data transformation was done through the implementation of a VBScript that each file in the Micros

Table A-1: Policy Scenarios and corresponding Microsoft Excel File with results for visualization in PowerView

Policy Scenario	**File Name**
Business-as-usual (BAU) with Current Climate	BAU_Water-EnergyNexus ArabianRegion_Final.xlsm
Business-as-*Usual with RCP8.5*	BAU-RCP8.5_Water-EnergyNexus ArabianRegion_Final.xlsm
High Efficiency Scenario (Demand Side Management)	HighEfficiency_Water-EnergyNexus ArabianRegion_Final.xlsm
Natural Resource Protection Scenario (Supply Side Adaptation)	Natural Resources Protection_Water-EnergyNexus ArabianRegion_Final.xlsm
Integrated Policy Scenario (both Supply and Demand Side Measures)	Integrated Policy_Water-EnergyNexus ArabianRegion_Final.xlsm

Tab.

A.4 Description of PowerView Visualizations

Each Data spreadsheet has at least one visualization associated. The PowerView visualization spreadsheets are identified with this format: "DatasetNumber_Results Type_Scenario". With a right-click on these spreadsheets, the different charts and tables that were produced using the corresponding WEAP and LEAP results can be seen. There is a general description that each PowerView visualization has; starting with a name that describes the corresponding visualization on the top part of the chart. Following below the visualization's name, the corresponding graphs are placed. Almost all of the charts have some tools to visualize results since output data start in 2000 and goes up to 2060. Within the charts, results for earlier and future years are accessible in PowerView by clicking on either the backward ◀ or forward ▶ icons along the horizontal axis, or scrolling through the years with the ▬ icon along the bar below. When those visualizer tools are used, the corresponding graphs are updated for the selected year to look at. For the bar charts with just putting the mouse pointer on any bar chart, a small window pop-up showing the corresponding data and information associated to this specific bar. In the same bar charts if there is interest on highlighting a specific element in the in the legend, click-right in the legend color bar, and it will be highlighted in the corresponding bar chart.

Tables get updated in the same way as charts do. This happens when different years are selected to be explored by clicking on either the backward ◀ or forward ▶ icons along the horizontal axis, or scrolling through the years with the ▬ icon along the bar below. For charts with a map in the background, with a right-click in the map, the map can be moved in any direction. Also with a right-click in the map and then spinning forward or backward the mouse wheel, a zoom-in or zoom-out is activated. In the same map chart the following visualization tools are located in the upper-right ⊖ ⊕ ⊙ corner.

For the groundwater storage volume chart, only four aquifers are currently plotted. If there is interest in looking at other aquifers, these other aquifers can be selected by first right-click in the chart. Then, the PowerView fields will pop-up in the right-side of the chart. Through check-in and uncheck-in the different aquifers in these fields, the aquifer groundwater storage volume is plotted in the chart.

A.5 Solving Issues with PowerView

Sometimes PowerView has issues showing the charts. If that happens, just follow the directions described in the following link. This is a Microsoft "bug".

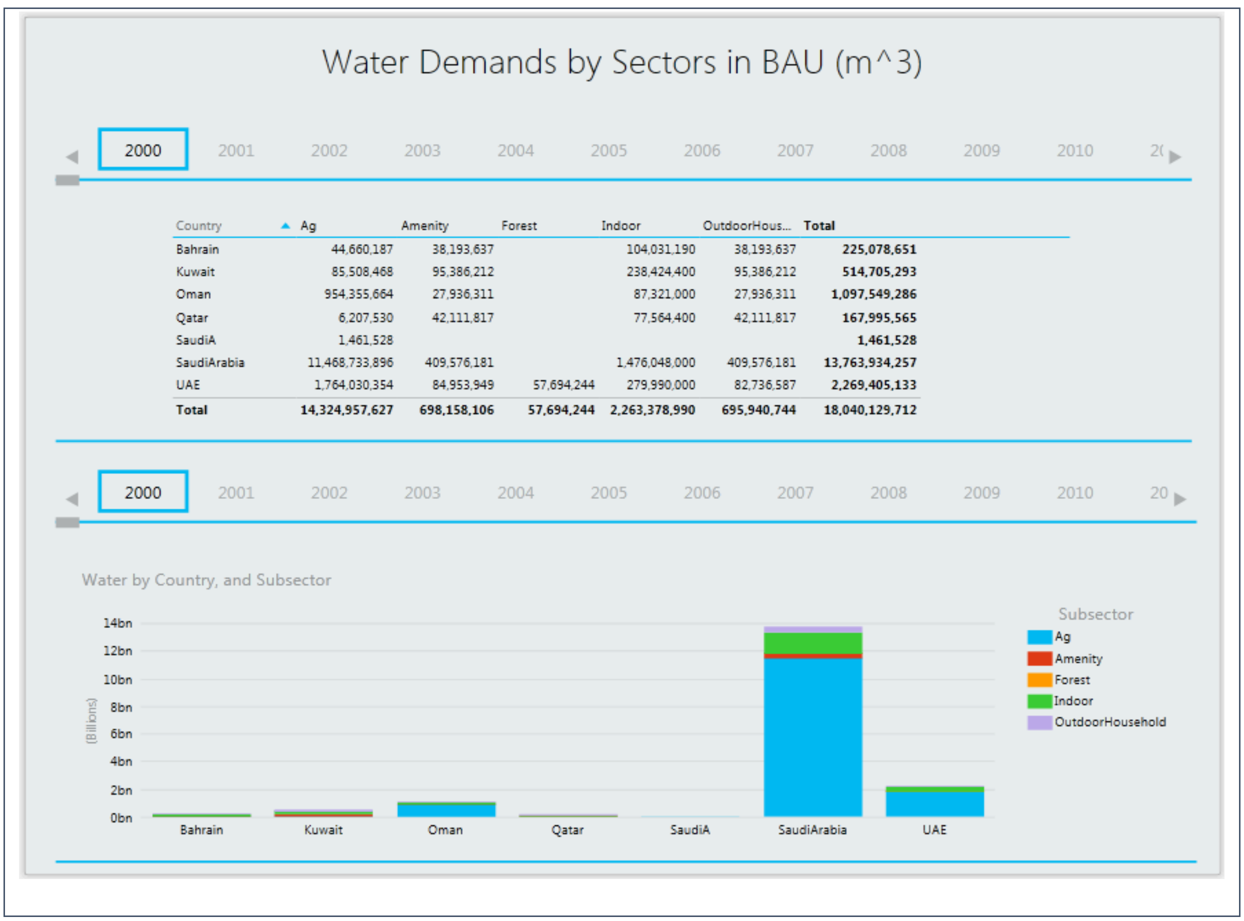
http://www.mssqlinsider.com/2013/02/how-to-enable-powerpivot-and-power-view-in-excel-2013/

A.6 Example WEAP Results from the Business As Usual (BAU) Scenario

This section provides a sampling of results from the validated WEAP and LEAP models for the Business As Usual Scenario that has historic climate data without climate change effects for the period 2000-2060. Figure A-2 shows the simulated water demands by the WEAP model for each country, plotted for the year of 2000 for the BAU scenario. In the top graph, the total indoor and outdoor water demand volumes are presented for each country. In the bottom graph, water demand volumes are split by subsectors (agriculture, amenities, forest and outdoor household).

The results illustrate some notable and well-known trends in the region, such as Saudi Arabia's large water demand and other variables between countries' outdoor and indoor water demand. Within the program, results for earlier and (eventual) future years are accessible in PowerView by clicking on either the backward or forward icons along the horizontal axis, or scrolling through the years with the icon along the bar below. In this scenario and year the supply delivered is equal to the water demands. In other words there are no unmet demands.

Figure A-2. PowerView water Demands for BAU Scenario, with 2000 only results shown


Water Demands by Sectors in BAU (m^3)

Country	Ag	Amenity	Forest	Indoor	OutdoorHous...	Total
Bahrain	44,660,187	38,193,637		104,031,190	38,193,637	**225,078,651**
Kuwait	85,508,468	95,386,212		238,424,400	95,386,212	**514,705,293**
Oman	954,355,664	27,936,311		87,321,000	27,936,311	**1,097,549,286**
Qatar	6,207,530	42,111,817		77,564,400	42,111,817	**167,995,565**
SaudiA	1,461,528					**1,461,528**
SaudiArabia	11,468,733,896	409,576,181		1,476,048,000	409,576,181	**13,763,934,257**
UAE	1,764,030,354	84,953,949	57,694,244	279,990,000	82,736,587	**2,269,405,133**
Total	**14,324,957,627**	**698,158,106**	**57,694,244**	**2,263,378,990**	**695,940,744**	**18,040,129,712**

Figure A-3 shows the corresponding supply delivered volumes for the Business As Usual Scenario

Figure A-3: Supply Water Delivered for the BAU Scenario for Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE; results shown for the year 2000 only

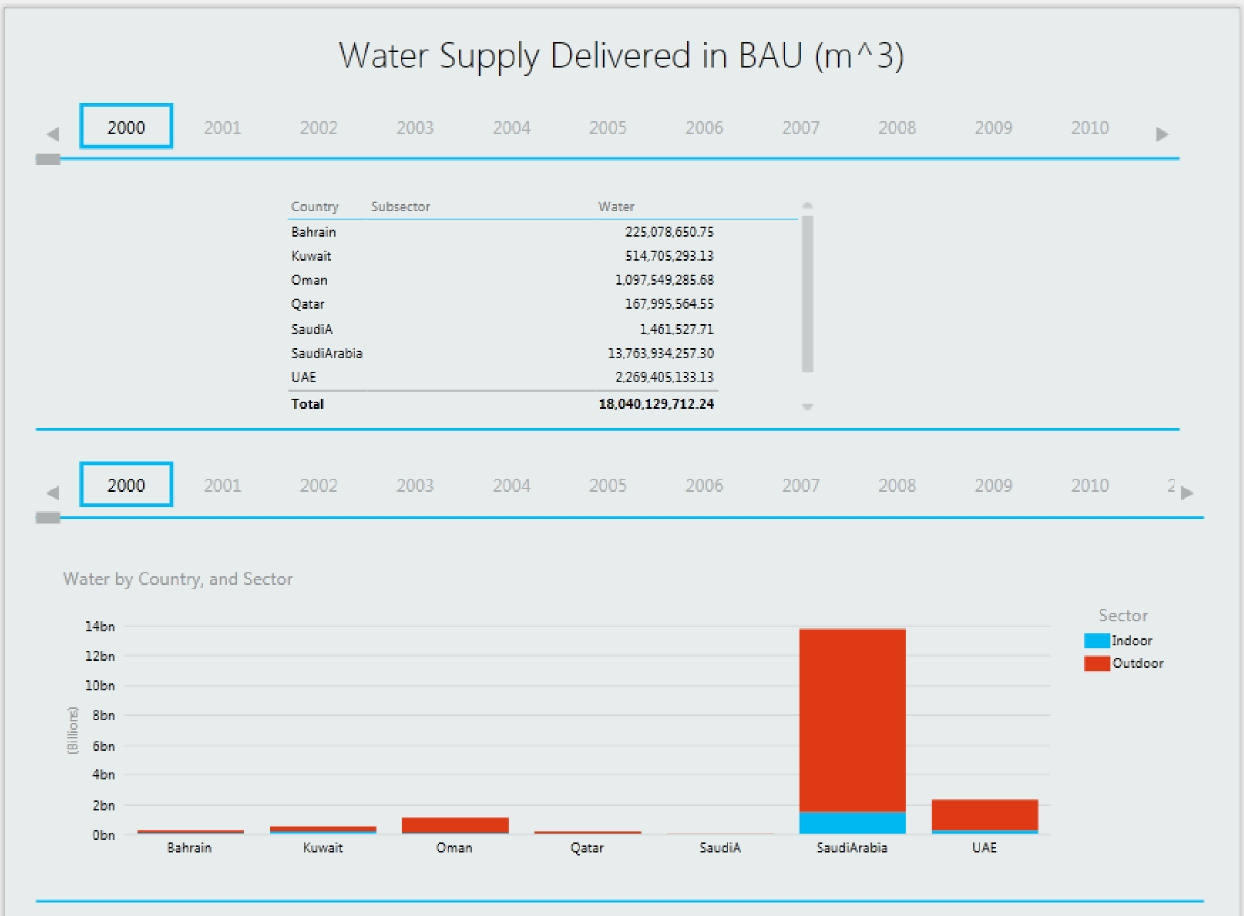


Figure A-4 also shows the spatial representation of supply water delivered for the BAU Scenario by country. This figure combines several types of results. In the bottom right corner of the figure, the total water demand in the Arabian Peninsula is presented, as a complete time series from

2000 to 2060. In the bottom middle section of the figure, a breakdown of demand is offered, while the bottom left sections contains a breakdown by country. As described above, a user can readily view results for earlier and (eventual) future years in the program by clicking on either the backward or forward icons along the horizontal axis, or scrolling through the years with the icon along the bar under the time axis.

Figure A-4: Supply Water Delivered for the BAU Scenario; with spatially representation demonstrated for Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE; results shown for the year 2000 only

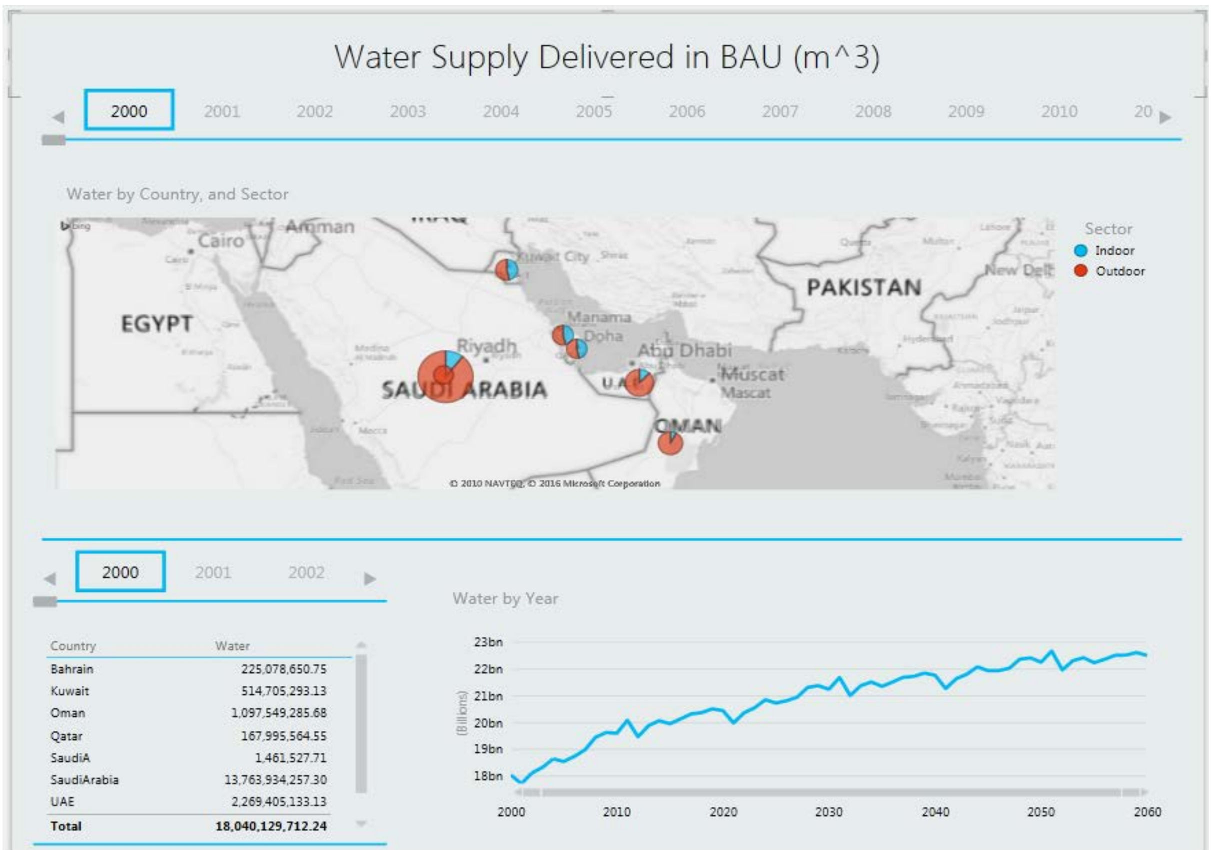
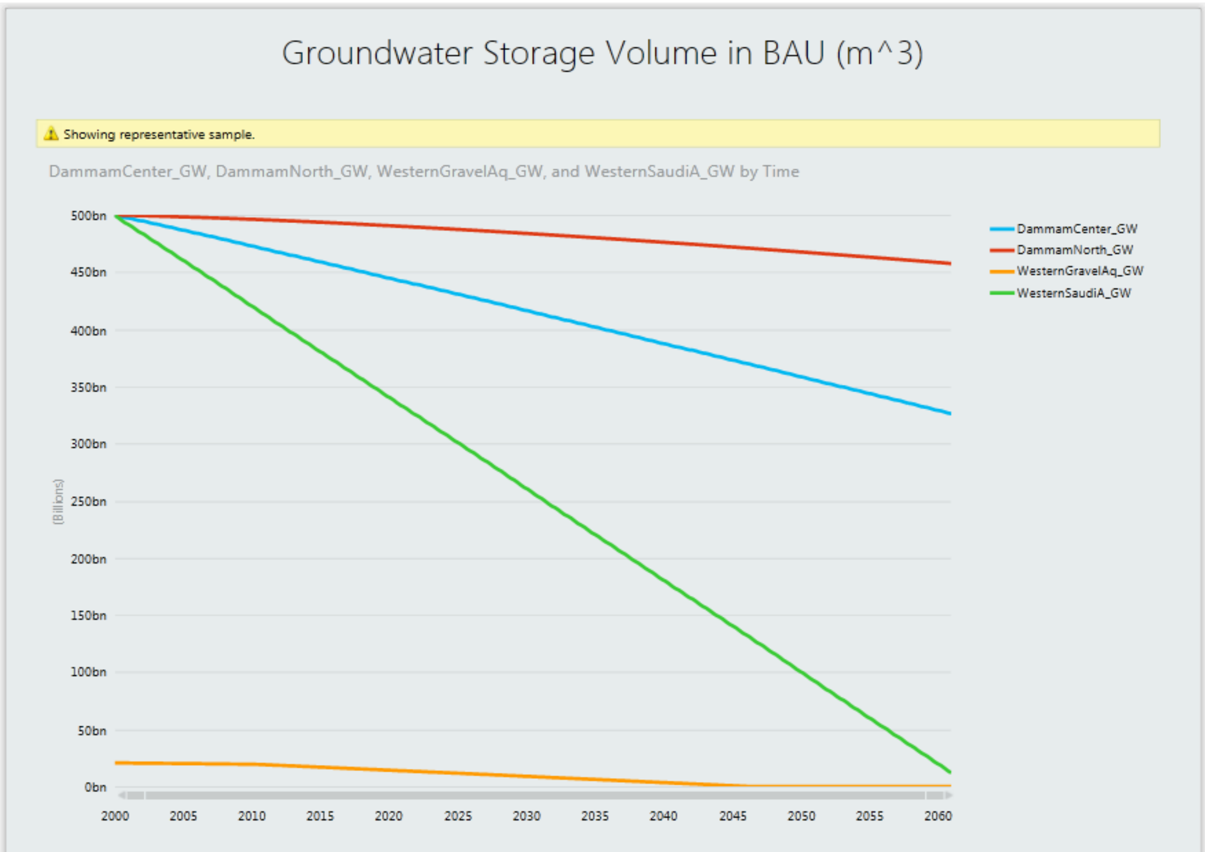


Figure A-5 shows groundwater storage for the Dammam aquifer under the BAU Scenario. The figure corresponds to the two sections in which the aquifer was split for modeling purposes. As shown in the figure, the northern section of the aquifer is relatively stable in terms of the total amounts of groundwater stored in this area, roughly 500 billion cubic meters. On the other hand, the central section of the aquifer shows a decrease in stored groundwater, decreasing from about 500 billion cubic meters in 2000 to about 320 billion cubic meters by 2060. The western Saudi Arabia aquifer shows a very strong decrease in storage volume, depleting the assumed storage capacity of 500 billion cubic meters in 2000 to about almost 20 billion cubic meters by 2060. The western gravel aquifer that supplies groundwater to Al Ain region in UAE and western Oman is also depleted over time, but not as a large percentage considering its small volume.

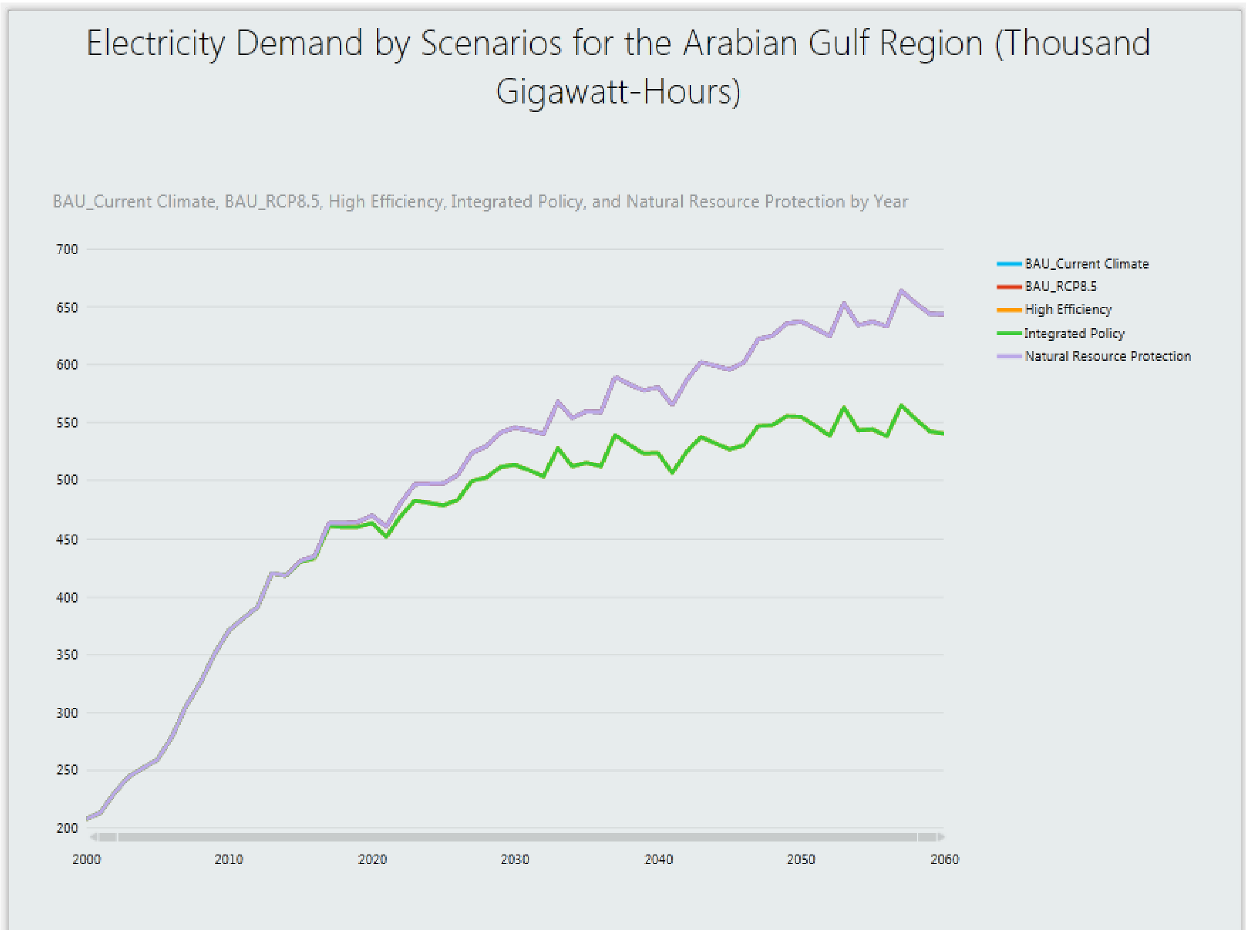
The coupled WEAP-LEAP modeling system can be used to explore policy scenarios of interest to the region. For illustrative purposes, a slice of the overall planning period of 2015-2060 has

Figure A-5.Groundwater storage for the Dammam aquifer in the Arabian Region corresponding to the three sections in which the aquifer was split for modeling purposes, for the historical period.



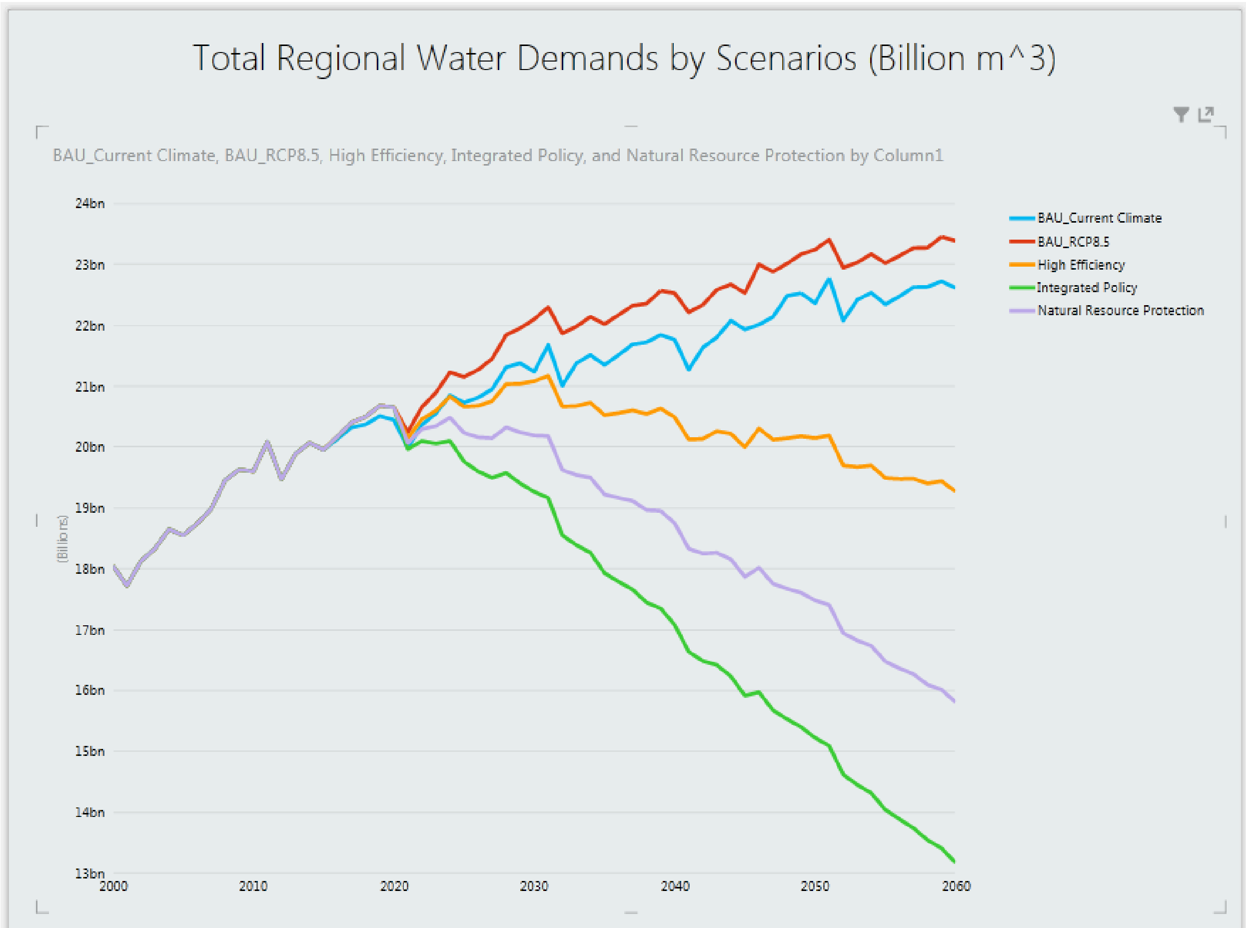
been considered, namely the period 2040 to 2060. Two scenarios are considered. The first is a "Business-as-Usual" (BAU) Scenario in which the modeled trends of the historical period are projected into the future in the absence of any policies to influence water consumption patterns at either the regional, national, or sub-national scales. The second scenario (BAU with climate change) uses all the same trends but includes climate change predictions on water and energy consumption patterns only (i.e., no policies introduced to influence water consumption patterns at either the regional, national, or sub-national scales). Three more Policy Scenarios are included which are the High Efficiency, Natural Resources Protection and Integrated Policy Scenarios which were described in Section 6 Scenarios Framework

Figure A-6. Total modeled electricity demand for the Arabian Gulf Region by scenarios for Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE



Figures A-7 and A-8 illustrate the results of the analysis for total regional water and energy demand by Policy Scenarios, respectively, for the 60-year period. The only difference between the two BAU futures is the changes in climate. For water, these changes produce a variable increase in water demand throughout the planning period. Significant changes can be observed in the High Efficiency, Natural Resources Protection and Integrated Policy Scenarios' water demands starting on 2020 when the different policies kick off until 2060. As expected the High Efficiency and Integrated Policy Scenarios have the lowest water demand (see policy assumptions). An increase in energy consumption is also evident, with roughly a consistent percentage increase in electricity generation over the period relative to the BAU with current climate (Figure A-7).

Figure A-7. Total modeled water demand for the Arabian Gulf Region by scenarios for Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE.



Note the significant decrease in energy consumption in the High Efficiency, Natural Resources Protection and Integrated Policy Scenarios. The reduction in energy consumption goes accordingly with assumptions taken in the each corresponding policy scenario as they are described in Figure A-7. The High Efficiency and Natural Resources Protection Scenarios can also be combined with the changes in policy implementation articulated in the Integrated Policy Scenario detailed in Section 6. The outputs of the analysis will focus on the differences in water use, electricity production, costs and GHG emissions for each BAU-Policy Scenario combination.

The total, discounted cost of production for the policy scenarios is shown in Figure A-8. For the year 2060, the Integrated Policy scenario has lower cost, but all costs have diminished since 2020.

Figure A-8. Total Cost of Production by Scenario

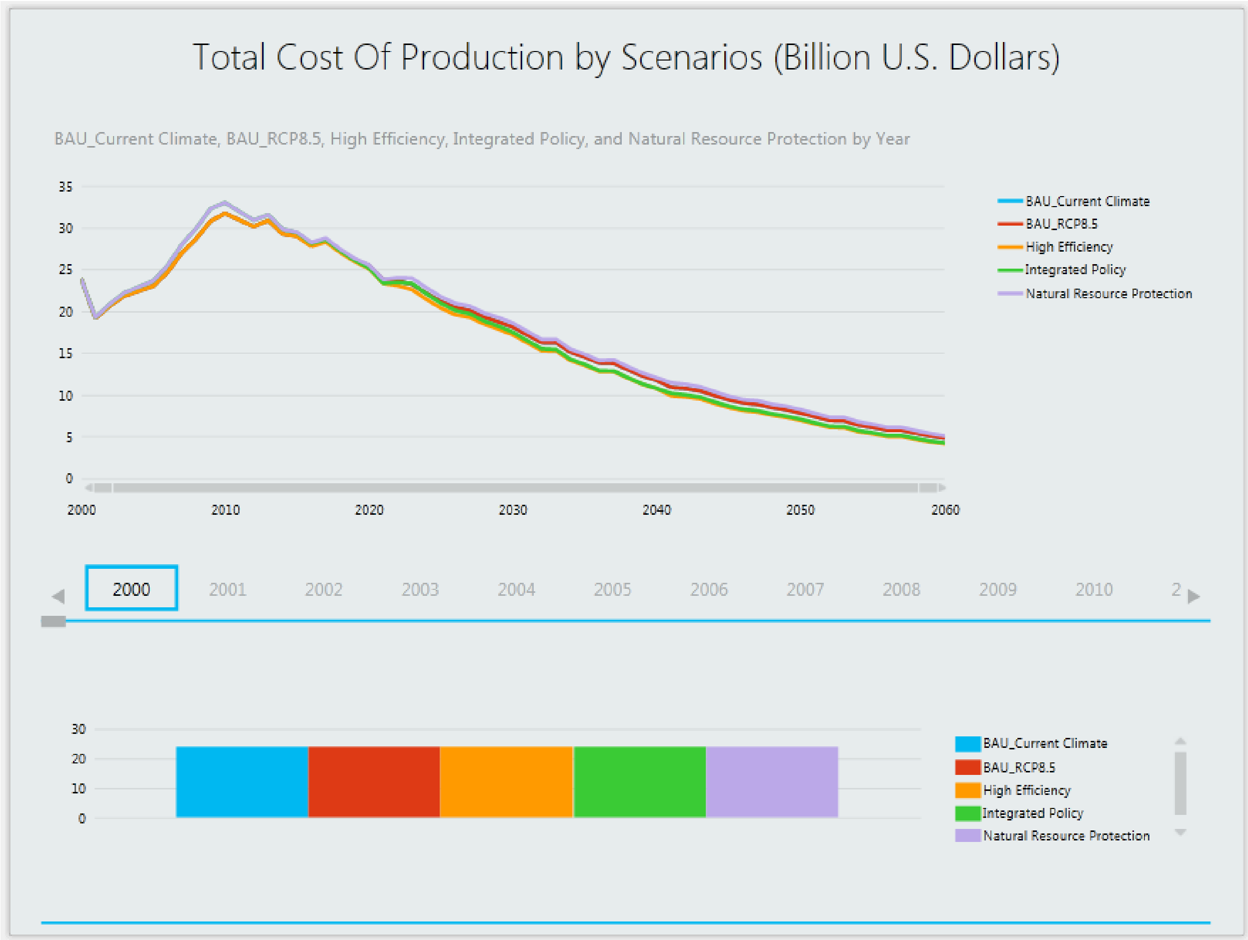
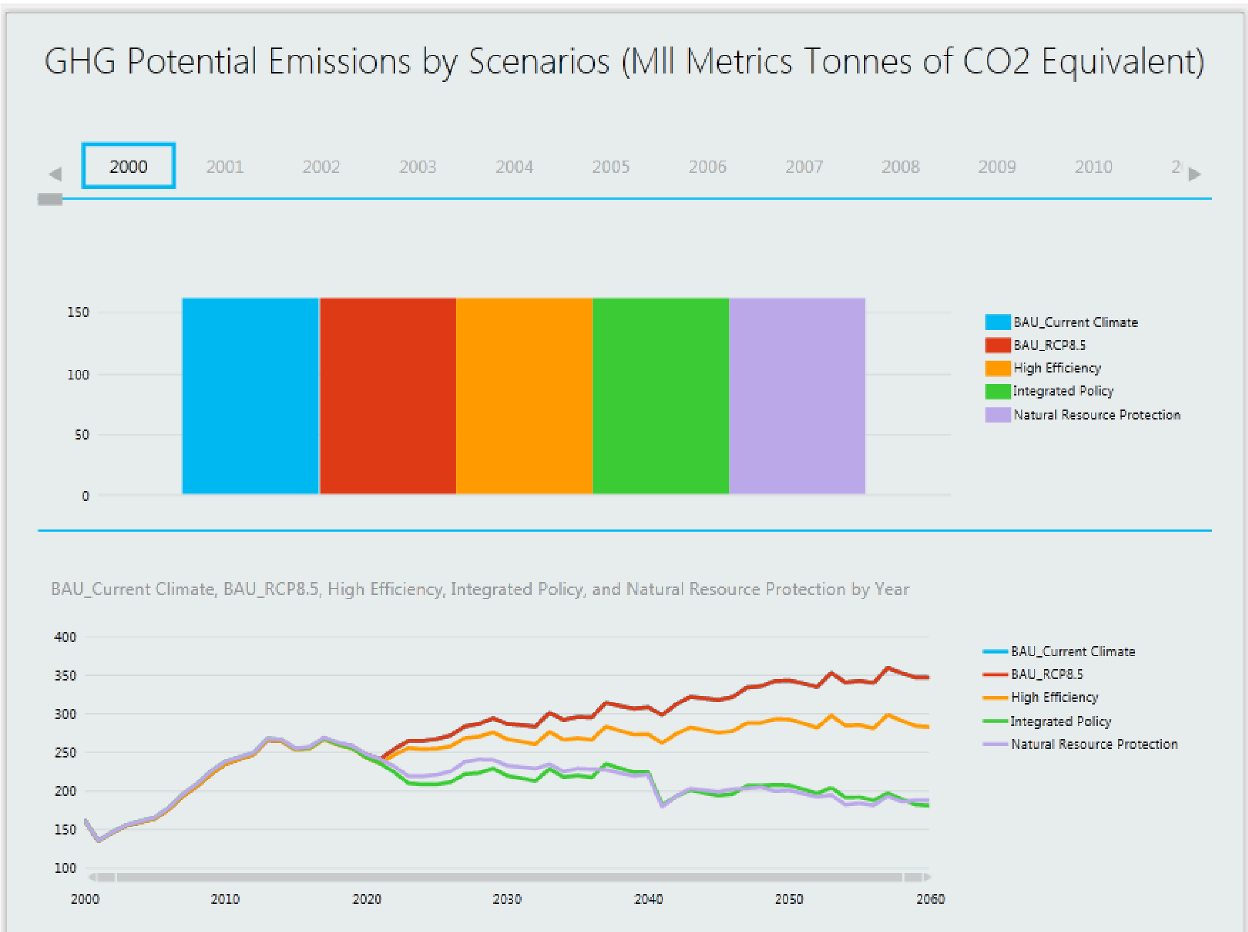


Figure A-9 shows the GHG emissions over the length of the models for the different scenarios. By the year 2060, there is wide divergence in GHG production, with the Integrated Policy Scenario producing less GHGs.

Figure A-9. GHG Potential Emissions by Scenarios



B. ANNEX Water and Energy System Assumptions

This annex provides a summary of the range of key assumptions that have been built into the WEAP and LEAP models for the Arabian Peninsula.

9.1. Population

The Population of the Arabian Peninsula drives water demand on a per-capita basis, which includes an estimate of historic, current and projections of future population growth in the region. The countries of the Arabian Peninsula populations are closely coupled with economic activity that generates immigration of workers. As such, population growth rates can be very volatile. The population numbers implemented in the WEAP model come from the United Nations Annual Total Population from 2000 to 2010 (mid-year estimates from UN population division available at http://esa.un.org/unpd/wpp/DVD/), and the predictions for growth in the future are the 2000-2010 average population growth rates by countries.

Figure B-1: Total population of different Gulf countries modeled in WEAP forecast developed by the United Nations (2015)

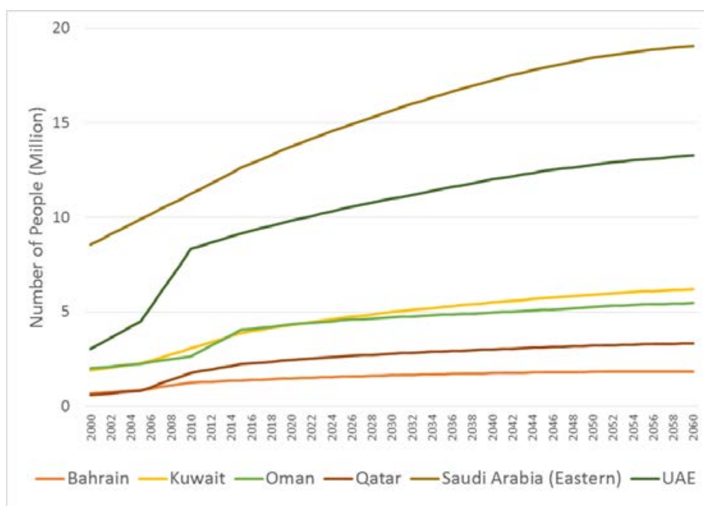


Figure B-1 shows the population values for the model between the years 2000 and 2060. Saudi Arabia has the largest population centers. Populations are modeled in WEAP using Demand Site objects (red circles on the schematic). Each site that exerts demands on the water system for supply based on the data entered within the demand sites. Population is only one component of the information contained in the demand sites, which can also be programmed to include water losses and reuses, monthly trends of demand variation, and water lost from the system as it passes through the demand site as well water consumption.

9.2. Land Uses Demanding Water

WEAP uses catchment elements to represent land use types that demand water from the system. We identified four land use types to include in our model: Amenity, agriculture, outdoor household use and forests. For each population center that exists in the WEAP model as a water demand site, e.g. Kuwait Countryside, which is itself an aggregation of any populations outside of Kuwait City, the model also has an "outdoor" catchment to account for the square kilometers of each of these land use types. Some of this data is still unavailable, and has been estimated in order allow the model to run. The estimation of these land use types are calculated as fraction of the Total Urban Land Cover (Angel, et al., 2000) reported for each country in the Arabian region in 2000. The estimated fraction for amenities, forest, and household is variable for each country in the region and those urban areas and corresponding fractions are shown in Table B-1.

Table B-1: Total urban land cover (Angel, et al. 2000) and estimated fractions of outdoor areas

		Fractions		
	Total Urban Land Cover	Amenities	Outdoor Household	Forest
Country	(Hectares)	(%)	(%)	(%)
Bahrain	22,891	15	15	-
Kuwait	39,322	20	20	-
Oman	38,215	5.0	5.0	-
Qatar	36,542	10	10	-
Saudi Arabia (Eastern)	306,052	9.0	9.0	-
UAE	74,684	9.75	9.5	6.5

9.3. Water Demand

The water demand for the populations currently varied by countries and these water demand per capita values were calculated from FAO AQUASTAT.

Table B-2 shows the annual water demand per capita for each country in the Arabian Peninsula and by scenario. These annual water consumption values correspond only to the residential, commercial and industrial sectors and were calculated for years between 2002 and 2006 based on FAO AQUASTAT dataset available and corresponding total populations by countries. For the future as the populations grow in the demand sites, the total water demand will grow too. Water consumption per capita values changed according to scenarios. All values in the BAU scenarios with and without climate change stay the same for the whole modeling time (2000 to 2060). For the High Efficiency, Natural Resources Protection and Integrated Policy Scenarios, the per capita values are the same as BAU until 2020. After 2020 the water consumption per capita values start decreasing gradually until they reach the corresponding values in Table B-2 (for more information about reduction in water consumption per capita assumption, please refer to Section 5, Scenario Framework).

Table B-2: Annual water demand by country and by scenarios

Country	Water Consumption Per Capita (m3/person/year)				
	BAU Without CC	BAU With CC	High Efficiency	Natural Resources Protection	Integrated Policy
Bahrain	156	156	Interpolation (2020:156 - 2060:75)	156	Interpolation (2020:156 - 2060:75)
Kuwait	124	124	Interpolation (2020:124 - 2060:75)	124	Interpolation (2020:124 - 2060:75)
Oman	39	39	Interpolation (2020:39 - 2060:75)	39	Interpolation (2020:39 - 2060:75)
Qatar	131	131	Interpolation (2020:131 - 2060:75)	131	Interpolation (2020:131 - 2060:75)
Saudi Arabia	69	69	Interpolation (2020:69 - 2060:75)	69	Interpolation (2020:69 - 2060:75)
UAE	92	92	Interpolation (2020:92 - 2060:75)	92	Interpolation (2020:92 - 2060:75)

For the land use areas demanding water, the demand is determined by land class characteristics such as Kc values, deep water capacity, deep conductivity and values for initial Z2 under the Soil Moisture Rainfall Runoff Model for water calculations. Within these expressions, these values interact with information about the climate. The climate is driven by precipitation, temperature, humidity values, wind speed, and cloudiness factors. Together these variables produce overall water demand for the land use catchments.

9.4. Water Supply

Groundwater is the main water supply in the Arabian Region. A total of twenty aquifers were identified in the region supplying groundwater resources to the different demand sites. The corresponding aquifers' names and initial storage capacity is shown in Table B-3. Some initial storage capacities were assumed by the project team and those are place holder data that can be provided by local stakeholders and regional experts

Table B-3: Initial storage of aquifers in WEAP Model in 2000 (BCM)

Name of Aquifer	Quantity	Source
AbuDhabiBrackish_GW	100	GTZ (2005)
DammamCenter_GW	200	(UN-ESCWA 2013)
DammamNorth_GW	100	(UN-ESCWA 2013)
EastBrackish_GW	102.5	(EAD, 2009)
EastFresh_GW	100	(EAD, 2009)
OmanEasternReg_GW	100	GTZ (2005)
ShallowEBrackish_GW	10.25	(EAD, 2009)
ShallowEFresh_GW	4	(EAD, 2009)
UAEEasternReg_GW	100	GTZ (2005)
UpperWBrackish_GW	70	GTZ (2005)
UpperWFresh_GW	12.5	GTZ (2005)
WestBrackish_GW	9.9	GTZ (2005)
WesternGravelAq_GW	20.6	(UN-ESCWA 2013)
WestFresh_GW	10	GTZ (2005)

Desalination Capacity - The WEAP model has 24 distinct desalination elements generating potable water from the Arabia Gulf. This data comes from the Climate Change Research Group dataset (Dougherty 2015) and Saif (2015). Under the current model, the desalination capacities were static – but after the implementation of Policy Scenarios the desalination capacity has grown in order to represent possible future conditions. Table B-4 shows the desalination capacity for each region in the WEAP model in the column "Capacity", along with their operational types (RO is reverse osmosis, MSF is multi-stage flash, MED is multiple effect distillation). After the implementation of the Policy Scenarios, we took the assumption that the desalination capacity will grow the Arabian Region. We implemented an assumption where the WEAP model uses a maximum capacity for the future of 1,000 MGD per each technology to satisfy the demand. The assumption was taken to represent the potential desalination capacity that the region has where water is not a constraint. This is an assumption taken based on the different Policy Scenarios description in order to satisfy those Policy Scenarios narratives.

Table B-4: Monthly desalination capacity in WEAP (MGD)

Desalination Plant	Identified Capacity	Implemented Capacity
Bahrain_Desal_MED	78.2	1,000
Bahrain_Desal_MSF	31.7	1,000
Bahrain_Desal_RO	81.8	1,000
Kuwait_Desal_MED	0.3	1,000
Kuwait_Desal_MSF	214.1	1,000
Kuwait_Desal_RO	68.0	1,000
Oman Desal_MED	-	1,000
Oman Desal_MSF	1.8	1,000
Oman Desal_RO	-	1,000
Qatar_Desal_MED	81.3	1,000
Qatar_Desal_MSF	284.2	1,000
Qatar_Desal_RO	21.0	1,000
SaudiArabia_AshSharqiyahRegDesal_MED	204.9	1,000
SaudiArabia_AshSharqiyahRegDesal_MSF	101.6	1,000
SaudiArabia_AshSharqiyahRegDesal_RO	184.4	1,000
UAE_EasternRegDesal_MED	32.3	1,000
UAE_EasternRegDesal_MSF	458.4	1,000
UAE_EasternRegDesal_RO	121.7	1,000
UAE_WesternRegDesal_MED	227.2	1,000
UAE_WesternRegDesal_MSF	930.7	1,000
UAE_WesternRegDesal_RO	192.6	1,000

Wastewater Treatment - Wastewater treatment plants serve much of the population in the area both as a way to reuse water and to ensure that the water returning to the environment has a certain water quality. Initially the data used to populate the wastewater treatment plant nodes in WEAP (brown circles) came from many different sources, some of which were outdated. An initial assumption was that wastewater treatment plants can only treat a percentage of water produced, and only supply treated water to particular places, and not the water that bypasses treatment, WEAP must impose several constraints. This initial assumption was omitted since this initial assumption constrained the wastewater treatment installed capacity and during the validation process, the wastewater treatment volumes were not able to replicate properly in the WEAP model. Thus, the assumption was omitted. After the implementation of the Policy Scenarios, we came across of defining again the future potential wastewater treatment capacity. Thus, the project team took another assumption I order to represent the future wastewater treatment capacity. The wastewater treatment capacity was defined as unlimited with the assumption that in the future wastewater treatment plants will be built to treat and reuse water in the Arabian Region. Each individual treatment plant will then have the capacity to treat as much water is produce in the urban areas.

9.5.Climate Data

A first project of the LNRRCC program was the Regional Atmospheric Modeling under Climate Change Project (RCMUCC), which resulted in a set of meteorological data for use in the impact studies of the LNRCC Programme. The RCMUCC project developed a set of current and future climate projects using a Regional Climate Model (RCM) for the Arabian Peninsula at fine spatial and temporal scale by dynamically down scaling the climate of the Arabian Peninsula using Global Climate Model (GCM) data as the lateral boundary conditions. Data from the RCMUCC project is used in support of the other climate change impact, vulnerability and adaptation assessments, including this Transboundary Groundwater project.

We have extracted from the RCMUCC project's database, time series of total monthly precipitation and monthly average minimum and maximum air temperature, monthly minimum and maximum humidity, and monthly average wind speed for the 19 locations that correspond to our water demand supply modeling in WEAP. In section 6.1 The Business-As-Usual Scenario it is shown a climate characterization of monthly average temperature, precipitation, relative humidity, and wind speed for Abu Dhabi as an example of the climate data used in the project. For LEAP, we have computed a heat index variable from temperature and humidity that is used to estimate the monthly electricity demand, both as a function of the heat index and the regional population.

Table B-5: Groundwater, wastewater and desalinated production according to FAO AQUASTAT report by country.

Country	Groundwater (MM^3/yr)				
	2002	2003	2004	2005	2006
Bahrain		236			
Kuwait	411				
Oman		1,176			
Qatar				218	
Saudi Arabia (Eastern)					7,411
UAE				2,800	
Total	411	1,411		3,018	7,411
Country	**Wastewater (MM^3/yr)**				
	2002	**2003**	**2004**	**2005**	**2006**
Bahrain		18			
Kuwait	82				
Oman		40			
Qatar				44	
Saudi Arabia (Eastern)					66
UAE				240	
Total	82	58		284	66
Country	**Desalinated water (MM^3/yr)**				
	2002	**2003**	**2004**	**2005**	**2006**
Bahrain		104			
Kuwait	420				
Oman		106			
Qatar				182	
Saudi Arabia (Eastern)					521
UAE				960	
Total	420	210		1,142	1,041

9.6. Validation of Regional Observed and Simulated Water Supply and Demand

The model has been validated for water production corresponding to the three main water sources in the region: groundwater, desalination and wastewater production; and we have used the FAO AQUASTAT database for each country in the region for validation (FAO AQUASTAT, 2008). It is important to highlight the total water production for Saudi Arabia, estimated to be 23,666 million cubic meters for Saudi Arabia in 2006. This volume of water came from the Saudi Arabia FAO AQUASTAT report (http://www.fao.org/nr/water/aquastat/). The groundwater production reported for Saudi Arabia in 2006 is 22,459 million cubic meters which is a very significant number that should be taken cautiously and verified.

Table B-6: Groundwater, wastewater and desalinated production according the WEAP model

Country	Groundwater (MM³/yr)				
Country	2002	2003	2004	2005	2006
Bahrain	139	142	146	149	156
Kuwait	84	85	86	85	84
Oman	147	150	152	151	153
Qatar	174	181	187	192	216
Saudi Arabia (Eastern)	3,956	4,039	4,093	4,007	3,988
UAE	104	112	120	129	150
Total	4,604	4,710	4,784	4,712	4,748
	Wastewater (MM³/yr)				
Country	2002	2003	2004	2005	2006
Bahrain	6	7	7	7	8
Kuwait	14	14	15	15	16
Oman	39	40	41	41	41
Qatar	5	5	6	6	7
Saudi Arabia (Eastern)	36	42	44	45	46
UAE	18	20	21	23	27
Total	118	129	133	137	146
	Desalinated water (MM³/yr)				
Country	2002	2003	2004	2005	2006
Bahrain	91	93	96	98	103
Kuwait	429	439	449	453	472
Oman	339	345	348	345	348
Qatar	-	-	-	-	-
Saudi Arabia (Eastern)	922	940	961	967	980
UAE	2,166	2,196	2,244	2,230	2,281
Total	3,946	4,014	4,097	4,093	4,184

Source: SEI US WEAP model: Regional W-E Arabian Region_07Aug16

Similarly, the corresponding historical volumes of the three types of water production that the WEAP models reproduces for the historical period of 2002-2006 are presented in Table B-6. These values are the result of the validation performed in the WEAP model.

A comparison between the water production from FAO AQUASTAT reports and corresponding water production from the WEAP model provides a sense of how well the model for the Arabian Region is able to reproduce historic conditions. These validation results are shown in Table B-7 as a percent change respect to the FAO AQUASTAT reports. The validation shows acceptable model approximation of past condition for groundwater, desalination, and wastewater reuse volumes. The total water production by country is represented by the model with ranges of underestimation of ~-18% for Oman up to -55% for Qatar (Table B-8). As mentioned in Section 4.2 WEAP Historic Period

Validation the WEAP model underestimates the numbers from FAO AQUASTAT based on the feedback that the project team obtained from regional stakeholders and regional water-energy specialists that was provided during the socialization of the models' data and draft technical results webinar on 26 January 2016. The specialists told specifically the project team that the FAO AQUASTAT numbers were larger than what those numbers are in reality. That is why the underestimation of water volumes achieved in the validation process. These validation numbers could be improved if the regional water-energy specialists would have provided the numbers to validate with. What we present here is what we consider a fair assessment.

Table B-7: Validation of groundwater, wastewater and desalinated water production

Country	Groundwater (Percentage)				
	2002	2003	2004	2005	2006
Bahrain		-40%			
Kuwait	-80%				
Oman		-87%			
Qatar				-12%	
Saudi Arabia					-46%
UAE				-95%	
Country	**Wastewater (Percentage)**				
	2002	**2003**	**2004**	**2005**	**2006**
Bahrain		-62%			
Kuwait	-83%				
Oman		0%			
Qatar				-86%	
Saudi Arabia					-30%
UAE				-91%	
Country	**Desalinated water (Percentage)**				
	2002	**2003**	**2004**	**2005**	**2006**
Bahrain		-10%			
Kuwait	2%				
Oman		226%			
Qatar				-100%	
Saudi Arabia					88%
UAE				132%	

Table B-8: Validation of total water production

Country	Total water production (Percentage)				
	2002	2003	2004	2005	2006
Bahrain		-32%			
Kuwait	-42%				
Oman		-59%			
Qatar				-55%	
Saudi Arabia					-37%
UAE				-40%	

Table B-9: Electricity demand coefficient for Commercial-Industrial-Household electricity uses by country.

Country	A	B	C	Population
Saudi Arabia	0.03	0.015	0.01	22.8
Bahrain	0.025	0.01	0.025	0.9
Qatar	0.06	0.04	0.05	0.7
UAE	0.05	0.03	0.06	3.1
Oman	0.03	0.01	0.002	2.5
Kuwait	0.06	0.03	0.04	2.3

Monthly per-capita electric energy intensities for each country (*PCEi*) were estimated from these data, using polynomial regressions for each region, *i*, given as $PCEi = a + b(Hi) + c(Hi)^2$ (MWh/hh); where Y= year; Hi= monthly heat index in ^{o}c for each region, and a, b, c are the coefficients of the fitted regression by region. The first and second elements of the regression imply levels of electricity demand per person where: a is a base-level of demand and b accounts for an annual trend in per-capita use. More electricity is used when it is warmer and more humid, thus a heat index is used to reflect the climate effect of electricity demand, and includes both a linear and a non-linear terms to express that, for some regions, a very high heat index implies much greater electricity use. Total monthly regional electricity demand (*REi*) is then simply, $REi = PCEi * Popi$, where total population projections (*Popi*) were extracted using growth rates by region, i. Table B-8 shows the regression coefficients a, b, c, for the commercial, industrial, and household electricity demand regression model used in LEAP.

LNRClimateChange@ead.ae

an initiative of

Abu Dhabi Global Environmental Data Initiative (AGEDI)
P.O Box: 45553
Al Mamoura Building A, Murour Road
Abu Dhabi, United Arab Emirates

Phone: +971 (2) 6934 444
Email : info@AGEDI.ae

AGEDI.org