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A Multi-Period Mixed Integer Linear Programming Model for Desalination and Electricity Co-generation in Kuwait

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by

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of the requirements for the degree of
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DEDICATION

I dedicate this to my lovely wife, Dr. Sana Al-Bustan; my children, Abdulhameed, Futoh, Sarah, Ramziah, and Awasha-Aisha (Suzanne) AlQattan; and my parents, Futoh and Abdulhameed AlQattan. No man could ever ask for a better family.

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Most importantly, I thank God and my country, Kuwait, for giving me the opportunity and strength to persevere and paving the way for me to become an academic researcher.

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ABSTRACT

Water is the root of life and the engine that drives agriculture, industry, economy and services. The demand for water often necessitates desalination, particularly in arid coastal environments where there are several desalination technologies in use today such as Multi-Effect Distillation (MED) and Reverse Osmosis (RO). The key utility requirement for technologies such as desalination and population in general include energy in one form or another. Therefore, desalination and co-generation are often integrated.

Another key utility is electricity which is generated from either renewable or non-renewable sources. The demands for water and electricity change over time and are subject to uncertainty.

In this dissertation, a country-wide large-scale energy and water cogeneration planning model for Kuwait was proposed and solved. Five different plant technologies where the planning horizon used was set to 37 years starting in year 2014 and until 2050.

A Mixed Integer Mathematical programming model was proposed and formulated using General Algebraic Modeling System (GAMS), the resulting model was solved using the CPLEX solver engine. In this research obtained detailed data on the consumption on water and energy in Kuwait and performed time series analysis of the population growth and individual behavior of water and energy consumption and novel method to represent cogeneration plants was implemented in the proposed mathematical programming model.

A modeling framework that involves a data spreadsheet and a proprietary model was implemented. The data spreadsheet and the model were formulated as a template that can receive data from different applications. In addition, automation using Visual Basic for Application (VBA) was made to the data spreadsheets such that the data is sent to the model template, Gams-Cylix, and are written back to the spreadsheet. An analysis was made between oil-based plants, natural gas (NG) plants, and solar-based plants for co-generation.

It was found that for water production solar-based plants can supply 50 percent or more of the demand during after period 2020 and after implementation and for electric power generation solar plants are limited. The results indicate the preferred technology for energy generation was NG-RO. With the implementation of solar based plants the electric power load is distributed among the technologies. NG-RO plants are more scalable and therefore were expanded to cope with the future demand.

The percentage of the electric power supplied by solar plant was below 35 percent across the planning horizon. By the end of the planning horizon the percentage of electric power supplied by solar base plants was nearly 20 percent. Near 70 percent of the electric power was supplied by NG RO by period 2050. Other technologies had a representation of less than 10 percent by the end of the planning horizon.

CHAPTER 1: INTRODUCTION

Water is an abundant resource, but, its availability for human consumption is scarce in many highly populated coastal regions. Sea water comprises about 97% of available water while fresh water available for human consumption is only about 1%. Obtaining safe, affordable drinking water plays a prominent role in today's world economy. Fresh water sources are becoming scarcer in some environments as population increases. The world's water consumption rate is growing each year as population grows and society gets more affluent. Developing economies in arid environments need to find sustainable sources of water to meet their increased demands. Desalination appears to be one of the promising methods of supplying potable water in arid and hyper arid areas such as Kuwait [1].

In order to desalinate salt water, sustainable energy is needed. Alternative sources of energy should be considered to manage the cost, as well as minimize environmental and ecological impact. These energy sources include non-renewable sources such as fossil fuels (coal, oil, natural gas), as well as renewable sources such as solar and/or nuclear.

Kuwait's water resource scarcity is a serious and growing problem. The fresh water resources presently available to Kuwait are limited to groundwater, desalinated sea water, and treated waste water effluents.

There is a growing demand for abundant economical, potable water as well as more environmentally friendly renewable energy (electricity) source. Until the late 1980s and early

1990s, Kuwait, in general and Kuwait City in particular, did not have a water problem. Water was accessible to all homes at any hour of day.

The problem became apparent after the first Gulf War in August 1990 as indicated in Effect of the Gulf War on Marine Pollution 1998, when water scarcity severely limited as the rate of oil fires this could be extinguished.

Although before the Gulf war many people migrated to Kuwait looking for jobs over the years, they did not have a significant impact on the water and electricity demand. The influx of immigration became significant after the Gulf War ended.

The population increase had a sudden and major impact on the infrastructure in general, and particularly on the consumption of electricity and water. The country was not prepared to handle the influx of people coming as refugees and contract workers during the reconstruction that took place both in Iraq and Kuwait.

The government of Kuwait considers water desalination and power generation as an integrated process. One of the government's goals is to identify economically feasible solutions to ensure water supply and meet electricity demand effectively despite the rising cost of oil (the primary raw material utilized in cogeneration processes in Kuwait). It is imminent for the future decision making to take into account different concepts of cogeneration and select the most economical and viable solution which not only takes into account capacity and demand but also considers renewable energy sources as well.

While Kuwait is an oil rich country, need for short and long term planning to meet the water and electricity demands in an effort to sustain the growing population dictate development of a mathematical modeling framework for optimized selection among alternative technologies to meet the demands in midst of changing realities.

In planning of economies, very often one uses forecasting and mathematical modeling. These allow one to see the effects of changes in the economic and technical realities over time. These models include techniques such as mixed integer linear programming. Although more advanced techniques are available, very often simpler models with reliable unique solutions are more advantageous.

This dissertation evaluates the merits of utilizing mathematical programming in planning of power and water resources over the next thirty years. The introduction is the subject of Chapter one which is followed by review of pertinent literature is the subject of Chapter two. A more comprehensive statement of the problem in hand is the subject of Chapter three, Collection and estimation of vast amount of necessary data is discussed in Chapter four also a vast amount of necessary GAMS models initial work is discussed in Chapter five.

A more comprehensive MILP selection method is discussed in Chapter six, and finally a vast amount of necessary conclusions is discussed in Chapter seven.

CHAPTER 2: BACKGROUND AND PROBLEM STATEMENT

In this chapter, a brief background on water and electricity co-generation technologies, co-generation methods and costs in Kuwait, major factors affecting co-generation technology selection, and energy implications of desalination technologies will be introduced. Overview of applicable mathematical programming techniques such as linear programming, mixed integer linear programming (MILP), and multi-period MILP will follow. The model developed by Sahinidis and Grossmann [67] will be introduced since it forms the basis of the planning approach. Their model was adapted to the addressing co-generation technology selection, associated capacity selection including plant expansions, and their timing over the planning horizon. The utility of net present value and annual equivalent value will be analyzed since they are used as the objective function of the model. Similar planning models for co-generation are going to be discussed next prior to stating the research objectives scope and key assumptions.

2.1 Water and Energy Co-Generation

The motivation for co-generation is efficient energy utilization and cost reduction while meeting demands for water and electricity which vary within a given time period as well as exhibiting an increase as population and societal affluence increase. A simplified schematic that illustrates the interrelations between inputs and outputs for our applicable case is shown in Figure 2-1, below. Three typical energy sources, oil, natural gas and sun, are used to generate electricity and waterfrom seawater. Naturally, there are more possible energy sources such as nuclear and more product markets such as process water and potable water one may incorporate for more comprehensive abstraction of reality.

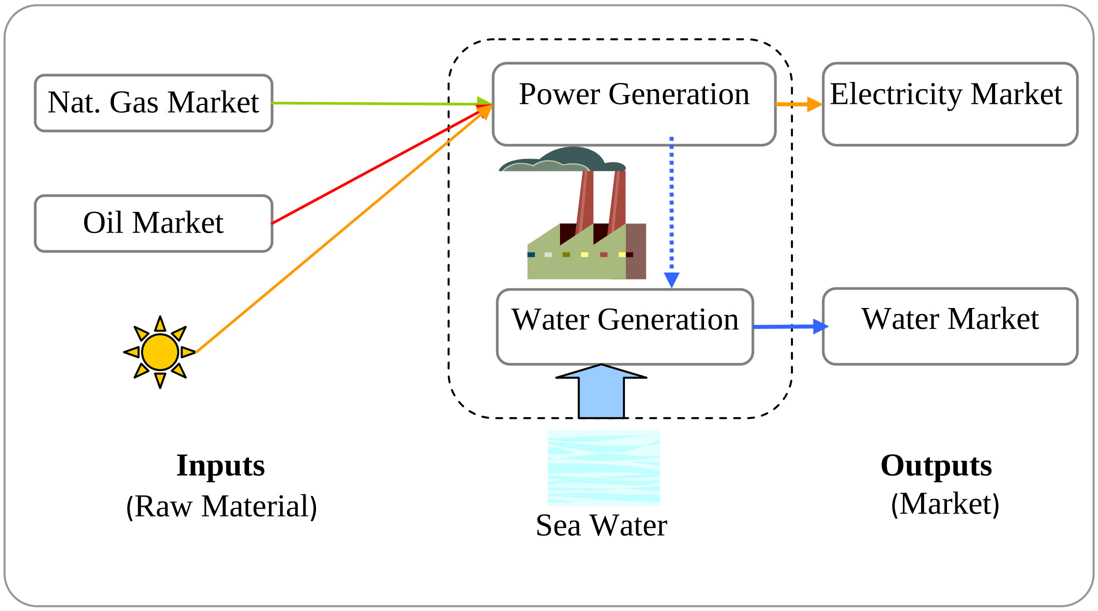

Figure 2-1 Main Model Display of Relationship between Inputs and Outputs

2.1.1 Co-Generation Technologies

The block-flow diagram shown in Figure 2-2 is the grass roots plant that has a battery limits desalination plant. The infrastructure includes an area of the plant that handles the saltwater intake, usually by pumping seawater to be used in the rest of the plant. A separate area will store and handle chemicals that will be used in the pre-treatment, the post-treatment, and the desalination processes. From the desalination plant, the distilled water will be sent to a post-treatment plant, where additional chemicals, such as chlorine, may be added. The distillate product will then be kept in a battery of storage tanks. The remaining brine from the desalination plant will also be processed and released as discharge. Some type of fuel will be used to generate electricity and steam for powering the main process equipment in the desalination plant.

Condensate from the desalination plant will be used to run turbines for additional power generation. The plant generates electricity as marketable product, in addition to water.

The main differences between the five processing options considered in this work are in the fuel used, the power generation step, and the desalination plant. For instance, a conventional reverse osmosis desalination plant uses natural gas as the fuel source, which is combusted to produce thermal energy. The thermal energy is converted to electrical energy in the power generation plant for use in the desalination plant. Solar panels can be used in the power generation step to convert light to electrical energy so that natural gas is not used at all.

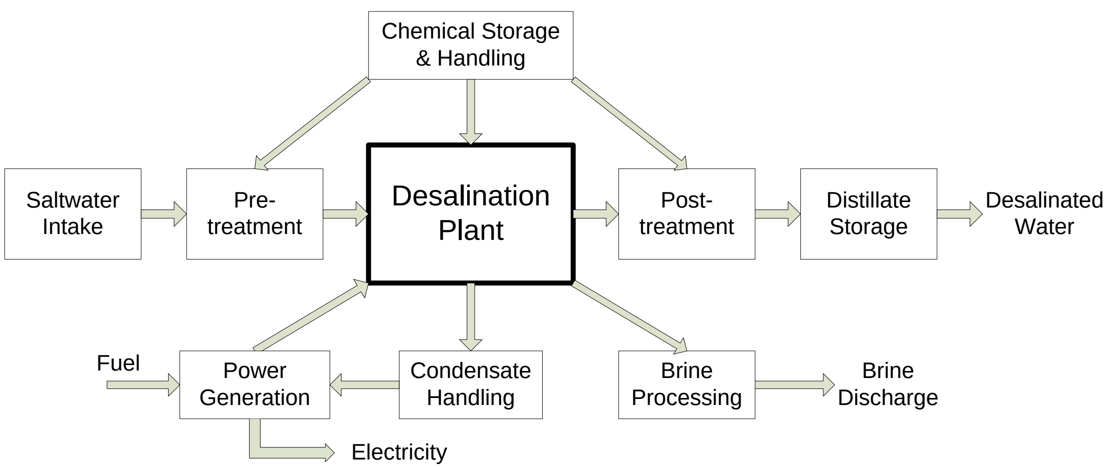

Figure 2-2 Typical Grass Roots Desalination Plant

These options are

- Option 1:Combined Electricity and Water Production using Multi-Stage Flash (CEWP-MSF)
- Option 2: Natural Gas Electricity and Water Production using Multi-Effect Distillation NGEWP-MED
- Option 3: Natural Gas Electricity and Water Production with Reverse Osmosis (NGEWP-RO)
- Option 4: Solar Energy Electricity and Water Production with Multi-Effect Distillation (SEWP MED)
- Option 5: Solar Electricity and Water Production with Reverse Osmosis (SEW RO)

There are many existing oil powered and multi-stage flash plants used and this makes our first option. The oil is used to generate the electricity as well as the steam that is utilized as the primary heating utility in these desalination plants. The multi stage flash section of this option is shown in Figure 2-3. Cold seawater is utilized to remove heat from several flash columns operating at different pressures to enable reuse streams for heat recovery. Some of the warmer seawater is then recycled to the system. The rest is added to the concentrated brine in the first, coldest flash column. Part of the brine is removed. The remaining brine is then sent to a multi-stage flash unit as the cooling liquid. The cool brine water is heated in a heat exchanger connected to the multi-stage flash units until it is close to its boiling point. Heating steam is then used to boil the brine solution in a brine heater. Each column is operated at a different pressure so that water vapor coming from the brine heater can condense into pure water. The remaining hot brine is then sent to the next flash column and more water vapor is condensed. The condensed water from each column is collected as the distillate.

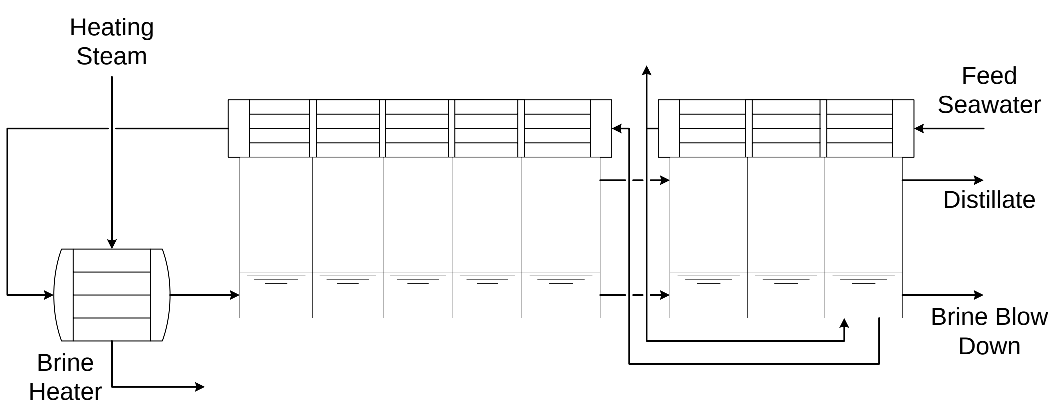

Figure 2-3 Multi-Stage Flash Process for Desalination

Natural gas has been a popular fuel source for power generation for decades, particularly to meet the peak load. With more recent discoveries, the use of natural gas is bound to increase more and more. The second option uses natural gas as fuel and multi effect distillation as the desalination technology. This desalination technology is shown in Figure 2-4. Here, feed seawater is used as the cooling fluid in a heat exchanger. The seawater is then sprayed in several columns. Natural gas is combusted to vaporize water in a boiler. Heating steam leaving the boiler is used to evaporate pure water from the seawater. The water vapor from each column is then used as heating steam for additional columns. The steam is then condensed in the original heat exchanger and added to the distillate. Concentrated brine is removed from the bottom of each column in the brine blow downstream.

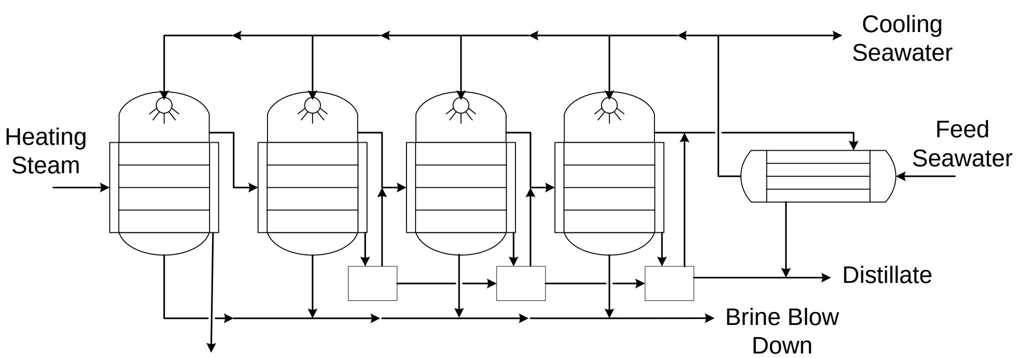

Figure 2-4 Multi-Effect Distillation Process for Desalination

Higher energy costs associated with evaporative technologies made membrane technologies such as reverse osmosis a popular alternative which is our third option. The membrane based desalination is shown as Figure 2-5. Feed seawater is treated with chemicals, like chlorine, in a mixing tank. The treated solution is then pumped into a membrane separation unit where desalinated water passes through the membrane and is treated again in the product treatment step where the distillate is recovered. The brine that does not pass through the membrane is used to generate electricity using a turbine.

Desire to use renewable resources are increasing environmental concerns, energy prices, and technological advances in photovoltaic research is responsible from increased market share of the solar power in electricity generation. Option four shown in Figure 2-6 captures such an integrated concepts with multi-effect distillation solar panels are used in an oil circuit to heat utility oil. Heat is removed from the oil and stored in a thermal storage tank. A pump is used to circulate the oil around this loop. Energy from the thermal storage tank is used to heat another utility stream. The second utility passes through a turbine to generate electricity before being used to boil water in a low pressure boiler. Steam coming from the boiler is used as the heating steam for the MED system. Natural gas is not needed in this setup, because the heat used to boil the heating steam is taken from the solar panels in the oil circuit.

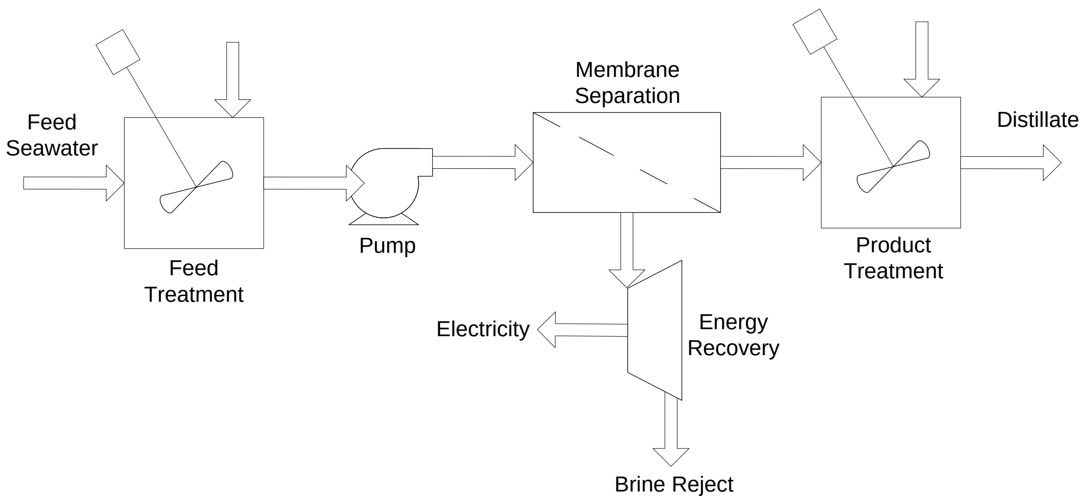

Figure 2-5 Membrane-Based Technology for Desalination

Solar technology can also be integrated with Membrane based desalination as shown in Figure 2-7 which makes our fifth option. Here, solar (photovoltaic) panels are used to store electricity in a battery. An AC/DC converter is used to convert the electricity from the battery into useable energy for the high pressure pumps used in the reverse osmosis setup. A flushing pump has been added to the conventional reverse osmosis setup which uses some of the distillate to clean brine from the membrane separation unit.

The co-generation technology selection depends on local and global economic factors such as capital costs, energy cost and availability, reliability of the technology, operating labor skill, feed water chemistry, water salinity, demand for each type plant size, space requirement, ease of operation, and geographical location are some of the key factors that effects the selection. Naturally, uncertainty associated with future makes the selection even more challenging.

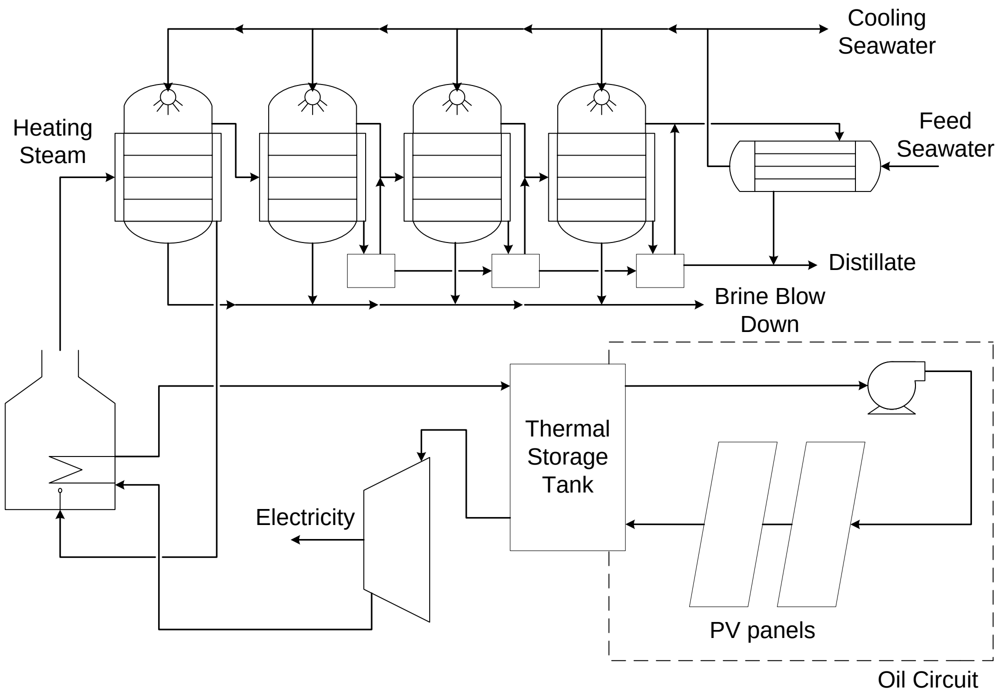

Figure 2-6 Solar Power and Multi-Effect Distillation for Desalination

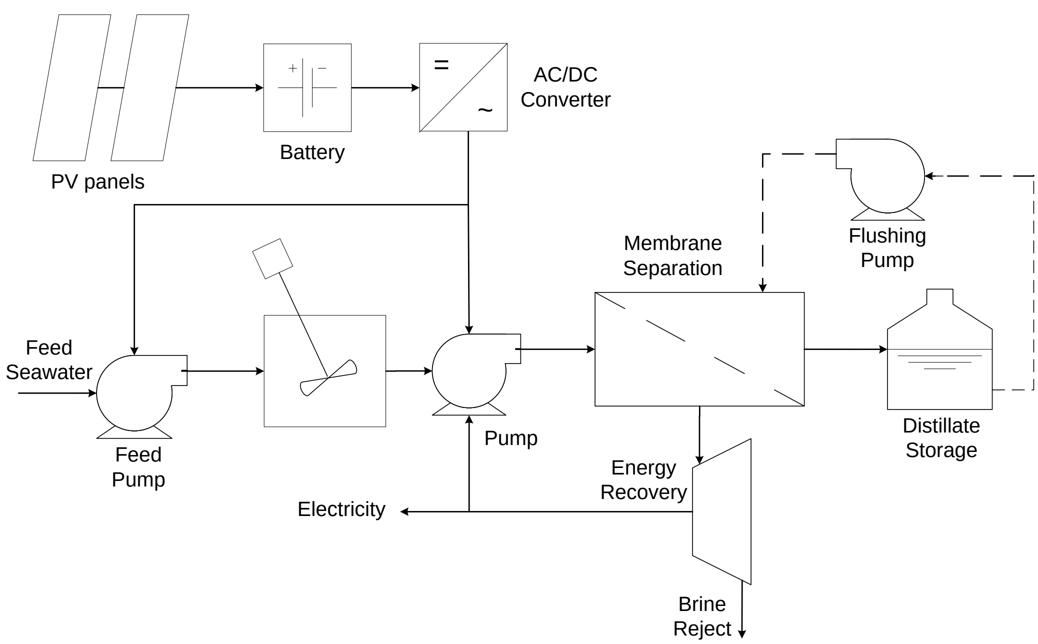

Figure 2-7 Solar Power and Membrane Processes for Desalination

2.2 Mathematical Programming Techniques for Capital Decisions and Planning

There are many approaches to technology selection and capital budgeting, and planning. There are excellent reviews and texts written on the matter. One of most popular quantitative approaches is use of models solvable using Mathematical Programming and optimization techniques. Within the mathematical programming domain, depending on the nature of decision variables and parameters, and availability of effective global algorithms there are portfolio of methods that can be utilized. Linear Programming, Quadratic Programming, Dynamic Programming, and Mixed Integer Linear Programming are arguably the more popular methods applicable for deterministic techniques and provide global as opposed to local solutions to these Planning models. Even a modest review in these techniques will be a voluminous but futile attempt since the focus of this work is modeling and application of these advanced techniques to aid decision.

The most popular optimization problem that is applicable to planning operations is linear programming (LP) problem. In the LP problem, an objective function that is subject to equality and inequality constraints is minimized or maximized. Both the objective function and the constraints are linear function of the decision variables which may have continuous numerical values [80].

When the decision variables can only have discrete values, we have integer programming. If we have both integer and continuous decision variables and the modeling equations are a linear function of the decision variables, we have Mixed Integer Linear Programming (MILP). The integer decision variables are usually represented to have (0,1) values. The objective function can be modeled as multi-period problem.

The economic feasibility criteria, objective function, to be used optimized can take many forms. Discounted Rate of Return, Benefit Cost Ratio, Net Present Value, and Equivalent Annual Worth are some of the more popular ones for maximization of a profitability criterion. These criteria require revenue term very often not easy to predict particularly for an extended period far into future. In such instances and when one can capture market demand that has to be met, use of objective function that is cost based is feasible. Minimization of net present cost or minimization of equivalent cost are then major the valid options. Naturally these criteria include capital charges and annual operating costs. For an extended period, annual equivalent cost provides a better scaled value.

2.3 Previous Models Developed for Similar Case Studies

The importance of this section is to show that the application of Multi-Period (MILP) to this problem is unique and has not been carried out before, therefore providing important, new technology that will help identify the most viable options for Kuwait and perhaps, extrapolated to the Middle East in general.

The research is to develop a Multi-Period (MILP) Model for Desalination and Electricity Co-generation in Kuwait is to allow for future trends, predictions and to evaluate different scenarios. This is the first Multi-period (MILP) research model in this subject and certainly the first application for Kuwait.

One recent paper investigated a Mathematical Model for a Dual Purpose Power Desalination Plant(DPPD) [60]. In this investigation the authors state that dual purpose plants are built to operate with a constant water production capacity while allowing variation of power generation according to the system's load demand. The authors' goal is a mathematical model was developed to represent the power and water production to help manage the system. The resulting optimization algorithm was formulated as a Mixed Integer Non Linear Programming (MINLP) model. However, this model was not multi-period and did not consider any new or renewable energy alternatives as an option.

In another work, Medeazza[59] assessed the long term sustainability of desalination technology in alleviating the long term fresh water demand limitation for the Canary Islands (Spain). The entire water supply of the island is dependent on DPPD technology. Medeazza proposed a model to build future scenarios that would accept changes in resulting impacts from altering the system characteristics and environmental concerns of desalination. The model was not a Multi-Period MILP, nor did it consider any energy technology options, Investigation suggested that this model is not suitable for an arid country such as Kuwait, which has no natural fresh water source.

In Afgan (2007), the economic feasibilities of multiple water desalination and electricity co-generation plant setups were evaluated under an assortment of criteria in order to define the potential each strategy had for development and meeting future energy demands.

In this same work (Afgan, 2007), a "general index of sustainability" is generated by evaluating the relative importance of—or, performing a sensitivity analysis on—a set of key criteria that directly affect the decision-making process for a desalination and electricity co-generation model. By doing so, the authors were able to look at the effects of each individual criterion, as well as combinations thereof, to create a meaningful analysis for the list of available options that were being considered in their paper. A weight coefficient was used as the relative measure of comparison between different options. Based on the results of the model, it was pointed out that natural gas was one of the most promising resources for co-generation. Also, nuclear energy shows promise for energy and water cogeneration options under multi-criteria assessment.

Erhard [61] noted that models must be able to incorporate economical aspects of the different technologies, as well as combinations of different designs (such as running the plant on both fossil fuels and renewable energies, like solar power), in order to generate an entire plant setup, in addition to the necessary requirements for being technically accurate (to include proper heat exchange networks to minimize loss of energy in the process, among others). Erhard's paper further describes two necessary conditions for defining such a problem: a Process Simulation Environment (PSE) to verify the design requirements, and a Model Development Kit (MDK) to empirically describe the process using numerical methods. Pairing conditions with an economic basis for calculations, Erhard explains how it is possible to create such an environment for feasible cogeneration in Middle East and North African (MENA) countries.

In his paper, Erhard employs RESYSproDESAL—a simulation model library—in order to calculate heating requirements for desalination processes for both seawater and brine, and to combine those with some cogeneration technology (whether it be solar or natural gas) in order to predict outcomes of a full-scale industrial plant.

The aforementioned models were not Multi-Period MILP and did they consider several energy technology options. Investigations suggested that those models are not suitable for an arid country such as Kuwait, which has no natural fresh water source. Another important contribution in this study is that data from different sources are critically evaluated, checked for consistency, and several parameters are recalculated. The specific objectives of this research is to develop a Multi-period Mixed Integer Linear Program model which takes into consideration current water and energy capacities and demands, as well as to predict future requirements for Kuwait.

2.4 Research Objectives and Scope

The specific objectives of this research is to understand and forecast the water and energy requirements of Kuwait, then to identify economically feasible solutions to ensure water supply and meet electricity demand; develop a Multi-period Mixed Integer Linear Program model which takes into consideration current water and energy capacities and demands, as well as to predict future requirements for Kuwait. The objectives also include forecasting suitable water and energy cogeneration options for Kuwait from 2009 to 2050, facilitating the decision making and forecasting of economically feasible water desalination and energy cogeneration processes based on changing scenarios.

The research scope include understanding and forecasting the water and energy requirements of Kuwait as well as raw material(s); develop a multi-period MILP model to select among alternatives technologies and production capacities; and analyze the MILP model results to develop optimum solutions to meet Kuwait's future demands for water and energy.

The government of Kuwait considers water desalination and power generation as an integrated process. One of the government's goals is to identify economically feasible solutions to ensure water supply and meet electricity demand effectively despite the rising cost of oil (the primary raw material utilized in cogeneration processes in Kuwait). It is imminent for the future decision making to take into account different concepts of cogeneration and select the most economical and viable solution which not only takes into account capacity and demand but also considers renewable energy sources as well.

The research scope includes review of the background, formulation of the approach to be taken, development of the model, gathering required data, implementation of the models, and analysis of the results. The initial starting point for the model is one developed by Sahinidis and

Grossmann [67]. Its adaptation, reformulation, implementation using GAMS environments, integrating data and optimization, gathering data, validating data and the codes, and analysis of results are all within the scope of the project. Concluding remarks and recommendations is anticipated to convince the stake holders that policy solutions based on systems science will save time, energy and money for Kuwait's next generation.

2.5 Key Research Assumptions

The main model needs several assumptions for it to be valid. The first assumption is that cogeneration plant settings are preset. That is, the technologies used for power generation and for water are determined prior to the problem formulation for each plant.The number of options is limited to five as discussed in Table 2-1 and detailed analysis of alternatives within each option is not considered at this stage.

Table 2-1 Multi-Period MILP Model for Desalination and Electricity Co-generation in Kuwait

Process Option Index	Raw Material (Fuel)	Technology	Abbreviation
1	Fuel Oil	Multi-stage Flash	CEWP-MSF
2	Natural Gas	Multiple Effect Mechanical Compression	NGEWP-MED
3	Natural Gas	Reverse Osmosis	NGEWP-RO
4	Solar	Multiple Effect Mechanical Compression	SEWP-MED
5	Solar	Reverse Osmosis	SEWP-RO

The second assumption is that the relationship between inputs, outputs and the operating level of the plant can be approximated by a linear function for both energy and material balance. This will allow the problem formulation to be a Multi-Period mixed Integer Program.

The third assumption is that each plant has an electricity generation process and a water generation process. The energy requirements for both processes are known. Existing plants and earlier studies are taken as the basis here. A summary is shown in Table 2-2 and Table 2-3.

Table 2-2 Comparison of Desalination and Electricity Co-generation Options for Kuwait

Option	Efficiency (%)	Electric Cost (USD/KWh)	WaterCost (USD/US Gallon)
1	35	0.06	0.002
2	52	0.05	0.003
3	52	0.05	0.002
4	20	0.47	0.004
5	20	0.47	0.004

Adapted from (Afgan, 2007)

Table 2-3 Comparison of Desalination and Electricity Co-generation Options for Kuwait

Option	Investment (10^9 USD)	WaterProduction (10^6 Gallon/year)	Electric ProductionCapacity (KWh/year)
1	3.8	159000	60,000
2	3.2	159000	60,000
3	4.1	159000	60,000
4	24.3	159000	60,000
5	24.7	159000	60,000

Adapted from (Afgan, 2007)

The fourth assumption is that the internal interaction between the power generation process and the water generation process is reflected in the fuel requirements of the plant.

The fifth assumption is there are only one market for water and one market for electricity.

CHAPTER 3: MODEL DATA ESTIMATION

Estimation of the vast amount of necessary data is discussed in Chapter 4, wherein this section of the research the initial work and initial statistical analysis for the main model is explained, such as the data collection, the creation of tables and figures, and related issues to this section of the research.

The vast amount of water and energy historical data for Kuwait is collected from different sources. Due to the confidentiality of governmental data in Kuwait and private-sector data from both Kuwait and the United States, obtaining historical data from these sources proved difficult. After several attempts, the data—originally in Arabic—was collected and organized into tables and translated to English. Each table has been adapted and summarized in the supplemental files. Figures were constructed to include linear least-squares and second-order polynomial regression, when appropriate, which could be used for the mathematical programming. In certain cases, as with population growth—which is inherently exponential—an alternative regression was employed.

Many aspects which may affect the decision-making process for implementing processes to meet the water and energy demands of Kuwait have been considered. After thorough analysis, four main elements appear to have the greatest effect: Kuwait's gross domestic product, population, electricity demand, and water demand.

3.1 Current Desalination and Power Generation Plant Technologies in Kuwait

Table 3-1, below, shows the current and future plans for expansion of the various Kuwait electricity and desalination plants. Data was compiled from the Kuwait Ministry of Electricity and Water (MEW) (Statistics Department & Information Center, 2012). There are nine main locations where these utility plants are being constructed in order to provide services to the greatest number of Kuwaiti citizens.

Table 3-1 Desalination and Power Generation Technologies with Total Installed Capacities and Expansions for Kuwait Water and Electricity Utility Services (Statistics Department & Information Center, 2012)

Kuwait Plant	Year Built	Total Installed Capacity			Technology	
		Water		Electricity	Desalination	Energy
		(MIG/Day)	(M USG/Day)	(MW)		
Sabiya	2006	50.0	60.0		MSF	
	2007	100	120			
	1998			600		Steam
	1999			1500		
	2000			2400		
	2008			250.2		Gas
	2009			500.2		
	2011			1320		SB - CCGT
Az-Zour South	1988	43.2	51.9		MSF	
	1989	57.6	69.2			
	1998	86.4	104			
	2001	115.2	138.3			
	(2013)	30.0	36.0			
	1987			600		Steam
	1988			1800		
	1989			2400		
	2010			2960		
	1987			55.5		Gas
	1988			111		
	2004			520		New Gas
	2005			1040		
	2008			825		Emergency Gas
	(2012)			826		
	(2013)			1011		

Table 3-1 Desalination and Power Generation Technologies with Total Installed Capacities and Expansions for Kuwait Water and Electricity Utility Services (Statistics Department & Information Center, 2012) (Continued)

	(2014)			1196		
Az-Zour North Co-Generation Plant	(2015)	102	122		R.O.	
	1983	19.2	23.1			
	1984	88.8	107		MSF	
	1985	110.4	132.6			
Doha West	1983			1200		Steam
	1984			2400		
	2008			84.6		
	2009			112.8		Gas
	2010			141		
	1978	18.0	21.6		MSF	
	1979	42.0	50.4			
Doha East	1977			300		
	1978			600		Steam
	1979			1050		
	1981			108		Gas
Doha (Stage I)	(2015)	50.0	60.0		R.O.	
Doha (Stage II)	(2016)	50.0	60.0			
	1971	6.0	7.2			
	1972	24.0	28.8		MSF	
	1975	36.0	43.2			
	1970			134		
	1971			402		
Shuaiba South	1972			536		Steam
	1974			804		
	1998			720		
	1992			25		Gas
	1998			0		
	2011	45.0	54.0		MSF	
Shuaiba North	2009			660		Gas
	2009			215.5		Steam
	1982	19.5	23.4		MSF	
Shuwaikh	2011	30.0	36.0		R.O.	
	2007			252		Gas

3.2 Kuwait Gross Domestic Production (GDP) and World Economy

Kuwait, like many other countries, has a number of oil fields that have matured and require substantial capital and technology transfers to increase, or sustain, oil production and should depend on renewable sources of energy to satisfy the future increase of water and energy demand. Table 3-2 and Table 3-3 show Kuwait's economical position and compare it with oil prices from the rest of the Middle East and the United States.

Table 3-2 Upstream Oil Costs of Selected Regions

Region	Exploration Costs (USD/Barrel)	Production Costs (USD/Barrel)	Total Cost (USD/Barrel)
Middle East	6.99	9.89	16.88
United States	21.58	12.18	33.76
On Shore	18.65	12.73	31.38
Off Shore	41.51	10.09	51.6

Source: (U.S. Energy Information Administration, 2009)

Table 3-3 Time Series of Fuel Prices for Select Countries in USD/Barrel

	Year							
	1998	2000	2002	2004	2006	2008	2010	2012
Kuwait								
Diesel	$0.49	$0.68	$0.68	$0.91	$0.79	$0.76	$0.79	$0.76
Super Gasoline	$0.64	$0.79	$0.76	$0.91	$0.83	$0.91	$0.87	$0.87
Saudi Arabia								
Diesel	$0.38	$0.38	$0.38	$0.38	$0.26	$0.34	$0.25	$0.25
Super Gasoline	$0.61	$0.91	$0.91	$0.91	$0.61	$0.61	$0.61	$0.61
United States								
Diesel	$1.02	$1.82	$1.48	$2.16	$2.61	$2.95	$3.18	$3.97
Super Gasoline	$1.21	$1.78	$1.51	$2.04	$2.38	$2.12	$2.88	$3.67

Source: (German Society for International Cooperation, 2012-2013)

Kuwait has a higher gross domestic production (GDP) per capita in U.S. dollars (USD) than the world average, and more recently the United States, as shown in Table 3-4. Figure 3-1 shows that the GDP per capita has grown from $17,100 USD in 1995 to $56,400 USD in 2012

(Statistics Department & Information Center, 2007-2012; World Bank, 2007-2012). It is projected that the GDP of Kuwait may reach between $70,900 and $99,200 USD by the year 2020.

Table 3-4 Gross Domestic Production (GDP) per Capita Comparison

GDP per Capita	USD
World Average	10,300
USA	51,700
Kuwait	56,400

Source: (World Bank, 2012)

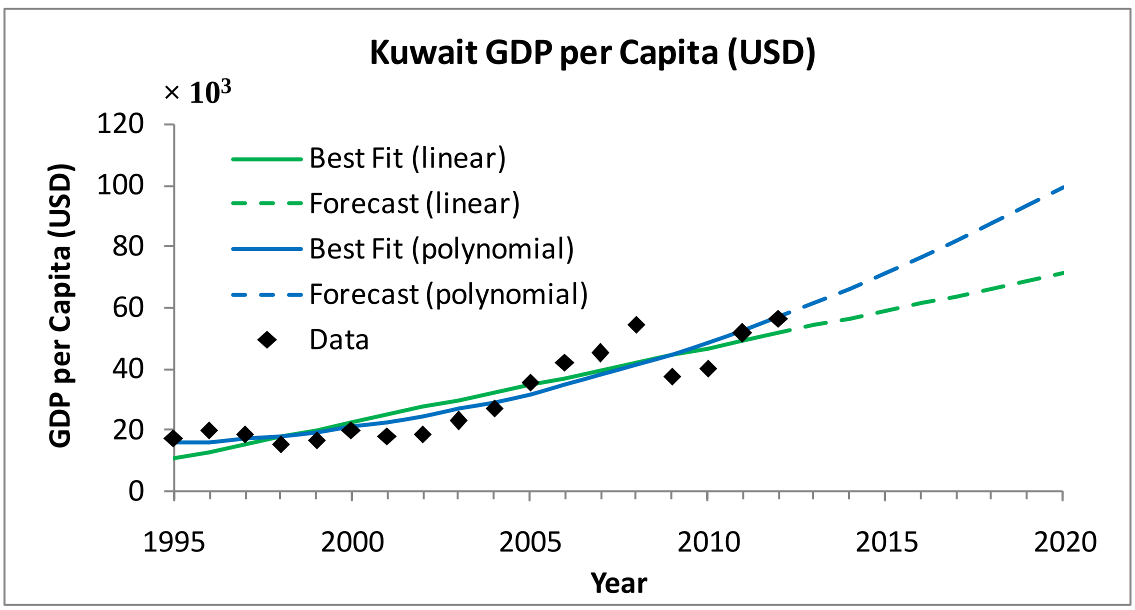

Figure 3-1 Kuwait Gross Domestic Production (GDP) per Capita in USD (1995 - 2020). Data from (Statistics Department & Information Center, 2007-2012; World Bank, 2007-2012)

Kuwait is economically booming, and since the reconstruction of Kuwait and Iraq, many international companies have invested in Kuwait. This is causing a rapid increase in Kuwait's GDP per capita, and Kuwait is becoming a significant trade center in the Gulf region. Physical data is provided for Kuwait GDP per capita in Figure 3-1 from 1996 to 2004. For Figure 3-1 and all subsequent figures, all available data has been extrapolated to the year 2020, taking 1996 as the base year (x = 0) for regression purposes. Figure 3-1, then, compares extrapolating the data using a linear equation ($y = 4{,}367x + 15{,}000$) or a second-order polynomial ($y = 485x^2 + 488x + 19{,}500$). Given the recent surge in GDP for Kuwait, it is expected that this trend will continue and GDP per capita values could increase to \$120,000 to \$310,000 per annum by the year 2020.

3.3 Kuwait Population

The population of Kuwait (Figure 3-2) increased by over 150% from 1992 (a population of 1,441,000) to 2011 (a population of 3,697,000). This population increase largely has to do with the influx of non-Kuwaiti people into the labor force who have aided in the reconstruction of Kuwait after the Iraq-Kuwait war. Due to the rapid expansion of the Kuwait economy, these non-Kuwaiti people now account for approximately 65 – 70% of the total population of Kuwait.

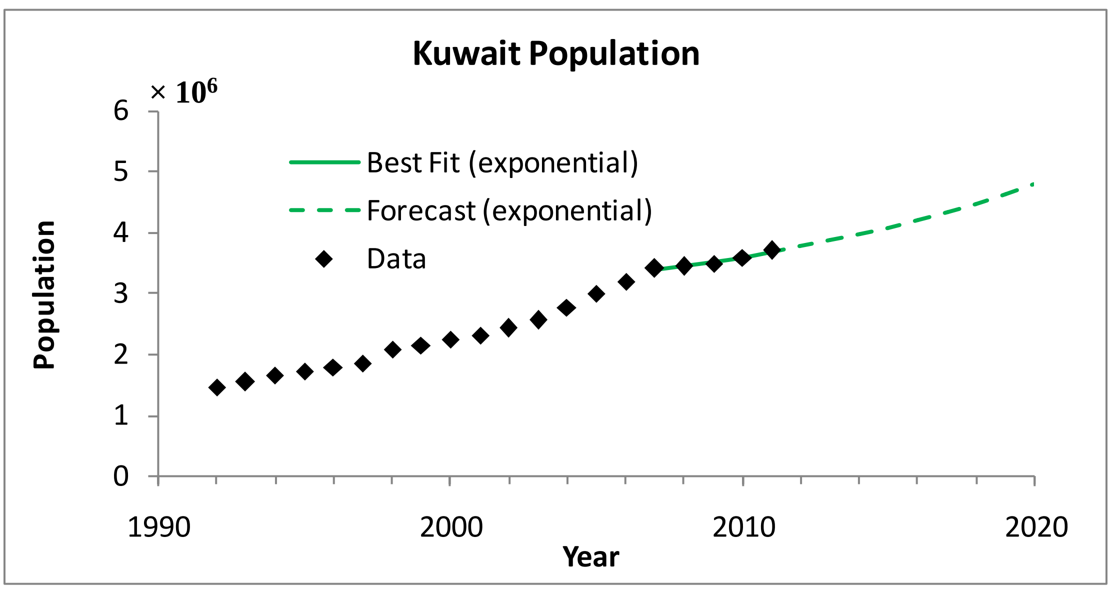

Figure 3-2 Kuwait Population (1992 – 2020). Data from (Statistics Department & Information Center, 2007-2012)

3.4 Kuwait Energy

3.4.1 Kuwait Energy Consumption per Capita per Year in kWh/year (1980 – 2020)

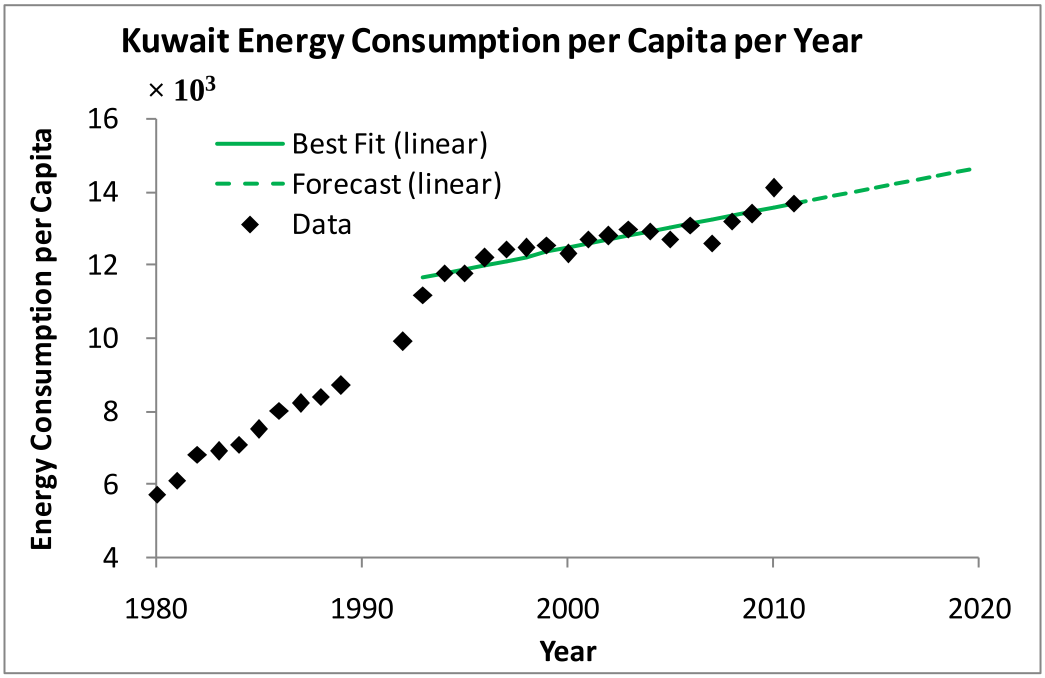

Figure 3-3 Kuwait Energy Consumption per Capita per Year in kWh/year (1980 – 2020). Data from (Statistics Department & Information Center, 2007-2012; Darwish & Al-Najem, 2005)

Figure 3-3, above, shows the energy consumption per capita per year in kWh/year of people in Kuwait. Data was gathered from 1980 to 2011. Taking the year 1996, again, as a basis (x = 0), linear least-squares regression was applied to data after 1994, where there was a significant shift in the energy consumption trends of the population of Kuwait. The regression line (y = 111x + 12,015) was extrapolated to estimate future energy demands for Kuwait in the year 2020. Due to the hot climate of Kuwait, energy demands are significantly greater than even those in the United States—compare 15,000 kWh per capita per year in Kuwait in 2007 to 13,000 kWh per capita per year in the United States—both of which are greater than the world average energy use of only 3,000 kWh per capita per year (Statistics Department & Information Center, 2007-2012).

3.4.2 Development of Maximum and Minimum Loads in MW per Year

Figure 3-4 shows the development of maximum and minimum energy loads, which are the lower and upper bounds for energy demand, from 1990 to 2020.

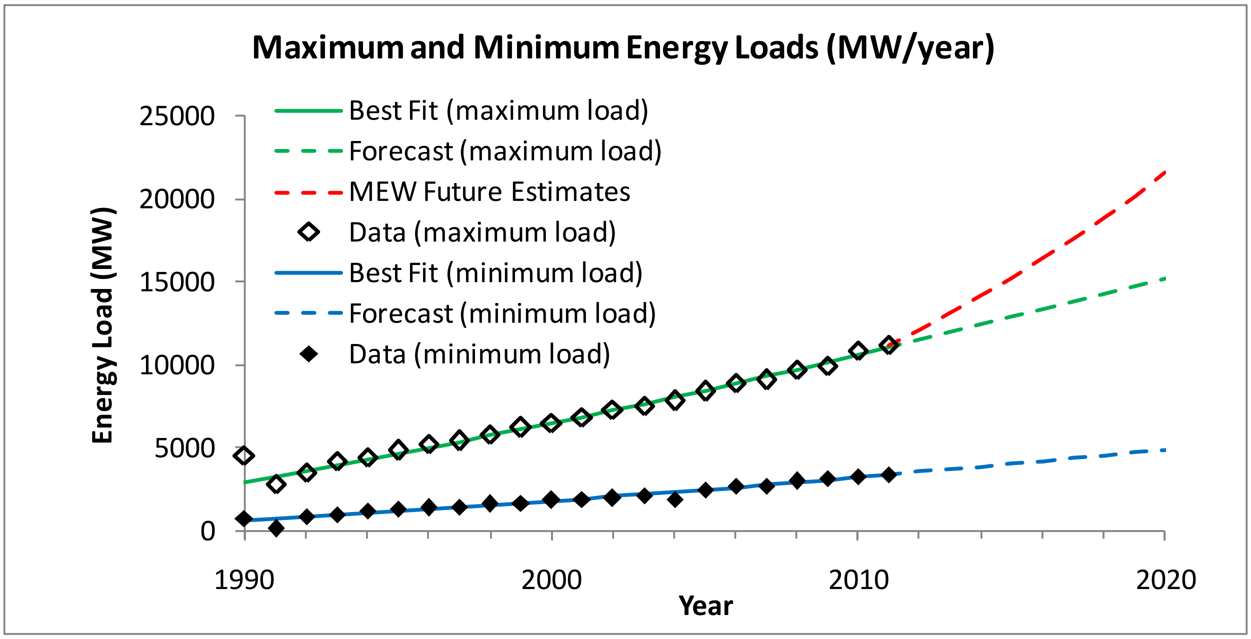

Figure 3-4 Development of Maximum & Minimum Loads in MW/year (1990 - 2020) (Lower and Upper Bounds for Demand of Energy in MW/year (1990 – 2020). Data from ("Middle East News and World Report", 1998; "Statistical Department and Information", 2007-2012)

From Figure 3-4, lower bounds for demand of energy have, for the most part, gradually increased since the 1980s. In 1990, the lower bound for demand of energy was about 720 MW/year. This has increased to 1,830 MW/year in 2000, and further still to 2,710 MW/year in 2006. The most recent data for the minimum energy load in Kuwait is 3,410 MW/year. Using a second-order polynomial ($y = 1.210x^2 + 123.18x + 1{,}253$) to model this trend in energy consumption, it is estimated that Kuwaiti energy demand will increase to over 4,900 MW/year in 2020—an increase of over forty percent.

Upper bounds for demand of energy have increased over the past few decades, as well. In 1990, the maximum energy load was 4,500 MW/year, and in 2000, the energy demand was 6,500

MW/year. From 2006 to 2011, the maximum energy load increased from 8,900 MW/year to over 11,000 MW/year. The Kuwait Ministry of Electricity and Water (MEW) future estimates project the maximum energy load for Kuwait will be over 21,000 MW/year in 2020.

3.5 Kuwait Fresh Water

Figure 3-5, shows the gross fresh water consumption (in millions of US gallons per year) for Kuwait, while Figure 3-6 and Figure 3-7 show the minimum and maximum consumption rates, respectively, from 1995 to 2020. For each figure, data ranging from 1995 to 2006 was forecasted using a best-fit linear equation.

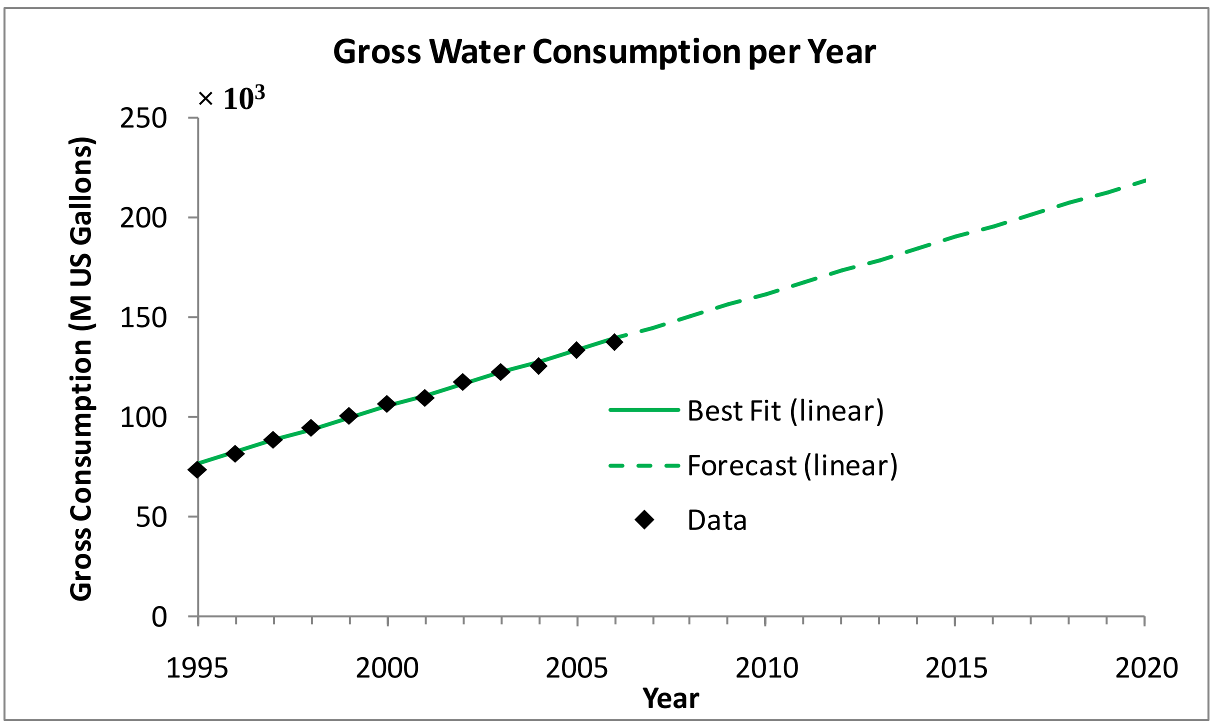

Figure 3-5 Gross Consumption of Fresh Water in Millions of US Gallons per Year from 1995 to 2020. Data from (Statistics Department & Information Center, 2007)

From 1995 to 2006, there was a steady increase in the gross consumption of fresh water in Kuwait from 74,000 M US gallons/year to 138,000 M US gallons/year. Kuwaiti consumption of fresh water is increasing rapidly, especially after the liberation of Kuwait from Iraq. Kuwait has supplies of between 1,000 m^3 (263,000 US gallons) and 1,700 m^3 (447,000 US gallons) per person per year (Alshawaf, 2008). Kuwait has water scarcity because their renewable water resource per capita is 75 m^3 (19,700 US gallons) per year per head of population (Statistics Department & Information Center, 2007). The continuation of the present water consumption trend would require the quadrupling of desalination capacity by 2025 (Statistics Department & Information Center, 2007).

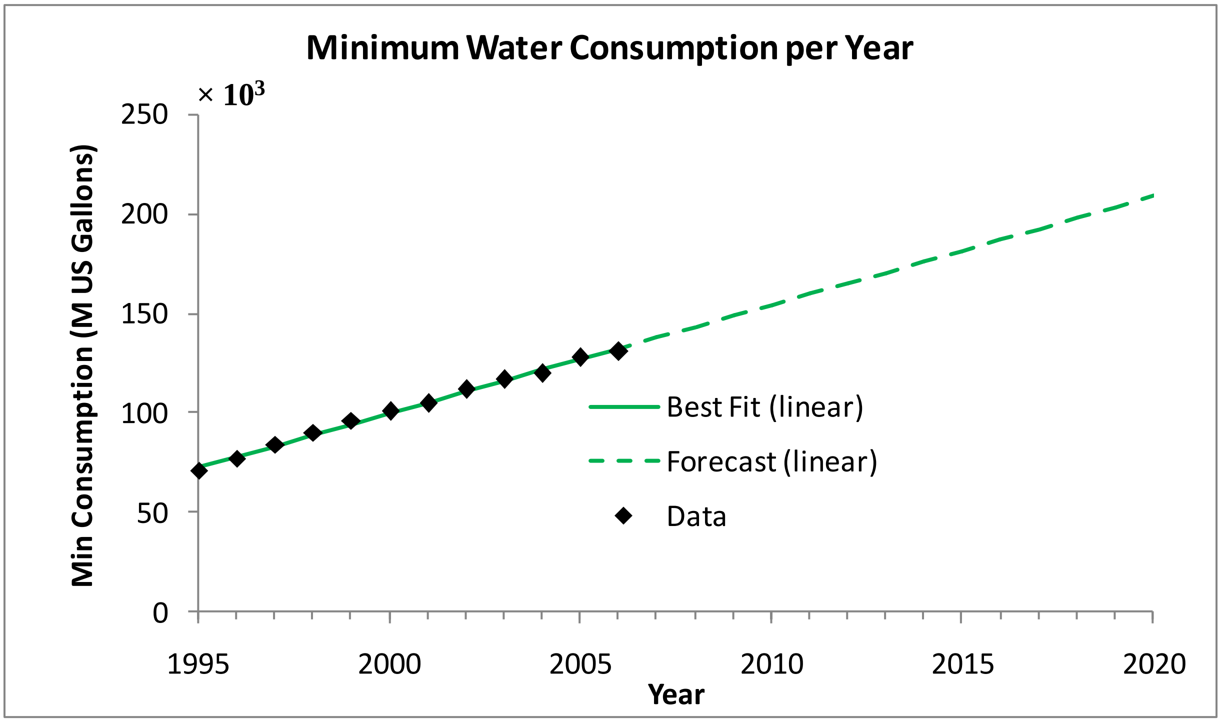

Figure 3-6 Minimum Consumption of Fresh Water in Millions of US Gallons per Year from 1995 to 2020. Data from (Statistics Department & Information Center, 2007)

From Figure 3-7 there was a yearly gradual increase from 1995 to 2006 of maximum consumption of fresh water in millions of US Gallon/year. In 1995, maximum yearly consumption of fresh water was 78,000 M US gallons/year, and in 2006, it was 145,000 M US gallons/year. There was also a yearly gradual increase from 1995 to 2006 in the minimum yearly consumption of fresh water, as shown in Figure 3-6. In 1995, minimum yearly consumption of fresh water was 71,000 M US gallons/year, and in 2006, it was 131,000 M US gallons/year.

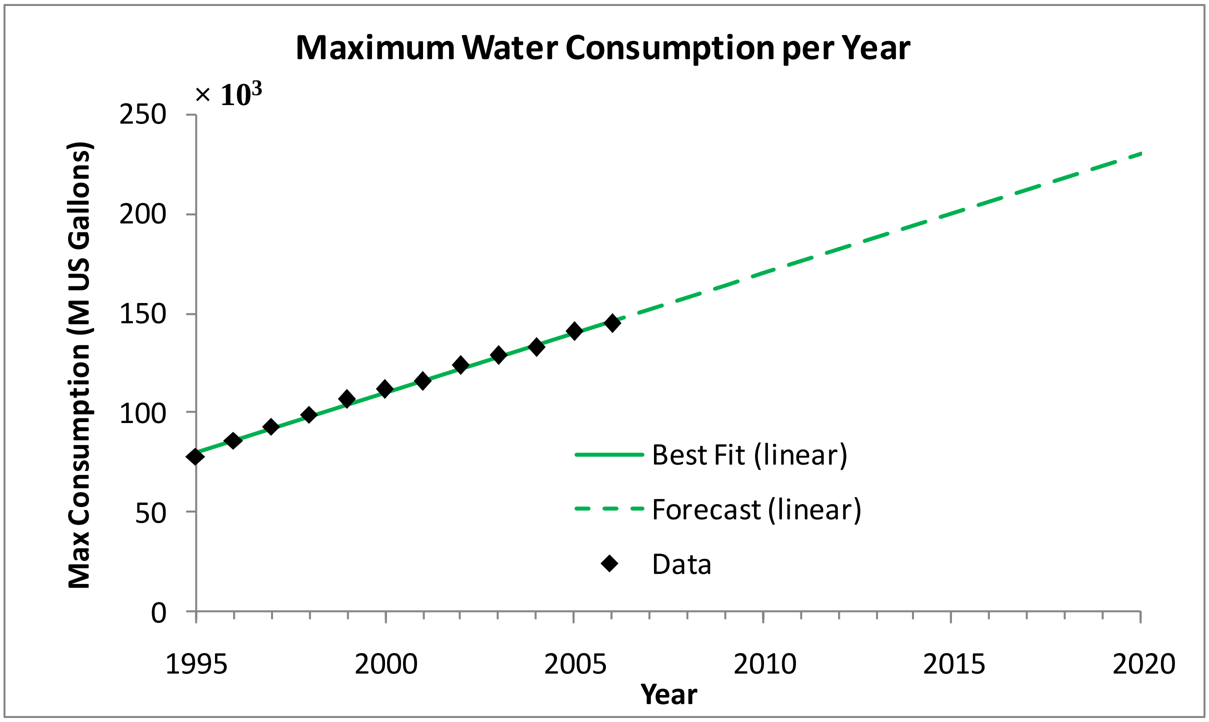

Figure 3-7 Maximum Consumption of Fresh Water in Millions of US Gallons per Year from 1995 to 2020. Data from (Statistics Department & Information Center, 2007)

In 2000, the national United States average freshwater withdrawal per capita was 1,464 US gallons per day, which is 534,000 US gallons/year (U.S. Department of Energy, 2006). The quantity of water consumed in Kuwait is 120 US gallons per capita per day, which is more than US by 87.6 gallons per capita per day (Rossi, 2006). Fresh water consumption in M US Gallon/year saw a yearly gradual increase from 1995 to 2006. Where in 1995, Kuwait fresh water consumption in M US gallons per year was 74,000; in 2006, it was 138,000 M US gallons per year.

3.6 Water and Electricity Capacity of New Plans

Figure 3-8, below, shows the Kuwait Ministry of Electricity and Water (MEW) future plan for additional load requirements for the electric power station from 2012 to 2020. In 2020, the expected energy load for the power station is 12,000 MW. The total accumulation of additional required energy load for the power station as given by the Kuwait MEW future plan is 16,000 MW.

Though the demand for both water and electrical energy is increasing, the percentage of government subsidies is still very high, thereby decreasing the end-user costs. Because of these low prices, some people misuse or carelessly use water and electricity in Kuwait. Water selling prices by the Kuwait Ministry of Electricity and Water and unit costs of fresh water and electricity that the Kuwait government subsidizes to support Kuwaiti citizens for living purposes have been increasing rapidly since the liberation of Kuwait and Iraq, due to the obligation the government feels toward its people to rebuild after losing everything. Policy solutions based on science will save time, energy, and money for Kuwait's next generation.

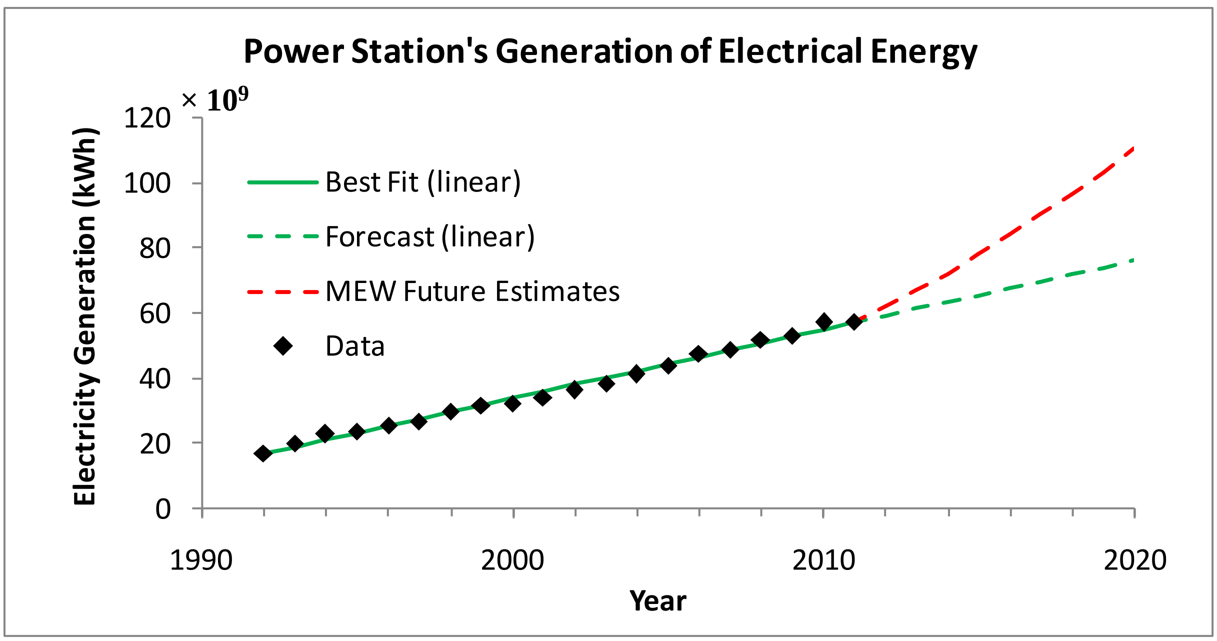

Figure 3-8 Kuwait Ministry of Electricity and Water (MEW) Future Plan for Additional Load Required for Electric Power Station in kWh/year (1992 – 2020). Data from (The Administration of Studies & Researches, 2008)

Table 3-5 shows the Kuwait Ministry of Electricity and Water (MEW) future plan for additional daily water consumption for building a desalination plant from 2010 to 2017. In 2010, the desalination plant output was 75 million imperial gallons (MIG) per day, or 90 million US gallons per day. In 2017, the expected desalination plant output, as per the Kuwait MEW future plan, is projected to be 151 MIG per day, or 181 M US gallons per day. From 2010 to 2017, the total accumulation of daily water consumption for building the desalination plant is 505 MIG per day, or 606 M US gallons per day.

Table 3-5 Kuwait Future Plan for Additional Daily Water Consumption in MIG/day and M US Gallons/day (2010 – 2017)

Year	**Additional Daily Water Consumption (MIG/day)**	**Additional Daily Water Consumption (M US Gallon/day)**
2010	75	90
2012	254	305
2014	25	30
2017	151	181
Accumulation of Additional daily consumption (2010 - 2017)	505	606

Source: (Kuwait Authority of Planning, 2008; The Administration of Studies & Researches, 2008)

3.7 Electricity and Water Selling Prices by Kuwait Ministry of Electricity and Water

Figure 3-9 shows the electricity selling prices by the Kuwait MEW. In 2000, the total income from selling electricity in Kuwait was 324 M Kuwaiti Dinar (KD), or about $1.15 billion USD, of which 90% was subsidized by the Kuwaiti government. In 2006, the total income from selling electricity was 1,014 M KD, or about $3.60 billion USD, of which 93% was subsidized by the Kuwaiti government. Data was extrapolated to the year 2020, taking 1996 as the base year (x = 0) for regression purposes. Assuming the trend of increasing cost of electricity continues, it is expected that by 2020, the total income from electricity for Kuwait could range from $9.25 billion USD (by linear regression) to over $23 billion (by second-order polynomial best-fit).

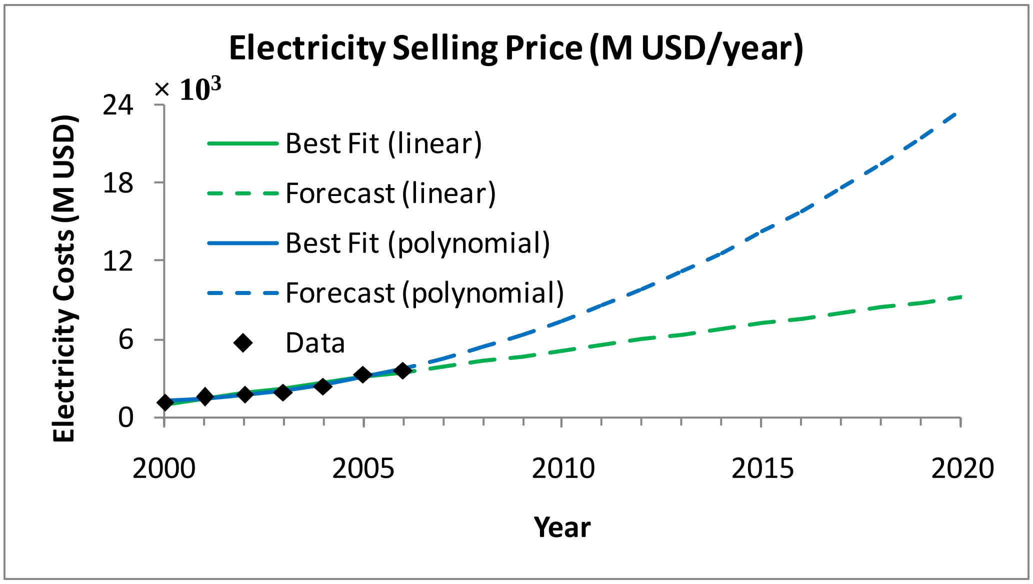

Figure 3-9 Electricity Selling Prices by Kuwait in M USD (2000 – 2020). Data from (Kuwait Authority of Planning, 2008; The Administration of Studies & Researches, 2008)

Figure 3-10 shows the water selling prices by the Kuwait Ministry of Electricity and Water. In 2000, the total income generated from selling water in Kuwait was 187 M KD, or about $663 million USD, of which 76% was subsidized by the Kuwaiti government. In 2006, the total income from selling water was 524 M KD, or about $1.86 billion USD, of which 83% was subsidized by the Kuwaiti government. Data was extrapolated to the year 2020, again taking 1996 as the base year (x = 0) for regression purposes. Assuming the trend of increasing cost of water continues, it is expected that by 2020, the total income from water for Kuwait could range from $3.83 billion USD (by linear regression) to $9.61 billion USD (by second-order polynomial best-fit).

Selling prices for both electricity and water have been gradually increasing since 2000. In 2002, the electricity selling price for individual consumers was 2 Kuwaiti fils (1 KD = 1,000 fils), or about 0.70 US cents, per kWh; for industrial consumers, 1 fils, or about 0.35 cents, per kWh; and for governmental or coastal areas, 10 fils, or about 3.5 cents, per kWh.

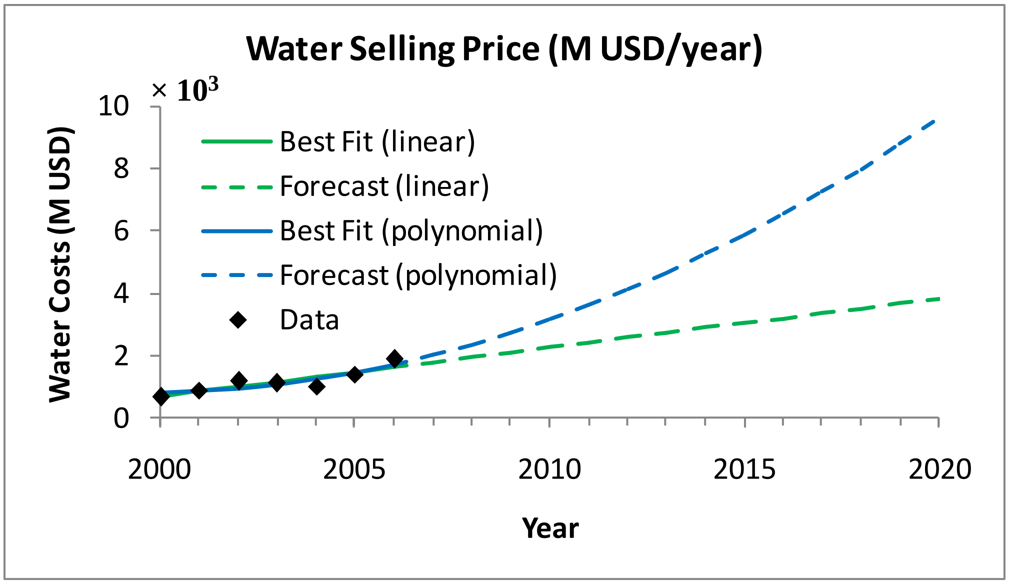

Figure 3-10 Water Selling Prices by Kuwait Ministry of Electricity and Water in M USD (2000 – 2020). Data from (Kuwait Authority of Planning, 2008; The Administration of Studies & Researches, 2008)

In the same year, water selling prices from the fresh water network were 211 fils (73.8 cents) per cubic meter; for industrial use, 66 fils (23.1 cents) per cubic meter; and for water tank station, 79 fils (27.6 cents) per cubic meter. For the desalination plant, brackish and fresh water are 158.5 fils (55.4 cents) per cubic meter; for the water network, 264 fils (92.3 cents) per cubic meter; and for brackish water home consumers, 26.4 fils (9.2 cents) per cubic meter.

Water selling prices by the Kuwait Ministry of Electricity and Water (MEW) for brackish water farms are 5.28 fils (1.85 cents) per cubic meter; for brackish water public farms, 13.21 fils (4.62 cents) per cubic meter; and for brackish water tanks, there is no charge (free).

3.8 Total Kuwait Revenue from Selling Electricity and Water Services

Figure 3-11 shows the total Kuwait revenue from selling electricity and water services in millions of United States dollars per year. In 2000, the total Kuwait revenue from selling electricity and water services was 143 M USD (40.9 M KD). In 2006, total revenue from selling these services was 320 M USD (91.5 M KD). It is projected that the total revenue from selling these services could reach between 450 M to 690 M USD (126 M to 194 M KD) by the year 2020.

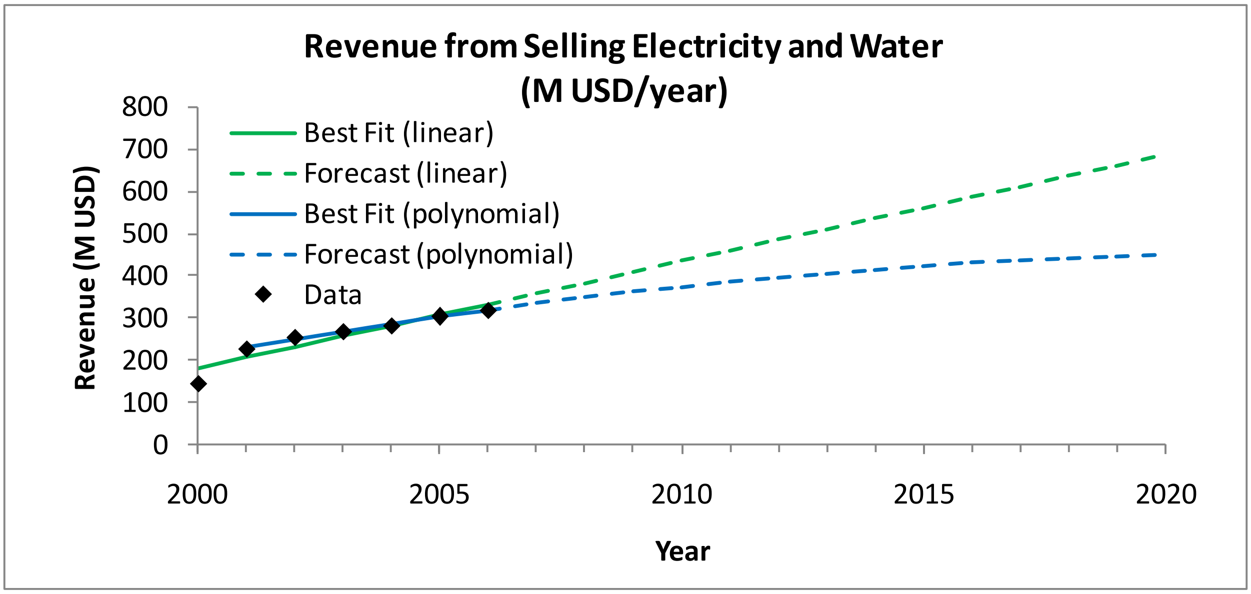

Figure 3-11 Total Kuwait Revenue from Selling Electricity and Water Services in M USD (2000 – 2020). Data from (Ministry of Finance of Kuwait, 2008; The Administration of Studies & Researches, 2008)

Figure 3-12 shows the total revenue from selling electricity service in Kuwait. There was a gradual yearly increase from 2000 to 2006. In 2000, the total Kuwait revenue from selling electricity services was 96.9 M USD (27.7 M KD). In 2006, total revenue from selling electricity service was 221 M USD (63.3 M KD). It is projected that the total revenue from selling electricity service could reach between 500 M to 750 M USD (141 M to 211 M KD) by the year 2020.

Figure 3-13 shows the total revenue from selling water service in Kuwait. In 2000, the total Kuwait revenue from selling water service was 45.2 M USD (12.9 M KD). In 2006, total revenue from selling water service was 98.6 M USD (28.2 M KD). It is projected that the total revenue from selling this service could reach up to 190 M USD (53.5 M KD) by the year 2020.

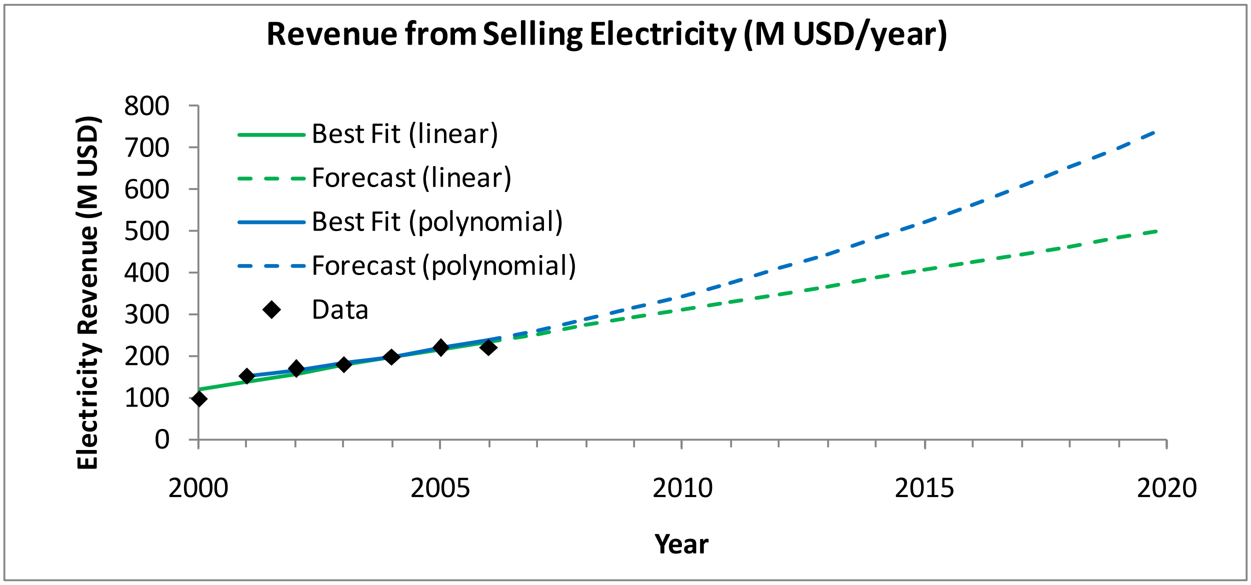

Figure 3-12 Total Kuwait Revenue from Selling Electricity Services in M USD (2000 – 2020). Data from (Ministry of Finance of Kuwait, 2008; The Administration of Studies & Researches, 2008)

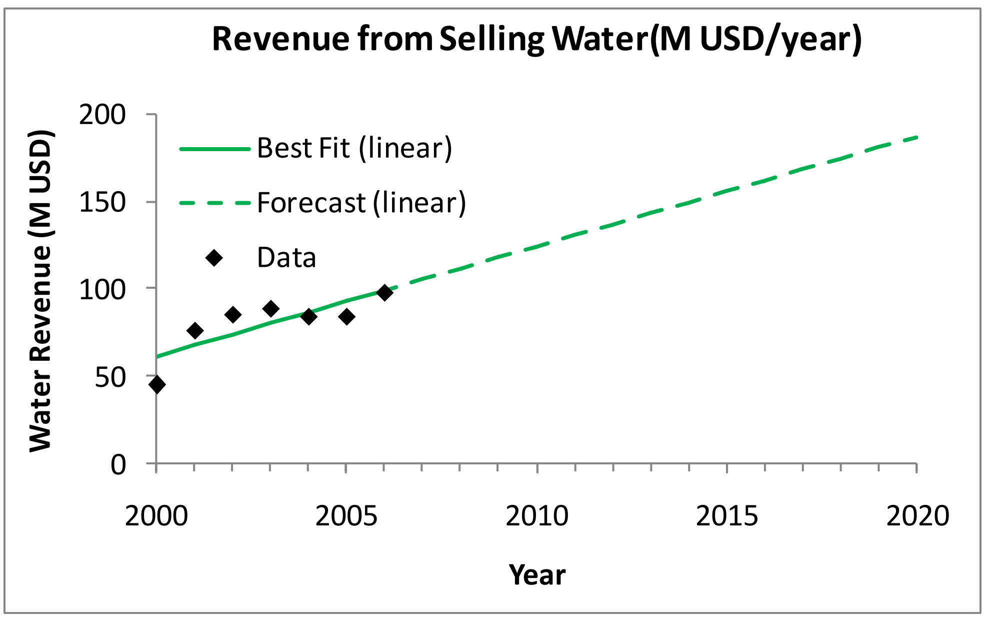

Figure 3-13 Total Kuwait Revenue from Selling Water Service in M USD (2000 – 2020). Data from (Ministry of Finance of Kuwait, 2008; The Administration of Studies & Researches, 2008)

3.9 Production Cost of Electric Energy

Figure 3-14 shows the production cost of electric energy in USD per kilowatt-hour. In 1985, the production cost of electric energy was 0.071 USD/kWh; in 1993, the cost was 0.057

USD/kWh; and in 2005, the cost was 0.097 USD/kWh**.** Kuwait's production cost of electric energy has been increasing rapidly after the liberation of Kuwait and Iraq, due to the demand for labor resulting from the reconstruction of Kuwait. Many foreign companies have started businesses based in Kuwait, which caused an increase in immigration to meet that labor demand.

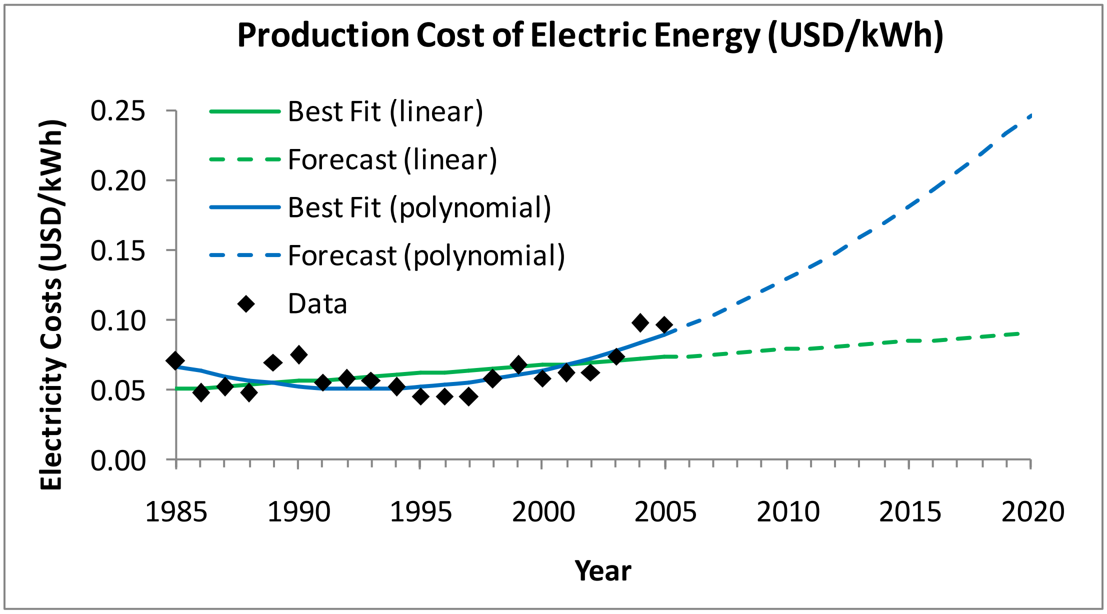

Figure 3-14 Production Cost of Electric Energy (1985 – 2020). Data from (The Administration of Studies & Researches, 2008)

3.10 Total Production Cost of Fresh Water

Figure 3-15 shows the total production cost of fresh water in USD per thousand US gallons. The cost of fresh water production has been increasing, on average, since 1985. In 1985, the production cost of water was $0.994 per thousand US gallons; in 2000, $1.099 per thousand US gallons; and in 2005, $1.675 per thousand US gallons. It is expected that total fresh water production costs could range from $5.14 to $12.3 per thousand US gallons by the year 2020. Like the increasing costs of electricity, the demand for labor as Kuwait becomes a major trading center in the Persian Gulf area and results in an increase in demand for fresh water.

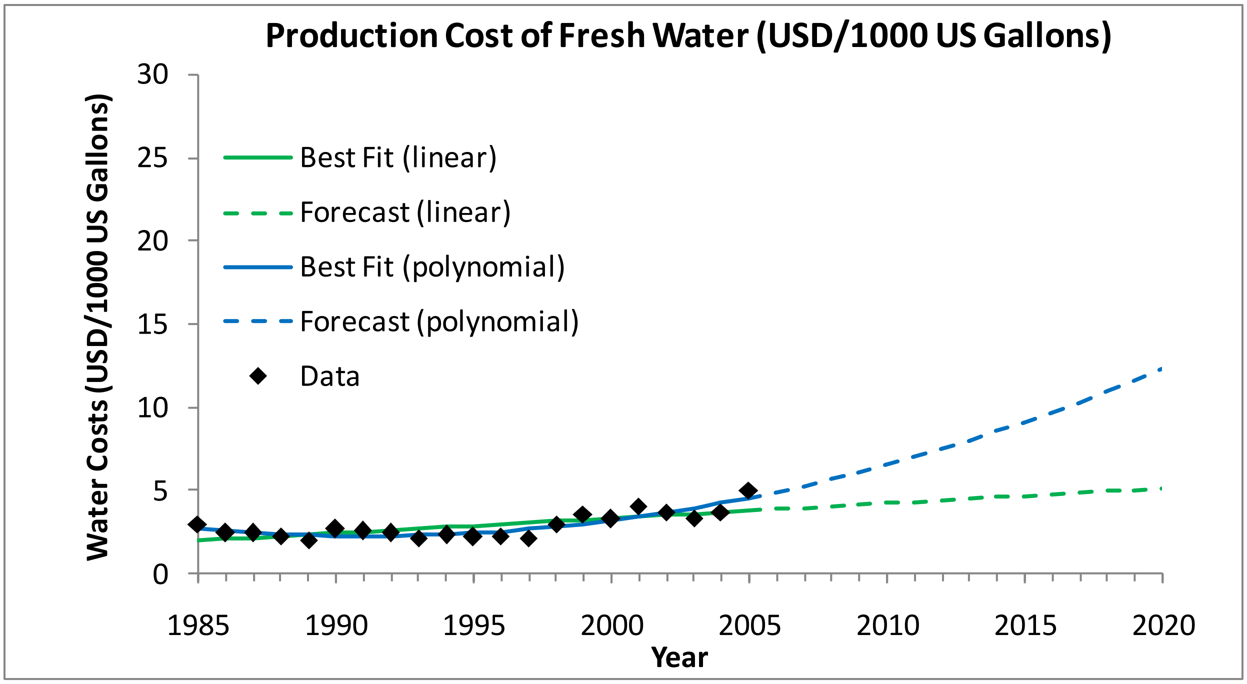

Figure 3-15 Total Production Cost of Fresh Water in USD per 1,000 US Gallons (1985 – 2020). Data from (The Administration of Studies & Researches, 2008)

CHAPTER 4: MATHEMATICAL PROGRAMMING MODEL FOR THE IMPLEMENTATION AND CAPACITY EXPANSION OF COGENERATION PLANTS IN KUWAIT

This section introduces the assumptions, notation and model for the cogeneration of water and electricity capacity expansion model.

4.1 Data Sets

Data sets define the main decision components of the model. The decision variables are formed by the Cartesian product of the sets. The decision variables are used in linear combinations to form the objective function and constraints.

i Plant technology defined as follows: 1 Oil-MSF, 2 NG-MED, 3 NG-RO, 4 SWEP-MED, and 5 SEW-RO ($i = 1,2, \dots, N$)

j Production inputs, including oil, sun, water, natural gas among others. Different plant technologies use different sets of inputs ($j = 1,2, \dots, J$)

k Plant number ($k = 1,2, \dots, K$). This set indicates the number of plant of each type

t Planning *horizon in years*, $t = 1,2, \dots ,37$. Data is based from year 2013 until 2050 $(1,2, \dots, T)$

m Markets to be supplied it consists of the set $\{water, electricity\}$.For representation purposes the set m is indexed as $m = 1, \dots, M$

4.2 Model Parameters

Model parameters refer to the realization of the data describing the system scenarios for which the model is constructed and validated. Model parameters in for the case of the cogeneration plant capacity expansion model constitute simplified representation of the operating conditions of the cogeneration plants. It also includes geographically aggregated demand forecasts.

$A_{ji}^{\min}$ Minimum amount of input j that can be purchased for plant of technology i (oil: barrels, natural gas: ft^3)

$A_{ji}^{\max}$ Maximum amount of input j that can be purchased for plant of technology i (oil: barrels, natural gas: ft^3)

C_i^{inv} Plant investment cost (fixed-charge) for plants of technology i ($/Plant)

C_i^{exp} Improvement cost (fixed-charge) for plants of technology i ($/Improvement)

C_{im}^{cap} Investment cost (variable) for plants of technology i for generation of product m ($/M US Gal/year, $/ MW/year)

C_i^{oper} Operational cost of plant i($/utilization percent)

C_{it}^{inp} Estimated cost of input $j$at time t (Oil: $/barrel; Natual Gas: $/ft^3$)

d_{mt}^{min} Minimum demand estimate for product of market m for planning period t(M US Gal/year, MW/year)

d_{mt}^{max} Maximum demand estimate for product of market m for planning period t(M US Gal/year, MW/year)

I_{ijm} Requirement of input j by plant of technology i to generate product for market m (Oil: barrels/MW, barrels/ M US Gal; Natural Gas: ft^3/MW, ft^3/ M US Gal natural gas: ft^3)

P_{mt} Sales price of product m at time t ($/M US Gal, $/MW)

$Q_{im}^{\min}$ Minimum or starting capacity for plants of technology i (M US Gal/year, MW/year)

$Q_{im}^{\max}$ Maximum capacity for plants of technology i (M US Gal/year, MW/year)

α Maximum operating level for new plants (Dimensionless from 0 to 1)

$\gamma_{im}^{\min}$ Minimum capacity expansion for plants of technology i (M US Gal/year, MW/year)

$\gamma_{im}^{\max}$ Maximum capacity expansion for plants of technology i (M US Gal/year, MW/year)

ψ^{up} Maximum increase in operating levels between successive periods expressed as a factor of the operating level of the previous period (dimensionless from 1 to infinite, used 1)

ψ^{lo} Minimum operating level for a plant based on the operating level of the previous period (dimensionless from 0 to1, used 0)

4.3 Decision Variables

The decision variable represents the factor in control of the decision-maker which in this case is a government entity in charge of the implementation of new cogeneration plants based on costs and available technology. The decision variables are indexed based on the previously defined sets.

a_{jikt} Amount of input j purchased by plant k of technology i at time t (oil: barrels, natural gas: ft^3)

q_{ikmt} Installed capacity for plant k of technology i for product m at time t (water: M US Gal/year; electricity MW/year)

v_{ikmt} Capacity expansion for plant k of technology i for product m at period t (water: M US Gal/year; electricity MW/year)

w_{ikt} Operating level for plant k of technology i at time t (Dimensionless from 0 to 1)

x_{ikmt} Amounts of product m generated by plant k of technology i at time t (water: M US Gal; electricity MW)

y_{ikt} 1 if plant k of technology i is open at the beginning of period$t$; 0 otherwise (dimensionless)

z_{ikt} 1 if plant k of technology i is expanded at the beginning of period$t$; 0 otherwise (dimensionless)

4.4 Model Construction

The proposed energy and water planning and management model was based on a 37-year planning horizon. The process and rationale for the construction of the model is presented in the following section. The model was adapted from multi-period MILP model of Sahinidis and Grossmann [9] originally developed for planning of chemical complexes. The five different plant technologies considered, after eliminating options not feasible for Kuwait such as Nuclear, are, Oil-Multi Stage Flash (Oil MSF), Natural Gas Multi-Effect (NG MED), Natural Gas Reverse Osmosis (NG RO), Solar Wind Energy Plant Multi Effect (SWEP MED), and Solar Wind Energy Plant Reverse Osmosis (SWEP RO). In this section, the demand for each product, investment and operational costs for each technology option, plant production capacity relations, and material and energy input requirements will be discussed first. The integrated MILP model will be subsequently described

4.4.1 Production-Demand Relationships

The demand for water and electricity was forecasted for the planning horizon of 37 years using historical data. Historical data on electricity and water consumption per capita, gross national income forecast per capita, and population growth data are used to forecast the lower and upper bounds for both water and electricity consumption. The specific are shown by AlQattan (2014). The produced quantities x_{ikmt} should fall between these lower and upper bounds. Figure 4-1 shows the water demand forecast and Figure 4-2 shows the electric power demand forecast for the planning horizon.

Constraints for the produced amounts for each of the products water $(m = 1)$ and electricity $(m = 2)$ in the lower bound demand forecast of the corresponding model are expressed as follows:

$$\sum_{i=1}^{N}\sum_{k=1}^{K} x_{ikmt} \geq d_{im}^{\min} \;\; \forall\, m, t \qquad (4.1)$$

Similarly, for the upper bound demand forecast, the produced amounts for each of the products water $(m = 1)$ and electricity $(m = 2)$ for all the periods $(t = 1,2, \ldots ,37)$ thecorresponding model constraints are expressed as follows:

$$\sum_{i=1}^{N}\sum_{k=1}^{K} x_{ikmt} \leq d_{im}^{\max} \; \forall \, m, t \tag{4.2}$$

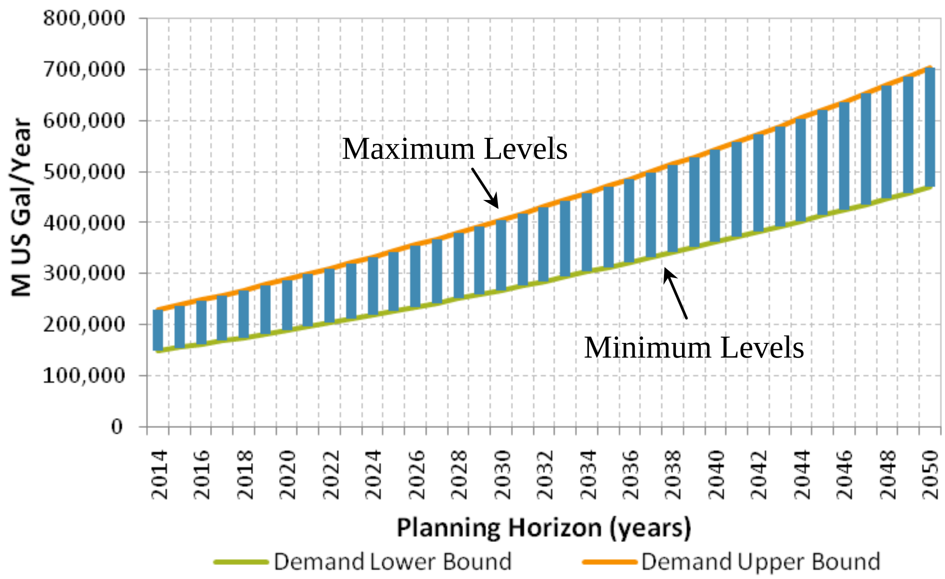

Figure 4-1 Water Demand Forecasts

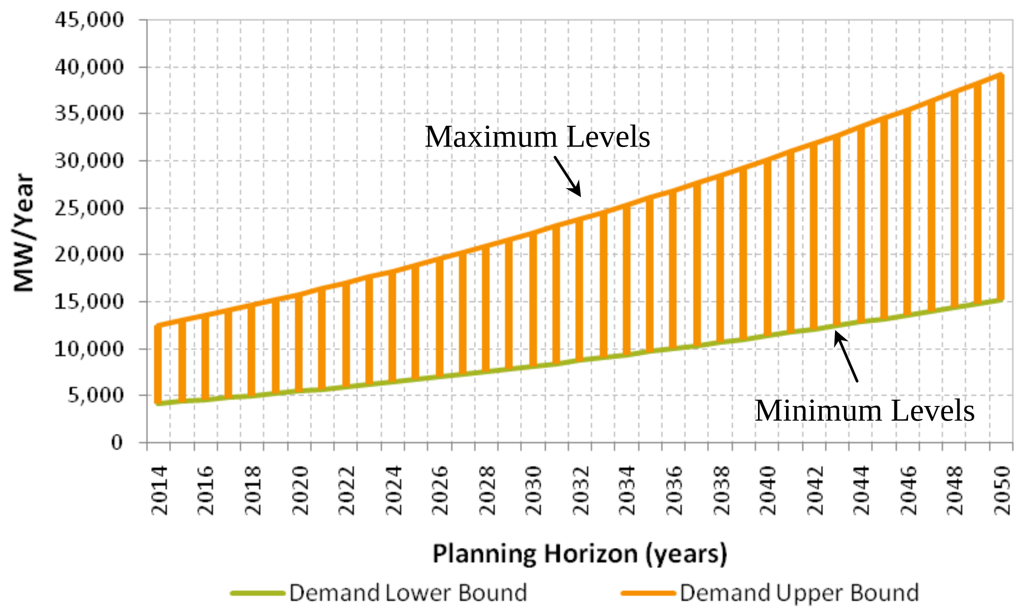

Figure 4-2 Electric Power Demand Forecasts

4.4.2 Plant Implementation Costs

Plant investment cost encompasses a series of aggregated costs such as land acquisition, equipment, and construction, among others,combined into a single parameter C_i^{inv}. The plants will start with an initial capacity of $Q_{im}^{\min}$. Once the plant is build, capacity can be expanded at a fixed cost C_i^{exp} and for each product (water, electricity), the variable cost for adding capacity is C_{im}^{cap}. The annual expense is expressed as the total cost of operation of a plant operating at 100% of its maximum capacity. This cost is multiplied by the operational level of the plant of the period (i.e. 80 percent) to obtain the operational costs of the period. The technology costs coefficients presented in the following Table 4-1 are estimated using information from Afgan (2007) and Kuwait official governmental publications and expanded in AlQattan (2014).

Table 4-1 Investment, Capacity Expansion and Operational Costs for Each Technology Option

PlantTechnology	Fixed-Charge Investment C_i^{inv}	Fixed-ChargeExpansion C_i^{exp}	Variable Cost per Capacity expansion unitC_{im}^{cap}		OperationalCostC_i^{oper}
	USD/Plant	USD/Expansion	Water USD/M US Gal	Electricity (USD/MW)	USD/ utilization percent
Oil MSF	143,089,000	14,308,900	72	1,359	25,756,020
NG MED	158,576,000	15,857,600	79	1,506	23,786,400
NG RO	130,542,000	13,054,200	65	1,240	23,497,560
SEWP MED	430,000,000	43,000,000	215	4,085	8,600,000
SEW RO	429,980,000	42,998,000	215	4,085	12,899,400

4.4.3 Production Capacity Relationships

The production capacity for each technology and their possible expansions are both subject to upper and lower bounds. The maximum and minimum bounds are heuristically derived based on size and investment costs of existing plants utilizing the corresponding technologies and their economy of scale factors. The lower bound corresponds to the minimum capacity necessaryto erect a new plant and the maximum recommended capacity forms the upper bound. These values are shown in Table 4-2.

Table 4-2 Minimum Initial Plant Capacity and Maximum Plant Capacity for Each Technology

	Minimum Initial Capacity ($Q_{im}^{\min}$)		Maximum Capacity ($Q_{im}^{\max}$)	
	Water (M US Gal/Year)	Electricity (MW/year)	Water (M US Gal/Year)	Electricity (MW/year)
Oil MSF	32,000	950	80,000	2,375
NG MED	25,000	1,400	62,500	3,500
NG RO	18,411	1,200	46,026	3,000
SEWP MED	9,500	150	23,750	375
SEW RO	12,000	130	30,000	325

The capacity expansion factors are designed to allow reasonable increments to the initially installed cogeneration capacity during the lifetime of the plant. The maximum capacity expansion parameters limit the amount of capacity that can be added at any given time. Lower expansion ratios suffer from economy of scale limits and very large expansions are bound by the ability of the existing infrastructure in the site to handle the expansion. These factors are expressed as a percentage of the capacity of the plant (e.g. 10 percent of $Q_{im}^{\max}$) and given in Table 4-3. The actual bounds or interval to limit the capacity expansion are presented in Table 4-4.

For model consistency, a plant cannot produce unless it is previously implemented. The implementation variable for a plant is y_{ikt} and it is use to express this condition as follows:

$$x_{ikmt} \leq Q_{im}^{\max} \sum_{h \leq t} y_{ikh}; \forall\, i, k, t \tag{4.3}$$

Table 4-3 Capacity Expansion Bound as Percentage of the Plant Capacity by Technology

	Minimum Capacity Improvement $\gamma_{im}^{\min}$ as % of initial capacity		Maximum Capacity Improvement $\gamma_{im}^{\max}$ as % of maximum capacity	
	Water (M US Gal/Year)	Electricity (MW/year)	Water (M US Gal/Year)	Electricity (MW/year)
Oil MSF	11%	21%	35%	24%
NG MED	11%	25%	30%	30%
NG RO	8%	16%	27%	29%
SEWP MED	21%	17%	31%	32%
SEW RO	17%	21%	32%	28%

This condition will hold as long as at most one plant of each type is open for the entire planning horizon. This condition is expressed in the following equation:

$$\sum_{t=1}^{T} y_{ikt} \leq 1; \forall\, i, k \tag{4.4}$$

Table 4-4 Capacity Expansion Bounds by Plant Technology

	Minimum Capacity Improvement $\gamma_{im}^{\min}$		Maximum Capacity Improvement $\gamma_{im}^{\max}$	
	Water (M US Gal/Year)	Electricity (MW/year)	Water (M US Gal/Year)	Electricity (MW/year)
Oil MSF	3,520	200	28,000	570
NG MED	2,750	350	18,750	1,050
NG RO	1,473	192	12,427	870
SEWP MED	1,995	26	7,363	120
SEW RO	2,040	27	9,600	91

The capacity for a plant at each period is given by the continuous variable q_{ikmt} for each plant k of technology i for each product m (water or electricity) for each period t of the planning horizon. The production for each product m cannot exceed such capacity. This relationship is expressed as follows:

$$x_{ikmt} \leq q_{ikmt} \; \forall \; i, k, m, t \tag{4.5}$$

The operating level of a plant is given by the continuous variable w_{ikt}.This variable expresses the operating level of a plant as a fraction of the maximum capacity. If this variable is set to 80 percent, then the plant will operate at 80 percent of the maximum capacity for water and 80 of the maximum capacity for electricity. This variable helps in coupling the production of water and electricity with the operating level of a plant avoiding situations where, for instance, only water production is active and there is no production of electricity. This relationship is expressed below:

$$x_{ikmt} \leq Q_{im}^{\max} w_{ikt} \; \forall \; i, k, m, t \tag{4.6}$$

The capacity of a plant is a non-decreasing function as can be observed in Figure 4-3. The plant starts with the initial capacity $Q_{im}^{\min}$ and remains constant until a capacity improvement occurs ($z_{ikt} = 1$).At that instant, the plant capacity is increased by v_{ikmt} . The capacity increase should be between the minimum $\gamma_{im}^{\min}$ and the maximum$\gamma_{im}^{\max}$. Plant capacity is incrementally increased until the maximum plant capacity $Q_{im}^{\max}$ is reached.

The constraint expressing capacity increases is shown below with the maximum allowable capacity increase for the plant represented by $\gamma_{im}^{\max}$:

$$v_{ikmt} \leq \gamma_{im}^{\max} z_{ikt} \; ; \forall \; i, k, m, t \tag{4.7}$$

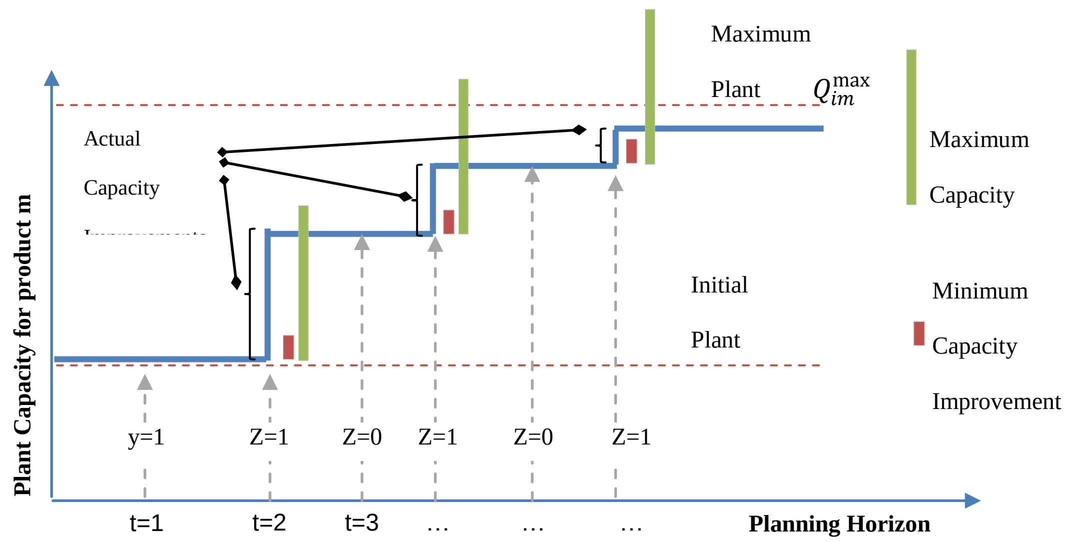

Figure 4-3 Plant Capacity as a Non-Decreasing Function

Similarly, when a capacity expansion occurs, the increase in capacity should be more than the minimum allowable level, γ_{im}^{min} . This is based on the minimum capacity for one turbine or generator. This constraint is expressed as follows:

$$v_{ikmt} \geq \gamma_{im}^{min} z_{ikt} \; ; \forall \; i, k, m, t \qquad (4.8)$$

The installed capacity for a plant can increase up to the maximum allowable capacity for each plant technology Q_{im}^{max} . This is expressed as follows:

$$q_{ikmt} \leq Q_{im}^{max} \; ; \forall \; i, k, m, t \qquad (4.9)$$

There cannot be capacity expansion unless the plant is already operational. Moreover, an additional constraint is that new plant capacity expansion can only occur b years or periods after original implementations. This "b" may be taken as 5. The general form for this time-related constraint is expressed as follows:

$$z_{ikt} \leq 1 - \sum_{h=t-b}^{t-1} y_{ikh} \; ; \forall \; i, k, t \geq b + 1 \qquad (4.10)$$

Additionally, there should be a period of $e = 5$ years between successive capacity expansions. This is expressed as follows:

$$z_{ikt} \leq 1 - \sum_{h=t-e}^{t-1} z_{ikh} \; ; \forall \, i, k, t \geq e + 1 \qquad (4.11)$$

To prevent substantial increase in production levels between periods, an additional set of constraints was introduced which prevented the model from drastically increasing production of one plant between successive periods. In addition, it can prevent sudden shifts of production from existing plant to newly implemented plants. It was assumed that no plant could increase production more than 1 times (ψ^{up}) the production of the previous period. For new plants, only 50% (α) of its capacity can be utilized during the first year of implementation.

$$w_{ikt} \leq \psi^{up} w_{ikt-1} + \alpha y_{ikt} \qquad (4.12)$$

Similarly, for downward shifts in production, the demand of the plants cannot be drastically decreased from one period to the next one. In this case, the production was constrained to 90% (ψ^{lo})of previous year production which means a reduction of 10% per year. This will allow gradual decommissioning of existing plants or maintaining them at minimum operating levels for use during periods of excess demand (ψ^{lo}).

$$w_{ikt} \geq \psi^{lo} w_{ikt-1}; \forall i, k, t \qquad (4.13)$$

4.4.4 Plant Inputs

Each cogeneration plant technology i has its own set of input requirements. Such input requirements, or recipe for each plant, is given by I_{ijm} and is presented in Table 4-5. The amount of materials acquired ($A_{ji}^{\min}$) for each plant technology i is fixed for open plants due to technical limits or contractual agreements that guarantee a set purchase amount for each period. In other words, the model assumes that once a plant is open, it should consume at least an amount of materials. For solar plants a one-to-one conversion was assumed provided that the solar radiation exposure is incorporated in the capacity of the plant. Lastly, an estimation of the sales price for water and electricity is also provided to add additional economic implications to the proposed capacity planning model. The prices for oil (per barrel) and natural gas (per 100 cubic ft) are presented in Figure 4-4.

Table 4-5 Amount of Inputs to Produce Water and Electricity by Plant Technology

		Amount of input I_{ijm}	
		per M US Gal	per MW
Plant i	Input j	Water	Electricity
Oil MSF	Crude Oil (barrel)	376	4,164
NG MED	Crude Oil (barrels)	150	3,200
	Natural Gas (100 cubic ft)	250	900
NG RO	Natural Gas (100 cubic ft)	421	1,200
SEWP MED	solar radiation (kwh/m^2)	1	1
SEW RO	solar radiation (kwh/m^2)	1	1

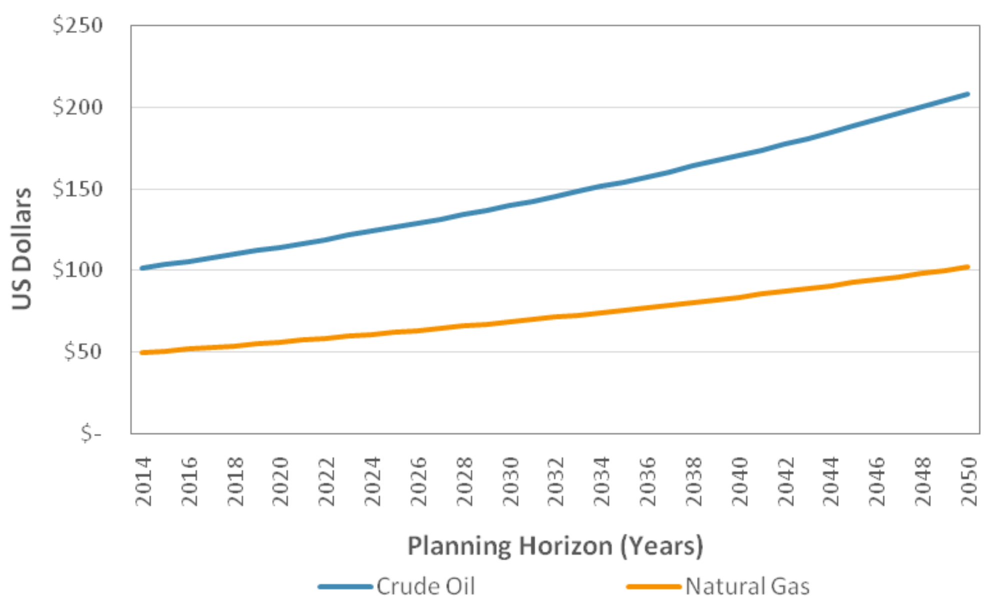

Figure 4-4 Input Costs for Crude Oil (Barrels) and Natural Gas (ft^3)

4.5 Mathematical Model

The mathematical model representing the cogeneration capacity planning model is presented below:

$$
\begin{aligned}
\max_{x,y,z,v,w,a} \sum_{t=1}^{T} \Bigg[& \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{i=1}^{N} P_{mt}\, x_{ikmt} \\
& - \Bigg(\sum_{k=1}^{K}\sum_{i=1}^{N} C_i^{imp}\, y_{ikt} + \sum_{k=1}^{K}\sum_{i=1}^{N} C_i^{exp}\, z_{ikt} \\
& + \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{i=1}^{N} C_i^{cap}\, v_{ikmt} + \sum_{k=1}^{K}\sum_{i=1}^{N} C_i^{op}\, w_{ikt} \\
& + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{i=1}^{N} C_{jt}^{inp}\, a_{jikt} \Bigg) \Bigg] NPV_t
\end{aligned}
\tag{4.14}
$$

Subject to:

$$\sum_{i=1}^{N}\sum_{k=1}^{K} x_{ikmt} \geq d_{im}^{\min} \quad \forall\, m,t \tag{4.15}$$

$$\sum_{i=1}^{N}\sum_{k=1}^{K} x_{ikmt} \leq d_{im}^{\max} \quad \forall\, m,t \tag{4.16}$$

$$x_{ikmt} \leq Q_{im}^{\max} \sum_{h \leq t} y_{ikh};\ \forall\, i,k,t \tag{4.17}$$

$$\sum_{t=1}^{T} y_{ikt} \leq 1;\ \forall\, i,k \tag{4.18}$$

$$x_{ikmt} \leq q_{ikmt} \quad \forall\, i,k,m,t \tag{4.19}$$

$$x_{ikmt} \leq Q_{im}^{\max} w_{ikt} \quad \forall\, i,k,m,t \tag{4.20}$$

$$v_{ikmt} \leq \gamma_{im}^{\max} z_{ikt}\ ;\forall\, i,k,m,t \tag{4.21}$$

$$v_{ikmt} \geq \gamma_{im}^{\min} z_{ikt}\ ;\forall\, i,k,m,t \tag{4.22}$$

$$z_{ikt} \leq 1 - \sum_{h=t-b}^{t-1} y_{ikh} \; ; \forall\, i, k, t \geq b + 1 \tag{4.23}$$

$$w_{ikt} \leq \sum_{h \leq t} y_{ikh} ; \forall\, i, k, t \tag{4.24}$$

$$q_{ikmt} \leq Q_{im}^{\max} ; \forall\, i, k, m, t \tag{4.25}$$

$$z_{ikt} \leq 1 - \sum_{h=t-e}^{t-1} z_{ikh} \; ; \forall\, i, k, t \geq e + 1 \tag{4.26}$$

$$a_{jikt} \geq \sum_{m=1}^{M} I_{ijm}\, x_{ikmt} \; ; \; \forall\, j, i, k, t \tag{4.27}$$

$$a_{jikt} \geq A_{ji}^{min} \sum_{h \leq t} y_{ikt} \; ; \forall j, i, k, t \tag{4.28}$$

$$a_{jikt} \leq A_{ji}^{max} \sum_{h \leq t} y_{ikt} \; ; \forall j, i, k, t \tag{4.29}$$

$$w_{ikt} \leq \psi^{up} w_{ikt-1} + \alpha y_{ikt} \tag{4.30}$$

$$w_{ikt} \geq \psi^{lo} w_{ikt-1} ; \forall i, k, t \tag{4.31}$$

$$y_{ikt} \in \{0,1\}; z_{ikt} \in \{0,1\} \tag{4.32}$$

$$v_{ikmt} \geq 0; q_{ikmt} \geq 0; w_{ikmt} \geq 0; x_{ikmt} \geq 0; a_{jiktm} \geq 0 \tag{4.33}$$

The objective function represents the net present value for the profit of selling water and electricity according to the demand forecast. The inner most part of the objective function represents the operational costs which are implementation, expansion, production and inputs. The constraint group (4.15) ensures that the generation of water and electricity at least meets the minimum demand for each period. On the other hand, constraint (4.16) enforces the ceiling for maximum sales for water and energy for the planning horizon. Constraint (4.17) ensures that there is no production of water of electricity from a specific plant unless that plant is open. Constrain (4.18) guarantees that a plant can be open or implemented at most once. It does not constrain that the plant may not be open at all. Constrain (4.19) establishes that the generation of water or electricity should not exceed the installed capacity. Constraint (4.20) limits the production to the operating level of the plant which is a fraction of the total capacity of the plant. Constraint (4.21) sets the upper limits of the capacity expansion for the generation of product m. Notice that constraint (4.21) also guarantees that expansion for generation of product m only occurs when a global plant capacity expansion (fixed charge) is decided. Similarly, constraint (4.22) sets the lower limits for capacity expansion for the generation of product m only when a global expansion (z_{ikt}) occurs. Constrain (4.23) enforces that capacity expansion occurs after b periods after plant implementation ($y_{ikt} = 1$). Constraint (4.24) guarantees that the operating level of a plant should be zero if the plant is not implemented. Constraint (4.25) enforces that the maximum installed capacity should not exceed the maximum capacity allowed for plant of technology$i$. Constraint (4.26) establishes that there will be at least e periods or years between capacity improvements for the same plant. Constraint (4.27) ensures that the required amount of inputs can be obtained at the beginning of each period for the generation of water and electricity. Constraint (4.28) limits the minimum amounts of inputs to be obtained for open plants. Similarly, constraint (4.29) establishes a ceiling on the amounts of inputs to be obtained for the generation of water and electricity for each plant technology i. Constraint group (4.30) restrict sharp changes in the production of a plant between consecutive periods for increasing productions levels, also for new plants this constrain ensures that the plant will be used at most half of its capacity ($\alpha = 0$) during the first year of operation. Constraint (4.31) limits the reductions in operating levels between successive periods for the same plant. It guarantees that production on certain period will be at least ψ^{lo} percent of the operating level in the previous period. Constraint (4.32) indicates the plant implementation and capacity expansion binary variables. Constraint (4.33) establishes the non-negativity conditions for capacity variables, operating levels, generation of water and electricity and inputs.

CHAPTER 5: SOLUTION OF THE PROPOSED PLANNING MODEL

The desalination and electricity cogeneration MILP formulation was implemented using GAMS (2013) and solved via CPLEX-MIP solver engine. In this work, multiple scenarios were analyzed. Aggregated demand, installed capacity and production analysis are followed by recommended technology options over time and the section will be concluded by analyzing relative costs of each technology and their distribution over time.

5.1 Aggregate Demand Profile, Installed Capacity, and Production

Figure 5-1 presents the lower and upper bound for water demand, installed capacity (staircase line) and aggregated production (points) for all plants by year. It can be observed in Figure 5-1 that the current water capacity can meet the optimistic demand (lower bound) for the planned forecast. By year 2050, the production will have a closer gap the demand.

For electric power, the model results are presented in Figure 5-2. The lower and upper bound for electric power demand are presented. The stepped line corresponds to the installed capacity in MW per year. The points correspond to the aggregated production for all plants. It can be observed that the installed capacity falls within the boundaries of the prediction for the demand at all times. This means that the planning solution may not be robust against all the values within the confidence interval of the demand forecast for electric power. The optimistic case of the demand is met at all times. The gap between the demand (lower bound) and the installed capacity for the electric power does not show a significant change during the forecasted 50 years period.

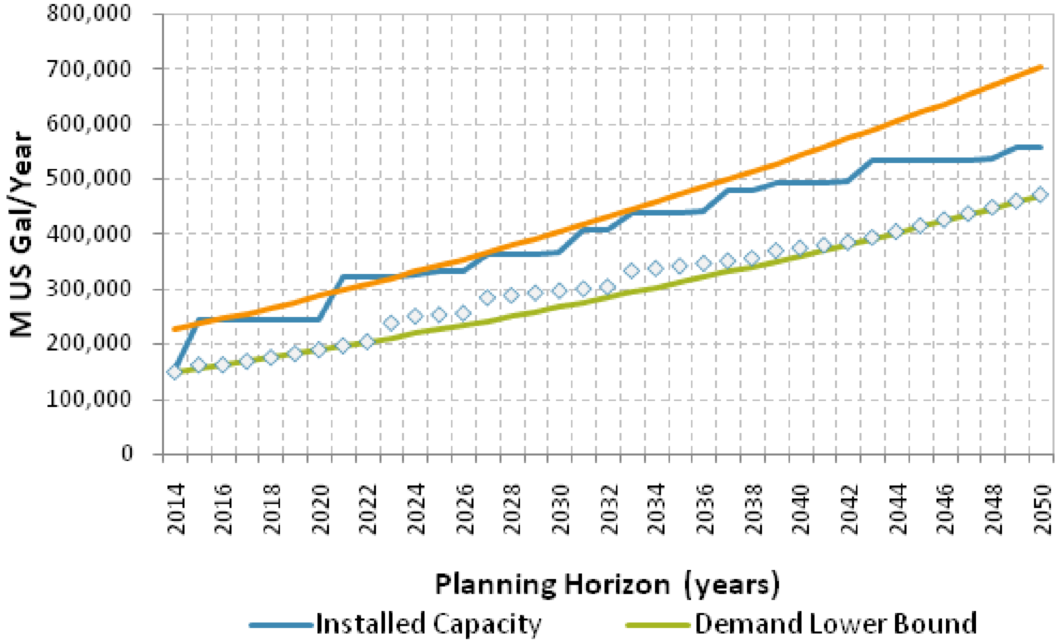

Figure 5-1 Water Demand and Production Scenarios

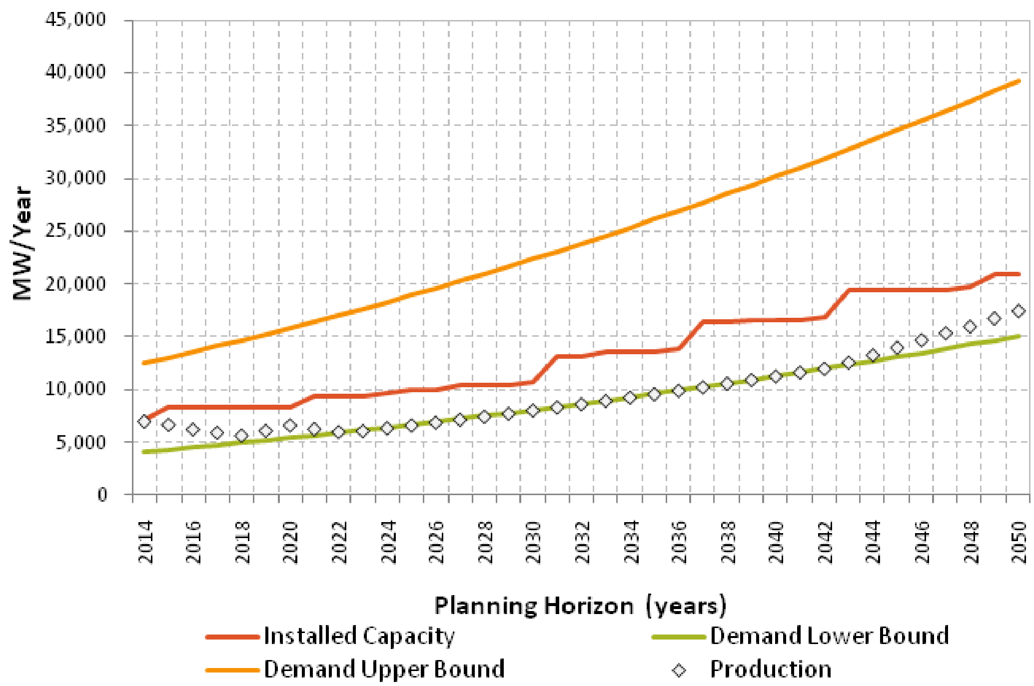

Figure 5-2 Electricity Production and Demand Scenarios

5.2 Technology Implementation and Capacity Expansion

Starting with existing plants, each year new plants may come on-line. The number of plants utilizing each of the five technologies from 2014 to 2050 is shown in Figure 5-3. The initial system capacity was met by plants with Multi Stage Flash (MSF) fueled by oil. The increasing price of oil poses as a significant constraint when determining the type of plant technology implemented afterwards. In contrast, SEWP MED and SEW RO plants can be developed in numbers to reach five plants during a period of six years. Even though the implementation costs for SWEPMED and SEW RO are significantly higher than that for oil and natural gas plants, relatively much lower operating costs and rising renewable prices make the solar plants a more attractive technology alternative in the early stages of the planning horizon.

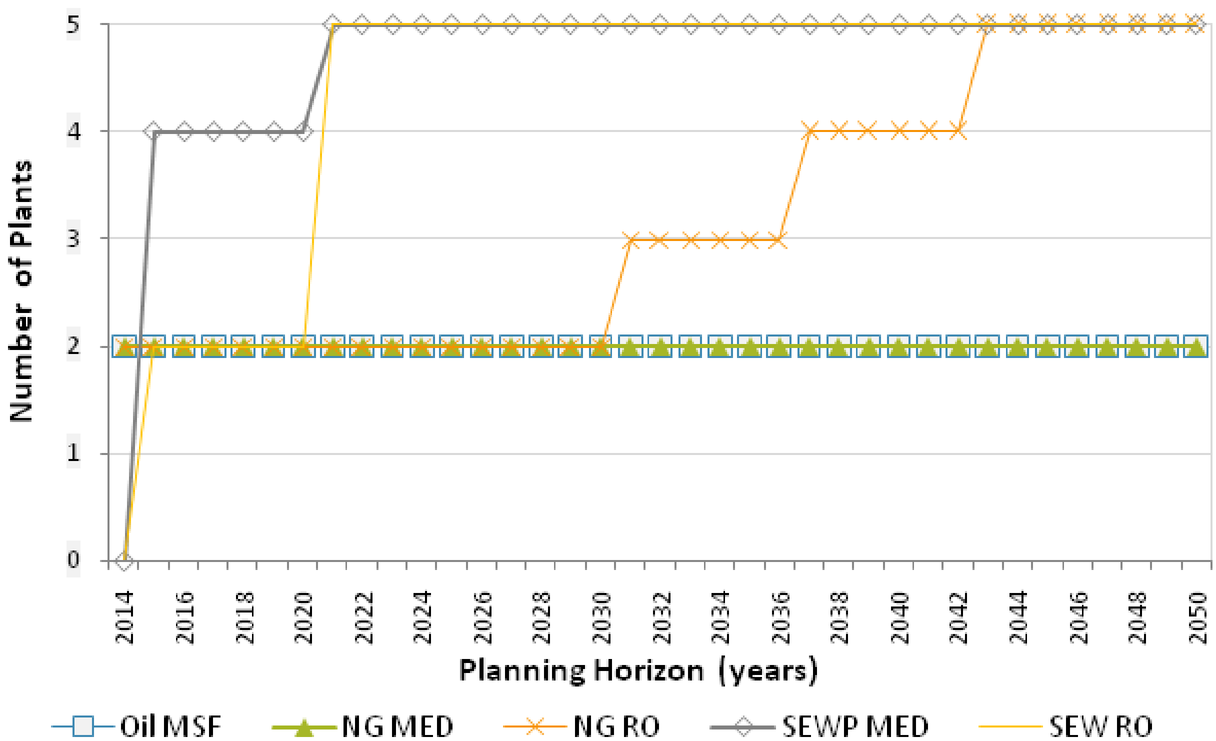

Figure 5-3 Plant Implementation by Technology and by Year

The installed capacity for water production through each technology is presented in Figure 5-4. It can be observed that initially, the solar based plants are the preferred technology and these are ramped up until they reached the maximum capacity and maximum number of plants. For further capacity increases, the next most cost-effective production system is natural gas (NG RO),which can be used after the effectiveness of the solar plants reach a maximum. This technology is used to continue expansion for the last 10 years of the planning horizon.

The production of water by plant technology by year is presented in Figure 5-5. It can be observed that the water production through oil and natural gas plants is gradually switched to solar plants in the first 10 years of the planning horizon. At the same time, during the initial stages of the planning horizon, there is a transition from fossil fuel to solar base production. By year 2038, the solar plant reached their maximum capacity and then the excess production is taken by the NG RO plants. The traditional oil-based plants are kept operational and are used to economically supply water demand when necessary.

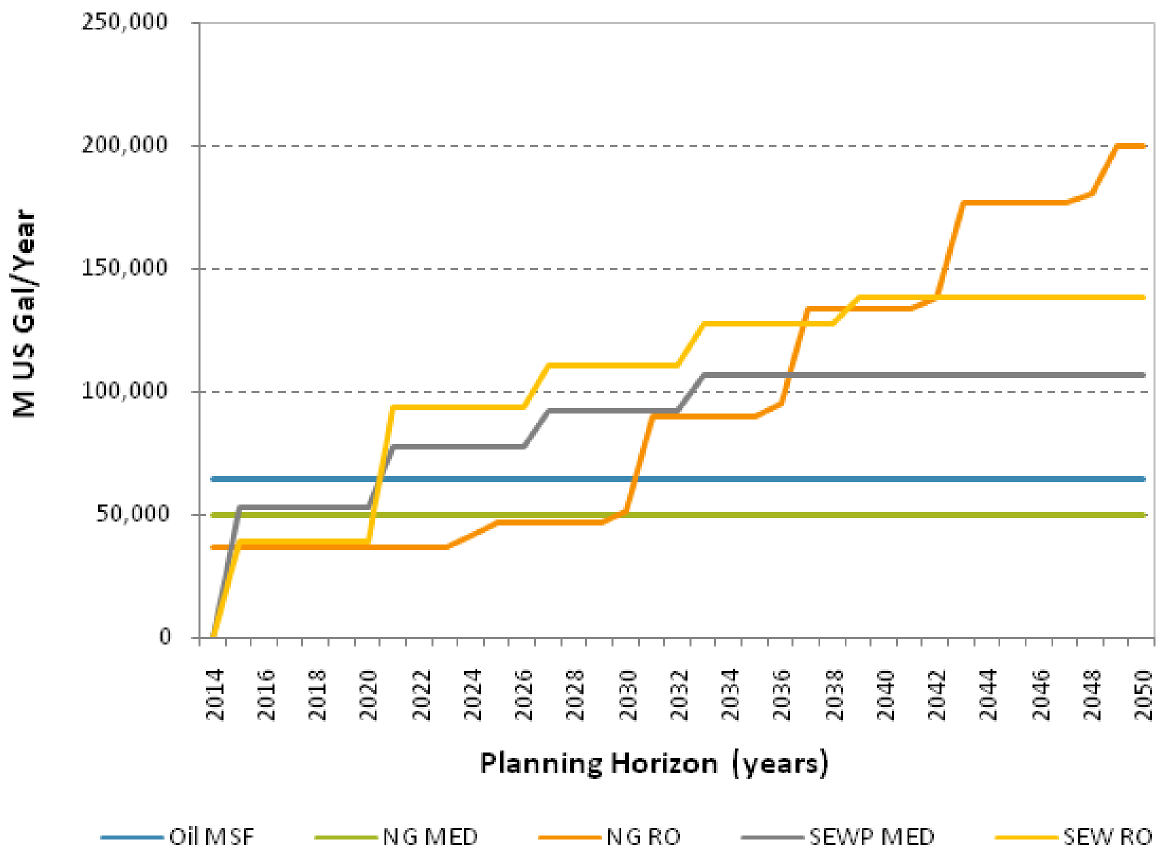

Figure 5-4 Water Capacity Expansions in Millions of US Gallons

Figure 5-6 presents the composition of the aggregated water production by plant technology. It can be observed that the production of water using solar-based plant increases during the first half of the planning horizon, and after the maximum is reached, thenproduction remains constant. In contrast, the production on oil-based plants is slowly decreased and kept at its economical minimum. These plants are strategically used only when it is technically and economically feasible. Beyond solar, NG RO turned out to be an economically feasible and scalable technology that is able to meet the future demand. If solar based plant can become more scalable, they will be the dominant technology in the future. It can be observed that by year 2050 the contribution to water production of oil based plants is less than 10 percent.

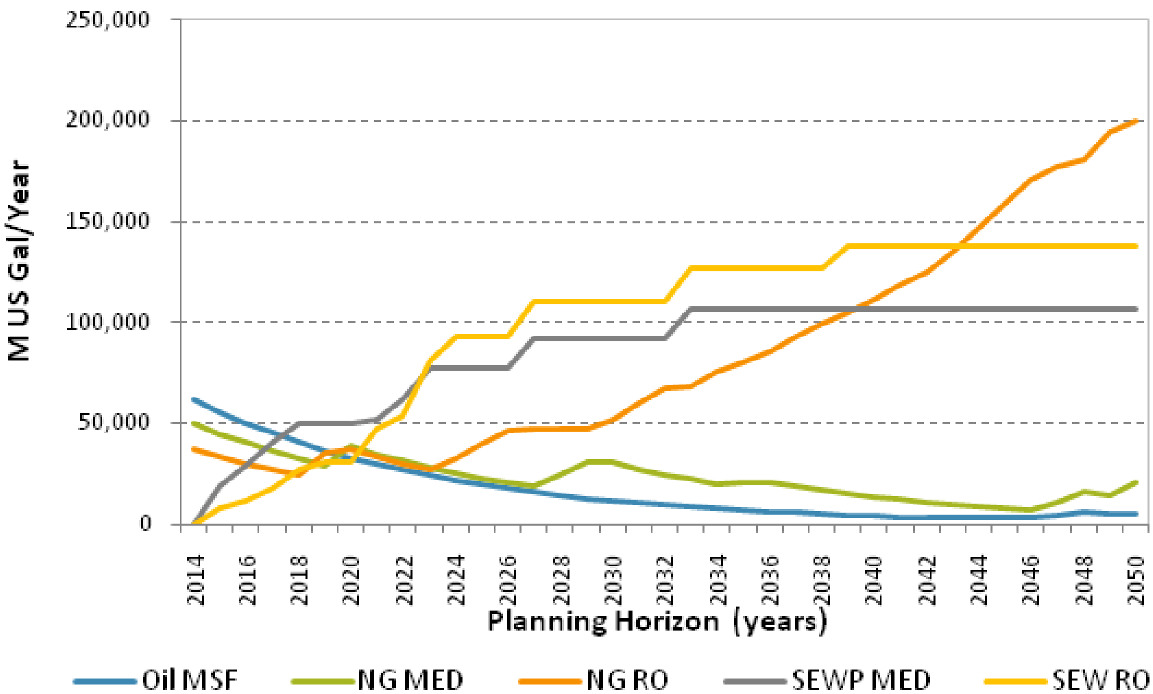

Figure 5-5 Millions of US Gallons Produced by Plant Technology

The installed capacity by for electric power generation is presented in Figure 5-7. It can be observed that the major limitation of solar plants is the generation of electric power. Even with the capacity increases it only achieves the base configuration for oil-based plants. On the other hand, NG RO technology is more scalable in terms of electric power generation and is more cost-efficient than oil-based plants.

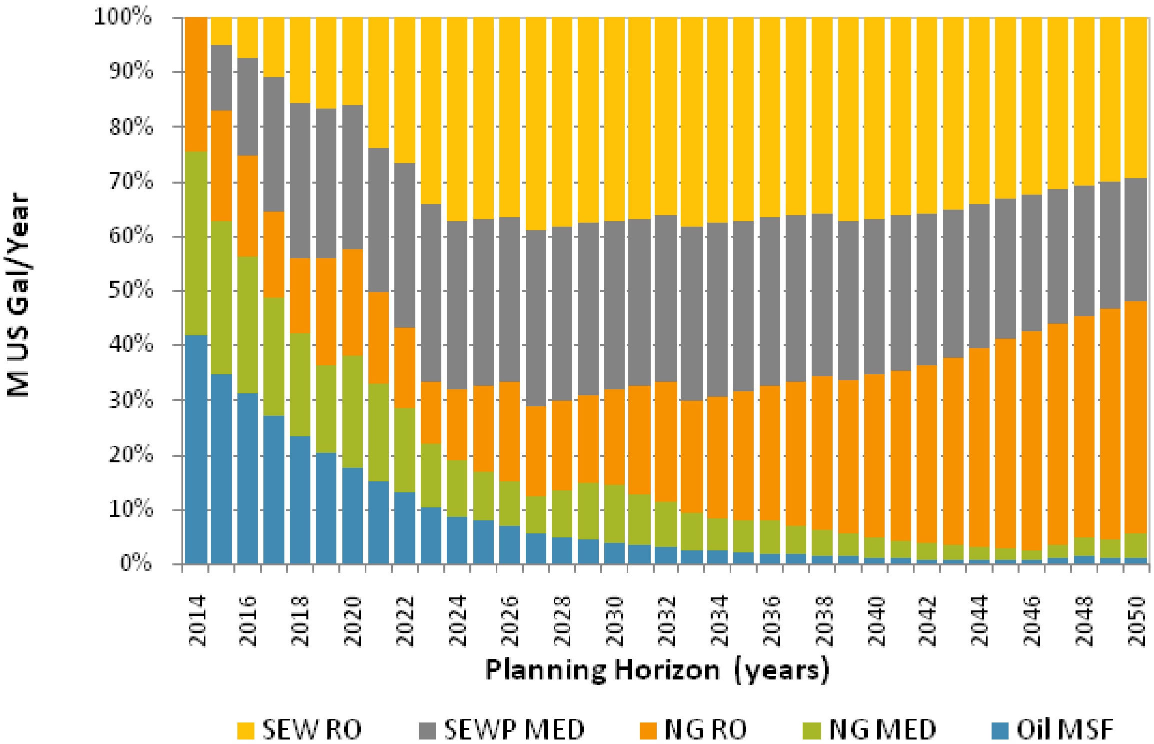

Figure 5-6 Distribution of Water Production by Plant Technology

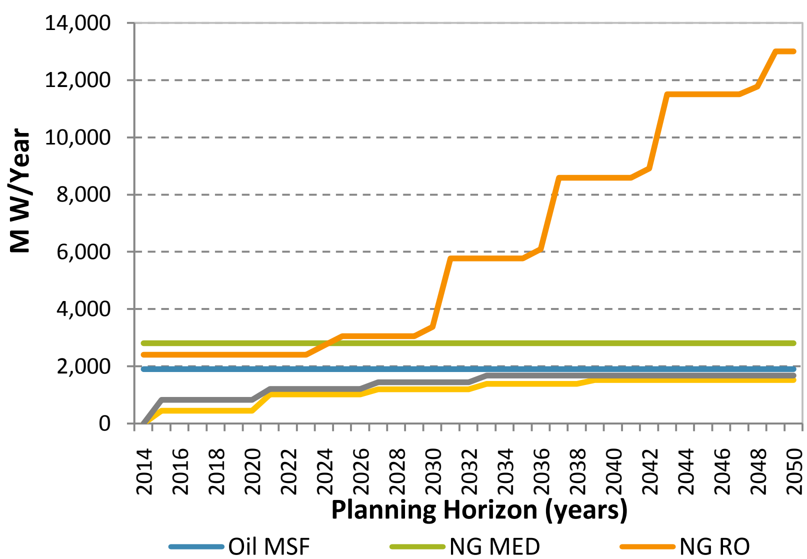

Figure 5-7 Electricity Capacity Expansion in Millions of Watts per Year

The composition of the total amount of electricity by plant type is presented in Figure 5-8. It can be observed that the generation of electricity is reduced in oil-based plants while NG RO dominates the generation due to its scalability. The contribution of solar plants in the total power generation by 2050 is at most 20 percent. The solar plant electricity generation capacity is primarily a technological limitation due to actual availability of sunlight.

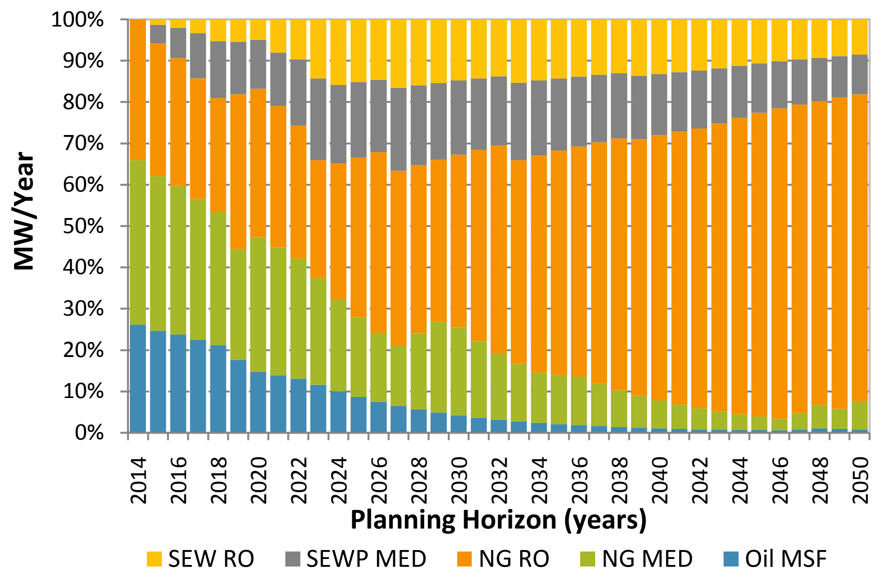

Figure 5-8 Distribution of Electric Power by Plant Technology

5.3 Relative Distribution of Revenues and Costs Over the Planning Horizon

The total cost of the operation including plant implementation for the planning horizon was $112,000,000,000 in present value dollars. The total revenues for the operation were estimated at $19,000,000. Figure 5-9 presents the revenues by collecting the service charges for the users of water and electricity. The revenues were calculated using the subsidized prices for water and electricity.

The total cost including inputs, implementation, capacity expansion and operation are presented in Figure 5-10. It can be observed that there is a peak early in the planning horizon due to the implementation of solar-based plants. After the solar plan implementation there is a general trend in lowering the total cost mostly driven by the reduction in oil dependency for water and electricity production. The increasing trend by the end of the planning horizon is due to the conversion from solar plant expansion to the utilization of natural gas technology, which becomes more favorable for the continuation of capacity expansion.

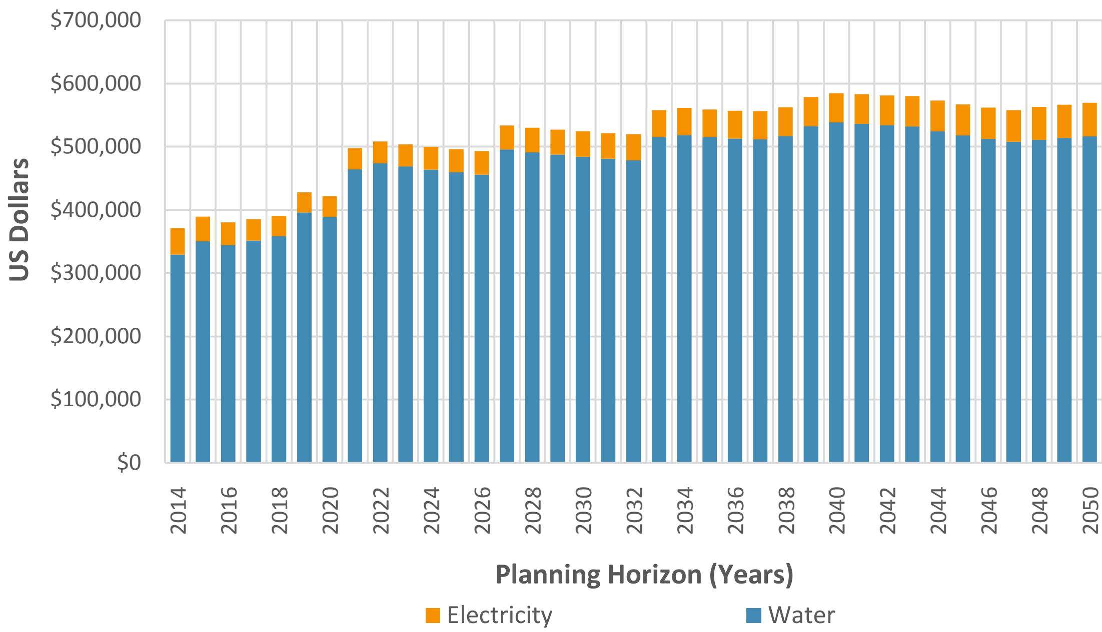

Figure 5-9 Water and Electricity Revenue Scenarios

The implementation cost by plant technology is presented in Figure 5-11. It can be observed that most of the implementation cost (new plants) is driven by solar-based cogeneration plants. It is also observed that implementation of natural gas occurred in the middle and by the end of the planning horizon.

The total cost of capacity expansion by technology is presented in Figure 5-12. It can be observed that capacity expansion is mostly driven by solar plants followed by natural gas plants. Natural gas plants were used to continue expansion after the solar plants reached their maximum number of plants and total capacity.

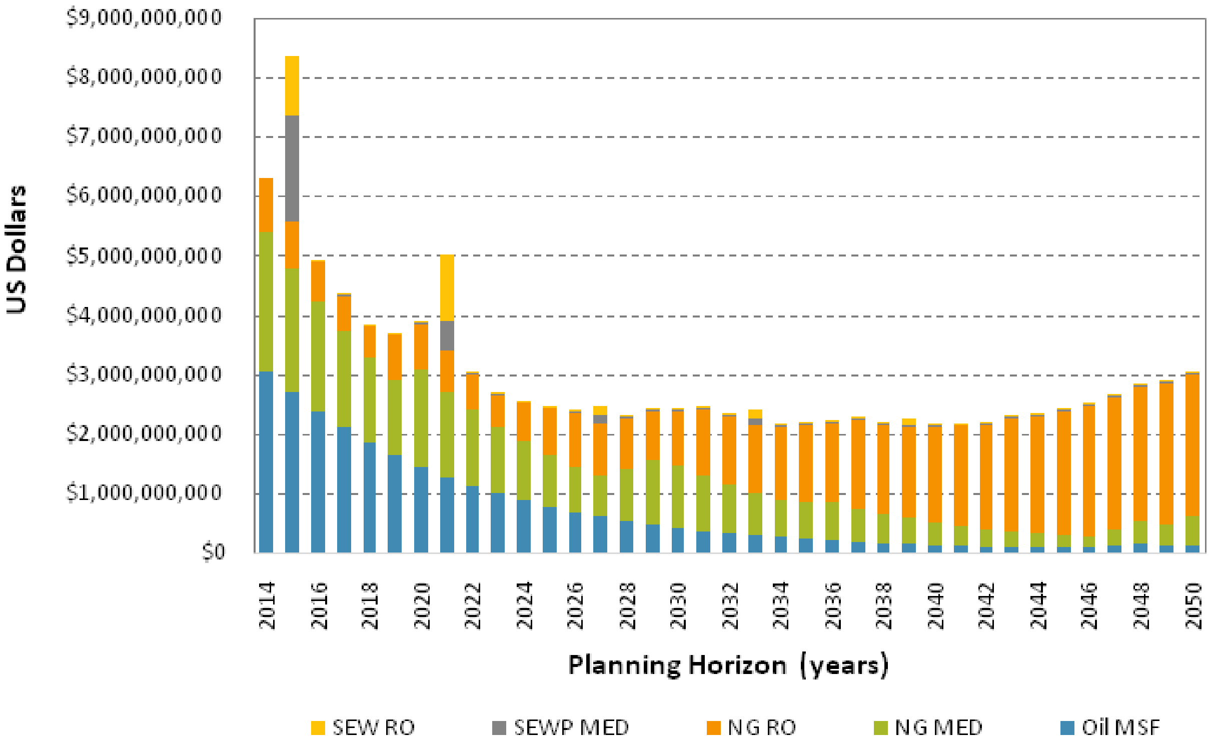

Figure 5-10 Total Cost of Materials by Technology in USD

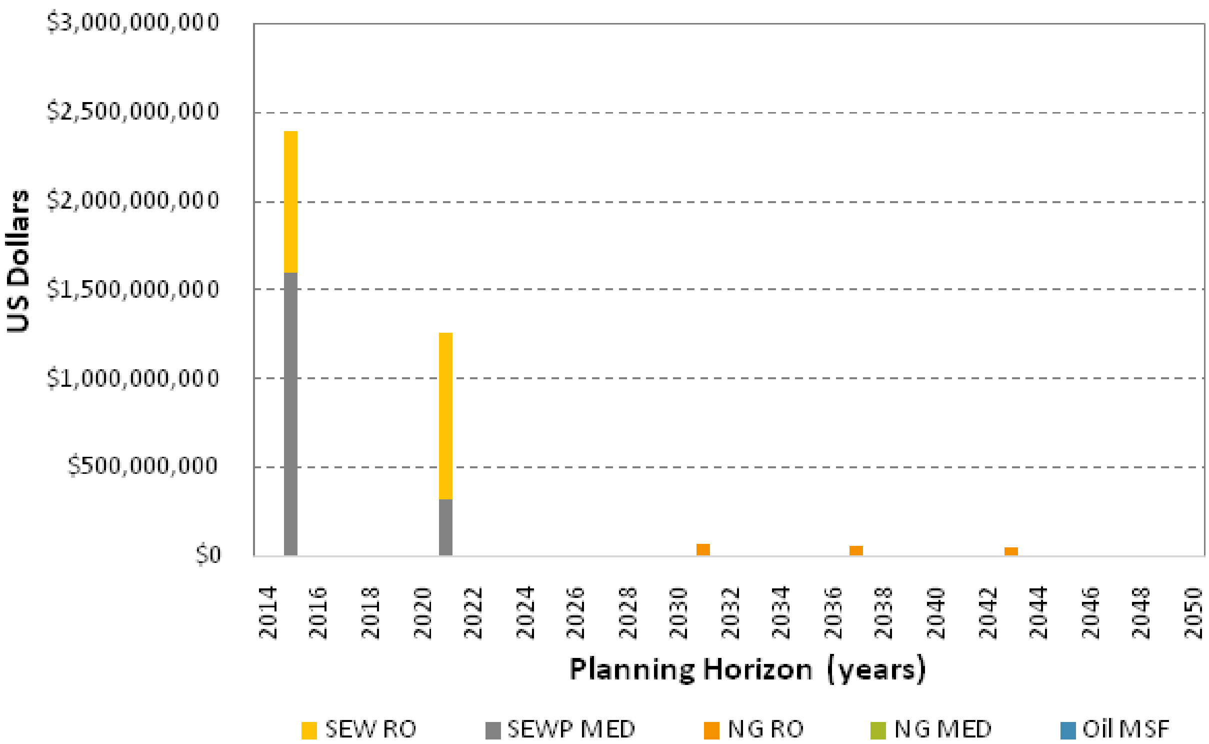

Figure 5-11 Cost of Implementation by Technology in USD

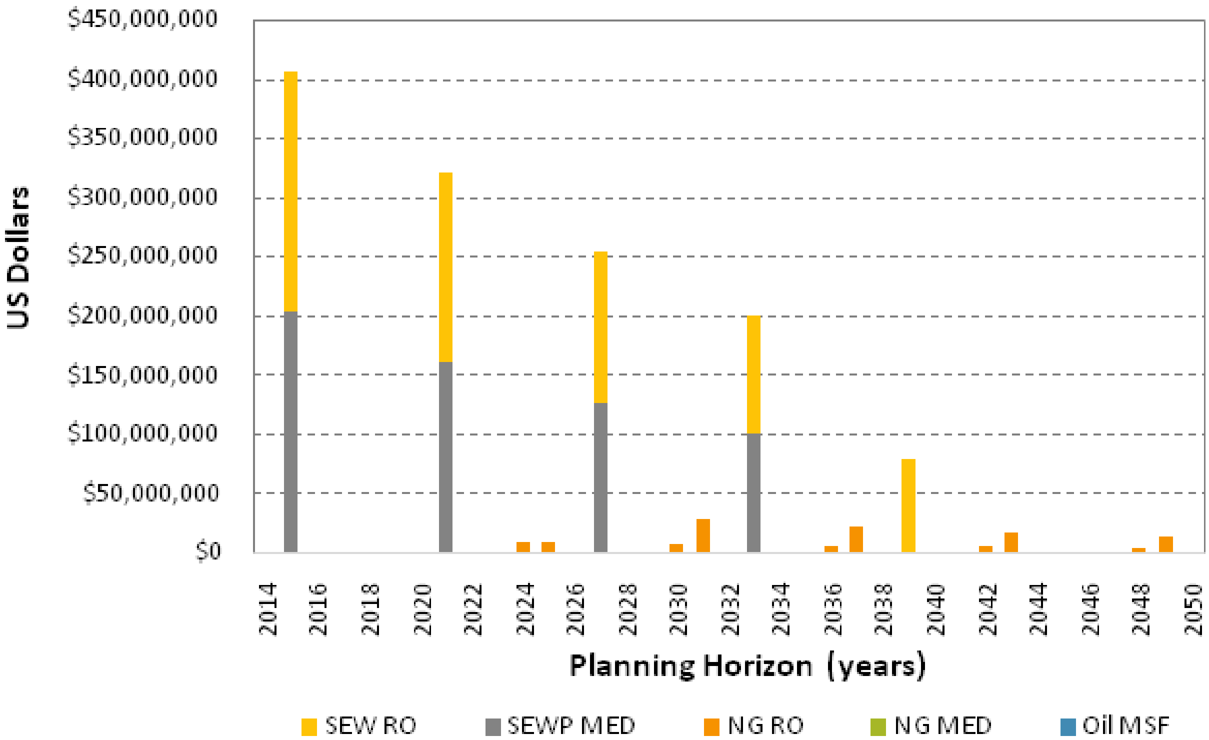

Figure 5-12 Total Cost of Expansion by Technology in USD

Figure 5-13 presents the operational cost by technology for the planning horizon. It can be observed that the operational costs of the oil and natural gas are decreased at the beginning of the planning horizon due to a shift in the preferred technology to solar. The solar plants replace the oil and natural gas plants over time, and, because of the increased production, their operational cost is increased. When solar plants have reached their technological capacity limit, further capacity expansion is achieved through implementation of natural gas plants. There is also slight shift from solar production capacity to natural gas to cope with increased future demand.

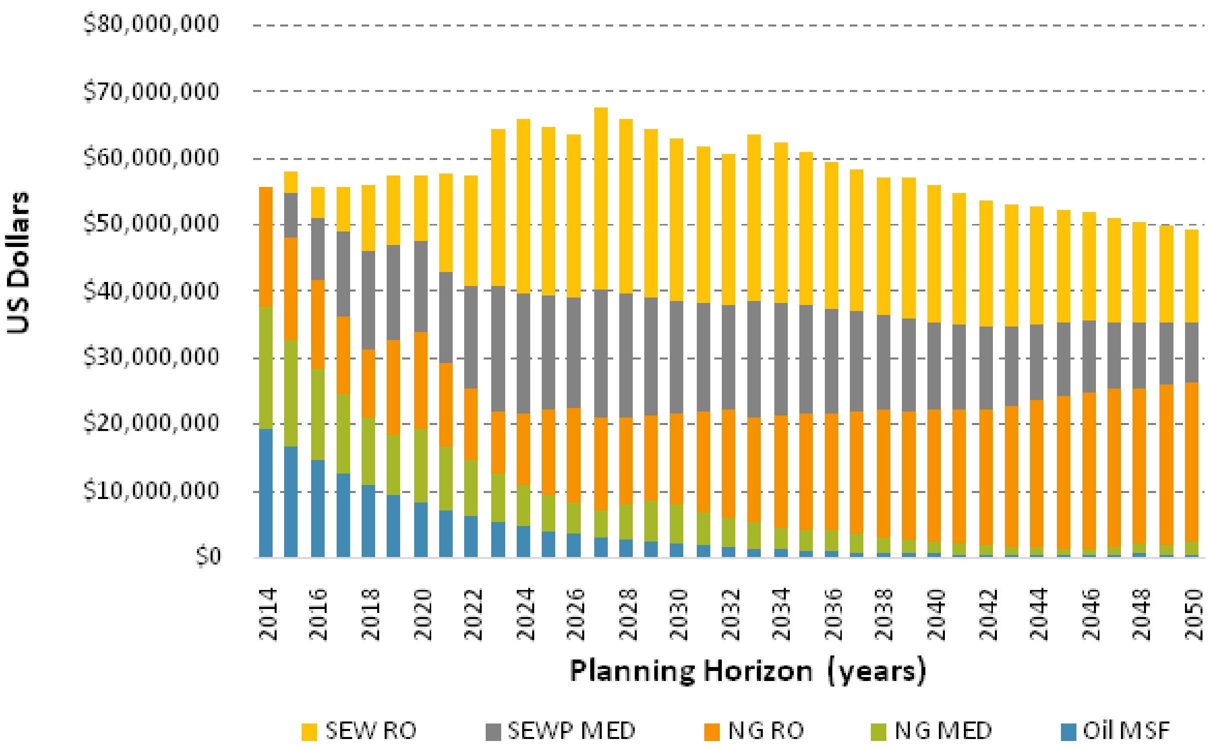

Figure 5-13 Total Cost of Operation by Technology in USD

CHAPTER 6: SCENARIO GENERATION AND SENSITIVITY ANALYSIS

In this research, strategies for technology selection and capacity planning, capacity expansion or new facilities, in water and energy cogeneration was developed through mathematical programming. The resulting decision problem was modeled and solved in the context county-wide resource planning. Given the extended planning horizon and the uncertainty related to the different model parameters three main sensitivity categories were established. The first sensitivity category is concerned with the escalation on the prices of oil and gas. The second sensitivity category is related with technological improvements on solar energy plants. The third sensitivity category is related to increases in demand.

6.1 Sensitivity Analysis for Increase in Input Prices

For increase in input prices, two scenarios were considered using a scale factor of 1.75 for the prices oil (O-1.75) and natural gas (NG-1.75) respectively. The O-1.75 scenario is presented in Figure 6-1. Similarly, for natural gas an escalation factor of 1.75 was used, the corresponding scenario was denoted as NG-1.75 and is presented in the Figure 6-2.

The comparison between the base scenario and the NG-1.75 scenario is presented in Figure 6-3. It can be observed that the installed capacity ramp up earlier in the NG-1.75 scenario as compared to the base scenario for water production. The production and installed capacity behave in a similar way in both scenarios.

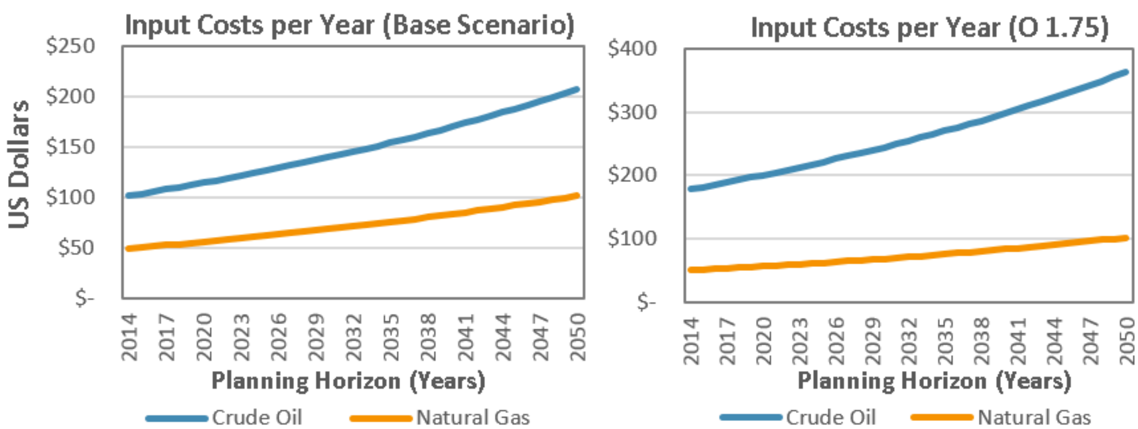

Figure 6-1 Comparison between Actual Input Cost and with an Escalation Factor of 1.75 for Oil (O-1.75)

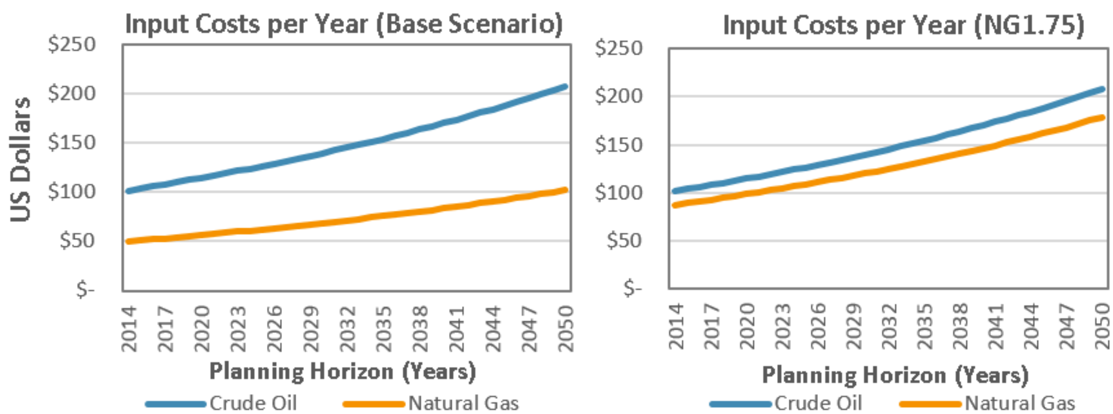

Figure 6-2 Comparison between Actual Input Cost and with an Escalation Factor of 1.75 for Natural Gas (NG-1.75)

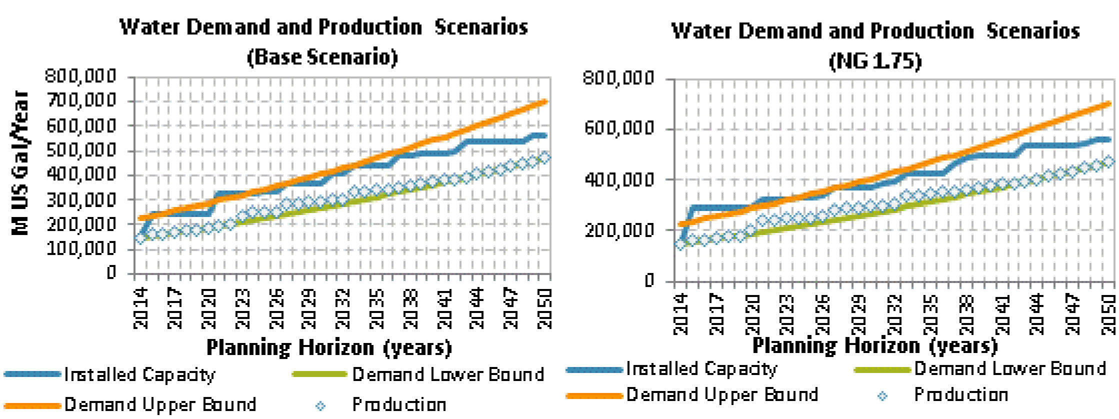

Figure 6-3 Comparison of Water Demand Production with Scenario NG-1.75

The water production result for the O-1.75 exhibit a similar pattern when compared to the NG-1.75 case. The installed capacity for water ramps up earlier but the rest of the planning horizon remains similar to the base scenario. The results for scenario O-1.75 can be observed in Figure 6-4.

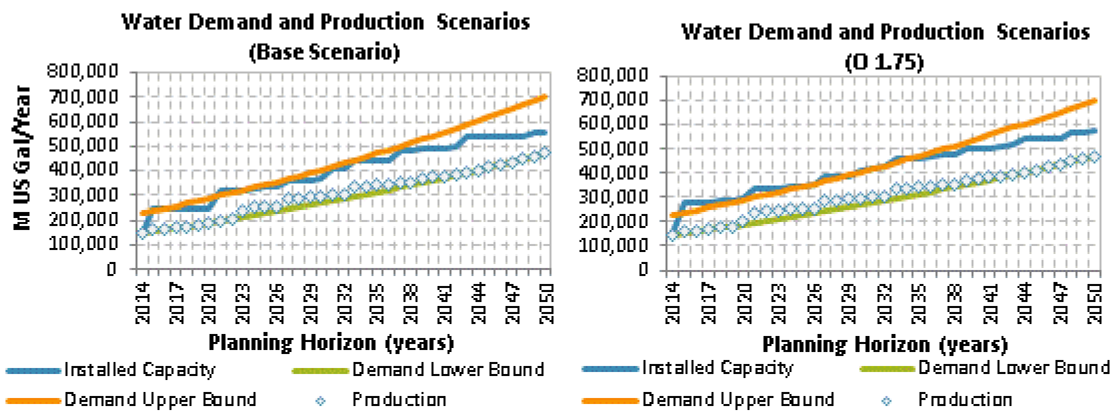

Figure 6-4 Comparison of Water Demand Production with Scenario O -1.75

The same scenarios can be analyzed for electricity generation. Figure 6-5 presents the comparison between the base scenario and the scenario NG-1.75. There were not significant differences observed in the behavior of the installed capacity and production.

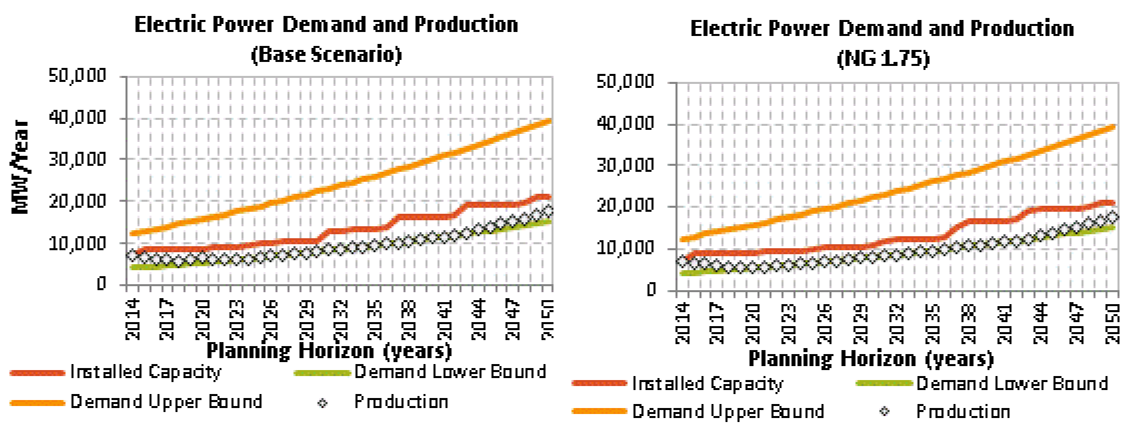

Figure 6-5 Comparison of Electric Power Demand and Generation with Scenario NG-1.75

Figure 6-6 presents the comparison between the base scenario and the scenario O-1.75. A much more smooth behavior in the installed capacity was observed in the O-1.75 scenario as compared to the base case. The electric power generation did not present significant variations.

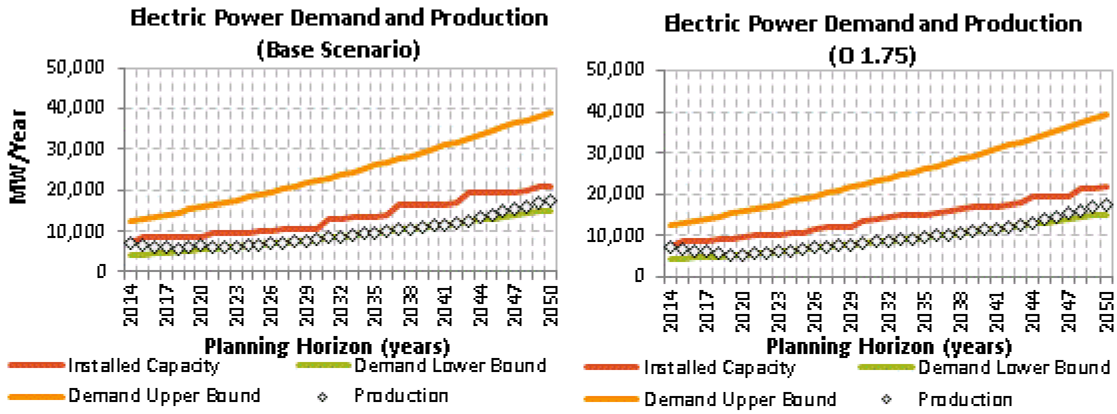

Figure 6-6 Comparison of Electric Power Demand and Generation with Scenario O-1.75

The installed capacity by plant technology for scenario NG-1.75 is presented in Figure 6-7. It can be observed that the expansion of natural gas plants is delayed while the expansion of solar plants is accelerated in the NG-1.75 scenario.

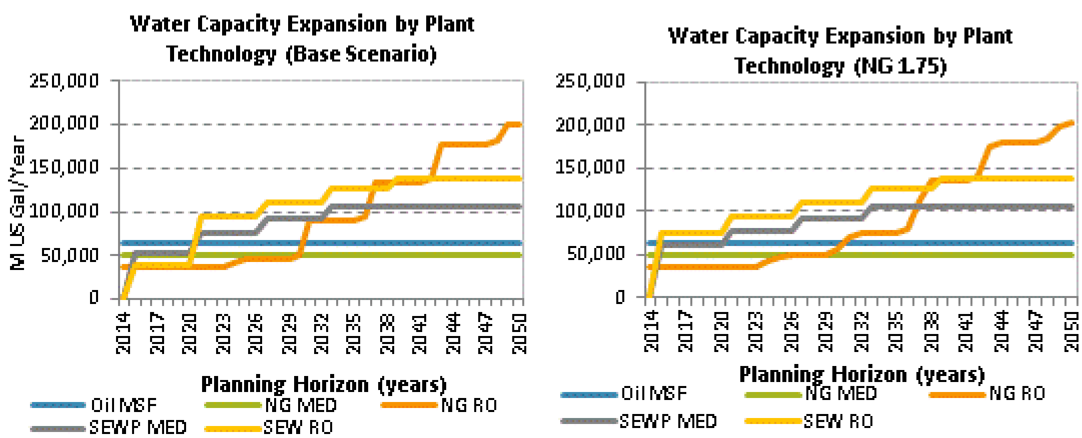

Figure 6-7 Installed Capacity by Plant Type for Scenario NG-1.75

For the O-1.75 scenario, there are significant changes in the way capacity expansion are scheduled in the planning horizon for water production. A comparison between the O-1.75 scenario and the base scenario is presented in Figure 6-8. It can be observed that the capacity for water is quickly ramped up early in the planning horizon in scenario O-1.75. On the other hand, the capacity for natural gas plants is constantly increasing nearly steady rate throughout the planning horizon.

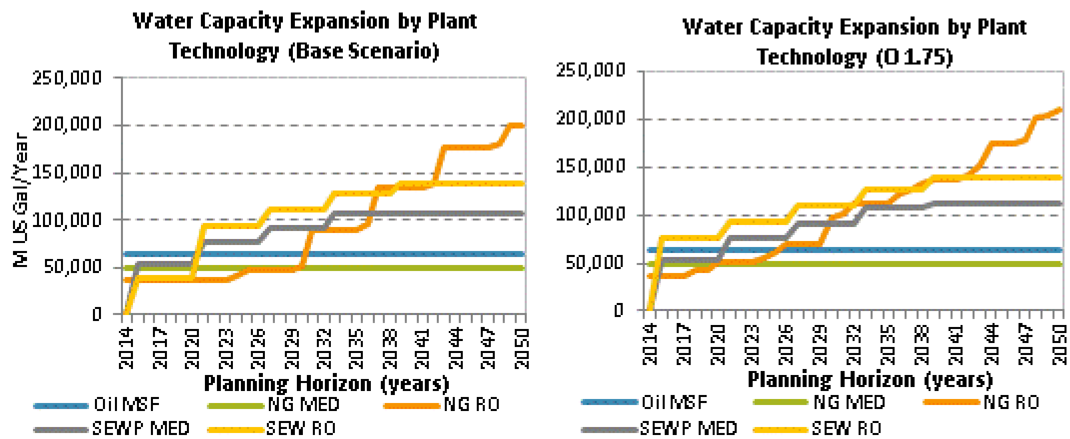

Figure 6-8 Installed Capacity and Production for Water by Plant Type for Scenario O-1.75

For electric power generation, the behavior for the plant is very similar. The main difference is the delayed implementation of capacity expansion for natural gas plants in the scenario of natural gas escalation. The corresponding graphing comparing the base scenario with the NG-1.75 scenario is presented in Figure 6-9.

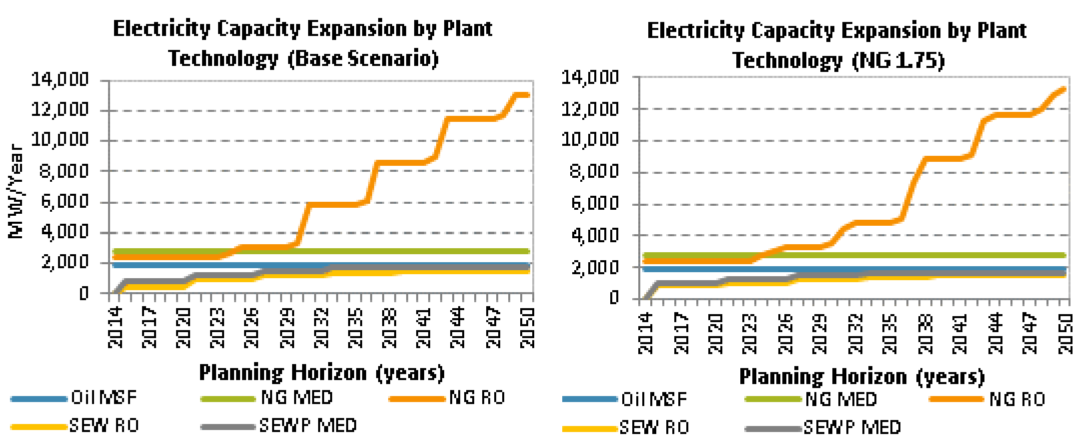

Figure 6-9 Installed Capacity by Plant Type for Scenario NG-1.75

The comparison between electric power generations as a scenario for the escalation of $1.75 on oil prices with the base case is presented in Figure 6-10. It can be observed that the capacity of natural gas plants is constantly increased in small amounts every time given the aspect of a nearly constant increase rate.

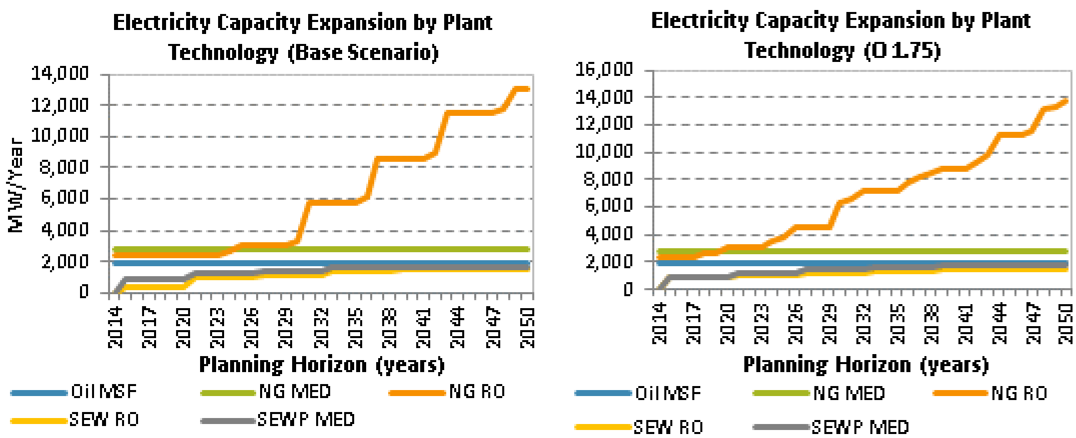

Figure 6-10 Installed Capacity by Plant Type for Scenario NG-1.75

In terms of production technology selection, there were not significant differences between the base scenario and with either the scenario NG-1.75 or the O-1.75 case for water production. These behaviors can be observed in Figure 6-11 for scenario NG-1.75 and in Figure 6-12 for scenario O-1.75.

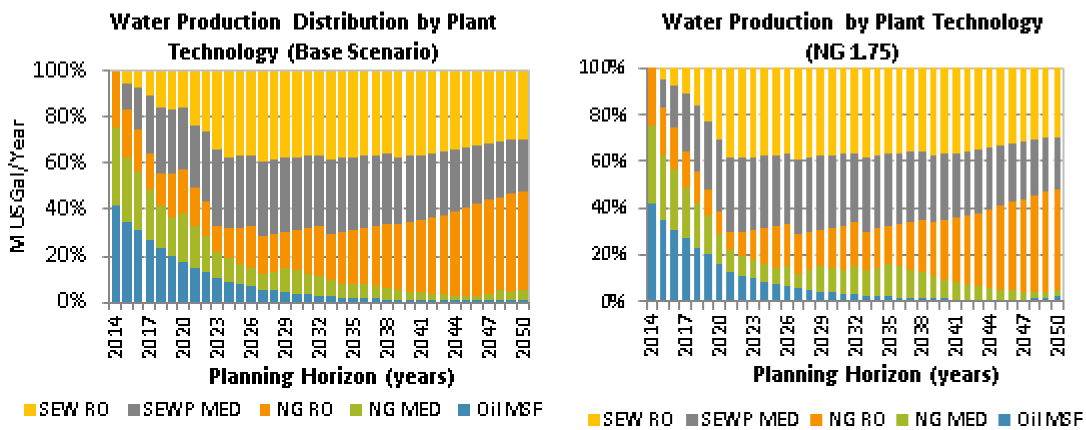

Figure 6-11 Production Distributions for Water by Technology for Scenario NG-1.75

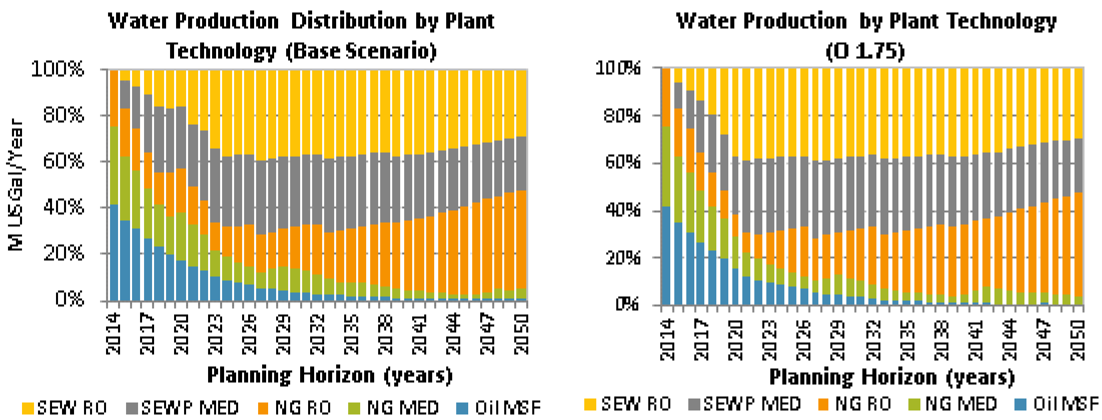

Figure 6-12 Production Distributions for Water by Technology for Scenario O-1.75

For generation of electric power, there were not significant differences between the base scenario and the production by technology with either the scenario NG-1.75 orthe O-1.75 case. These behaviors can be observed in Figure 6-13 for scenario NG-1.75 and in Figure 6-14 for scenario O-1.75.

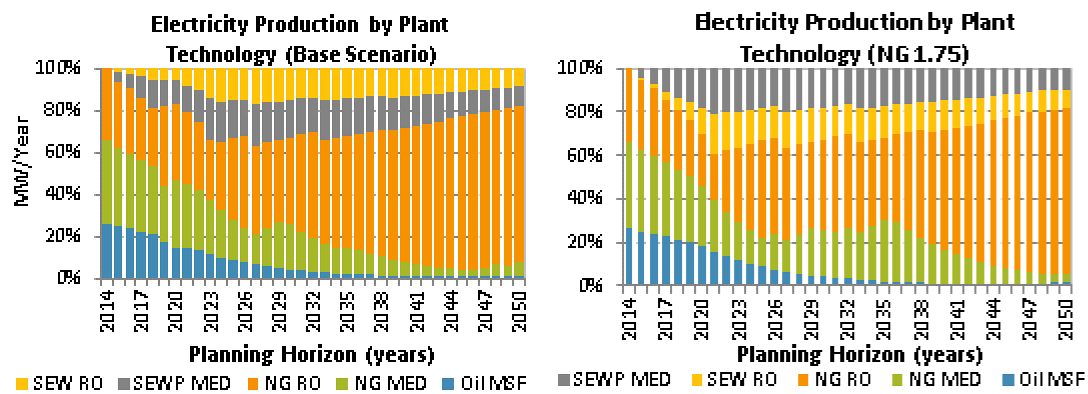

Figure 6-13 Production Distributions for Electricity by Technology for Scenario NG-1.75

In general, the capacity increase schedule was not very sensitive to increases in price of Oil and Natural Gas due to the availability of solar-based plants. Since solar base plants are preferred over oil plants in the base model, increasing the oil costs in oil plants only further supported this result.

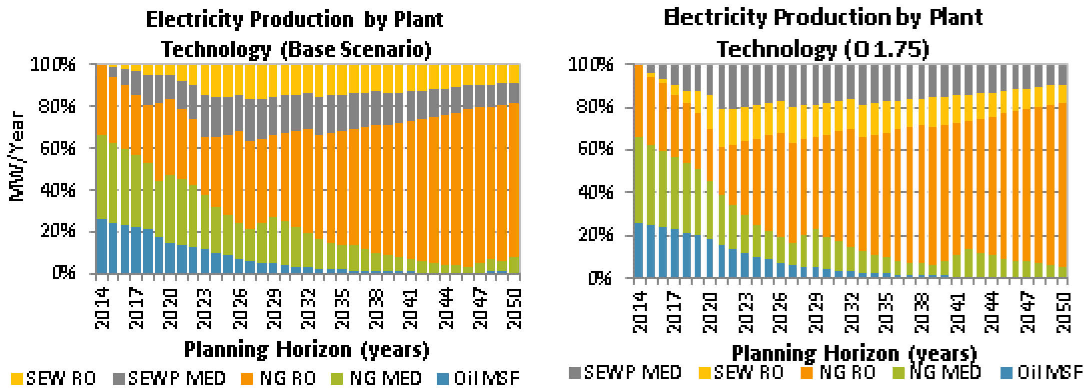

Figure 6-14 Production Distributions for Electricity by Technology for Scenario O-1.75

6.2 Sensitivity Analysis for Technological Improvement in Solar Plants

One aspect of the utilization of solar-base plants is the limitations of its water and electric power generation capabilities. If the ongoing technological focus in trust continues and results in breakthroughs, solar plants capacity may increase by 1.5 (S1.5) to 3 (S3) times the current. Then, the installation and production schedule may change. In this section, such changes are considered.

In Figure 6-15, the results for installed water capacity and demand for S. 1.5 is presented. For scenario S1.5, It can be observed how the installed capacity surpasses the upper bound of the demand and the production of water increases. This indicates that is more economically feasible for the planning horizon to increase the capacity of solar plants.

For the scenario S3.0, the production of water is more cost effective, as it can be observed in Figure 6-16. Water can be produced up to the upper bound of the demand. In fact, the installed water capacity can cover all the demand scenarios for the entire planning horizon.

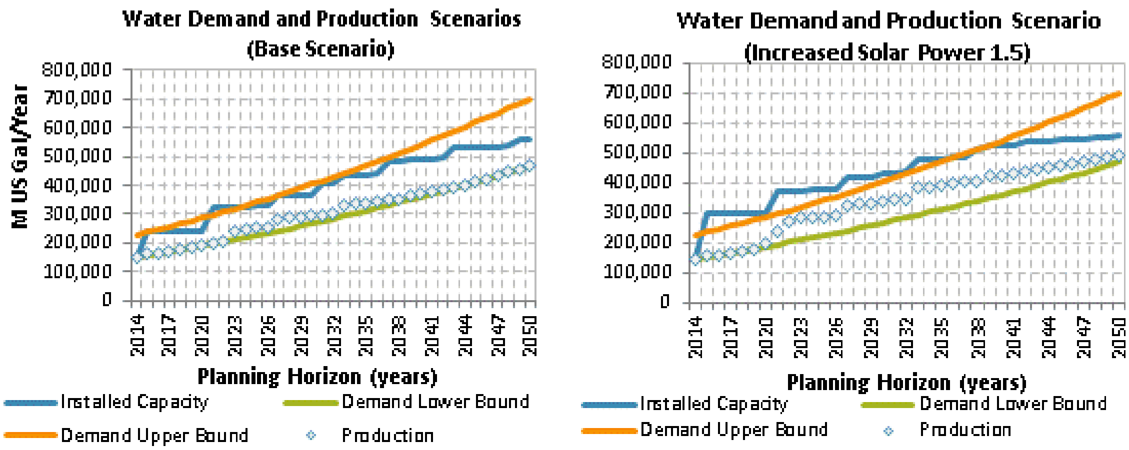

Figure 6-15 Comparison of Water Demand Production with Scenario S1.5

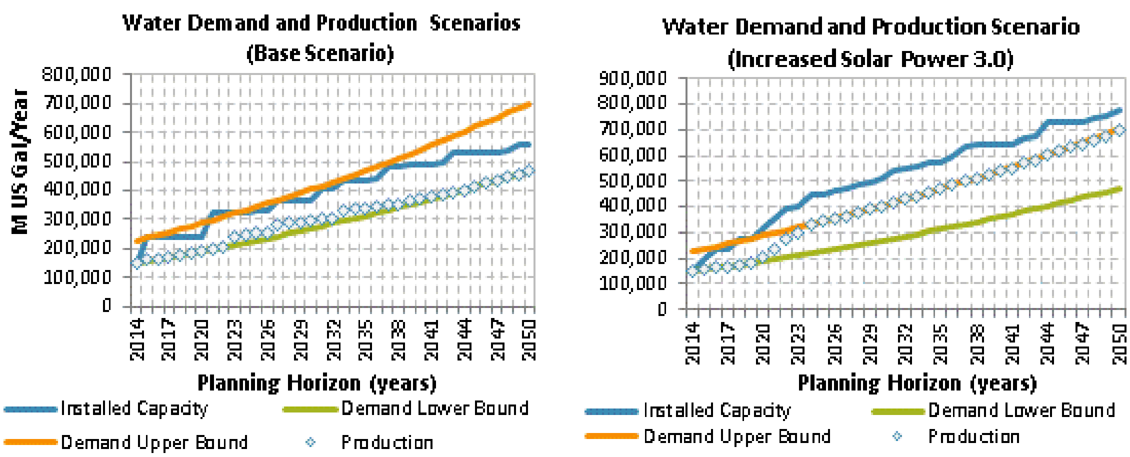

Figure 6-16 Comparison of Water Demand Production with Scenario S3.0

In contrast, for electric power generation the production remained very similar to the base case scenario for both S1.5 (Figure 6-17) and S3.0 (Figure 6-18) scenarios. This is mainly because of the implementation of solar plant have more effect in water production than in electric power generation.

For installed capacity for water, it can be observed that for both scenarios S1.5 (Figure 6-19) and S3.0 (Figure 6-20) water capacity is ramped up until capacity is reached for solar plants. For scenario S1.5, natural gas plant are still necessary but only to a maximum of nearly 130,000

M US Gal/year while in the base scenario natural gas plant were expanded up to 200,000 M US Gal/year. For scenario S3.0, the expansion of natural gas plant is minimal.

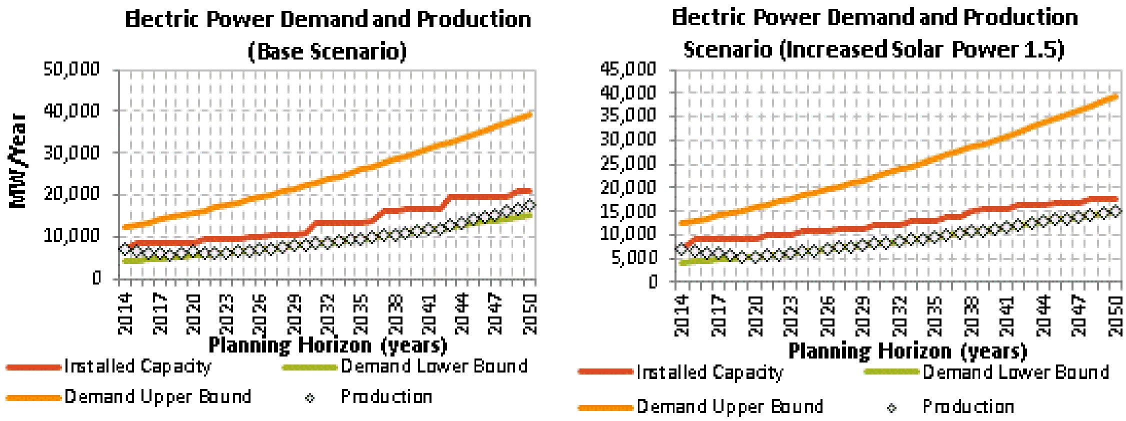

Figure 6-17 Comparison of Electric Power Demand and Generation with Scenario S1.5

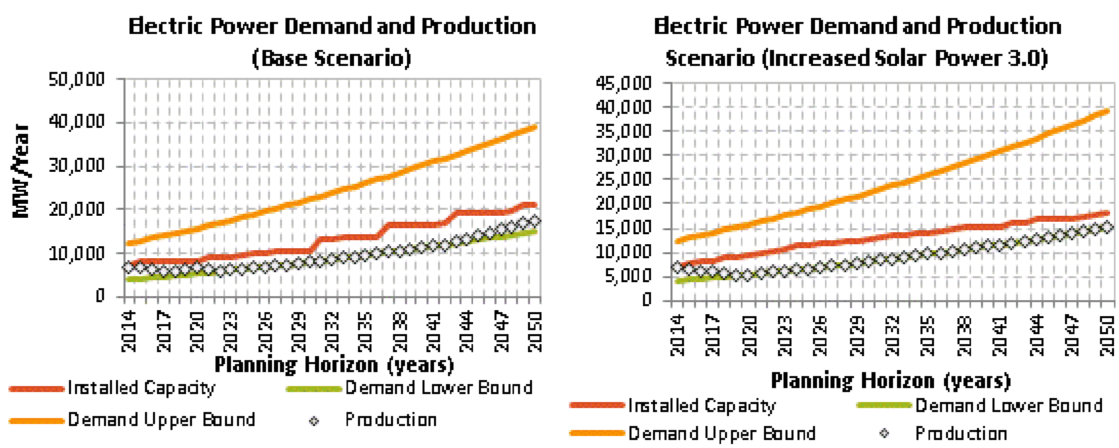

Figure 6-18 Comparison of Electric Power Demand and Generation with Scenario S3.0

For installed capacity for electric power generation, it can be observed that for both scenarios S1.5 (Figure 6-21) and S3.0 (Figure 6-22, Figure 6-20) that the natural gas plants are required. Even in scenario S3.0, the installed capacity even out across natural gas plants and solar plants. Oil-based plants are not expanded.

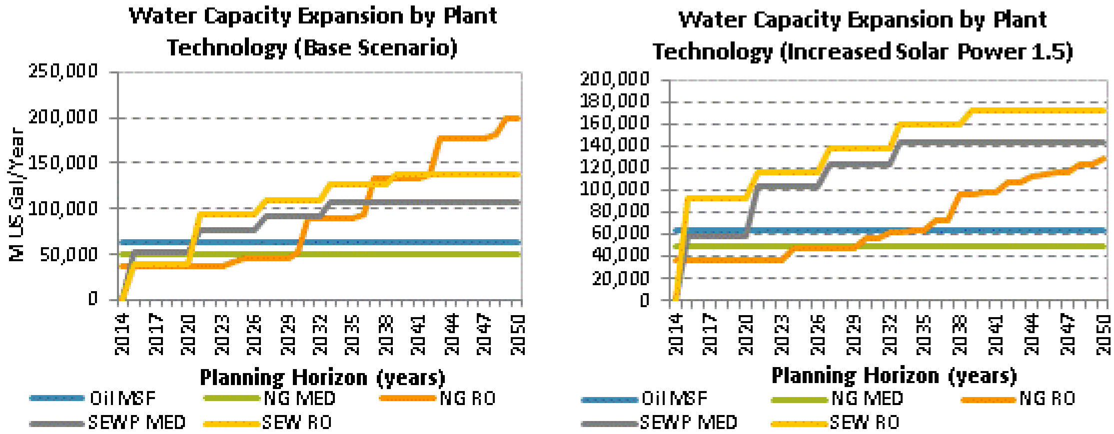

Figure 6-19 Installed Capacity (Water) by Plant Type for Scenario S1.5

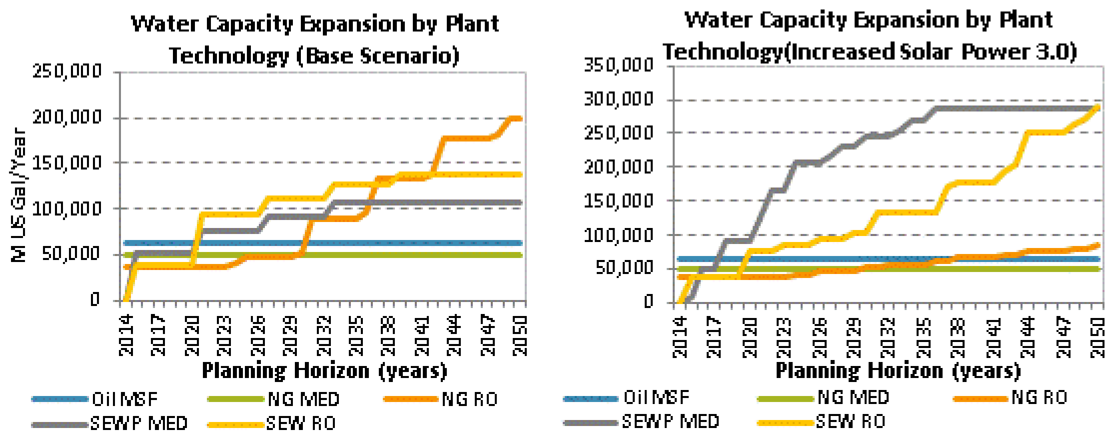

Figure 6-20 Installed Water Capacities by Plant Type for Scenario S3.0

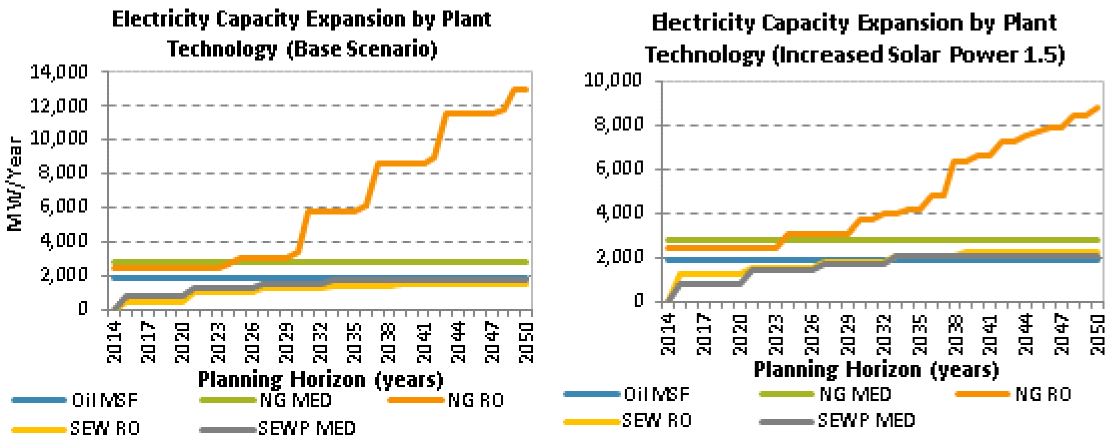

Figure 6-21 Installed Electric Power Capacity by Plant Type for Scenario S1.5

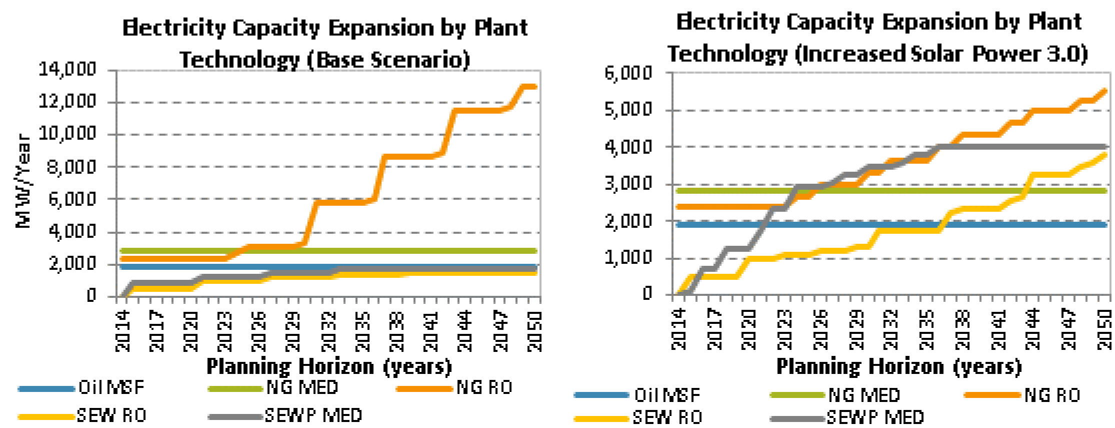

Figure 6-22 Installed Electric Power Capacity by Plant Type for Scenario S3.0

The composition of water production by plant technology is presented in Figure 6-23 for scenario S1.5 and in Figure 6-24 for scenario S3.0. For scenario S1.5, the composition of the water production is very similar to that of the base scenario having nearly 60 percent of the water produced by solar-based plants. However, for scenario S3.0,nearly 80 percent of the water was produced by solar-based plants.

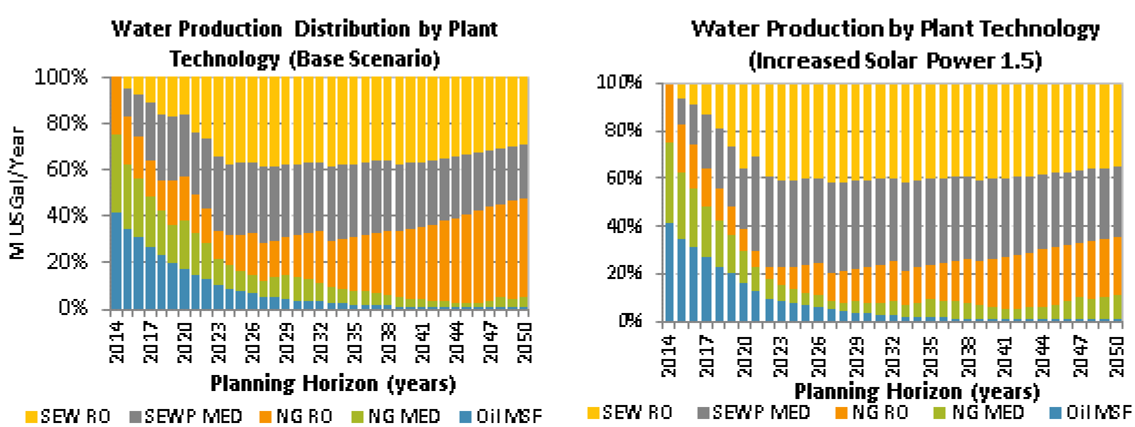

Figure 6-23 Production Distributions for Water by Technology for Scenario S1.5

The composition of electric power generation by plan technology is presented in Figure 6-25 for scenario S1.5 and in Figure 6-26 for scenario S3.0. Therefore, for scenario S1.5, the composition of the electric power production is very similar to that of the base scenario having nearly 30 percent or less of the total electricity produced by solar-based plants. However, for scenario S3.0,close to50 percent of the water was produced by solar-based plants.

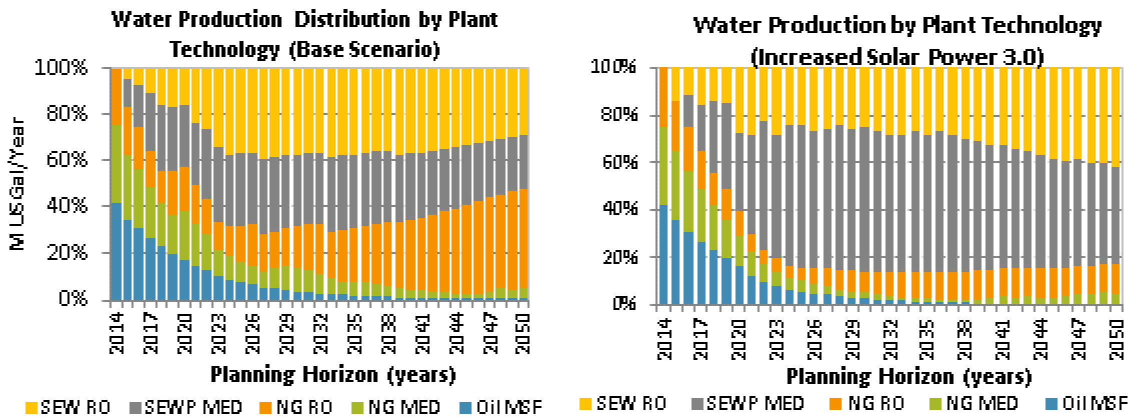

Figure 6-24 Production Distributions for Water by Technology for Scenario S3.0

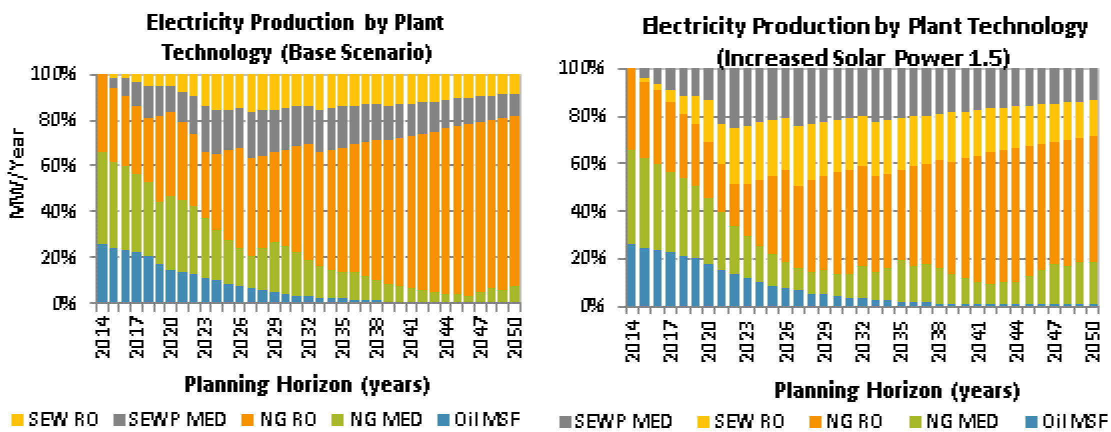

Figure 6-25 Production Distributions for Electric Power by Technology for Scenario S1.5

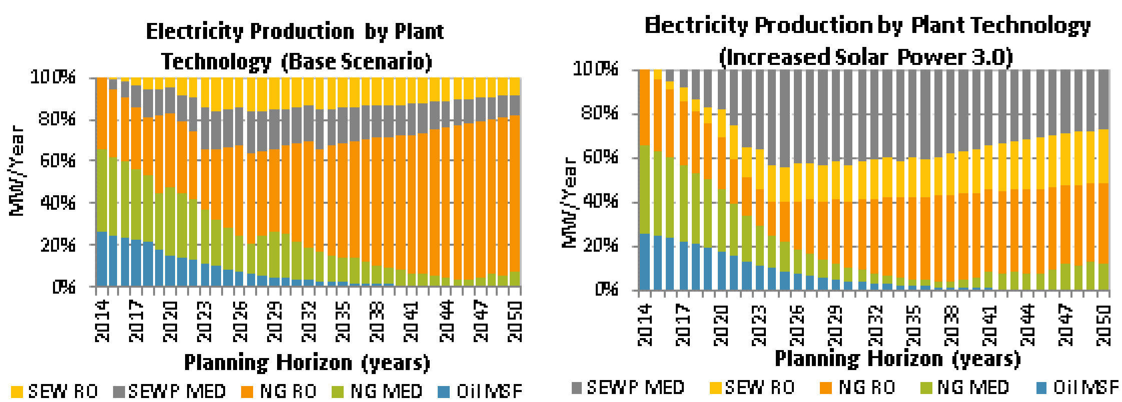

Figure 6-26 Production Distributions for Electric Power by Technology for Scenario S13.0

The sensitivity analysis demonstrated that the planning model is very sensitive with respect to technological improvements in solar-based plants, especially with respect to water. The best scenario based on the insights gained form this modeling exercise is that if solar plants increase their effectiveness to produce electric power the benefits will be of great importance for the society.

For technological improvement in solar plants, two scenarios with scale factors of 1.5 and 3 were used. The results are expressed based on the operating costs, number of plants of each type, installed capacity and production and total costs.

6.3 Sensitivity Analysis of Increase in Demand for Water and Electricity

For the third category of scenarios, increases in capacity for both water and electricity were introduced. These scenarios were introduced though escalation factors. In the scenario D1.5, the demand in 1.5 times that of base case while in the scenario D2.0, the demand is increased two times. The comparison between the base scenario and the D1.5 scenario is presented in Figure 6-27. It can be observed that the installed capacity in the D1.5 scenario is closer to the lower bound on the demand as compared to the base scenario for water production. With an increased demand the installed production capacity is very close to the demand leading to a higher utilization of the existing capacity.

The water production results for the D2.0 behave in a similar way than those of the D1.5. The installed capacity for water is closer to the lower or optimistic bound for the demand with an increased utilization of the installed capacity. The results for scenario D2.0 can be observed in Figure 6-28.

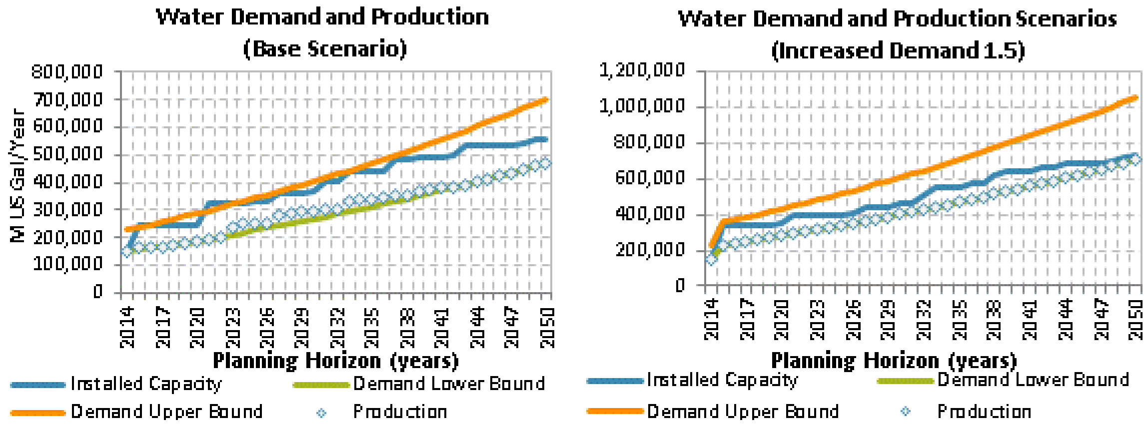

Figure 6-27 Comparison of Water Demand Production with Scenario D1.5

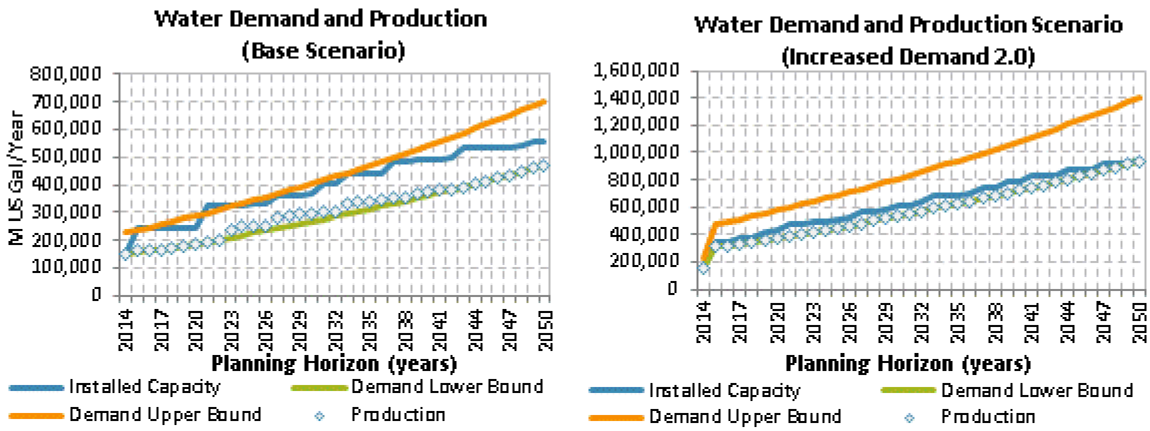

Figure 6-28 Comparison of Water Demand Production with Scenario D2.0

For electric power generation the behavior was very similar to the water production scenario for both D1.5 (Figure 6-29) and D2.0 (Figure 6-30) scenarios. In all the cases, the generation was close to the lower bound of the demand.

For installed capacity for water, it can be observed that for both scenarios D1.5 (Figure 6-31) and S3.0 (Figure 6-32) water capacity is ramped up until capacity is reached for solar plants. Natural gas plants are expanded besides the solar plants to cope with the increased demand. For the D2.0 scenario, all the plants are expanded. Under these scenarios, the supply costs are high and it is not profitable to produce beyond the required minimum demand. This was not the case for increased solar plant capacity.

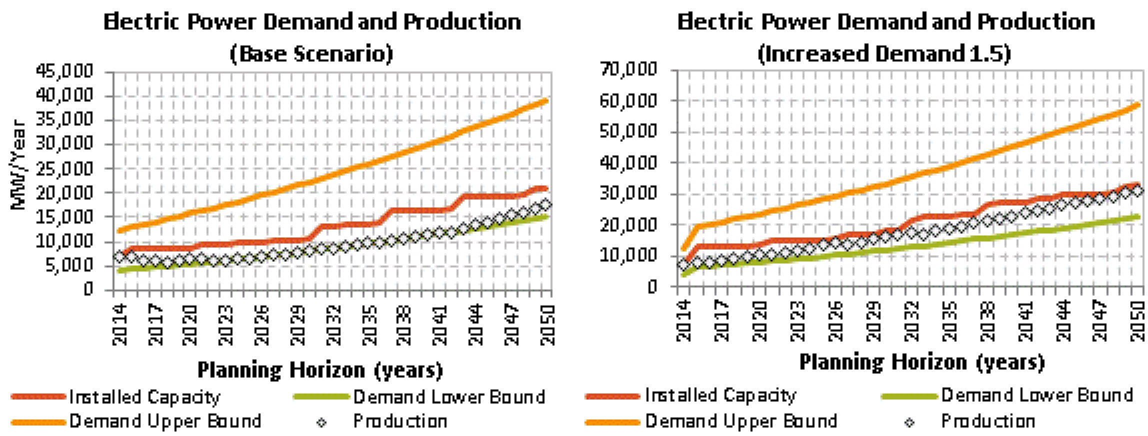

Figure 6-29 Comparison of Electric Power Demand Production with Scenario D1.5

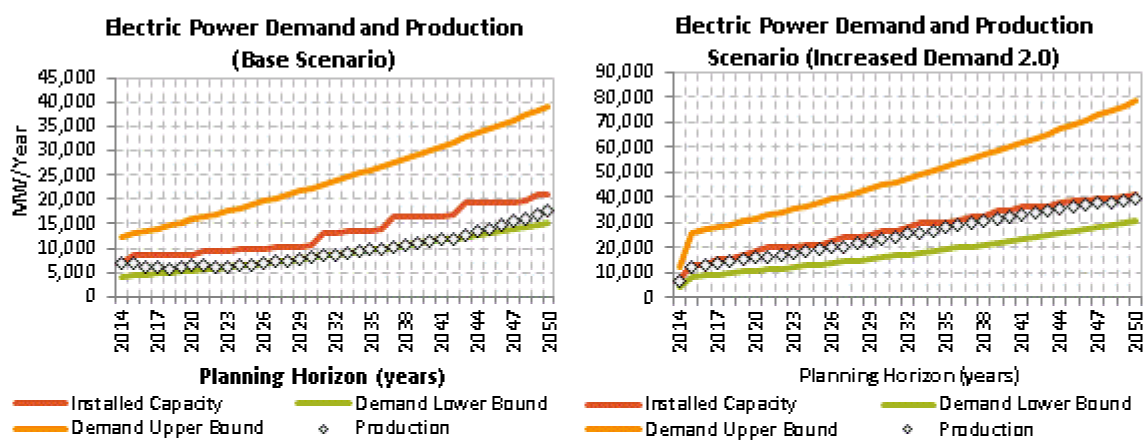

Figure 6-30 Comparison of Electric Power Demand Production with Scenario D2.0

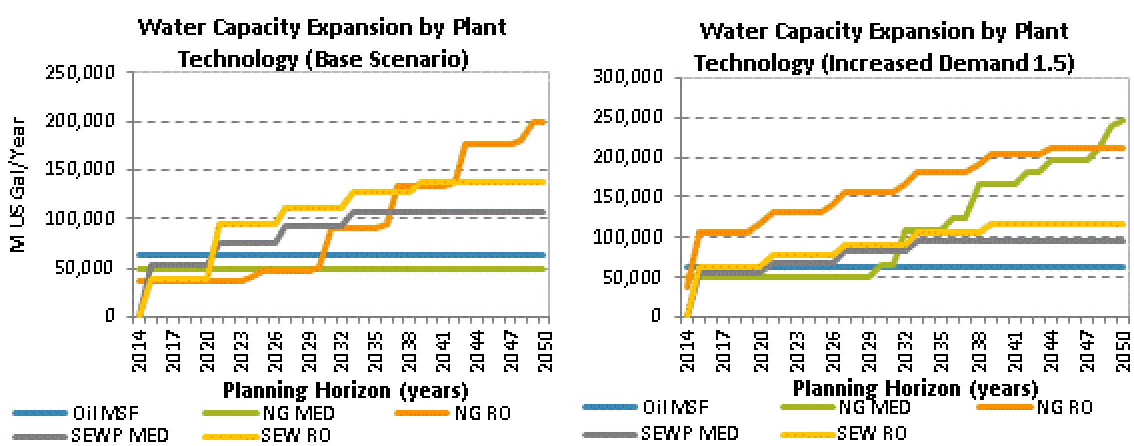

Figure 6-31 Installed Water Capacities by Plant Type for Scenario D1.5

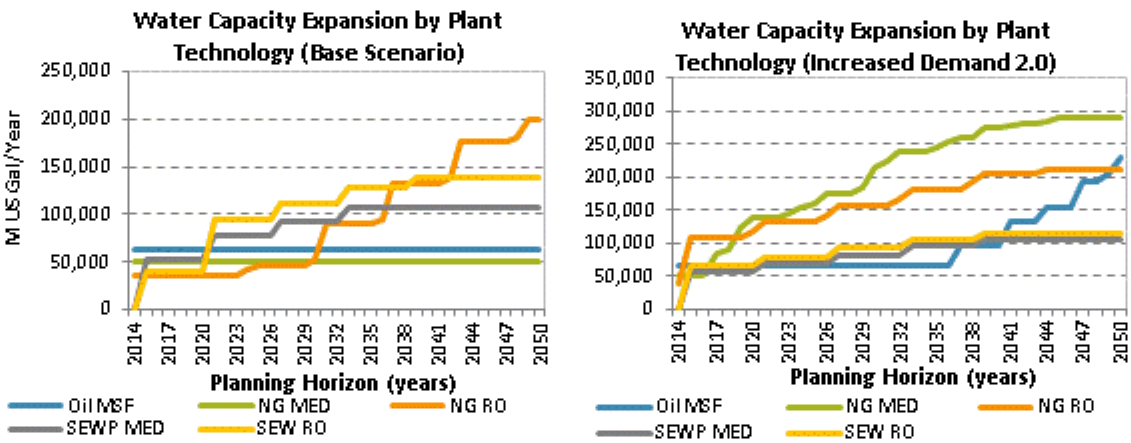

Figure 6-32 Installed Water Capacities by Plant Type for Scenario D3.0

For installed capacity for electric power generation, it can be observed that for both scenarios D1.5 (Figure 6-33) and D3.0 (Figure 6-34) that natural gas plants are required. In scenario D2.0 oil plant were also expanded to cope with the increased demand.

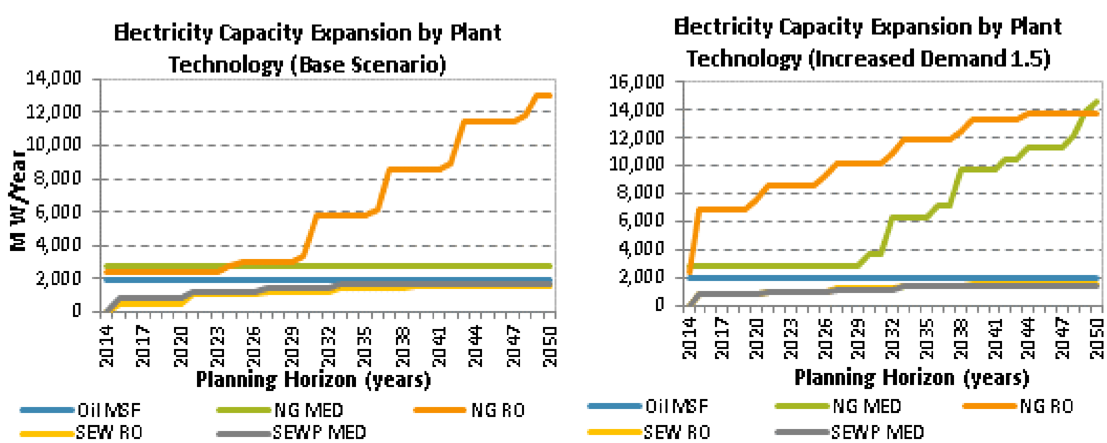

Figure 6-33 Installed Electric Power Capacities by Plant Type for Scenario D1.5

The composition of water production by plan technology is presented in Figure 6-35 for scenario D1.5 and in Figure 6-36 for scenario D2.0. For scenario D1.5, the composition of the water production technology is mostly based on natural gas with over 60% by the end of the planning horizon the production of water from solar based plants is nearly 30%. For scenario D2.0, the participation of oil plants increased to 20% by the end of the planning horizon the participation of solar plants decreased from 40% to 20% due to the capacity limitation and expansion of plants of other technologies.

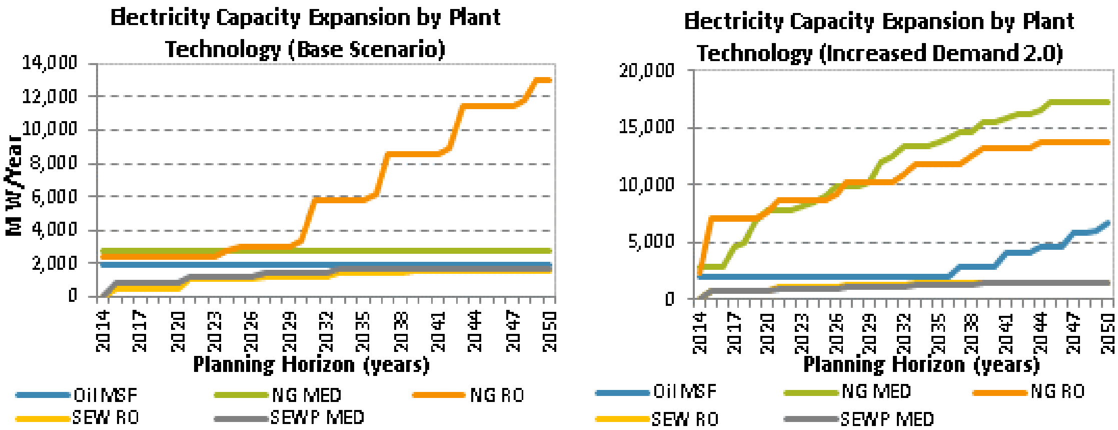

Figure 6-34 Installed Electric Power Capacities by Plant Type for Scenario D2.0

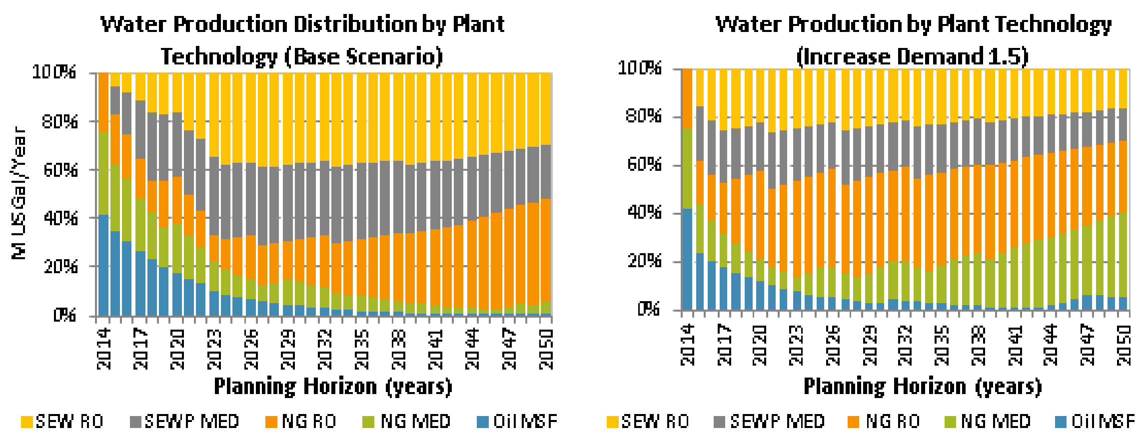

Figure 6-35 Production Distributions for Water by Technology for Scenario D1.5

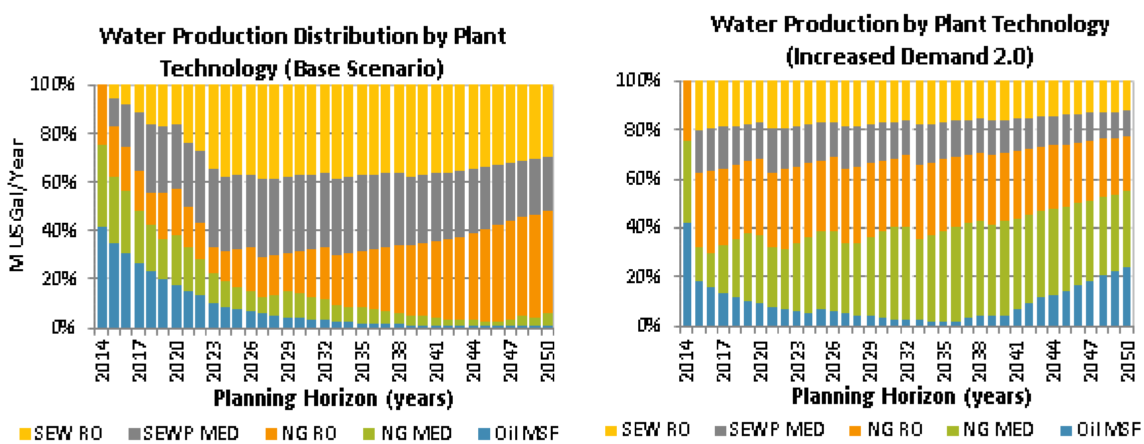

Figure 6-36 Production Distributions for Water by Technology for Scenario D2.0

The composition of electric power generation by plant technology is presented in Figure 6-37 for scenario D1.5 and in Figure 6-38 for scenario D2.0. For scenario D1.5, the composition of electric power generation technology is dominated by natural gas plants with over 80 percent across the planning horizon. This is mainly due to the limitation of solar plants with respect other technologies for the generation of electric power. For scenario D2.0, this oil plants are expanded and the participation of solar plant is less than 10 percent of the total energy generation.

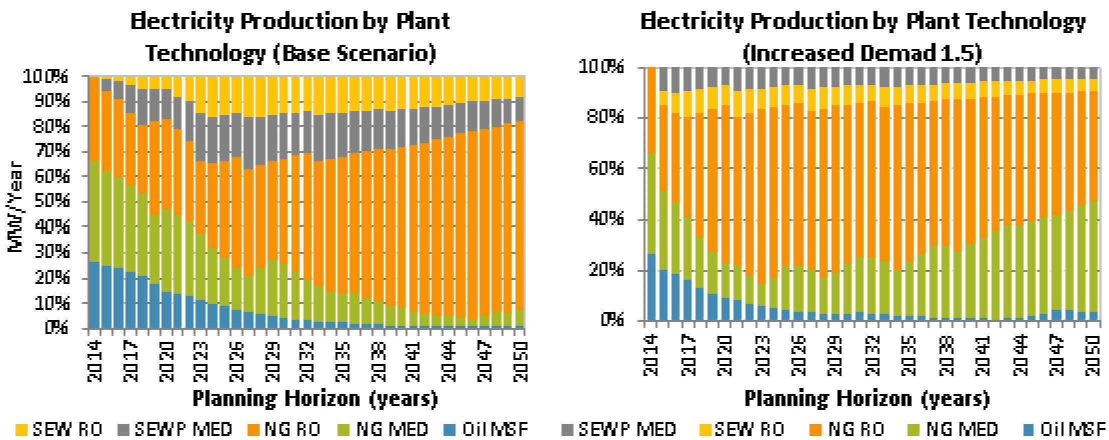

Figure 6-37 Production Distributions for Electric Power by Technology for Scenario D1.5

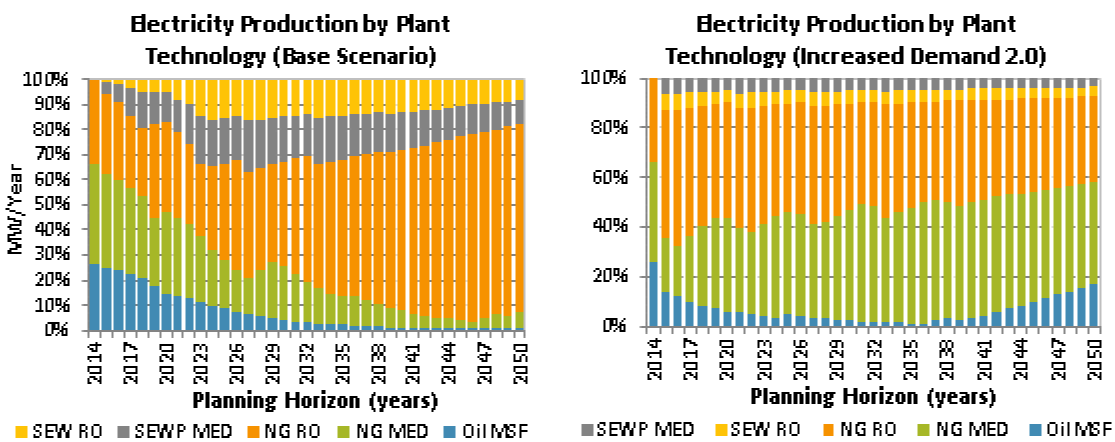

Figure 6-38 Production Distributions for Electric Power by Technology for Scenario D2.0

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

In this dissertation, a country-wide large-scale energy and water cogeneration planning model for Kuwait was proposed and solved. Five different plant technologies were modeled, Oil-Multi Stage Flash (Oil MSF), Natural Gas Multi-Effect Distillation (NG MED), Natural Gas Reverse Osmosis (NG RO), Solar Electricity and Water Production with Multi Effect Distillation (SEWP MED), and Solar Electricity and Water Production with Reverse Osmosis (SEWP RO). The planning horizon used was set to 37 years starting in year 2014 and ending in 2050 (mid 21st century).

A Mixed Integer Mathematical programming model was proposed and formulated using the General Algebraic Modeling System (GAMS), using the CPLEX solver engine. The conclusions and recommendations for future work are presented in this section.

7.1 Conclusions

Detailed data on the consumption on water and energy in Kuwait are obtained. Time series analysis of the population growth and individual behavior of water and energy consumption are performed. The results of this analysis yielded lower and upper bound confidence intervals for the projected demand for water and energy in Kuwait. The lower and upper bounds for the demand scenarios were adjusted for inflation to add more realism to the data inputs to the model.

A novel method to represent cogeneration plants was implemented in the proposed mathematical programming model. The proposed model governs the utilization and capacity expansions for cogeneration plants done in such way that both occur simultaneously. In addition, the proposed modeling framework allows variations in capacity expansion.

The proposed formulation for the base scenario included time constraints that restricted the continuous application of improvements for the same plant. This added more realism to the model since improvement may not take place immediately. The propose model also included utilizing preservation constraints that prevented sudden drops in production levels due to the implementation of a new facility. This added more validity to the model to reflect national policies, preserve existing investments, and promote job market drops.

A modeling framework that involves separation from data and model was implemented. The data was kept in and spreadsheet and the model were formulated as a template that can receive data from different spreadsheets that follow a predetermined structure. In addition, automation using VBA code was made to the data spreadsheets such that the data is sent to the model template, GAMS-Cylix, and writing the results back to the spreadsheet. This approach can be further improved and adapted into a decision support tool for policy makers in Kuwait or other similar arid regions.

Taking into consideration the base scenario is was found that oil plants are not cost effective in the long run due to the escalating oil prices and other competing technologies. Despite their large implementation cost, solar-based plants turned out to be the most promising technology for long term planning. The second best technology in terms of cost effectiveness was NG-RO.

In general oil-based plants or natural gas plants are more scalable than solar based plants. This had an effect in long term planning since solar base plants reached their maximum capacity by the year 2038. At that point in time, plants with the second best technology (NG RO) have to be expanded to cope with the increased future demand.

For water production solar-based plants can supply 50 percent or more of the demand after 2020 is implemented. If capacity expansion and transition of production from other technologies to solar plants. By the end of the planning horizon nearly 50 percent of the water can be supplied from NG RO plants and the remaining near-50 percent by solar-based plants. The participation of other technologies by the end of the planning horizon is less than 5 percent.

For electric power generation, solar plants are limited. The preferred technology for energy generation was NG RO. With the implementation of solar based plants the electric power load is distributed among the technologies. NG RO plants are more scalable and therefore were expanded to cope with the future demand.

The percentage of the electric power supplied by solar plant was below 35 percent across the planning horizon. By the end of the planning horizon the percentage of electric power supplied by solar base plants was nearly 20 percent. Near 70 percent of the electric power was supplied by NG RO by period 2050. Other technologies had a representation of less than 10 percent by the end of the planning horizon.

In terms of revenues, the utilities are heavily subsidized in Kuwait. Due to such subsidy the total profit is artificial. The costs were divided into implementation, expansion, operation and inputs. Most of the implementation costs were driven by the construction of solar-based plants which occurred before period 2022. A few implementations of NG RO plants occurred after period 2030 to cope with increased demand and limitations of energy generation scalability for solar based plants. The expansion costs were driven by the solar plants especially in the early stages of the planning horizon. The model indicated that it was more cost effective to implement solar plants at the beginning of the planning horizon and ramp up their capacity as feasibility allows. The second technology leading the expansion costs was the natural gas. Operational costs were driven initially by oil-based plants. As production was shifted form such plants, natural gas was the technology taking the majority of the operational costs followed by solar plants. Most of the costs saving of the operation were mainly driven by the shift from oil based plant to other technologies such as solar and natural gas. By the end of the planning period the input cost was dominated by natural gas.

Based on the sensitivity analysis, the proposed solution is not sensitive to increases in the oil or gas prices. This is due to the shift from oil and natural gas technologies to solar-based plants that occurred under the regular scenario. Increasing prices only help to ramp up the shift in production to solar-based plants earlier in the planning horizon.

The sensitivity analysis was performed for increases in the capacity or scalability for solar plant technologies. It was found that a 3-fold improvement in the electric power generation is needed to avoid depending on other technologies for power supply for increased future demand.

The sensitivity analysis also tested the proposed model solution against increased water and electricity demand. It was found that if plant capacity expansion increases based on some scaling factors (in this paper, 1.5 and 3.0 were considered) due to technological advancements, then that co-generation plant technology will become more favorable.

7.2 Recommendations for Future Work

The proposed model is constrained by a set of assumptions which take into account the physical complexity of installing and operating new plant technologies in Kuwait. Relaxation of such assumptions can give origin to more complex problems regarding the long term planning of water and energy supply model for Kuwait. Some of these variations of the objective function are presented below.

It is recommended for future analysis that reliability and maintenance of plants be included. This will add additional layers of realism to the model as well as complexity. A reliability model based on the hours of operation and stochastic failures can be incorporated in the modeling framework. The resulting model could be a Non-linear mixed integer or a stochastic mixed integer if the reliability functions are discretized. In the latter case, the resulting model will be of increased dimensionality requiring specialized algorithms for its solution such as Benders decomposition.

Another area of further exploration consists in the geographic disaggregation of the demand and plant locations. Incorporating socio-economic geo-referenced data and projected land use will allow the model to not only provide recommendations on the types of technology but also in the location of the plants with respect to proximity to the livable areas of the country.

Another aspect that should be incorporated in the modeling approach considers emissions from the different technologies. This will enable decision makers to justify the implementation of greener technologies not only from an economic point of view but from an environmental perspective.

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APPENDICES

Appendix A: List of Symbols

A.1 Nomenclature

i	Plant technology defined as follows: 1 Oil-MSF, 2 NG-MED, 3 NG-RO, 4 SWEP-MED, and 5 SEW-RO ($i = 1,2, \dots N$)
j	Production inputs, including oil, sun, water, natural gas among others. Different plant technologies use different sets of inputs ($j = 1,2..J$)
k	Plant number ($k = 1,2, \dots K$). This set indicates the number of plant of each type
t	Planning *horizon in years*, $t = 1,2,3 \dots 41$. Data is based from year 2010 until 2050 $(1,2, ..T)$
m	Markets to be supplied it consists of the set $\{water, electricity\}$. For representation purposes the set m is indexed as $m = 1, ..M$
$A_{ji}^{\min}$	Minimum amount of input j that can be purchased for plant of technology i (oil: barrels, natural gas: ft^3)
$A_{ji}^{\max}$	Maximum amount of input j that can be purchased for plant of technology i (oil: barrels, natural gas: ft^3)
a_{jikt}	Amount of input j purchased by plant k of technology i at time t (oil: barrels, natural gas: ft^3)
C_i^{imp}	Plant implementation cost (fixed-charge) for plants of technology i ($/Plant)
C_i^{exp}	Improvement cost (fixed-charge) for plants of technology i ($/Improvement)
C_{im}^{cap}	Implementation cost (variable) for plants of technology i for generation of product m ($/M US Gal/year, $/ MW/year)
C_i^{oper}	Operational cost of plant i($/utilization percent)
C_{it}^{inp}	Estimated cost of input $j$at time t (Oil: $/barrel; Natual Gas: $/$ft^3$)
d_{mt}^{min}	Minimum demand estimate for product of market m for planning period t(M US Gal/year, MW/year)
d_{mt}^{max}	Maximum demand estimate for product of market m for planning period t(M US Gal/year, MW/year)

I_{ijm}	Requirement of input j by plant of technology i to generate product for market m (Oil: barrels/MW, barrels/ M US Gal; Natural Gas: ft^3/MW, ft^3/ M US Gal natural gas: ft^3)
P_{mt}	Sales price of product m at time t ($/M US Gal, $/MW)
$Q_{im}^{\min}$	Minimum or starting capacity for plants of technology i (M US Gal/year, MW/year)
$Q_{im}^{\max}$	Maximum capacity for plants of technology i (M US Gal/year, MW/year)
q_{ikmt}	Installed capacity for plant k of technology i for product m at time t (water: M US Gal/year; electricity MW/year)
v_{ikmt}	Capacity expansion for plant k of technology i for product m at period t (water: M US Gal/year; electricity MW/year)
w_{ikt}	Operating level for plant k of technology i at time t (Dimensionless from 0 to 1)
x_{ikmt}	Amounts of product m generated by plant k of technology i at time t (water: M US Gal; electricity MW)
y_{ikt}	1 if plant k of technology i is open at the beginning of period$t$; 0 otherwise (dimensionless)
z_{ikt}	1 if plant k of technology i is expanded at the beginning of period$t$; 0 otherwise (dimensionless)

A.2 Greek Symbols

α	Maximum operating level for new plants (Dimensionless from 0 to 1)
$\gamma_{im}^{\min}$	Minimum capacity expansion for plants of technology i (M US Gal/year, MW/year)
$\gamma_{im}^{\max}$	Maximum capacity expansion for plants of technology i (M US Gal/year, MW/year)
ψ^{up}	Maximum increase in operating levels between successive periods expressed as a factor of the operating level of the previous period (dimensionless from 1 to infinite, used 1)
ψ^{lo}	Minimum operating level for a plant based on the operating level of the previous period (dimensionless from 0 to1, used 0)

A.3 General Acronyms List

Ph.D. ....The Doctor of Philosophy degree

RO ....Membrane Processes

RO ....Reverse Osmosis

MED......................................Multiple-Effect Mechanical Compression

MED......................................Multi-Effect Distillation

MSF.......................................Multi-Stage Flash

MILP ....Mixed Integer Linear Programming Model

M US Gallon ....Million US Gallons

IMP ....Imperial Gallon

MIG.......................................Million Imperial Gallons

BBL.......................................Billion Barrels

SCF ....Square Feet

KD...Kuwaiti Dinar

USD.......................................United State of America Dollar

MEW.....................................Kuwait Ministry of Electricity and Water

MENA...................................Middle East and North Africa

GAMS ....General Algebraic Modeling System

GPD.......................................Gross Domestic Production

MW ....Megawatt

KWh.....................................Kilo Watt Hour

GWh......................................Gig watt Hour

BTU......................................British Thermal Unit

m^3..cubic meter

ft3 ....cubic feet

US Cents/KWh.......................US Cents /Kilo Watt Hour

Fils/KWh................................Kuwaiti Fils per Kilo Watt Hour

Fils/1000 IMP ....Fils per Thousand Imperial Gallons

Mgd.......................................Million Gallons Per day

M USD/KWh ....Million US Dollars per Kilo Watt Hour

A.4 Main Model GAMS Acronyms List

Option1 ....Combined Electricity and Water Production by Oil Fuel as Multi-Stage Flash (MSF)

Option 2 ....Natural Gas Electricity and Water Production with Multiple-Effect Mechanical Compression (MED)

Option 3 ....Natural Gas Electricity and Water Production with Membrane Processes (e.g. Reverse Osmosis (RO))

Option 4 ....Solar Energy Electricity and Water Production with Multiple-Effect Compression (MED)

Option 5 ....Solar Energy Electricity and Water Production with Membrane Processes (e.g. Reverse Osmosis (RO))

CEWP-MSF...........................Combined Electricity and Water Production by Oil Fuel as Multi-Stage Flash (MSF)

NGEWP-MED.......................Natural Gas Electricity and Water Production with Multiple-Effect Mechanical Compression (MED)

NGEWP-RO ....Natural Gas Electricity and Water Production with Membrane Processes (e.g. Reverse Osmosis (RO))

SEWP-MED...........................Solar Energy Electricity and Water Production with Multiple-Effect Compression (MED)

SEWP-RO..............................Solar Energy Electricity and Water Production with Membrane Processes (e.g. Reverse Osmosis (RO))

A.5 Initial Main Model GAMS

w2Water................................Option 2 Output for Main Model

w3Water................................Option 3 Output for Main Model w4Water ....Option 4 Output for Main Model

w5Water ....Option 5 Output for Main Model

e1Electricity ....Option 1 Output for Main Model

e2Electricity ....Option 2 Output for Main Model

e3Electricity ....Option 3 Output for Main Model

e4Electricity ....Option 4 Output for Main Model

e5Electricity ....Option 5 Output for Main Model

POP ....Population

L ....Lower Bound

U..Upper Bound

NP ....Number of Processes

NR..Number of Raw Material

NM ....Number of Markets

NT ....Number of Time Periods

AC ....Air Conditioning

TR C.......................................Transportation Cost in Million Kuwaiti Dinars

PR C.......................................Production Cost of Electricity in Million Kuwaiti Dinars

V S ....Value of Subsidize in Kuwaiti Fils

PER S.....................................Percentage of Subsidize by Kuwaiti Government

T C ....Total Cost of Electricity before Selling by Kuwait Ministry of Electricity and Water to Citizens in Million Kuwaiti Dinars

T C M KD ....Total Cost of Electricity Selling Prices by Kuwait Ministry of Electricity and Water in Million Kuwaiti Dinars

T C USD ....Total Cost of Electricity Selling Prices by Kuwait Ministry of Electricity and Water in Million US Dollars per Kilo Watt Hour

A.6 Complex GAMS (Model One) Acronyms List

COMPLEXEIGHT ....Model One

E1, E2,…, En ....Equation Number

IPSEpro ....Process Simulation Environment

PSE..Simulation Environment

MDK ....model development kit

RESYSproDESAL.................special model library

Kton/ year...............................Kilo ton per year

tons/hr ....tons per Hour

COMPLEX ....Model One

A.7 Multiplan GAMS (Model Two) Acronyms List

MULPLAN ....Model Two

IPSEpro ....Process Simulation Environment

PSE..Simulation Environment

MDK ....model development kit

MULTFIVE ....Model Two

RESYSproDESAL.................special model library

A.8 Initial Main Model GAMS Code List

A.8.1 Parameters

capInvest ....Capital Investment

nExp ....Number of Expansions

NPV..Net Percent Value

NPV Factor ....Discount Factor for Net Present Value Factor

a^L_{jlt} $\boldsymbol{a}^L_{ijt}$, $\boldsymbol{a}^U_{ijt}$ ....Lower (L) and Upper Bound (U) for Purchases of Raw Materials j for plant i during period t

$\boldsymbol{d}^L_{ijt}$, $\boldsymbol{d}^U_{ijt}$ ....d^L_{jlt} a^L_{jlt} d^U_{jlt} Lower (L) and Upper Bound (U) for Demand of product m (Electricity and Water) during period t

CI_t $\boldsymbol{CI}_t$ ....Capital Investment Constraint for period t

$NEXP_i$ $\boldsymbol{NEXP}_i$ ....Maximum Number of New Plants of process i

Q_{i0} $\boldsymbol{Q}_{io}$ ....Existing Capacity of Process i at the start of the planning period

a^L_{jlt} $\boldsymbol{QE}^L_{it}$, $\boldsymbol{QE}^U_{it}$ ....Lower (L) and Upper Bound (U) for new plants using process i at time t

$\boldsymbol{\alpha}_{it}$ ....Variable Cost of adding Capacity to process i at time t

$\boldsymbol{\beta}_{it}$ ....Construction Cost for Opening a new plant using process i at time t

γ_{jlt} $\boldsymbol{\gamma}_{mt}$ ....Prices of Sales of product m (Electricity and Water) during time period t

Γ_{jlt} $\boldsymbol{\Gamma}_{mt}$ ....Cost of Raw Material j during time period t

$\boldsymbol{\delta}_{it}$ ....Unit Operating Cost of process during time period t

$\boldsymbol{\eta}_{ijm}$ ....Material Requirements of plant i with respect to Raw Material j to generate product m (in the case of Water could be Salt Water)

$\boldsymbol{\mu}_{im}$ ....Output of Product m from plant i with respect to the Operating level of the plant

A.8.2 Decision Variables

$\boldsymbol{I}_{ijmt}$ I_{ijt} :.................................Amount of Raw Material j consumed by a plants using process i to generate product m during period t (Operating at level Wit). It does not depend on k but it depends only on the technology of the plant.

$\boldsymbol{O}_{imt}$ O_{ijt} :................................Amount of Product m (Electricity, Water) produced by plants type i during period t

$\boldsymbol{P}_{ijt}$ ....Amount of Raw Material j purchased by plants i at the beginning of period t

$\boldsymbol{Q}_{it}$ ....Capacity of Plants with process i at the beginning of period t

QE_{ikt} ....Built Capacity of new plants with process i at the beginning of period t

QI_{ikt} ....Capacity of Individual plants k with process i at the beginning of period t

QP_{ikt} ....Capacity of Plants k with process i at the beginning of period t

S_{imt} ....Amount of Product m (Electricity and Water) sold from plant i at the beginning of period t.

W_{it} ....Operating Level of plant with process i during time period t

A.9 Complex GAMS (Model One) Code List

A.9.1 Binary Variables

YI ....Denotes Selection of process I when equal to one

YII...Denotes Selection of process II when equal to one

YIII..Denotes Selection of process III when equal to one

A.9.2 Positive Variables

PAPurchases of A (tons per hr)

PB..Purchases of B (tons per hr)

SC..Sales of C (tons per hr)

BI...Production Rate of B in process I (tons per hr)

BII ....Production Rate of B in process II (tons per hr)

BIII..Production Rate of B in process III (tons per hr)

CII ....Production Rate of C in process II (tons per hr)

CIII..Production Rate of C in process III (tons per hr);

Variable Profit........................Objective Function

A.9.3 Equations

E1 ....Select at most one of process II or III

E2 ....Mass Balance for B

E3 ....Mass Balance for C

E4 ....Mass Balance around process I

E5 ....Mass Balance around process II

E6 ....Mass Balance around process III

E7 ....No Purchases of A unless process I is selected

E8 ....No Production of BII unless process II is selected

E9 ....No Production of BIII unless process III is selected

OBJ ....Objective Function definition

A.10 Multiplan GAMS (Model Two) Code List

BETA (I, T)............................Fixed Investment Coefficient

LAM (J, K, T) ....Cost for Purchase of one unit of chemical

WCAPF (I).............................Working Capital factor

EXCAP (I) ....Existing Capacities (kton/year)

SVALF (I)..............................Salvage Value factor

NPRO....................................Number of Processes

NPER ....Number of Periods

NCHE....................................Number of Chemicals

NMAR...................................Number of Markets

INTR ....Interest Rate

TAX ....Tax Rate

T ....Time Periods

I ....Processes

J ....Chemicals

K..Markets

LENP (T) ....Length of Time periods (years)

LINVEST (T)........................Limit on Investment

JMM (I).................................Main Product for each process

LNEXP (I).............................Limit on the Number of Expansions

QELB (I, T)...........................Lower Bounds on Expansion

QEUB (I, T) ....Upper Bounds on Expansion

PLB (J, K, T).........................Purchase Lower bounds

SLB (J, K, T).........................Sales Lower bounds

VARIABLES Q (I, T)...........Capacities

QE (I, T)................................Capacity Expansions

Y (I, T) ....Integer Decision Variables

W (I,*, T) ....Low Rates

S (J, K, T)..............................Sales

P (J, K, T)..............................Purchases

Appendix B: Sample of GAMS Model and Output

B.1 Sample of GAMS Main Model

```
*GAMS MODEL DO NOT MODIFY
*Cogeneration Model-----------------------------------------------------------

$Title Location and Capacity Modeling of Cogeneration Plants
$setnames "%gams.input%" filepath filename fileextension
$setglobalgPath %filepath%
$setglobalposFile "PosProc.gms"
$setglobalpreFile "dataInput.gms"
$setglobalrunDataInput %filepath%%preFile%
$setglobalrunPosProc %filepath%%posFile%
$setglobalxlF "StandAlone.xlsm"

Sets
m Markets /w,e/
f  Trick for max plants /1/

*Time periods and subsets of timeperiods
t Time Periods years /1*37/
g(t)
xT(t)/1/

*Plant technologies and subsets
i Plant technology /1*5/
xI(i)/1,2,3/

*Number of plants per technology
k Max number of plants /1*10/
l(k)
xK /1,2/

*INput set
j Production inputs /1*5/
alias (t,h)

;

*set for existing plants
setiniPlants(i,k,t);
iniPlants(i,k,t)$(xI(i) and xK(k) and xT(t))=yes;

parameters
```

demandLB(t,m) Lower bounds for demand of water and electricity
demandUB(t,m) Upper bounds for demand of water and electricity
minCap(i,m)   Min Cap for production of product m on new plants of tech i
maxCap(i,m)   Max Cap for production of product m on new plants of tech i
minCapImpFac(i,m) Min capacity factor for cap improvement
maxCapImpFac (i,m) Max capacity factor for cap improvement
prodInputs(i,j,m) Prod input j used by plant i for product m
NPVFact(t) Factors for net present value
impCost(i) Plant implementation cost fixed part
capImpCost(i) Plant capacity expansion cost fixed part
capExpCost(i,m) Plant capacity expansion cost variable
inputCost(t,j) Input costs per unit per period
operCost(i) Plant operating cost as function of oper level w
minInptPur(i,j) Minimuminput purchase mat j plant i
maxInptPur(i,j) Maximum input purchase mat j plant i
prices(t,m) Sales prices for markets m at time t
maxPlants(f)
iniCost(i,k,t) implementation cost for plants
dRate /0.04/
nPZ /5/

B.2 Sample of GAMS Main Model Output

```
GAMS Rev 233  WIN-VIS 23.3.3 x86/MS Windows          10/09/13 09:24:47 Page 1
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
C o m p i l a t i o n


*GAMS MODEL DO NOT MODIFY
*Cogeneration Model-----------------------------------------------------
GAMS Rev 233  WIN-VIS 23.3.3 x86/MS Windows          10/09/13 09:24:47 Page 2
Location and Capacity Modeling of Cogeneration Plants
C o m p i l a t i o n



Sets
m Markets /w,e/
f  Trick for max plants /1/

*Time periods and subsets of timeperiods
t Time Periods years /1*37/
g(t)
xT(t)/1/
```

```
*Plant technologies and subsets
i Plant technology /1*5/
xI(i)/1,2,3/
*Number of plants per technology
k Max number of plants /1*10/
l(k)
xK /1,2/
*INput set
j Production inputs /1*5/
alias (t,h)
;
*set for existing plants
setiniPlants(i,k,t);
iniPlants(i,k,t)$(xI(i) and xK(k) and xT(t))=yes;
parameters
demandLB(t,m) Lower bounds for demand of water and electricity
demandUB(t,m) Upper bounds for demand of water and electricity
minCap(i,m)   Min Cap for production of product m on new plants of tech i
maxCap(i,m)   Max Cap for production of product m on new plants of tech i
minCapImpFac(i,m) Min capacity factor for cap improvement
maxCapImpFac (i,m) Max capacity factor for cap improvement
prodInputs(i,j,m) Prod input j used by plant i for product m
NPVFact(t) Factors for net present value
impCost(i) Plant implementation cost fixed part
capImpCost(i) Plant capacity expansion cost fixed part
capExpCost(i,m) Plant capacity expansion cost variable
inputCost(t,j) Input costs per unit per period
operCost(i) Plant operating cost as function of oper level w
minInptPur(i,j) Minimuminput purchase mat j plant i
maxInptPur(i,j) Maximum input purchase mat j plant i
prices(t,m) Sales prices for markets m at time t
maxPlants(f)
iniCost(i,k,t) implementation cost for plants
dRate /0.04/
nPZ /5/
;
```

```
66  *----------------------------------------------------------
67  *DATA INPUT
68  *----------------------------------------------------------
75  *This writes an external command file to read variables
76  *and populate a GDX file with the input data
98  *execute external file commands contained in
99  *cmdInput.txt file that we just wrote
GDXIN   C:\Users\Owner\AppData\Local\Temp\Temp1_StandAloneModel.zip\StandAloneMo
        del\InputData.gdx
--- LOAD  demandLB = 1:demandLB
--- LOAD  demandUB = 2:demandUB
--- LOAD  minCap = 3:minCap
--- LOAD  maxCap = 4:maxCap
--- LOAD  minCapImpFac = 5:minCapImpFac
--- LOAD  maxCapImpFac = 6:maxCapImpFac
--- LOAD  prodInputs = 7:prodInputs
--- LOAD  impCost = 8:impCost
--- LOAD  capImpCost = 9:capImpCost
--- LOAD  capExpCost = 10:capExpCost
--- LOAD  inputCost = 11:InputCost
--- LOAD  operCost = 12:operCost
--- LOAD  minInptPur = 13:minInptPur
--- LOAD  maxInptPur = 14:maxInptPur
--- LOAD  prices = 15:prices
--- LOAD  maxPlants = 16:maxPlants
103  *----------------------------------------------------------
104  *END DATA INPUT
105  *------------------------------


. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .


---- totalCosts  Total costs

totalCosts

          (.LO, .L, .UP, .M = 0, 0, +INF, 0)
       1      objCost
       1      objProfit

GAMS Rev 233  WIN-VIS 23.3.3 x86/MS Windows          10/09/13 09:24:47 Page 6
Location and Capacity Modeling of Cogeneration Plants
Model Statistics    SOLVE coGen Using MIP From line 320
```

MODEL STATISTICS

BLOCKS OF EQUATIONS 26 SINGLE EQUATIONS 32,686
BLOCKS OF VARIABLES 15 SINGLE VARIABLES 14,063 6 projected
NON ZERO ELEMENTS 169,088 DISCRETE VARIABLES 1,800

GENERATION TIME = 0.609 SECONDS 11 Mb WIN233-233 Dec 15, 2009

EXECUTION TIME = 0.624 SECONDS 11 Mb WIN233-233 Dec 15, 2009
GAMS Rev 233 WIN-VIS 23.3.3 x86/MS Windows 10/09/13 09:24:47 Page 7
Location and Capacity Modeling of Cogeneration Plants
Solution Report SOLVE coGen Using MIP From line 320

S O L V E S U M M A R Y

MODEL coGenOBJECTIVE totalProfit
TYPE MIP DIRECTION MAXIMIZE
SOLVER CPLEX FROM LINE 320

**** SOLVER STATUS 1 Normal Completion
**** MODEL STATUS 8 Integer Solution
**** OBJECTIVE VALUE -113570543395.9388

RESOURCE USAGE, LIMIT 475.382 1000.000
ITERATION COUNT, LIMIT 19142 2000000000

ILOG CPLEX Nov 1, 2009 23.3.3 WIN 13908.15043 VIS x86/MS Windows
Cplex 12.1.0, GAMS Link 34
Cplex licensed for 1 use of parallel lp, qp, mip and barrier.

Cplex MIP uses 1 of 2 parallel threads. Change default with option THREADS.
MIP status(102): integer optimal, tolerance

Fixed MIP status(4): unbounded or infeasible
Presolve found the problem infeasible or unbounded.
Rerunning with presolve turned off.
Fixed MIP status(3): infeasible
Dual infeasible or unbounded.Switching to primal to aid diagnosis.
Fixed MIP status(3): infeasible
Final solve did not return an optimal solution.
Returning a primal only solution to GAMS (marginals all set to 0.0).
Solution satisfies tolerances.

MIP Solution: -113570543395.938750 (11489 iterations, 20 nodes)
Best possible: -103190990152.349010
Absolute gap: 10379553243.589737
Relative gap: 0.091393

---- EQU MinDem Minimum demand satisfaction by market m at time t c1

	LOWER	SLACK	UPPER	MARGINAL
w.1	1.4897E+5	.	+INF	EPS
w.2	1.5531E+5	.	+INF	EPS
w.3	1.6180E+5	.	+INF	EPS
w.4	1.6843E+5	.	+INF	EPS
w.5	1.7521E+5	.	+INF	EPS
w.6	1.8213E+5	.	+INF	EPS
w.7	1.8921E+5	17203.080	+INF	EPS
w.8	1.9643E+5	35035.702	+INF	EPS
w.9	2.0380E+5	37765.635	+INF	EPS
w.10	2.1131E+5	35167.292	+INF	EPS
w.11	2.1898E+5	29884.632	+INF	EPS
w.12	2.2679E+5	24701.599	+INF	EPS
w.13	2.3475E+5	19666.086	+INF	EPS
w.14	2.4285E+5	31652.945	+INF	EPS
w.15	2.5110E+5	33104.802	+INF	EPS
w.16	2.5950E+5	31876.626	+INF	EPS
w.17	2.6805E+5	27146.129	+INF	EPS
w.18	2.7674E+5	23246.358	+INF	EPS
w.19	2.8558E+5	18541.572	+INF	EPS
w.20	2.9457E+5	30649.302	+INF	EPS
w.21	3.0371E+5	32183.385	+INF	EPS
w.22	3.1299E+5	31002.653	+INF	EPS
w.23	3.2242E+5	26288.297	+INF	EPS
w.24	3.3200E+5	22376.493	+INF	EPS
w.25	3.4172E+5	18449.183	+INF	EPS
w.26	3.5160E+5	16426.773	+INF	EPS
w.27	3.6162E+5	14450.005	+INF	EPS
w.28	3.7178E+5	10707.445	+INF	EPS
w.29	3.8210E+5	5189.695	+INF	EPS
w.30	3.9256E+5	.	+INF	EPS
w.31	4.0317E+5	.	+INF	EPS
w.32	4.1392E+5	.	+INF	EPS
w.33	4.2483E+5	.	+INF	EPS
w.34	4.3588E+5	.	+INF	EPS
w.35	4.4707E+5	.	+INF	EPS

w.36	4.5842E+5	.	+INF	EPS
w.37	4.6991E+5	.	+INF	EPS
e.1	4079.713	2965.434	+INF	EPS
e.2	4286.200	2369.672	+INF	EPS
e.3	4498.455	1781.453	+INF	EPS
e.4	4716.479	1251.284	+INF	EPS
e.5	4940.271	736.032	+INF	EPS
e.6	5169.831	223.353	+INF	EPS
e.7	5405.160	.	+INF	EPS
e.8	5646.257	.	+INF	EPS
e.9	5893.122	.	+INF	EPS
e.10	6145.756	.	+INF	EPS
e.11	6404.158	.	+INF	EPS
e.12	6668.329	.	+INF	EPS
e.13	6938.268	.	+INF	EPS
e.14	7213.975	.	+INF	EPS
e.15	7495.451	.	+INF	EPS
e.16	7782.695	.	+INF	EPS
e.17	8075.708	.	+INF	EPS
e.18	8374.489	.	+INF	EPS
e.19	8679.038	.	+INF	EPS
e.20	8989.355	.	+INF	EPS
e.21	9305.442	.	+INF	EPS
e.22	9627.296	.	+INF	EPS
e.23	9954.919	.	+INF	EPS
e.24	10288.310	.	+INF	EPS
e.25	10627.470	.	+INF	EPS
e.26	10972.398	.	+INF	EPS
e.27	11323.094	.	+INF	EPS
e.28	11679.559	.	+INF	EPS
e.29	12041.792	.	+INF	EPS
e.30	12409.793	10.579	+INF	EPS
e.31	12783.563	358.070	+INF	EPS
e.32	13163.101	706.413	+INF	EPS
e.33	13548.408	1055.904	+INF	EPS
e.34	13939.483	1360.343	+INF	EPS
e.35	14336.327	1728.915	+INF	EPS
e.36	14738.938	2097.763	+INF	EPS
e.37	15147.319	2467.241	+INF	EPS

. . . .
. . . .
. . . .

LOWER LEVEL UPPER MARGINAL

```
---- VAR totalReve~      .   1.8728E+7     +INF       EPS
---- VAR totalProf~     -INF  -1.14E+11     +INF       EPS
---- VAR totalCosts      .   1.136E+11     +INF       EPS

totalRevenues  Total revenues for the operation
totalProfit  Total implementation and operation cost
totalCosts  Total costs


**** REPORT SUMMARY :        0     NONOPT
                        0 INFEASIBLE
0  UNBOUNDED
GAMS Rev 233  WIN-VIS 23.3.3 x86/MS Windows           10/09/13 09:24:47 Page 8
Location and Capacity Modeling of Cogeneration Plants
E x e c u t i o n


**** Exec Error at line 324: division by zero (0)


EXECUTION TIME       =        0.249 SECONDS      6 Mb  WIN233-233 Dec 15, 2009
```

B.3 Sample of GAMS Main Model Output Scenario

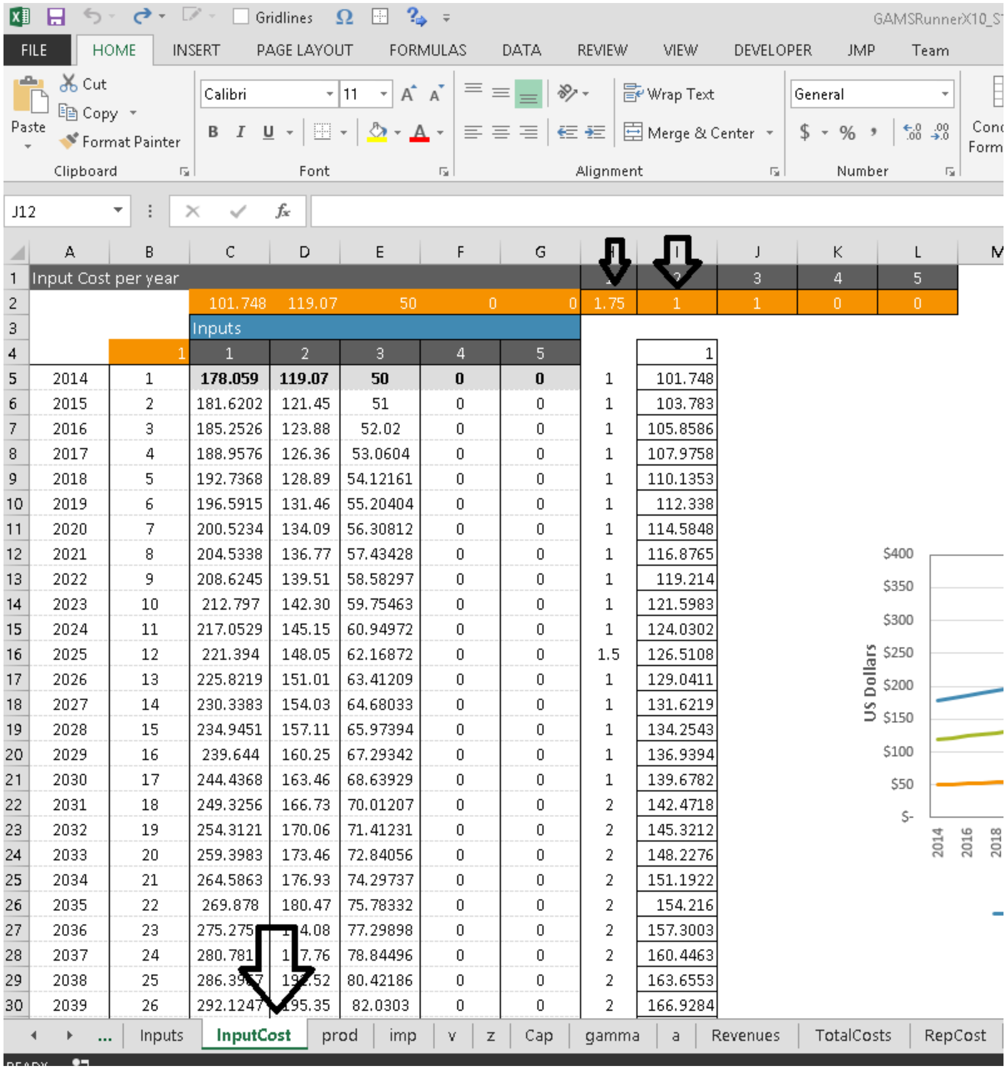
Scenario 1 S1:

S1_O175: Increase oil prices in 1.75
S1_G175: Increase gas prices in 1.75

C_{it}^{inp}: Estimated cost of input j at time t (Oil: \$/barrel; Natual Gas: \$/ft^3)

```
parameters
demandLB(t,m) Lower bounds for demand of water and electricity
demandUB(t,m) Upper bounds for demand of water and electricity
minCap(i,m)    Min Cap for production of product m on new plants of tech i
maxCap(i,m)    Max Cap for production of product m on new plants of tech i
minCapImpFac(i,m) Min capacity factor for cap improvement
maxCapImpFac (i,m) Max capacity factor for cap improvement
prodInputs(i,j,m) Prod input j used by plant i for product m
NPVFact(t) Factors for net present value
impCost(i) Plant implementation cost fixed part
capImpCost(i) Plant capacity expansion cost fixed part
capExpCost(i,m) Plant capacity expansion cost variable
inputCost(t,j) Input costs per unit per period
operCost(i) Plant operating cost as function of oper level w
minInptPur(i,j) Minimu minput purchase mat j plant i
maxInptPur(i,j) Maximum input purchase mat j plant i
prices(t,m) Sales prices for markets m at time t
maxPlants(f)
iniCost(i,k,t) implementation cost for plants
dRate /0.04/
nPZ /5/
```

Figure B-1 Scenario 1 S1: S1_O175: Increase Oil Prices in 1.75



	A	B	C	D	E	F	G	H	I	J	K	L
1	Input Cost per year									3	4	5
2			101.748	119.07	50	0	0	1.75	1	1	0	0
3			Inputs									
4		1	1	2	3	4	5		1			
5	2014	1	**178.059**	**119.07**	**50**	**0**	**0**	1	101.748			
6	2015	2	181.6202	121.45	51	0	0	1	103.783			
7	2016	3	185.2526	123.88	52.02	0	0	1	105.8586			
8	2017	4	188.9576	126.36	53.0604	0	0	1	107.9758			
9	2018	5	192.7368	128.89	54.12161	0	0	1	110.1353			
10	2019	6	196.5915	131.46	55.20404	0	0	1	112.338			
11	2020	7	200.5234	134.09	56.30812	0	0	1	114.5848			
12	2021	8	204.5338	136.77	57.43428	0	0	1	116.8765			
13	2022	9	208.6245	139.51	58.58297	0	0	1	119.214			
14	2023	10	212.797	142.30	59.75463	0	0	1	121.5983			
15	2024	11	217.0529	145.15	60.94972	0	0	1	124.0302			
16	2025	12	221.394	148.05	62.16872	0	0	1.5	126.5108			
17	2026	13	225.8219	151.01	63.41209	0	0	1	129.0411			
18	2027	14	230.3383	154.03	64.68033	0	0	1	131.6219			
19	2028	15	234.9451	157.11	65.97394	0	0	1	134.2543			
20	2029	16	239.644	160.25	67.29342	0	0	1	136.9394			
21	2030	17	244.4368	163.46	68.63929	0	0	1	139.6782			
22	2031	18	249.3256	166.73	70.01207	0	0	2	142.4718			
23	2032	19	254.3121	170.06	71.41231	0	0	2	145.3212			
24	2033	20	259.3983	173.46	72.84056	0	0	2	148.2276			
25	2034	21	264.5863	176.93	74.29737	0	0	2	151.1922			
26	2035	22	269.878	180.47	75.78332	0	0	2	154.216			
27	2036	23	275.275[illegible]	[illegible]4.08	77.29898	0	0	2	157.3003			
28	2037	24	280.781[illegible]	1[illegible]7.76	78.84496	0	0	2	160.4463			
29	2038	25	286.39[illegible]7	19[illegible].52	80.42186	0	0	2	163.6553			
30	2039	26	292.1247	[illegible]95.35	82.0303	0	0	2	166.9284			

Figure B-2 S1_G175: Increase Gas Prices in 1.75

---##############################

Scenario 2 S2:

One aspect of the utilization of solar-base plants is the limitation of its water and electric power generation capabilities. If the research provides a breakthrough and solar plants increase their current capacity in 1.5 (S1.5) to 3 (S3) times then the installation and production schedule may change. In this section such changes are considered.

S2_S15: Increase plant capacity for solar in 1.5 times

S2_S30: Increase plant capacity for solar in 3 times

$\gamma_{im}^{\min}$: Minimum capacity expansion for plants of technology i (M US Gal/year, MW/year)

```
parameters
demandLB(t,m) Lower bounds for demand of water and electricity
demandUB(t,m) Upper bounds for demand of water and electricity
minCap(i,m)    Min Cap for production of product m on new plants of tech i
maxCap(i,m)    Max Cap for production of product m on new plants of tech i
minCapImpFac(i,m) Min capacity factor for cap improvement
maxCapImpFac (i,m) Max capacity factor for cap improvement
prodInputs(i,j,m) Prod input j used by plant i for product m
NPVFact(t) Factors for net present value
impCost(i) Plant implementation cost fixed part
capImpCost(i) Plant capacity expansion cost fixed part
capExpCost(i,m) Plant capacity expansion cost variable
inputCost(t,j) Input costs per unit per period
operCost(i) Plant operating cost as function of oper level w
minInptPur(i,j) Minimu minput purchase mat j plant i
maxInptPur(i,j) Maximum input purchase mat j plant i
prices(t,m) Sales prices for markets m at time t
maxPlants(f)
iniCost(i,k,t) implementation cost for plants
dRate /0.04/
nPZ /5/
```

Figure B-3 Scenario 2 S2: S2_S15: Increase Plant Capacity for Solar in 1.5 Times

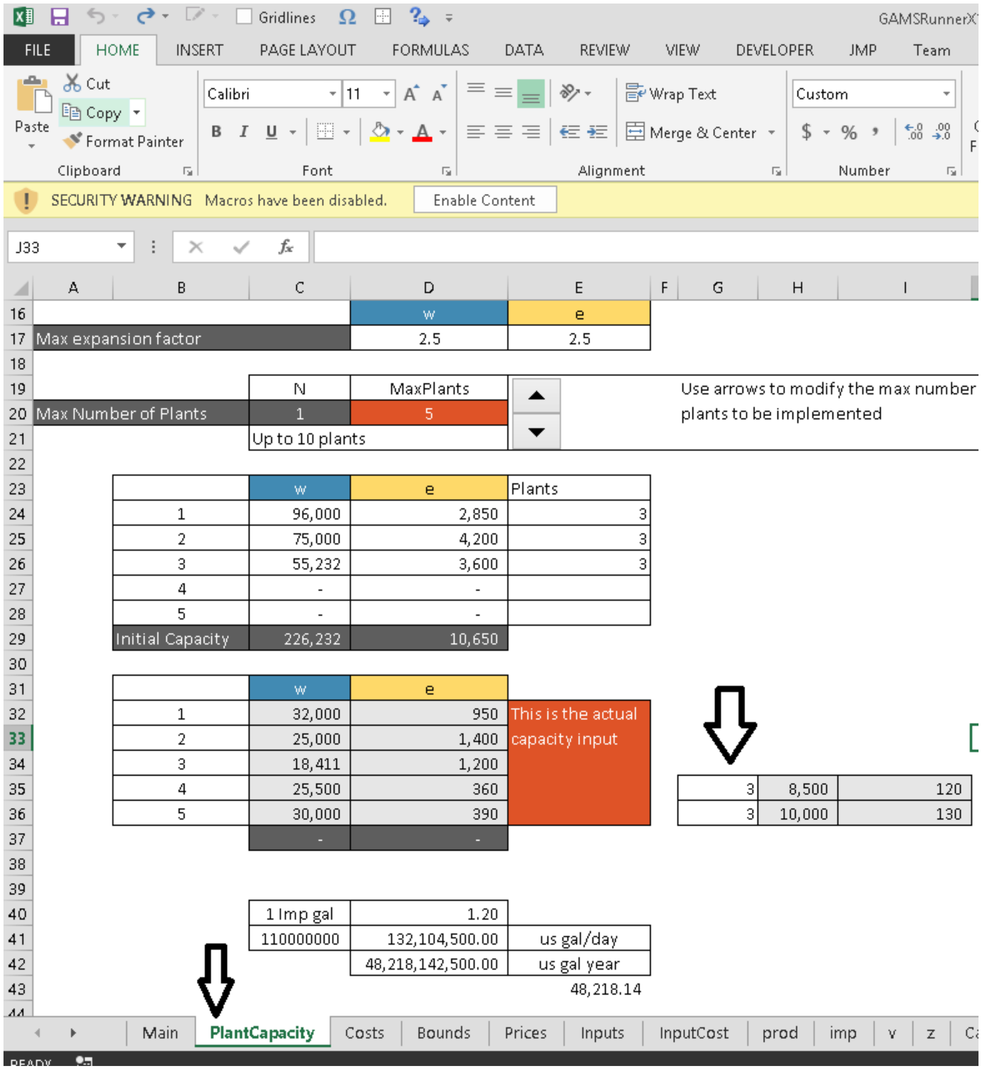


Figure B-4 S2_S30: Increase Plant Capacity for Solar in 3 Times

------------------------##
Scenario 3 S3

For scenario 3, increase values of demand for both water and electricity were introduced. Two scenarios were introduced by means of escalation factors. The scenario D1.5 increases the demand in 1.5 times, similarly in the scenario D2.0 the demand is increased two times

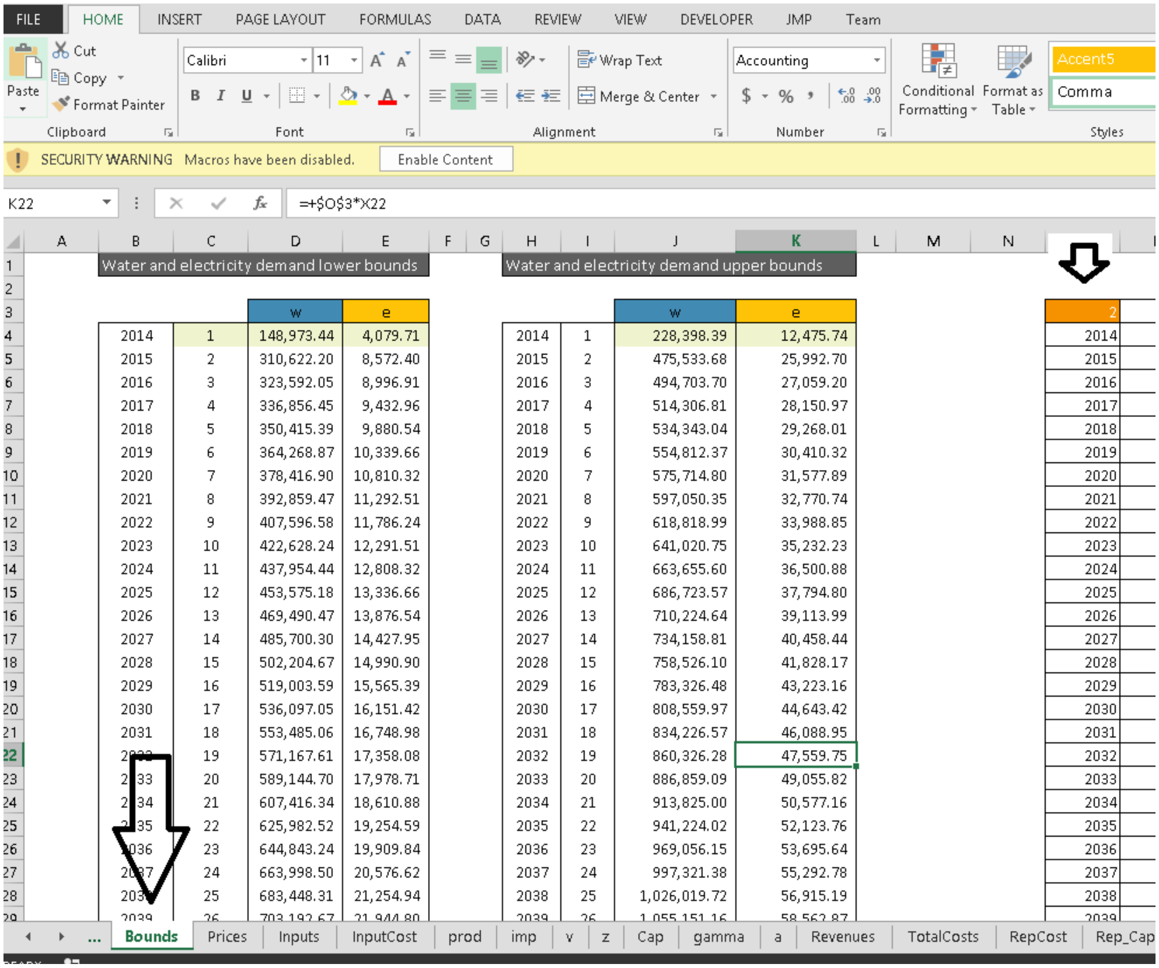
S3_D15: Increase plant capacity for oil in 1.5
S3_D30: Increase plant capacity for gas in 2.0

d_{mt}^{min}: Minimum demand estimate for product of market m for planning period t (M US Gal/year, MW/year)

d_{mt}^{max}: Maximum demand estimate for product of market m for planning period t (M US Gal/year, MW/year)

```
parameters
demandLB(t,m) Lower bounds for demand of water and electricity
demandUB(t,m) Upper bounds for demand of water and electricity
minCap(i,m)    Min Cap for production of product m on new plants of tech i
maxCap(i,m)    Max Cap for production of product m on new plants of tech i
minCapImpFac(i,m) Min capacity factor for cap improvement
maxCapImpFac (i,m) Max capacity factor for cap improvement
prodInputs(i,j,m) Prod input j used by plant i for product m
NPVFact(t) Factors for net present value
impCost(i) Plant implementation cost fixed part
capImpCost(i) Plant capacity expansion cost fixed part
capExpCost(i,m) Plant capacity expansion cost variable
inputCost(t,j) Input costs per unit per period
operCost(i) Plant operating cost as function of oper level w
minInptPur(i,j) Minimu minput purchase mat j plant i
maxInptPur(i,j) Maximum input purchase mat j plant i
prices(t,m) Sales prices for markets m at time t
maxPlants(f)
iniCost(i,k,t) implementation cost for plants
dRate /0.04/
nPZ /5/
```

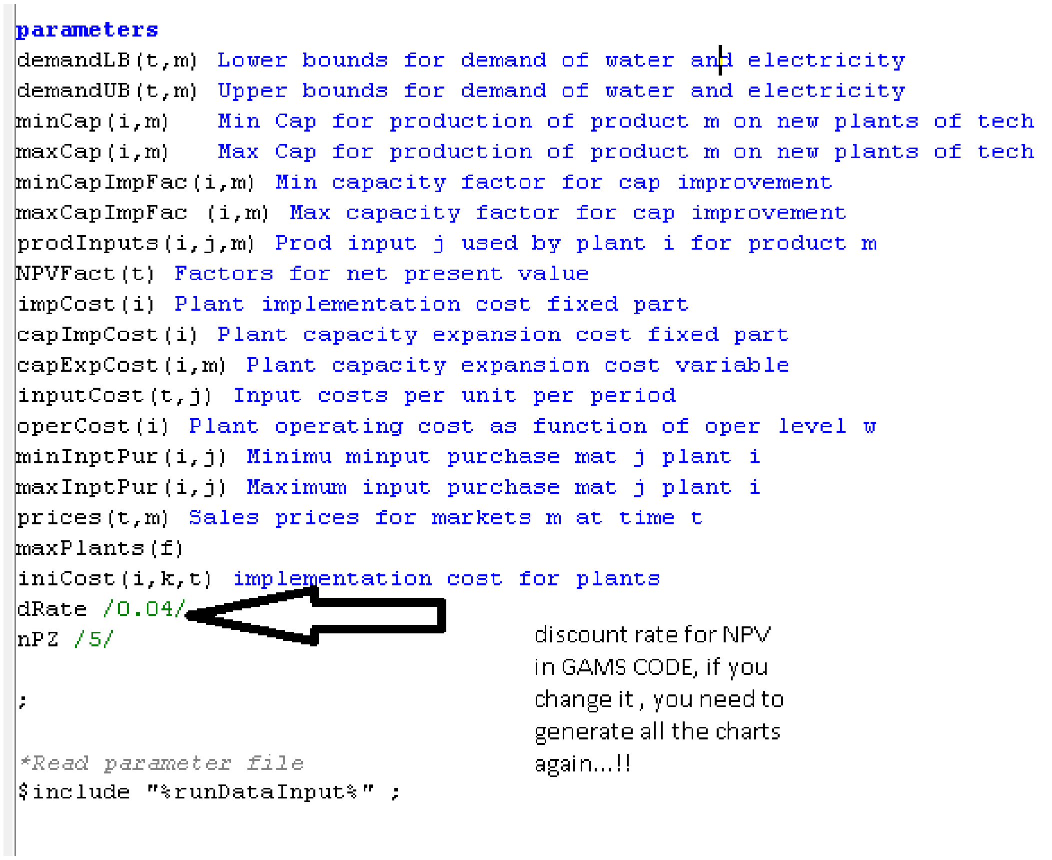
Figure B-5 Sensitivity Analysis of Increase in Demand for Water and Electricity – S3



	B	C	D	E	H	I	J	K	
1	Water and electricity demand lower bounds				Water and electricity demand upper bounds				
3			w	e			w	e	2
4	2014	1	148,973.44	4,079.71	2014	1	228,398.39	12,475.74	2014
5	2015	2	310,622.20	8,572.40	2015	2	475,533.68	25,992.70	2015
6	2016	3	323,592.05	8,996.91	2016	3	494,703.70	27,059.20	2016
7	2017	4	336,856.45	9,432.96	2017	4	514,306.81	28,150.97	2017
8	2018	5	350,415.39	9,880.54	2018	5	534,343.04	29,268.01	2018
9	2019	6	364,268.87	10,339.66	2019	6	554,812.37	30,410.32	2019
10	2020	7	378,416.90	10,810.32	2020	7	575,714.80	31,577.89	2020
11	2021	8	392,859.47	11,292.51	2021	8	597,050.35	32,770.74	2021
12	2022	9	407,596.58	11,786.24	2022	9	618,818.99	33,988.85	2022
13	2023	10	422,628.24	12,291.51	2023	10	641,020.75	35,232.23	2023
14	2024	11	437,954.44	12,808.32	2024	11	663,655.60	36,500.88	2024
15	2025	12	453,575.18	13,336.66	2025	12	686,723.57	37,794.80	2025
16	2026	13	469,490.47	13,876.54	2026	13	710,224.64	39,113.99	2026
17	2027	14	485,700.30	14,427.95	2027	14	734,158.81	40,458.44	2027
18	2028	15	502,204.67	14,990.90	2028	15	758,526.10	41,828.17	2028
19	2029	16	519,003.59	15,565.39	2029	16	783,326.48	43,223.16	2029
20	2030	17	536,097.05	16,151.42	2030	17	808,559.97	44,643.42	2030
21	2031	18	553,485.06	16,748.98	2031	18	834,226.57	46,088.95	2031
22	[illegible]	19	571,167.61	17,358.08	2032	19	860,326.28	47,559.75	2032
23	2033	20	589,144.70	17,978.71	2033	20	886,859.09	49,055.82	2033
24	2034	21	607,416.34	18,610.88	2034	21	913,825.00	50,577.16	2034
25	2035	22	625,982.52	19,254.59	2035	22	941,224.02	52,123.76	2035
26	2036	23	644,843.24	19,909.84	2036	23	969,056.15	53,695.64	2036
27	2037	24	663,998.50	20,576.62	2037	24	997,321.38	55,292.78	2037
28	2038	25	683,448.31	21,254.94	2038	25	1,026,019.72	56,915.19	2038
29	2039	26	703,192.67	21,944.80	2039	26	1,055,151.16	58,562.87	2039

Figure B-6 Sensitivity Analysis of Increase in Demand for Water and Electricity – S3

Discount Rate was 4% and it is in the parameter in the GAMS model.



```
parameters
demandLB(t,m) Lower bounds for demand of water and electricity
demandUB(t,m) Upper bounds for demand of water and electricity
minCap(i,m)    Min Cap for production of product m on new plants of tech i
maxCap(i,m)    Max Cap for production of product m on new plants of tech i
minCapImpFac(i,m) Min capacity factor for cap improvement
maxCapImpFac (i,m) Max capacity factor for cap improvement
prodInputs(i,j,m) Prod input j used by plant i for product m
NPVFact(t) Factors for net present value
impCost(i) Plant implementation cost fixed part
capImpCost(i) Plant capacity expansion cost fixed part
capExpCost(i,m) Plant capacity expansion cost variable
inputCost(t,j) Input costs per unit per period
operCost(i) Plant operating cost as function of oper level w
minInptPur(i,j) Minimu minput purchase mat j plant i
maxInptPur(i,j) Maximum input purchase mat j plant i
prices(t,m) Sales prices for markets m at time t
maxPlants(f)
iniCost(i,k,t) implementation cost for plants
dRate /0.04/
nPZ /5/

;

*Read parameter file
$include "%runDataInput%" ;
```


Figure B-7 Discount Rate was 4% and is in the Parameter in the GAMS Model

Appendix C: Publications

In this research, the potential publications could be:

1. A Multi-Period MILP Model for Water and Energy Supply Planning
2. Water Supply Energy Considerations with Oil Rich Arid Coastal Environments
3. New Optimization Model adapted for Water and Energy Supply Planning
4. Back Ground Research and Problem Statement, Methodology of the Optimization Model with Application of Methodology
5. Extension of Methodology and Further Analysis of Results