Water-Energy Nexus in the UAE in relation to Climate Change and Adaptation Policy Scenarios

by

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Table of Contents

Abstract

Water and Energy systems that were once considered disparate, are coupled in many ways. Generation, transmission and distribution of each system relies on the other system. The interaction becomes significantly stronger in economies dependent on desalination for their water resources. One such country is the United Arab Emirates. The water-energy nexus faces serious challenges under climate change as cooling needs and outdoor water demands rise. This thesis models the impact of climate change on the water-energy nexus in the UAE. It explores a set of climate change adaptation policy scenarios and quantifies their respective economic, water and energy savings. Hence, it provides an analytical assessment of the nexus that can inform data-driven policy making. This thesis views the nexus through a qualitative lens and a quantitative lens. The qualitative piece presents the organizational mapping and structuring of the UAE institutions across the water-energy-climate nexus. It highlights gaps in cross-sectoral interactions that need to be overcome for a sustainable future. The second piece presented in this thesis is analytical in nature. It uses two specialized water and energy softwares called the Water Evaluation and Planning System (WEAP) and the Long-range Energy Alternatives Planning System (LEAP) and couples them together to model the nexus. The water-energy nexus model is tested for different individual and aggregate adaptation policy scenarios to assess a wide range of effects on the nexus. These scenarios are also run for six sub-regions within the UAE (Abu Dhabi, Al Ain, Western region, Dubai, Eastern region and Fujairah) to understand the underlying demand sectors driving the water-energy nexus in these sub-regions. The results of this extensive scenario analysis have informed policy recommendations for long-term planning of the water-energy nexus in the UAE. Important findings from this study include the huge savings potential from indoor consumption reduction (up to 1200 million cubic meters of water and 60 million gigajoules of electricity per year by 2060) and the need for irrigated land regulation (saves up to 700 million cubic meters of water and 5 million gigajoules of electricity per year by 2060) in the UAE. The sub-regional analysis highlights the need for sub-regionalized policy goals that govern regions based on their demand differences.

1. Introduction

Water and energy systems are inherently intertwined since the production and distribution of both commodities relies on the other. Groundwater pumping, wastewater treatment and desalination require energy while cooling of power plants requires huge amounts of water. Thus, the two systems are coupled in a way that certain tradeoffs can exist (Abulibdeh, 2017). Therefore, optimal planning for both systems becomes an important consideration. The UAE has very much acknowledged this nexus in terms of supply because of its cogeneration plants that use excessive heat during electricity production for desalination. However, long term planning for both systems as a nexus is required. The nexus also faces serious challenges from climate change as adaptation strategies are missing in the UAE's policy frameworks. A study conducted by a team of MIT researchers led by Professor Jeremy Pal and Professor Elfatih Eltahir shows that extreme heatwaves in the Arab Gulf could make the region inhabitable by 2070 if carbon emissions remain uncut (Pal & Eltahir, 2016). The UAE is already a water scarce region and with the increase of temperatures and decrease in rainfall in the region, the water-energy nexus will be impacted on both the supply and demand sides (Juvonen, 2015). Decreased rainfall and high temperature will result in waning water supply and increased energy demand for cooling purposes and extraction and production of water (Arderne, 2016). Figure 1.1 shows the overlaid maps of the water and electricity grid networks in the UAE showing an inherent coupling in both the supply and consumption sectors.

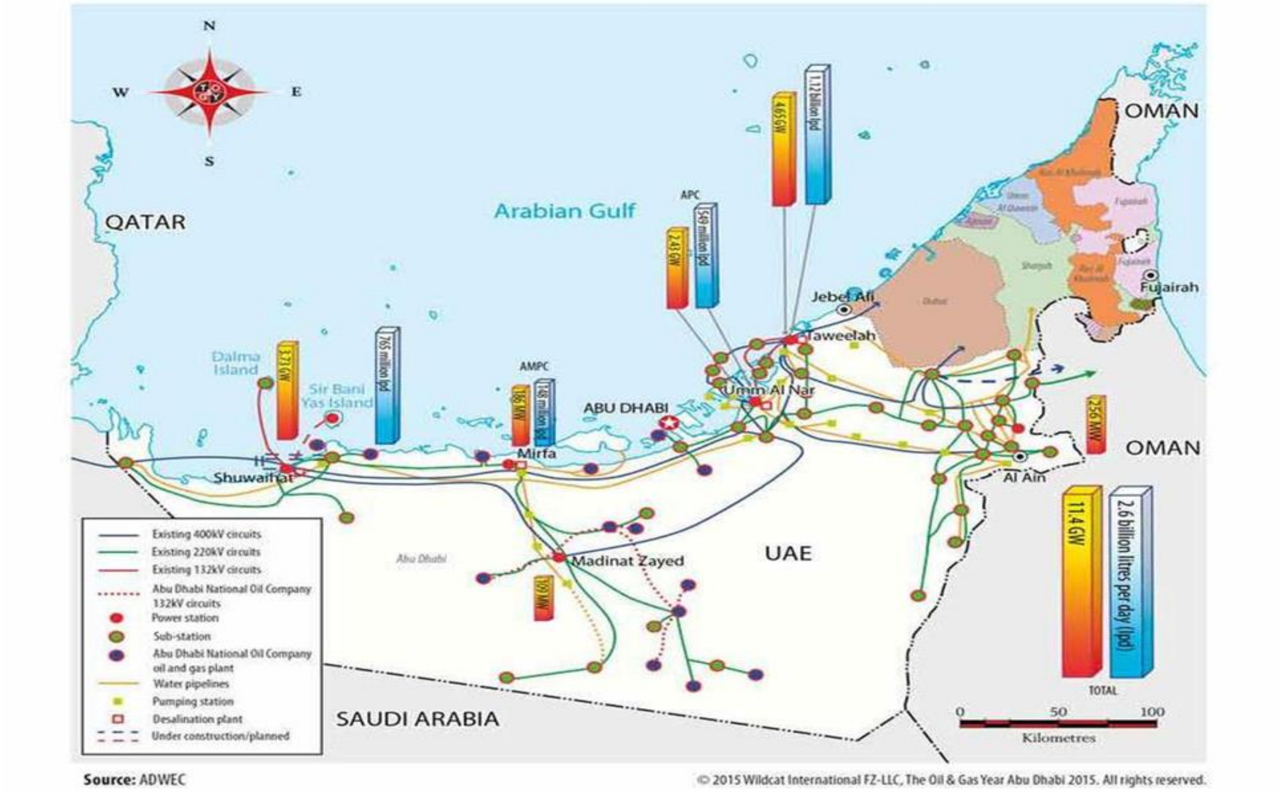


Figure 1.1. Map of the ADWEC electricity and water network (ADWEC, 2015)

Figure 1.1 shows the water and electricity grid maps of the Abu Dhabi water and Electricity Company (ADWEC). Power plants and desalination plants are co-located at Umm al Nar and Taweelah in Abu Dhabi; Mirfa and Shuweihat in Western region and Al Ain and Qidfa (Fujairah). This map confirms the existence of the nexus in the UAE and helps build our analytical study through this approach.

The objective of this thesis is to simulate different policy scenarios pertinent to the water-energy nexus under climate change and use insights from the analysis to make policy recommendations. This is done by conducting a two-tier analysis including a qualitative analysis and a quantitative analysis. The qualitative pat includes an institutional analysis which involves mapping the evolution of different water and energy institutions in the UAE and a cross-sectional analysis including the policies created and initiatives taken for improvement of the efficiency of the nexus. The quantitative tier of the analysis involves use of WEAP and LEAP which are simulation modeling softwares built by Stockholm Environment Institute (SEI). They are being used as coupled models that spatially map the nexus in the UAE by calculating nodal demands and supplies. The results not only show potential water and energy savings but also economic monetary benefit to the UAE which can inform long-term planning in the UAE. Along with this, this thesis provides the first ever focus on regionalization of the water-energy nexus in the UAE.

The value added of this thesis is that it will enable the process of identifying areas of vulnerability in the nexus, such as whether it is the demand or the supply that gets more affected by climate change. The results of this simulation modeling will play a significant role in understanding the interactions, balances and tradeoffs of the water-energy nexus under climate change. The nature of this study is transdisciplinary, therefore a variety of qualitative and quantitative tools have been employed to study the water-energy nexus.

The Problem Framing and Representation of the Nexus chapter entails the framing of the water-energy nexus in previous literature and examines key graphical representations of the nexus. The qualitative methods chapter employs the technique of institutional analysis and simple trend analysis to study the organizational structures in the UAE that govern the water-energy nexus. The quantitative studies chapter delve into previous quantitative studies of the water-energy nexus in the UAE and focuses on a study done by the Abu Dhabi Global Data Initiative (AGEDI). This study forms the foundation of my thesis as it uses the integrated WEAP-LEAP tools to analyze the water-energy nexus in the UAE and test scenarios. The fifth chapter forms the crux of my research which tests modified disaggregate scenarios as an extension to the AGEDI study as well as sub-regionalizes these results for Abu Dhabi, Al Ain, Western region, Dubai, Eastern region and Fujairah. This section is key because it helps understands the policies that have the capability of producing most gains in the sub-regions. This chapter is followed by policy recommendations based on the results of the WEAP-LEAP policy scenario analysis.

2. Problem Framing and Representations of the Nexus

This chapter presents a review of existing methods employed to study the water-energy nexus. This is being done to provide a knowledge base of existing methods and resources in literature to build a research foundation. This systematic review can also help in the development analytical tools that can add on to existing research and can give us a more holistic view of the water-energy nexus. Albrecht et al (2018) conducted a similar systematic review of literature on the Water-Energy and Food nexus. They shortlisted articles that were most promising in terms of guiding future research whereas this study will focus on categorizing different tools used to study the water-energy nexus as well as the range of graphical representations that best visualized the results (Albrecht, Crootof, & Scott, 2018). A system characterization of the water-energy nexus will show how these integrated systems have been modeled and visualized to provide a useful premise for this research.

The simplest diagrammatic representation of the water-energy nexus was developed by the US Department of Energy in 2006 as shown in Figure 2.1.

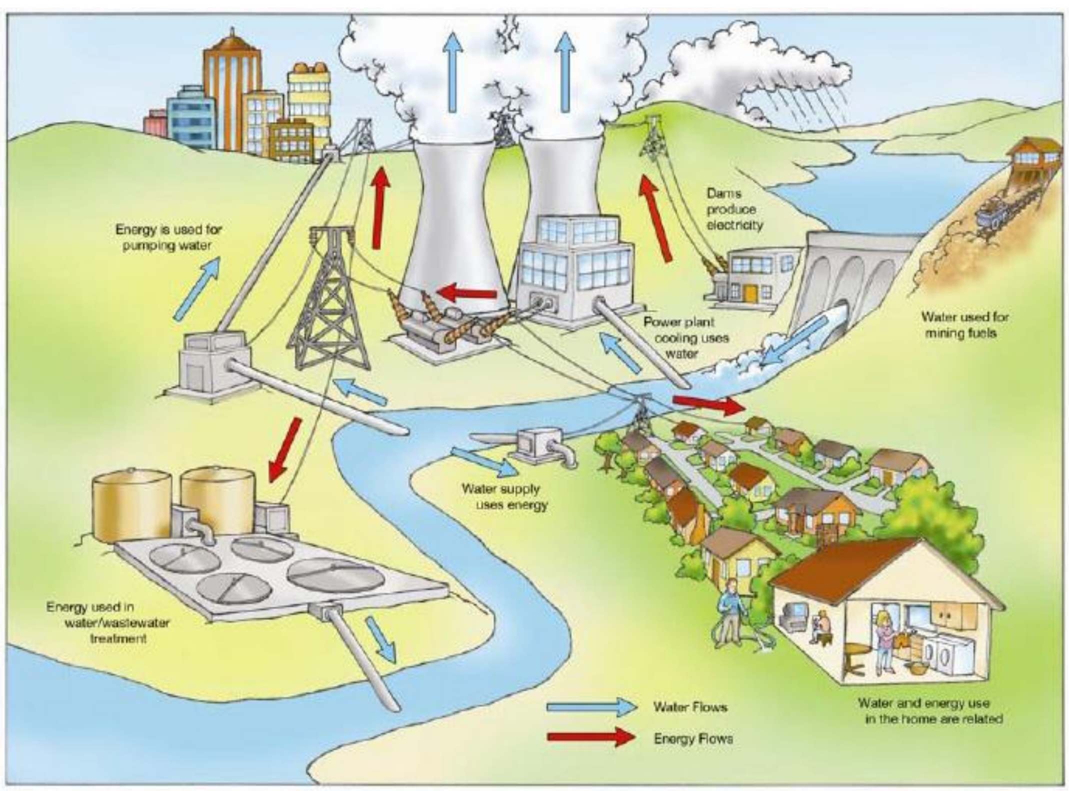


Figure 2.1. The inter-dependencies of the water and energy systems embodying the water-energy nexus (US Department of Energy, 2006)

This figure shows the flows and interdependencies of the water and energy systems in a simple urban setting. Water is needed for various power generating processes extending from the mining of fossil fuels to the cooling of thermal power plants, while energy is required for pumping, transmitting and treating wastewater. This was an early endeavor by the Department of energy to visualize the water-energy nexus. There has been a lot more work on visualization and studying the water-energy nexus after this diagrammatic representation. An extensive literature review has helped with categorizing the various methods used to study and represent the water-energy nexus across the globe.

2.1. Optimization Models:

Optimization models have been the most popular approach towards the water-energy nexus. Optimization models can be classified into resource management optimization models that are physical models meant for quantifying efficient resource allocation and decision optimization models oriented towards prioritizing goals and meeting objectives. For example, Dubreuil et al built a resource-allocation optimization model for energy in the Middle East by integrating waste water and non-conventional water resource variables (Dubreuil, Assoumou, Bouckaert, Selosse, & Maizi, 2013). Lubega and Farid built the first co-optimization model for economic dispatch for power and water systems with respect to the supply side in the UAE establishing that co-generation plants in the UAE enable a co-optimization strategy from a purely engineering systems perspective (Lubega & Farid, 2014). Following that, the multi-plant model for real-time simultaneous economic dispatch of power and water was developed for the UAE (Santhosh, Farid, & Youcef-Toumi, 2014). Then came the different capacity expansion optimization and ramping capabilities models of desalination and power plants in the UAE (Saif & Almansoori, 2016). More recent studies have incorporated renewable energy sources in these optimization models reaching the conclusion that integration of renewables decreases both carbon emissions and water withdrawals (Hickman, Muzhikyan, & Farid, 2017). These studies tend to build a unique optimization model and apply it to different scenarios and then demonstrate the efficacy of the model using a case study. For example, a study by Saif et al used mixed integer linear programming model for the CLEW (Climate, Land, Energy and Water) systems to optimize infrastructure operation and capacity and then showed the efficacy of this model by applying it to Mauritius (Saif & Almansoori., 2017). In case of decision modeling, multiple objective programming (MOP) and Bi-level Programming have been used in the realm of the water-energy nexus to assist decision makers in devising frameworks involving water-energy-climate tradeoffs and interactions. "In MOP, multiple objectives are optimized simultaneously (at the same level), while in bi-level programming, optimization of multiple objectives are performed from the upper- to the lower- level" of decision making hierarchy (Zhang & Vesselinov, 2016). Fuzzy Goal Programming integrates both decision optimization model and resource allocation model. It assigns a numerical value of a goal and tries to minimize the distance matrix of goals from the objective functions in the decision process. Javaraman et al have presented a Fuzzy Goal Programming perspective on UAE to assess economic goals with respect to energy and water consumption. (Jayaraman, Liuzzi, Colapinto, & Malik, 2017).

Li et al present a representation of the nexus (Figure 2.2) and build a co-optimization mathematical model for the micro water-energy nexus on the distribution side. This is synonymous with a simple cyber-physical system where utilities are governed by internet of things (IoT). The electricity distribution side includes a micro grid distribution network while the water distribution side entails pipes, pumps and tanks, etc. (Li, Yu, Al-Sumaiti, & Turitsyn, 2018).

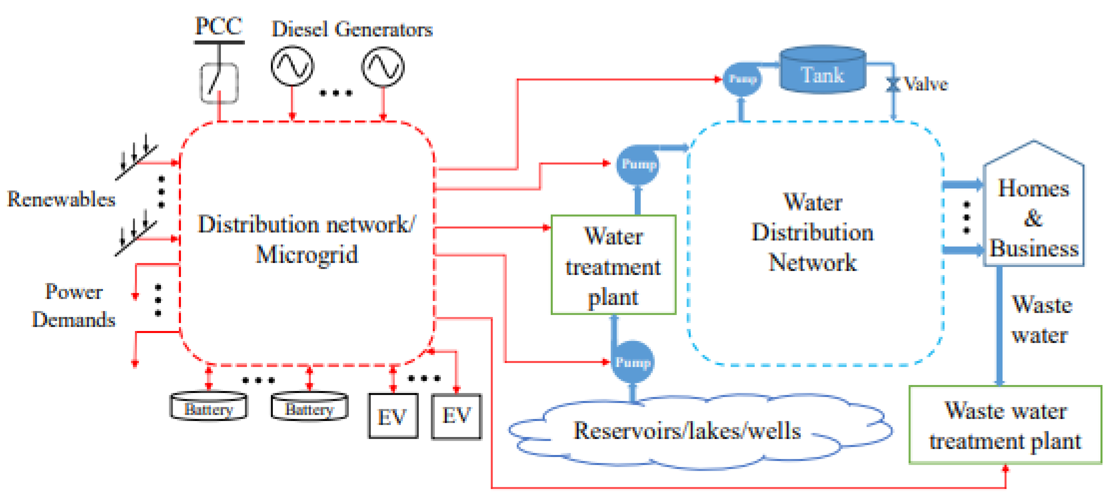


Figure 2.2. Urban water-energy systems (Li, Yu, Al-Sumaiti, & Turitsyn, 2018).

The results of these optimization models are represented in different forms, mostly flow diagrams. Lubega and Farid have done the most work on graphical representation of the water energy nexus through a systems engineering perspective to show the flow of materials and energy in the water-energy nexus. They have written two papers to elaborate the need for representing the water energy nexus graphically in order to understand a systems engineering perspective on the nexus. The modeling tool they have developed for this purpose is based on Systems Machine Learning. The first diagram (Figure 2.3) that runs through both their papers is the system boundary input-output model diagram, which is important in terms of designing or engineering of a facility. The diagram shows that water, electricity and wastewater are within the system boundary while other products like fuel, recycled water, etc. are open for consumption by other sectors therefore they are outside the boundary. Hence, anything that is on the grid network is represented within the system boundary (Lubega & Farid, 2014).

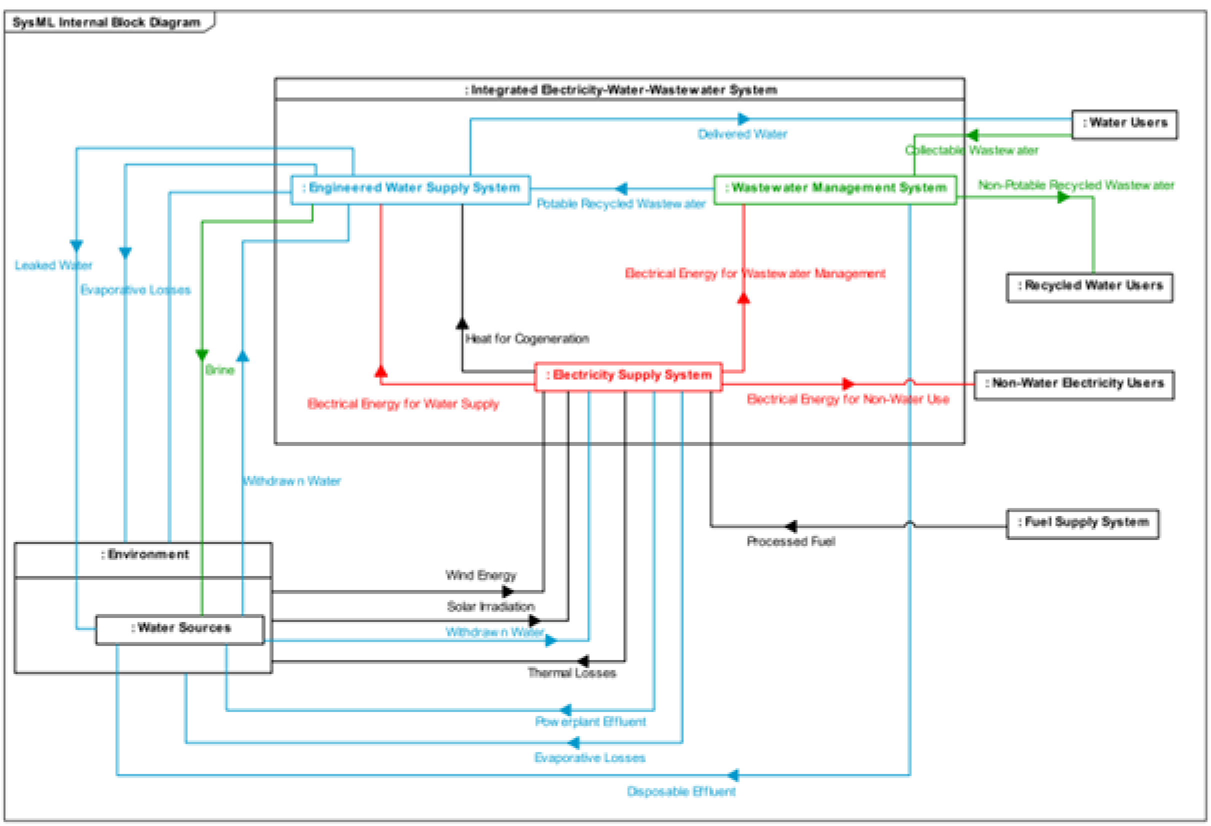


Figure 2.3. System Boundary and Internal Block Diagram (Lubega & Farid, 2014)

Venkatesh et al (2014) present a similar matter and energy flow diagram of the urban water-energy-carbon nexus with the help of case studies of four cities including Nantes (France), Turin (Italy), Oslo (Norway) (Figure 2.4) and Toronto(Canada). They use five indicators as key parameters to represent this nexus: The raw water supply, water treatment plants, water distribution network, wastewater collection and wastewater treatment because they are energy intensive processes. Raw water is acquired through extraction or desalination. Water treatment plants require chlorination or UV disinfection. Water distribution requires pumping at higher altitudes. Wastewater collection requires a power input to remove blockages in the transmission network. Wastewater treatment consumes electricity for aeration and filtration processes. According to their study, city size has a huge impact on carbon emissions from the urban water systems while industrial activity has a marginal impact (Ventakesh, Chan, & Brattebo, 2014).

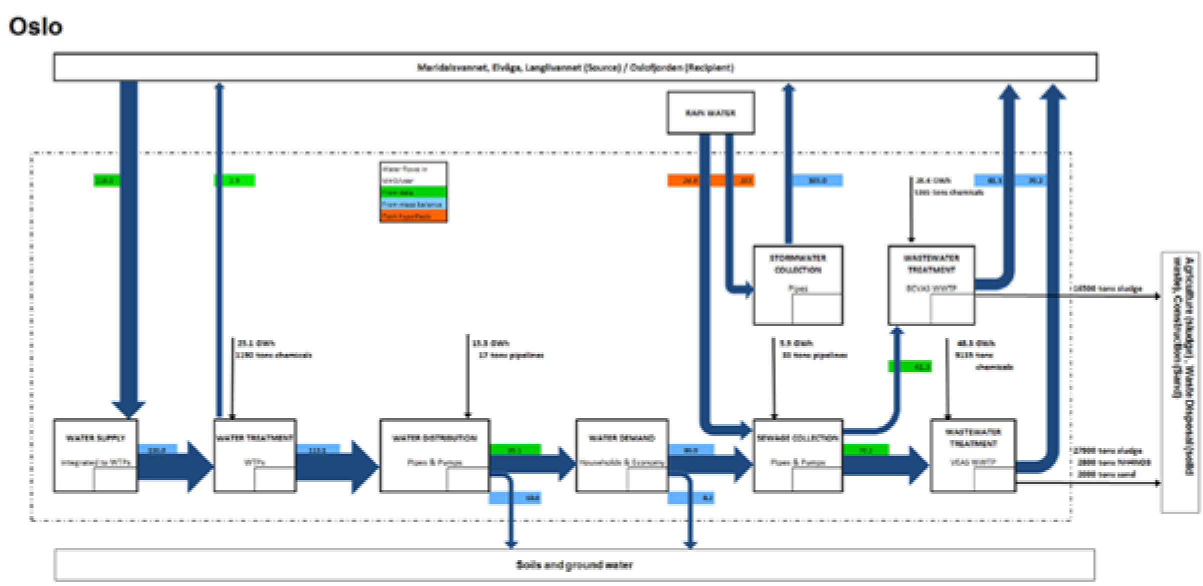


Figure 2.4. Oslo water-energy-carbon nexus thematic (Ventakesh, Chan, & Brattebo, 2014).

2.2. Life Cycle Analysis and Input-Output Models:

In terms of mathematical models, there has been less work done on a unified flow analysis for water-energy systems. Life cycle analysis has been used in the realm of the water-energy nexus as an integrated framework for tracing multiple flows in the water-energy sector and then incorporating them with other analyses. For example, Yang and Chen combined input-output analysis and network environ analysis to map electricity generation related water consumption and costs for the wind power systems in China (Yang & Chen, 2016). This approach has helped in devising water and energy conserving strategies for water-stressed Inner Mongolia in China (Yang & Chen, 2016).

A subset of life cycle analysis is input-output models. A study was conducted using the case study of Beijing that entailed a modified input-output analysis of urban energy and water consumption. It took into account the hybrid water flow that includes direct water flow and water flow pertinent to energy production and combined it with hybrid energy flow including the direct energy flow and the energy flow associated with water production and distribution (Saif, Mezher, & Arafat, 2014). This hybrid flow network was then modeled to assess impact of water-energy nexus flows on the economic sector using input-output analysis. The results identified the largest inflow and outflow sectors. Industry manufacturing was found to result in the largest outflow of hybrid energy while agriculture was found to be reliant on the largest inflow of hybrid water (Wang, Cao, & Chen, 2017). Other studies incorporate input-output analysis to assess interconnections of water and electricity, water for electricity and electricity for water and to track resource and carbon emission flows and their complex interactions with the economy (Chen, et al., 2017). Life cycle assessment models are holistic in nature and systemic in process, however they require a lot of data and the methodologies used to assess environmental impacts can influence the model (Chen & Chen, 2011).

2.3. System Dynamics

Systems approach is one of the most applied methodologies in the research of water-energy nexus. It is a useful tool to articulate the complicated relationships between different variables including endogenous variables (water consumption, water demand, energy demand, etc.) and exogenous variables (land, climate, food, etc.) (Qi & Chang, 2011). It incorporates various feedback loops and quantifies system interactions. The use of stocks and flows is key in understanding the nexus (Wolfe, et al., 2016). Siddiqi conducted one of the first sub-regional studies of the water-energy nexus in the MENA region and did a quantitative analysis based on the systems approach to evaluate the comparative dependency of electricity production on freshwater and seawater (Siddiqi & Anadon, 2011). The system dynamics approach has also been effectively used to model the Water-Energy-Food nexus and the Water-Energy-Climate nexus in the UAE (Shrestha & Kumar, 2017) .

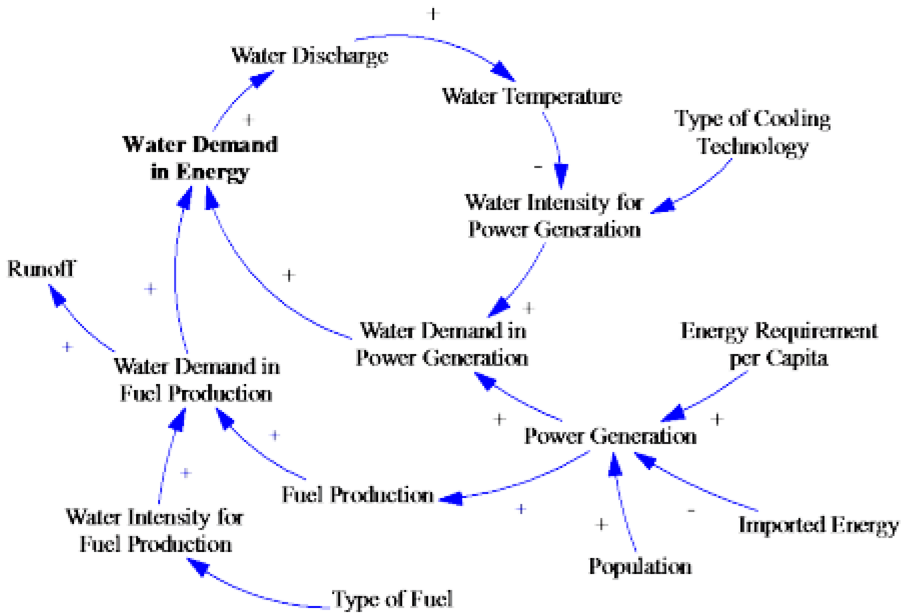


Figure 2.5. Causal Loop Diagram of Water Demand in Energy Sector (Zhuang, 2014).

This Causal Loop Diagram of Energy demand in Water Sector shows the reinforcing (positive sign) and balancing (negative sign) loops that are part of the water energy nexus when it comes to energy consumption in water extraction, purification, distribution and wastewater treatment (Zhuang, 2014).

2.4. Sankey Diagram Analysis

Sankey Diagrams are flow charts that can be used to visualize different flows based on the width of the branches. They are great representations for how flows occur from primary sources to the consumption sector along with losses. They are also a good way to visualize different system breakdowns, for example, it is easy to see that oil production makes up a major chunk of primary energy source in the UAE in the following figure.

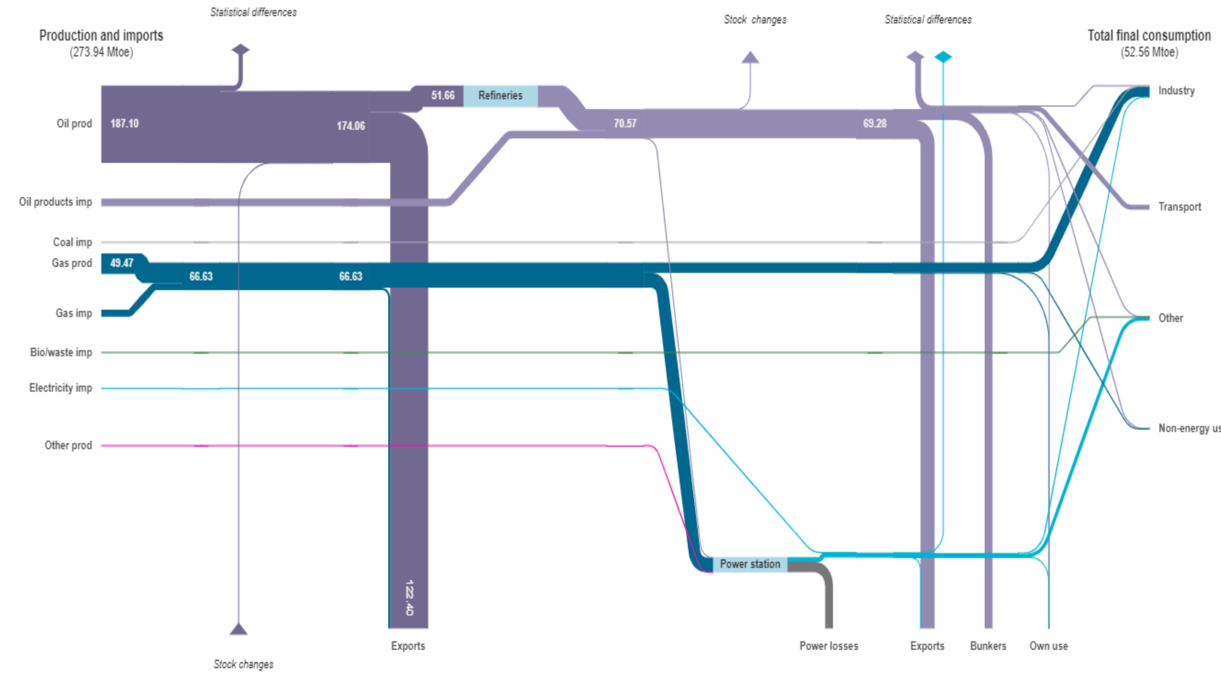


Figure 2.6. Energy Sankey Diagram of the UAE. Source (International Energy Agency, 2016)

Figure 2.6 shows the UAE energy Sankey diagram. It can be seen that oil and coal still make the largest fuel supply in the country despite this attempt to transition towards renewables. Renewables make a small percentage in the other production section in the diagram above. Moreover, the UAE relies on an International market for fuel imports and exports. Apart from exporting oil, it is interesting to see that the UAE imports some bio-waste and electricity from its immediate neighbors.

2.5. WEAP and LEAP Modeling

The Water Evaluation and Planning System (WEAP) and the Long-range Energy Alternatives Planning System (LEAP) are discipline centric spreadsheets or modeling frameworks that were developed by the Stockholm Environment Institute (SEI) for interdisciplinary water and energy research. WEAP looks at water and energy demands based on agricultural pumping and desalination for commercial and residential uses. The energy use gets passed onto LEAP. WEAP is a spatial model that simulates water supply and demand incorporating climatic conditions. Climatic data is incorporated to reflect how climate change will affect water demand and energy use for this sector in WEAP. Figure 2.7 explains how the integrated models are inter-connected.

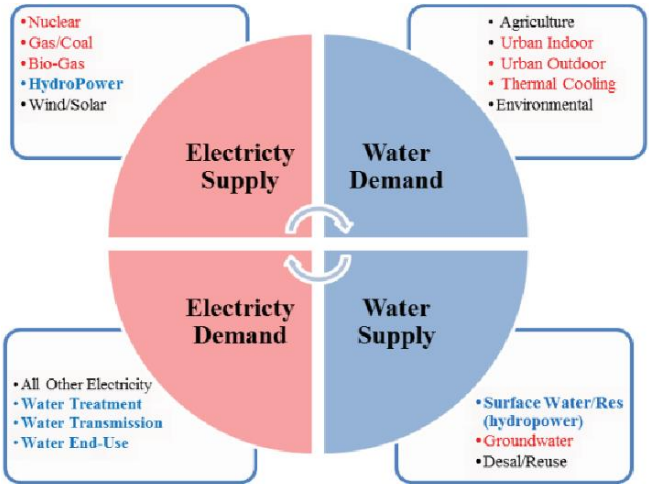


Figure 2.7. The interdependencies of the WEAP and LEAP models (Yates & Miller, 2013).

In the above figure the red shows the energy side while the blue shows the water side. The text colors represent the cross model dependencies, for example cooling requirements (shown in red color on top right) depend on electricity demand that LEAP calculates but the water requirement is estimate in WEAP. Similarly, the water needed for hydropower plants is calculated in WEAP but accounts for energy supply in LEAP. The following figure shows how the two models can be coupled together.

The advantages of using WEAP and LEAP are that these are spatial models that allow regional insights. The power of the WEAP and LEAP models lies in the option to conduct a detailed scenario analysis and the option to plot graphs for a wide range of variables that enable not only a physical approach to the water-energy nexus but also an economic analysis, for example, the net benefits variable and the average costs of water variable.

A review of these research methods shows that there has been a diverse set of techniques and visualizations used to study and represents results from the water-energy nexus. It can be seen that many optimizations studies have been used for the water-energy nexus in the UAE. These studies provide great insight into the networks through an engineering systems perspective and can help design systems better. This study, on the other hand, takes a different approach to studying the nexus in the UAE. It employs a more simple simulation modeling instead of and runs different adaptation policy scenarios under climate change. This simulation modeling is done through WEAP and LEAP that enable a deeper analysis of the water-energy nexus through a demand sector and sub-regional lens. This approach helps authorities identified in the next chapter to develop long-term plans based on a policy-driven spatial analysis.

3. Qualitative Research on the Water-Energy Nexus in Context of the UAE

This chapter provides is an important step towards contextualizing the water-energy nexus within the UAE. It creates a backdrop of qualitative research methods before delving into the modeling exercise that this study aims to achieve. The first section briefly summarizes the economics of the water-energy nexus in the UAE and the role these sectors have played in the economic development of the UAE. It also elaborates on the long-terms plans and goals that the government has set for the UAE. The second section deals with a cross-sectional institutional analysis. The institutional mapping exercise identifies important governmental and non-governmental stakeholders in the water-energy nexus and their respective initiatives in this sector. It also tracks the laws and policies that govern the water-energy nexus. Along with this, the energy and water supply and demand trend analysis at the end of this chapter creates a sense of the evolutionary trajectory of the nexus with regards to the UAE.

3.1. Economic Overview of the Water-Energy Nexus in the UAE

The United Arab Emirates (UAE) is a federation of seven emirates at the Southeast end of the Arabian Peninsula bordering Saudi Arabia to the South and Oman to the east. As the second largest economy in the Middle East, the UAE has enjoyed rapid development since its founding. Its oil reserves, recorded at six percent of the world's total, has historically been its main export and the underpinning of its economy. In 2017, petroleum products accounted for 50% of its US$ 142 billion total exports, in part due to the federation's continued effort to diversify its economy.

While diversification of the economy contributes to future economy growth, a similar approach in electricity usage is required in order to sustain the corresponding increase in usage. In 2017, the UAE government set out the following goals for diversification of energy generation and reduction of carbon emission in 2050: 44 percent from renewable energy sources, 38 percent from natural gas, 12 percent from clean coal, 6 percent from nuclear power, and an overall reduction of carbon dioxide emission of 70 percent (UAE Ministry of Energy and Industry, 2018). The reality is that in 2016, of the 28.8 GW total installed generation capacity, 92.4 percent was natural gas based, up from 87 percent in 2015 (US Energy Information Adminstration, 2017). On the demand side, electricity consumption in the UAE has more than doubled in a decade from just over 54 GW in 2005 to nearly 127 GW in 2015 (CEIC Data, 2015). Per capita, electricity consumption is among the highest in the world at about 11 thousand kWh (CEIC Data, 2015).

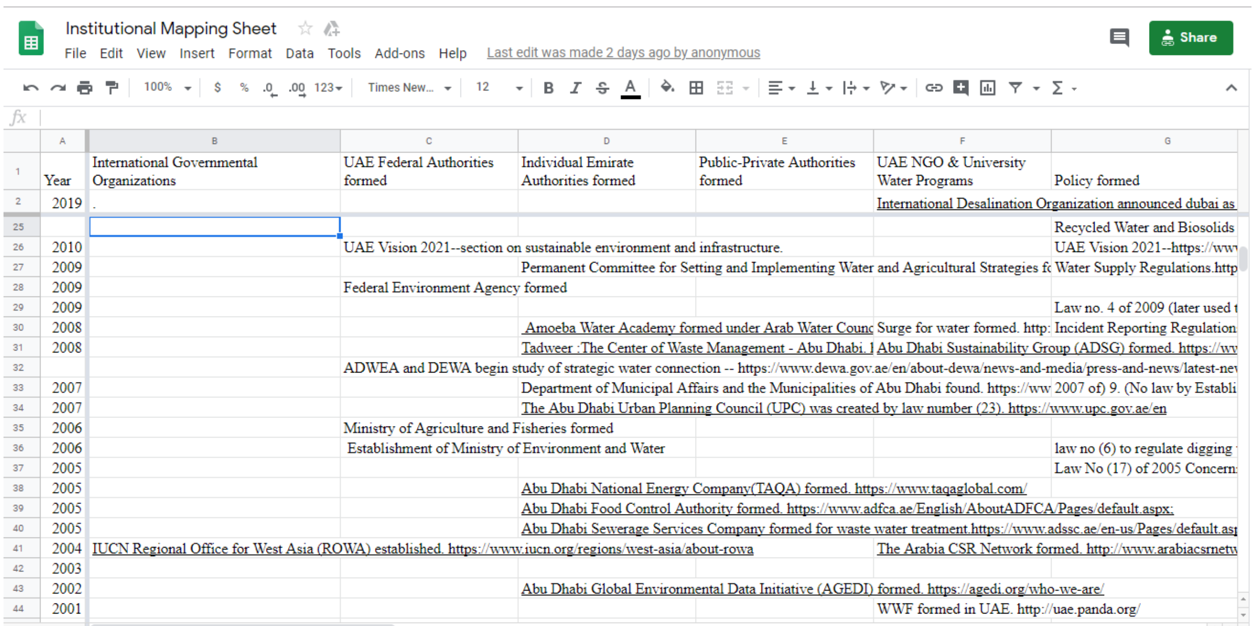
In the same year, the Water Security Plan for 206 was announced aiming at improving efficiency of the water supply and demand management along with emergency production and distribution. According to the Official Government Portal, “the overall objectives of the strategy are to reduce total demand for water resources by 21 percent, increase the water productivity index to USD 110 per cubic meter, reduce the water scarcity index by three degrees, increase the reuse of treated water to 95 percent and increase national water storage capacity up to two days” (Ministry of Energy and Industry, 2017). However, like the electricity sector, water demands have significantly grown in the last two decades and there is a greater inbuilt capacity of generation through Multi-Stage Flash desalination plants in the UAE. However, the government is pushing this transition towards solar-driven Reverse Osmosis through new projects such as the Taweelah Reverse Osmosis project which is going to be the world’s largest desalination facility (Kader, 2018).

The implementation of policies transforming the status quo to meet the ambitious goals set in UAE National Energy Plan 2050 demand cooperation from several key government entities and utilities in the power and water sector. The UAE Water Strategy Plan of 2036 also set six different connecting networks between water and energy entities in the UAE.

This diversification effort includes direct government investments in infrastructure expansion and improvements, high education institutions, aerospace and IT industries, and the development of a nuclear energy program with the goal of building four nuclear power reactors by 2020. On the clean-tech front, Masdar City is a 22 billion dollar project underway that aspires to be the world’s most sustainable urban communities, a low-carbon development made up of a rapidly growing clean-tech cluster, business free zone and residential neighborhood with restaurants, shops and public green spaces. Projects such as Masdar City benefit from both foreign investments and labor. The UAE set up free trade zones offering full ownership and zero taxes, which over-time attracted over 17,000 companies and FDI estimated at over US$73 billion. The foreign investment in any of UAE’s three stock exchanges is unrestricted with the exception of government-related entities foreign investors. Foreign workers accounts for over 80% of UAE’s 9.4 million population (2017), with roughly 1.1 million migrant construction workers help making ambitious infrastructures projects, luxury hotels, large port facilities, and stunning skyscrapers a reality. The almost 16 million tourists that poured into Dubai in 2018 is a testament to the success of these projects and the increased economic diversity of the UAE (Australian Government Department of Foreign Affairs and Trade, 2019).

3.2. Institutional Analysis

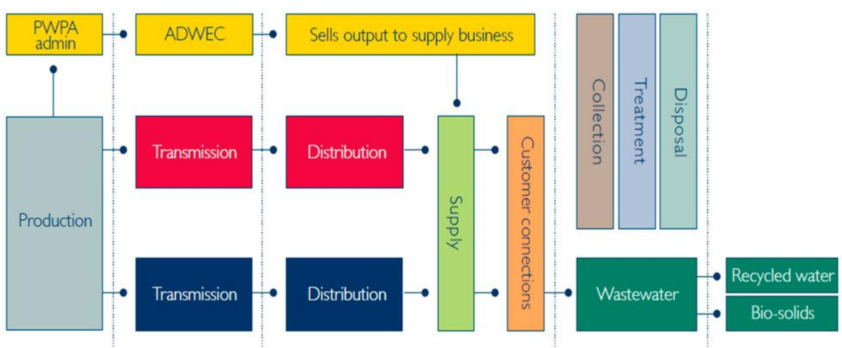
An Institutional analysis was used to map the evolution and jurisdiction of organizations in the water sector, energy sector and also joint organizations embodying the nexus. This was done by preparing an excel spreadsheet which had years as the rows and institutions as columns including international government organizations, UAE federal authorities, emirate-level authorities, public-private entities, UAE NGO and university programs, policies and initiatives. This section discusses the columns on the spreadsheet which constitute a cross-sectional analysis of current institutions in the UAE water-energy nexus.



	A	B	C	D	E	F	G
1	Year	International Governmental Organizations	UAE Federal Authorities formed	Individual Emirate Authorities formed	Public-Private Authorities formed	UAE NGO & University Water Programs	Policy formed
2	2019	.				International Desalination Organization announced dubai as	
25							Recycled Water and Biosolids
26	2010		UAE Vision 2021--section on sustainable environment and infrastructure.				UAE Vision 2021--https://ww
27	2009			Permanent Committee for Setting and Implementing Water and Agricultural Strategies fc			Water Supply Regulations.http
28	2009		Federal Environment Agency formed				
29	2009						Law no. 4 of 2009 (later used t
30	2008			Amoeba Water Academy formed under Arab Water Counc		Surge for water formed. http:	Incident Reporting Regulation
31	2008			Tadweer :The Center of Waste Management - Abu Dhabi. I		Abu Dhabi Sustainability Group (ADSG) formed. https://wv	
32			ADWEA and DEWA begin study of strategic water connection -- https://www.dewa.gov.ae/en/about-dewa/news-and-media/press-and-news/latest-nev				
33	2007			Department of Municipal Affairs and the Municipalities of Abu Dhabi found. https://ww			2007 of) 9. (No law by Establi
34	2007			The Abu Dhabi Urban Planning Council (UPC) was created by law number (23). https://www.upc.gov.ae/en			
35	2006		Ministry of Agriculture and Fisheries formed				
36	2006		Establishment of Ministry of Environment and Water				law no (6) to regulate digging
37	2005						Law No (17) of 2005 Concern:
38	2005			Abu Dhabi National Energy Company(TAQA) formed. https://www.taqaglobal.com/			
39	2005			Abu Dhabi Food Control Authority formed. https://www.adfca.ae/English/AboutADFCA/Pages/default.aspx;			
40	2005			Abu Dhabi Sewerage Services Company formed for waste water treatment.https://www.adssc.ae/en-us/Pages/default.asp			
41	2004	IUCN Regional Office for West Asia (ROWA) established. https://www.iucn.org/regions/west-asia/about-rowa				The Arabia CSR Network formed. http://www.arabiacsrnetw	
42	2003						
43	2002			Abu Dhabi Global Environmental Data Initiative (AGEDI) formed. https://agedi.org/who-we-are/			
44	2001					WWF formed in UAE. http://uae.panda.org/	

Figure 3.1. Institutional Mapping Sheet with organizational entities and policies as columns and years as rows

At the national level, The Ministry of Energy and Industry (MOEI) was formed as the principle entity to "ensure the organization, proposal of policies and the preparation of future strategies for industrial development" (UAE Ministry of Energy and Industry, 2019). The Ministry of Climate Change and Environment (MOCCAE) is responsible for developing plans, strategies, and policies related to the environment and mitigation of climate change (UAE Ministry of Climate Change and Environment, 2019). These two national ministries coordinate with other regulatory agencies and utilities at the individual emirate level. In Abu Dhabi emirate, the Department of Energy (DoE-AD) was established in 2018 as the agency responsible for planning and direction of Abu Dhabi's energy sector, as well as regulating the industry (UAE Department of Energy, 2019). The DoE-AD absorbed the former Abu Dhabi Water and Electricity Authority (ADWEA), which through its fully owned subsidiary, the Abu Dhabi Water and Electricity Company (ADWEC) acts as the single buyer and seller of water and electricity. ADWEC performs this function by entering long term agreements with independent power producers (IPPs), independent water and power producers (IWPPs), and distribution companies (DISCOs), most of which are partially owned by the former ADWEA (Abu Dhabi Water and Electricity Company, 2019) . The Abu Dhabi water and energy organizational structure can be depicted in the following diagram.



PWPA – Power and Water Purchase Agreement

Figure 3.2. Abu Dhabi electricity and water organizational structure (Paul, Al-Tenaiji, & Braimah, 2016)

As shown in this figure 3.2, the Independent Water and Power Producers (IWPPs) and Generation and Desalination systems (GDs) operate under 20 yearlong power and water purchase agreements with the ADWEC being the sole buyer of the water and electricity products. The regulation of ADWEC and these IWPPs along with granting and monitoring licensing comes under the responsibility of the Regulation and Supervision Bureau (RSB).

Until recently, the Dubai Electricity and Water Authority (DEWA) owned and operated all facets of the sector from generation to distribution (UAE Ministry of Energy and Industry, 2018). To meet rising electricity demand and generation fuel mix diversification goal, the emirate is moving towards a IWPPs and IPPs model. Starting in 2015 with the clean coal power 1.2 GW Hassyan plant and the 200MW second phase of the Mohammed Rashid solar park, DEWA continue to award contracts to enhance the emirate's portfolio of clean and renewable fuel sources in order to decrease its reliance on natural gas (US Energy Information Adminstration, 2017).

The Sharjah Electricity and Water Authority(SEWA) and Federal Electricity and Water Authority (FEWA) provides electricity and water to Sharjah and the four Northern Emirates through mostly gas and diesel generation, but have not set renewable energy goals (UAE Ministry of Energy and Industry, 2018).

In the coming years, UAE will increase its reliance on IPPs and IWPPs for new electricity generation capability. The four-reactor 5.6 GW Barakah Nuclear Power Plant project has been under contraction since 2012, commissioned by the state run Emirates Nuclear Energy Corporation (ENEC) and built by a coalition of contractors with Korea Electric Power Corporation as the lead (US Energy Information Adminstration, 2017). The completed Barakah plant in 2020 is expected to meet about 25% of the projected energy need of the country. The Sheikh Mohammed bin Rashid Solar Park is the largest single-site solar park in the world with a potential 5GW generation capacity, of which 213 MW has been online and 800MW awarded to a consortium led by Masdar (US Energy Information Adminstration, 2017).

Increased demand in the water and energy sector has led to privatization of desalination plants in the UAE. The setting up of Independent Water and Power Projects (IWPPs) allowed foreign companies to form joint ventures with state owned companies. In each IWPP, the private company owns a 40% share while the government entity owns 60% of the share. This has improved efficiency and promoted the adoption of new technologies on the front of the water-energy nexus (Fanack Water, 2017).

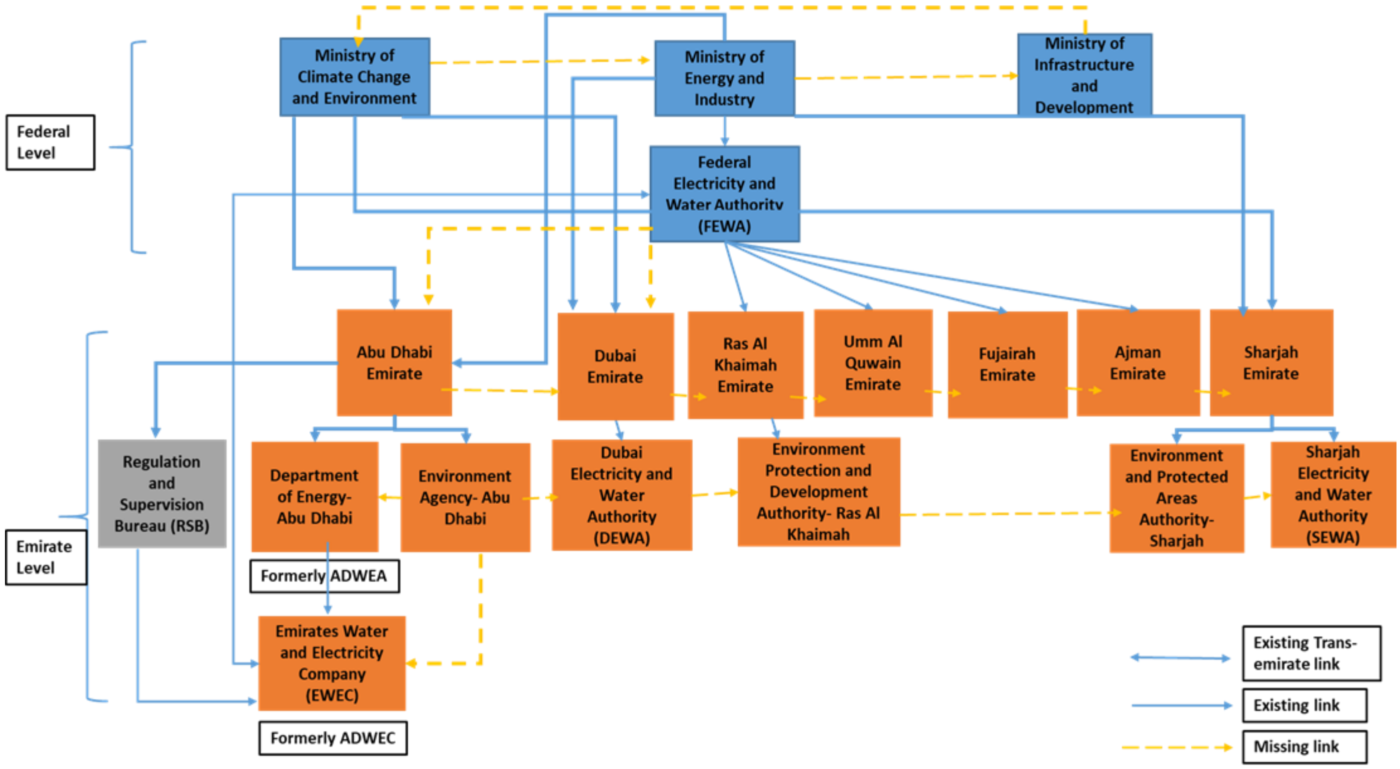


Figure 3.3. Institutional Chart of the water-energy nexus in the UAE.

Figure 3.3 illustrates the water-energy nexus related organizational structuring of the UAE. The Ministry of Energy and Industry at the federal levels monitors and regulates water and energy institutions across emirates. It directly works with the Federal Electricity and Water Authority (FEWA) which is responsible for the northern emirates of Ajman, Umm Al Quwain, Ras Al Khaimah and Fujairah (UAE Government, 2019). The Ministry of Energy and Industry directly monitors the Department of Energy in Abu Dhabi, Dubai Electricity and Water Authority (DEWA) and Sharjah Electricity and Water Authority (SEWA). There are gaps in institutional collaborations between FEWA and the southern emirates.

The Ministry of Climate Change and Environment works across the water-energy nexus issues under climate change. It directly works with the Environment Agency in Abu Dhabi (EAD) (formerly the Abu Dhabi Water and Electricity Authority (ADWEA)), Environment Protection and Development Authority in Ras Al Khaimah and the Environment and Protected Areas Authority in Sharjah (UAE Government, 2019). It also directly works with the emirate municipalities of Dubai, Ajman, Umm Al Quwain and Fujairah. However, the Ministry of Climate Change and Environment does not work with other important federal ministries of

Energy and Industry; and Infrastructure and Development. It also does not work with the water and energy institutions under different emirates. These institutions include Department of Energy- Abu Dhabi, DEWA and SEWA.

At the emirate level, there are the emirate governments or what are called municipalities in the UAE. There are seven administrative municipalities, each representing an emirate. The water and energy institutions that operate under these municipalities include environmental authorities and water-energy nexus authorities such as DEWA. These two types of authorities do not work together. The water-energy nexus authorities such as Ministry of Energy- Abu Dhabi have multiple subsidiaries working under them. This includes the Emirates Water and Electricity Company (EWEC) which was renamed from Abu Dhabi Water and Electricity Company (ADWEC) in 2018 (Gulf News Business, 2018). EWEC would now work closely with FEWA. These subsidiaries are regulated by the Regulation and Supervision Bureau (RSB) for the emirate of Abu Dhabi. Other emirate level institutions are only regulated by the Ministry of Energy and Industry. Another missing link at this level is between emirate level environment agencies and water and electricity subsidiary companies.

This Institutional Analysis piece emphasizes the need for organizations to operate at the cross-section of both energy and water systems to achieve long-term sustainability goals. This piece also sheds light on the dynamic restructuring that most organizations in the UAE have undergone. For instance, the Ministry of Environment and Water evolved to include domestic climate change affairs in 2016 (UAE Ministry of Climate Change and Environment, 2019). Moreover, there has been a growth of collaborative initiatives between different water and energy entities in the UAE.

3.3. Demand and Supply Trend Analysis

This section analyses data published in a Statistical report released by ADWEA in 2016 that covers water and electricity statistics in the region from 1999 to 2016. It includes statistics for Abu Dhabi, Al Ain and the Western region while system refers Sharjah and Dubai along with Abu Dhabi, Al Ain and Western Region. However, Individual statistics of Dubai and Sharjah are not available in this report. The purpose of this section is to organize available data into charts and graphs, in order to describe trends in demand and supply for different regions and months and observe basic correlations between the electricity and water statistics. Overviewing the historical energy and water demands enable us to consider how these historical trends factor in to the demand and supply projections.

3.3.1. Annual Energy Demand by Region

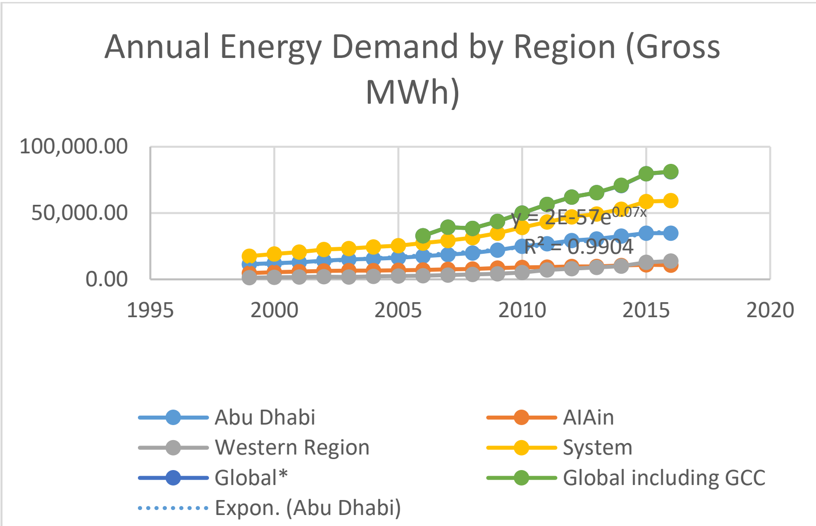


Figure 3.4. Annual Energy demand trends for the world, system (UAE) and key sub-regions in the UAE

The graph in Figure 3.4 shows how Gross Annual Energy Demand varies across the different regions over the years 1999-2016. Here, the global trends are seen along with regional (GCC trends) and the system (UAE) trends. This graph also includes sub-regional energy trends of Abu Dhabi, Al-Ain and Western region while the other sub-regions are cumulatively shown under the system trend line. A sudden hike in global energy including GCC energy demand can be seen in 2007 and it dips back in 2008.A possible explanation of this fluctuation could be the global financial crisis of 2007-2008. From there on, there is a linear growth in demand. The demand has grown the most for Western region and the least for Al Ain in the UAE, which will be interesting to compare with modeling results in later chapters.

3.3.2. System Energy Demand by Month

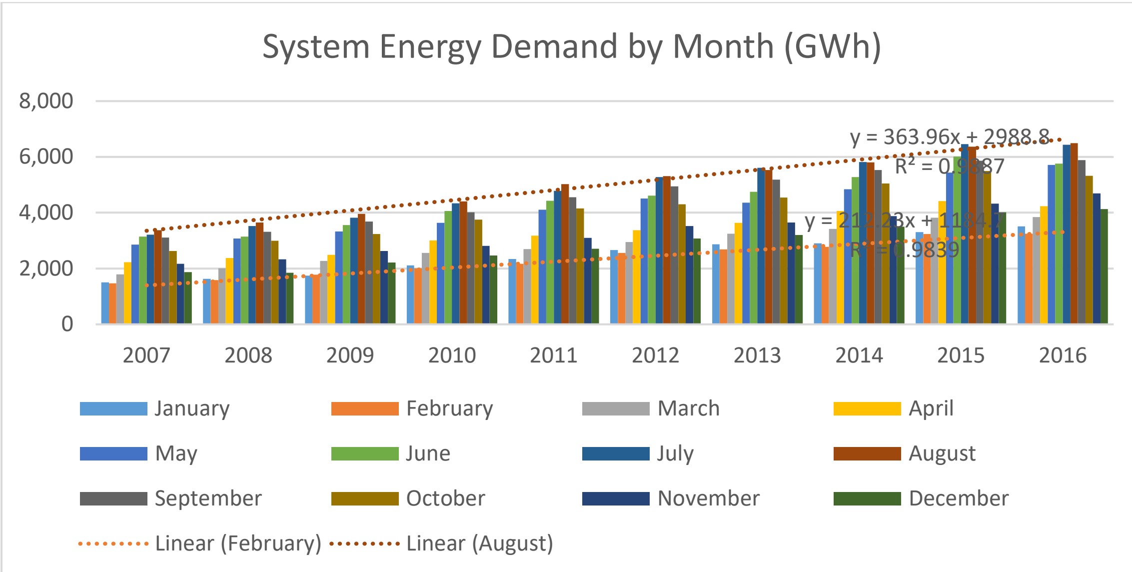


Figure 3.5. UAE energy demand by month

Figure 3.5 shows how the whole system energy demand for the UAE as it grew from 2007 to 2016. The seasonality can be observed through the seasonal periodicity in energy demands. The highest demand was observed in the month of August because of cooling requirements while the lowest is observed in February. There has been an overall 7.2% growth in August's energy demand from 2007 to 2016. This reflects the demand in cooling requirement in these past years.

3.3.3. Annual Water Production by Region

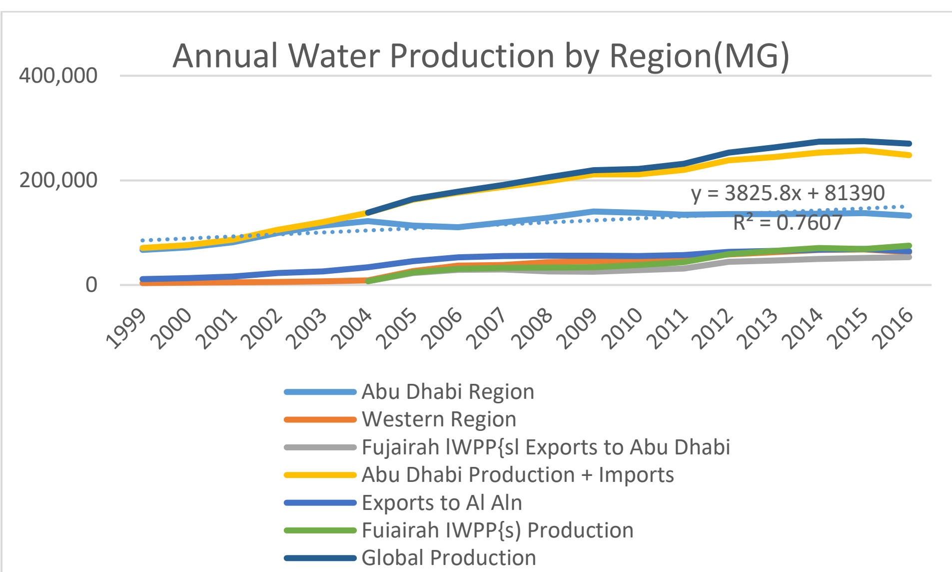


Figure 3.6. Annual water production by sub-regions in the UAE.

The plot in Figure 3.6 shows how the annual water production by region has varied from 1999 to 2016. The water production to meet water demand can be seen to have grown. Along with this, it is worthy to note that the largest increase in annual average growth was seen in Fujairah IWPP Production and the lowest growth was seen in Abu Dhabi region. This could potentially reflect a rapid population growth in Fujairah while Abu Dhabi water demands were pretty stable.

3.3.4. Water and Energy Systems Side-by-Side Trend and Correlation

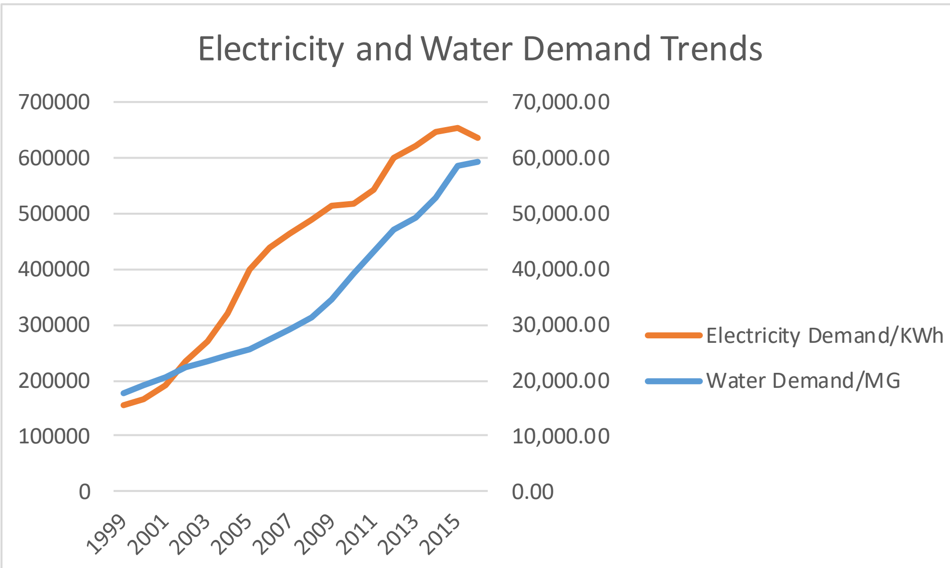


Figure 3.7. Side by side water and energy trends for the UAE

Figure 3.7 is a plot of the water and energy demands in the UAE from 1999 to 2016. A significant rise on both demands can be observed. An investigation into their correlation showed a statistically significant correlation of 0.79 with p value <0.005. This means a strong a positive correlation between the two systems. Hence, confirming the existence of a strong nexus.

This chapter provides qualitative insights into the UAE water-energy nexus. It was observed that the UAE has developed extensive long-term plans for their water and energy systems. The government is promoting the transition to renewables. Along with this, more inter-organizational connections and collaboration being developed to collectively plan for the energy and water systems in the UAE. The Institutional analysis piece shows the linkages of UAE entities to operate at the water-energy intersection and the dynamic organizational restructuring in this sphere. The last piece of trend analysis confirms the need for organizational synergies and long-term sustainability frameworks as the water and energy demands in the UAE significantly rise.

4. Examining Previous Quantitative Research done through WEAP-LEAP

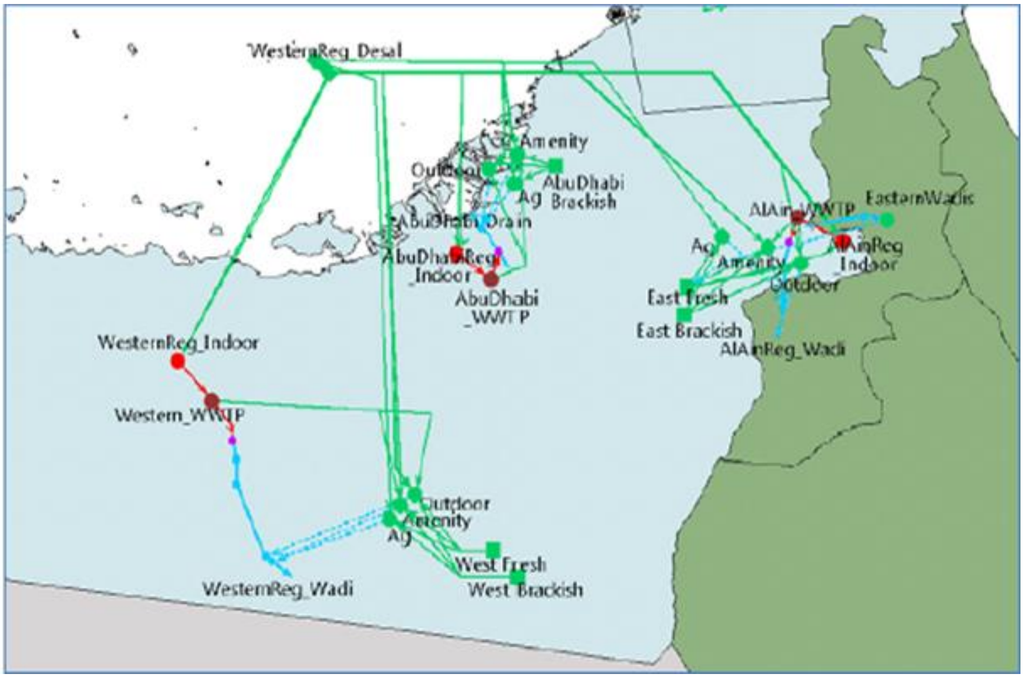
This chapter dives into the fundamentals of the analytical part of the thesis as inspired by a WEAP-LEAP assessment conducted by the Abu Dhabi Global Environmental Data Initiative (AGEDI). This was the first study that conducted a long-term policy scenario analysis in the UAE. Therefore, this chapter covers the comprehensive AGEDI study by first introducing the reader to the modeling tools of WEAP and LEAP. Second, it follows through the policy design process that AGEDI went through in order to guide through policy design for this thesis. Third, it analyzes sub-regional demand projections under the Business-as-Usual (BAU) scenario of the AGEDI study.

4.1. Introduction to AGEDI WEAP and LEAP Model Structures

The Abu Dhabi Global Data Initiative (AGEDI) developed a UAE wide study of the Water-Energy Nexus using an integrated water and energy planning framework based on the Water Evaluation and Planning (WEAP) and Long-range Energy Analysis and Planning (LEAP) decision support system. The water systems model divides the country into five water resource demand and supply zones (regions) that consider municipal, industrial, and agriculture demands supplied by both desalination and groundwater The models of water and energy demand in WEAP and LEAP include climate dependent factors. AGEDI 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 called the High Efficiency (HE) scenario and then a supply-oriented scenario called the Natural Resource Protection (NRP) scenario.

4.1.1. Water Evaluation and Planning (WEAP)

WEAP is a simulation based water evaluation and planning model. It follows a spatial format that allows the user to create supply and demand nodes. Supply nodes can include aquifers, desalination plants, wastewater treatment plants, etc. while demand nodes include different demand regions that that the user can categorize into sectors. For this study, AGEDI divided the demand sectors in the UAE into agriculture, outdoor, indoor and amenities sectors. Figure 4.1 shows the schematic of the WEAP model map of the UAE water network including transmission links along with demand and supply nodes.



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

Figure 4.1. Zoomed in WEAP model structure for Abu Dhabi (including Abu Dhabi, Al Ain and Western region sub-regions)

Figure 4.1 shows the zoomed in screenshot of the Abu Dhabi emirate from the WEAP model. This schematic includes desalination plants, return flow networks, national aquifers, wastewater treatment facilities, demand catchment sites, etc. WEAP provides a holistic picture of the water network in this region.

4.1.2. Long-range Energy Analysis and Planning (LEAP)

LEAP simulates energy supply (generation) and demand. The strength of LEAP is that it allows us to track the carbon equivalent of fuel sources like natural gas and coal, etc. It functions by mining datasets and building relationship between water and energy systems to model the nexus. It enables the development of scenarios that are linkable to other softwares such as

WEAP. It analyzes greenhouse emissions levels and does the cost and benefit analysis of different policy alternatives. The process of data mining of local and international data resources by LEAP to build credible models of water-energy system of the UAE is shown using a schematic in figure 4.2 (Stockholm Environment Institute, 2005).

The LEAP model follows a Sankey diagram as shown in the figure below.

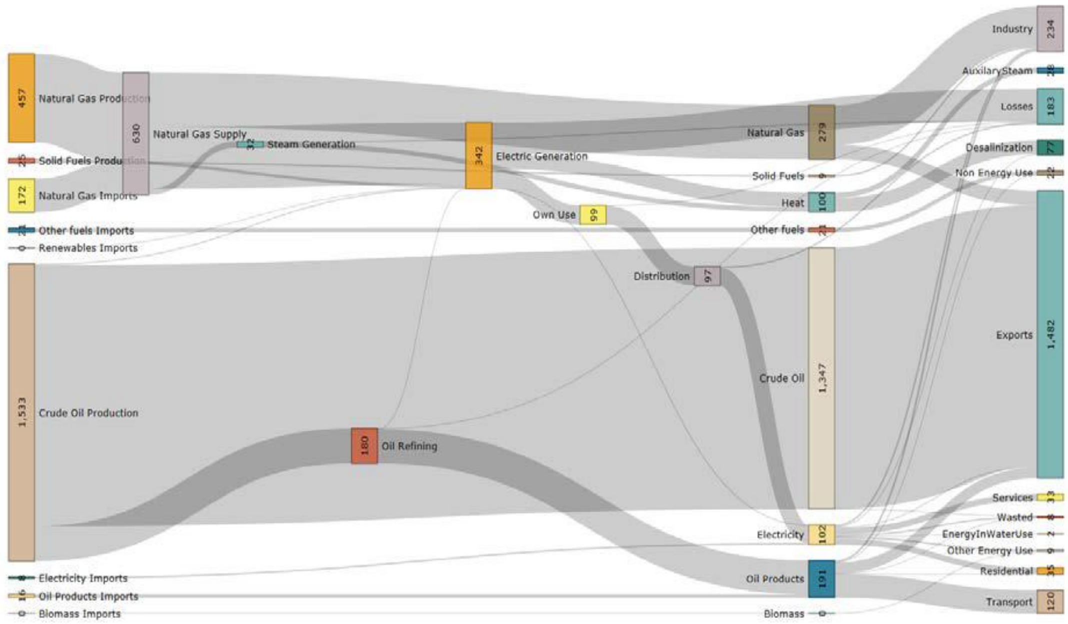
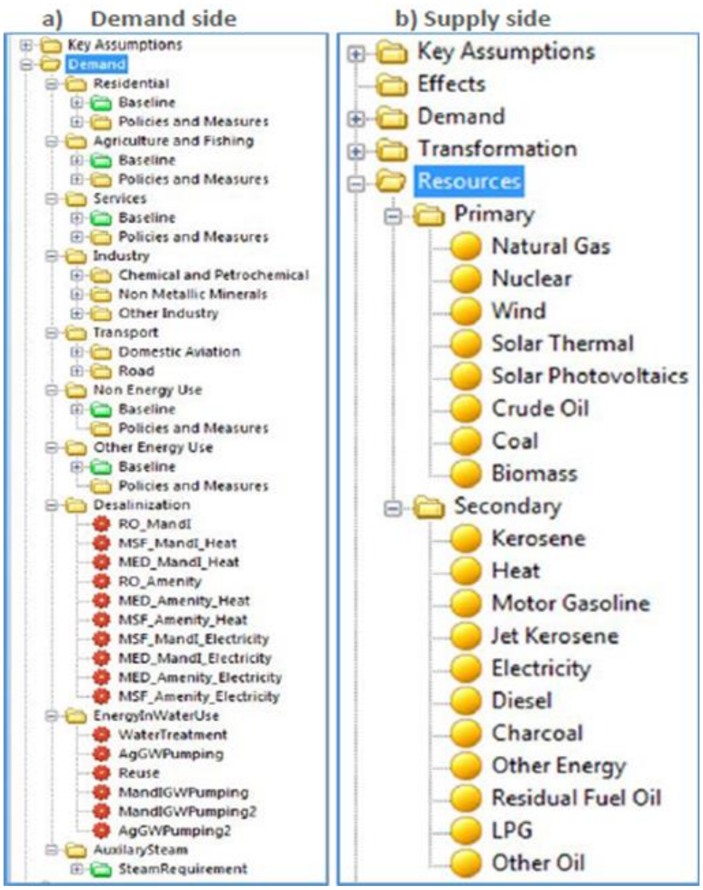


Figure 4.2. UAE LEAP Sankey structure.

This figure is a schematic of the LEAP model structure that models the energy sector from primary fuel sources to the electricity generation process to the consumption sector. This Sankey diagram maps the information made available by the International Energy Agency on their website.

There are multiple levels of representations in the AGEDI LEAP model. It divides the country into six modeling regions (Western, Abu Dhabi, Al Ain, Dubai, Fujairah, and Eastern). This includes Dubai, the Eastern Region and the Fujairah Region, with shared groundwater access between these three demands regions. Dubai and the Eastern Region emirates share wastewater treatment capacity and desalinated water sources, but have distinct urban indoor, outdoor, amenity and agricultural demand sites. The Fujairah Region has its own wastewater treatment plan.



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

Figure 4.3. LEAP model structure for the UAE

This representation shows the aggregate supply and demand for all of the UAE, however it has high level of detail for the sub-regions. Water use is divided into different sectors of agriculture demand, amenity demand, indoor demand and outdoor demand. On the supply side we have different types of technologies that produce this water such as RO, MSF and MED. For each region we have a representation of those supply technologies as well as groundwater.

4.1.3. WEAP-LEAP Coupling

Figure 4.4. WEAP-LEAP Integrated Model Window.

This figure shows how different scenarios in the WEAP model can be coupled with the LEAP model so inputs from WEAP can flow into LEAP. This can be achieved by advanced settings in the softwares. Each scenario in WEAP must be linked with its respective LEAP scenario. Once the baseline data of water demands and supplies is calculated by WEAP based on population growth and economic growth, the electric energy demand for this water supply is passed on to LEAP.

4.2. AGEDI Scenarios and Results

This section lists the scenarios designed and analyzed by AGEDI and the policies that each of those scenarios constitutes. This section is broken down into scenarios and results. The results section would then analyze results under different scenarios for the UAE.

4.2.1. Scenarios

4.2.1.1. Policy Scenario: Business-as-Usual

The Population growth trends for this scenario are taken from the United Nations (UN) report in 2015 with uniform growth of 1.8% until 2060. Precipitation and annual average temperature forecasts are taken from AGEDI's Local, National, and Regional Climate Change Program (LNRCCP) (Yates, et al., 2015). This includes climatic trends for the 1985-2004 period through 2060. The trajectory of greenhouse gas emissions and their resulting concentrations in the atmosphere are factored in using the Intergovernmental Panel on Climate Change (IPCC) RCP8.5 projections.

4.2.1.2. RCP 8.5

This scenario is built on the Business-as-usual scenario. The RCP 8.5 incorporates the temperature and precipitation projections of the RCP 8.5 model. This assumes that the climate change signal manifests itself as a 2°C warming by 2060 assuming a 15% increase in cooling degree days. This increase in cooling degree days is applied to both the residential and service sectors. The warming is assumed to increase total electricity demand by 0.5% from 2015 to 2060.

4.2.1.3. Policy Scenario: High Efficiency (HE)

The High efficiency scenario is based on the RCP 8.5 scenario, hence including the RCP 8.5 climate projections. It tests the reduction of electricity and water consumption on the demand side using policy tools. The water policies as part of the high efficiency include reducing indoor consumption and setting outdoor and amenity caps to reduce water consumption. This also includes improved efficiency in irrigation program that will include use of sprinkler systems, etc. for efficient irrigation and a water loss prevention program. The electricity policies include demand side efficiency and peak load management. The following table shows the exact policy goals that were used for the High Efficiency scenario.

Policy Components		**Policy Target**
Water	Indoor water use efficiency and conservation program	75 gal/capita/day by 2060, declining from BAU-RCP8.5 levels starting in 2030
	outdoor garden and amenity caps	Maintain 2015 levels
	Improved irrigation efficiency	20% reduction in outdoor water use by 2060
	Water loss reduction program	25% reduction in water losses by 2060

Electricity	Peak load management of space cooling load	15% reduction in peak summer space cooling load
	Demand side electric efficiency and conservation program	7,000 kWh/capita/year by 2060

Table 4.1. Source AGEDI (Abu Dhabi Global Environmental Data Initiative, 2015)

4.2.1.4. Policy Scenario: Natural Resource Protection (NRP)

The Natural resource and Protection ((NRP) scenario is also built on the RCP 8.5 scenario, hence including the RCP 8.5 climate projections It tests policies applied to the supply-side to conserve natural resources, therefore having a focus on caps on carbon emissions and coal use; and transitioning to renewables in the energy realm and wastewater treatment and phase-out of groundwater extraction using fossil fuels in the realm of the water sector. The water policies for this scenario include a groundwater phase-out, increases treatment of sewage effluent and transition to reverse osmosis. The electricity policies include a cap for carbon emissions as well as clean coal. It also includes a renewable portfolio standard.

Policy components		**Policy targets**
Water	Fossil groundwater phase-out	4.5% per year reduction
	Increased use of treated sewage effluent	90% of all TSE is reused by 2060, staring in 2030.
	Sustainable desalination	60% RO starting 2030
Electricity	Carbon dioxide cap	2005 Carbon dioxide level in the UAE by 2060
	Renewable portfolio standard	PV solar capacity at 0.25 GW/year through 2060, starting in 2021
	Clean Coal Capacity Cap	Cap at 2,400 MW by 2025

Table 4.2. Source AGEDI (Abu Dhabi Global Environmental Data Initiative, 2015)

4.2.1.5. Policy Scenario: Integrated Scenario

The Integrated Scenario is a combination of both High Efficiency and Natural Resource Protection scenarios. It includes all water demand side and supply side water and electricity policies. This scenario is also based on the RCP 8.5 scenario and includes the climate change projections.

4.2.2. Results

This section depicts and analyzes the results of the AGEDI study and analyzes them. The AGEDI study does most work in scenario analysis of demand sectors as a result of different policies. The following figures show some of the major graphs that the study came up with.

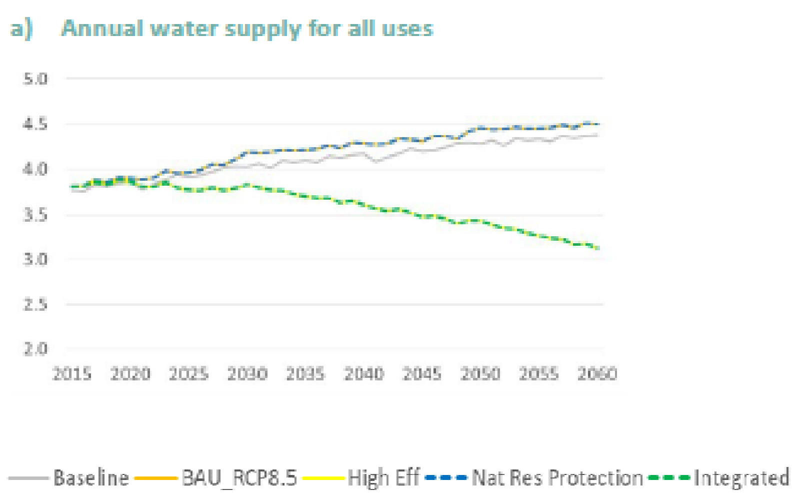


Figure 4.5, Water supply for all demand sectors in the UAE in billion cubic meters

As shown in Figure 4.5, it can be seen that the highest water supply is needed under the Business as usual scenario and the Natural resource Protection scenario, this is because no conservation policies are applied on both of these scenarios. In both these scenarios, water supply rises by 0.36% a year. However, in case of the High efficiency demand side scenario, there is a saving of only 0.44% per year.

The AGEDI report also conducts a sector wise analysis and it is found that in the Natural resource Protection scenario, desalination becomes the main source to supply water for irrigation which involves a growth of around 2.1% in the water supply from desalination. Groundwater depletion is the highest in the Business as Usual scenarios. According to the AGEDI analysis, the effect of climate change on water demand is small but non-trivial. It causes an additional demand of 4.4BCM in the agricultural sector, 0.7BCM in the amenity sector.

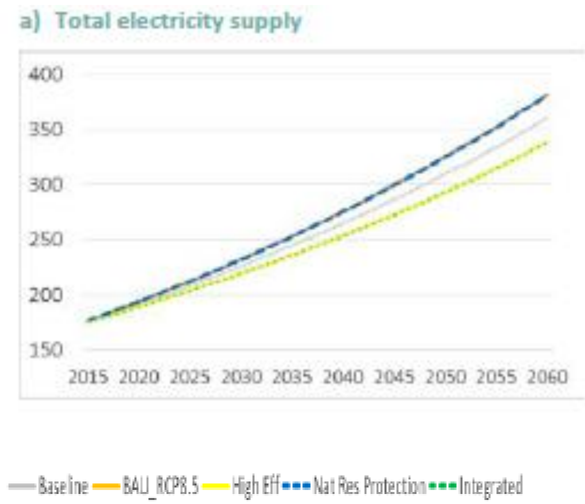


Figure 4.6. Electricity supply trends for all of UAE (Abu Dhabi Global Environmental Data Initiative, 2015)

The electricity supply shows the most significant impact of climate change. Electricity supply would increase around 5.5% per year under climate change according to the results of the AGEDI model. The Natural resource Protection shows an increase while the High efficiency scenario shows a decrease in the electricity consumption. The Integrated scenario results in almost a 25% decrease in electricity consumption in 2060 compared to the RCP 8.5 scenario.

4.3. Sub-Regionalization of Results based on Demand Sectors

This section delves into the sub-regional demands for different sector categorizations in the UAE as shown under the business as usual scenario projections. The time range for these results is from 2015 to 2060 as based on the AGEDI study. This process of studying future projections of the worst case scenario helps in understanding sub-regional dynamics before delving into sub-regional policy analysis in Chapter 5. This future projection analysis also guides region-specific policy design. The different demand sectors are agriculture, outdoor, indoor and amenities.

4.3.1. Agriculture

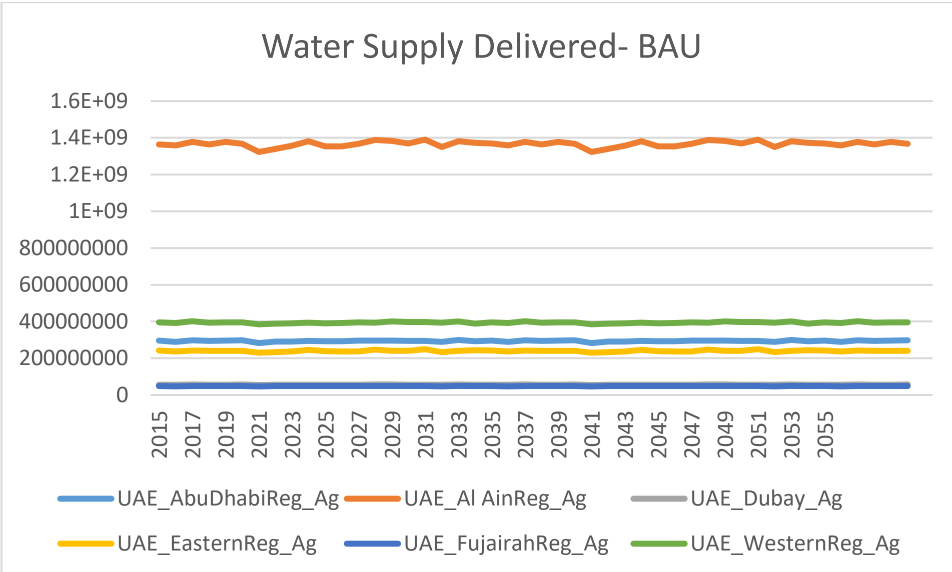


Figure 4.7. Sub-regional trends of water supply delivered to the agricultural sector under BAU scenario

In this graph (Figure 4.7) it can be seen that the region that takes up most of the water supply for the sector of Agriculture is Al Ain. Western Region is the second largest demand area while Fujairah is the lowest demand area. Another interesting trend is that in the baseline scenario, there is no projected growth in the demand of this sector.

4.3.2. Amenity Sector

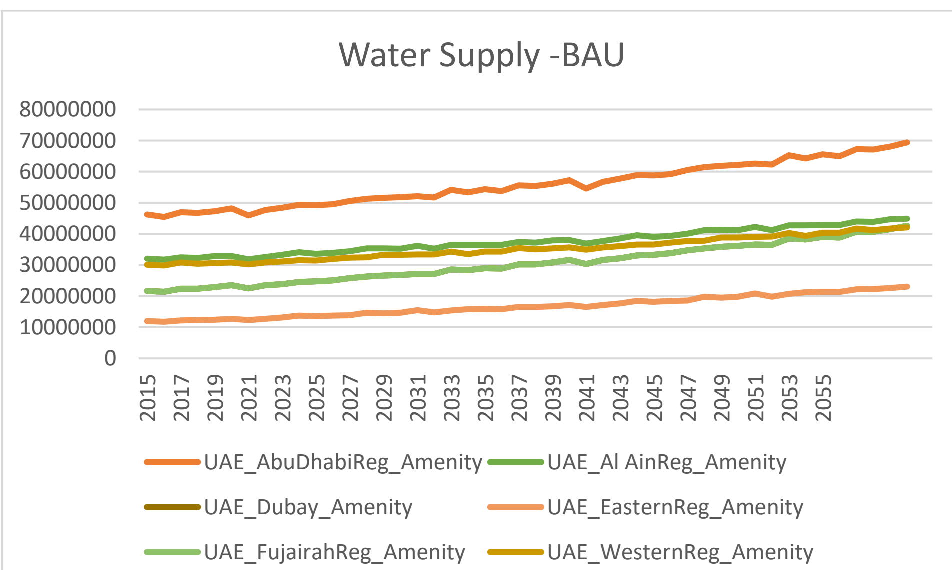


Figure 4.8. Sub-regional trends of water supply delivered to the amenity sector under BAU scenario

As shown in Figure 4.8, in the case of amenities (includes water needs for landscapes and gardens), Abu Dhabi region has the largest demand for water supply, while Al Ain has the second largest and Eastern region has the lowest. Also, there is an upward trend in the demand for this sector. The rate of growth of demand for water supply in amenities is pretty similar for all regions.

4.3.3. Indoor Sector

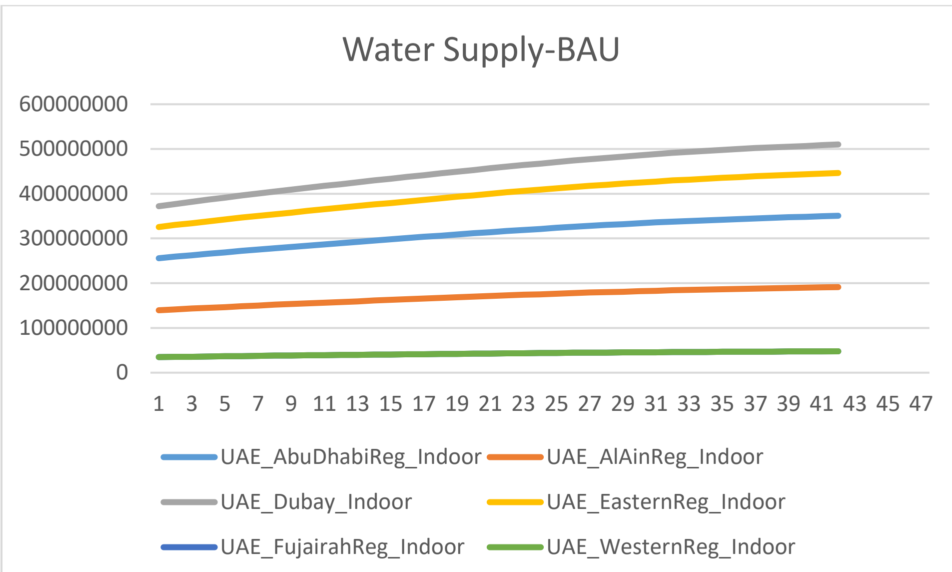


Figure 4.9. Sub-regional trends of water supply delivered to the indoor sector under BAU scenario

As seen in Figure 4.9, for indoor demand, Dubai ranks the highest while Eastern Region is the second and Western region the last. There is a very small growth factor in this sector.

4.3.4. Outdoor Sector

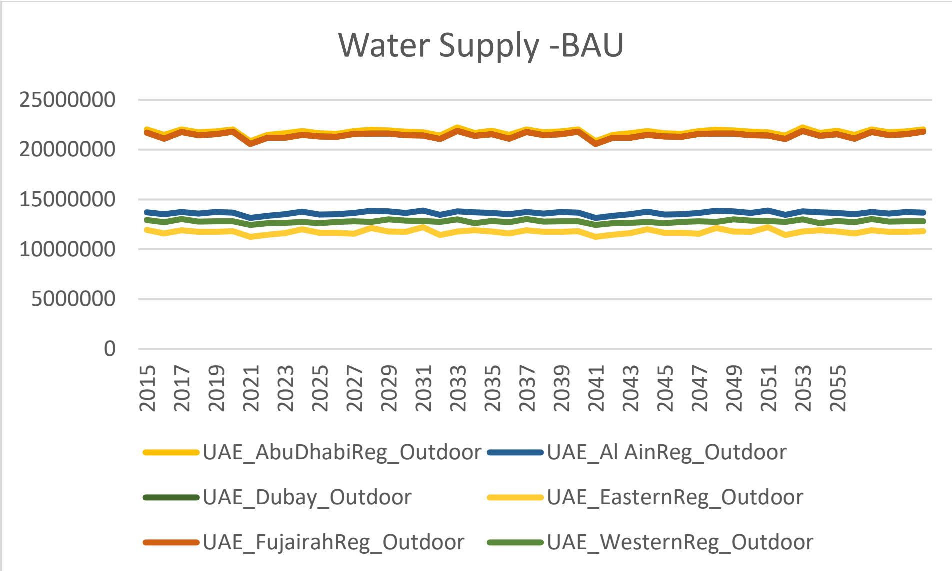


Figure 4.10. Sub-regional trends of water supply delivered to the outdoor sector under BAU scenario

As shown in Figure 4.10, in the outdoor water demand, there is no growth in demand for all regions. Abu Dhabi and Fujairah have the largest and the same outdoor water demand, while Eastern region has the lowest demand based on its sparse population.

This chapter has summarized the methods used by the Abu Dhabi Global Environmental DATA Initiative (AGEDI) for studying the UAE water-energy nexus. It gives a firm foundation to use this model further for sub-regional analysis. It is evident that the integrated WEAP and LEAP modeling provides great analytical insight into the nexus and can play a critical role in designing and testing policy scenarios that best suit a country's needs and sustainability goals.

5. Integrated Modeling of Modified Scenarios and Results

This chapter forms the crux of the thesis. It entails policy scenario analysis using WEAP and LEAP which is inspired from the AGEDI study analysis but adds value in two ways. First, it disaggregates the High efficiency (HE) and Natural Resource protection (NRP) policy scenarios that AGEDI used and modifies them based on current UAE sustainability goals. Disaggregation of policies in scenario analysis is important to observe the effects of individual policies and reduce interaction effects between different policies Second, it takes the water-energy nexus analysis to the sub-regional level dividing the UAE into Abu Dhabi, Al Ain, Western region, Dubai, Eastern region and Fujairah. This sub-regionalization of the nexus in the UAE is key because this would be the first ever look at how economic drivers in each sub-region shape the water-energy nexus and what policies are most impactful for each sub-region.

This chapter begins with an overview of the aggregate policy scenarios designed by the Abu Dhabi Global Environmental Data Initiative. It then disaggregates those policy scenarios to individual water policies and it updates them based on recently announced goals. It should be emphasized that this study only modifies and disaggregates the water policies that AGEDI used. It does not modify electricity policies because of a particular focus on water demand driven electricity use.

This UAE results section begins with verification of the AGEDI scenario results in my modeling work with those of the AGEDI technical report. This is followed by presentation of the UAE individual and aggregate policy scenario results shown for the three key variables of water supply delivered, electricity use and net benefit for the water sector which would be described in detail in the respective subsections.

This subsection starts with the Business as usual and RCP 8.5 scenario comparison. The next subsection is the sub-regional analysis that delves into the finer-grain details of the water-energy nexus with respect to its sub-regions and depicts the results of the individual and aggregate scenarios to make sense of the sub-regional gains of each scenario.

5.1. AGEDI Scenarios vs. Modified Scenarios

This subchapter reviews the AGEDI policy scenarios and introduces the modified individual and aggregate scenarios that are being tested in this study. This subsection includes tables to categorize and define policy scenarios and also includes hypothesized effects of each policy on the water-energy nexus. Following the policy design and description is important in understanding the respective scenario effects on the nexus.

Table ES-1: Policy scenarios analyzed

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

Table 5.1. AGEDI policy scenarios (Abu Dhabi Global Environmental Data Initiative, 2015).

As illustrated in Table 5.1, the AGEDI study included both water and electricity policies and categorized them into the demand-side policies or the High Efficiency scenario and the supply-side policies or the Natural resource and Protection scenario.

My study also includes both of these water and energy polices for a complete nexus analysis. However, it disaggregates and modifies the water policies while using the same electricity policies that AGEDI designed. My modified individual policies along with their descriptions are shown in Table 5.2.

Policy name	Policy description	Policy Categorization (AGEDI)	Hypothesized effect (in terms of savings)
Groundwater Ban	A ban on groundwater pumping and a 50% reduction in irrigation.	Natural resource Protection	Energy: +
			Water: +
			Net Benefit: +
			Energy: +

Reverse Osmosis Fraction	The default mix of Reverse Osmosis technology breakdown that the model assumes for MSF, MED and RO is 60%, 20% and 20%, respectively. This policy calls for a growth of RO fraction from 20% in 2020 to 100% in 2060.	Natural resource Protection	Water: = Net Benefit: +
Wastewater reuse	Wastewater reuse fraction changed from a default of 50% in 2019 to a uniform growth to 100% in 2060.	Natural Resource Protection	Energy: + Water: = Net Benefit: +
Water Loss reduction	30 % reduction in water losses in transmission links over the course of 2020-2060.	High Efficiency and Conservation	Energy: + Water: + Net Benefit: +
Indoor Consumption Reduction	550lpd per capita indoor consumption in 2020 changed to 100 lpd per capita in 2060.	High Efficiency and Conservation	Energy: + Water: + Net Benefit: +

Table 5.2. Individual modified policy scenarios

The per capita indoor consumption for the UAE was estimated to be 550liters per day by the Abu Dhabi Environment Agency in 2008 (Environmental Agency-Abu Dhabi, 2008). In 2013, the per capita indoor consumption in Abu Dhabi was claimed to be 168 liters per day water based on a waterwise study by the Regulation and Supervision Bureau after assessing indoor consumption patterns of 150 villas in Abu Dhabi (Regulation and Supervisin Bureau, 2013). However, the 550 liters per capita per day indoor consumption was reiterated in Khaleej Times in 2016 (Khaleej Times, 2016). Therefore the AGEDI technical report also uses this value under the Business-as-Usual scenario and this would be the assumption for the sake of this study.

The modified individual scenarios are then grouped back together and run in the model along with electricity policy scenarios. This categorization is based on the framework AGEDI used for its categorization. Categorizing policies that incentivize demand side efficiency as High Efficiency (HE) and policies that entail resource conservation as Natural resource protection (NRP). These aggregate scenarios are summarized in Table 5.3 along with both their water and electricity constituents.

Aggregate Scenario name	**Policy constituents**	
	Water Policies (modified policies)	**Energy Policies (AGEDI policies)**
Modified Natural Resource Protection	1. Groundwater ban 2. Reverse Osmosis fraction 3. Wastewater reuse	1. Carbon dioxide cap 2. Renewable Portfolio standard 3. Clean Coal Capacity Cap
Modified High Efficiency	1. Water loss reduction 2. Indoor consumption reduction	1. Demand side electric efficiency and conservation program 2. Peak load management of space cooling load
Modified Integrated	1. Groundwater ban 2. Reverse Osmosis fraction 3. Wastewater reuse 4. Water loss reduction 5. Indoor consumption reduction	1. Carbon dioxide cap 2. Renewable Portfolio standard 3. Clean Coal Capacity Cap 4. Demand side electric efficiency and conservation program 5. Peak load management of space cooling load

Table 5.3. Aggregate modified policy scenarios

5.2. United Arab Emirates (UAE) Results

This major subsection includes results from the WEAP-LEAP modeling process depicting the effect of different policy scenarios on the UAE regional and sub-regional water-energy nexus. This subsection verifies the model results for AGEDI scenarios by comparing my results with those reported in the technical report. I also compare the BAU and RCP8.5 scenarios. The model is then run for both individual scenarios and aggregate scenarios in the same order as defined in the previous subsection.

The results are quantified and shown for the three key dependent variables. These are the water supply delivered, electricity consumed and net benefit variable as displayed in WEAP. The electricity use variable in the model shows the electricity consumption based on the transmission link flow. It does not take into account energy losses. It is measured in million gigajoules. The second variable used to present results is the water supply required (which is the water demand but includes losses, reuse and demand side management). It is measured in billion cubic meters (BCM). The net benefits of water sector are calculated by benefit-cost analysis. A positive value shows a net benefit and a negative value shows a net cost. The benefits variable is calculated as "Per unit water revenue on transmission link flows now apply to the flow OUT of a transmission link instead of the flow INTO the transmission link, to reflect the fact that customers are not charged for water lost in transmission. (Flows out equal flows in minus losses to evaporation or groundwater) (Stockholm Environment Institute, 2017).The costs, on the other hand, are calculated within a levelized cost framework that includes costs of pumping water, wastewater treatment, etc. This shows that the net benefits in the water sector variable actually embodies a partial nexus because of it accounts for the wastewater treatment energy costs and groundwater pumping energy costs. The costs for the water sector do not, however, include desalination energy costs.

5.2.1. Replication of AGEDI Results

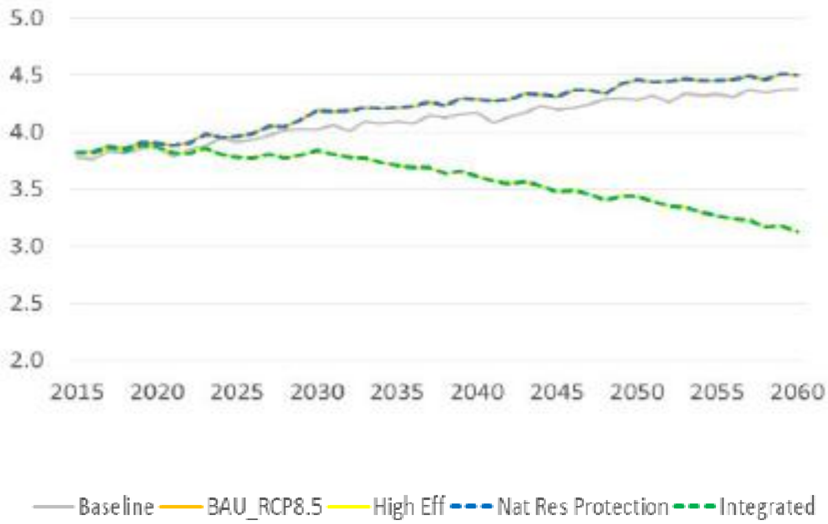


Figure 5.1. Water supply across all AGEDI scenarios (2015-2060) as shown in the technical report (Abu Dhabi Global Environmental Data Initiative, 2015).

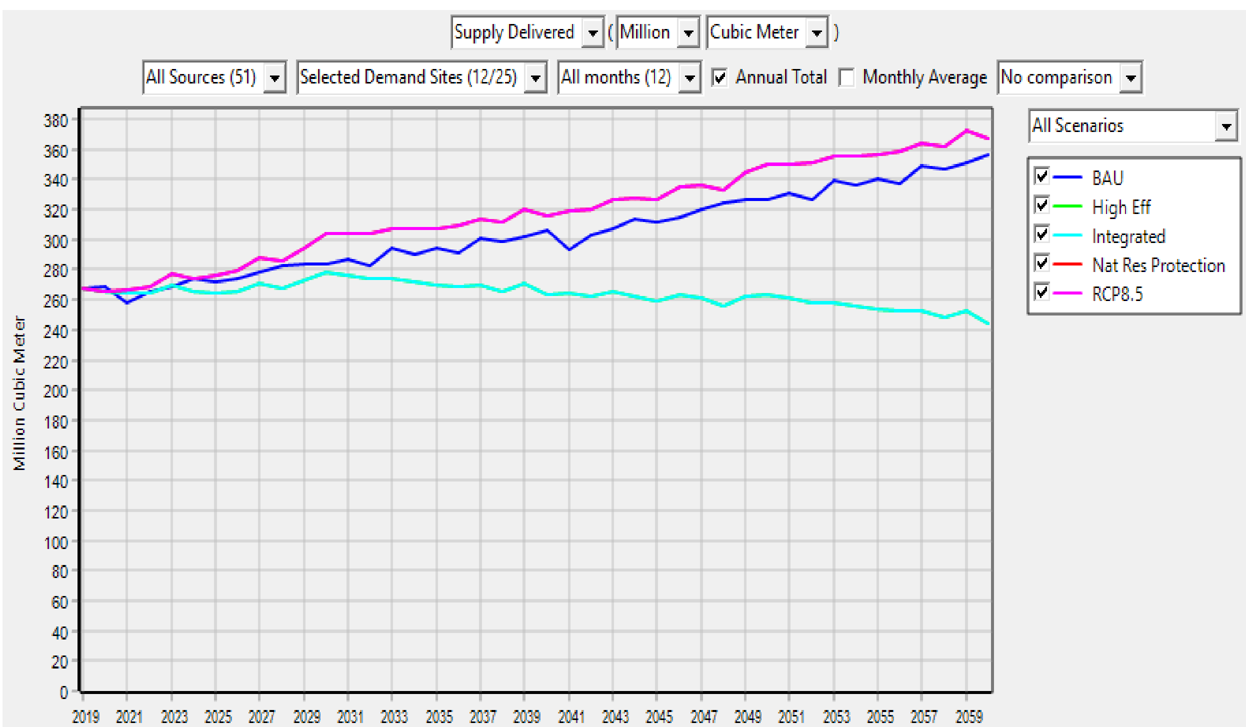


Figure 5.2. Water supply across all sectors for AGEDI scenarios in the UAE as observed for this study (BAU as dark blue line, RCP 8.5 as pink line and Integrated as light blue line.

High Eff and NRP differences are too small to be seen in this graph hence they are overlapping with the pink RCP 8.5 line)

These two graphs are an important step in verifying that the model setup for this thesis was effectively functioning the same as the AGEDI model. Next, the water supply for all of the UAE is plotted for the BAU, RCP 8.5, High Efficiency, Natural Resource Protection and the integrated scenario. These show the greater supply requirement under the RCP8.5 scenario and the savings that the Integrated scenario can result in. It is important to note that the High Efficiency and Natural Resource Protection lines are both applied to the RCP 8.5 policy scenario because their differences are much smaller as compared to the joint Integrated scenario. They do, however, cause savings even when not combined together.

5.2.2. BAU vs RCP 8.5 Scenario

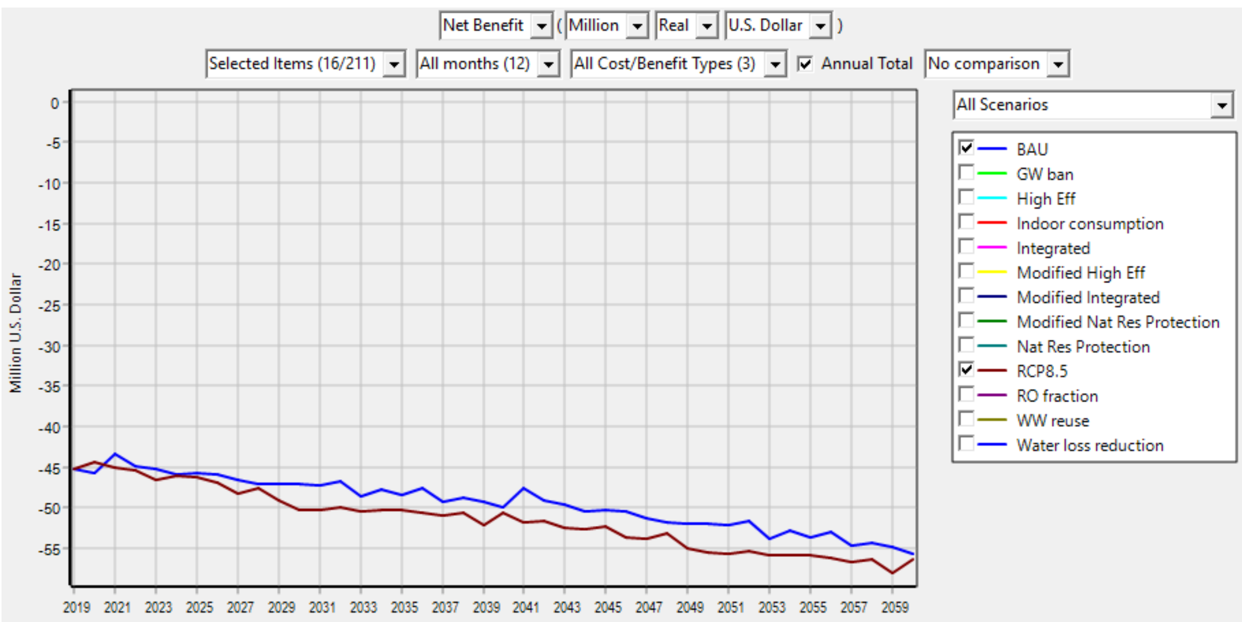


Figure 5.3. The net benefit in the water sector under BAU (blue line) and RCP 8.5 (brown line)

While Figure 5.3 shows the net benefit in the water sector for both the RCP8.5 and BAU scenarios, table 5.4 tabulates the differences with regards to not only the cost differences but also energy and water differences.

Water Difference/Million Cubic Meters/year by 2060	Energy Difference/ Thousand Gigajoule/year by 2060	Net water benefits difference/ Million Dollars/year by 2060
220	**10**	**10.46**

Table 5.4. Water, energy and cost differences between RCP8.5 and BAU scenarios.

Figure 5.3 shows the net benefit difference between the BAU and RCP 8.5 scenarios. It can be seen that there is an additional cost of 10.46 million dollars per year in the water sector alone by 2060 because of climate change. Moreover, as seen in Table 5.4, an additional 220 million cubic meters of water and an additional 10 thousand gigajoule of electricity are required under the RCP 8.5 scenario with comparison to the BAU scenario. These differences are no as large as one would expect because they are a direct reflection of the assumptions that were made prior to modeling these scenarios. As a result of 2 ° Celsius, temperature rise in RCP 8.5, the model assumes a 15% total increase in cooling days that was applied to the service and residential sector demands. The increase in electricity demand was assumed to be only 0.5% from 2019 to 2060. The increase in indoor water consumption was assumed to be zero from 2019 to 2060. These assumptions underestimate the impact of RCP 8.5 on the water-energy nexus, hence there is a smaller observed difference compared to what makes intuitive sense. Furthermore, multiple studies conducted in the UAE have found a larger impact of population growth on water demand compared to climate change. This is an important finding in context of countries like the UAE where the population is largely based on short-term residents and temporary migrants (Vörösmarty, Green, Salisbury, & Lammers, 2000).

5.2.3. Individual Policy Scenario Analysis

5.2.3.1. Electricity Consumption under Modified Policy Scenarios

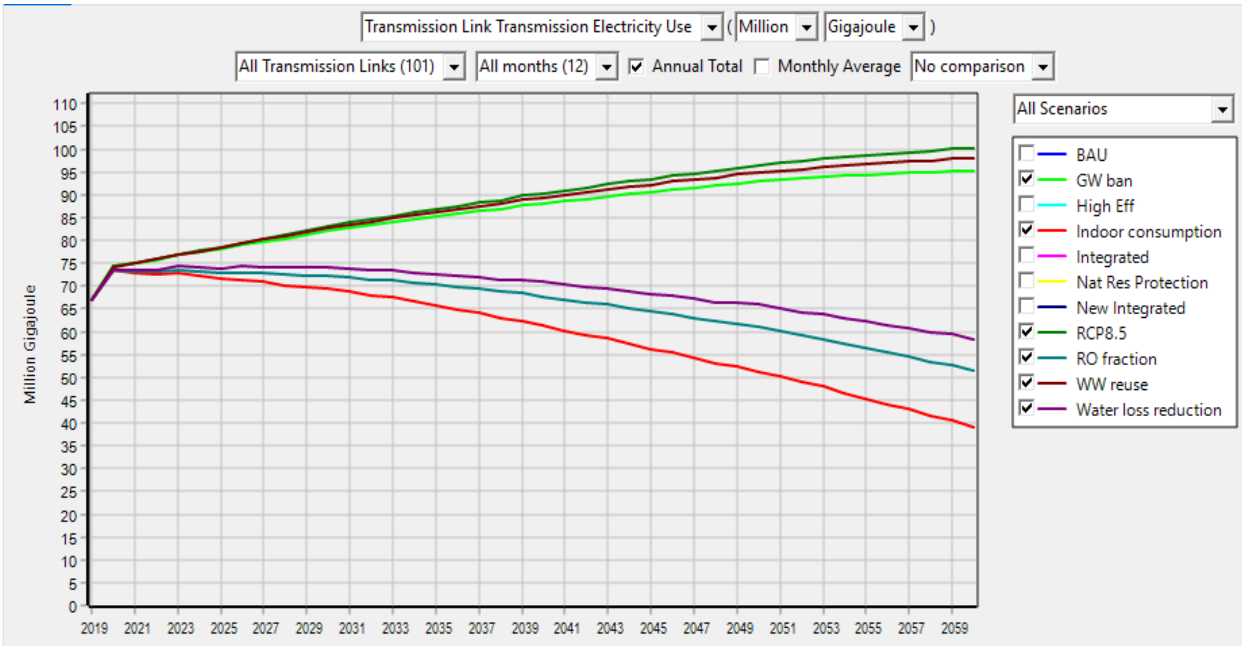


Figure 5.4.UAE Electricity use for individual policy scenarios (Indoor consumption as red line, RO fraction as teal line, water loss reduction as purple line, GW ban as light green line, wastewater reuse as brown line and RCP8.5 as dark green line)

The graph in Figure 5.4 shows the effect of individual policy scenarios on the electricity consumption variable for all of the UAE. It can be seen that the indoor consumption scenario has the most savings on electricity consumption in the UAE. This is because indoor consumption (red line) reduction from 550 liter per capita per day to 100 liter per capita per day reduces demand so significantly that less desalination is required to provide this water, hence driving the electricity consumption down. The second most effective policy is the RO fraction policy (teal line) because different desalination technologies are not equally energy intensive. Multi-stage flash (MSF) requires 16kWh to produce each cubic meter of water while Multiple-effect Distillation (MED) requires 14kWh/m^3 and Reverse Osmosis (RO) requires only 6.5kWh/m^3. Hence the transition from a 60% MSF to 0%, 20% MED to 0% and 20% RO to 100% by 2060 causes a sharp decline in the net energy consumption by the UAE. The wastewater reuse policy (brown line) is the least beneficial in terms of energy savings because although 50% outdoor water is being treated and reused but wastewater treatment itself is an energy intensive process requiring 0.8kWh/m^3 of water.

5.2.3.2. Water Consumption under Modified Policy Scenarios

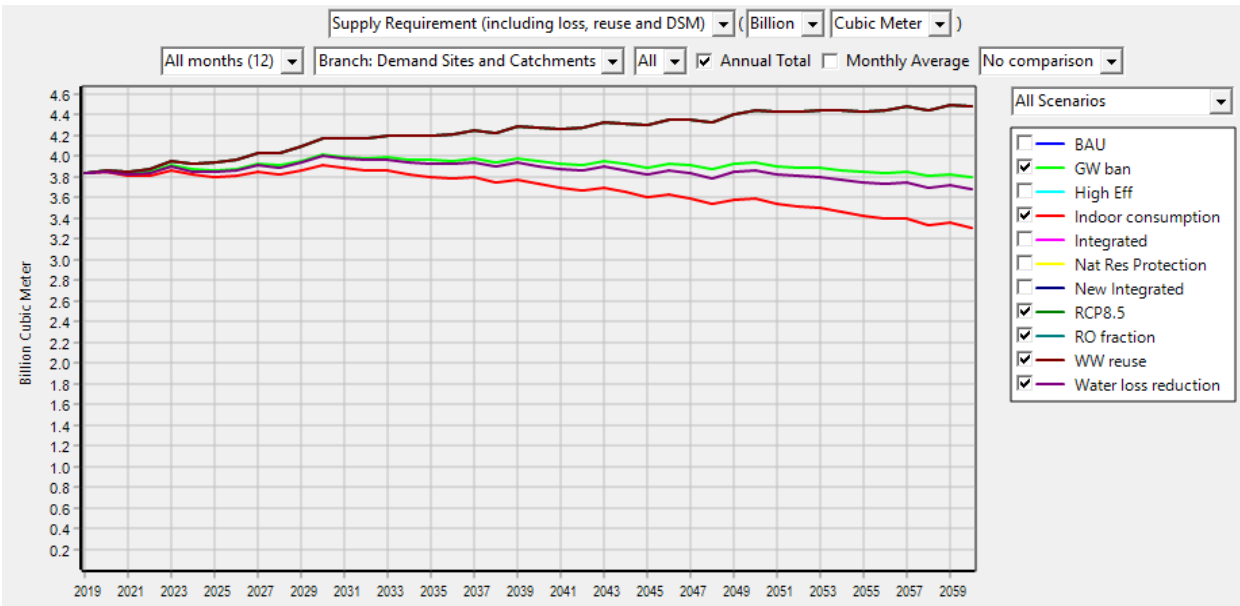


Figure 5.5. UAE Water supply requirement for individual policy scenarios.

This graph shows the impact of individual policy scenarios on the water supply delivered in the UAE. The most water saving policy was again the indoor consumption reduction policy because the demand for water goes down by 400 liters per capita per day. The water loss reduction policy that saves 30% leakage and loss from the water transmission networks is the second most effective policy. The groundwater ban policy causes a 50% reduction in irrigation land, and hence it is the third most water saving policy. There are no changes in the water supply required under the wastewater reuse and RO fraction policies because of how the policies are designed.

5.2.3.3. Net Economic Benefits for the Water Network

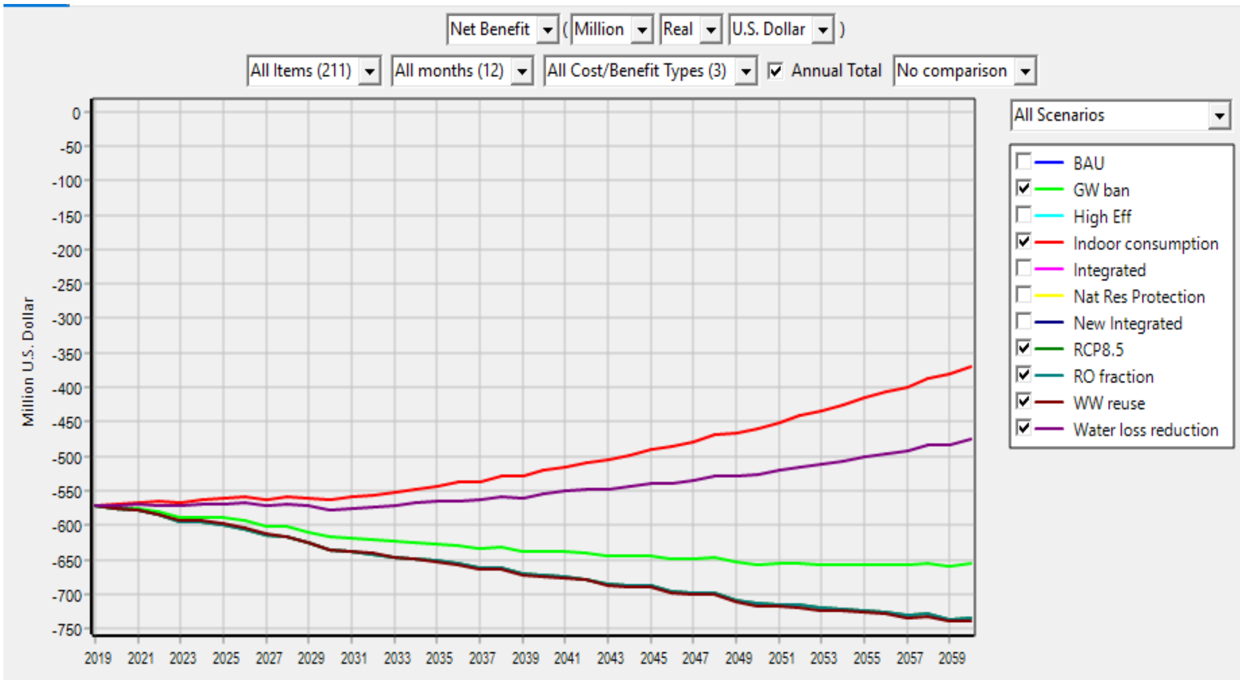


Figure 5.6. UAE Net benefits in the water sector for individual policy scenarios.

This graph shows the change in net benefits of the water sector under modified individual policy scenarios. These net benefits of modified water policies embody a partial nexus because they factor in groundwater pumping costs as well as wastewater treatment costs, etc. that are energy intensive processes. The most economically beneficial policy is the indoor consumption policy, saving around 80 million USD per year by 2060. This is because as less water supply is required to provide for a lower demand, the cost saving for desalinating each cubic meter of water is $1 USD.

The values for savings in electricity consumption, water consumption and net benefits in the water sector are tabulated in the Appendix. The following table compares the observed results with the hypothesized results.

Policy name	Policy description	Policy Categorization (AGEDI)	Hypothesized effect(in terms of savings)	Observed effect(in terms of savings)
GW Ban	A ban on groundwater pumping and a 50% reduction in irrigation	Natural resource Protection	Energy: +	Energy: +
			Water: +	Water: +
			Net Benefit: +	Net Benefit: +
RO Fraction	The default mix of Reverse Osmosis technology breakdown that the model assumes for MSF, MED and RO is 60%, 20% and 20%, respectively. This policy calls for a growth of RO fraction from 20% in 2020 to 100% in 2060.	Natural resource Protection	Energy: +	Energy: +
			Water: =	Water: =
			Net Benefit: +	Net Benefit: +
Wastewater reuse	Wastewater reuse fraction changed from a default of 50% in 2019 to a uniform growth to 100% in 2060.	Natural Resource Protection	Energy: +	Energy: +
			Water: =	Water: =
			Net Benefit: +	Net Benefit: -

Water Loss reduction	30 % reduction in water losses in transmission links over the course of 2020-2060.	High Efficiency and Conservation	Energy: +	Energy: +
			Water: +	Water: +
			Net Benefit: +	Net Benefit: +
Indoor Consumption	550lpd per capita indoor consumption in 2020 changed to 100 lpd per capita in 2060.	High Efficiency and Conservation	Energy: +	Energy: +
			Water: +	Water: +
			Net Benefit: +	Net Benefit: +

Table 5.5. Hypothesized vs Observed results for individual policy scenarios

Table 5.5 makes a comparison between the hypothesized results and the observed results in terms of savings for the three variables across all policy scenarios. The observed results met the hypothesized results for all scenarios except the wastewater treatment scenario net benefit variable. Despite water and energy savings for the wastewater treatment scenario, there is a net cost on the water sector. This can be explained by the cost of wastewater treatment and reuse. These costs can be seen in the cost levelization framework in the appendix.

5.2.4. Aggregate Policy Scenario Analysis

This subsection includes the analysis of the modified aggregate scenarios for the three variables: electricity use, water supply delivered and net benefits for the water sector. These scenarios include modified water policies under the High Efficiency (HE) and Natural resource protection (NRP) scenarios.

5.2.4.1. Electricity Consumption under Modified Aggregate Scenarios

The electricity use variable for different aggregate scenarios is as follows:

5.2.4.1.1. NRP vs. Modified NRP Scenario

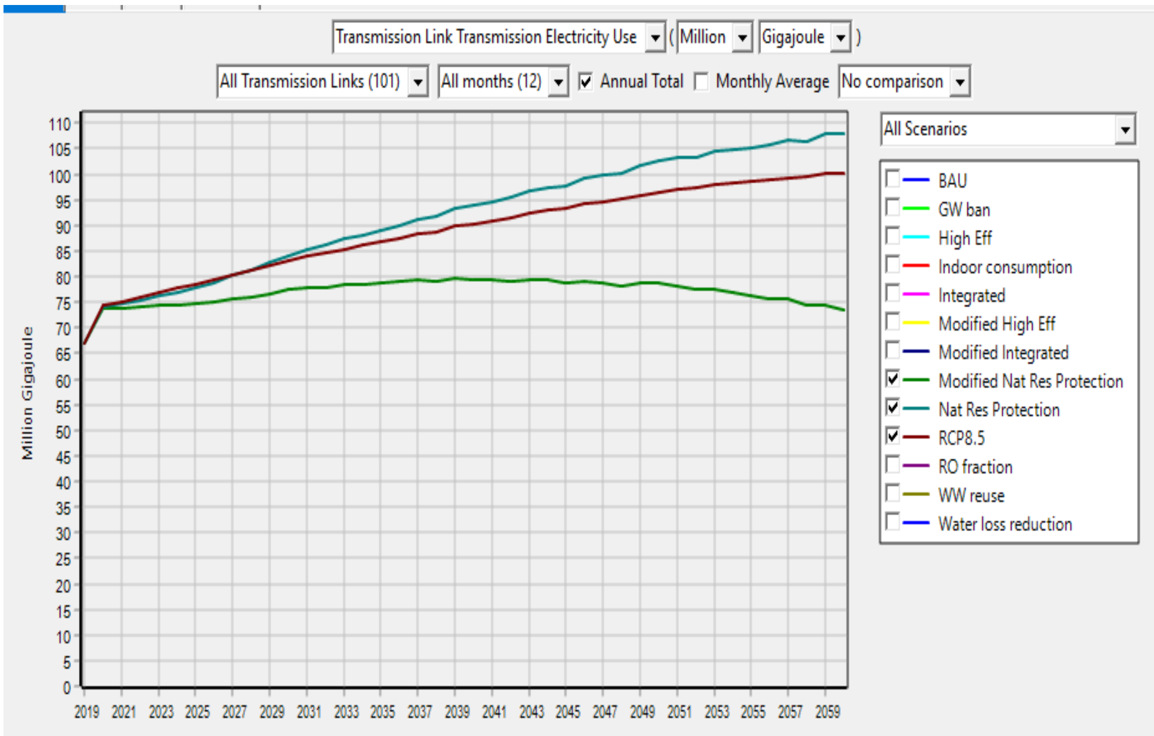


Figure 5.7. Electricity use for Natural Resource Protection vs Modified Natural Resource Protection scenario in the UAE

As illustrated in Figure 5.7, the Modified Natural Resource protection scenario (dark green line) enables more energy savings compared to the non-modified scenario(teal line). A major source of this difference is the groundwater ban scenario. In the non-modified AGEDI version, there was a substitution of groundwater with desalinated water to provide for agricultural water supply, which increases the energy consumption more than the RCP 8.5(brown line). However, in the modified NRP scenario, groundwater is not substituted with desalinated water, instead there is a 50% reduction in irrigation land, which leads to a decrease in the energy consumption for groundwater and desalination to provide for agriculture.

5.2.4.1.2. HE vs. Modified HE Scenario

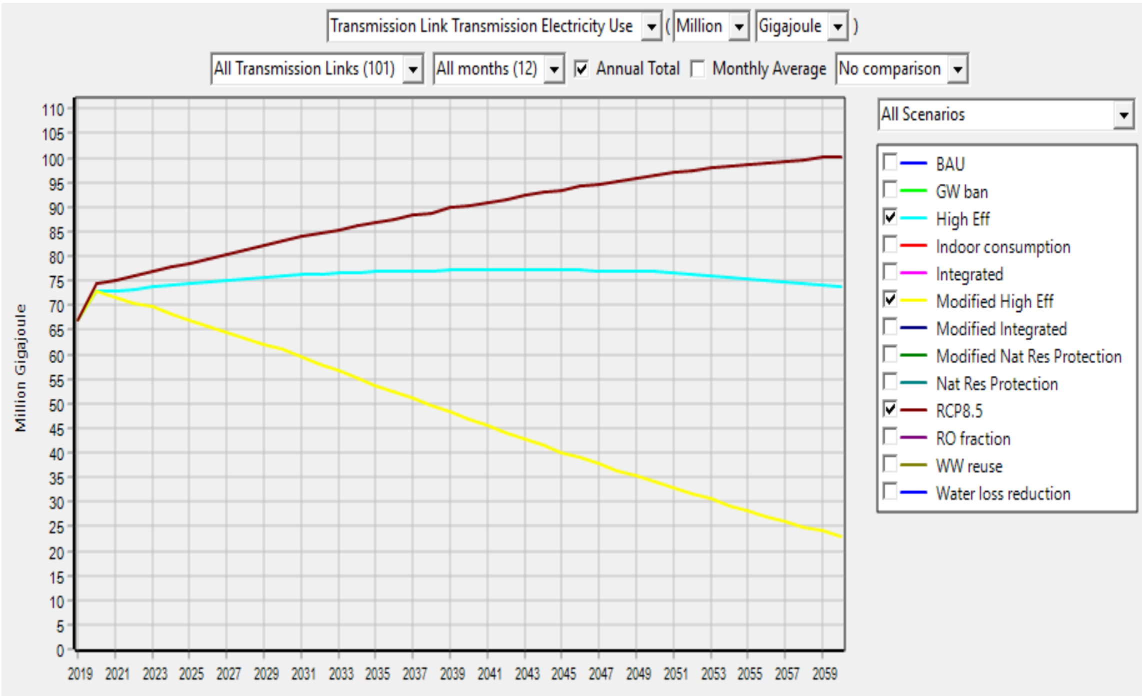


Figure 5.8. Electricity use for High Efficiency vs Modified High Efficiency scenario in the UAE

Figure 5.8 shows the comparison of the modified high efficiency and the non-modified high efficiency scenario. It can be seen that the modified scenario (yellow line) does significantly better than the non-modified scenario (light blue line) which in turn is doing better than RCP8.5 (brown line). The individual policy predominantly driving the energy consumption down is the indoor consumption policy that has been modified in the modified High Efficiency scenario. Driving down the indoor consumption from 550 lpcd to 100lpcd causes significant energy savings.

5.2.4.1.3. Integrated vs. Modified Integrated Scenario

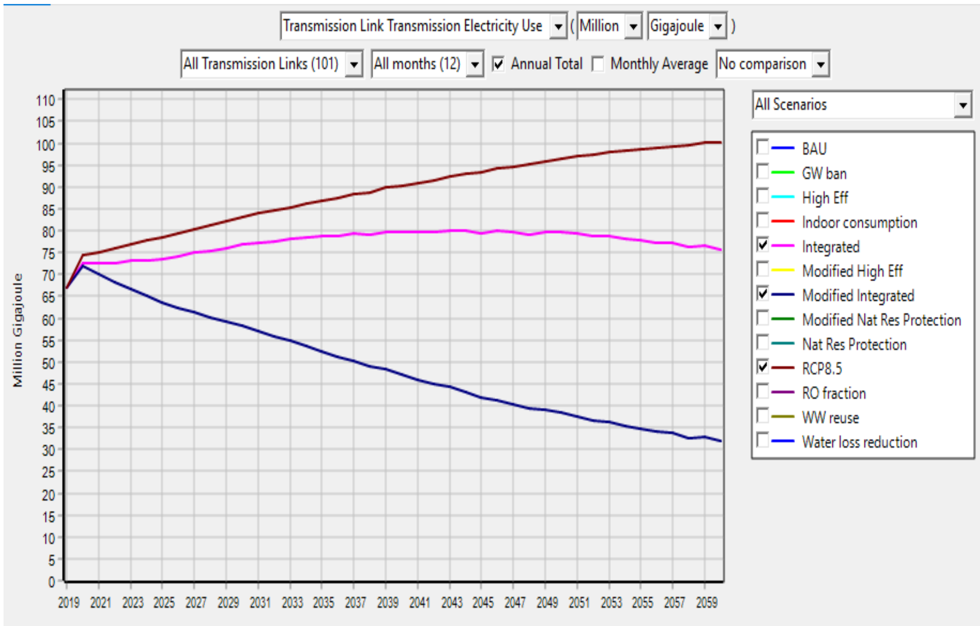


Figure 5.9. Electricity use for Integrated vs Modified Integrated scenario in the UAE

As illustrated in Figure 5.9, the modified integrated scenario (dark blue line) does significantly better than the non-modified Integrated scenario (pink line) because of the modified water policies. These are combination effects of both HE and NRP aggregate scenarios.

5.2.4.2. Water Consumption under Modified Aggregate Scenarios

5.2.4.2.1. NRP vs. Modified NRP Scenario

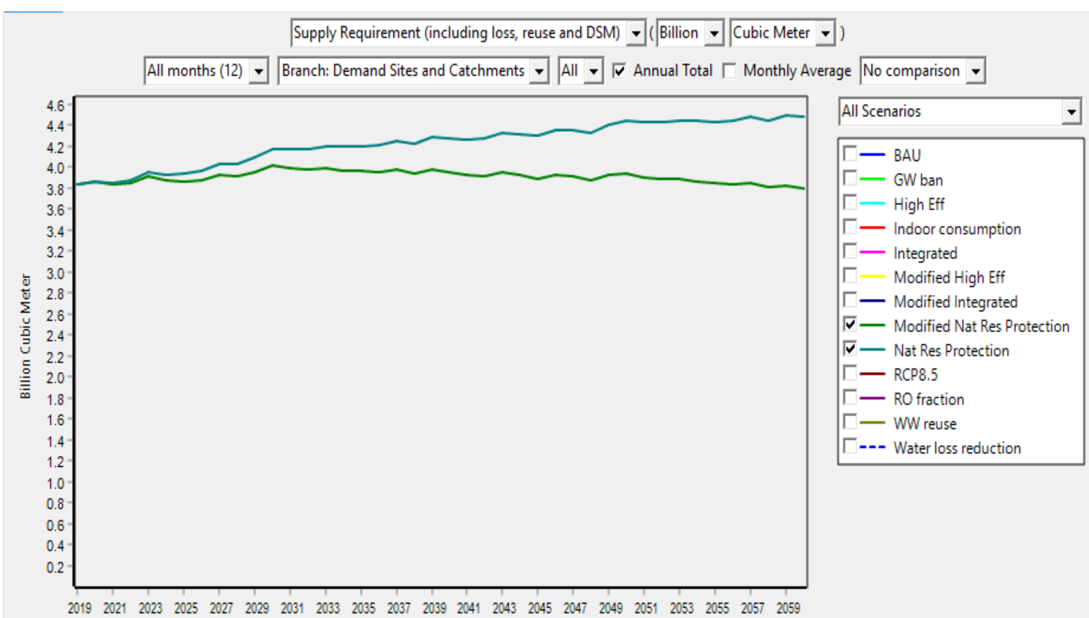


Figure 5.10. Water supply delivered for Natural resource Protection vs Modified Natural resource Protection scenarios in the UAE

As illustrated in Figure 5.10, in case of the water supply delivered variable, there is moderate water saving because of the modified NRP scenario (dark green line). The NRP scenario itself(teal line) is no different from the RCP8.5 line because it was assumed by AGEDI that when groundwater phase-out is enforced, there is a substitution of groundwater with desalinated water to keep the supply constant, hence the supply required remains the same. However, in case of the modified policy, there is a 50% reduction in irrigated land, thus driving down the water supply required.

5.2.4.2.2. HE vs. Modified HE Scenario

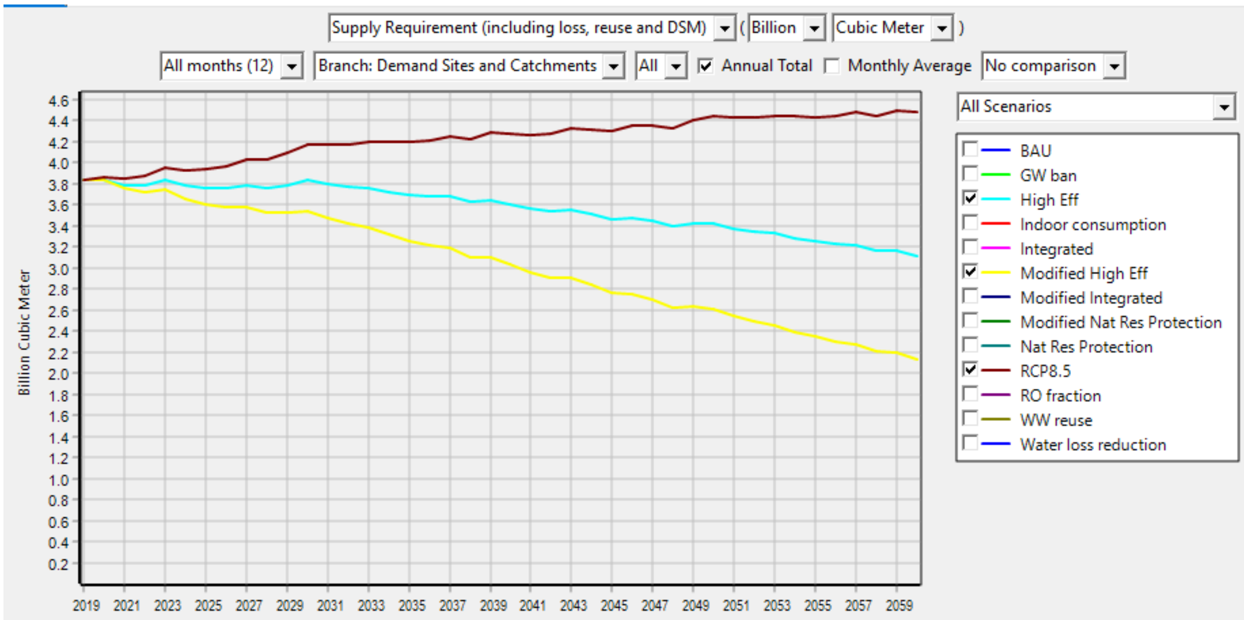


Figure 5.11. Water supply delivered for High Efficiency vs Modified High Efficiency scenario in the UAE

As illustrated in Figure 5.11, the modified HE scenario (yellow line) causes significant water savings because of the reduction in indoor water consumption as compared to the non-modified HE scenario (light blue line). Both of the scenarios show water savings compared to the RCP 8.5 scenario (brown line)

5.2.4.2.3. Integrated vs. Modified Integrated Scenario

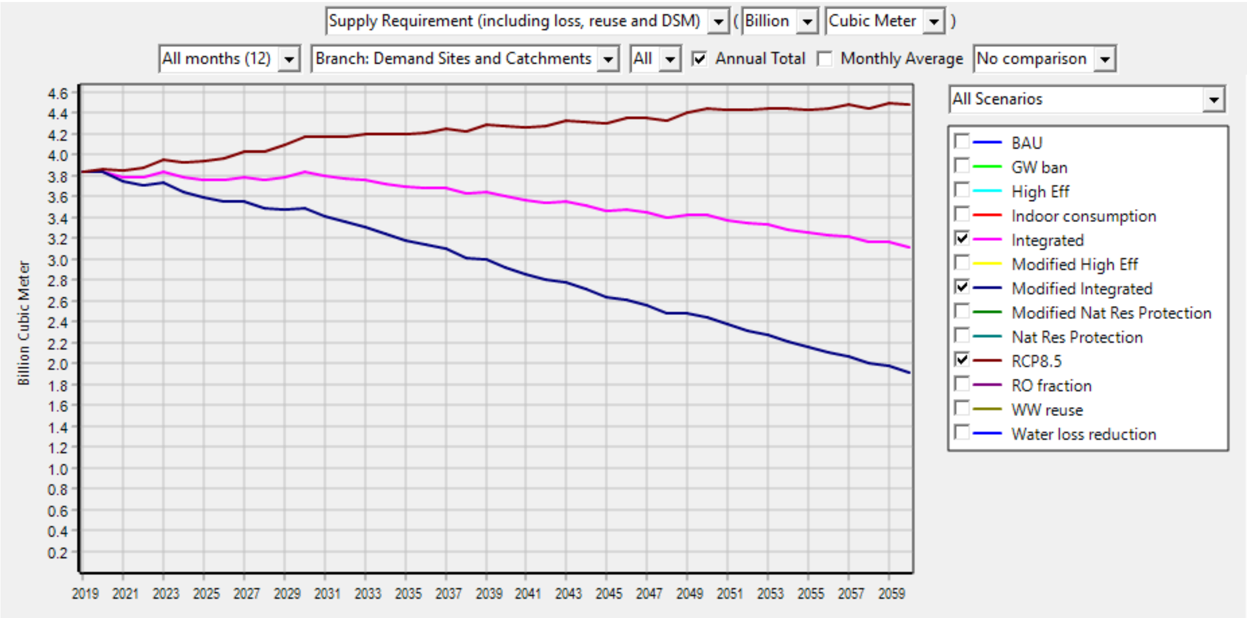


Figure 5.12. Water supply delivered for Integrated vs Modified Integrated scenario in the UAE

Figure 5.12 depicts moderate water saving due to the modified Integrated scenario (dark blue line) as compared to the non-modified integrated scenario(pink line). These are cumulative effects of the HE and NRP scenarios on the water sector because of the modified water policies that this study designed.

5.3. Sub-Regional Analysis of the Modified Scenarios

The sub-regional analysis zooms into different areas of the UAE and enable the understanding of nature of the water-energy nexus as driven by region-specific factors. This study divided the UAE into six sub-regions: Abu Dhabi, Al Ain, Western region, Dubai, Eastern region and Fujairah. Abu Dhabi emirate constitutes of the Abu Dhabi region, Al Ain region and Eastern region. It is important to note that the sub-regional division is not on emirate level. This section would run individual and aggregate scenarios for all these sub-regions and quantifies the gains and losses for each scenario with respect to the sub-regions.

5.3.1. Individual Policy Scenario Analysis

This part test the individual policies for the sub-regions for the three variables: electricity use, water supply delivered and net benefits in the water sector.

5.3.1.1. Abu Dhabi Sub-Region Water-Energy Nexus

5.3.1.1.1. Electricity Consumption under Modified Policy Scenarios

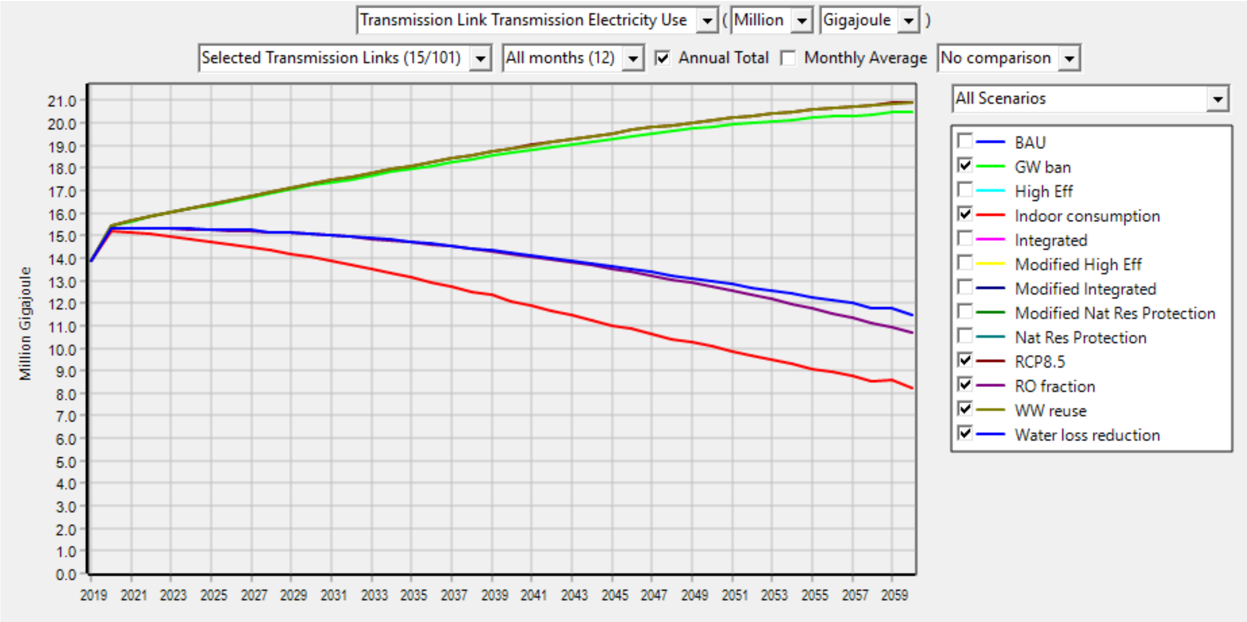


Figure 5.13. Electricity use in Abu Dhabi for individual policy scenarios

As illustrated in Figure 5.13, the policy scenario that leads to the most energy saving in Abu Dhabi is indoor consumption (red line). This is a reflection of the fact that Abu Dhabi is the third largest sub-regional consumer in terms of indoor water consumption within the UAE as shown in figure 4.9 in Chapter 4. Hence, the indoor consumption policy is very impactful in Abu Dhabi because of its large fraction of indoor water consumption. The second most electricity saving policy for this region is the RO fraction policy (purple) because of the transition from MSF to RO which is less energy intensive. The third most effective policy is the water loss reduction policy that saves 30% of water losses in transmission networks. The groundwater ban policy is the least energy saving policy in Abu Dhabi. This can be explained by the fact that Abu Dhabi does not have a large agricultural setup hence the observed effect seen by this policy is small.

5.3.1.1.2. Water Consumption under Modified Policy Scenarios

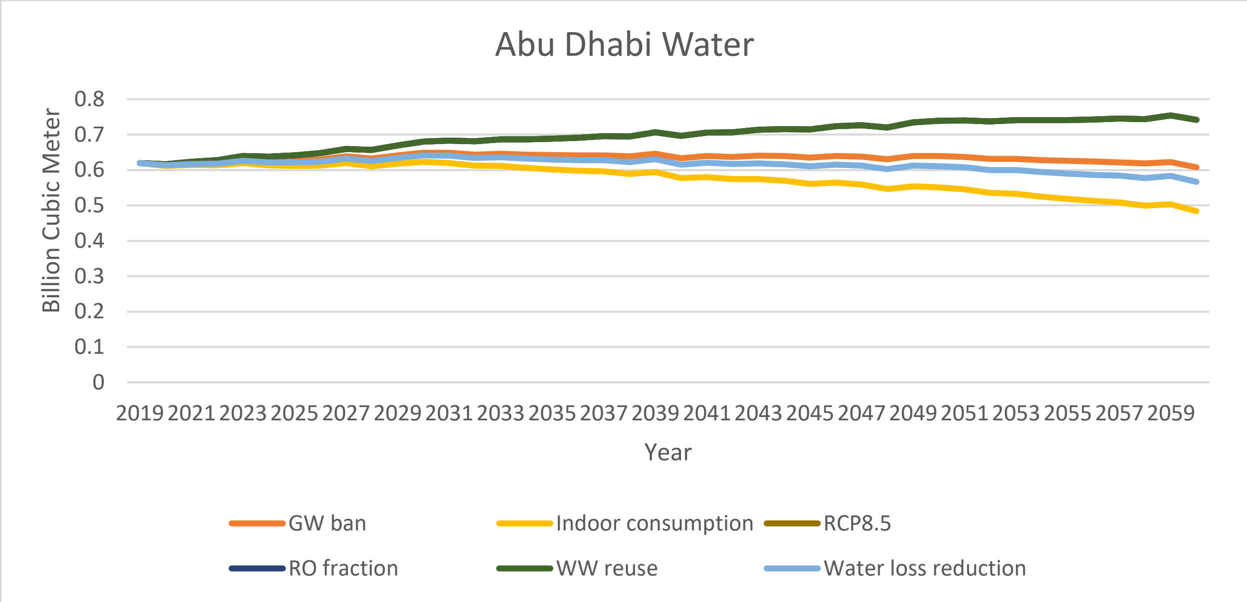


Figure 5.14. Water supply delivered in Abu Dhabi across individual policy scenarios

As illustrated in Figure 5.14, the indoor consumption policy is the most effective in Abu Dhabi in terms of saving water. The water loss reduction policy ranks second while the groundwater ban ranks third. The wastewater reuse policy and the RO fraction policies rank last. Again, this is because of the urban nature of Abu Dhabi where indoor consumption policy makes a huge impact while agricultural policies make low impact.

5.3.1.2. Al Ain Sub-Region Water-Energy Nexus

5.3.1.2.1. Electricity Consumption under Modified Policy Scenarios

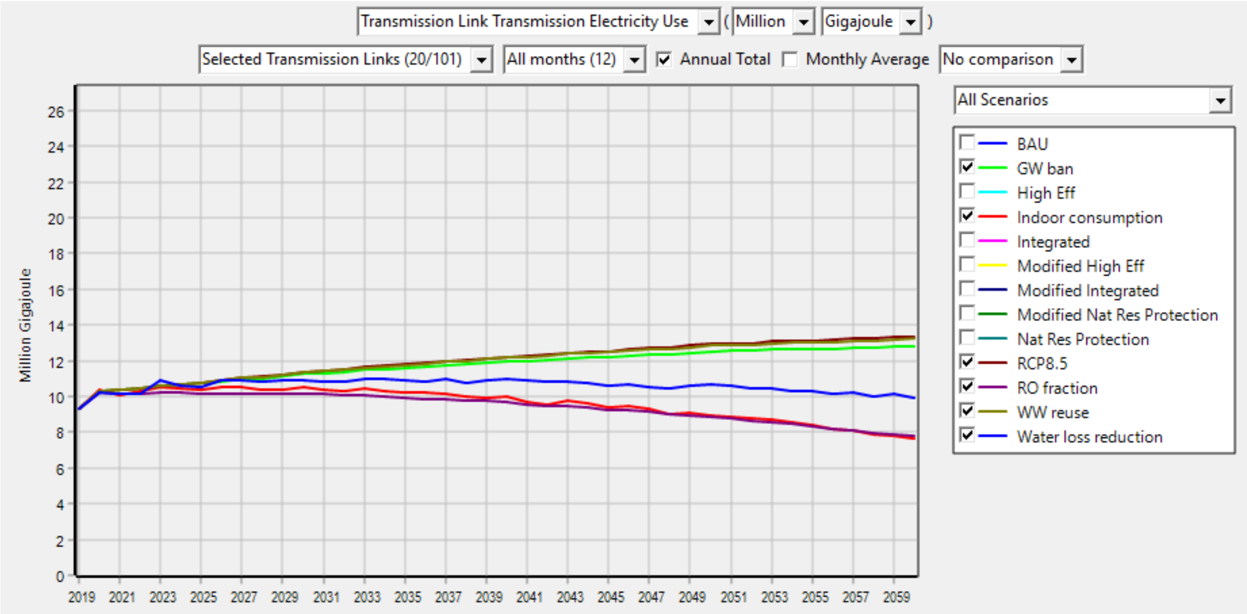


Figure 5.15. Electricity use in Al Ain for individual policy scenarios

Figure 5.15 shows that the impact of indoor consumption policy (red) and the RO fraction policy (purple) on Al-Ain are the highest and almost the same with indoor consumption ranking the first by 2060. These are moderate effects as compared to the Abu Dhabi region because of the difference in scale as Abu Dhabi is a much larger region by population. The water loss reduction policy (dark blue) also causes some energy savings, however the groundwater ban policy (light green) causes very little energy savings. This is a peculiar result because Al Ain has been a predominantly agricultural region and takes the most agricultural water supply amongst all sub-regions (Abu Dhabi Global Environmental Data Initiative, 2015). However, this may be because water supply to Al Ain city's date palm orchards comes from the Fujairah desalination plant.

5.3.1.2.2. *Water Consumption under Modified Policy Scenarios*

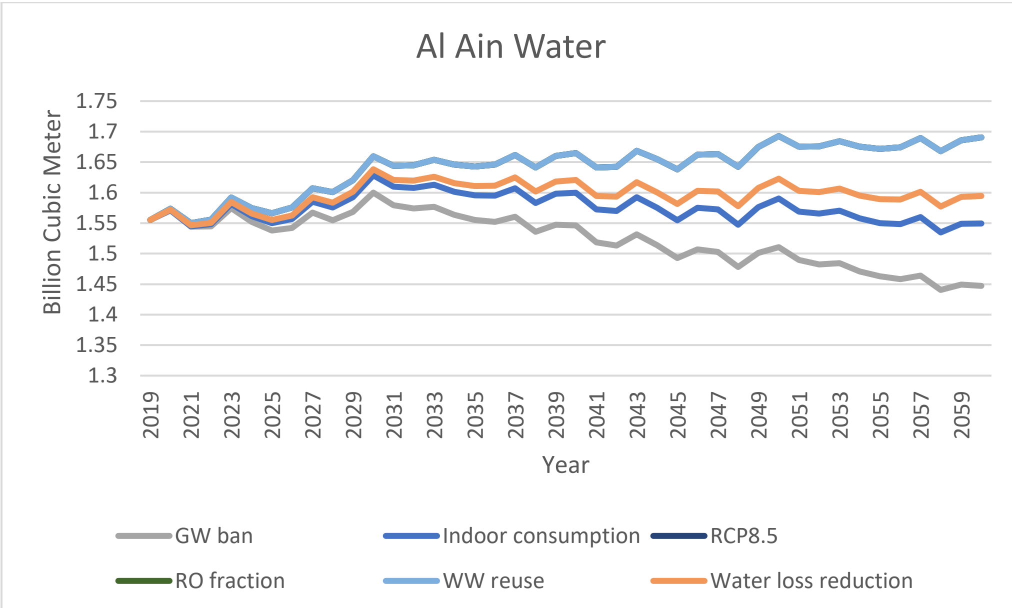


Figure 5.16. Water supply delivered in Al Ain across individual policy scenarios

As illustrated in Figure 5.16, the groundwater ban policy saves the most water in the region. This makes sense because Al Ain requires the largest water supply for its agricultural sector compared to other sub-regions a shown in Figure 4.7 in Chapter 4. The Indoor consumption policy ranks the second in water saving while water loss reduction and wastewater reuse rank third and fourth respectively. This graph shows fluctuations because the range of water supply is very small compared to other regions, hence magnifying the fluctuations. Also, Al Ain has the most significant variability and amount of rainfall in the hills above it. Therefore, the model is taking the variability of rainfall into account.

5.3.1.3. Western Sub-Region Water-Energy Nexus

5.3.1.3.1. Electricity Consumption under Modified Policy Scenarios

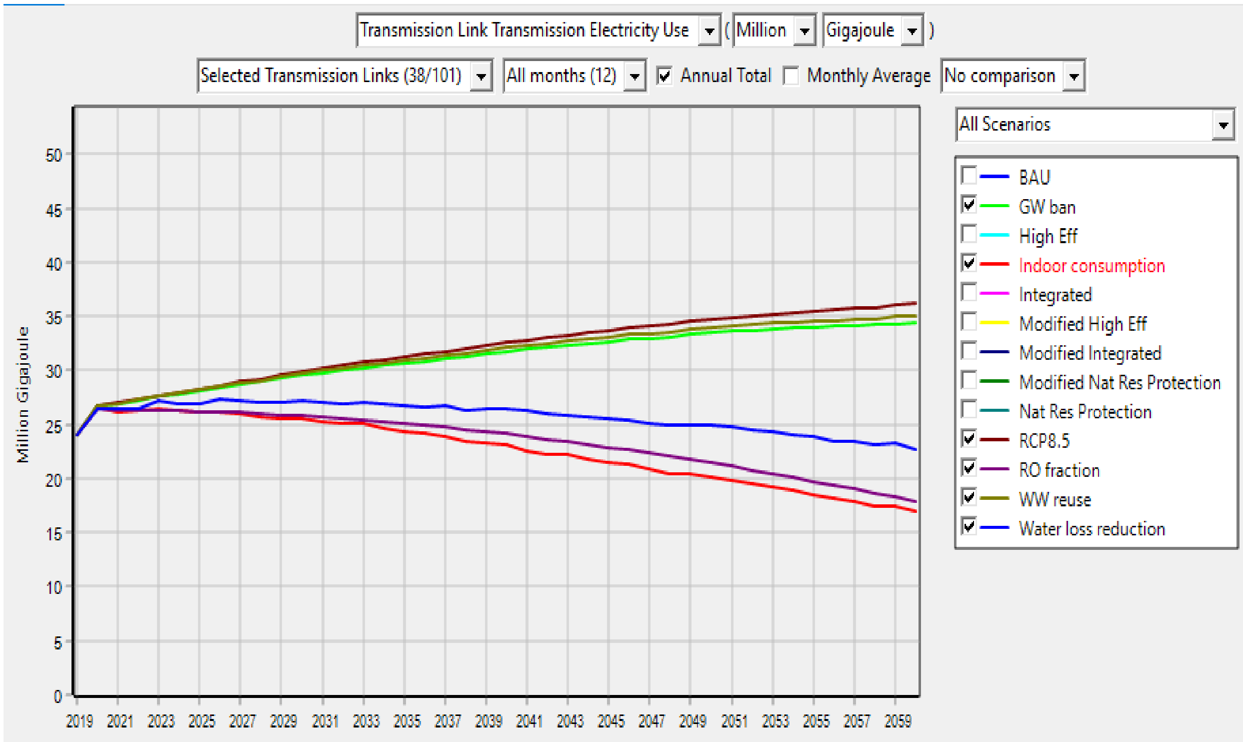


Figure 5.17. Electricity use in Western region for individual policy scenarios

As illustrated in Figure 5.17, the indoor consumption policy(red) saves the most energy in the Western region while RO fraction (purple) rank second and water loss reduction(dark blue) rank third. Groundwater ban (light green) makes very little impact while wastewater reuse makes even less. This graph reflects that the residential sector water demand is bigger than the amenity, agriculture and outdoor demands in the region. Moreover, the RO policy scenario is so impactful because the western region is closer to the RO desalination plants on the nodal network.

5.3.1.3.2. Water Consumption under Modified Policy Scenarios

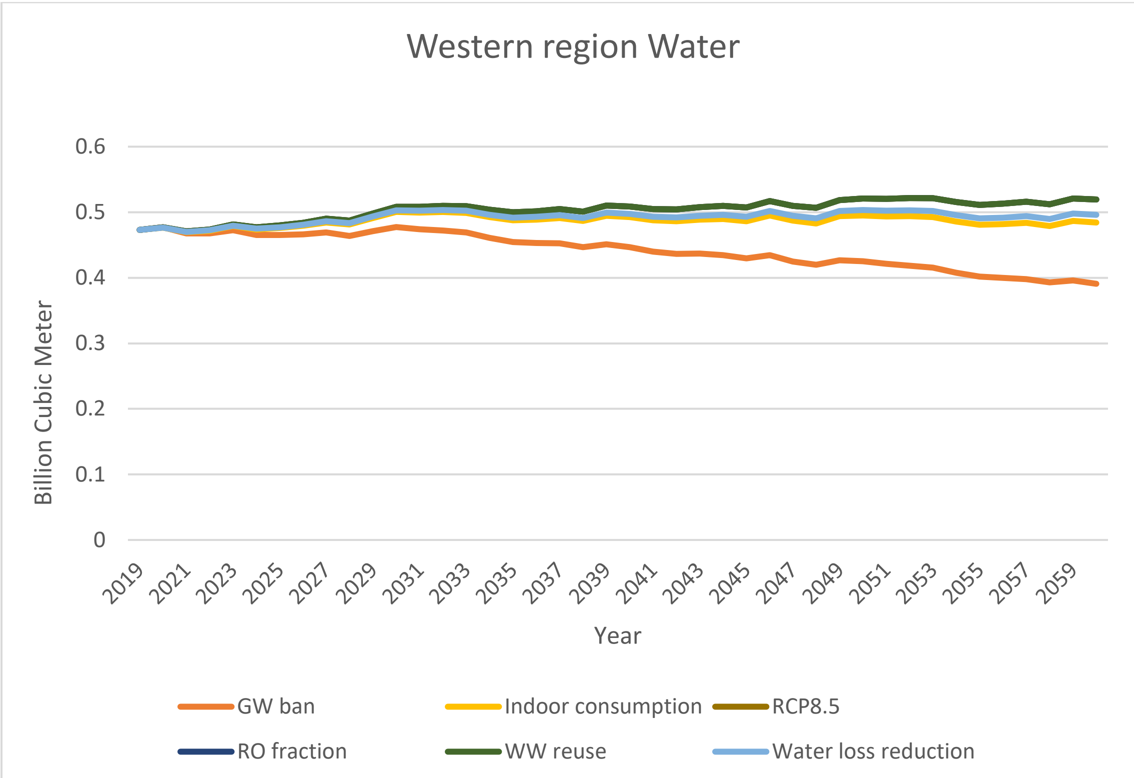


Figure 5.18. Water supply delivered in Western region across individual policy scenarios

As illustrated in Figure 5.18, the groundwater ban policy saves the most water in the Western region. This makes intuitive sense because the western region is largely agricultural hence this policy makes the most impact. The mix of urban and agricultural sectors leads to significant energy savings through indoor consumption reduction and significant water saving through groundwater phase-out. It is interesting to see that other policies have very little effect on the water supply in the Western region and are very close to each other in terms of impact on the water sector.

5.3.1.4. Dubai Sub-Region Water-Energy Nexus

5.3.1.4.1. Electricity Consumption under Modified Policy Scenarios

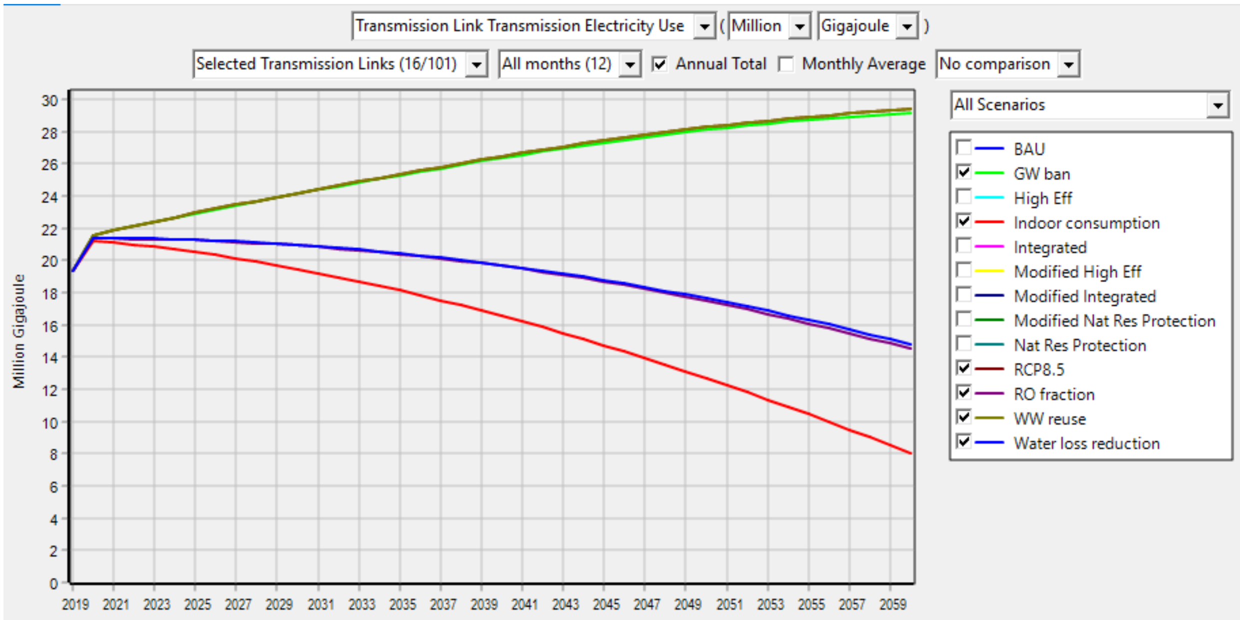


Figure 5.19. Electricity use in Dubai for individual policy scenarios

As illustrated in Figure 5.19, Dubai is affected the most by the indoor consumption policy. This is because of its largest share in indoor consumption water supply within the UAE as shown in Figure 4.9 in Chapter 4. The RO fraction policy ranks second while the water loss reduction ranks third in terms of saving Electricity. The Groundwater ban policy does not affect Dubai as much. This could be because of small agricultural sector. However, it is surprising that the wastewater reuse policy is not as effective given that Dubai has one of the largest outdoor sector water supply required according to Figure 4.10 in Chapter 4.

5.3.1.4.2. Water Consumption under Modified Policy Scenarios

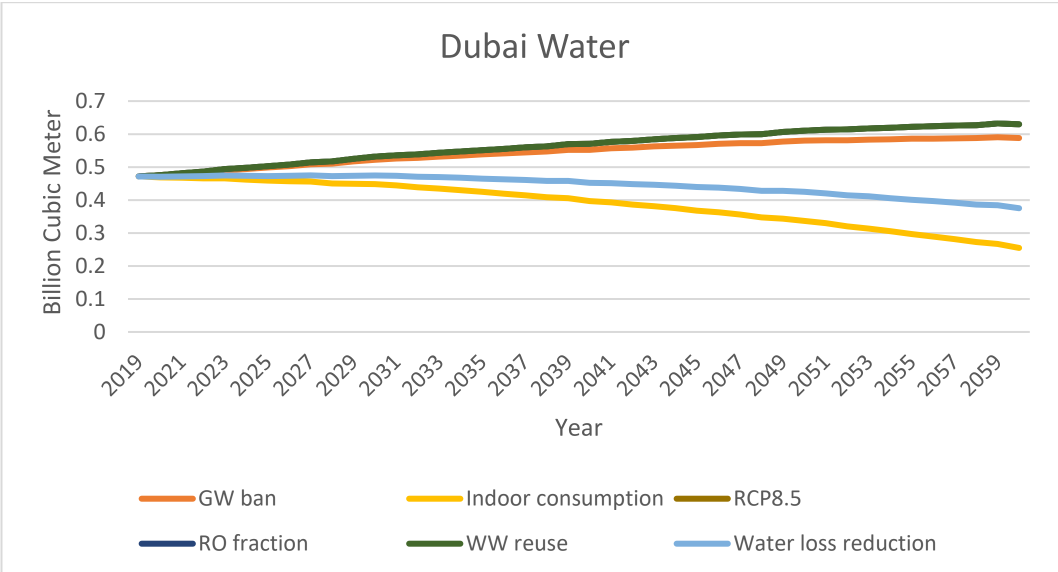


Figure 5.20. Water supply delivered in Dubai across individual policy scenarios

As illustrated in Figure 5.20, Dubai saves the most water under the indoor consumption policy because of its largest population density in the UAE and biggest indoor sector water supply fraction in the UAE. Water loss reduction is the second best policy in terms of water savings. This could be explained by the fact that the total water supply for the Dubai region is bigger than any other region in the UAE, hence water losses in the transmission system make a significant fraction of the total water supply. The groundwater ban, RO fraction and wastewater reuse policies do not make that much of a difference for Dubai.

5.3.1.5. Eastern Sub-Region Water-Energy Nexus

5.3.1.5.1. Electricity Consumption under Modified Policy Scenarios

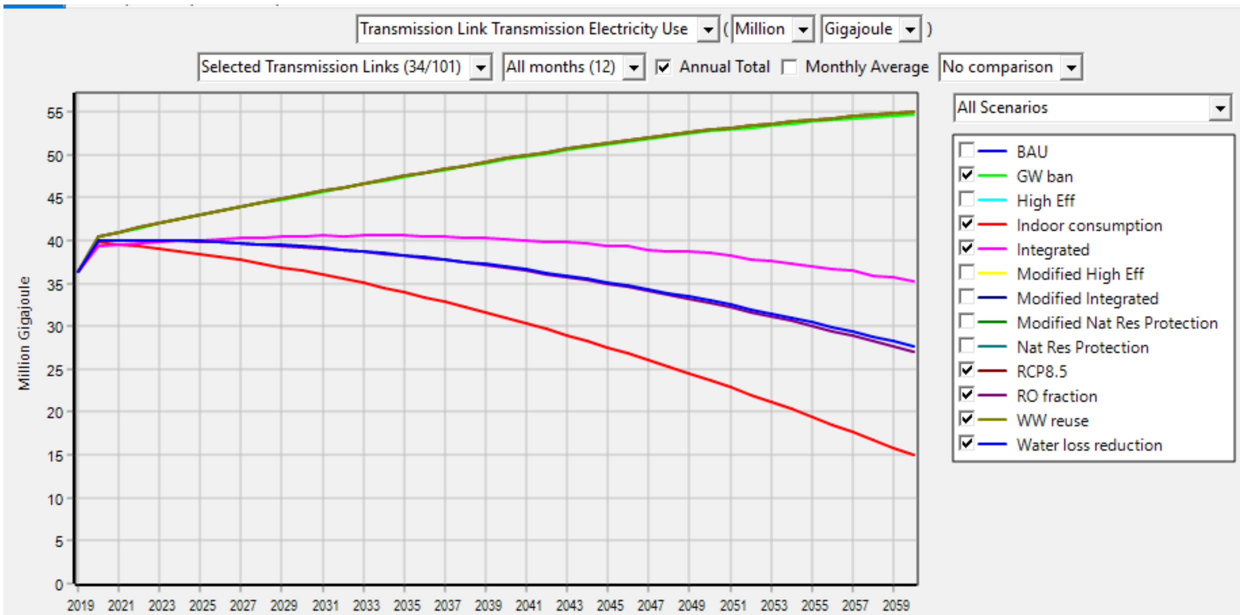


Figure 5.21. Electricity use in Eastern region for individual policy scenarios

Figure 5.21 shows the electricity use for the Western region for each policy scenario. It can be seen that as for most of the regions, the indoor consumption policy (red line) saves significant energy. The RO fraction (purple line) and water loss reduction (dark blue line) are then significant policies in terms of electricity savings. The groundwater ban policy produces no energy savings in the region, this is peculiar because the western region is largely an agricultural region like Al Ain. This could be because the model takes an input of supply preference and aims at meeting demand so even though desalinated water supply is marked as the last preference, it appears in this graph that some demand is being fulfilled through desalinated water.

5.3.1.5.2. Water Consumption under Modified Policy Scenarios

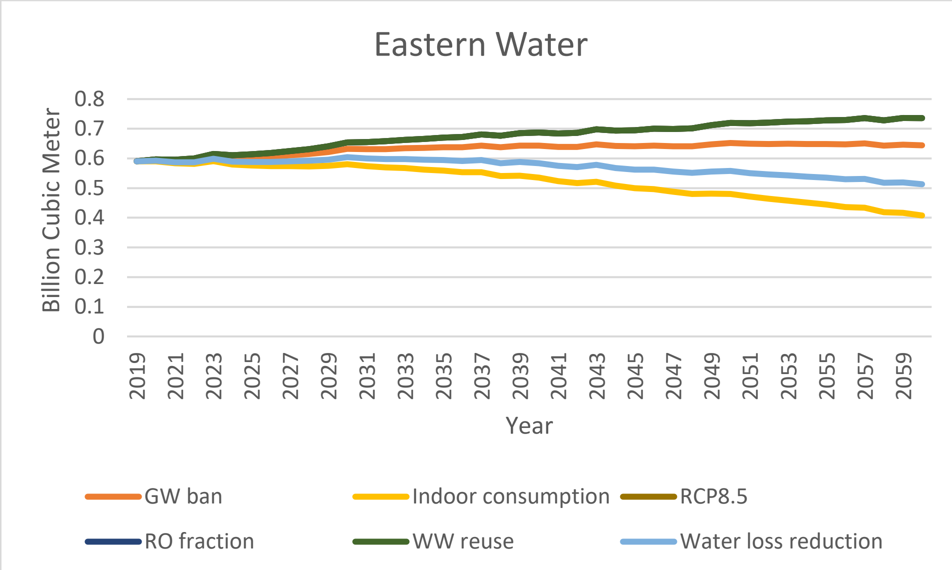


Figure 5.22. Water supply delivered in Eastern region across individual policy scenarios

As shown in Figure 5.22, the water supply delivered for the Eastern region is most impacted by the indoor consumption policy and then the water loss reduction policy. Again, it is curious to see the Groundwater ban policy not affecting this region as much despite its agricultural landscape. Again, this could be because the model takes an input of supply preference and aims at meeting demand so even though desalinated water supply is marked as the last preference, it appears in this graph that some demand is being fulfilled through desalinated water. The wastewater reuse and RO fraction policies make the least impact on this region.

5.3.1.6. Fujairah Sub-region Water-Energy Nexus

5.3.1.6.1. Electricity Consumption under Modified Policy Scenarios

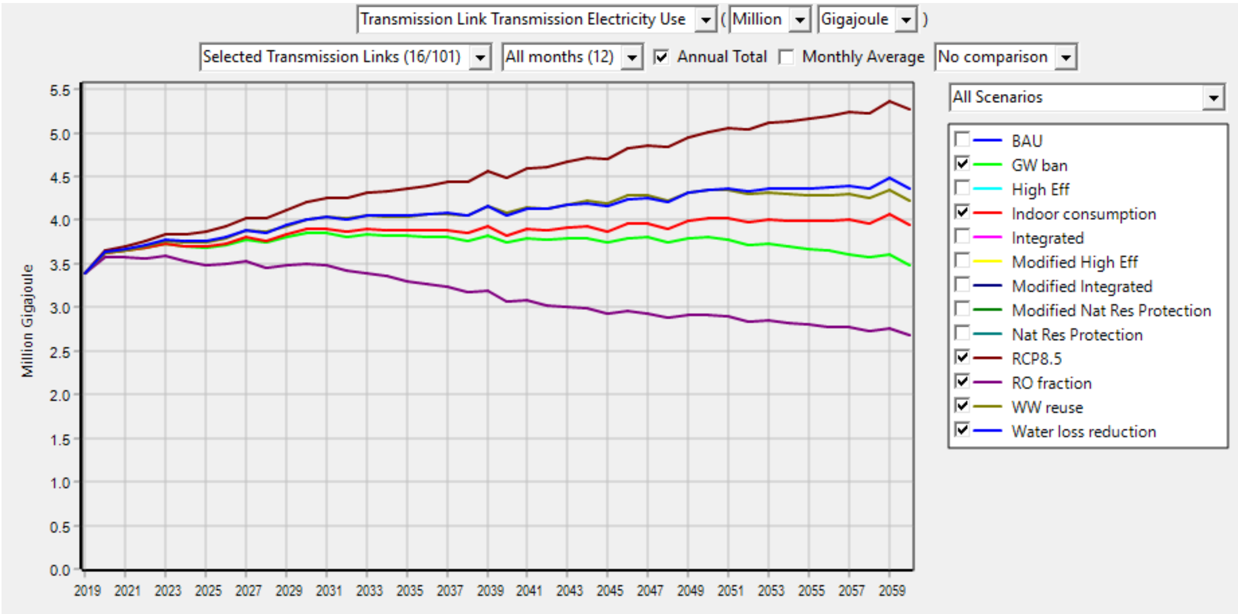


Figure 5.23. Electricity use in Fujairah for individual policy scenarios

Figure 5.23 shows the electricity use in Million gigajoules for the Fujairah region. This is the only region where RO fraction (purple line) makes such a huge impact. A possible explanation for this is that the model accounts for the three desalination plants in Fujairah. This includes a Reverse osmosis plant, a MSF plant and a MED plant. Hence, the RO transition shows the most energy benefits for this region. Apart from Fujairah, Eastern region and western region have RO plants. The groundwater ban (light green) policy shows the second most electricity savings benefits because of Fujairah's agricultural landscape. The indoor consumption policy does not affect the regions much because a smaller indoor sector is directly reflective of the same population density of this region. The policy that leads to the least electricity savings is the water loss reduction policy (dark blue line). This could be explained by the fact that the inbuilt water transmission link network in WEAP for Fujairah is smaller and more compacta s compared to other regions. Hence, a smaller amount of water losses in the transmission process means that the water loss reduction policy is less impactful for the region.

5.3.1.6.2. Water Consumption under Modified Policy Scenarios

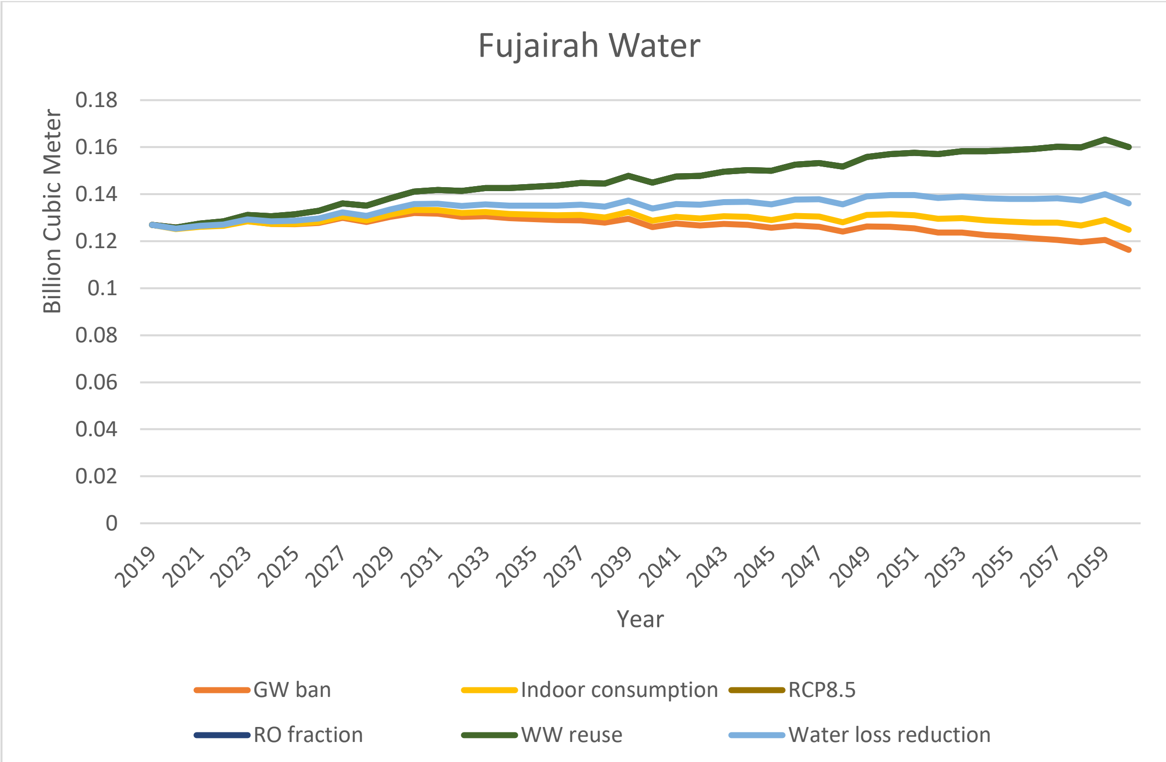


Figure 5.24. Water supply delivered in Fujairah across individual policy scenarios

As shown in Figure 5.24, the groundwater ban is the most water savings policy for Fujairah. The indoor consumption policy is next while the water loss reduction policy ranks third. The RO fraction policy that was saving the most electricity does not change anything in case of water savings because the water supply remains the same, only the desalination technology is being changed under that scenario. The water loss reduction policy is significant in water savings but not as significant in energy savings because the wastewater treatment process itself is energy intensive, however there are significant water savings that show in the water supply delivered like in this figure.

5.3.2. Aggregate Policy Scenario Analysis

5.3.2.1. Electricity Consumption under Modified Aggregate Scenarios

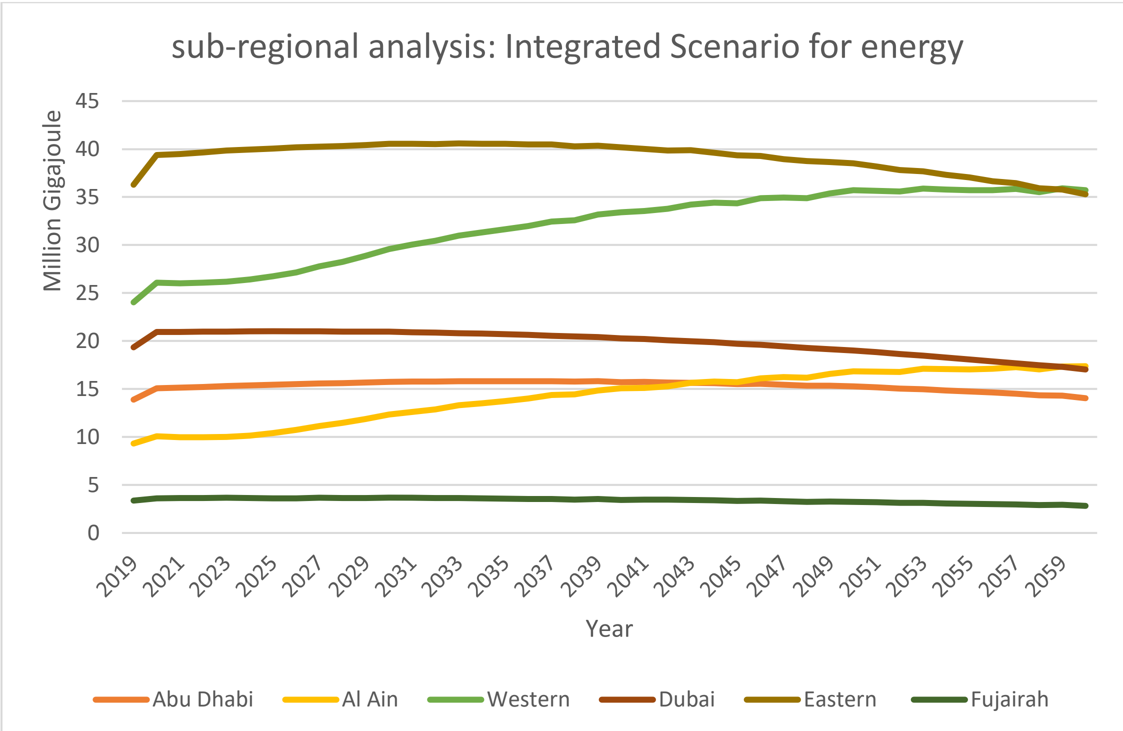


Figure 5.25. Electricity use under the Integrated Scenario for all of the UAE sub-regions

Figure 5.25 shows the electricity use for all the sub-regions under the Integrated scenario. It can be seen that there are moderate declines in electricity consumption in the Eastern region, Dubai and Abu Dhabi. However, there is a significant increase seen for the Western region and the Al Ain region. This is because as the groundwater phase-out is imposed with a substitution of groundwater with desalinated water to fulfill water supply, a bigger energy production strain comes into play for these regions. Fujairah's electricity demand remains pretty stable under this scenario.

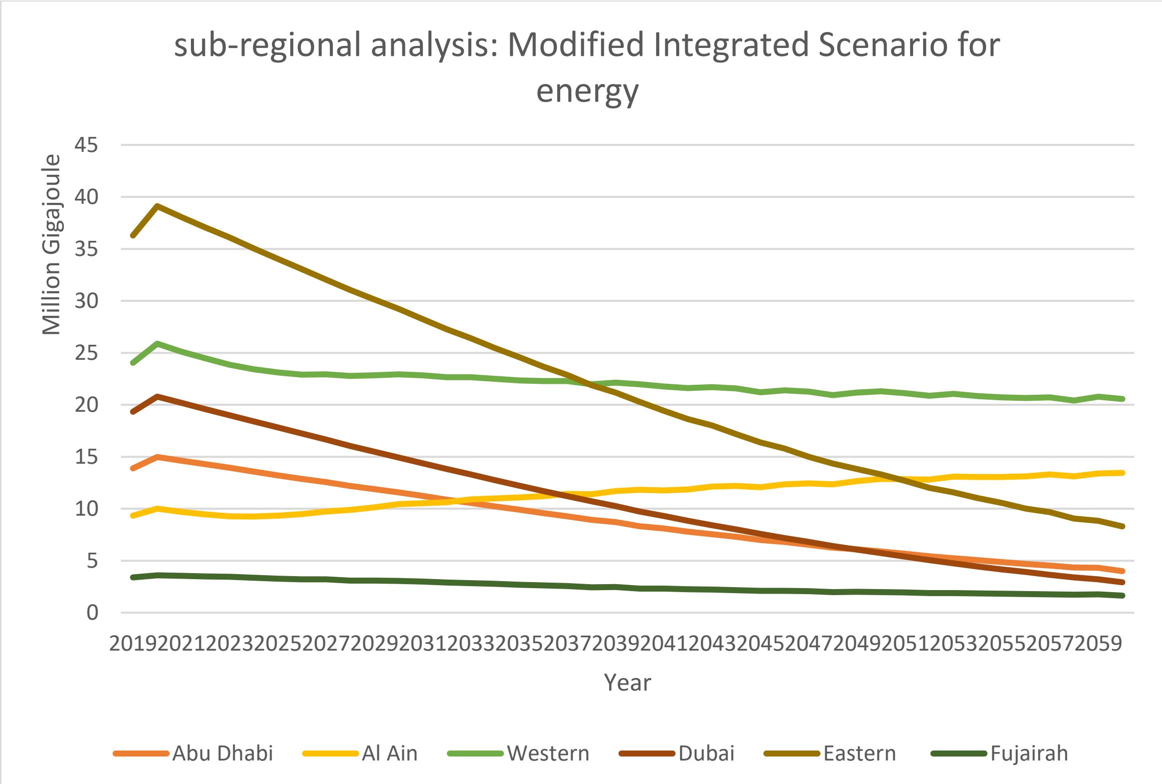


Figure 5.26. Electricity use under the Modified Integrated Scenario for all of the UAE sub-regions

The Modified Integrated scenario in Figure 5.26 drives down the electricity use significantly for all the regions except Al Ain. The most electricity savings can be seen for the Eastern region. It is interesting to see that for Al Ain, the modified scenario does not change the electricity consumption much compared to the non-modified integrated scenario. This could be because of the fact that it already takes a very small fraction of the total electricity consumption in the UAE, so the scale of the impact of the modified scenario is very little. Similar effects can be seen for Fujairah which shows similar trend lines for both the Integrated and the modified Integrated scenarios.

5.3.2.2. Water Consumption under Modified Aggregate Scenarios

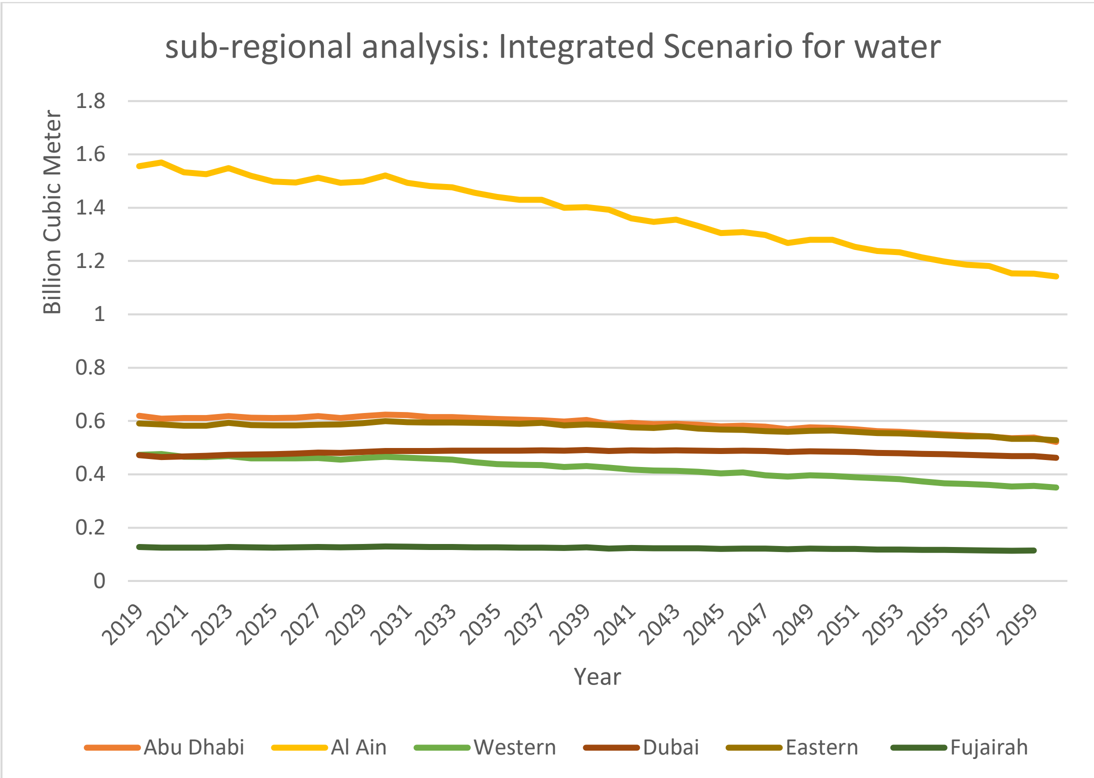


Figure 5.27. Water supply delivered under the Integrated scenario for all of the UAE sub-regions

Under the Integrated scenario designed by AGEDI, there is a significant water saving for the Al Ain region as shown in Figure 5.27. Again, these are scale effects that have manifested themselves since Al Ain makes a major fraction of the total UAE water supply delivered. Other scenarios show much less water saving for the other regions under the Integrated scenario.

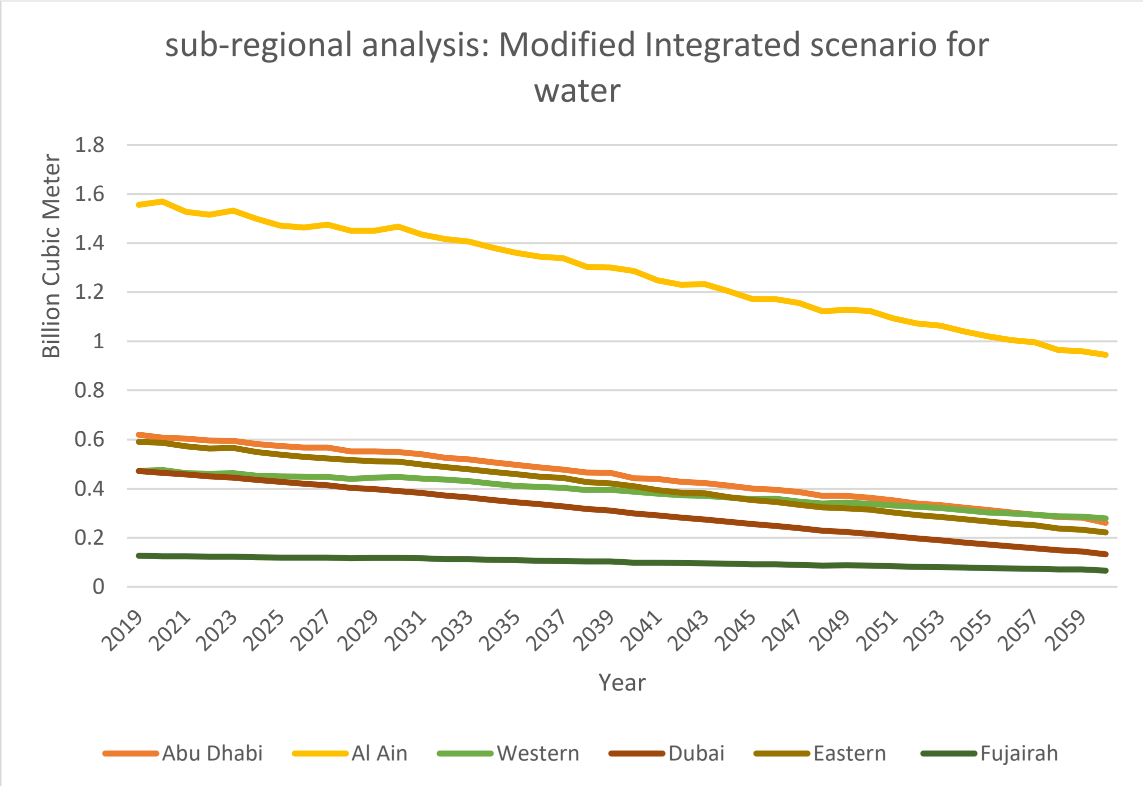


Figure 5.28. Water supply delivered under the Modified Integrated scenario for all of the UAE sub-regions

As shown in Figure 5.28, the modified Integrated scenario does a great job in impacting the water supply in all regions and causing a gradual decline. This shows that the modified Integrated scenario not only stabilizes the water and electricity demands but also helps reduce them under climate change.

This analytical chapter provides many important findings that can be useful in long-term planning. For the whole of the UAE, the indoor consumption policy proves to be the most energy and water saving and also provides the most economic gains in the water sector. The second most beneficial policy for all of the UAE is the water loss reduction policy. Water losses in the transmission networks are a major challenge not only in the UAE but across the world. They also require massive maintenance and repair costs to overcome. However, overcoming this problem could lead to massive energy, water and monetary savings. The groundwater ban policy along with a 50% reduction in irrigated land can be a controversial one, however it provides the third most gains for the UAE system. The least beneficial policy is the wastewater reuse policy according to the model. This is an underestimation of savings because of the model structure. The water supply delivered variable in WEAP does not separately calculate the volume for the wastewater reused, in fact it just calculates the volume available in the transmission links at any one point. As a consequence, the electricity saved because of this water saving is not factored in either. Therefore, the impact of the wastewater reuse policy should be much greater than this model predicts.

In terms of regional analysis, the economic drivers for different regions are clearly shaping the water-energy nexi in those sub-regions. For example, the groundwater ban scenario is most water saving in the agricultural sub-regions (Al Ain, Eastern region and Western region). Similarly, the Reverse Osmosis policy scenario creates a large impact on the sub-regions that house desalination plants (Fujairah). Dubai and Abu Dhabi show massive gains under the indoor consumption policy because their large residential sectors.

6. Policy Recommendations

This chapter articulates a set of policy recommendations based on the qualitative and the WEAP-LEAP analysis in this thesis. These recommendations include both national and sub-regional recommendations.

6.1. Additional Studies Required for Filling the Knowledge Gaps

Literature review shows that there have been significant endeavors in optimization modeling of the water-energy nexus in the UAE. However, there is a lack of policy analysis in this field. The AGEDI study is the only study that conducts a policy scenario analysis to guide future policies for adapting to climate change. Furthermore, there is a gap in terms of forecasting studies under climate change which makes it hard to assume how electricity and water demands would grow under RCP8.5. Another gap that exists is risk analysis studies under climate change that asses vulnerable network elements of the water-energy nexus.

Furthermore, there is a dearth of studies that assess demand and supply breakdowns of the water-energy nexus in the sub-regions of the UAE. This is important because the sub-regions have very different population sizes and demand sectors. For example, Dubai has a high indoor consumption because of its high population density while Al Ain has a high agricultural water demand because of its agrarian focus. Second, different regions have different goals in terms of carbon emissions, wastewater reuse and transition to renewables, etc. Therefore, regional analysis becomes imperative in order to understand how the nexus pieces come together. Hence the policy recommendation for this section will be to encourage more studies that are climate change centric and include the sub-regional nexus. The government could promote this by funding projects at universities in the field of the water-energy nexus and organize competitions to encourage groups of students to come up with innovative solutions to the biggest nexus challenges. Moreover, accessibility of data is key for nexus studies. There should be easy access to acquire data that could be used for quantitative analytics for the region. Furthermore, in order to achieve demand side management, there need to be more GCC specific databases that include costs and performance of demand side water saving and energy efficient devices (Abu Dhabi Global Environmental Data Initiative, 2015). All these studies are important elements in further studying the water-energy nexus and made for integral parts of my study. Analyses like mine, require a stronger data foundation that can be provided by additional demand forecasting studies, climate change risk assessment studies and appliance efficiency studies.

6.2. The Need for Climate Change Adaptation Frameworks in Water-Energy Nexus Policies

The AGEDI WEAP-LEAP analysis is the first study that shows the effect of climate change on the water-energy nexus, therefore its strength not only lies in policy scenario analysis but also the Business as usual –RCP 8.5 projections. The business as usual scenario shows that from 2020 to 2060 while the UAE population grows by 33%, total water use grows by 12.5% (from 4BCM to 4.5BCM) and total energy use in all sectors grows by 133%. Climate change causes an additional 2% water demand and 15% electrical energy demand from 2020-2060. This research quantifies the impact of climate change in the system and emphasizes the need for adaptive planning for climate change.

The policy recommendation based on this section will be for the Climate Change and Environment Ministry to not only take measures for climate change mitigation but also take measures for climate change adaptation. There are enough policy goals geared towards a lower-carbon system, however, there is dearth of planning on what the future will look like under higher temperatures, humidity and salinity levels. The UAE does not seem to be taking rising ocean salinity into account in all its long term plans (Abu Dhabi Global Environmental Data Initiative, 2016). Research shows that man-made climate change is increasing the salinity of oceans (NASA Global Climate Change, 2009). This is particularly threatening for countries like the UAE because they heavily rely on desalination for their water supply and desal plants can optimally function only until a salinity level of 49PSU. The predicted salinity levels for the Arabian Gulf are above 50PSU (Glavan, 2019). Therefore, the UAE Climate Change and Environment Ministry needs to designate resources to formulate a detailed adaptation plan for the UAE since high salinity levels will mean a huge challenge to desalination as a source of water supply in the UAE.

6.3. The Efficacy of the Indoor Consumption Reduction Policy

WEAP-LEAP analysis for the UAE shows that the major electricity and water consumption saving policy is the Indoor consumption reduction policy. By reducing the indoor consumption from 550lpcd to 100lpcd has massive gains for the water-energy nexus as well as the economy.

This transition in consumption can save 0.8 Billion cubic meters of water, 40 Million gigajoules of electricity and 280 million US dollars a year. This result shows the significance of behavioral patterns in management of the water-energy nexus. Therefore, driving down indoor consumption will need both awareness campaigns and a policy framework. One major strategy that could be used is Utility incentive programs that could be designed to incentivize citizens to reduce indoor consumption. Utility incentive programs have been successful in places like California for reduction in natural gas consumption (Gloede, 2015).

6.4. Groundwater Phase-out is Ineffective without Reduction in Irrigation

The WEAP-LEAP analysis shows that the sole implementation of the groundwater phase-out policy designed by AGEDI that substitutes groundwater with desalinated water to meet supply proves to be more energy consuming and costly for the system. However, there are massive gains when this groundwater phase-out is coupled with a reduction in irrigation. This shows that the UAE not only needs stringent groundwater extraction policies but also needs to cut down on irrigated land. This would be a highly controversial move but the gains from the water-energy nexus seem to be much more in economic terms compared to the gains from agricultural produce. According to the World Bank, the UAE agricultural value added (net output of a sector after adding up all outputs and subtracting intermediate inputs) was a mere 0.80155 % of its GDP in 2016 (World Bank, 2016). On the other hand, the modified groundwater phase-out policy that includes a 50% irrigation reduction saves around $80 million USD each year by 2060.

6.5. The Need for Sub-Regional Goals and Policies for achieving them

An important finding from the regional analysis is that each sub-region needs its own policies based on the region’s demand sector. For example, the WEAP-LEAP analysis shows that agricultural regions such as Fujairah and Eastern region get impacted the most by groundwater-phase-out, while large cities with huge residential sectors such as Dubai and Al Ain get the most savings through the indoor consumption policy. Similarly, sub-regions that have installed Reverse Osmosis capacity make the most gains through the RO policy. Moreover, demand and supply side policies also show different results based on which sub-region has access to more supply nodes and how big are its demand catchments. Dubai makes more gains through demand-side policies while Eastern Region benefits more from supply side conservation policies.

Therefore, policies should be region specific and take into account the gains based on regional demand sectors. Therefore, a policy recommendation for this section will be to have more decentralized goals based on the capacity, demand and water-energy landscape of each region. Overarching goals are important to lead and have a national policy but these should not be pushed on different emirates. Moreover, it will be useful to have gradual policy steps to achieve goals pertinent to the water-energy nexus and climate change. Detailed feasibility studies need to be conducted for sub-regional projects and a well thought out step by step development plans need to be laid out.

AGEDI has made valuable research contributions for the UAE as well as the Middle East. Their analyses range from water-energy nexus to climate change impacts on marine life. Such studies play a crucial role in evidence-informed policymaking. It is also important for governments to directly work with research and analytics units. AGEDI is a very good example of this as it is part of the Environmental Agency Abu Dhabi. This thesis proves that a comprehensive research foundation provides an important stepping stone for other researchers that can added finer grain details to the analysis. More research extensions can help achieve a comprehensive outlook of the water-energy nexus in the UAE.

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8. Appendix

8.1. Water-Related Data Sources

Node	Variable in WEAP	Numeric Value	Numeric Value Made of	Unit	Year	Source
Demands: Abu Dhabi, Western, Al Ain, Dubai, Eastern, and Fujairah Regions	Annual Activity Level	Interpolation values: (2000,671, 2010,1832, 2020,2161, 2030,2415, 2040,2639, 2050,2814, 2060,2922)	% of UAE Population by regions (22, 3, 12, 32, 28, and 3 Respectively by regions)	1000 cap	[in function]	United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision, custom data acquired via website.
Catchments Abu Dhabi	Ag - Date Palms	10,464	40% of Ag areas in Abu Dhabi	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
	Ag - Foder	8,633	33% of Ag areas in Abu Dhabi	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Vegetables	1,570	6% of Ag areas in Abu Dhabi	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Other Crops	5,493	21% of Ag areas in Abu Dhabi	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Amenity - Amenity	2,054 (1.5% growth rate)	74684 * 0.0275	ha	2000	2.75% of total urban land cover (Lincoln Institute of Land Policy (Table-Urban-Land-Cover-Data_Lincoln Institute of Land Policy.xlsx) [1]
	Amenity - Forest	1,867	74684 * 0.025	ha	2000	2.5% of [1]
	Outdoor - Household	1,867	74684 * 0.025	ha	2000	2.5% of [1]
Catchments Western Region	Ag - Date Palms	17,440	50% of Ag areas in Western Region	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
	Ag - Foder	11,510	33% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Vegetables	2,093	6% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Other Crops	3,837	11% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Amenity - Amenity	1,120	74684 * 0.015	ha	2000	1.5% of [1]
	Amenity - Forest	1,494	74684 * 0.02	ha	2000	2.0% of [1]
	Outdoor - Household	1,120	74684 * 0.015	ha	2000	1.5% of [1]
Catchments Al Ain Region	Ag - Date Palms	79,352	70% of Ag areas in Western Region	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
	Ag - Foder	22,672	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Vegetables	6,802	6% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Other Crops	4,534	4% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Amenity - Amenity	1,120	74684 * 0.015	ha	2000	1.5% of [1]
	Amenity - Forest	1,494	74684 * 0.02	ha	2000	2.0% of [1]
	Outdoor - Household	1,120	74684 * 0.015	ha	2000	1.5% of [1]
Catchments Dubai	Ag - Date Palms	2,976	60% of Ag areas in Western Region	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
	Ag - Foder	992	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Vegetables	298	6% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Other Crops	694	14% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Amenity - Amenity	1,867	74684 * 0.025	ha	2000	2.5% of [1]
	Amenity - Forest	0	0	ha	2000	ASR UAE (CD) 2014. Ministry of Energy
	Outdoor - Household	1,867	74684 * 0.025	ha	2000	2.5% of [1]
Catchments Eastern Region	Ag - Date Palms	9,275	40% of Ag areas in Western Region	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
	Ag - Foder	4,638	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Vegetables	4,638	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy

	Ag - Other Crops	4,638	20% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Amenity - Amenity	1,120	74684 * 0.015;	ha	2000	1.5% of [1]
	Amenity - Forest	0	0	ha	2000	ASR UAE (CD) 2014. Ministry of Energy
	Outdoor - Household	1,120	74684 * 0.015;	ha	2000	1.5% of [1]
Catchments Fujairah Region	Ag - Date Palms	2,130	50% of Ag areas in Western Region	ha	1996	Date Production and Marketing in the United Arab Emirates (Datepalm1_43.pdf)
	Ag - Foder	1,405	33% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Vegetables	256	6% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Ag - Other Crops	468	11% of Ag areas in Western Region	ha	2010	ASR UAE (CD) 2014. Ministry of Energy
	Amenity - Amenity	1,867	74684 * 0.025	ha	2000	2.5% of [1]
	Amenity - Forest	0	0	ha	2000	ASR UAE (CD) 2014. Ministry of Energy
	Outdoor - Household	1,867	74684 * 0.025	ha	2000	2.5% of [1]
Desal for : Western Region, Eastern Region, and Fujaira Regions	Inflow - MSF	1000	Assumption	MGD	[in function]	Model uses a maximum capacity for the future of 1,000 MGD per each technology to satisfy the demand in each region
	Inflow - MED	1000	Assumption	MGD	[in function]	Model uses a maximum capacity for the future of 1,000 MGD per each technology to satisfy the demand in each region
	Inflow - RO	1000	Assumption	MGD	[in function]	Model uses a maximum capacity for the future of 1,000 MGD per each technology to satisfy the demand in each region
WTP for: Abu Dhabi, Western, Al Ain, Dubai-Eastern, and Fujairah Regions	Daily capacity	N/A	Assumption	MCM /Day	[in function]	WTPs have daily treatment capacities to treat all wastewater coming from the different demand sites. Any untreated water flows into wadis in the model.
AbuDhabi Brackish GW	Initial Storage	40		BCM		AGEDI
Western Fresh GW	Initial Storage	2		BCM	2005	GTZ
Western Brackish GW	Initial Storage	27		BCM	2005	GTZ
East Fresh GW	Initial Storage	31		BCM	[in function]	AGEDI
East Brackish GW	Initial Storage	63		BCM	[in function]	AGEDI
Eastern Region GW	Initial Storage	100		BCM	[in function]	AGED

Figure 8.1. Water-related data sources. Source AGEDI Technical Report (Abu Dhabi Global Environmental Data Initiative, 2015).

8.2. Levelized Costs of Water

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

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

Figure 8.2. Costs of water sector (Abu Dhabi Global Environmental Data Initiative, 2015).

8.3. Water, Electricity and Cost savings for Individual Policy Scenarios

Policy Scenario	Water Savings/ million Cubic meters	Electricity Savings/million Gigajoules	Water Network Cost Savings/ million US dollars
GW ban	**684.8**	**4.9**	**79.8**
Indoor consumption	**1173.1**	**61.1**	**366.0**
RO fraction	**0**	**48.7**	**0.00054**
WW reuse	**0**	**2.2**	**-3.7**
Water loss reduction	**796.9**	**42.0**	**260.0**

Figure 8.3. Water savings, electricity savings and water network cost savings for individual policy scenarios.