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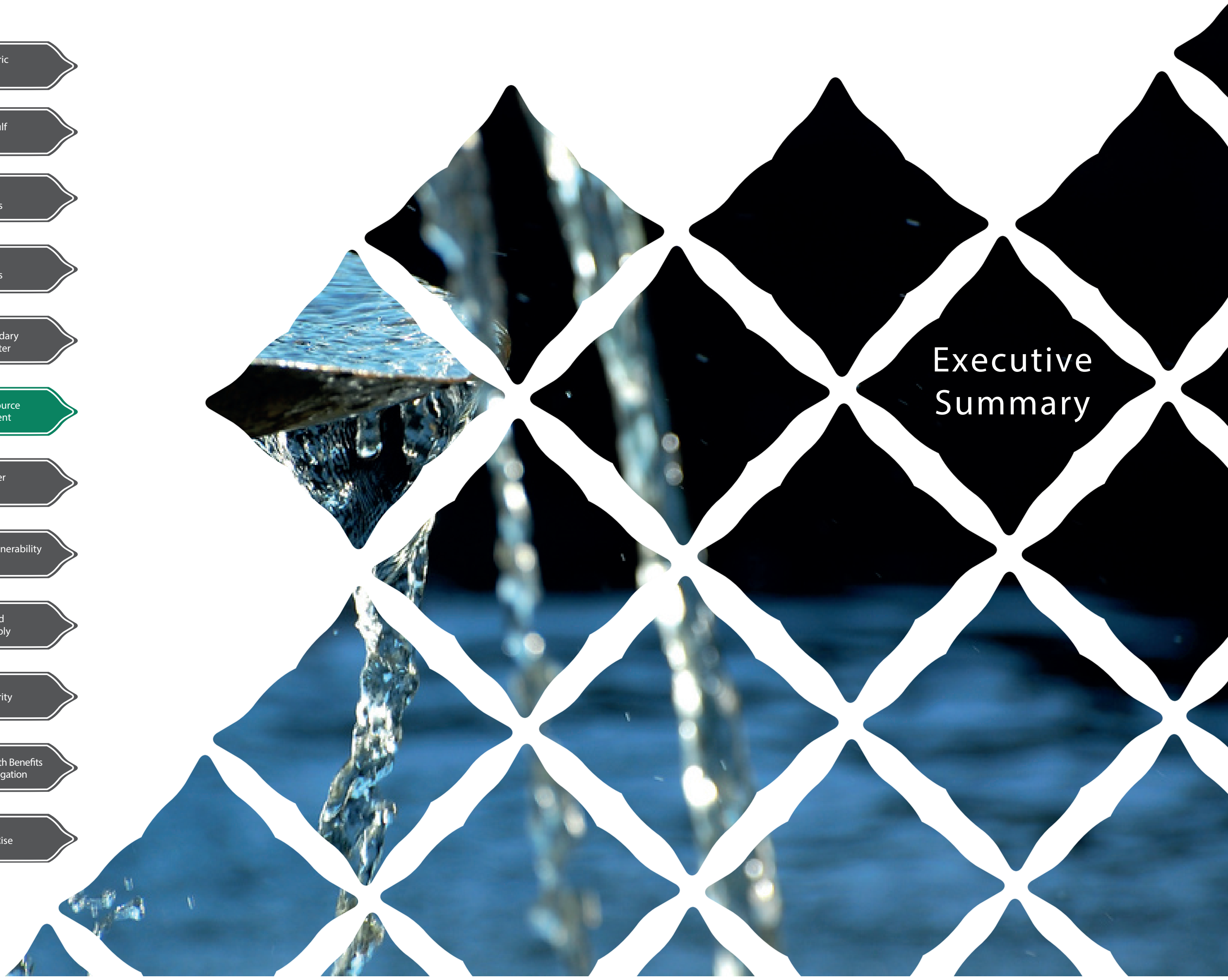
CLIMATE CHANGE PROGRAMME

WATER RESOURCES: NATIONAL 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



Executive Summary

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1. Introduction

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

Energy management has also been recognized as a serious challenge to long-term sustainable development. This is in large part due to the role of energy-intensive desalination activities which accounts for an increasing share of water supply. In the UAE, large desalination plants are combined with power plants for electricity generation to meet on-site requirements and to satisfy national electricity needs. All three major types of desalination technology currently used for desalination – Reverse Osmosis (RO), Multi-Stage Flash (MSF), and Multi-Effect Distillation (MED) – consume significant levels of electricity and lead to corresponding levels of greenhouse gas emissions. Currently, there are 35 desalination plants in the UAE with a total capacity of 700 million m^3/year. Individual municipalities, with the aid of the Federal Government, are expected to increase their desalination capacity soon for some urban centers, mainly in Abu Dhabi, Dubai and Sharjah, to meet the demands of growing population and economic development.

This suggests that reliance on desalination is as much of an energy challenge as it is a water challenge. And, effective water and energy resource management at the national level, already challenging, will be exacerbated by climate change. To capture the interactions between water, energy, and climate change, a "water-energy nexus" framework has been applied. The "Water-Energy Nexus" (W-E nexus) is a framework that views water as part of an integrated water and energy system, rather than as an independent resource. For the UAE, this is an important assessment framework for several reasons. First, climate change has already begun to affect rainfall and temperature patterns across the UAE and the rest of the region, with an intensification of changes in the coming years. Second, socioeconomic growth trends indicate that the population in the country's arid environment is likely to continue to increase and will require additional desalination capacity to satisfy increasing water demands, further affecting the management of electricity and water systems. Finally, a W-E Nexus strategic approach could help to inform the technology research, development, demonstration, and deployment currently underway at several centers of excellence in the country.

2. Approach

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

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

Regional atmospheric modeling

As part of the LNRCCP's regional atmospheric modeling sub-project, future climate changes were evaluated for the UAE at a high spatial resolution (i.e., 4 km). Some of the outputs of this research were incorporated into the analytical framework to capture the impact of climate change on the supply and demand for water and energy resources. Two greenhouse emission scenarios were modeled. One scenario assumed the IPCC's Representative Concentration Pathway 8.5 (RCP8.5), analogous to business-as-usual emissions; the other assumed RCP4.5, analogous to global greenhouse gas mitigation activities significantly limit the increase in greenhouse gas concentrations in the atmosphere. Under climate change, Average future temperature will increase on the order of 2° to 3°C higher over land areas across winter and summer months. (Yates, *et. al.,* 2015).

The results of regional atmospheric modeling were incorporated into the analytical framework of the national water-energy nexus study. This was an important consideration as an already hot region will become even hotter, leading to additional energy for end uses like air conditioning and additional water for end uses like irrigation to account for higher evaporation rates. An algorithm was developed for, and incorporated into, the modelling framework that addresses the projected seasonal change in average temperatures across the UAE. Other modelled climatic variables such as rainfall, humidity, wind, and extreme events were not incorporated in the analytical framework due to their negligible impact on water and energy.

Regional ocean modeling

As part of the LNRCCP's regional ocean modeling sub-project, future climate changes were evaluated for the Arabian Gulf, on which much of the UAE's desalination activities depend. The Arabian Gulf has historically been one of the most stressed marine environments on earth. It is a semi-enclosed, highly saline sea between latitudes 24°N and 30°N surrounded by a hyper-arid environment and limited freshwater inflow via the Tigris, Euphrates, and Karun rivers at the delta of the Shatt al Arab in Iraq. Under climate change alone, the Arabian Gulf will become even more highly stressed, with significant increases in temperature throughout coupled with zones of large salinity increases (Edson, *et. al.,* 2015).

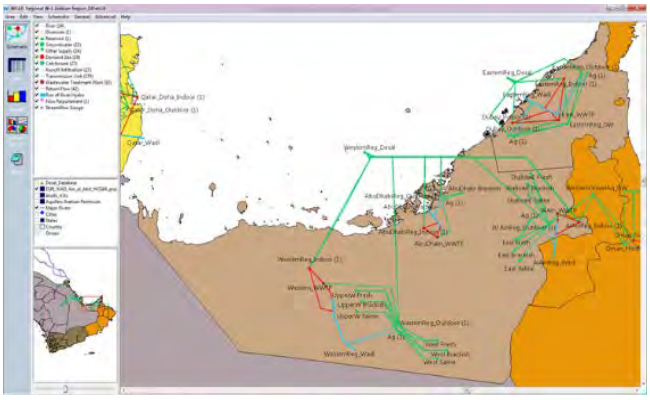
The results of LNRCCP sub-project #10 regarding average salinity impacts from climate change and desalination were incorporated into the analytical framework of the national water-energy nexus study. This was considered necessary due to the relationship between feedstock salinity and the energy required for desalination (i.e., the higher the salinity, the more energy is needed to remove the salt). In shallow areas throughout the Southern Gulf, desalination activity represents a significant impact on average salinity. Depending on the brine discharge rate scenario, average salinity is projected to rise between 1.1 and 2.6 psu in the Southern Gulf. An algorithm was developed for, and incorporated into, the energy system model that addresses this change in Gulf salinity. The other modelled ocean variable - sea surface temperature – was not incorporated into the analytical framework due to its comparatively negligible impact on the energy needed for desalination.

Water system modeling

WEAP software was used to build a water system model for the UAE. WEAP provides an sector-specific integrated approach to water resources planning by linking quantification of water availability and water allocation routines, hydrologic processes, system operations and end-use quantifications within a single analytical platform (Yates et al. 2005). The modeling software incorporates the multiple dimensions critical to water resources management, including surface water and ground water hydrology, water quality, water demands, population growth, reuse, system losses and consumption. WEAP represents water supply and demand centers in a spatial way because the focus is the flow of water from abstraction sites to consumption sites.

The water system model was built for the whole of 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, irrigation demands, and groundwater availability/recharge. The model was developed using a monthly time step to examine water quantity availability in the UAE to balance supplies and demands in the country. An illustrative, schematic view of the model is shown in Figure 1. The schematic demonstrates the aggregated nature of the national representation of water supply (green lines) and demand (red dots) and their linkages. A final version of the national water system model is available for download (for a limited time) at www.ccr-group.org/national-water-energy-inspector-full.

Figure 1: Schematic representation of the national water system model



Energy system modeling

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

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

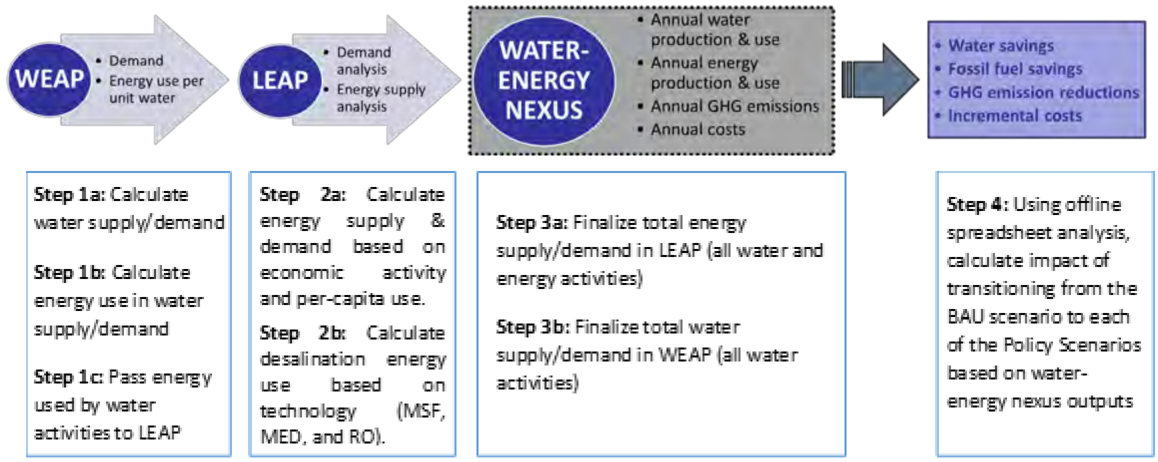
The energy system model focused on a subset of energy supply sources and energy demand sectors. Specifically, the power/water supply, residential, services, and industrial sectors were considered, with a special emphasis on energy uses associated with water resource use.

The model represents national electric generating and desalination stations together with their associated fuel and energy transformation methods used to create electricity and freshwater. The model was developed using a monthly time step to examine energy supply and demand in the UAE. A final version of the national energy system model, after receiving and incorporating all stakeholder feedback, will eventually be available for download at www.ccr-group.org/national-water-energy-inspector-full.

Integrated water-energy system modeling

The development of an integrated water-energy system model for the UAE is the final component of the analytical approach. This involved the coupling of the calibrated water and energy systems models via a software link, which was exclusively a one-way pass of energy used in water production, as determined within the water system model, which was then added to the energy demand component of the energy system model in LEAP. Since the volume of water used in energy production is negligible for the UAE, no information is passed

Figure 2: Sequence of steps used to analyze the national water-energy nexus under climate change



from the energy system model back to the water system model, hence only the one-way pass of outputs from the water system model to the energy system model was needed. There were four (4) major steps involved in analyzing the water-energy nexus under climate change as illustrated in Figure 2.

Cost modeling

Cost modeling focused on a few key metrics that could be reasonably estimated and used to compare among the policy scenarios. A levelized cost approach was used to allow for comparison among the various technology alternatives. Levelized costs are defined as a constant annual cost that is equivalent on a present value basis to the actual annual costs.

That is, if one calculates the present value of levelized 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, levelized 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.

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

Energy-related costs correspond only to those costs associated with the energy used for water-related activities. On the water side, this includes the costs of electricity for desalination, groundwater pumping, wastewater treatment, water reuse transmission, as well as the costs of process heat for desalination using thermal technologies (IEA, 2015; EIA, 2016). On the energy side, this includes costing to account for the impact of new demand-side electricity efficiency programmes and new supply-side renewable energy investments. All other costs such as those associated with fuel use (e.g., transport sector gasoline/diesel use, industrial sector natural gas use) or electricity/fuel use in other sectors (e.g., agriculture and fishing sector) are ignored as they were beyond the scope of this water-energy nexus study.

3. Policy scenario framework

The validated water-energy system coupled model was used to analyze the impact of potential policy scenario that could promote resilience of water and energy systems in the UAE in the face of climate change. Establishing a plausible policy scenario framework is fundamental for using the coupled model to explore challenges and opportunities for transitioning to more climate-resilient development paths. This scenario framework consists of five (5) scenarios, as briefly described in the bullets below:

- *Business-As-Usual scenario, without climate change:* Assumes extension of past trends regarding per capita water and energy consumption, assuming no change in regional climate
- *Business-As-Usual scenario, with climate change:* Assumes extension of past trends regarding per capita water and energy consumption, assuming climate change unfolds in the region consistent with RCP8.5.

- *High Efficiency and Conservation scenario:* Assumes that the UAE will implement aggressive policies to reduce the consumption of water and electricity on the demand side (see Table 1). The overall aim of this policy scenario is to reduce per capita water and energy use across the country. A total of six (6) specific policies were assumed across water and energy activities that would be phased in through 2060, with the phase-in start year depending on the specific policy. The effect of climate change was incorporated into the scenario.
- *Natural Resource Protection scenario:* Assumes that the UAE will implement aggressive supply-side policies to conserve its natural resources, specifically groundwater and energy (see Table 1). The overall aim of this policy scenario is to protect fossil groundwater resources from any further depletion and to reduce the use of fossil fuels. A total of six (6) specific policies were assumed for resource planning across water and energy that would be phased in through 2060, with the phase-in start year depending on the specific policy. The effect of climate change was incorporated into the scenario.
- *Integrated Policy scenario:* Assumes that the UAE will implement all 6 demand-side and all 6 supply-side policies collectively (see Table 1). The overall aim of this policy scenario is to optimize efficiency and natural resource protection in the country. The scenario assumes a future in the UAE where there is a broad consensus among national policymakers that the implementation of all the policies and measures embedded in the *High Efficiency* and *Natural Resource Protection* Scenarios are essential. The effect of climate change was incorporated into the scenario.

Table 1: Specific policies analyzed within the water-energy nexus scenarios

Sector	Demand-side policies	Supply-side policies
Water policies	1. Indoor water use efficiency and conservation programme	1. Fossil groundwater phase-out
	2. Introduction of outdoor garden and amenity caps	2. Increased use of treated sewage effluent
	3. Improved irrigation efficiency	3. Sustainable desalination
	4. Water loss reduction programme	
Electricity policies	5. Demand side electric efficiency and conservation programme	5. Carbon dioxide cap
	6. Peak load management of space cooling load	6. Renewable portfolio standard
		7. Clean coal capacity cap

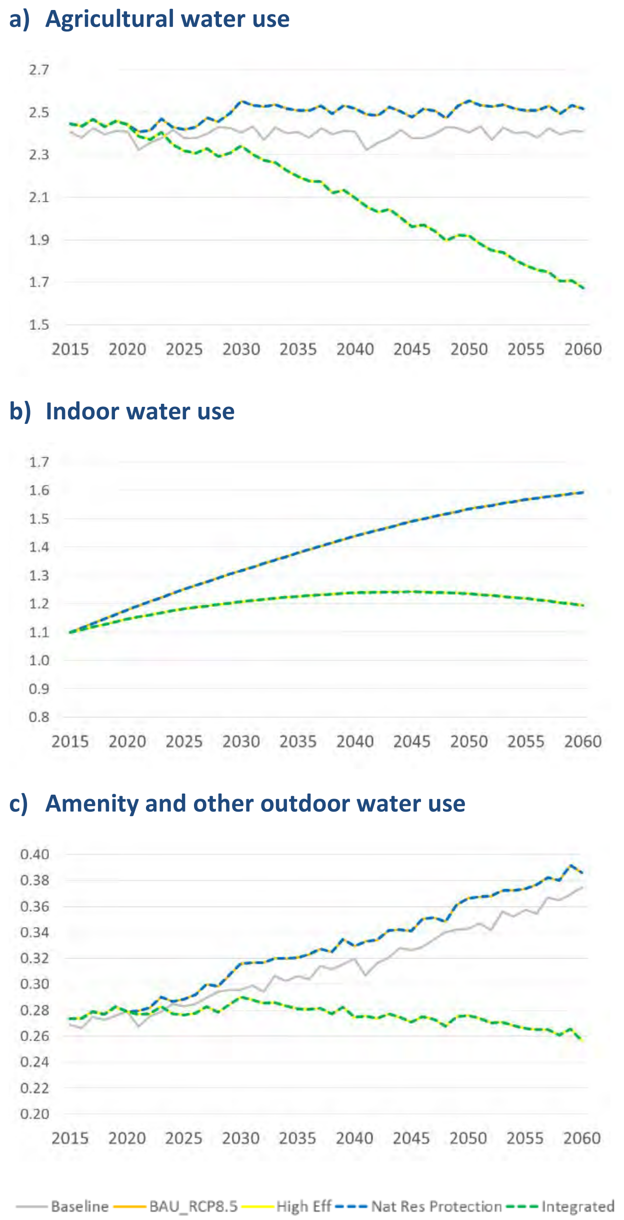
4. Costs & benefits of climate-resilient development paths

The essential findings of the study focus on several key metrics, water demand electricity demand, greenhouse gas emissions, and incremental costs. Brief descriptions of the key outcomes are outlined below.

Water demand

A comparison of water demand across the all end uses and scenarios appears in Figure 3. Regarding agricultural water use, an additional 4.4 BCM is consumed in the agricultural sector due to climate change over the 2015-2060 period, about 3.9% more than what would have been consumed without climate change. Regarding indoor water use, the implementation of efficiency and conservation measures lead to a total *reduction* in indoor water demand by about 8.8% over the 2015-2060 period, or about 0.19% per year (i.e., about 8.5 BCM in total indoor water savings). Amenity and other outdoor water use show similar trends – there is a *reduction* in water demand by about 6.2% over the 2015-2060 period (i.e., about 2.4 BCM in total amenity savings).

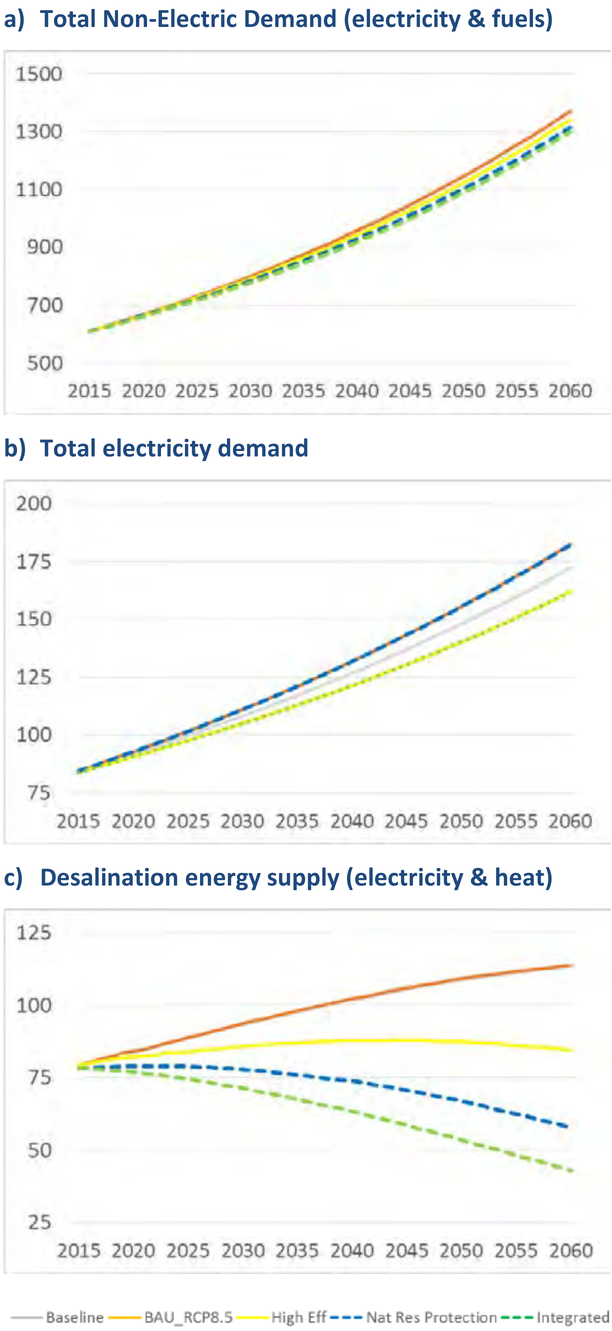
Figure 3: Water demand across all scenarios, 2015-2060 (BCM)



Electricity demand

A comparison of electricity demand across all energy types and scenarios appears in Figure 4. Regarding total energy use (i.e., fuels plus electricity), there is about 379 TWh more energy consumed in the BAU-RCP8.5 scenario relative to the BAU scenario. This represents the impact of climate change alone. Notably, the impact of the Integrated Policy Scenario shows less total energy use than in the BAU-RCP8.5 scenario, and all other scenarios. Regarding total electricity demand, the high efficiency and conservation scenario shows a decline in electricity use, while the Natural Resource Protection scenario shows higher electricity use due to greater desalination from thermally based sources including MSF and MED. Regarding desalinated water use, the impact of the policy scenarios (High Efficiency and Conservation, Natural Resource Projection, and Integrated) is particularly apparent in desalinization energy used, with reductions in 2060 of about 20% and 45%, respectively. Moreover, over the period 2015-2060, electricity use associated with desalinization is about 55% less in the Integrated scenario than the BAU scenarios.

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



Greenhouse gas emissions

Figure 5 shows the total annual carbon dioxide equivalent emissions across the policy scenarios. Regarding demand and transformation of fuels, the Natural Resource Protection scenario and the Integrated scenario shows sharp reductions in GHG emissions overall, as there is a substantial shift away from fossil-fuel generated energy. Regarding emissions from total electricity generation, the *Natural Resource Protection* scenario shows the greatest reduction in emissions compared with the other policy scenarios even though over the analysis period 2015 to 2060 there are higher demands for electricity. The policies under this scenario assume that electricity generation is primarily solar- and nuclear-based rather than fossil-based. The higher energy demands force the introduction of new solar capacity earlier in the simulation period, resulting in less natural gas generation and thus lower GHG emissions. Regarding water-related emissions, the High efficiency and conservation scenario shows a leveling out of GHGs associated with water supply and demand while the Natural Resource Protection and Integrated Policy scenarios show the sharpest declines in emissions due to a transformation of the electric supply system to more renewable based.

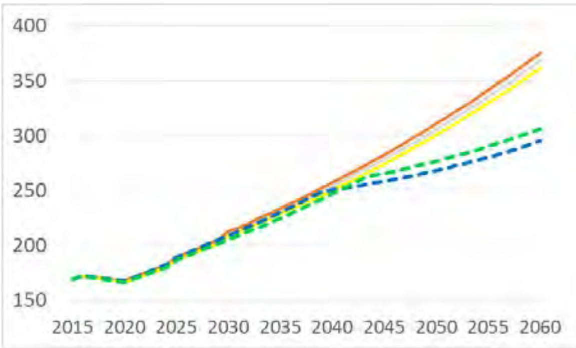
Incremental costs and overall summary

Table 1 summarizes the costs and benefits associated with the implementation of the policy scenarios within the water-energy nexus. At the outset, it is important to note that a) costs represent the costs to society from the implementation of the policies, rather than any segment of society; b) benefits are presented in physical units and are limited to water savings, fossil fuel savings, and greenhouse gas emission reductions; the magnitude of other benefits (e.g., fossil-fuel use) are accessible through the water and energy models themselves; and c) the reported costs and benefits are incremental in nature; that is, they result from shifting the development pathway from the BAU to each of the other alternative development pathways. Highlight are briefly described in the bullets below relative to cumulative impacts over the 2015-2060 period.

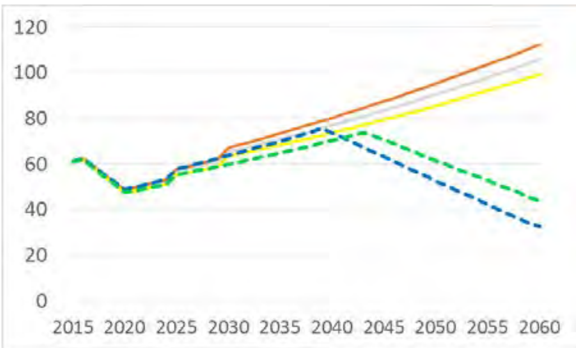
- **Under the BAU-RCP8.5 scenario (i.e., with climate change)** there is a net increase in cumulative GHG emissions of 138 MMT when compared to the BAU scenario. Climate change results in increased water use and energy use, and results in an additional cost of about $4 billion to meet water and energy demand over the period.

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

a) Demand and transformation of electricity and fuels



b) Total Electricity Generation



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

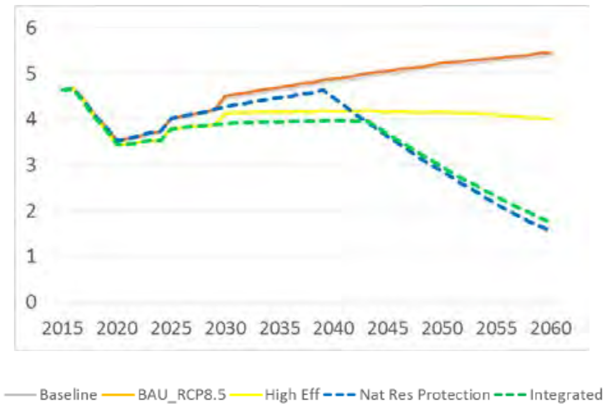


Table 7-1: Summary of Costs and benefits associated with the implementation of the policy scenarios

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

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

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

- Assessing national green growth scenarios in the context of climate change in a hyper-arid environment where energy-intensive desalinated water makes up a significant share of water supply requires a focus on both water and energy. The water-energy nexus approach offers an analytical framework that considers water and energy as an integrated system where alternative policy scenarios can be readily evaluated.
- Pursuing an economic diversification agenda employing a green growth framework can lead to significant environmental benefits. These benefits can be achieved at net economic savings in the case of a scenario emphasizing energy/water efficiency investments (-$10.2 for each tonne of CO2e avoided), and at modest economic cost in the case of a scenario emphasizing renewable energy investments ($13.2 for each tonne of CO2e avoided). Taking advantage of the synergies across efficiency and renewable green growth strategies achieves maximum benefits at very low cost ($3.4 for each tonne of CO2e avoided).

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