IDENTIFYING PATHWAYS TOWARD SUSTAINABLE ELECTRICITY SUPPLY AND DEMAND USING AN INTEGRATED RESOURCE STRATEGIC PLANNING MODEL FOR SAUDI ARABIA

by

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A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Energy and Environmental Policy

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ABSTRACT

Despite holding 16% of proved oil reserves in the world (equivalent to more than 266 billion barrels), Saudi Arabia might be on an unsustainable path to become a net oil importer by the 2030s. Decades of domestic energy subsidies accompanied by a high population growth rate have encouraged inefficient production and high domestic consumption of fossil fuel energy, which has resulted in environmental degradation, and significant social and economic consequences. In addition, the government's dependence on oil as a main source of revenue (89%) to finance its development programs cannot be sustained due to oil's exhaustible nature and rapidly increasing domestic consumption.

In Saudi Arabia, the electricity and water sectors consume more energy than other sectors. The literature review conducted as part of this dissertation revealed that electricity use in Saudi Arabia is following an unsustainable path (7–8% annual growth over the last decade). Due to the country's extremely hot weather during the summer, air conditioning represents 70% of the residential sector's total annual energy consumption. The water sector is another major energy consumer due to an unprecedented demand for water in the Kingdom (per capita consumption is twice the world average). Saudi Arabia's water stems mostly from desalination plants, which are currently responsible for producing approximately 18% of world's total desalinated water output.

Since the Kingdom started restructuring its power sector in the 2000s, multiple entities have been involved in fragmented planning activities on the supply-side as

well as to a certain extent on the demand-side; moreover, comprehensive integrated resource strategic plans have been lacking at the national level. This dissertation established an integrated resource strategic planning (IRSP) model for Saudi Arabia's electricity and water sectors (i.e., the EWS model). This model is a useful optimization tool for integrating demand-side and supply-side resources and for aligning fragmented energy policies among various entities with overall economic, social, and environmental objectives. With all of its components and details, the IRSP can clearly determine the Kingdom's future vision of its utility sector, including goals, policies, programs, and an execution timetable, taking into consideration economic, environmental and social benefits. To provide input to the EWS model, a weather-based hybrid end-use econometric demand forecasting model was developed to comprehensively project electricity demand in all sectors and regions until 2040. This proposed forecasting model evaluates weather and climate change impacts on Saudi Arabia's electricity demand.

On the supply-side, the analytical economic efficiency and technical assessments reveal that Saudi Arabia can supply almost 75% of its electricity from renewable energy sources by 2040. On the demand-side, the results also reveal that there is a significant achievable potential for saving 26% of peak demand by 2040. Even with the strong potential for demand-side management and renewable energy identified in Saudi Arabia, the development of sustainable energy systems in the country's utility sector will not occur automatically. For this purpose, several actions are proposed for developing the sustainable energy roadmap, strategies, and policies for Saudi Arabia's utility sector by addressing three key steps: (1) formulating a long-term goal that incorporates national targets for Saudi Arabia, (2) facilitating the achievement of these goals through the implementation of sound policies and regulations, and (3) creating effective governance structures and administrative processes to ensure that new policies and regulations are enforced and reviewed regularly. The dissertation suggests several important conclusions related to the design of effective intervention policies for a sustainable Saudi utility sector, supporting its position as a new vehicle of growth that facilitates national and socio-economic development and economic diversification plans.

Chapter 1

INTRODUCTION

1.1 Problem Statement

Domestic energy consumption in the Kingdom of Saudi Arabia (KSA) is skyrocketing. The country relies exclusively on oil and natural gas as its primary energy sources, which respectively contributed to 142 million tons of oil equivalent (Mtoe) and 97.4 Mtoe in 2014 (BP, 2015, pp. 11-24). In 2014, oil consumption grew 7.3%, ranking Saudi Arabia as the world's eighth largest oil consumer given that it domestically consumes a quarter of its crude oil and natural gas production (BP, 2015). In 2010, Khalid Al-Falih, Saudi Arabia's current Minister of Energy, Industry and Mineral Resources and the Chairman of Saudi Aramco (the national oil company), warned that even with production increases, the country's oil export capacity might fall by three million barrels per day by 2028 if rising domestic energy demand is not curtailed by more efficient energy usage (Woertz, 2013, p. 2; Al-Falih, 2010). Likewise, a number of studies show that the Kingdom is on a path to becoming a net oil importer by the 2030s on a business as usual scenario (Taher & Hajjar, 2014, p. 36; Lahn & Stevens, 2011, p. 2; Daya & El-Baltagi, 2012; Woertz, 2013, p. 2; Hashim, 2014, p. 5; MoWE, 2009). This drastic paradigm shift would significantly impact government revenues and global energy governance. Moreover, oil revenues account for more than 89% of the government income (Taher & Hajjar, 2014; SAMA, 2013, p.

132) and shifting to a net importer would drastically alter the way the government plans and delivers services to its citizens.[1]

Under these circumstances, the position and role of the electricity and water desalination sectors are becoming increasingly important. These two sectors represent approximately 42% of total primary energy consumed in Saudi Arabia and are growing faster than the national gross domestic product (GDP) (K.A.CARE, 2010, p.14). According to the 2014 British Petroleum (BP) Statistical Review of World Energy, the kingdom generated around 292 billion kilowatt hours (kWh) of electricity in 2013, which was 7% more than in 2012 and more than double than in 2000 (EIA, 2014a, p. 15).[2] Understanding the challenges associated with decoupling crude oil from power generation in Saudi Arabia or entirely stopping the use of oil for electricity generation, reducing electricity demand, using natural gas only to balance energy supply and demand, and adopting renewables all have the potential to result in substantial economic, environmental, and social benefits (Alyousef & Abu-ebid, 2012, p. 281; Helman, 2012; Lahn & Stevens, 2011, p. 27).

A review of Saudi Arabia's utility sector reveals that the country's high demand for electricity can be attributed to many factors. The Kingdom's growing population and economy (i.e. wealth) have led to substantial increases in power and water demands, while the energy efficiency of the power and water desalination

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[1] Based on the average proportion of government income between 2006 and 2012 (SAMA, 2013, Chart 9.6).

[2] This figure represents only the sold energy by the Saudi Electricity Company (SEC); it does not include internal energy consumption by other companies, such as Aramco, supplied from their own generators. In 2013, 311 TWh of energy was produced by all generators in Saudi Arabia.

industries remains underdeveloped. Many steam turbine power plants have not been optimized for efficiency, only a few combined cycle gas turbine (CCGT) power plants have been installed, and many outdated, inefficient simple cycle gas turbine power (SGGT) plants are in operation (SEC, 2014). Based on existing fuel consumption and electricity production figures, the country's average power generation efficiency is 32%, which is lower than the global average fossil-fuel power generation efficiency of 35% (EIA, 2012; Matar, Murphy, Pierru, Rioux, & Wogan, 2015).[3] Additionally, the fuel mix in power generation facilities consists of natural gas (45%) as the main fuel source for CGTG and combined heat and power (CHP), and some of simple cycle (SC) and steam turbine (ST) power plants. Crude oil and diesel (55%) are the main fuel source for the majority of SC and ST power plants. This inefficient fuel mix increases domestic consumption, which is detrimental to exports of highly valued crude oil. In fact, heavy fuel oil (HFO) and diesel are often imported at international prices and sold domestically at subsidized prices during peak power demand in summer (Fattouh, 2013, p. 5). The age of plants and the increasing demand necessitate new plant capacity and thus substantial capital investments in the power and water desalination industries.

Carbon dioxide (CO_2) emissions from the power and desalination sectors are predicted to rise from 405 million tons in 2012 to 830 million tons in 2030,

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[3] For a reasonable comparison, the efficiency of Saudi power generation has been compared to the global average efficiency of gas- and oil-fired power. The efficiency gap is even higher when compared to the United Kingdom, which has a power generation efficiency of 38.9% (ECRA, 2009a).

respectively (Alyousef & Abu-ebid, 2012, p. 287).[4] Until recently, Saudi utilities were exempted from environment protection regulations due to relaxed governmental mandates for power plants. The landmark “Paris Agreement” that countries recently concluded to halt climate change adds another layer of clean power generation requirements (UNFCCC, 2016).[5] In 2015, Saudi Arabia presented its plans and measures to the UNFCCC as part of its Intended Nationally Determined Contribution (INDC) report. According to UNFCCC (2015), the nation aims to focus on economic diversification and adaptation activities in order to reduce emissions up to as much as 130 million tons of CO_2 eq per year by 2030.

Owing to the above factors, Saudi Arabia needs a transition for increasing the share of natural gas in electricity generation, diversifying its fuel mix in power generation technologies, and improving the overall efficiency of power generation in its electricity and water desalination industries. The transition aims to serve dual objectives: first, reducing fuel consumption (and therefore freeing more fuel for international export) or shifting fuel consumption towards the petrochemical sector or other greater-value sectors (Nachet & Aoun, 2015, p. 20); and second, having a much cleaner environment (Taher & Hajjar, 2014, p. 1).

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[4] Taher and Hajjar (2014, pp. 31-35) report that the Saudi electricity and desalination sectors presently represent approximately 69% of domestic CO_2 emissions.

[5] The Paris Agreement is part of the United Nations Framework Convention on Climate Change (UNFCCC) and aims to bring all nations together to overcome the climate change issue as a collective force. Almost 200 nations committed themselves to reducing greenhouse gas emissions in December 2015, with 194 UNFCCC members having signed the treaty by December 2016. In November 2016, Saudi Arabia joined 116 other nations in ratifying the agreement.

Addressing the electricity and water sector (EWS) requires an integrated and holistic approach. Key elements of the approach include: (1) creating a comprehensive integrated resource strategic plan (IRSP)[6] for the power and water sectors; and (2) undertaking joint electricity-water development that takes the international experiences of IRSP into consideration. This dissertation is thus based on the following hypotheses:

- The IRSP framework provides a sound method to improve the social, economic, and environmental conditions in the Kingdom by delivering a least cost solution for a multifaceted set of objectives.
- Incorporating sustainable energy options into the utility sector should serve a wide range of interests in approaching utility sustainability, including those of the government, public, and industry.

This dissertation reviews international experiences related to balancing supply and demand efficiently, taking the two hypotheses, Saudi Arabia's resource constraints, and environmental factors into consideration. The potential of incorporating sustainable energy options and an optimal fuel mix into the Saudi utility sector to enhance social, economic, and environmental performance of both the sector and the country in general is investigated as a conceptual question. The goals of this research are to (1) create a rational framework for optimizing the fuels mix on the

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[6] Comprehensive IRSP has never been implemented in the Saudi utility sector. Instead, different entities have carried out scattered integrated resource plans (IRPs). The Electricity and Cogeneration Regulatory Authority (ECRA) has identified IRPs as one solution to the challenges facing the electricity industry in Saudi Arabia (Qahtani, 2012, p. 31).

supply-side and achieving more energy efficient usage on the demand-side and (2) recommend sustainable policy strategies for the Saudi utility sector that reflect this framework's analytical outcomes.

1.2 Rationale of the Research

This research was selected for four specific reasons. First, Saudi Arabia's unique role as both the world's main oil exporter[7] and a global energy price regulator, which enables it to stabilize the global oil market by managing export volumes, could be weakened by continued high domestic energy consumption. This situation could result in a high price volatility in world markets (Stevens, 2009). In addition, oil accounts for approximately 90% of Saudi Arabia's total export revenues and a significant share of government revenue. High domestic energy consumption would have detrimental impacts for government revenues as well as for sustainable economic growth and development in the future (Taher & Hajjar, 2014).

Second, since power sector restructuring began in the Kingdom, multiple entities have been involved in planning activities on the supply-side as well as to a certain extent on the demand-side. This includes the Saudi Electricity Company (SEC), independent water and power producers (IWPP), the Electricity and Cogeneration Regulatory Authority (ECRA), the King Abdullah City for Atomic and Renewable Energy (K.A.CARE), and Saudi Aramco. None of these entities can fully develop IRSP alone. In light of the apparent failure of the traditional monopoly model

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[7] Taher and Hajjar (2014) reported that Saudi oil reserves represent more than 250 billion barrels, which is equal to 25% of recorded global reserves, making Saudi Arabia the nation with the largest oil reserves in the world.

of vertically integrated utility sector planning, another planning method (such as an IRSP) that aims to maximize benefits, including all potential national resources on both the supply-side and demand-side, needs to be developed (Hu, Han, & Wen, 2013).

Third, due to the extremely hot weather conditions and resultant high use of air conditioning in Saudi Arabia, the average electricity demand in summer is around twice as high as in winter. Base-, intermediate-, and peak-load demand differ widely between day and night and from season to season. As a consequence of partnership between the SEC and Ministry of Water and Electricity (MoWE), load management and demand response initiatives led to some success in terms of the sustainability policies already in place, resulting in over 1,000 megawatts (MW) of peak load savings as of 2012. No other formal reports on the total DSM impacts in Saudi Arabia are available (Faruqui & Hledik, 2011, p. 23). Despite the benefits of implementing DSM, its potential remains highly untapped in Saudi Arabia (Nachet & Aoun, 2015, p. 15). These conditions require further optimization of the fuel mix and adopting effective economic electrical dispatch. In addition, the effective implementation of DSM initiatives will bring significant benefits to the kingdom in the form of avoided energy and capacity costs as well as emission reductions.

Fourth, planned investments in renewable energy were far from realization in Saudi Arabia in the past few years. At the end of 2013, the country had a total of only 19 MW of installed solar capacity (Nachet & Aoun, 2015, p. 22). With the absence of policy, financing, and market incentives (including infrastructure-scale investments) at the national level, the uncoordinated and scattered efforts were largely ineffective in the past (Taher & Hajjar, 2014, p. 17; Al-Ajlan, Al-Ibrahim, Abdulkhaleq, &

Alghamdi, 2006; Alyousef & Abu-ebid, 2012). The situation has improved as a revised renewable plan has been recently announced for the first phase tenders of 9.5 GW of solar, PV and CSP by 2023 under a new roadmap “Saudi Arabia’s Vision 2030” for future economic development (Kneller, 2017). As an example of the potential role that renewable energy has in solving the aforementioned problems, based on approximately 2,000 kWh/m²/year of direct normal irradiance (DNI), the potential annual energy yield of concentrated solar power (CSP) technology in the Kingdom has been estimated to be around 124,560 tera-watt hours (TWh) (Farnoosh, Lantz, & Precebois, 2013). This amount is approximately 500 times the country’s total 2012 electricity consumption. Based on renewable energy potential, sustainable joint electricity-water development should be prioritized by Saudi Arabia as a first step toward optimizing the supply-side fuel mix and deepening efficient DSM strategies.

1.3 Background

1.3.1 Overview of Saudi Arabia’s Utility Sector

Saudi Arabia’s electricity sector has gone through three major stages: (1) development by private enterprises in the 1930s; (2) consolidation into publicly owned and government-managed companies in the early 1960s; and (3) privatization and restructuring in the 2000s.

In the first stage, electricity generation was left to small local companies that were organized as business cooperatives and met the electricity needs of their members. They later expanded to supplying neighboring residential areas and powering street lighting. Small-scale power distribution firms and power plants began to emerge in cities during the early 1950s, all of which were commercial rather than government or public entities. The power they generated was sold at varying rates that were independently set according to the local cost of electricity generation (ECRA, 2014; Hagihara, 2013).

Hagihara (2013, p. 115) described the evolution of the Saudi electricity sector and its institutions from the early 1960s, when the electricity sector's second stage began:

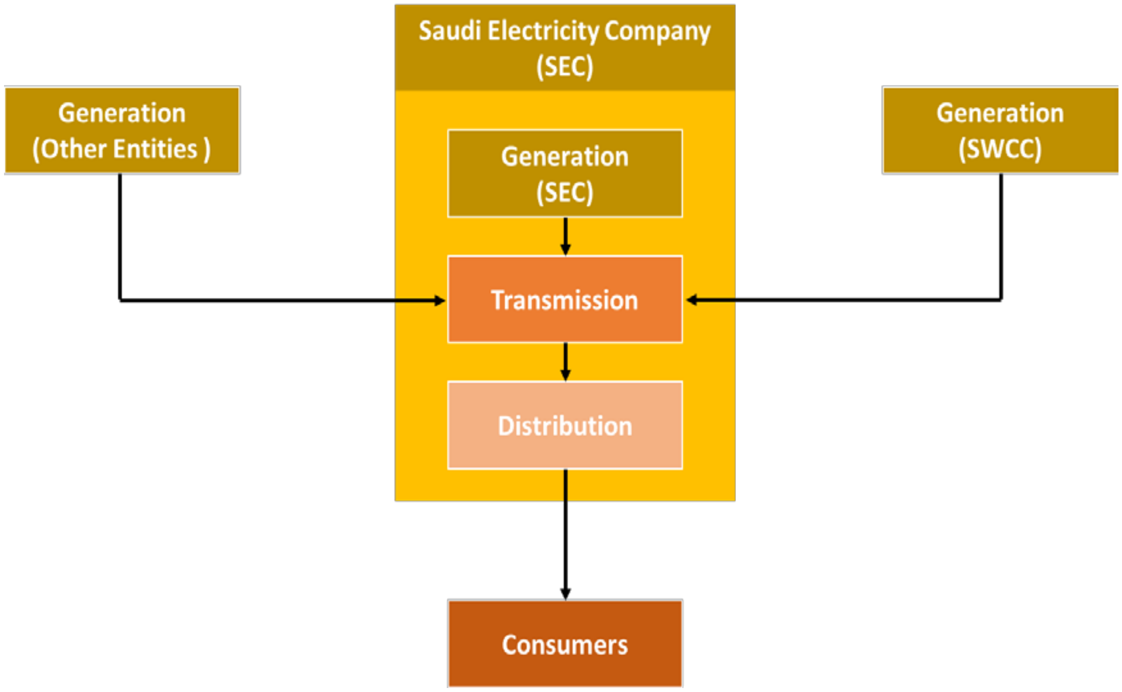
> The Department of Electricity Affairs was established under the Ministry of Commerce. The department started administrative work on legislation and licensing. Based on King Faisal's declaration "Electricity for Every Person," the Department of Electricity Services was spun off from the Ministry in 1972 and began planning works for kingdom's electrification. The department was consolidated with the Ministry of Commerce and Industry and named the Industry and Electricity Agency in 1974, and in 1975 the Ministry was renamed the Ministry of Industry and Electricity (MIE). MIE was responsible for planning the overall expansion of generation bulk power transmission but the power companies themselves were widespread, small-scale, regional monopolies and thus operated inefficiently. To address these challenges, the government started to consolidate power companies, changed them into semi-governmental organizations and set a unified tariff across the country. On 1981, four Saudi Consolidated Electricity Companies (SCECOs) were established in the East, West, South and Central provinces, and at later time small power companies in the Northern Province were also consolidated.

The Saudi government's decision to privatize the power sector in 1995 in order to achieve greater electricity sector restructure represents the beginnings of the third stage. The SEC, which incorporated all of the earlier electrical energy companies in the Kingdom, was formed in April 2000 pursuant to Council of Ministers Decision (CMD) #169 of December 30, 1998 (ECRA, 2006). The Saudi Electricity Regulatory Authority (SERA) was formed on November 13, 2001 per CMD #236. In 2004, the Council of Ministers added the co-production of electricity and desalination of water to ECRA's responsibilities and changed its name to the Electricity and Co-Generation

Regulatory Authority (ECRA, 2006). This shift has encouraged private sector to participate in the power industry investment through independent power producers (IPPs) and build, own, and operate (BOO) contracts. The implementation regulations for the Electricity Law describe ECRA's functions as follows (2007):

> The Electricity & Cogeneration Regulatory Authority (ECRA) is a financially and administratively independent Saudi organization, which regulates the electricity and water desalination industry in Saudi Arabia to ensure the provision of adequate, high quality, and reliable services at reasonable prices. Its mission is to develop and pursue a regulatory framework, in accordance with government laws, regulations, policies, and standards, as well as international best practices, in order to guarantee the provision of safe, reliable, reasonably priced and efficient electric power and desalinated water to the consumers of Saudi Arabia.

In 2003, the Industry and Electricity Agency and the Water Agency were separated from their ministries (respectively the MIE and the Ministry of Agriculture) and merged under the MoWE. The government also undertook a vertical separation of the SEC into generation, transmission, and distribution companies. Since circa 2010, the first phase of the electricity sector's restructuring has progressed accordingly, as illustrated in Figure 1.1.



Source: modified from ECRA, 2014, p. 41

Figure 1.1 Saudi electricity sector – present organizational structure

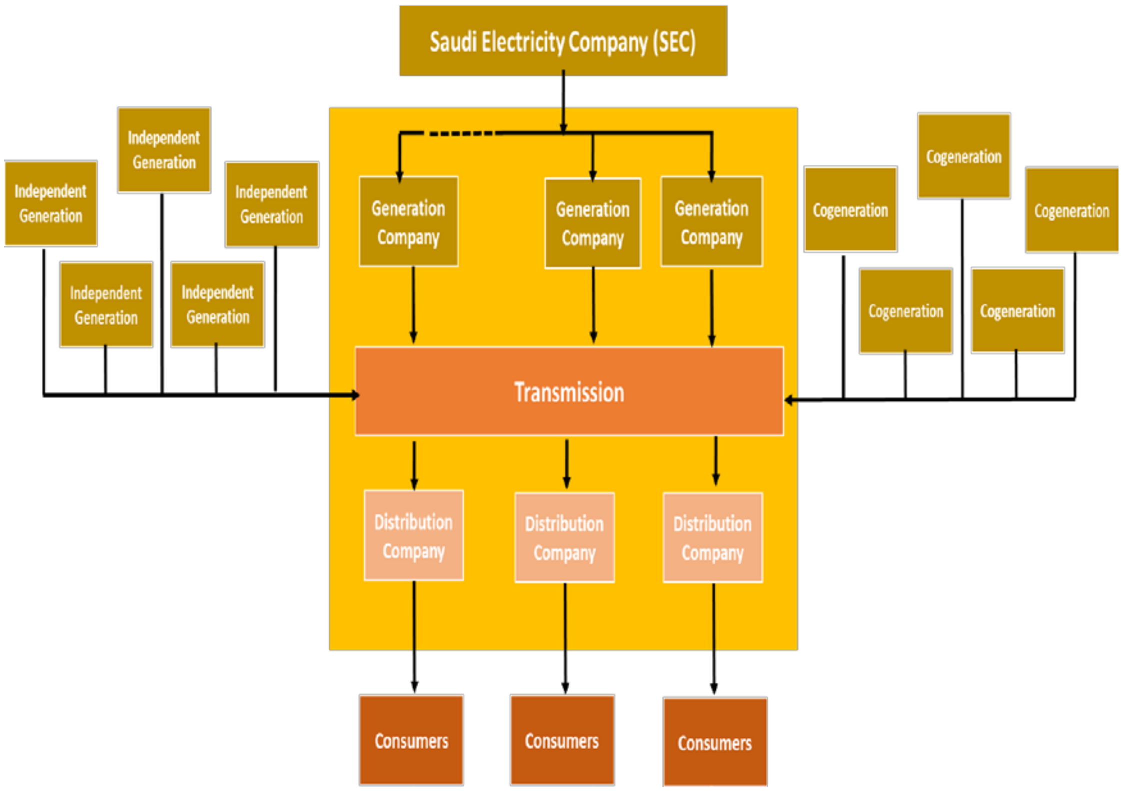
In its efforts to improve the economic competitiveness of the Saudi electricity sector, ECRA (2014, p. 42) has presented the following steps:

- Establishing a transmission company that maintains an open and unbiased policy of access to the transmission system for use by all producers and large consumers without discrimination.
- Creating a special entity (known as the "principal buyer") to manage the electricity industry income and enter into clear and transparent contracts with all service providers (in the areas of generation, transmission, and distribution), which are the reviewed and approved by ECRA. The principal buyer is responsible for ensuring that all parties abide by the contracts.
- Designing a clear, transparent, and fair electricity "wheeling" tariff for the transmission system.

- Creating several competing entities in the field of generation.
- Introducing competition in wholesale electricity services to the distribution companies and large consumers.
- In the long run, introducing competition in the field of distribution and service provision to consumers.

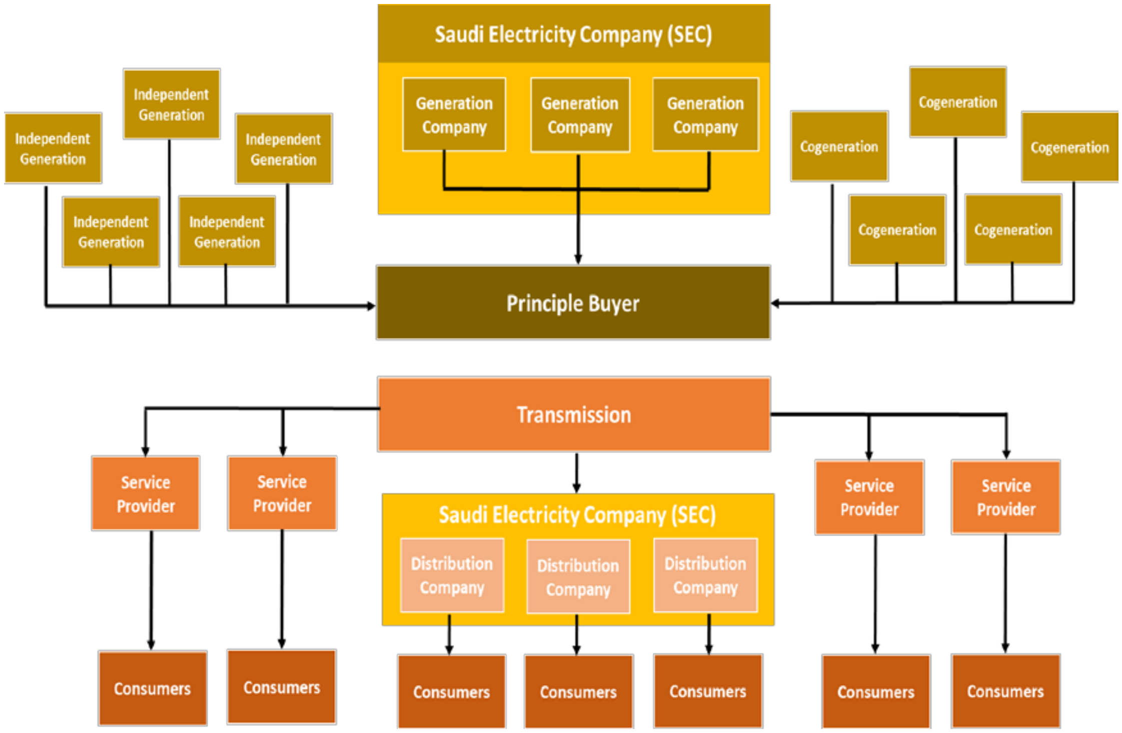
In 2012, the SEC established the National Transmission Company, a limited liability company that it wholly owns (ECRA, 2014, p. 43). As ECRA has reported about the status of the first phase of restructuring (Figure 1.2), the SEC is expected to establish, in the near future, an independent electricity system operator that will be responsible for the load control centers, operating the network on an economic basis, and maintaining the security of supply. It will concurrently create four generation companies that it will wholly own, as well as a distribution company that will develop a plan to break distribution up into several local distribution companies to bolster competition and improve the efficiency of service provision. Nonetheless, there is an obvious delay in implementing the first phase of the restructuring plan and subsequently a need to develop a strict roadmap to move faster. Once this phase is complete, a transition to the plan's second phase will take place. This second phase entails opening competition in the wholesale market. It also includes meeting the conditions for transitioning to the third (and final) phase of the restructuring plan, namely the formation of a competitive electricity market (Figure 1.3) (ECRA, 2014, p. 44).

As outlined earlier, the kingdom's electricity industry began as private business people, saw government participation in the 1970s, came under state ownership, supported by IPPs with foreign investors, and, with vertical separation, has once again entered private ownership.



Source: modified from ECRA, 2014, p. 43

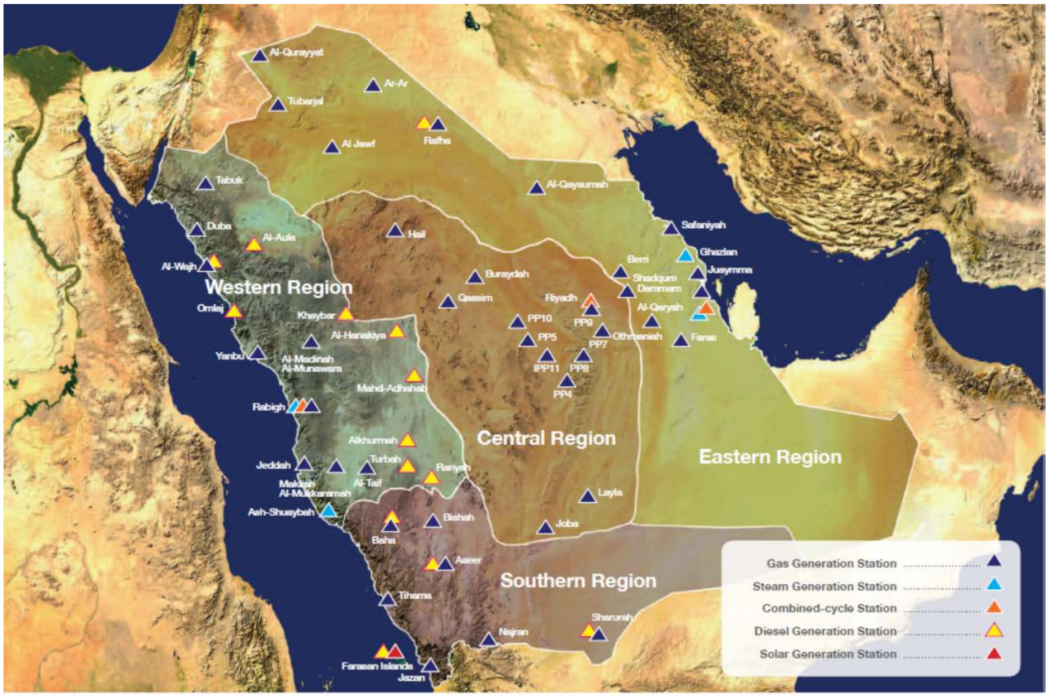
Figure 1.2 Proposed post-phase I electricity industry structure



Source: modified from ECRA, 2014, p. 44

Figure 1.3 Proposed structure of the electricity industry following full restructuring plan implementation

Figure 1.4 shows the SEC's generating plants and the main four electricity operating areas, namely the Eastern Operating Area (EOA), Central Operating Area (COA), Western Operating Area (WOA), and Southern Operating Area (SOA). Existing 380kV lines interconnect these areas with a total transfer capacity of 10 GW (SEC, 2014). Nonetheless, many small rural towns and villages are not connected with the main power grid in Saudi Arabia and still are supplied from diesel generators; challenges related to fuel procurement, transportation, and operation must be overcome to serve these widespread rural areas.



Source: SEC, 2014, p. 17

Figure 1.4 Electric power generating stations and operating areas in Saudi Arabia[8]

In addition to the SEC's generating plants, Figure 1.4 also shows other companies that own plants and sell power to the SEC, such as the Saline Water Conversion Corporation (SWCC), IWPPs, and Saudi Aramco; further details are provided in Table 1.1.

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[8] Many gas generation stations run using dual fuels (natural gas and liquid fuels).

Table 1.1 Generating facilities and their capacities in Saudi Arabia

Producing Entity	**No. of Plants**	**Capacity (MW)**
Saudi Electricity Company	46	51,525
Independent water and power producers	18	12,029
Saudi Aramco	6	1,189
Saline Water Conversion Corporation	6	5,018
Total	76	69,761

Data sources: SEC, 2014; Hagihara, 2013; ECRA, 2014

Saudi Arabia is the world's leading desalinated water producer. The total production capacity of all entities licensed by ECRA to participate in this activity in 2013 was 6,166,678 m^3/day (Figure 1.5). the state-owned SWCC is the second-largest electricity generator, responsible for providing 60% of domestic desalinated water. In 2013, SWCC produced 24.8 TWh in 2013 (ECRA, 2014, p. 100). The SWCC aims to raise its desalination capacity rapidly, with an increase in its generation capacity (IEA, 2014). In 2013, a total of approximately 75 TWh of primary energy (Fath, Sadik, & Mezher, 2013, p. 161) was used to produce 6,166,678 m^3/day of water and 24.8 TWh of electricity in Saudi Arabia (ECRA, 2014, p. 100). Saudi Arabia utilizes multiple effect distillation (MED), multi-stage flash distillation (MSF), and reverse osmosis (RO) (World Bank, 2007; Hagihara, 2013; Alyousef & Abu-ebid, 2012; Taher & Hajjar, 2014), which respectively account for 14.6%, 72.8%, and 12.7% of water production (Taher & Hajjar, 2014, p. 6). [9] The desalination process consumes not only electricity but also natural gas and oil, which is used to boil water (particularly in the MED and MSF processes). Taher and Hajjar (2014, p. 35), and BP (2015, p. 40) further report that 8.7% of the KSA's 202.7 million toe energy consumption represents primary and secondary energy, at a total of 18 million toe. The average cost of desalinated water is USD 0.8/m^3, although the current water pricing system is insufficient to recover the cost. The water supplied to the public is almost free, with an average Saudi family paying less than USD 2 per month for water (Ouda, 2013, p. 10). Due to the country's rapid population growth, the Kingdom will inevitably increase its demand for desalination and consequently consume more oil domestically (Hagihara, 2013, p. 115).

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[9] Younos & Tulou (2009) defined the three main desalination technologies:

(1) MED involves various effects. One of them is the transformation of saltwater into potable water. This is achieved by spraying cold saltwater over hot tubes, which creates vapor through evaporation. The vapor runs through the tubes and is then collected as condensation. Brine, which is collected in the bottom of the effect, will either be removed or used in the next effect.

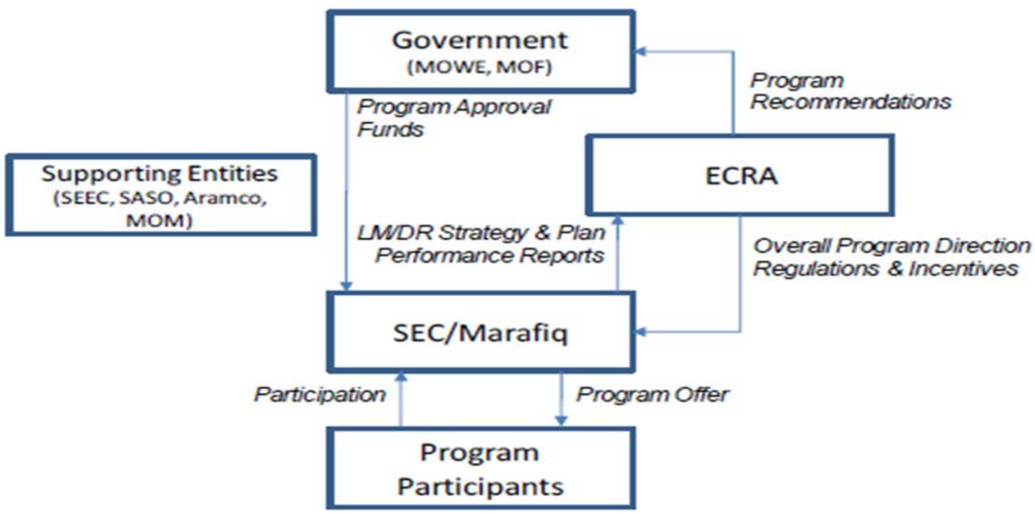
(2) MSF entails a number of differing flashing stages. In one of them, the saltwater moving through the tubes is lower in temperature than the vapor outside the tubes. Saltwater is preheated through a heat exchange before being emptied into the brine pool. The saltwater then evaporates, filling the vapor space that preheats the saltwater entering the system. Again, potable water is gathered from the condensation of the vapor, with the brine being used in the following stage.

(3) RO works based on osmosis. Here, salt is removed from the water through the difference in osmotic pressure between the pure water and saltwater. Saltwater is subject to higher pressure than the osmotic pressure. This causes the pure water to move through the synthetic membrane pores that have been separated from the salt. The salt is then removed from the system in the form of a concentrated solution.

Source: ECRA, 2014, p. 99

Figure 1.5 Desalination plants and major designated water pipelines in Saudi Arabia

Until 2012, the SEC was the main player in DSM implementation in Saudi Arabia. Since this date, ECRA, the MoWE, the Saudi Arabian Standards Organizations (SASO), the Saudi Energy Efficiency Center (SEEC) and various other institutions have been responsible for approving programs, policies and regulations as well as supporting funding, determining tariffs and incentives, and providing guidance along with DSM monitoring and implementation services. Nachet and Aoun (2015, p. 14) report that the Saudi Energy Efficiency Program was established in 2012 with the aim of managing all national DSM activities, emphasizing on industry, transportation and construction – the three sectors that together represent over 90% of energy consumption in the KSA. Present DSM organizational structure and implementation responsibilities are outlined in Figure 1.6, below:



Source: Faruqui and Hledik, 2011, p. 176

Figure 1.6 DSM organizational structure and responsibilities prior to 2012

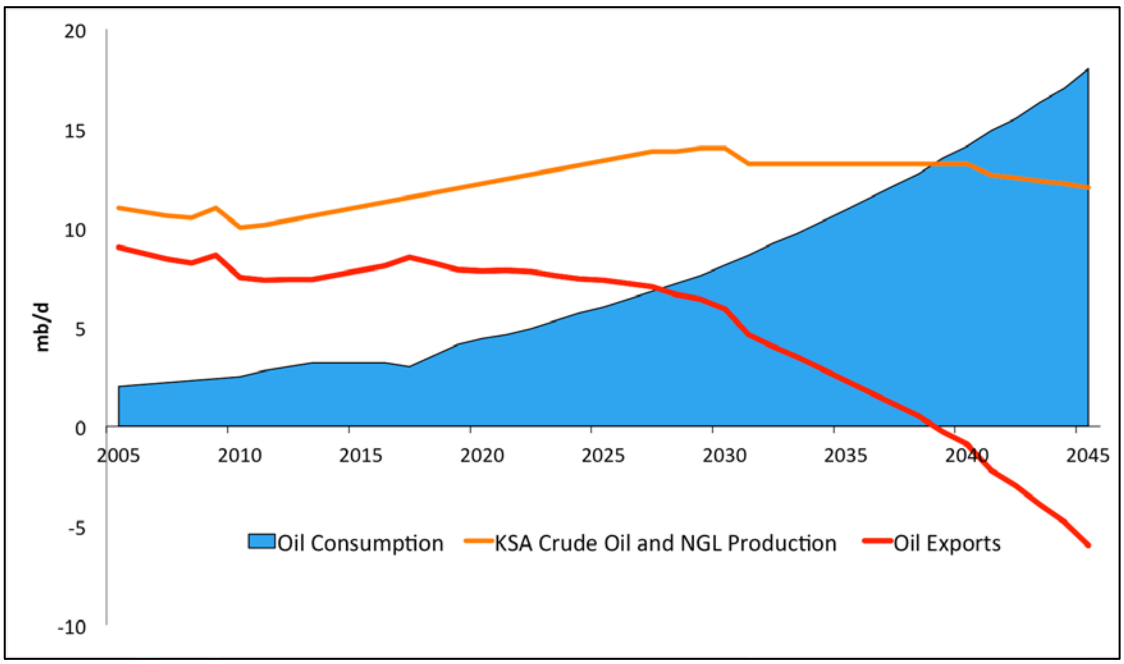
Despite the recent public awareness programs concerning the need to use energy more efficiently launched by SEEP, the DSM potential remains largely untapped in Saudi Arabia due to a lack of incentives, and enormous electricity price subsidies (Nachet & Aoun, 2015, p. 15). Furthermore, current responsibilities are not precisely defined and organizational tasks are somewhat unclear between different institutions, as noted by Faruqui and Hledik (2011, p. 176):

> This has contributed to the lack of historic DSM progress and impact within Saudi Arabia to date. It is also unclear what resources have been spent on DSM implementation within Saudi Arabia or the level of funding allocated to DSM activities by each organization. What is clear is that the organizations have not been successful in clearly tracking results, chronicling past programs, and identifying lessons learned. Redefining the current organizational structure and responsibilities, and identifying possible alternative structures, will help to increase the likelihood of successful implementation of future DSM programs in Saudi Arabia.

1.3.2 Saudi Arabia's Energy Consumption Problem and its Associated Economic, Social, and Environmental Impacts

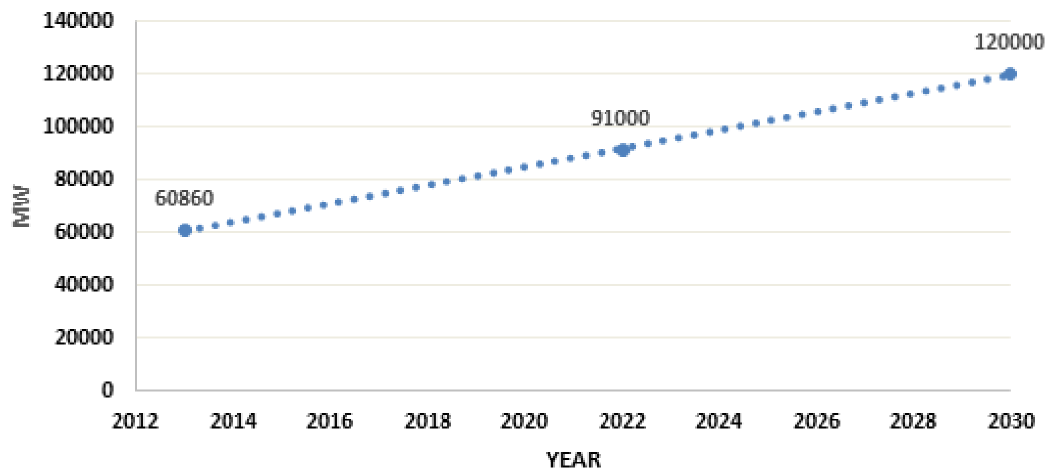
As established throughout this dissertation, the Kingdom's current rate of energy consumption – equal to 25% of domestic oil production – has reached unsustainable levels. Under a business-as-usual scenario, many researchers suggest that Saudi Arabia will become a net oil importer within two decades. For instance, Lahn et al. (2011) have projected that this will happen by 2038. Other energy analysts have projected that Saudi Arabia could turn into a net oil importer as early as 2030 if current energy demand growth patterns continue (Daya & El-Baltagi, 2012; Taher & Hajjar, 2014, p. 36). This is in line with the MoWE's forecast that, based on current trends, primary energy consumption in the Kingdom will double by 2030, which will in turn lead to decreased oil exports (MoWE, 2009). Figure 1.7 illustrates a business-as-usual scenario. As illustrated in Figure 1.8, trends indicate that Saudi power demand will reach 120 GW by 2030 (K.A.CARE, 2010). Although the future might see more oil reserves being discovered, production increasing, population growth declining, or new policies and technology that reduce consumption patterns emerging, Lahn and Stevens (2011, p. 1) summarize the impact of the current rapid growth of local energy consumption:

> Saudi Arabia's place in the world oil market is threatened by unrestrained domestic fuel consumption. In an economy dominated by fossil fuels and dependent on the export of oil, current patterns of energy demand are not only wasting valuable resources and causing excessive pollution, but also rendering the country vulnerable to economic and social crises.



Source: Lahn and Stevens, 2011, p. 2

Figure 1.7 Domestic oil balance projections based on a business-as-usual scenario



Data source: K.A.CARE, 2010, p. 16

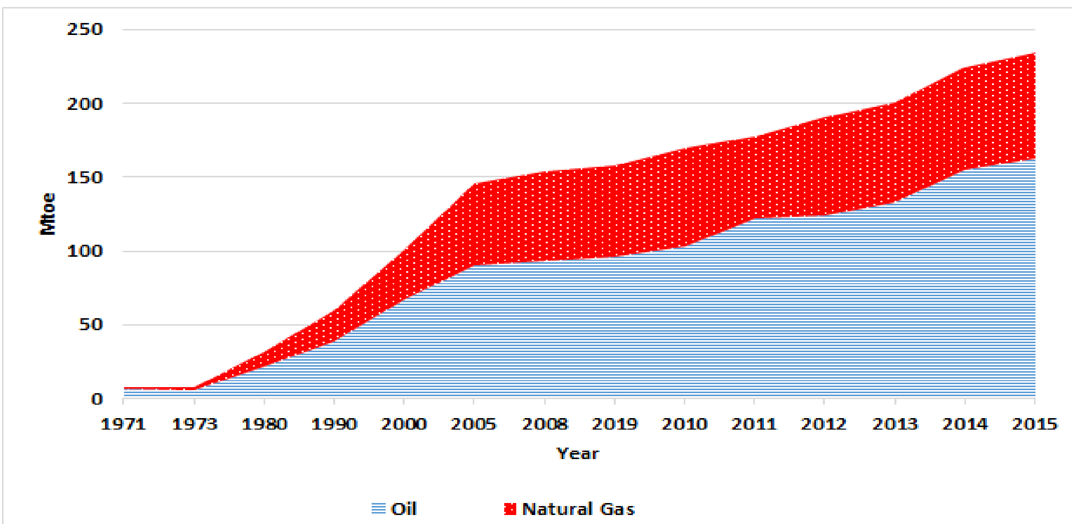
Figure 1.8 Electricity demand growth forecast for Saudi Arabia (in MW)

Lahn and Stevens (2011, p. 4) have identified four main trends in Saudi Arabia's historical energy consumption pattern and evolution since 1970:

- Energy consumption has been rising since the early 1970s and shows no response to subsequent dips in the price of oil;
- Oil and gas continue to account for all of Saudi Arabia's energy production, with oil continuing to dominate the energy mix;
- Progressive diversification into gas began in the early 1970s; and
- Oil's share in the energy mix has nevertheless begun to rise again in last six years.

In 2014, Saudi Arabia exported 359.8 Mtoe of oil in primary energy and 69.8 Mtoe of oil products in secondary energy (i.e. refined products and ethylene polymers). Local energy consumption equaled all natural gas (69.5 Mtoe), non-exported oil (133.1 Mtoe), and imported oil products (21.6 Mtoe) consumption, totaling 200 Mtoe or 4 million barrels of equivalent per day (Figure 1.9). As Lahn and

Stevens (2011, p. 5)[10] report, this is equal to the total level of consumption in the UK despite the Saudi population being less than half the size of that in the UK. Over the last 10 years, an increasing amount of oil has been consumed due to natural gas shortages. Consequently, there has been a significant shift in that all domestically-produced natural gas is also consumed within the country. Additionally, largely due to strong demand for cooling in the power sector, inadequate supply of natural gas has resulted in higher oil burning. The domestic national energy fuels mix in 2015 hence saw an increase in the share of oil to approximately 69% (BP, 2016).



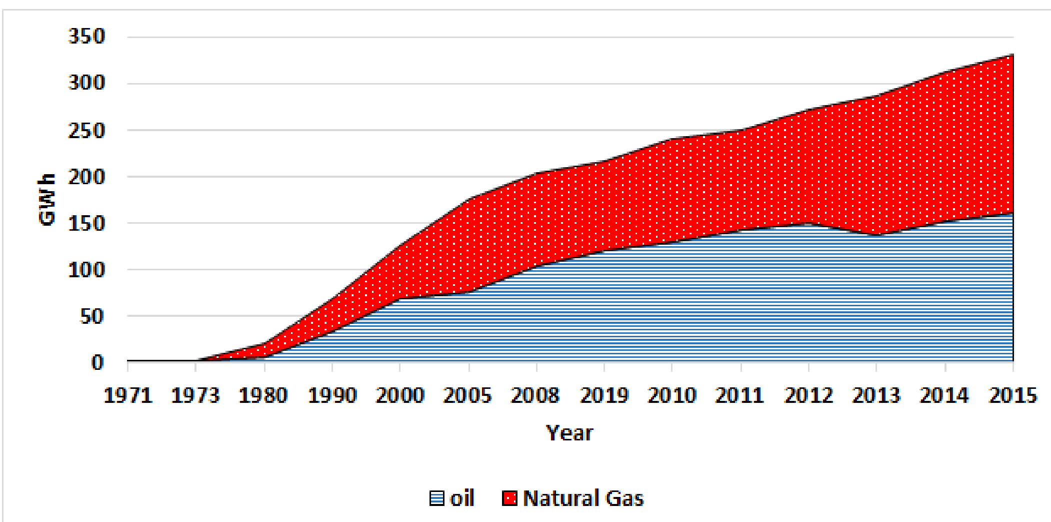
Data source: BP, 2016, pp.13-25; IEA, 2016

Figure 1.9 Saudi Arabia's local energy consumption of oil and natural gas

[10] Although the comparison is meant to show the high energy demand in Saudi Arabia with countries that have higher population, such as UK. It is also critical to recognize the geographical differences between the two countries, such as the large and harsher landscape of Saudi Arabia that contributed to higher energy consumption.

Water desalination and power generation plants consumed approximately 42% of the primary energy produced in Saudi Arabia (IEA, 2013; SEC, 2014). As such, these sectors are playing an increasingly key role in shaping the kingdom's energy demand. Similar to the national energy mix, the current fuels mix in the electricity and water desalination sectors—which sees natural gas (45%) as the main fuel in steam power plants and crude oil and diesel (55%) as the main fuels in simple cycle gas turbine plants—results in an inefficient use of fuel (Figure 1.10). Alyousef and Abu-ebid (2012, p. 284) describe the potential benefits of changing the fuel mix in electricity generation as follows:

> Thus, there could be a great potential in the power sector for gas to replace oil which will then lead to additional oil exports and so contributing to economic and environmental benefits. The switch from oil dominated electricity generation sector to more natural gas, will lead to more oil becoming available to export, improved generation efficiency and reduction in CO_2 emissions.

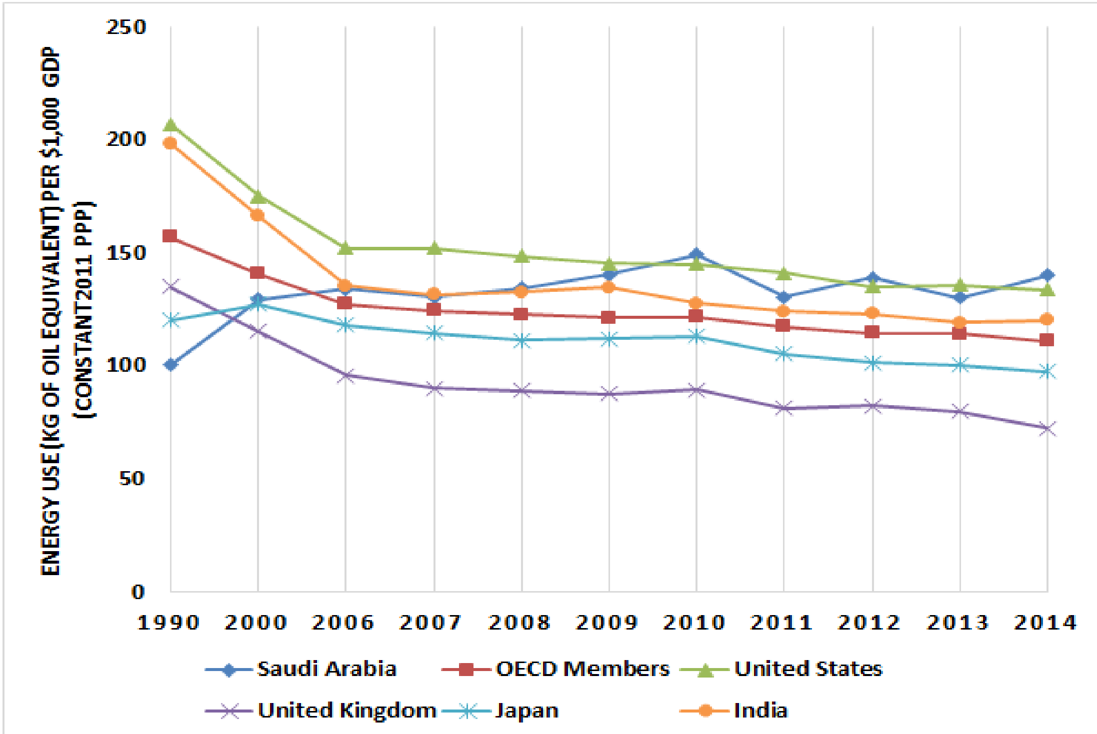


Data source: IEA, 2016, p. 54; IEA, 2012, pp. 353–367

Figure 1.10 Saudi Arabia's historical fuel mix in the electricity sector

Energy plays a key role in the country's economic growth and contributes significantly to enabling its population to achieve a decent standard of living. However, the overuse of energy resources over time has resulted in waste and thus missed opportunities to invest these valuable resources elsewhere in the country. Since the kingdom's economy is approximately 90% dependent on oil, the issue of energy overconsumption has additional resonance. The economic objective behind the extraction and export of oil is to develop longer-term sustainable sources of income for the country. (Lahn & Stevens, 2011, p. 6).

The World Bank's (2014) figures on Saudi Arabia, India, Japan, the US and the UK with regards to energy intensity in kg oil equivalent (kg-oe) use of GDP are illustrated in Figure 1.11. Until stability was achieved in 2011, Saudi energy intensity can be seen to have been increasing annually. However, even at the stable level, other nations outperform Saudi Arabia in terms of efficiency. Compared to other countries, Saudi Arabia's energy intensity was more efficient during the early 1990s because the Saudi population was smaller during this period, with lower energy consumption. By 2013, however, Saudi Arabia can be seen to have been 1.6 times less efficient than the UK, at 130 kg-oe/USD $1000 compared to 79 kg-oe/USD $1000, respectively. This was because the growth of Saudi Arabia's energy demand surpassed its GDP growth and its efficiency worsened (Hagihara, 2013). From 2008 to 2010, Saudi Arabia's energy intensity increased, which led to a dramatic decline in energy efficiency despite the distorting effect of international oil prices on countries that depend on oil exports. In 2014, Saudi Arabia's energy intensity was 14% higher than the average for Organization for Economic Co-operation and Development (OECD) countries and almost the same as the global average (IEA, 2016).

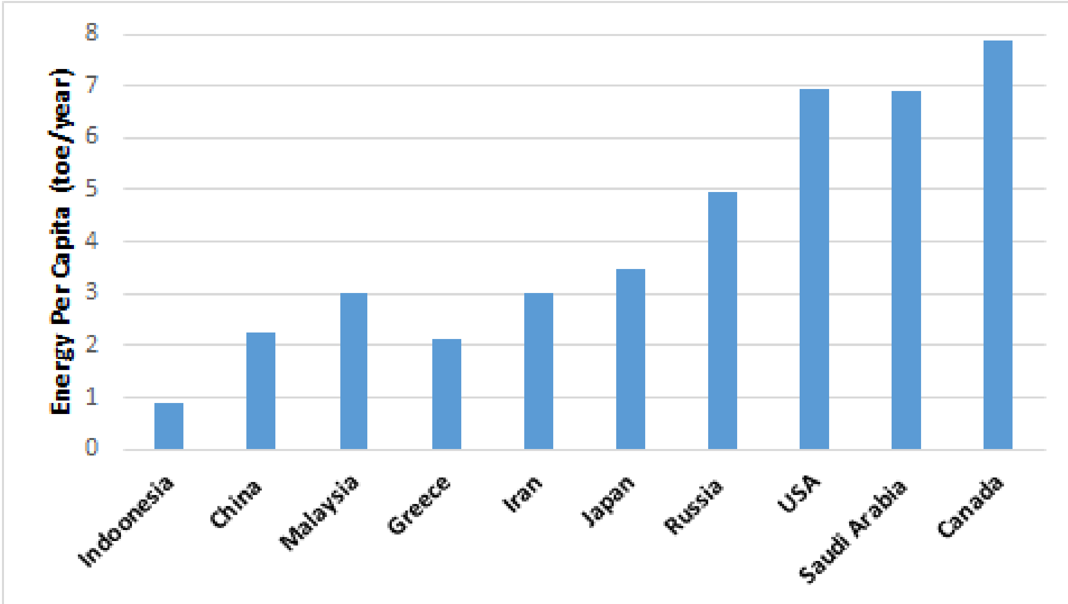


Data source: World Bank, 2014; IEA, 2016

Figure 1.11 Energy intensity in Saudi Arabia and selected countries

As illustrated in Figure 1.12, Saudi per-capita energy consumption is approximately double that of Japan and slightly lower than the United States. Hagihara (2013, p. 112) compares the rapid increase of per capita energy consumption in Saudi Arabia with consumption trends in other countries:

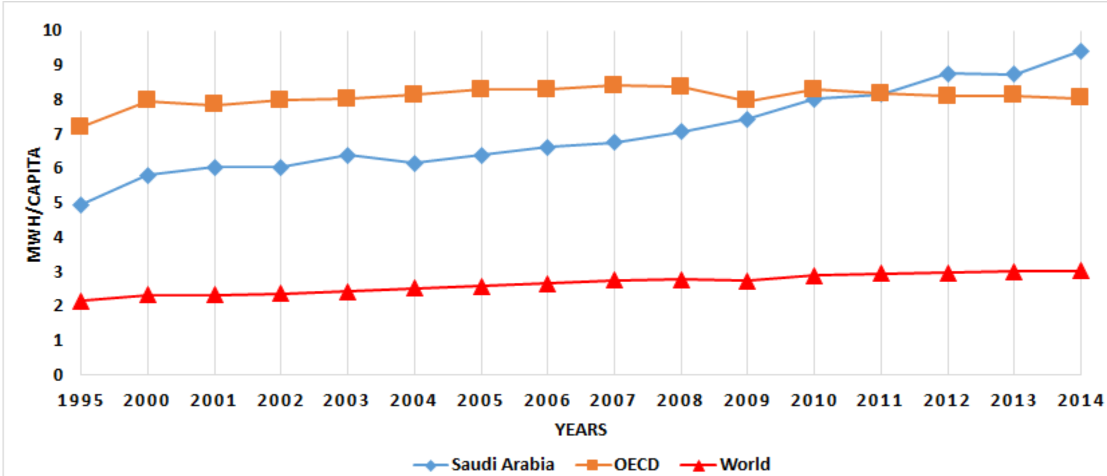
> Americans consume a lot of energy but consumption has become stable. On the other hand, Saudis have used a rapidly increase amount, especially in the latter half of 1970s for establishing basic infrastructures and a modern life. Domestic consumption continued to rise during the oil depression from 1983 to 1990. The Saudi consumed 6,514 kg-oe in 2008 1.7 times more than the Japanese (3,882 kg-oe) and per capita is still increasing.



Data source: IEA, 2016

Figure 1.12 Energy consumption per capita in Saudi Arabia and selected countries

Figure 1.13 shows per capita electricity consumption in MWh (IEA, 2013). Saudi Arabia's current level of energy consumption is 17.2% higher than the per-capita average OECD electricity consumption and nearly three times higher than the per-capita global average, at 9.41 MWh. While the OECD region's per-capita electricity consumption has stabilized over the years, the KSA's consumption continues to rise.

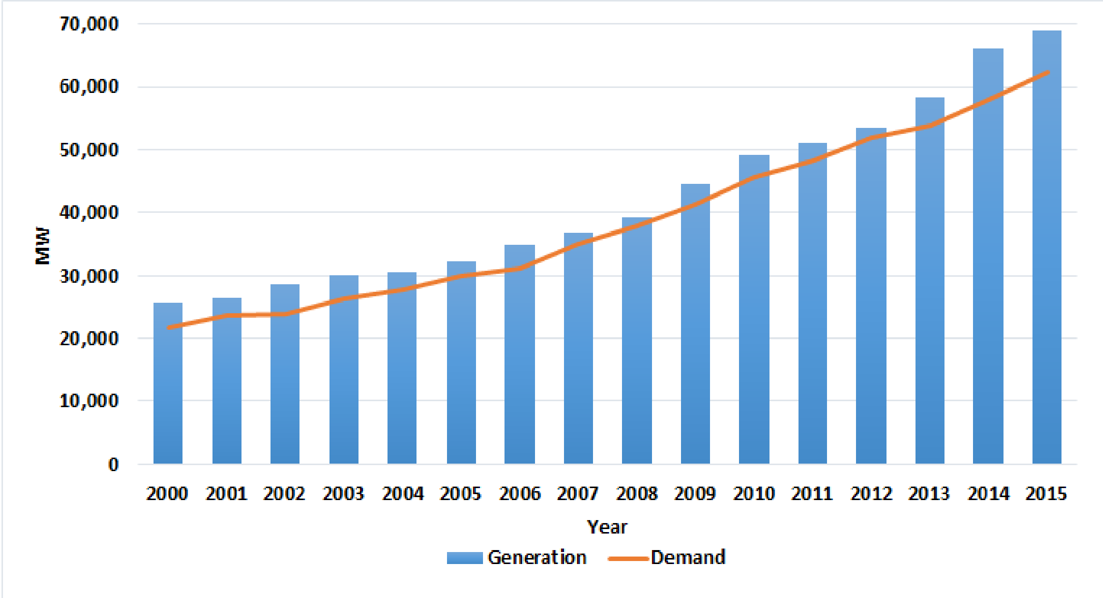


Data source: IEA, 2016

Figure 1.13 Electricity consumption per capita: Saudi Arabia, OECD average, and world average

In the last 25 years, the Kingdom has undergone rapid economic and population growth, which has led to a rapid increase in electricity demand (Farnoosh, Lantz, & Precebois, 2013, p. 112). As illustrated in Figure 1.14. dometsic electricty generation capacity has risen at an average annual growth of 7.25% since 2000. In 2015, the annual growth was approximately 8%, which resulted in 330,367 giga-watt (GWh) of electric energy being generated; this was 2.6 times Saudi Arabia's generation capacity in 2000 (ECRA, 2016).[11]

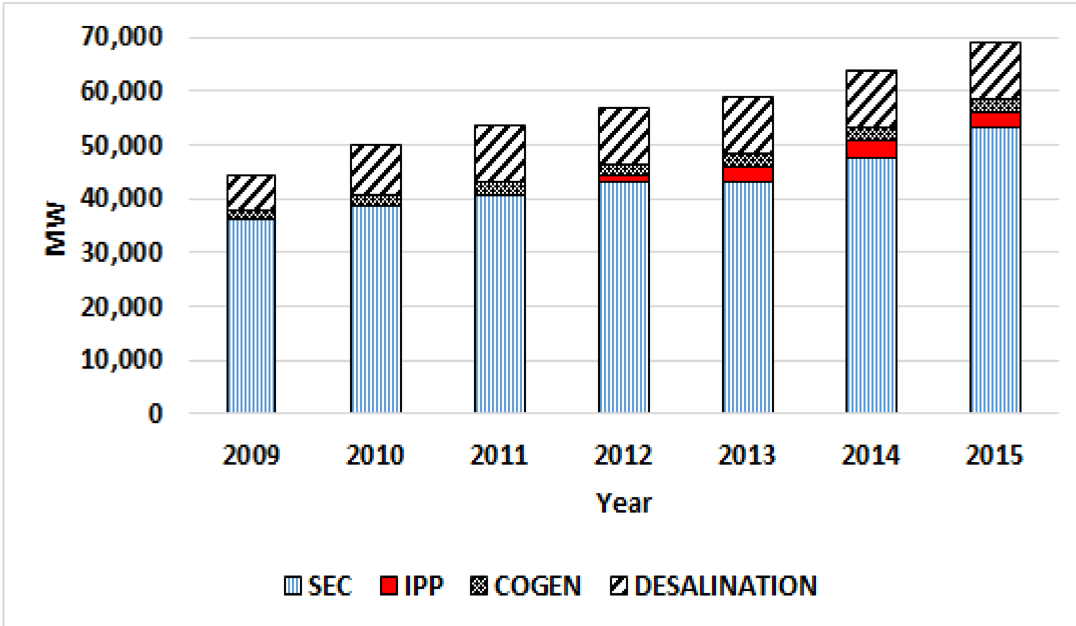
[11] This total represents energy generated by the SEC for transmission and distribution through the national grid. It does not include energy generated and consumed by other producers.



Data source: SEC, 2014; SEC, 2015; SEC, 2016; ECRA, 2016

Figure 1.14 Electric peak demand and generating capacity in Saudi Arabia, 2000–2014

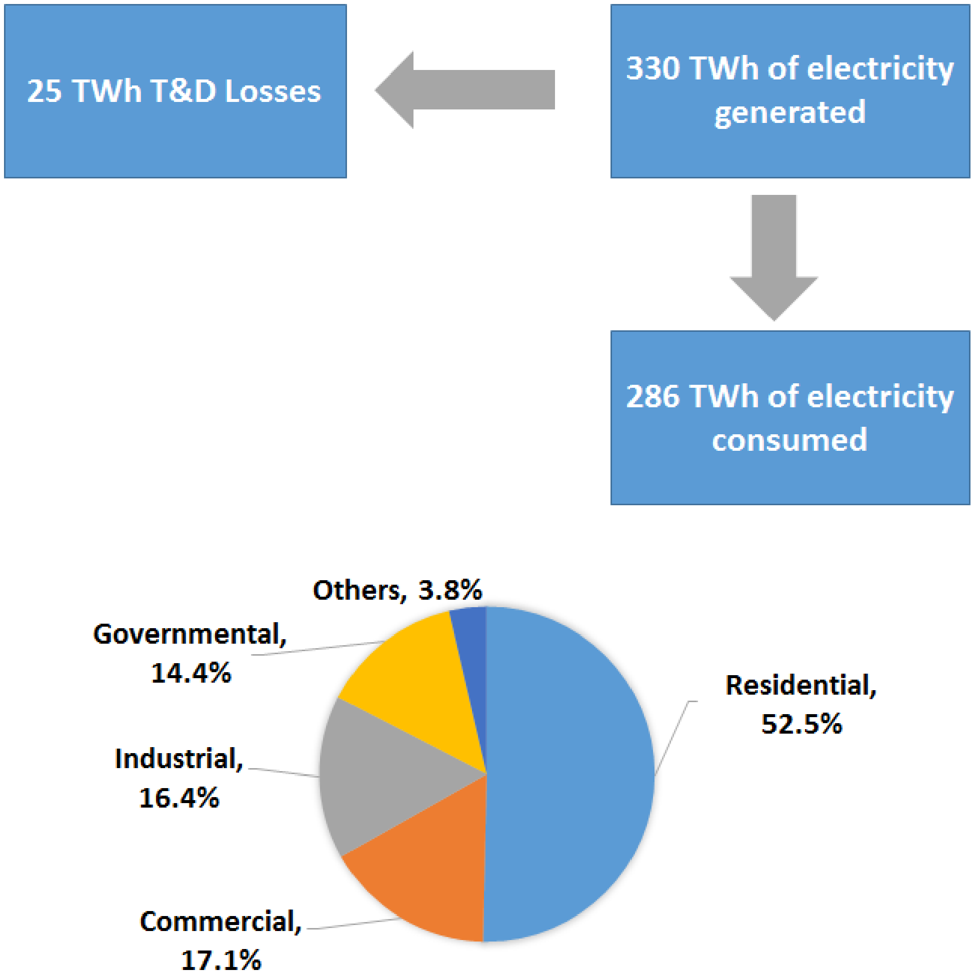
Over 70% of Saudi Arabia's power generation plants are owned and controlled by the SEC. Desalination plants account for 17.3% of the facilities, while cogeneration (mainly at Saudi Aramco sites) and IPPs together own 12.1% (see Figure 1.15).



Data source: SEC, 2014; Hagihara, 2013; ECRA, 2015

Figure 1.15 Breakdown of electric generating capacity in Saudi Arabia among the main electricity producers, 2009–2015

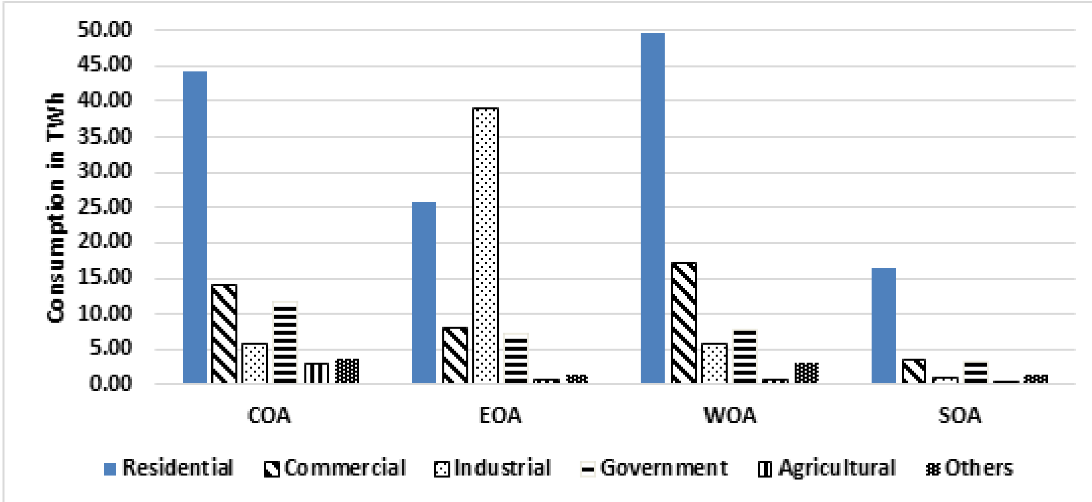
Analyzing the breakdown of SEC electricity consumptions by sector in 2015, SEC produced 330 TWh of electricity in 2014, of which 7.7% was lost in both transmission and distribution networks. Total electricity sold was approximately 286 TWh in 2015, mainly from the residential sector (50.1%). Electricity consumption in Saudi Arabia increased by an average of 6.4% per year from 2000 to 2015; as a result of population growth, it is expected to reach 381 TWh by 2021 (SEC, 2014). The country's electricity flow is illustrated in Figure 1.16.



Data source: ECRA, 2016

Figure 1.16 Electricity flow in Saudi Arabia

Figure 1.17 breaks down Saudi Arabia's energy consumption by operating area. The residential segment accounts for the largest share of consumption in all areas, except for the EOA (which is home to the country's major oil, gas, and petrochemical industries).



Data source: SEC, 2015

Figure 1.17 Energy sold per operating area in Saudi Arabia, 2014

Since the 1980s, the growth rates of Saudi Arabia's commercial and residential sectors have been higher than that of other sectors, which is similar to what other developed countries have experienced. However, other countries have not witnessed such a dramatic rate of change. As such, the rapid increase in commercial and residential electricity consumption in Saudi Arabia invites an evaluation of the country's present domestic energy situation. Hagihara (2013, p. 121) describes the unique characteristics of Saudi Arabia's demand as follows:

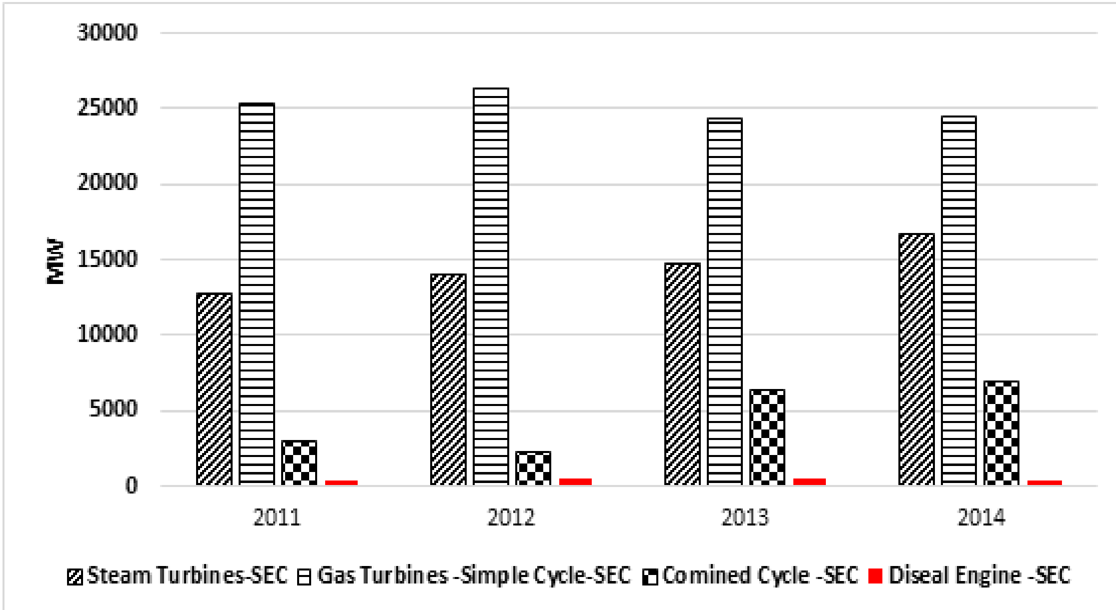
> Saudi Arabia's electricity demand is unique in that it is not the industrial but the residential sector that consumes a lot. Generally, as modernization has progressed, expensive and convenient secondary energy, especially electricity, has been used to provide an increasingly comfortable life style, but in Saudi Arabia with its severe climate conditions, this has always been the first priority.

Another unique challenge in the Saudi context is the significant variation in peak demand both between seasons (i.e. 43% between winter to summer) and within the same day (SEC, 2014, p. 152; Faruqui & Hledik, 2011, p. 54). Alyousef and Abu-ebid (2012, p. 289) explain this issue as follows:

> Perhaps the biggest problem facing the energy supply sector is the large seasonal variation in electricity consumption. In the hot summer season, there is increasing energy demand for air conditioning, especially by the residential and commercial sectors.

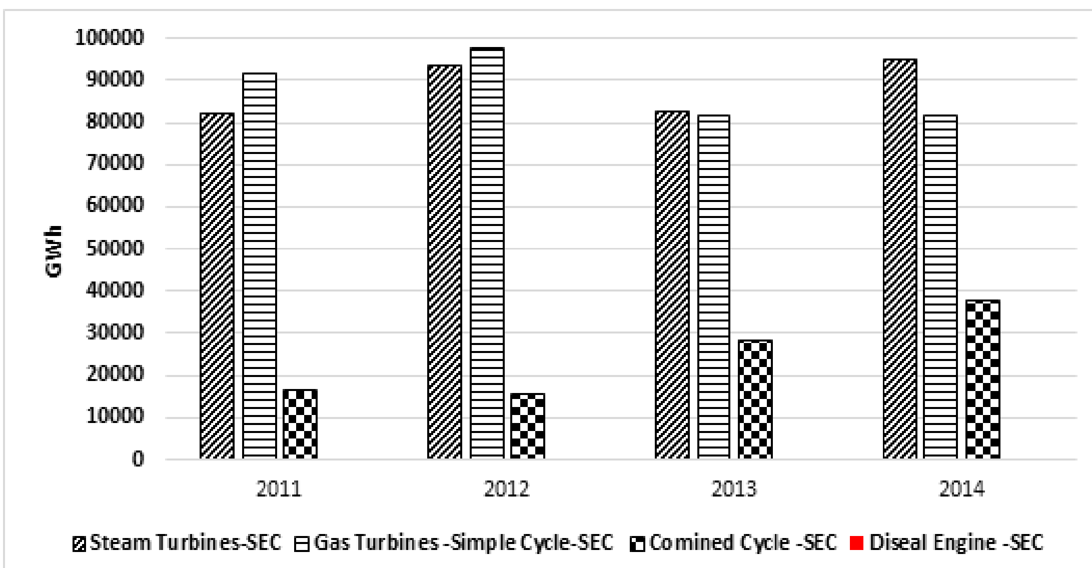
1.3.3 Power Generation Efficiency and Existing/Potential Future Technologies in Saudi Arabia

In 2014, more efficient CCGTs accounted for only 14% of total Saudi power generation capacity; outdated steam and gas turbines represented the majority of the country’s capacity (Figure 1.18). The current mix of power generating stations (Figure 1.19) results in inefficient operations. Furthermore, around 20% of the existing generation facilities were built more than 30 years ago (Figure 1.20). Based on current fuel consumption and electricity production levels, these facilities have an average power generation efficiency between of 32%; in comparison, the world average is 35% (EIA, 2012; Matar et al., 2015).



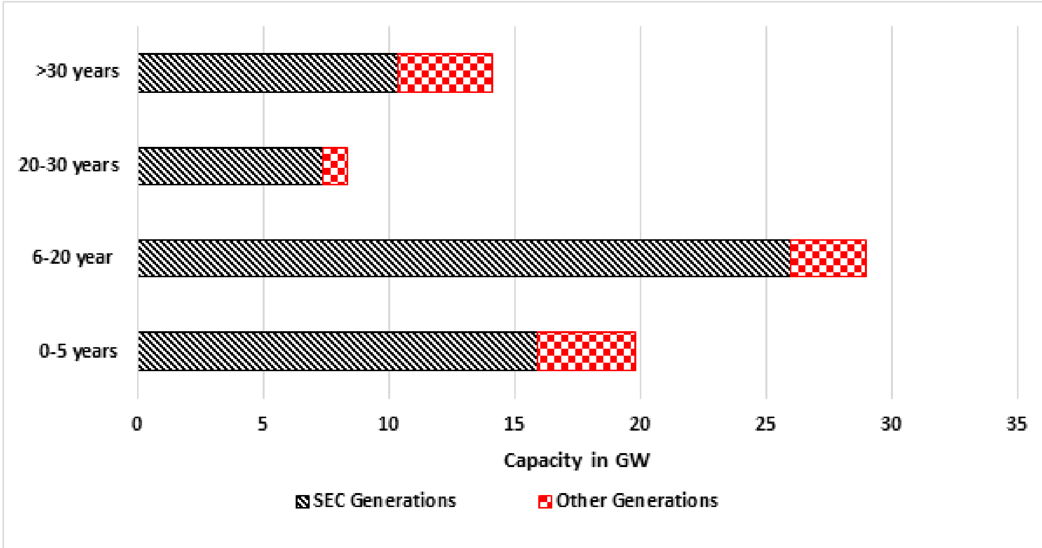
Data source: SEC, 2014

Figure 1.18 Breakdown of Saudi Arabia's generation capacity by different generation technologies, 2011–2014



Data source: SEC, 2014

Figure 1.19 Breakdown of electricity produced by different generation technologies in Saudi Arabia, 2011–2014



Data source: SEC, 2014

Figure 1.20 Age of power generation units in Saudi Arabia

Energy efficiency also depends on climatic conditions at the site of the energy's utilization. For example, ambient temperature and the cooling water temperature for the condenser influence a power plant's efficiency, with high temperatures adversely impacting the output and efficiency of power generation. Technical advances in conventional power plants can only partly compensate for unfavorable climatic conditions. Even with the application of the best available technology, the energy efficiency of power plants in Saudi Arabia remains considerably lower than those in countries with more favorable climatic conditions, as shown in Table 1.2. Efficiency is significantly hampered by the Kingdom's hot climate, cooling temperature, and outdated generation technologies; the result is that Saudi fuel consumption per kWh is 30% higher than European levels with an average power generation efficiency of 36%.

Table 1.2 Comparison of generation efficiency indices in Europe and Saudi Arabia

Regional Benchmarks	Northern Europe	Central Europe	Saudi Arabia
Annual average ambient temperature	15 °C	15 °C	35 °C
Average cooling water temperature	10 °C seawater once through	15 °C cooling tower	28 °C seawater once through
Annual average efficiency			
Steam power plants	Coal fired 45%	Coal fired 44%	Oil fired 41%
Combined cycle gas turbine power plants	Natural gas fired 55%	Natural gas fired 55%	Natural gas fired 50%
Simple cycle gas turbines power plants	Natural gas fired 34%	Natural gas fired 33%	Natural gas fired 33%

Data source: EURELECTRIC, 2013

The energy generated in 2013 from all generation facilities in Saudi Arabia (311 TWh) had negative environmental impacts, especially because most of these facilities have been in operation for more than ten years and have relatively low efficiency. This energy generation corresponds to approximately 911 TWh at the power station inlet and produces 522.1 million tons of CO_2 emissions annually.[12] Assuming a constant growth rate of 6.4% (which is close to the rate from 2000 to 2013), the consumption of Saudi's utility sector will reach 510 TWh in 2021. If the same oil-gas fuel mix is maintained, the annual CO_2 emissions associated with this

[12] The calculation is based on emissions of 350 g/kWh from gas and 700 g/kWh from oil (Alyousef et al., 2012). More accurate results could be obtained by calculating the emissions from each technology.

consumption will be 803.7 million tons, or 54% higher than in 2013. This calculation is relatively close to the estimations made by Alyousef and Abu-ebid (2012) for the business-as-usual scenario.

Renewable technologies could bring significant benefits to Saudi Arabia, especially solar energy given that the country lies in the world's "sunbelt" region; for example, Saudi Arabia enjoys 40% more sun than Spain. the Arabian Peninsula receives around 2200 kWh/m2 horizontal solar radiation per year (Hepbasli & Alsuhaibani, 2011). This radiation is associated with enormous areas of uninhabited land that can offer vast potential for harnessing the energy of the sun. On a daily basis, the sunshine that falls on the huge swath of Saudi Arabia is sufficient to generate 72 years' worth of electricity at 12,425 TWh (Aljarboua, 2009, p. 1). Saudi Arabia could thus be a solar exporter in addition to a major oil and gas exporter (Hertog & Luciani, 2009).

Analyzing the potential of wind energy, the country's western and central areas have the highest wind speeds, which range from 8 to 9 m/s based on wind speed at 100 m height. Such speeds enable wind power to be generated with a capacity factor of more than 50% (K. A. CARE, 2016).

In addition, the nuclear power development also offers promising solutions for the existing energy situation in the Kingdom. Despite its economic and risk challenges, nuclear energy is a viable option to support the deployment of renewables, due to the intermittent supply of the latter. In addition, nuclear energy could play a significant role solution in stabilizing atmospheric emissions and contributiing to the kingdom's economic development as a result of greater employment opportunities and expertise in this arena (Nachat & Aoun, 2015, p. 24).

1.3.4 Subsidies and the Financial Status of the Utility Sector

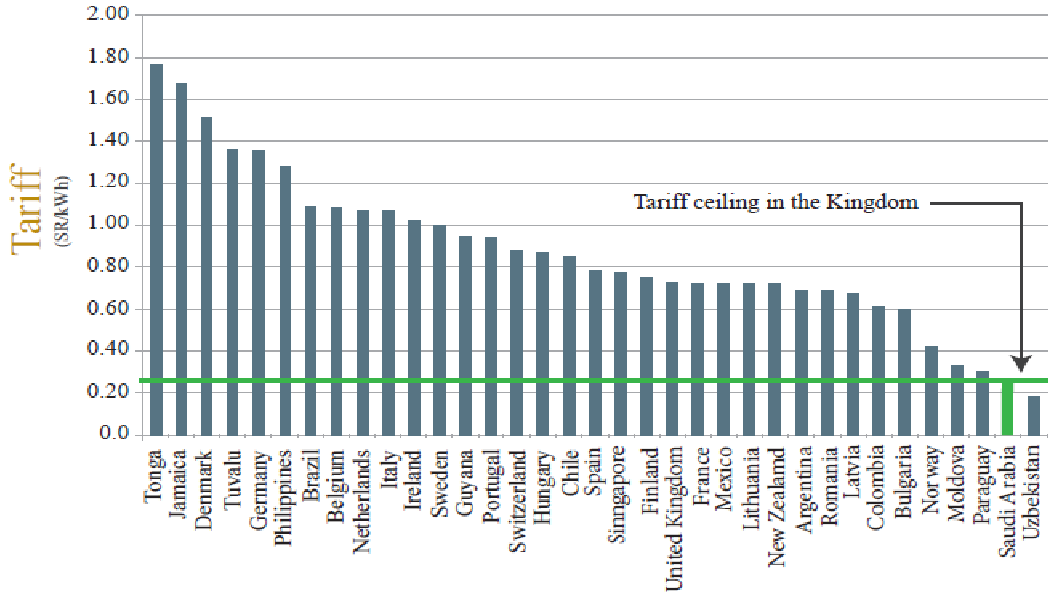
Large subsidies in the Saudi energy sector disadvantage both renewable energy resources and energy efficiency and hinder large-scale deployments of related technologies. In essence, they act as an automatic brake on the private sector's development of renewable energy resources and energy efficiency. For instance, prior to 2016, the Saudi Arabia power sector traditionally pays approximately USD 0.75 per million British thermal units (MMbtu) for natural gas, which is roughly equivalent to buying oil at USD 5 per barrel. Consequently, Saudi Arabia can provide electricity at approximately USD 0.05 to 0.06 per kWh, which is roughly half the price of electricity for end customers in the United States (Ferroukhi, Doukas, & Androulaki, 2013). The water sector pays an even lower price of only USD 0.35 per MMbtu for natural gas (Matar et al., 2014). Such subsidies have increased the pressure on both fossil fuel reserves and the government's finances as a result of soaring electricity demand and energy intensity. The Energy Sustainability Index issued by World Energy Council (2013, p. 20) illustrates the situation in Saudi Arabia.

> Low cost energy does little to incentivize energy efficiency or the reduction of energy consumption – and the region's environmental sustainability performance reflects this. Emission and energy intensity both continue to increase and remain the worst in the world. Meanwhile, CO_2 emissions from electricity generation also remain extraordinarily high, with virtually no use of either nuclear power or renewables at the moment.

The low domestic fuel price level in Saudi Arabia allows power plants to be operated at low costs, independent of their level of technical efficiency. The most economical energy projects are thus implemented with technologies that require low investment costs, which is a situation that favors the installation of inefficient plants. The low fuel prices offer no motivation for either energy efficiency or the reduction of fuel consumption in Saudi power generation; consequently, too much fuel is consumed in relation to the power generated. If current practices continue, domestic fuel consumption will increase significantly in the future. A recent ECRA study indicated that tariffs based on subsidized fuel prices resulted in a low efficiency of fuel utilization and affected the margin of competition among the country's various IWPPs (ECRA, 2014, p. 38). As part of the government's plan to further raise fuel prices to meet the global average over the coming five years while simultaneously reducing subsidies, Saudi Arabia increased domestic gas and oil prices for power generation in January 2016: gas prices were increased from USD 0.75/MMBtu to USD 1.25/MMBtu, while crude oil, HFO, and diesel prices were respectively raised by 39%, 100%, and 200% (Krane & Hung, 2016, p. 4).

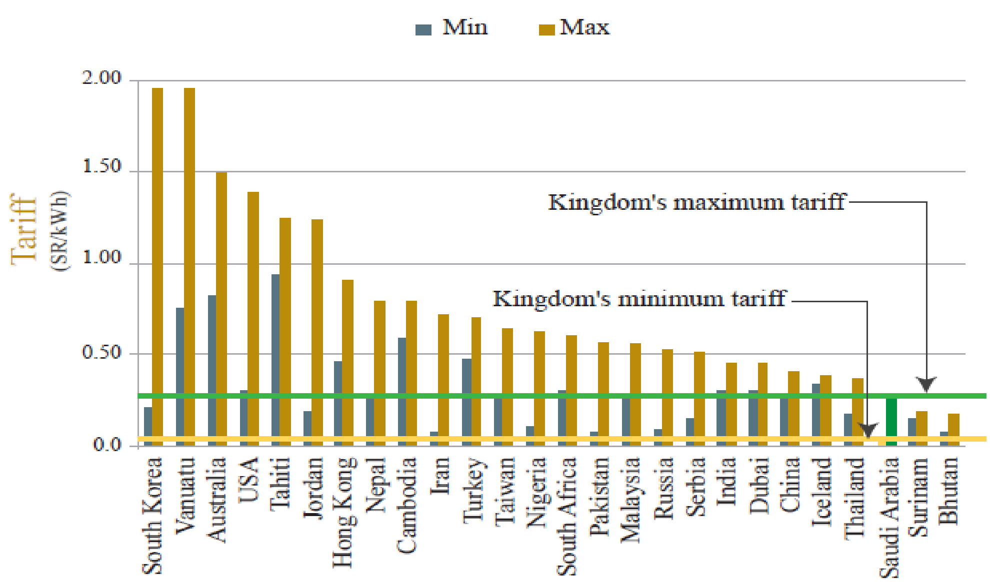
Subsidies are also applicable to the tariff system in Saudi Arabia. Non-targeted subsidies[13] initially contributed significantly to encouraging the country's present high consumption of electricity. In January 2011, the government re-evaluated the tariff policy and subsequently changed the tariff system to remove gradually subsidies, especially for high energy consumers. The electricity tariff in Saudi Arabia is one of the least expensive when compared to both the fixed tariff and maximum and minimum tariffs in other countries in the world (see Figures 1.21 and 1.22).

[13] As Taher and Hajjar (2014, p. 1) explain, non-targeted subsidies are those given without consideration of status or income.



Source: ECRA, 2014, p. 93

Figure 1.21 Comparison of the upper limit of the electricity tariff in Saudi Arabia with the fixed tariff in several other countries around the world



Source: ECRA, 2014, p. 94

Figure 1.22 Comparison of the electricity tariff in Saudi Arabia with the tariffs in other countries around the world

In January 2016, the Saudi government raised the tariffs for high energy customers in all sectors. In the residential sector, the tariff was raised for consumption categories of 5000 kWh and above.[14] In other sectors, a system of stepped tariffs increases prices as consumption increases (Table 1.3).

Table 1.3 A comparison of Saudi Arabia's electricity tariff system in 2011 and 2016 (in Halala/kWh)

<table>
<tr><th rowspan="2">Consumption Range (kWh)</th><th colspan="2">Residential</th><th colspan="2">Agricult-ure</th><th colspan="2">Private Hospitals, Schools, and Industrial</th><th colspan="2">Commercial</th><th colspan="2">Governm-ent</th></tr>
<tr><th colspan="10">2011 and 2016 tariffs, in Halala/kWh</th></tr>
<tr><td>1–1,000
1,001–2,000</td><td>5</td><td>5</td><td>5</td><td rowspan="2">10</td><td rowspan="9">12</td><td rowspan="9">18</td><td rowspan="2">12</td><td rowspan="2">16</td><td rowspan="9">26</td><td rowspan="9">32</td></tr>
<tr><td>2,001–3,000
3,001–4,000</td><td>10</td><td>10</td><td rowspan="2">10</td></tr>
<tr><td rowspan="2">4,001–5,000
5,001–6,000</td><td rowspan="2">12</td><td rowspan="2">20</td><td rowspan="3">12</td><td rowspan="4">20</td><td rowspan="4">24</td></tr>
<tr><td rowspan="6">12</td></tr>
<tr><td>6,001–7,000</td><td>15</td><td rowspan="5">30</td></tr>
<tr><td>7,001–8,000</td><td>20</td><td rowspan="2">16</td></tr>
<tr><td>8,001–9,000</td><td>22</td><td rowspan="3">26</td><td rowspan="3">30</td></tr>
<tr><td>9,001–10,000</td><td>24</td><td rowspan="2"></td></tr>
<tr><td>More than 10,000</td><td>26</td></tr>
</table>

Date source: ECRA, 2011; SEC, 2016

[14] Consumers of 5000 kWh or less represent 95.96% of customers and use about 76.3% of the electricity in the residential sector (NEEP, 2008, p. 134). The new tariff system should therefore not impact low-income customers.

In addition, the industrial sector also became subject to the time of use (TOU) tariff, which maintains a 12 Halalal/kWh unit price scale below 1,000 kVA and 14 Halala/kWh between October and April, and a 10/26 Halala/kWh in off-peak/peak time from May to September as shown in Table 1.4. The TOU tariff requires the installation of a digital meter, with customers charged a seasonal tariff if no meter is installed. Otherwise, the customer is given the choice between TOU or the lower seasonal tariff.[15]

Table 1.4 Saudi Arabia's industrial electricity tariff system (in Halala/kWH)

<table>
<tr><th rowspan="3">Consumption Period</th><th colspan="3">Seasonal Tariff (EM Meters)</th><th colspan="6">TOU Tariff (Digital Meters)</th></tr>
<tr><th rowspan="2">Consumption Hours</th><th colspan="2">Tariff</th><th colspan="4" rowspan="2">Consumption Hours</th><th colspan="2">Tariff</th></tr>
<tr><th>< 1000kVA</th><th>>= 1000kVA</th><th>< 1000kVA</th><th>>= 1000kVA</th></tr>
<tr><td>OCT-APR</td><td>All</td><td>12</td><td>14</td><td colspan="4">All</td><td>12</td><td>14</td></tr>
<tr><td rowspan="11">MAY-SEP</td><td rowspan="11">All</td><td colspan="2" rowspan="11">15</td><td colspan="4">Off-Peak Hours</td><td colspan="2" rowspan="6">10</td></tr>
<tr><td colspan="2">Day</td><td colspan="2">Hours</td></tr>
<tr><td>From</td><td>To</td><td>From</td><td>To</td></tr>
<tr><td>SAT</td><td>THU</td><td>00:00</td><td>08:00</td></tr>
<tr><td>FRI</td><td></td><td>00:00</td><td>09:00</td></tr>
<tr><td></td><td></td><td>21:00</td><td>00:00</td></tr>
<tr><td colspan="4">Peak Hours</td><td colspan="2" rowspan="4">26</td></tr>
<tr><td colspan="2">Day</td><td colspan="2">Hours</td></tr>
<tr><td>From</td><td>To</td><td>From</td><td>To</td></tr>
<tr><td>SAT</td><td>THU</td><td>12:00</td><td>17:00</td></tr>
<tr><td colspan="4">Other Hours</td><td colspan="2">15</td></tr>
</table>

Source: Hagihara, 2013, p. 128; ECRA, 2011

The first stage of the restructuring of the Saudi electricity sector, which was initiated in 2008, included the establishment of both a single buyer model to

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[15] The Saudi Riyal is pegged to the U.S. dollar at a rate of USD 1 for SAR 3.75. In addition, 1 SAR = 100 Halala.

accompany the unbundling of the SEC and an independent transmission company. This phase involves the introduction of open access to the grid by major customers and the implementation of a wheeling tariff set by ECRA. The power wheeling took place between non-utilities generation in one location to another customer or to feed the non-utilities. Based on data presented in the SEC's annual report for 2013, the total energy sold in Saudi Arabia that year was 256,688 GWh, which represents a revenue of SAR 35,672,129 million and a production cost of SAR 33,784.02 million. The revenue and cost per kWh stand at 13.8 Halala/kWh and 13.1 Halala/kWh respectively (SEC, 2014). On the other hand, ECRA reported a deficit of 1.5 Halala/kWh, which amounts to SAR 3.85 billion annually and is covered by governmental subsidies. This result shows that the SEC has a surplus, not a deficit. However, this calculation relies on governmental subsidies for fuel. Saudi Arabia could increase its income by reducing diesel imports and oil burning for power generation during the peak summer. As such, strengthening the SEC's financial status is an urgent requirement (Hagihara, 2013). Another factor contributing to these financial problems is the high investment required to ensure that increased supply and generation capacity targets can be met. To achieve these targets, ECRA has estimated that SAR 526 billion in funding will be required through 2020 for electricity generation, transmission, and distribution (ECRA, 2014, p. 102).

The issue of subsidies for electricity tariffs for non-industrial customers is extremely sensitive and has social implications. Many policy analysts have suggested balancing economic and social goals instead of eliminating subsidies, as explained by Matar et al. (2014, p. 3):

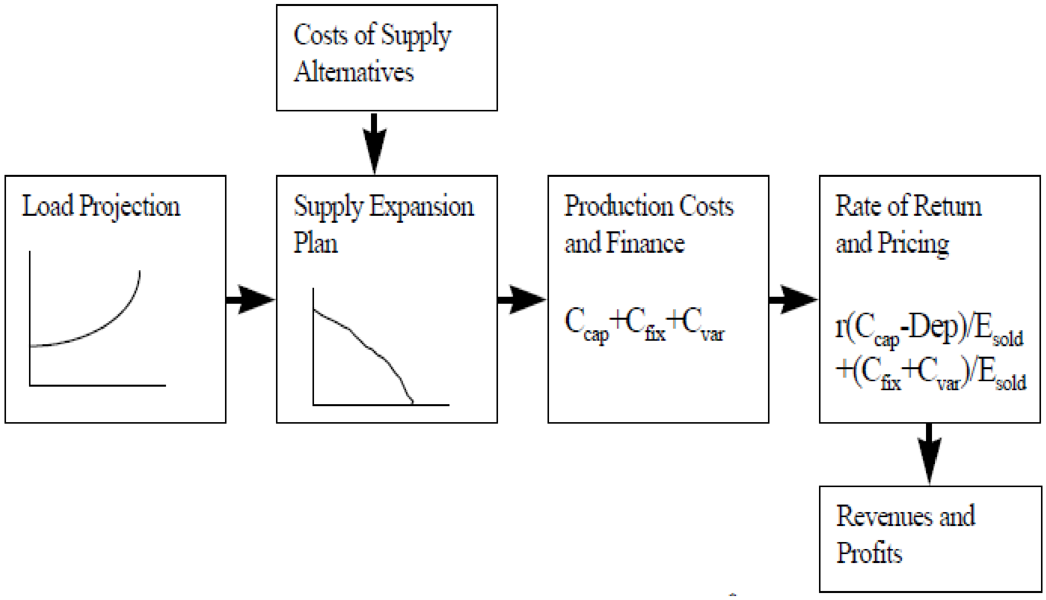
> The generally held notion is that the best way to reduce the inefficiencies associated with currently low domestic energy prices is to

use price incentives, by moving to world market prices throughout the economy. However, this would force higher prices on consumers, and that would undermine the social goal of making energy affordable to society. As a start to improving the efficiency of energy use in Saudi Arabia, we examine the potential for improvements in energy-intensive sectors while maintaining consumer prices at current levels.

1.4 A Global Perspective on Attempts to Conserve Energy

1.4.1 Evolution of Resource Planning

Traditional methods of resource planning in the electricity sector focused only on supply-side investments, i.e. adding more generation plants, and expanding transmission and distribution networks with demand-side options being ignored. In too many cases, the evaluation of supply-side options was even restricted to cost-benefit analysis and a few number of major technologies (Tellus Institute, 2000, p. 3; Almeida et al., 1993, p. 2; Sim, 2011, p. 50). Resource planning has consequently focused on expanding supply resources to meet projected growth of the demand with the objective of minimizing the economic cost of this supply expansion and ensuring high supply reliability (Figure 1.23).



Source: Swisher, Jannuzzi, and Redlinger, 1997, p. 17

Figure 1.23 The traditional least-cost electric planning model[16]

Instead of applying the least-cost supply expansion model, modern utility planning has shifted toward integrated resource plans (IRPs), which is illustrated in Figure 1.24. Consequently, various technologies are being combined with numerous alternatives of potential resources, including technologies for DSM on the demand-side, in addition to decentralized, renewable resources, and non-utility generating sources in the supply-side. It also means integrating a wider range of cost components into the assessment and identification of technical resource options, including

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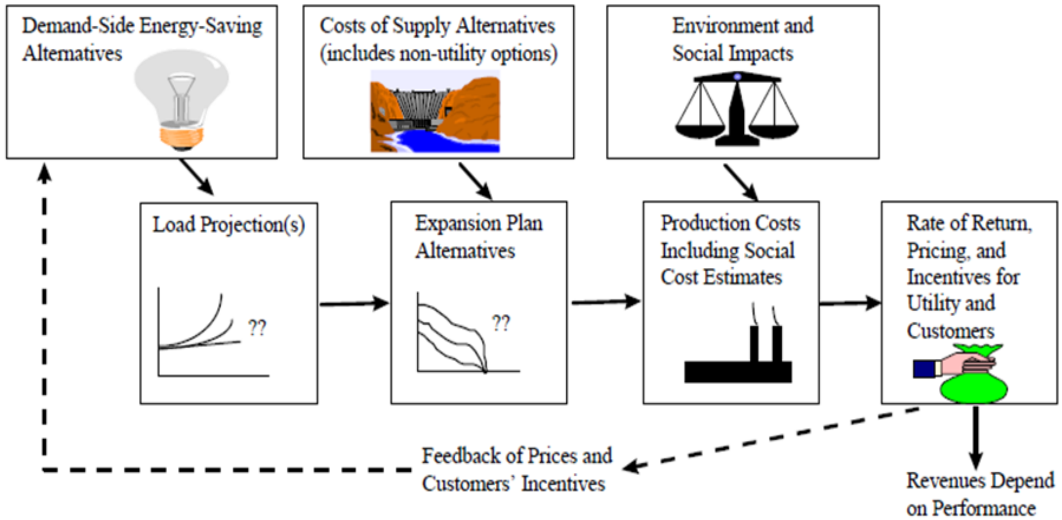
16 This model is useful in understanding the tendency towards overbuilding utilities in nationalized systems and regulated monopolies. Production costs are equal to the sum of capital costs (C_{cap}), fixed operating costs (C_{fix}) and variable operating costs (C_{var}). The classical approach to planning ensures that all of these costs are completely recovered along with a fixed return (r) on capital investment. This is adjusted in consideration of depreciation (Dep) and applied across total energy sales (E_{SOLD}).

environmental and other social costs (Swisher et al., 1997). The IRP concept, which has been around since at least the late 1980s (Sim, 2011, p. 50), was used as the basis for developing the broader concept of integrated resources strategic planning (IRSP). This later version of the concept eliminated the negative impact that deregulation of the power sector had on IRP. The deregulation of power sector by seperating generation, transmission, and distribution brings about a parting of power grid and power generation companies, which has a significant impact on both the fundamental foundation and implementation conditions for consolidated resource planning. While the link between the transmission and generation of power still remains, individual companies set the overall social and environmental benefits aside and target the maximum benefits for themselves as a result, these companies generally abandoned the IRP. In contrast, IRSP resolves this problem and ensures that the overall social and environmental costs are taken into consideration (Hu et al., 2013). Furthermore, Sim (2011, p. 51) points out that IRSP prescribes mandatory competition between resource options. This represents one of the main assertions of IRSP, since it is only through competition that customers can be served with the most beneficial options. Additionally, it is essential to consider all of the cost impacts of selecting resource options to the utilities.



Source: Swisher et al., 1997, p. 29

Figure 1.24 The integrated electric production cost and load model

1.4.2 Global Practice of IRP/IRSP in the Electricity Sector

Hu et al. (2013) cited China as an example of a country that has successfully applied the IRSP model, which should be utilized to measure the nation's potential for energy saving, fuel consumption, investment, capacity demand and emissions for the year 2020. Similar to the Saudi context, China's rapid economic development, rising living standards, and continuously increasing proportion of fossil fuel energy consumption have made electricity's position and role in the energy sector increasingly important. The country's electricity supply and demand face challenges related to energy shortages and environmental impacts as a result of the Chinese economy extensive development. China is experiencing a significant increase in energy consumption, which is expected to rise to 7.9 trillion kWh by 2020. Using the IRSP model on both the supply and demand-side, Hu et al, (2013) optimized its installed capacity to 1.88 TW (compared to 2.1 TW using traditional resource strategic planning). Through the reduction of spending in operations, power grid development and power plants, the IRSP model can also bring about a 5.4% decrease in CO_2 emissions and yield cost savings of over USD$156 billion (Hu et al., 2013, p. 59).

A successful example of IRSP that focuses on energy efficiency measures is a regional plan developed by the Northwest Power and Conservation Council, which is a regional planning organization in the United States. Passed by the U.S. Congress in 1980, the Pacific Northwest Electric Power Planning and Conservation Act provides the foundation for the IRSP's mandate. The council is charged with developing IRSP plan every five years for the Booneville Power Administration (BPA). The plan focuses equally on supply- and demand-side resources whilst also highlighting energy efficiency as key to fulfilling demand for electricity. Thus, energy efficiency is given a 10% cost advantage compared to supply-side resources under the assumptions of the plan. According to International Rivers (2013, p. 16) and the State & Local Energy Efficiency Action Network (2011, p. 11), this has had a significant impact on the BPA's activities in Montana, Idaho, Oregon and Washington. The IRSP was created with a 20-year view, and by taking into account some 750 potential future scenarios. Based on the IRSP plan, the BPA appears to have set a target to use energy efficiency to fulfill 85% of forecasted demand growth. The objective here is to ensure that ambitious energy efficiency levels are reached, at 1200 MW and 5900 MW in 5 and 20 years, respectively. It is believed that investments made in energy efficiency will be 50% cheaper than equivalent investments on the supply-side. These aggressive savings are explained by SEENAction (2011) as follows:

> The council has good reason to be confident that the Sixth Plan is not overly optimistic. Its evaluation of efficiency efforts from 1980 through 2008 found that nearly 4,000 MW of savings had been achieved,

> cutting demand growth in half and saving consumers $1.8 billion on electric bills.

PacifiCorp is a utility company with a customer base of approximately 1.7 million. In 2011, the company submitted its reviewed IRSP for approval across six states in the West. Its IRSP takes into consideration a total of 67 conditions, including changes to the price of natural gas and CO_2 levels, state-specific renewable energy policies, and the nature of the transmission system. According to reports by SEENAction (2011) and IR (2013), energy efficiency could achieve savings of 2500 MW and is the biggest resource to be applied through to 2030, based on data gathered from simulation trials of 100 portfolios. Con Edison also serves as a good example of a distribution utility in the retail market. Con Edison adopted IRSP despite this being an optional tool, taking both supply- and demand-side resources into account and placing the same level of importance on them. This decision was in response to its evaluation of its distribution network in 2003, wherein Con Edison noticed that capacity was running short whilst load continually increased. SEENAction (2013).

Although its efforts are made based on focused energy efficiency and IRP programs, Japan provides a great international example of promoting progressive efficiency standards and can be applied effectively in Saudi Arabia. In Saudi Arabia, IRSP requires considering DSM options, specifically appliance efficiency standards, given that the industrial sector consumes 20% of the domestic electricity demand. According to the literature, Japan is currently amongst the most energy efficient nations around the globe (Lahn & Stevens, 2011, p. 34):

> Its almost total dependency on oil and gas imports has encouraged it to seek both diversification of supply and demand-side solutions. Japan’s energy efficiency and demand program, begun in the 1970s, is considered to be a world leader, having resulted in lower energy intensity and brought the benefits of greater security of supply and

> improved balance of payments. Between 1973 and 2003, Japan cut its energy intensity by approximately 37%. Most of the effective measures were taken early on and the pace of improvement has slowed since the mid-1980s. Some of the most significant improvements were in the industrial sector. Between 1973 and 2005, energy efficiency improved by 20% in the steel sector, by 52% in the pulp and paper sector, and by 29% in the chemical sector. These improvements have been largely achieved through the implementation of the provisions of the Energy Conservation Law, which required companies that consumed over 3,000 kilojoules (kj) of energy to appoint energy managers and submit mid- and long-term energy reduction plans and reports on energy usage. While companies with smaller energy usage were also required to take action, they only had to appoint energy officers and make reports on energy usage. In addition, subsidies were made available for energy-management systems and high-performance equipment. These simple measures bought significant initial benefits and captured the ‘low-hanging’ fruit of better energy management and good housekeeping.

At 2011, an ECRA study considered case studies of DSM implementation in five countries and one U.S. state. Table 1.5 summarizes the positive impacts that implementing DSM had in these countries. These case studies suggest that Saudi Arabia’s peak demand could be decreased through the demand-side management.

Table 1.5 Summary of demand-side management experiences in six countries/states

Country or State	**Main Source of Demand-side Management**	**Identified Impacts**
China	TOU pricing, interruptible power contracts	10,000 MW reduction (3,000 not from involuntary load shedding)
California	Reliability-triggered demand response	3,300 MW (6% of peak)
Brazil	Power rationing program	20% reduction in total consumption
Australia	Interruptible power contracts, TOU pricing	350 MW participating in ancillary services market
South Korea	Reliability-triggered demand response	2,700 MW (4.5% of peak)
Italy	TOU pricing	10% of peak

Source: Faruqui and Hledik, 2011, p. 19

1.5 Research Design and Methodology

The key questions related to meeting Saudi Arabia's electricity demand (which is the country's largest energy challenge) and transitioning to a sustainable utility sector are as follows:

- What is the most optimal and economic generation-mix plan for the utility sector to meet the projected demand in 2040, using the least cost combination of technology options in the supply-side and demand-side? How will this plan conserve energy and avoid the burning of high-value fuel?
- How can the plan address and maximize the social and environmental benefits of utility sector performance?
- Which sustainable energy policy options are best for achieving the development and successful implementation of the plan?

1.5.1 Electricity and Desalinated Water Utility Model for Saudi Arabia

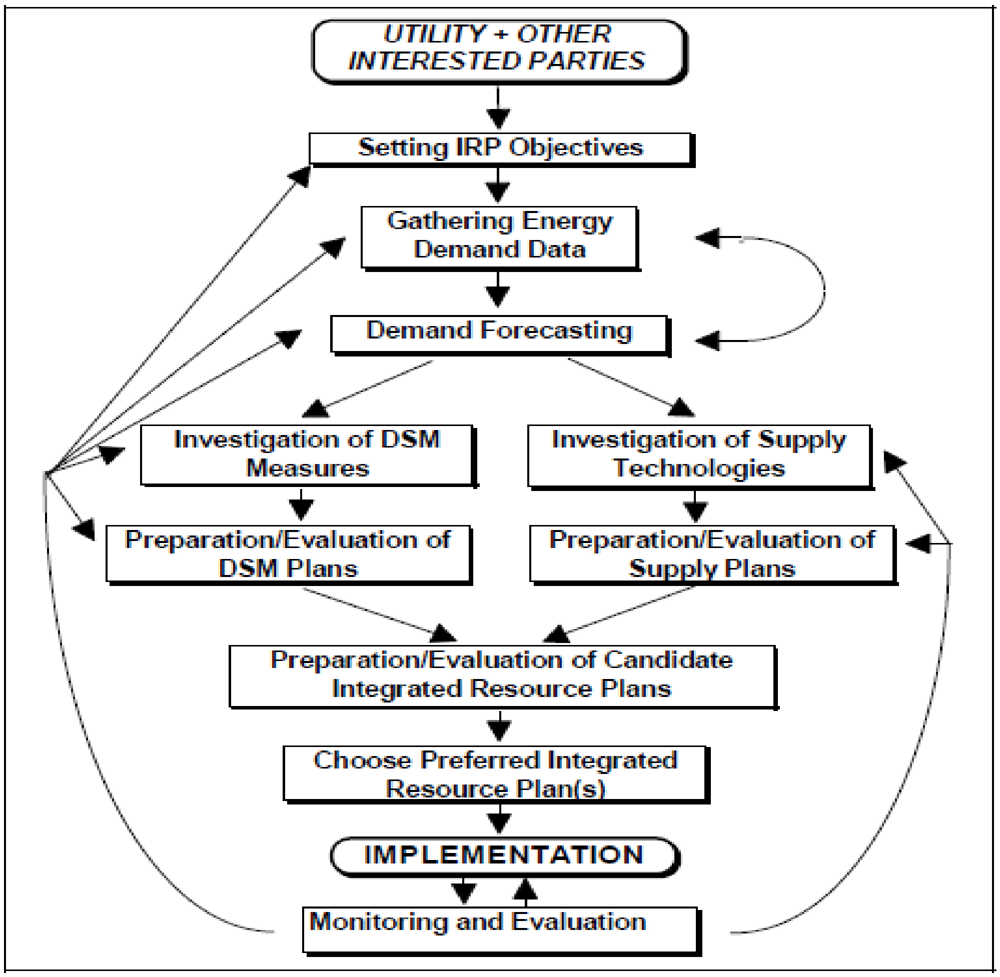
As explained earlier, IRSP is the best national-level resource planning method for power sector that integrate the supply- and demand-side resources in an efficient, economical, and rational way to reduce the overall planning costs (Hu et al., 2013). For Saudi Arabia, the key part of IRSP is to integrate and optimize the electricity and water sectors' resources to select the IRSP model that provides the best plan to meet certain objectives. The Tellus Institute (2000, p. 7) lists the following broad objectives in its best practices guide for electricity integrated resource planning:

- Minimizing power production and distribution costs to maintain minimum revenue requirements for the utility;
- Reducing electricity supply prices for residential and industrial customers, taking the scenario of administered prices versus other scenarios into consideration;
- Adopting sustainable and efficient energy technologies on the supply-side and demand-side to increase the efficiency, reliability, security, and diversification of the energy supply;
- Considering utilization opportunities of conventional and unconventional fuels supply;
- Providing social benefits to increase local employment in the electricity sector and the economy at large; and
- Decreasing the negative effects of electricity generation in order to protect the environment from damage.

Hu et al. (2013) and the Tellus Institute (2000) provide the following steps for IRSP development (see Figure 1.25):

- Outline the objectives of the IRSP and clarify the planning period;
- Project the future load demand;

- Assess the supply-side resources (considering inter alia existing resources, new generating units that it may be possible to build in the future, and future supply) and demand-side resources (considering various DSM measures); and
- Integrate and optimize all the resources for implementation.



Source: Tellus Institute, 2010, p. 4

Figure 1.25 The integrated resources planning process

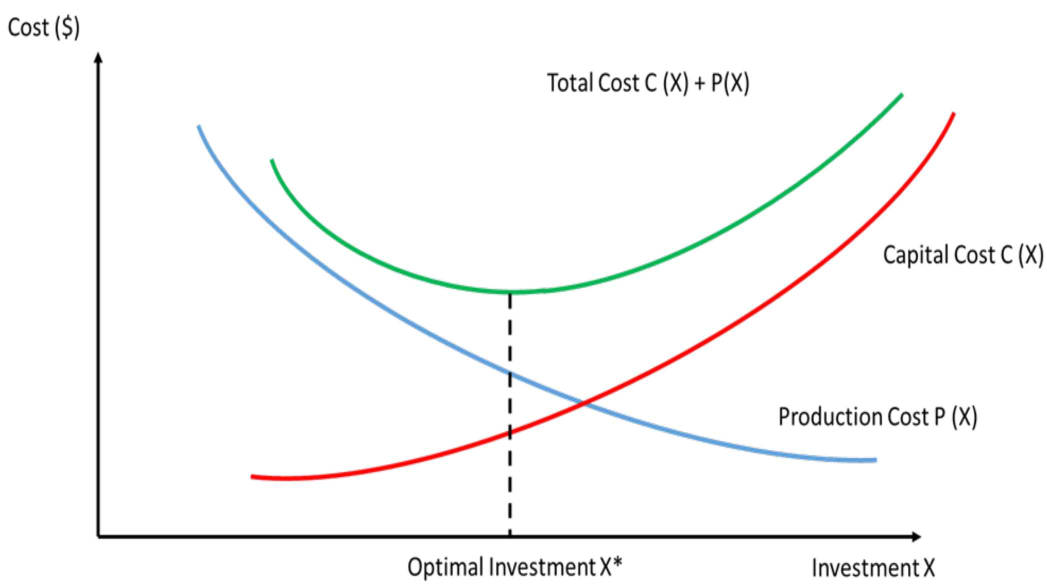
A demand forecast is used to assess factors such as the appropriate generation resources, the potential generation capacity required, the ways in which distribution and transmission systems must be increased, and in which regions and consumer groups these needs are focused on. The literature review identified two types of load forecasting models (Tellus Institute, 2000):

- Bottom-up/end-use approaches or end-use forecasting: These models build up forecasts of electricity demand through an evaluation of what functions and tasks electricity enables users to achieve. They are quite detailed but also data intensive.
- Top-down approaches, such as econometric forecasting (Swisher, 1997, pp. 27-44; Tellus Institute, 2000, p. 9-12): Top-down approaches identify the previous correlations between peak/electricity demand and certain economic/demographic variables and then apply these correlations to the future as a forecast. Thus, top-down models predict the future based on past behavior. These variables can include household income, the price of electricity for specific consumer groups, the price of household essentials, employment sectors, labor productivity, tourism, physical or monetary output from the industrial or agricultural sectors, a breakdown of output from subsectors of the commercial sector, the use of alternative fuels, and the price of these fuels.

Based on limitations in the available load data, this research develops a bottom-up or end-use forecasting model for Saudi Arabia’s largest consuming sector (i.e. the residential sector, which accounts for 50% of electricity consumption); econometric forecasting models are concurrently created for other sectors. While these models are adequate for forecasting demand for the IRSP analysis, it is recognized that the bottom-up approach would be more accurate and provide a better perspective on DSM and energy efficiency measures.

1.5.2 Constructing an Integrated Resource Strategic Planning Optimization Model for the Electricity-Water Sector

The EWS IRSP model uses an optimization software tool to develop the optimal scheme by combining different fuel mixes to meet future demand. The optimal plan will be characterized by the minimum fixed and variable costs for new types of units (taking into consideration DSM measures) in the period being studied. The main objective is therefore to minimize the net present value of forward-looking costs, as shown in the example in Figure 1.26.



Source: Energy Exemplar, 2012, p. 19

Figure 1.26 Example of IRSP objectives using capital and production costs

The literature presents three different supply- and demand-side resource optimizations. The first approach entails DSM policy impacts being factored into the model as a specific input through the inclusion of demand-side resources in the demand forecast. The second approach is considered more beneficial, and involves the incorporation of demand-side resources into the demand forecast through the optimization of supply-side options against more than one demand forecast. Finally, the third approach considers extra investment on the demand-side as a resource that can create negative energy and demand at a certain cost. The following formula has been presented based on the third approach (Hu et al., 2013):

$$\text{Min Z} = \min \{\text{GF} + \text{BF} - \text{CZ}\} \qquad (1.1)$$

Where Z is the overall electricity production cost, GF is the total annual fixed production unit costs within the given planning period, BF is the total annual unit operating costs within the given planning period, and CZ is the production units' annual residual value at the end of the specificed planning period.

The three sub-items of GF, BF, and CZ are expressed respectively by Equations 1.2, 1.3, and 1.4:

$$GF = \sum_{y=1}^{Y} \sum_{m=1}^{M} (C_{y,m} \quad F_{y,m})\, \beta_y \qquad (1.2)$$

where *Y* is the planning period, *y* is the year, *M* is the quantity of unit types, *m* is the unit type serial number (e.g., 1, 2, 3… with 12 representing coal, gas, hydro, nuclear power, wind power, etc.), $C_{y,m}$ is the new installed capacity of the *m* unit type in the *y* year, $F_{y,m}$ is the cost per unit capacity of the *m* kind of unit in the *y* year, and β_y is the coefficient of the time value of capital.

$$BF = \sum_{y=1}^{Y}\{ \sum_{m=1}^{M1}(E_{y,m} \ \ V_{y,m}) + \ \sum_{m=M1+1}^{M}(E_{y,m} \ \ (V_{y,m})] \ \beta_y \ \} \tag{1.3}$$

Where $E_{y,m}$ is the overall generating capacity of the *m* type of unit during the *y* year, $V_{y,m}$ is the per-unit variable cost of the *m* type of unit during the *y* year, and *M1* is the quantity of conventional power supply types.

$$CZ = \ \sum_{y=1}^{Y}(R_{y,m}) \ \beta_y \tag{1.4}$$

Where $R_{y,m}$ is the new *m* type of unit's residual value during the *y* year at the end of the given planning period.

$$E_{y,m} = (Ci_{y,m} + \psi_{y,m}\ C_{y,m})\ H_{y,m} \tag{1.5}$$

where $Ci_{y,m}$ is the installed capacity of the *m* type of unit during the *y* year at the beginning of the given planning period, $\psi_{y,m}$ is the coefficient of the new capacity expressed as an equivalent average capacity of the *m* type of unit during the *y* year, and $H_{y,m}$ is the average quantity of hours per year that the *m* type of unit can use during the *y* year.

1.5.3 Defining Resource Constraints

There are specific constraints associated with integrated resources strategic planning that ensure that power supply remains stable, secure and reliable, including emissions, subsidies, fuel resources, the capacity of new and existing generators, the reliability of the power system, the minimum/maximum output load, and load demand. In this research, the constraints are clearly defined before the IRSP optimization model is constructed. The below examples of constraint definitions (e.g., social objectives to create more jobs or limit changes to subsidies) can be also developed:

- Electricity demand constraints: After subtracting losses in conventional power supply and efficiency measures, generation capacity should be not less than the predicted value of electricity demand.
- Installed capacity constraints: The conventional power supply's yearly installed capacity and efficiency should be no higher than the set value.
- Fuel resource constraints: The annual consumption of a specific fuel resource should be no higher than the amount of resource available.
- Pollutant emission constraints: Annual CO_2, NOx, and SOx emissions from fossil-fuel generation facilities should be less than a set value.

1.5.4 Potential Optimization Tools for Research

Since the research methodology requires an optimization tool that can co-optimize the supply and demand and identifying the optimal feasible configuration of the modeled sector, only bottom-up optimizations models are considered for detailed evaluations (Bhattacharyya, 2011, p. 397). Examples of such models include MARKAL, TIMES, Strategist, and PLEXOS Table 1.6 summarizes the evaluations of these tools that were undertaken as part of the current study.

Table 1.6 Summary of the evaluation of bottom-up optimization tools

	PLEXOS	**MARKAL, TIMES, Strategist**	**Evaluation**
Technical parameters for generation	Capacities, min, stable generation, max. generation ramp rates, heat rates, min. up and down time, failure rates, maintenance rates and time.	Capacities, efficiencies, availabilities factors, technical life, starting year.	PLEXOS can capture technical and reliability data of generation that the other assessed software tools cannot capture.
Technical parameters for transmission lines	Models all types of transmissions (AC and DC) and addresses congestion problems in its long-term expansion plan.	Limited capability to model transmission.	PLEXOS does consider transmission details while the other assessed tools do not
Model resolution	Detailed grid and generation representation including the modeling of renewable technology deployment.	Grid operations should be approximated, generating units should be classified into generalized technology categories, and the resolution of models requires simplifications.	PLEXOS has the best resolution to capture the details of different generation technologies.
Economic parameters	Individual fuel costs, variable O&M rates, start costs, CO_2 costs, and emissions per fuel type.	Capital cost, O&M cost (fixed and variable), discount rates.	The breakdown of costs is more detailed in PLEXOS than in the other tools.
Environmental parameters	Emissions (CO_2, NOx, SOx).	Emissions (CO_2, NOx, SOx).	All of them address all environmental parameters

In the evaluation, PLEXOS focuses exclusively on the electrical system modeling and the primary inputs (such as load and fuel prices) are generally exogenous in nature (Chiodi, Deane, Gargiulo, & Gallachóir, 2012). In contrast, the electrical power system within whole energy system models by other software tools is entirely endogenous and controlled by the combined behavior of the supply sectors that deliver primary fuels and end-use sectors that are influenced by exogenous energy service demand. For research that specifically addresses electricity modeling, PLEXOS, which is a sophisticated power system modeling tool that is used for electric power market modeling and planning worldwide, is best suited; this is due to its capabilities in relation to modeling the details of electrical systems, which are superior to those of other energy models in the market (e.g., TIMES and MARKAL) (Chiodi et al., 2012).

Based on the above evaluations, the PLEXOS Integrated Energy Model[17] was selected as the simulation tool for this study. While PLEXOS is commercial software, it is free to academic institutions for non-commercial research. PLEXOS can achieve power system optimization for periods ranging from 12 months or 1-5 years to as long as 40 years, making it an ideal tool for short-term, medium-term and long-term tasks. In the majority of cases, deterministic linear programming methods are used for modeling. The aim of such methods is to reduce an objective function subject to the predicted electricity delivery cost as well as to various constraints, such as those related to transmission and operation, fuel costs, environmental licensing, operational features of generating plants and the number of plants available for use. The power of linear programming lies in its ability to efficiently identify the optimal solution to a problem with numerous decision variables (Chiodi et al., 2012). The PLEXOS

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[17] PLEXOS Integrated Energy Model software is developed by Energy Exemplar: http://energyexemplar.com/

software has been used in approximately 100 sites in 17 countries, including the United States, Russia, and European, Asian, Pacific, and African nations (Energy Exemplar, 2012). PLEXOS has a proven record in the area of policy analysis and development. Common policy analysis applications of PLEXOS include (Panagiotakopoulou, 2012, p. 2):

- Designing, analyzing, and benchmarking electricity market rules and their effect on market participants;
- Assessing the effectiveness of renewable technology policies and their resulting impact on carbon emissions, prices, transmission grid operations, and investment incentives;
- Forecasting market entry, assessing future technology and fuel mixes, and examining the development of system adequacy; and
- Examining market competitiveness and power.

Furthermore (and most importantly), ECRA and other entities are currently working on developing an integrated long-term resource plan in Saudi Arabia using a different modeling tool. This research can therefore help shape the development of the electricity and water sectors by contributing to this plan. Using PLEXOS along with the tool could contribute important added value to improve electricity sector modeling in Saudi Arabia.

1.5.5 Sources of Data and Information

This work utilizes international experience in three core areas of research: demand forecasting, IRSP, and sustainable energy policies in the electricity and desalination sectors. Literature sources include published books, articles, reports, and World Wide Web entries. The study’s theoretical framework was based on these sources and applied to the creation of an IRSP model for the Saudi Arabia’s utility.

In Saudi Arabia, important local sources for research included annual reports from the SEC and ECRA. In addition, daily information on power production and consumption patterns was obtained from the SEC's Power Control Center and proved to be extremely valuable for analyzing the current and future power electricity supply and demand data. Additional information was collected from local ministries and institutions, including the Central Department of Statistics & Information (CDSI), the Ministry of Economic Planning (MEP), the MoWE, the Ministry of Petroleum and Mineral Resources, the Saudi Arabia Monetary Agency (SAMA), and K.A.CARE.

Due to the fast-changing structure of the electricity and desalination sectors and new developments in Saudi Arabia, most of the available sources rapidly became outdated. However, the SEC and ECRA have issued several local reports and studies on demand forecasting and DSM in recent years. Furthermore, international organizations have published reports and studies on IRSP; among them, the best practice guide for IRSP for electricity and the United Nations Environment Program's IRSP were particularly useful (e.g., Swisher et al., 1997; Tellus Institute, 2000).

1.6 Organization of the Dissertation

Following this introduction, Chapter 2 evaluates comprehensively the supply- and demand-side potential in Saudi Arabia. In relation to the supply-side, the chapter provides a review of Saudi Arabia's supply electricity generation potential, focusing on renewables (e.g., solar, wind, and nuclear energy sources). It analyzes these potential sources economically, taking the unique environmental characteristics of the country (such as its extreme ambient temperature, dust accumulation, and water scarcity) into consideration. In relation to the demand-side, the chapter focuses on identifying the most attractive DSM measures that Saudi Arabia could consider. Due to the limited implementation of DSM in the Kingdom, measures are assessed using DSM best practices in the world and adjusted to suit the unique environmental, economic and cultural situations of Saudi Arabia (Faruqui & Hledik, 2011). The chapter applies the IRP scenario-based projection framework required to quantify the technical, economic, and market potential of measures available through DSM.

Chapter 3 describes the methodological approach that this study applies for forecasting the future long-term electricity demand in Saudi Arabia using weather-based hybrid end-use econometric models. Based on the evaluation of DSM measures presented in Chapter 2, the demand forecasting model is utilized to forecast the hourly electricity demand for all regions in Saudi Arabia, taking various energy efficiency scenarios into consideration.

Chapter 4 presents the proposed EWS IRSP model used in this study and the algorithm of the integrated energy tool (i.e. PLEXOS). It also describes the data requirements, variables, and constraints and presents the datasets used in the development of the IRSP model.

Chapter 5 explains the model objectives and metrics as well as the scenario development techniques. It also presents results of the IRSP model from 2016 to 2040 based on an in-depth analysis of the interrelations between energy, economics, environment, and society. It also conducts a sensitivity analysis of different variables that are likely to have a major impact on the study's results presented in the previous chapter

Chapter 6 review comprehensively the existing regulatory policy framework for Saudi Arabia's utility sector. It also offers policy recommendation for identifying pathways toward sustainable electricity supply and demand for the Saudi utility sector.

Finally, it concludes the study by presenting some findings, recommendations, limitation, and suggestions for further studies.

Chapter 2

EVALUATION OF SUPPLY-SIDE AND DEMAND-SIDE POTENTIAL IN THE SAUDI ELECTRICITY AND WATER SECTORS

Integrated resource strategic planning integrates supply-side resources, such as renewables, and demand-side resources, such as energy efficiency measures, to supply electricity to the end-users at a minimum cost, taking into account social and environmental costs and benefits. One vital step in IRSP is to identify, evaluate, and select promising options on both the supply-side and demand-side for further consideration in the integrated electricity-water sector model (EWS IRSP), which combine both supply-side and demand-side resource portfolio plans. This chapter presents comprehensive evaluations of supply- and demand-side potential in Saudi Arabia.

2.1 Supply-Side Potential in Saudi Arabia

This section provides an overview of Saudi Arabia's electricity supply generation potential, focusing on nuclear energy sources and renewables, such as solar and wind. Renewable energy technologies can provide significant benefits especially in relation to solar energy as Saudi Arabia lies in the world's sunbelt region. As noted earlier, Saudi Arabia receives approximately 2200 kWh/m^2 average horizontal radiation every year, (Hepbasli & Alsuhaibani, 2011), which is associated with enormous areas of uninhabited land with vast potential for harnessing solar energy. To illustrate the current potential of solar and wind energy in Saudi Arabia, Figure 2.1

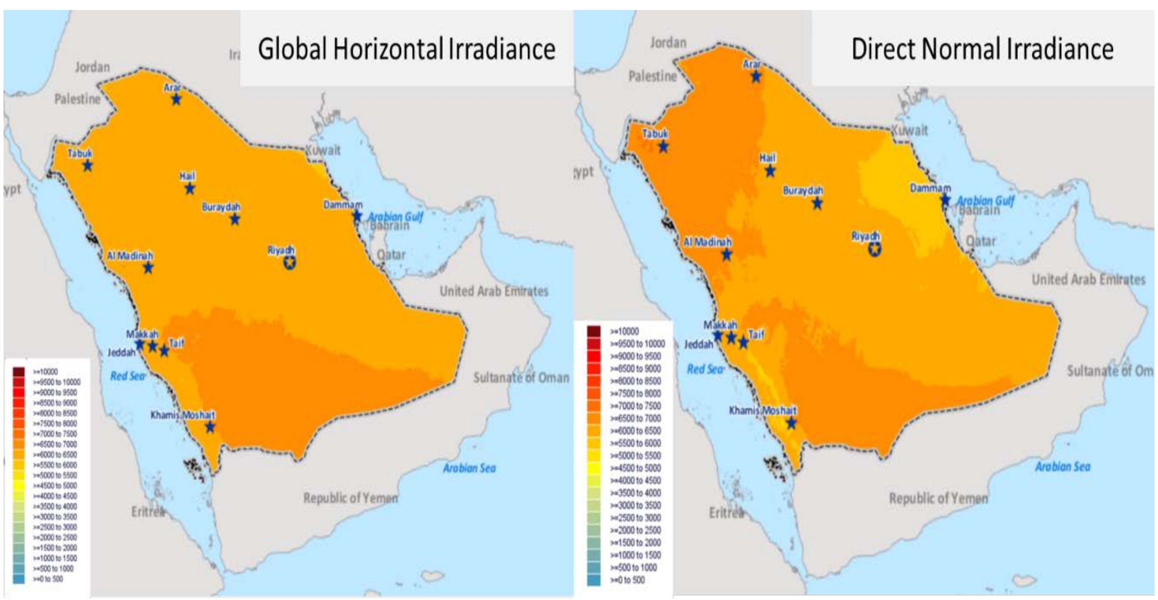
shows the area each technology requires to fully supply the country's electricity demand (approximately 1200 TWh) in 2040.[18]

Figure 2.1 Estimated land size for renewables capable of meeting Saudi Arabia's full electricity needs by 2040

[18] For utility-scale 11 MW PV, the assumptions included a capacity factor of 28.1%, thin-film technology with 11% efficiency, a one-axis tracking system, a ground coverage ratio of 40%, and a GHI daily average of 6,017 W/m². For 125 MW Tower CSP technology with dry-air cooling with 10-hour storage and Solar Multiple of 2, the capacity factor was assumed to be 59%. For 1 MW wind, a capacity factor of 50% was assumed with 60 acres/MW (AWEA, 2016).

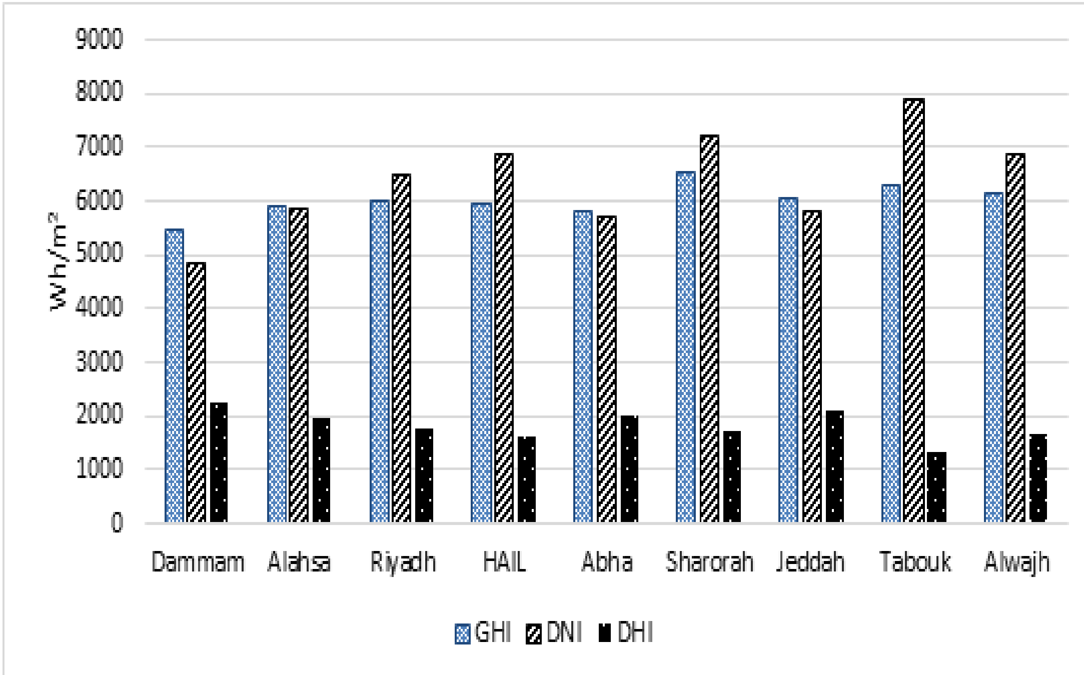
2.1.1 Solar Energy Technology

Saudi Arabia has the potential to be a major exporter of both oil/gas and solar energy (Hertog & Luciani, 2009). Compared with Spain, Saudi Arabia enjoys 40% more solar irradiation. The estimated solar capacity of the Arabian Peninsula is nearly 12,425 TWh, which is enough to power the Kingdom for 72 years (Aljarboua, 2009, p. 1). Figure 2.2 shows the annual average daily global horizontal irradiance (GHI) and direct normal irradiance (DNI) for the country. Figure 2.3 summarizes the GHI, DNI, and diffuse horizontal irradiance (DHI) for nine Saudi cities in the country’s four main regions, namely: (1) the eastern region (Dammam and Alahsa), (2) the central region (Riyadh and Hail), (3) the southern region (Abha and Sharorah), and (4) the western region (Jeddah, Tabouk, and Alwajh).



Data source: K.A.CARE, 2016

Figure 2.2 Average daily GHI and DNI values in Saudi Arabia

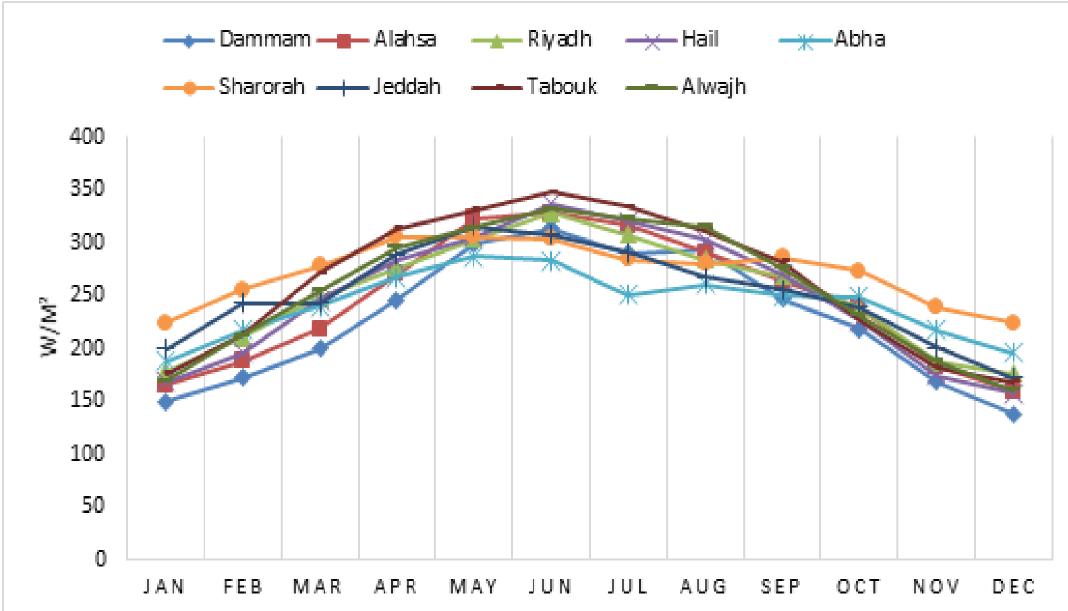


Data source: Meteonorm, 2016

Figure 2.3 Solar irradiance summary for different cities in Saudi Arabia, 1992–2010

2.1.1.1 Photovoltaic Potential

For the nine cities noted above, the annual average daily GHI ranged from approximately 5400 Wh/m² to 6500 Wh/m². In the summer, it ranged from circa 6800 Wh/m² to more than 8400 Wh/m² (with an hourly GHI of 220 Wh/m² and 350 Wh/m² cases for both cases), as indicated in Figure 2.4. In the winter, the average daily GHI during ranged from approximately 3300 Wh/m² (with an hourly GHI of 137 Wh/m²) to more than 5376 Wh/m² (with an hourly GHI of 224 Wh/m²). This potential shows that photovoltaic (PV) technologies are likely to be effective in all regions within Saudi Arabia. Nonetheless, performance of some of PV technologies may be degraded due to extreme high temperatures (Zell et al., 2015).



Data source: Meteonorm, 2016

Figure 2.4 Summary of average monthly mean hourly GHI for different cities in Saudi Arabia, 1992–2010

The high ambient temperatures in Saudi Arabia have a strong impact on PV cell efficiency and therefore result in power reductions. These reductions depend on the temperature power coefficient of the module, which in turn depends on the cell type and is provided by supplier as %/ºC (Baras et al., 2012). Zell et al. (2015) highlight the following challenges associated with PV in Saudi Arabia:

> GHI values are high at all locations in the country with relatively low variability. This indicates that GHI values are well-suited for strong photovoltaic (PV) technology performance at any location with relatively low levelized cost of electricity. However, extreme high temperatures (over 30 degee C annual average in some locations) may degrade the performance of some types of photovoltaic technologies

To evaluate the potential performance of PV in Saudi Arabia, hypothetical 10 MW silicon PV (with 17% efficiency) and thin-film PV (with 11% efficiency) utility-scale plants in Riyadh were selected. Both systems were assumed to have one-axis tracking facing south. The temperature power coefficients for the silicon and thin-film PVs were assumed to be 0.407 and 0.248 respectively, with a ground coverage ratio (GCR) of 0.3 for both PVs. [19]Figure 2.5 shows the average daily power output of each system during a selected summer month (i.e. July) and on an annual basis, using the system advisor model (SAM) tool. The annual capacity factors for the silicon and thin-film PV systems were calculated to be 26.3% and 28.1%, respectively. The thin-film PV produced 8%–9% more power than the silicon PV during the summer and 6%–7% more power on an annual basis.

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[19] The ground coverage ratio (GCR) represents the ratio of the photovoltaic array area to the overall ground area. In the case of an array with modular rows, the GCR represents the length of one row divided by the distance between the bottom of a row and the row adjacent to it (SAM, 2017).

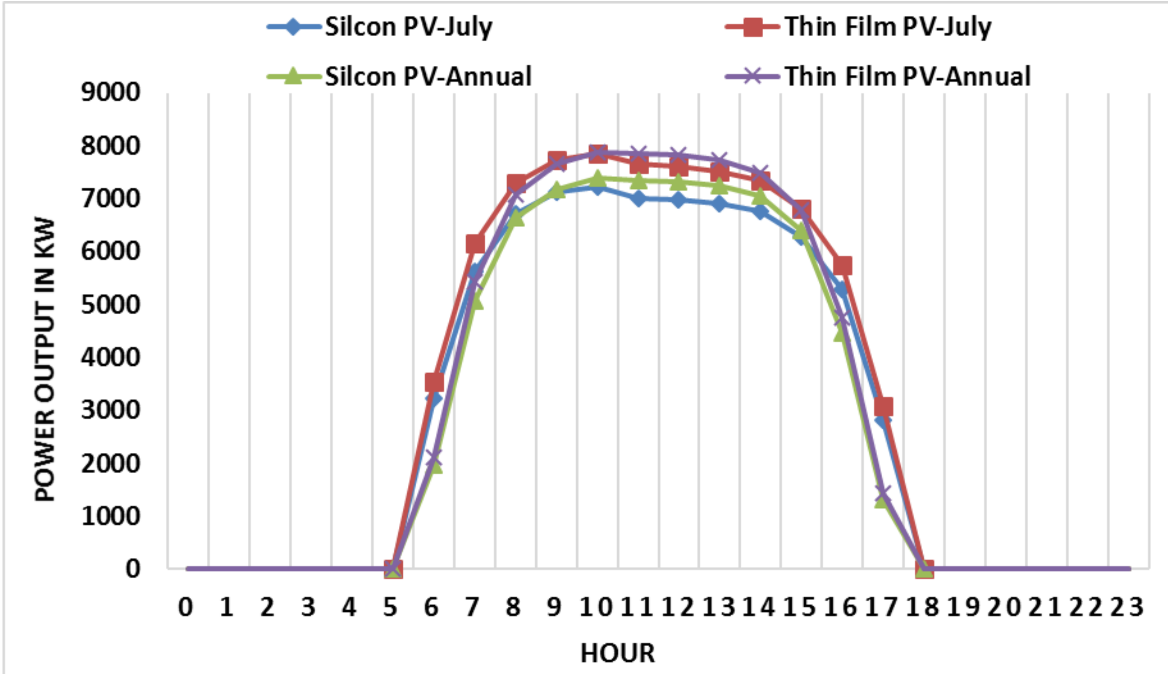

Figure 2.5 Daily average power output of 10 MW silicon and thin-film PV systems

Figure 2.6 shows the levelized cost of electricity (LCOE) analysis for these hypothetical silicon and thin-film PV systems. For the silicon PV, the LCOE cost increase ranged from 5.5% to 8%, was observed in comparison with the thin-film PV system for eight Saudi cities. Thus, the thin-film PV performed better in Saudi Arabia than the silicon PV. The total land area required for silicon and thin-film PVs was calculated to be 52.4 and 87 acres, respectively. Although thin-film PVs require 66% more space, this should not be an issue due to Saudi Arabia's vast areas of abandoned land.

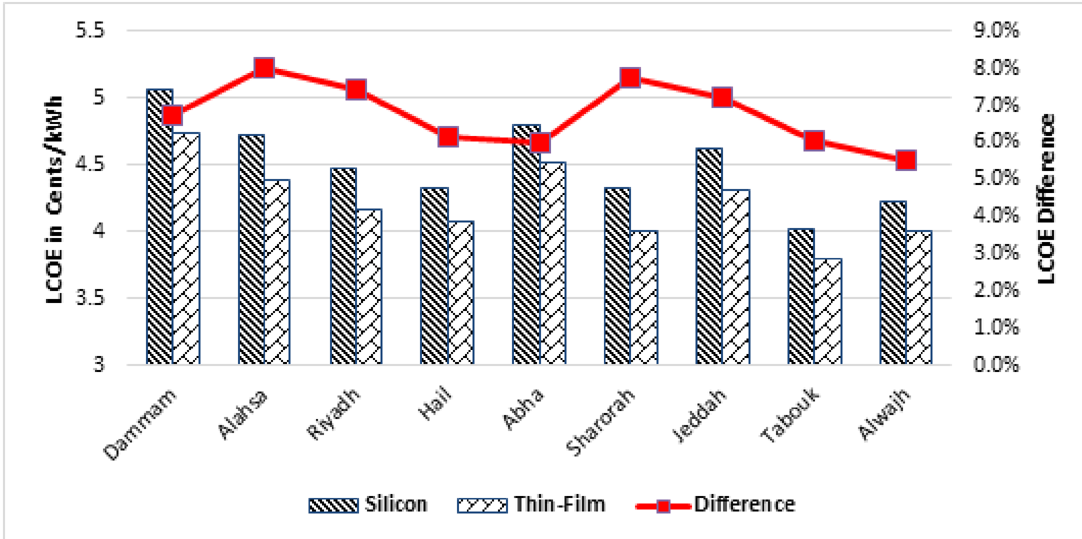

Figure 2.6 The LCOE of 10 MW silicon and thin-film PV systems for different cities in Saudi Arabia (calculated over plant lifetime)[20]

While Saudi Arabia has significantly more solar radiation than other regions in the world, it also has many problems related to dust and sand movement and accumulation on solar PVs. The dust issue creates a particularly key challenge for the deployment of solar energy in the Saudi Arabia. Gastli and Armendariz (2013) illustrated the effects of accumulated dust on the power output of solar panels:

> It is reported that 10 mg/cm² of dust deposition decreases the power output by more than 90 percent. Also, 4 grams of dust per square meter can reduce solar panel's efficiency by 40 percent. In regions where rain falls frequently, the most important natural means of cleaning dust accumulation is rain. However, in the GCC [Gulf Cooperation Council] region where rain is very scarce, advanced surface coatings and artificial cleaning techniques should be considered and developed.

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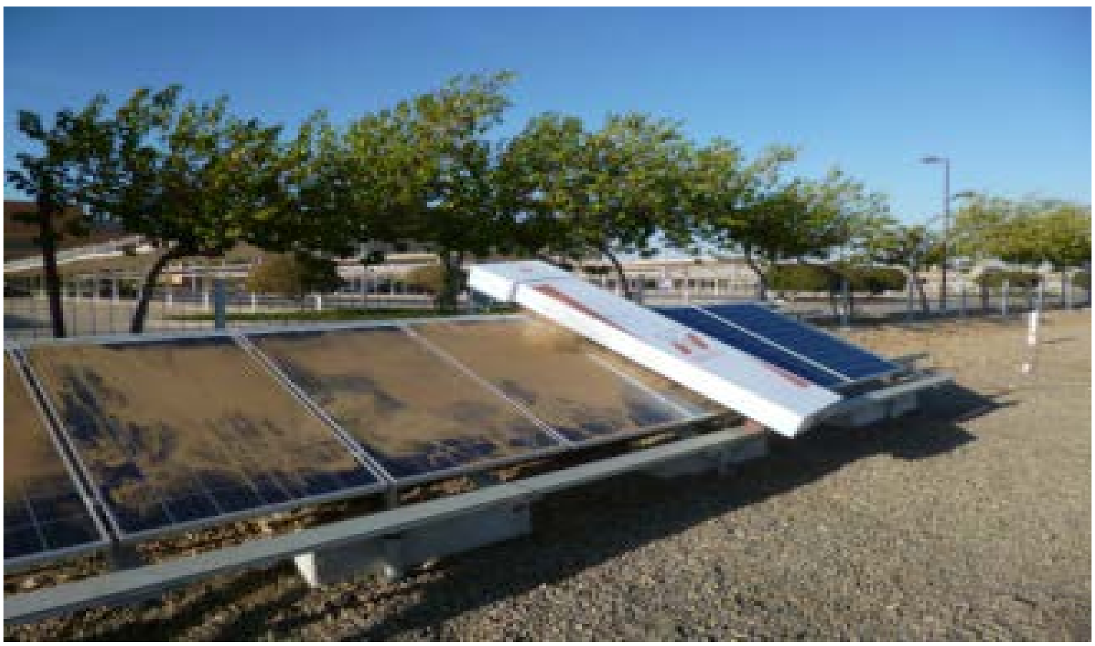
[20] SAM was applied to calculate the LCOE with the inclusion of the total PV costs, using a basic dispatch model to calculate the output of the plant, thus providing a LOCE for the plant's lifetime.

Figure 2.7 shows the NO Water Mechanical Automated Dusting Device (NOMADD), an intelligent ecological desert solar panel cleaning technology designed to mitigate the dust accumlation problem in Saudi Arabia. It is also a cost-effective solution, as it offers a three-year payback period against all captured costs of manual cleaning, including water consumption (Magistretti, 2016).



Source: Magistretti, 2016

Figure 2.7 Application of the NO Water Mechanical Automated Dusting Device (NOMADD)

Tracking is another factor that impacts the performance of PVs in Saudi Arabia. Figure 2.8 shows the daily average power output for fixed tracking at 20 degrees, one-axis tracking, and two-axis tracking. One-axis tracking increases the capacity factor of 10 MW thin-film PV systems by approximately 6.4% in comparison with a fixed tilt at 20 degrees. In contrast, two-axis tracking increases the capacity factor by only 1.5% compared to one-axis tracking.

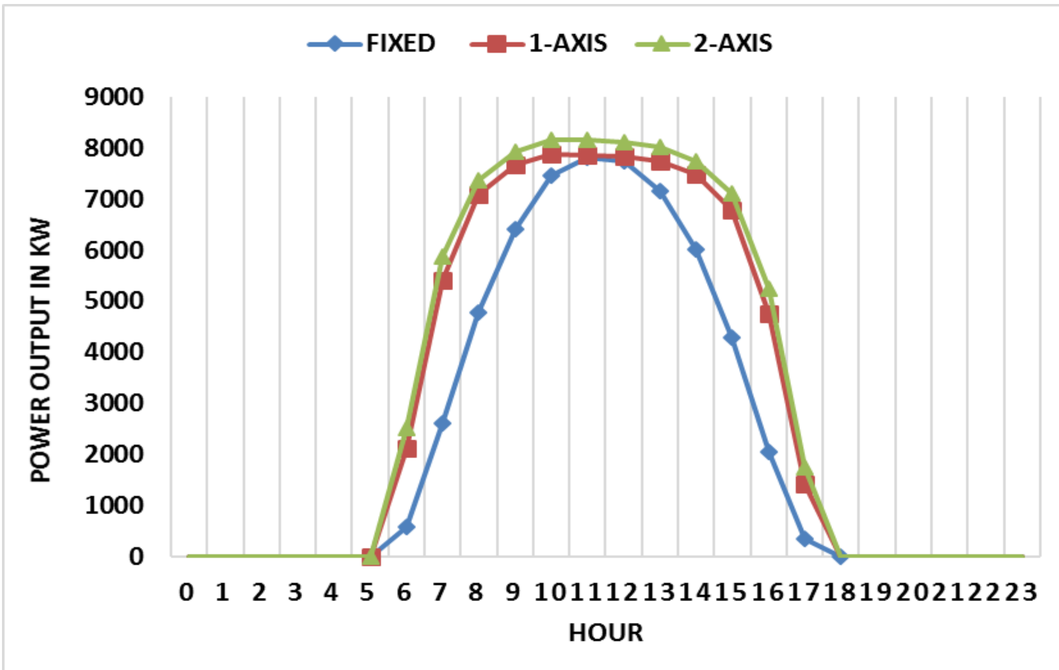


Figure 2.8 Daily average power output of 10 MW thin-film PV systems with fixed, one-axis, and two-axis tracking

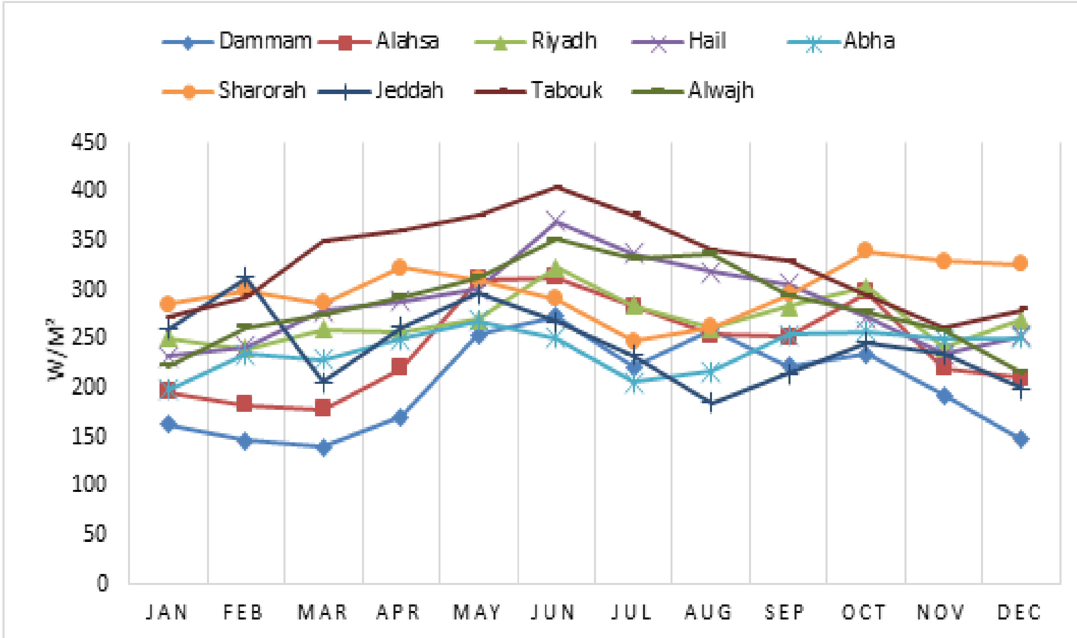
2.1.1.2 Concentrated Solar Power Potential

Saudi Arabia is a potential location for the deployment of any concentrated solar technology due to its high direct solar radiation. Large-scale CSP projects can be very valuable for the country; along with freeing up oil and natural gas for utilization in higher value-added applications. CSPs also have the potential to enable Saudi Arabia to become a key solar energy exporter in the future (KICP, 2009, p. 38).

Faranoosh et al. (2014, p. 8) provide an example that illustrates CSP's potential for generating electricity in the Kingdom.

> Just for giving an example, within about 2000 KWh/m²/y of DNI, it has been estimated that the potential annual energy yield of CSP technology in Saudi Arabia is around 124,560 TWh. This amount represents around 650 times the total electricity consumption of the country in 2009. This reflects the fact that CSP technology must be considered between the most suitable renewable technologies in the Saudi's future energy mix

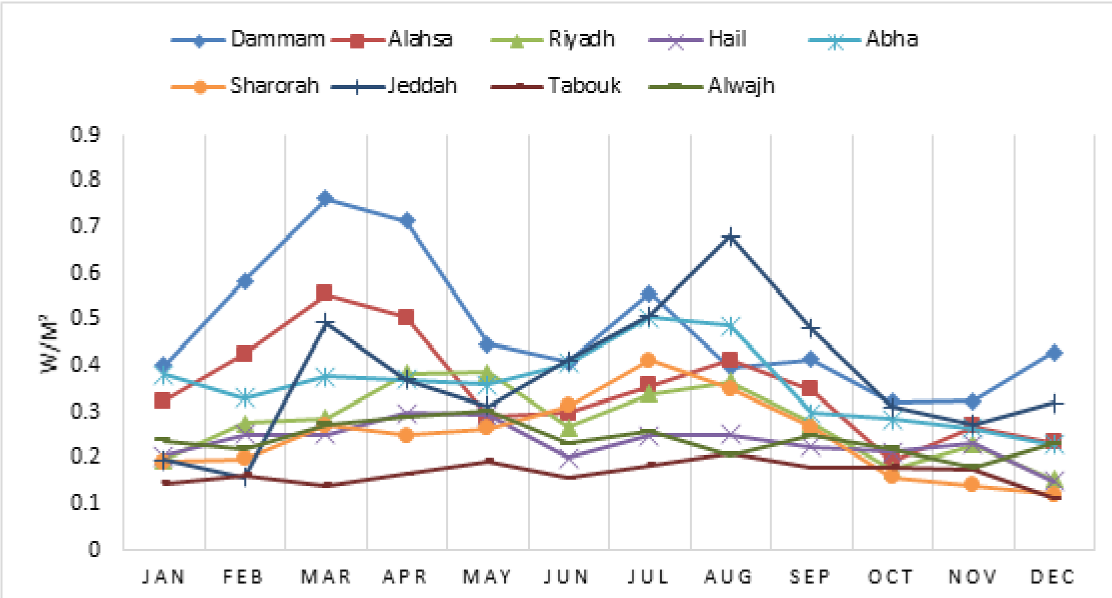
Unlike GHI, annual average daily DNI was much more variable across the stations in the nine cities, ranging from 4800 Wh/m² to over 7800 Wh/m². As previously shown in Figure 2.2, the annual DNI values are relatively higher in the northwestern and southwestern parts of Saudi Arabia. In the summer, the average daily DNI ranged from approximately 6500 Wh/m² (with an hourly DNI of 221 Wh/m²) to more than 9700 Wh/m² (with an hourly DNI of 404 Wh/m²), as indicated in Figure 2.9. In the winter, the average daily GHI ranged from circa 3500 Wh/m² (with an hourly DNI of 146 Wh/m²) to more than 6700 Wh/m² (with an hourly DNI of 280 Wh/m²).



Data source: Meteonorm, 2016

Figure 2.9 Summary of the average monthly mean hourly DNI in different cities in Saudi Arabia, 1992–2010

The scartering level of direct (DNI) due to clouds, aerosols, and other atmospheric constraints can be examined by comparing the daily mean values of diffuse (DHI) and global (GHI) (Vignola et al., 2012; Zell et al., 2015). Figure 2.10 shows diffuse fraction or the monthly mean daily ratio of DHI/GHI for the nine Saudi cities considered. The values ranged from 0.18 in Tabouk (in the northwestern part of the country) to 0.7 in Dammam (in the eastern part of the country). Coastal cities, such as Jeddah and Dammam, had the highest ratio due to the effect of humidity. Both cities in the northwest had higher DNI values and clearer skies due to the load diffusion factor. Northwestern sites were superior to eastern sites for concentrating solar technologies, although most regions in Saudi Arabia do have sufficient solar resources for the deployment of CSP technology.



Data source: Meteonorm, 2016

Figure 2.10 Summary of average monthly mean hourly DHI/GHI ratios in different cities in Saudi Arabia, 1992–2010

A report published by U.S. Department of Energy in 2010 provided an overview of cooling options and costs for a number of different CSP technologies along with the associated water requirements. The report suggested that these CSP technlgies consume the same or even slightly more water than coal-fired and nuclear power plants (Gastli & Armendariz, 2013, p. 7). As an example of large amounts of water required in CSP, Gastli and Armendariz (2013) evaluated the consumption for parabolic trough CSP:

> For instance, parabolic trough technology requires large amounts of water to condense steam, make up for the steam cycle, and wash mirrors. Current commercial technologies of water-cooled parabolic trough plant consume approximately 3m^3/MWh, of which 2 percent is used for mirror washing. For example, a 100MW parabolic trough power plant will need 300 m3/hour, 4,800 m^3/day and 1,752,000 m^3/year. This means a very large amount of water is required, which may create a challenge to the application of CSP power plants in the GCC region where water resources are very scarce.

Opting for CSP power plants with dry cooling technologies can mitigate the issue of water consumption for CSP cooling. Two technologies are currently implemented at a commercial level: solar tower (ST) and parabolic trough (PT). With a proven record of 12 billion kWh in operations, PT is more mature than ST (Agboola, 2015, p. 3). After conducting a detailed comparison of the two technologies, Cekirge and Elhassan (2015) concluded the following:

> ST systems are more efficient, at least 30 percent, land area per energy output is 20 to 30 percent in favor of ST systems, no pollutants or environmentally hazardous materials are utilized in ST systems, hence the energy produced to pollution ratio is much higher, Operating and Maintenance expenses are around 15 to 20 percent less in ST systems, Without heat storage sub-systems, ST systems require 15 to 20 percent less upfront investment when considering output based calculations of ST and PT plants, and with storage sub-system factored in, this figure is around 30 to 40 percent in favor of ST systems.

To evaluate the performance of the ST and PT technologies in Saudi Arabia, a hypothetical 215 MW CSP plant with a dry cooling system and eight hours of thermal energy storage (TES) was assumed to be built in northwestern part of the country (which is the region with the highest DNI values and lowest diffusion factor throughout the year). Steam turbines can be used to generate electricity from sunlight in ST and PT CSP plants, which can both generate electricity during nighttime hours using TES (Jorgenson et al., 2013, p. 9). Although the main steam turbine parameters are practically the same for ST and PT configurations, the solar collection method is different; as such, the hourly electrical energy may be significantly different from each system. Furthermore, as a result of towers operating at higher operating temperatures, PT turbine efficiencies tend to be lower than that of ST.. Figure 2.11 shows the seasonal and daily variations in the availability of solar resources and generated power for ST and PT in a 215 MW plant, using SAM analysis. It is noteworthy that the resource availability for ST was almost constant throughout the year, unlike PT (which exhibited a strong seasonal pattern). As shown in Table 2.1, ST generated 22% more power annually than PT, with a levelized cost of USD 0.125/kWh (which was USD 0.065/kWh lower than PT).

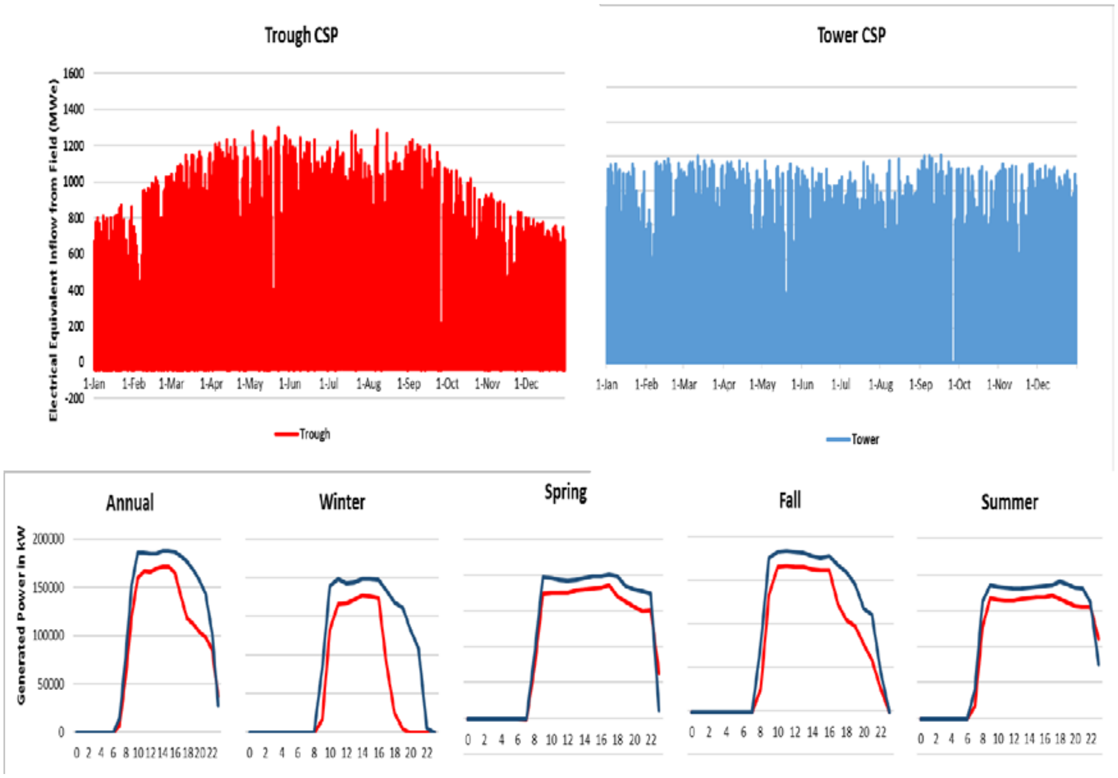


Figure 2.11 The variation in solar resources and power output for a hypothetical 215 MW ST and 215 MW PT CSP plant in Tabouk, Saudi Arabia: the seasonal (in the top) and average daily (in the bottom)

Table 2.1 Dry-cooled ST versus dry-cooled PT CSP simulation results with six hours of thermal storage at Tabuk, Saudi Arabia

CSP Technology	**Capacity (MW)**	**Annual Generation (GWh)**	**Capacity Factor (%)**	**LCOE (cents/kWh)**
Dry-cooled tower	215	913	55.8	12.52
Dry-cooled trough	215	745	44.0	17.92

The solar multiple (SM), which is a critical design parameter in CSP, normalizes the solar field size with reference to the power block. Jorgenson et al. (2013) explain the effect of different SMs on the performance of CSP:

> A system with an SM of 1 is sized for the solar collector to provide the power block exactly enough energy to operate at its rated capacity under reference solar conditions. A larger SM implies a larger solar collector area. For instance, a CSP plant with a power block rating of 300 MW and an SM of 2. Any electrical energy delivered from the solar field that exceeds the maximum thermal rating of the power block rating must be stored—or dumped for systems without storage. Excess energy from an oversized solar field (an SM greater than 1) can be sent to thermal storage and subsequently delivered to the power block resulting in a higher plant capacity factor.

Analyzing the impact of various SMs is therefore critical for identifying the optimal design of CSP at different thermal storage capacities. Increasing SM by considering TES can raise the utilization level of the power block, which in turn increases the capacity factor and lowers the LCOE of the plant as a whole. On the other hand, as the SM and TES capacity increase, the capital cost increases and LCOE is affected. As such, a tradeoff between energy storage, solar field size, and capacity factor exists. In this analysis, the SAM tool can be applied to determine the lowest LCOE for the optimal configuration. Figure 2.12 provides an example of ST CSP with various SM values and storage capacity levels to determine the least LCOE of the plant using SAM analysis. The analysis was again undertaken for a hypothetical CSP ST 215 MW plant in Tabuk, which is in northeastern Saudi Arabia. The minimal LCOE for a high-SM, high-storage plant – that is, 2.5 SM and TES of 12 hours – is demonstrated in Figure 2.12. This configuration would result in a higher capacity factor but generate almost a flat output, which would require a significant amount of the solar energy to be stored during sunlight hours and discharged at night. Such configuration can be effectively used to replace base-load fossil fuel-based generation. Furthermore, CSPs with lower SMs and storage (e.g. an SM of 2 and 8 hours of TES) can be utilized as intermediate and peaking generation.

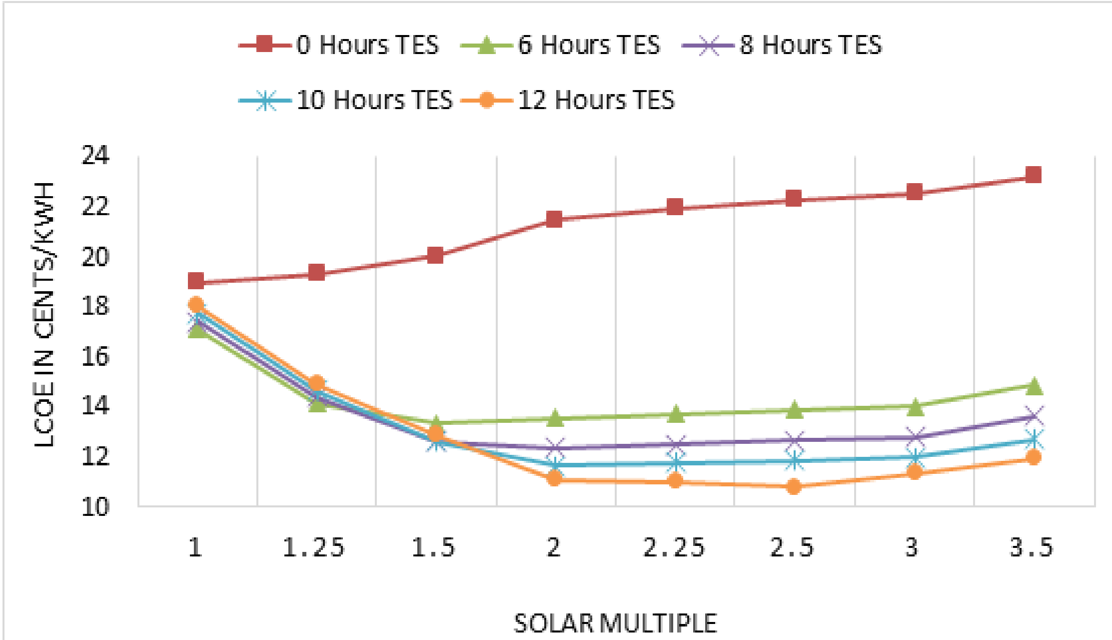


Figure 2.12 The size and cost of the solar field and power block determine the LCOE of a 215 MW ST CSP project, measured over the plant's lifetime

In addition, CSP can also be effectively used in Saudi desalination plants to produce water efficiently and reduce these facilities' current reliance on oil and gas. The scarcity of water has triggered Saudi Arabia to install massive seawater desalination facilities and made it the largest producer of desalinated water in the world (Aljarboua, 2009, p. 1). Baras et al. (2012) explored the possibility of deploying water and power production (cogeneration) plants using CSP. Their research concluded that such plants showed an economic promise of the CSP application in seawater compared to conventional fossil fuel-powered desalination plants and will result in saving Saudi Arabia's natural resources (Baras et al., 2012, p. 5). In the proposed desalination plants, CSP is the optimal choice for desalination coupling with two types of desalination technolgies (MED and RO), as explained by Al-Qaaraghouli and Kazmierski (2012):

> In a CSP/MED plant, the needed temperature of the supplied heat should be around 70 degrees C; therefore, there is sufficient energy in the turbine exhaust to provide this heat. In a CSP/RO plant, the CSP system could provide electricity to run the pumps of the RO unit and some low-temperature heat from the turbine exhaust to raise the temperature of the feed water to the unit to improve the performance of the membrane, which results in reducing the RO unit power consumption.

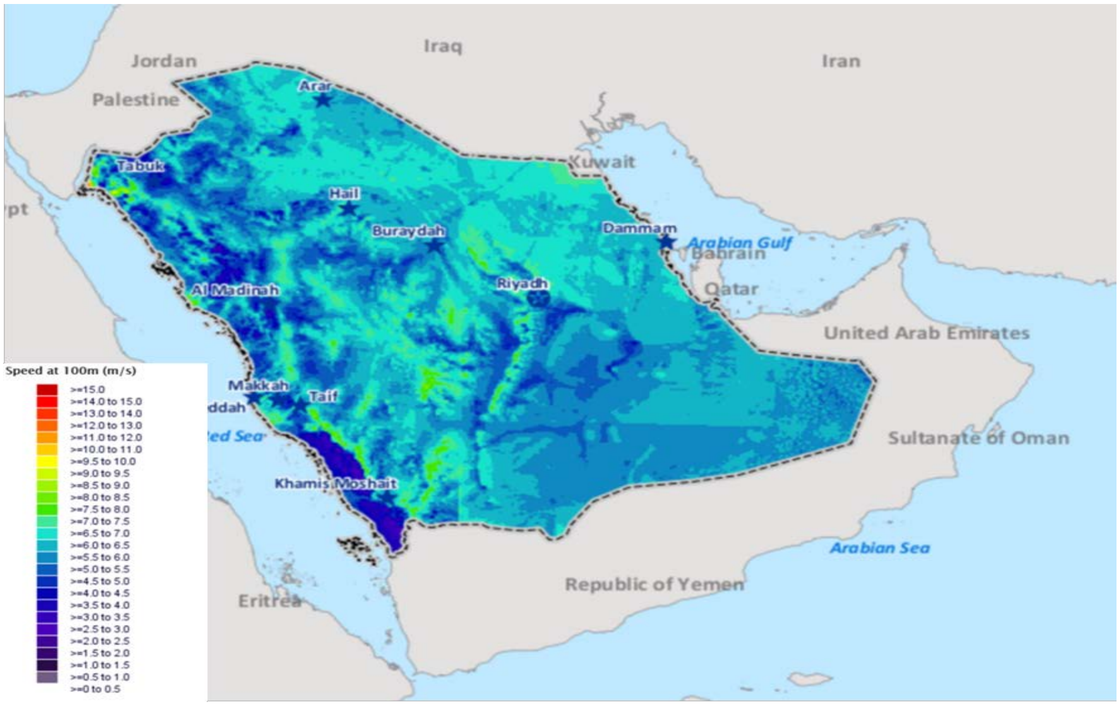
Unlike other thermal desalination technologies, RO operates with the lowest electricity requirements (i.e. 3.5 kWh/m^3 for the Red Sea and 4.5 kWh/m^3 for the Arabian Gulf). The low energy requirements of RO in comparison with thermal desalination technologies are due to the latter's heat (steam) requirements, such as MED (Moser, Terib, & Fichter, 2013, p. 123). Furthermore, the production cost associated with RO technology is lower than for all other desalination technologies (Al-Qaraghouli & Kazmierski, 2012, p. 6). After assessing the cost of CSP/MED and CSP/RO technologies, Moser, Terib, and Fichter (2013) concluded that the levelized water cost in RO plants was either lower than or equal to the cost in MED plants at three geographical locations (namely the Mediterranean Sea, the Red Sea, and the Arabian Gulf) when located in regions with a good DNI irradiation (i.e. 2,400–2,800 kWh/m^2/y).

2.1.2 Wind Energy Technology

Researchers have conducted several studies to assess the feasibility of installing wind turbines in different locations in Saudi Arabia. In many areas of the country, the annual mean wind speed exceeds 4 m/s at 20 m height. Wind energy is found to be sufficient for electricity production at 1,789 annual full load hours. As such, wind energy is believed to be economically feasible. Wind energy potential has been estimated to generate 20 TWh/year of renewables (Bachellerie, 2012, p. 138). According to Welch et al. (2008, p. 8):

> We find that because of the convergence of improved technology, greater efficiency, and with the increasing cost of traditional, competing sources such as oil and natural gas, wind energy is close to becoming self-sustaining financially without the extensive federal government support that exists today.

Figure 2.13 illustrates wind speeds at 100 m in Saudi Arabia. The western and central areas have the highest wind speed, ranging from 8 to 9 m/s. Such speed can facilitate wind power generation with a capacity factor of more than 50%. Figure 2.14 shows the Kingdom’s normalized hourly and monthly wind generation profile.



Data source: K.A.CARE, 2016

Figure 2.13 Wind speeds at a height of 100 m in Saudi Arabia

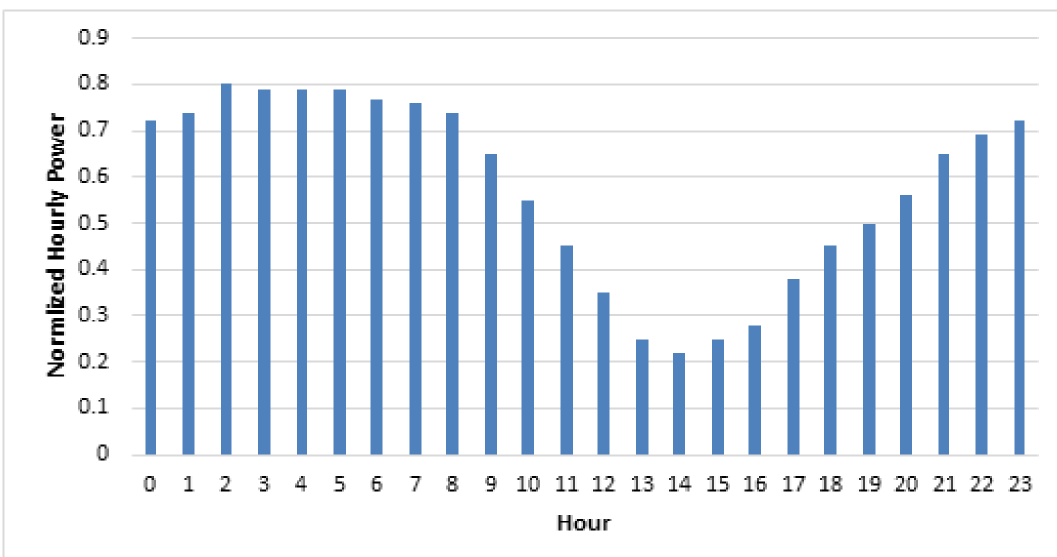


Figure 2.14 Normalized hourly wind generation output in Saudi Arabia (with an average wind of 8–9 m/s)

2.1.3 Nuclear Energy Technology

Saudi Arabia is also attracted to nuclear energy due to its perceived benefits of lower carbon emissions than fossil fuel generation, low operating costs, greater reliability, and cheap fuel price. Many policymakers and industry analysts consider nuclear power the best alternative to costly fossil-fuel technologies, while others perceive the technology as risky. For instance, "Denmark and Germany do not consider nuclear as an option, while France still expects to provide a significant share of electricity from nuclear power plants" (Meeus, 2011, p. 8). Such policy fragmentation extends to the decision as to whether to categorize nuclear technology as a form of sustainable energy. This dissertation agrees with Jacobson and Delucchi (2011) of pursuing a "portfolio of solutions for stabilizing atmospheric CO_2 including increasing the use of renewable energy and nuclear energy, decarbonizing fossil fuels and sequestering carbon, and improving energy efficiency" for a more resilient grid (Jacobson, 2010, p. 1). On the other hand, Scheer (2004) excludes nuclear from the new "solar economy system" because it is derived from the fossil fuel uranium. Klare (2013, p. 27) argues that the Fukushima nuclear plant disaster (March 11th, 2011) impacted Japan's electricity generation and changed strategies for nuclear expansion around the world:

> Although there is no likelihood that nuclear power will disappear from the world's energy portfolio, once-lofty notions of a "renaissance" in nuclear power seem to have evaporated. In early 2011, prior to the Fukushima disaster, the EIA predicted that net output of the world's power reactors would grow by 89 percent between 2008 and 2035, but this projection now appears wildly optimistic.

Saudi Arabia has a preliminary plan to invest circa USD 112 billion over the next 20 years in building approximately16 nuclear power reactors capable of generating 17 GW of electricity (Farnoosh et al., 2014, p. 7). These reactors will be most likely be located along the Arabian Gulf or the Red Sea. This analysis thus modeled a gradual addition of 17 GW of generation capacity from nuclear energy by 2040.

2.1.4 Other Renewable Energy Technologies

Other renewables, such as geothermal energy potential, do exist in Saudi Arabia (Alnather, 2006). As geothermal wells can be exhausted over time, Farnoosh et al. (2013) asserted that geothermal technology is not a totally renewable source. These geothermal resources can be classified as hydrothermal and dry rock. Due to the high capital cost of exploiting geothermal energy in comparison to fossil fuel-based generation, Alnatheer (2006) argued that it is not economical, even when compared with other renewable energy sources (i.e., solar and wind energy sources). Based on these considerations, integrating geothermal energy into the future energy mix in Saudi Arabia was not considered in this research.

2.1.5 High Efficiency Fossil Fuel-Based Generation Potential

Reducing the reliance on oil and gas for generating electricity by investing in renewable energy sources is a major factor in resolving Saudi Arabia's energy consumption problem and realizing economic, environmental, and social benefits for the country. Increasing generation efficiency is another factor that can substantially help to reduce fuel consumption. As explained in Chapter 1, efficient CCGTs accounted for only 14% of total Saudi generating capacity, while old steam and gas turbines contributed the rest of generating capacity in 2014. According to current electricity generation and fuel consumption figures, these facilities have an average power generation efficiency of 32%; in comparison, the world average is 35% (IEA, 2012). Investing in today's best available efficient technologies may therefore be one vehicle to promote efficiency and reduce both fuel consumption and environmental impacts. In a speech reported by state media, the CEO of the SEC, Ziyad Al-Shiha, said that Saudi Arabia will save around 200 million barrels of liquid fuel annually as a result of switching its power stations to more efficient CCGT (Reuters, 2014a).

2.2 Demand-Side Potential in Saudi Arabia

One key IRSP implementation process is to technically and economically quantify the potential of demand-side alternatives, which is required for designing an integrated supply-side and demand-side plan that meets the cost minimization criteria, taking into consideration environmental and social benefits maximization. The primary focus of such an analysis is on energy efficiency capable of minimizing the total consumption of energy. Nonetheless, many energy efficiency measures, such as raising cooling system efficiency, do in fact provide peak reduction. Nachet and Aoun (2015) highlighted the great potential to yield rapid, cost-effective outcomes in the Saudi context using energy efficiency measures:

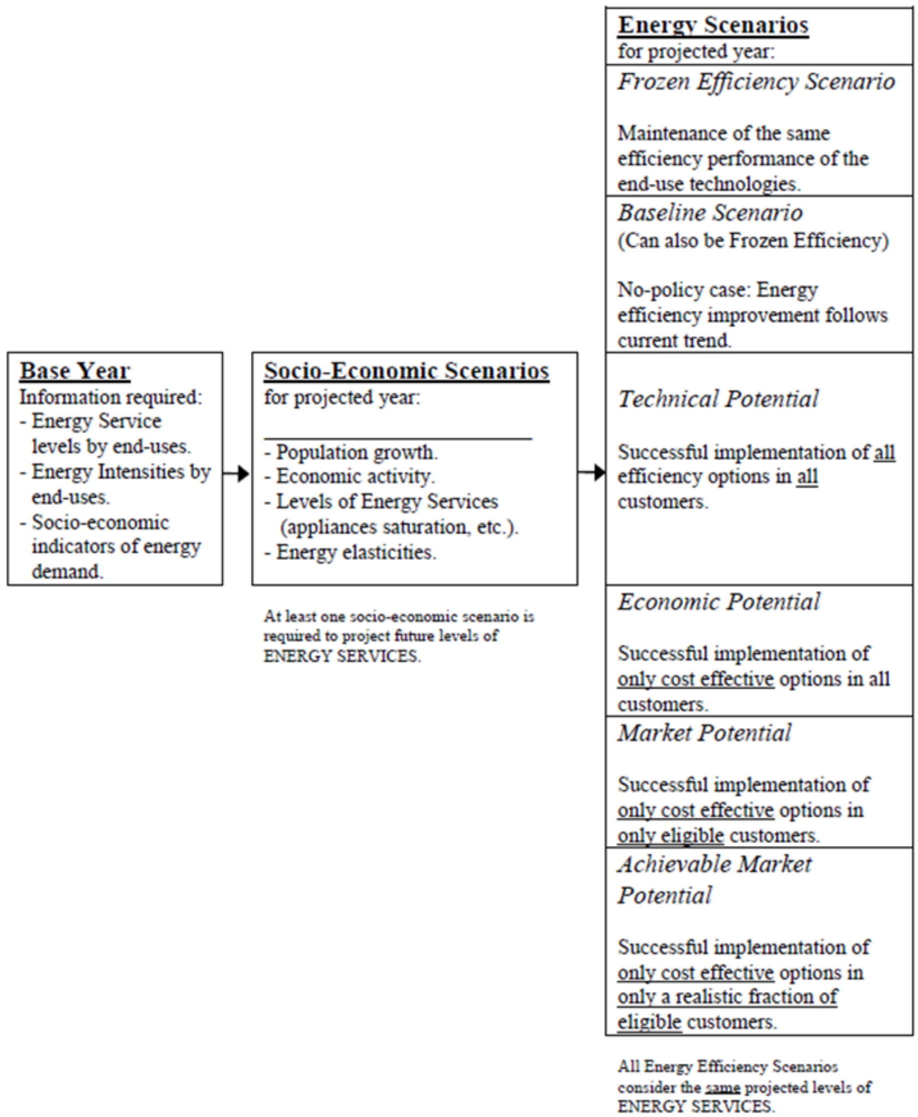
> Achieving greater energy efficiency would allow Saudi Arabia to divert some of the $100 billion in planned capital investments in the domestic power sector over the next decade to other sectors or applications, such as renewable energy. Also, many energy efficiency measures can pay for themselves in form of reduced energy costs that compensate the investment associated with the deployed efficiency measures.

This analysis also focuses on load management (LM) and demand response (DR) measures that are designed to reduce peak consumption but with little or no impact on the current level of net energy consumption. In this chapter, it has been assumed that total consumption will not change due to LM/DR measures. Faruqui and Hledik (2011) provide two justifications for this assumption:

> First, LM/DR programs are typically utilized for a limited number of times per year (typically only around 100 hours). As a result, even if the peak reductions are quite large in the hours for which they are called, they are small relative to total consumption over the course of the entire year. Second, LM/DR programs often reduce consumption during peak hours, but cause an increase in consumption during off-peak hours. As a result, even the small reductions that are realized at peak times are offset by these off-peak increases.

2.2.1 Scenario-Based Projection Framework

Figure 2.15 summarizes the scenario-based projection framework required to quantify the DSM potential resources. This potential is identified by calculating the difference between frozen/baseline energy efficiency performance and enhanced energy efficiency performance. The framework steps require the development of four main scenarios: (1) the frozen energy efficiency scenario, (2) the technical potential scenario, (3) the economic potential scenario, and (4) the market potential scenario (Swisher, Jannuzzi, & Redlinger, 2007, p. 48). In this section, the focus is on quantifying the demand-side potential in Saudi Arabia by exploring these scenarios. However, a detailed demand forecasting model, along with its results and analysis, is presented in Chapter 3, to project demand in the future for all sectors and various scenarios in Saudi Arabia.



Source: Swisher, Jannuzzi, and Redlinger, 2007, p. 48

Figure 2.15 The steps in projecting energy demand -side management scenarios in the scenario-based projection framework

2.2.1.1 The Frozen Energy Efficiency Scenario

The first step in this framework is to develop a forecast for the frozen energy efficiency (FEE) scenario. This scenario makes an abstraction of new load requirements by assuming that historical factors and their relationship to GDP, population, and number of households from 1992 to 2014 will continue into the future (Swisher, Jannuzzi, & Redlinger, 1997, p. 28). End-use efficiency enhancements are not incorporated in the projection for this scenario. Therefore, present energy efficiency remains constant. Since IRSP has not been a common practice in Saudi Arabia, it is possible that the results achieved under this scenario will be in line with the formal forecasts.

2.2.1.2 The Technical Potential Scenario

This scenario, which is the second step in the framework, considers all the possible technical energy efficiency improvements that can be considered in the annual projection in relation to all equipment, buildings, and processes. This scenario can address the potential savings that either could be realised through the instant transformation of all systems or by replacing gradualy the current systems with systems greater in efficiency. Swisher, Jannuzzi, and Redlinger define technical energy efficiency potential as:

> The improvement in end-use energy efficiency that could result if the most efficient technologies known today were to attain 100% market saturation during one lifetime of the technologies (10-20 years).

The technical potential of any energy efficiency measure can be defined using the following formula:

$$\text{EE Technical Potential (TP)} = \text{S x EEM x P} \quad (2.1)$$

Where S is the energy efficiency savings expressed as kWh or kW per unit, EEM is the quantity of energy measure units in the building, and P is the customer population.

2.2.1.3 The Economic Potential Scenario

Only energy efficiency (EE) measures that are cost effective need to be considered in the economic potential scenario, which is the third step in the framework. Swisher, Jannuzzi, and Redlinger highlighted the importance of economic screening in the IRSP:

> This threshold tests whether a given measure is considered profitable to society, consumers, the utility, or another agency performing the IRP. Costs of competing supply-side alternatives are taken into account, and environmental and other external costs can be included. Thus, the economic energy-efficiency potential is the energy efficiency improvement that would result from maximum use of cost-effective technologies.

2.2.1.4 The Market Potential Scenario

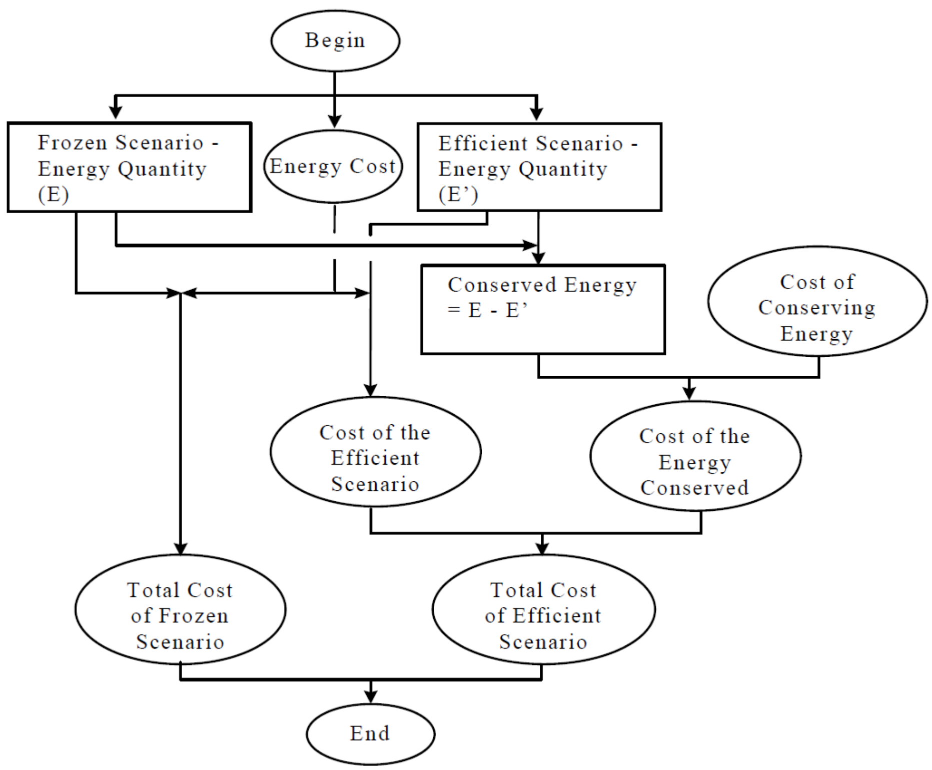
As implementing all cost effective measures via DSM and other EE programs is not feasible, the market potential scenario (which is the fourth step in the framework) captures the perceived amount of savings that will be practically realized. The achievable market potential addresses only a portion of the total market potential over time, based on the estimated market acceptance rates (Swisher, Jannuzzi, & Redlinger, 2007, p. 48). The achievable market potential of any EE measure can be defined using the following formula:

EE Achievable Market Potential (ATP) = Cost Effective EETP x AR (2.2)

Where EETP is cost-effective EE technical potential and AR is the estimated market acceptance rates.

2.2.1.5 Evaluation of DSM Cost Effectiveness

Figure 2.16 presents a flow chart that illustrates how the cost of alternative efficiency scenarios can be compared with the FEE scenario, since these scenarios have their own specific estimated projected energy demands, DSM/efficiency initiative implementation, and subsequent new energy supply investment.



Source: Swisher, Jannuzzi, and Redlinger, 2007, p. 49

Figure 2.16 Flow chart for evaluating energy efficiency alternatives

Among various screening tests, the total resource cost (TRC) test is considered in this research in analyzing various EE scenarios in Saudi Arabia. Since this test offers clarity as to whether there is a reduction in ratepayer and utility total costs, this test is the most commonly-adopted approach taken to determine the cost-effectiveness of DSM. Swisher, Jannuzzi, and Redlinger (2007, p. 55) define this test as follows:

> The Total Resource Cost (TRC) Test (also called the All Ratepayers Test) compares the total costs of a DSM program (including costs incurred by the utility and participant) and the avoided costs of energy supply. From this perspective, a program is cost effective if benefits, that is the total avoided supply costs, exceed the total costs incurred by the utility and the customer.

A benefit-cost (B/C) ratio is calculated to determine the economic attractiveness of each DSM measure. As shown in the following formula, three factors are taken into consideration: the measure's electricity savings, the marginal supply-side avoided costs resulted from the load profile change, and the measure's cost.

$$\text{Benefits-Cost (B/C) Ratio} = \frac{\text{Saving of EE measure X Marginal Supply\_Side Cost}}{\text{Cost of EE Measure}} \qquad (2.3)$$

Supply-side avoided costs, which include transmission line costs and generation costs, were calculated at two levels in the form of $/MWh. These costs represent the demand savings achieved through the use of EE measures (see Fig. 2.15). The first of the two levels is the market-based avoided electricity costs, which are determined by global oil prices. The second of the two levels is the current-based avoided electricity cost, which is determined by 2016 oil prices in Saudi Arabia. These costs were calculated for the FEE and high energy efficiency (HEE) scenarios (based on the estimated achievable market potential) for the period 2017–2040 using the EWS IRSP model for Saudi Arabia developed in this dissertation. The higher avoided electricity cost is included to assess the EE measures in Saudi Arabia in comparison to those in other countries (Faruqui & Hledik, 201, p. 104). The annual energy savings for every measure were multiplied by all appropriately avoided costs per year before discounting the savings based on the present-value equivalent in order to calculate the costs.[21] The avoided electricity costs for the two levels are calculated to be USD 247/MWh and USD 62/MWh, respectively. Moreover, the avoided cost of reducing generation capacity (peak), including transmission and distribution costs, was assumed to be USD 726/kW.[22] These capacity costs were used in the economic evaluations of LM/DR measures.

2.2.2 The Current Status of Energy Efficiency Standards in Saudi Arabia

In relation to air conditioners (ACs) sold in the domestic market, current Saudi standards require all units to meet a specific minimum energy efficiency ratio (EER), namely 9.5 Btu/watt for window ACs and 11.5 for split-cycle ACs; this represents an increase from the current average of approximately 7.5 (SASO 2663, 2014, p. 8). Table 2.2 compares the current average EER values of Saudi Arabia with those of

[21] A social discount rate of 3% was used in the analysis. Further details will be provided in Section 4.2.2 about the rational of using discount rate.

[22] In its modeling for peaking units, The U.S. EIA considers an estimate of USD 666/kW. Faruqui and Hledik (2011, p. 52) also explored utilities on the US East Coast and discovered marginal costs driven by peak demand to be over USD$60/kW. For the purpose of validating these values, the EWS IRSP model for Saudi Arabia was used to check the cost savings in peak generation installations associated with implementation of DSM measures; the results were found to be fairly close to this assumption (i.e. circa USD 748/kW).

other countries/regions. The Kingdom's values are the lowest; at a high temperature (i.e. 46 degrees C), its EER even drops to 5.4 (Al-Shaalan, 2012, p. 441).

Table 2.2 EER values in Saudi Arabia and other major countries/regions

Country/region	**EER (BTU/Wh)**
Saudi Arabia	7.5
China	7.8
Europe	8.9
United States	9.8

Source: Al-Shaalan, 2012, p. 442

Saudi standards have been extended to cover lighting and white goods as well as building insulation as of 2017.[23] The EERs for all ACs are also raised to a value of at least 12 by the end of the modeling timeframe in this scenario. All new residential buildings are required to have roof, wall, and window insulation. The Saudi Energy Efficiency Program (SEEP) will start mandating new thermal insulation regulation for residential buildings effective January 2017 (SEEP, 2015, p. 17).[24] White goods improve their efficiency over time, as they reflect changes across a number of different end-use types (e.g., refrigeration and washing machines). Lighting improves substantially through the adoption of LED technologies.

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[23] White goods refer to consumer durables such as air conditioners, refrigerators, stoves, etc. (businessdictionary, 2017)

[24] The new thermal insulation regulation sets the minimum thermal resistivity requirements (known as U-values) for new-rise residential buildings. Depending on the climate zone, U-values for roofs range from 0.2 to 0.27 while U-values for walls range from 0.34 to 0.45.

2.2.3 Energy Efficiency Measures in the Residential Sector

Since the residential sector accounted for approximately 50% of Saudi electricity consumption in 2014 (SEC, 2015), this research utilizes an end-use model to investigate DSM improvements instead of econometric models. Swisher, Jannuzzi, and Redlinger (1997, p. 29) emphasized the advantage of employing end-use demand models to study DSM improvements:

> End-use projection models (or engineering models) are much more detailed than econometric models, though their analytical formulation can be quite simple. The end-use approach is very well-suited to the purposes of energy efficiency projections because it is possible to explicitly consider changes in technology and service levels.

The annual end-use demand can be calculated as follows:

$$\sum_{i=1}^{n} N_i \, P_i M_i I_i \qquad (2.4)$$

Where N_i is the quantity of customers qualified for end-use *I*; P_i is the penetration (total units/customers) of end-use *I*; M_i is the degree to which end-use *I* is used; and I_i is the energy intensity of energy service *i*.

The final report published in 2008 by Saudi Arabia's National Energy Efficiency Program (NEEP) is the only available source for input data for end-use models in the country. This input was gathered based on surveys completed by various types of households in different regions in Saudi Arabia. Although the data is eight years old, it is expected to still be valid as few demand-side initiatives have been implemented in recent years. As shown in Table 2.3, the NEEP has classified residential users into low (L), medium (M), and high (H) categories based on their consumption ranges. This table reveals that almost 95% of the residential users consume 76% of total electrical energy utilized by the residential sector in Saudi Arabia, while less than 5% of the users consume the remaining 24%.

Table 2.3 Breakdown of residential energy users and electricity consumption per category

Consumption Range (kWh/Month)	**% of Customers**	**% of Consumption**
1 to 5000 (L)	95.40	76.30
5000 to 10000 (M)	4.00	14.10
>10000 (H)	0.60	9.70

Data source: NEEP, 2008, p. 134; SEC, 2007

Table 2.3 shows the breakdown of electrical consumption for each of the three categories stipulated in Table 2.2. DSM measures are categorized based on end-use, with five main categories: space cooling; building envelope measures (including insulation and high-efficiency windows), lighting, water heating; and appliances (Faruqui & Hledik, 2011). For the purpose of DSM improvement investigation in this chapter, it was assumed that the same consumption pattern would continue in the future and that shares of electricity consumption per category would remain constant.

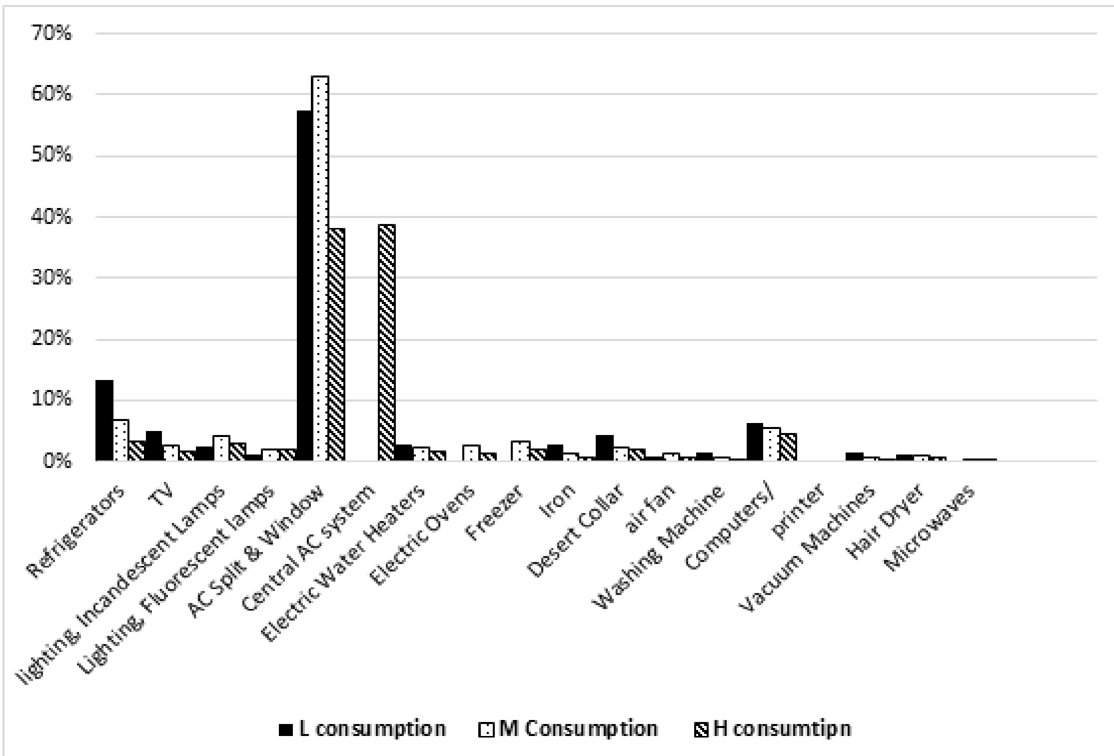
Table 2.3 Estimated electrical consumption for different consumption categories in Saudi Arabia[25]

Appliance	Quantity/Category			Watt /Unit	Hour/ year	Annual Consumption (kWh/year)		
	L	M	H			L	M	H
Refrigerators	1.00	2.00	3.73	440	5519	2428	4857	9057
TVs	1.55	3.28	7.40	220	2628	896	1896	4278
Lighting, incandescent lamps	3.50	23.10	63.10	66	1971	455	3005	8208
Lighting, fluorescent lamps	2.68	18.70	62.95	32	2628	223	1557	5241
AC (split & window)	1.17	5.16	11.81	2200	4082	10508	46343	106069
AC (central systems)	0.00	0.00	3.00	8800	4082	0	0	107775
Electric water heaters	0.68	2.42	5.81	2200	324	485	1725	4141
Electric ovens	0.00	1.00	2.00	2640	690.3	0	1822	3644
Freezers	0.00	1.00	2.23	440	5518	0	2428	5415
Irons	1.00	2.00	3.56	1320	374.4	494	988	1759
Desert cooler	1.00	2.25	6.90	264	2916	770	1732	5312
Fans	0.76	4.88	9.34	132	1458	146	939	1798
Washing machines	1.00	2.00	3.00	660	421	278	556	834
Computers/ printers	0.66	2.36	7.03	2648	657	1148	4107	12230
Vacuum cleaners	1.00	2.00	3.47	1760	164	289	579	1003
Hair dryers	0.72	2.30	5.91	880	329	208	665	1708
Microwaves	0.00	1.00	2.32	1760	137	0	241	556

Data source: NEEP, 2008, p. 167

[25] The consumption of watt/unit and hour/year for all appliances has been slightly adjusted to meet the actual residential demand for the reference year of the survey (namely 2007). For example, many studies suggest that the annual average consumption of split and window AC units in Saudi Arabia does not exceed 9000kWh (Abdul-ur-Rehman, Al-Sulaiman, Budaiwi, & Shakir, 2015; Alrashed & Asif, 2015).

Figure 2.17 clearly shows that air conditioning is the primary energy consumer in Saudi houses in general; regardless of the level of consumption, it represents 60–66% of the total annual energy consumption for each housing category. Most households have split or window AC units; only a small percentage (16.7%) have central air conditioning.



Data source: NEEP, 2008, p. 167

Figure 2.17 Percentage of consumption of each appliance consumption categories in Saudi Arabia’s residential sector

As shown in Equation 2.4, the number of households is critical for calculating the demand and analyzing the demand-side measures in the end-use (engineeringoriented) model for the residential sector. In this sector, the level of energy services depends on several factors, including the number of customers eligible for end-use (Swisher, Jannuzzi, & Redlinger, 1997, p. 29). As the literature review did not reveal any published projections concerning the number of Saudi households in the future, an econometric model based on population and GDP projections was created to forecast this figure (see Table A.1 in Appendix A). While GDP was expected to be a significant explanatory factor, it was found to be statistically irrelevant when combined with the population. Figure 2.18 shows both the historical trend and future forecast in relation to the number of Saudi households.

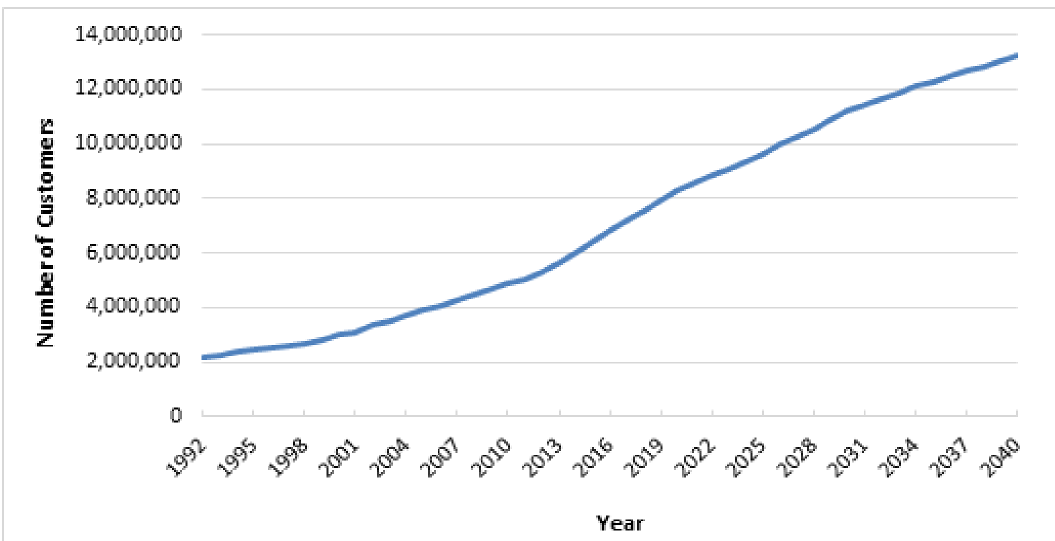


Figure 2.18 Households in Saudi Arabia: Historical trends and future projections, 1992–2040

Market acceptance rates (AR), lifetime (LT), costs and energy savings are the key characteristics assigned to the measures, as shown in Tables 2.4 and 2.5.

Adjustments were carried out in accordance with the higher temperatures experienced in Saudi Arabia when dealing with cooling, building and other end-uses impacted by the weather (Faruqui & Hledik, 2011, p. 101).[26] The electric savings over baseline for each measure was calculated using different references, such as the California Database for Energy Efficient Resources (DEER), the Database of Energy Efficiency Measures (DEEM), the LoadMAP Energy Efficiency Potential Study tool (a proprietary database owned by Global Energy Partners), and U.S. Green Buildings Council's LEED New Construction & Major Renovation database (Faruqui & Hledik, 2011, p. 100).

[26] The AR used by Faruqui and Hledik (2011) was obtained from a popular report created in partnership between Global Energy Partners and the Brattle Group entitled, "Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the U.S.", published by the Electric Power Research Institute in January 2009. In this analysis, the ARs for cooling and building EE measures have been adjusted by assuming a gradual increase over the planning period until reaching 100% and 75% respectively.

Table 2.4 Input data for cooling EE measures evaluations in the residential sector

End-Use	Energy efficiency measure	Unit	LT (in years)	Electric savings over baseline (%)	Overall per EE cost (SR/unit)	Type of cost [27]	AR (%)
Cooling	Central AC, high efficiency.	Each	14	30	4,708	I	100
Cooling	Split AC, high efficiency	Each	14	30	2,354	I	100
Cooling	Room AC, high efficiency	Each	14	30	1,348	I	100

Source: modified from Faruqui and Hledik, 2011, pp. 101&116

[27] (I) represents the incremental cost adopted in scenarios wherein decisions are made upon the purchase and installation of either current or high-efficiency unit. (F) represents the total cost used for scenarios wherein the measure is used alongside an existing end-use.

Table 2.5 Input data for other EE measures evaluations in the residential sector

End-Use	Energy efficiency measure	Unit	LT (in years)	Electric savings over baseline (%)	Overall per EE cost (SR/unit)	Type of cost	AR (%)
Building	Insulation, ceiling	ft² of roof area	50	9	6	F	75
	Insulation, wall cavity	ft² of wall	50	7	0.03	F	75
	Windows, high efficiency	ft² of window area	25	8	70	I	75
	Windows, shading	ft² of window area	10	10	49	F	49
Lighting	LED lamps	Each	10	88	99	F	100
Water heating	Pipe-hot water,	Each	15	1	117	F	100
	Water heater, tank	Each	15	2	180	F	100
	Water heater, electric,	Each	9	2	873	I	100
Appliance	Washing machine,	Each	12	9	3,224	I	94
	Dishwasher, higher	Each	12	3	496	I	49
	Home office equipment,	Each	4	1	46	I	100
	Range and oven,	Each	18	1	617	I	44
	Refrigerator/ freezer,	Each	14	2	710	I	99
	TVs and home electronics,	Each	11	0.30	12	I	97

Source: modified from Faruqui and Hledik, 2011, pp. 101&116

Based on the data inputs described above, energy savings technical, economic and, market potential of residential EE measures will be presented in the following sections.

2.2.3.1 Energy Savings Technical Potential of Residential EE Measures

Figure 2.19 illustrates the Saudi residential market analysis for 2017-2040. These predictions were made using the aforementioned method. Building insulation and cooling measures accounted for 90% of total technical savings potential in the residential sector. These savings were attributed to the low-efficiency cooling systems and poor building insulation currently being used. The energy savings potential associated with lighting systems was high, especially if LED lamps are used widely during the planning period (2017–2040).

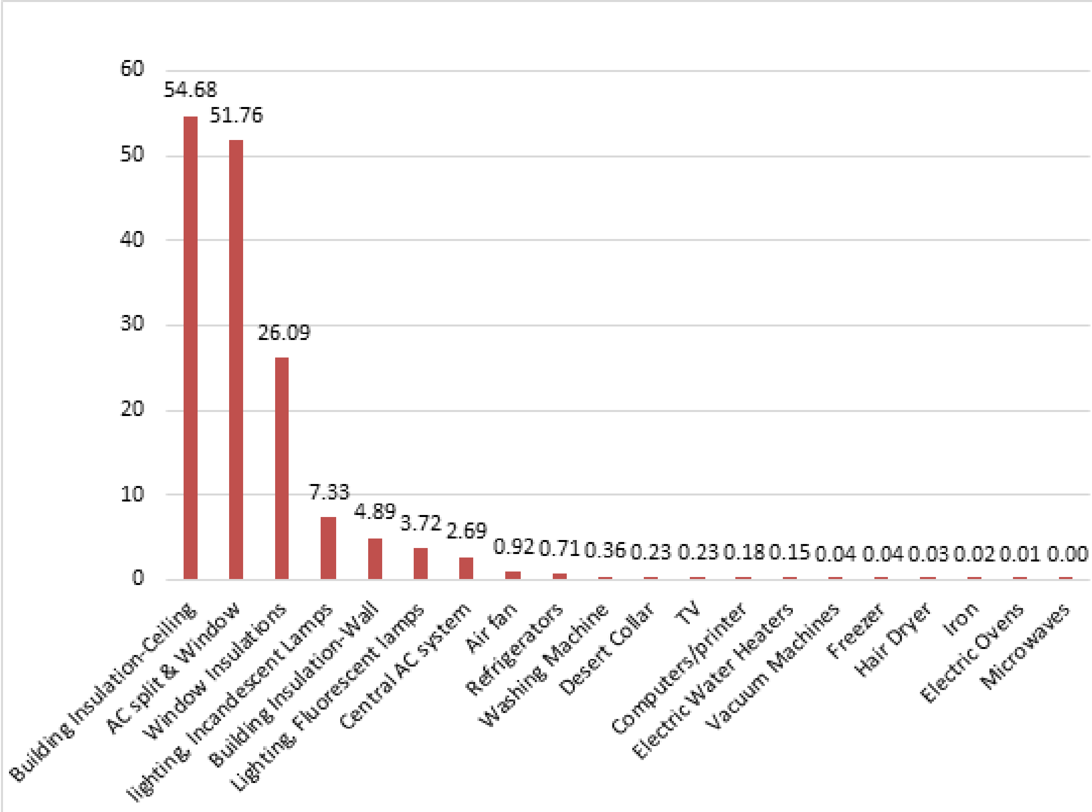


Figure 2.19 Technical potential of residential EE measures, 2040 (in TWh)

2.2.3.2 Economic Potential of Residential EE Measures

Figure 2.20 presents the B/C ratios of the residential EE measures included in Table 2.3. Cooling and building energy measures emerged as cost-effective for Saudi Arabia (even at avoided electricity cost), due to the current subsidized fuel prices. This was attributed to the high peak demand reduction contributions from cooling and building insulation measures. Nonetheless, some appliances were not found to be cost-effective measures (e.g., washing machines and microwaves) due to the high incremental costs involved in enhancing the efficiency levels of such equipment.

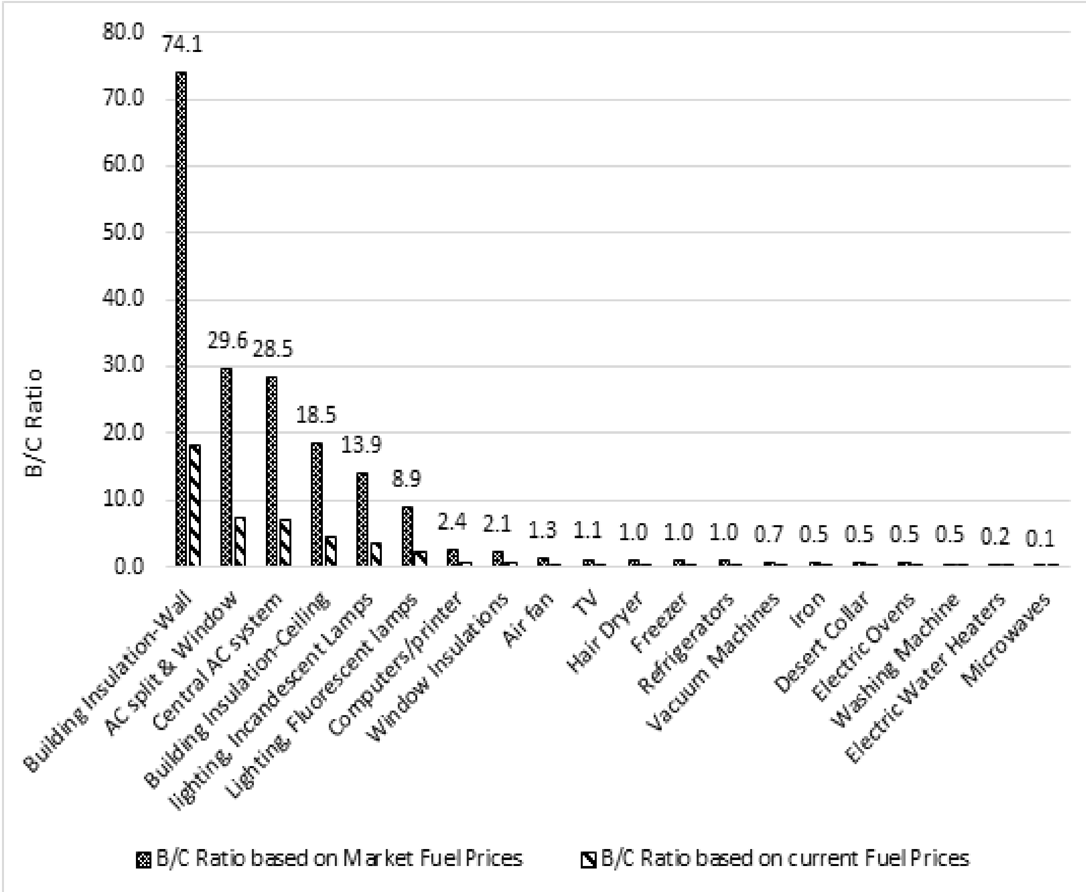


Figure 2.20 B/C analysis results for residential EE measures, 2040

Figure 2.21 indicates the levelized costs associated with all measures in the residential sector. The analysis revealed that the major potential EE measures have a levelized cost that is significantly lower than the electricity retail rate (circa USD 0.04/kWh).

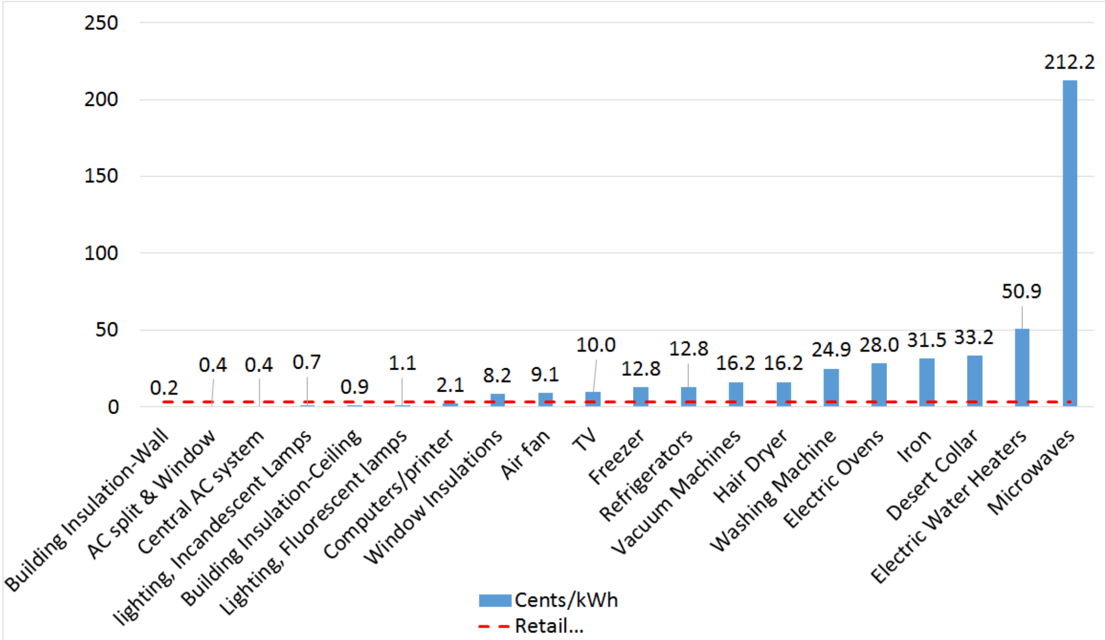


Figure 2.21 Levelized costs for residential EE measures (in cents/kWh)[28]

2.2.3.3 Market Potential of Residential EE Measures

Figure 2.22 indicates a market potential of 133 TWh by 2040 for the residential EE measures. Due to the expected implementation of cooling and building standards (as mentioned in Section 2.2.2), it is anticipated that residential EE cooling measures (in cooling and building) will represent more than 88% of the achievable market potential by 2040.

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[28] Levelized costs for efficient microwaves (not shown in Figure 2.29) was found the most expensive EE measures with 212 cents/kWh.

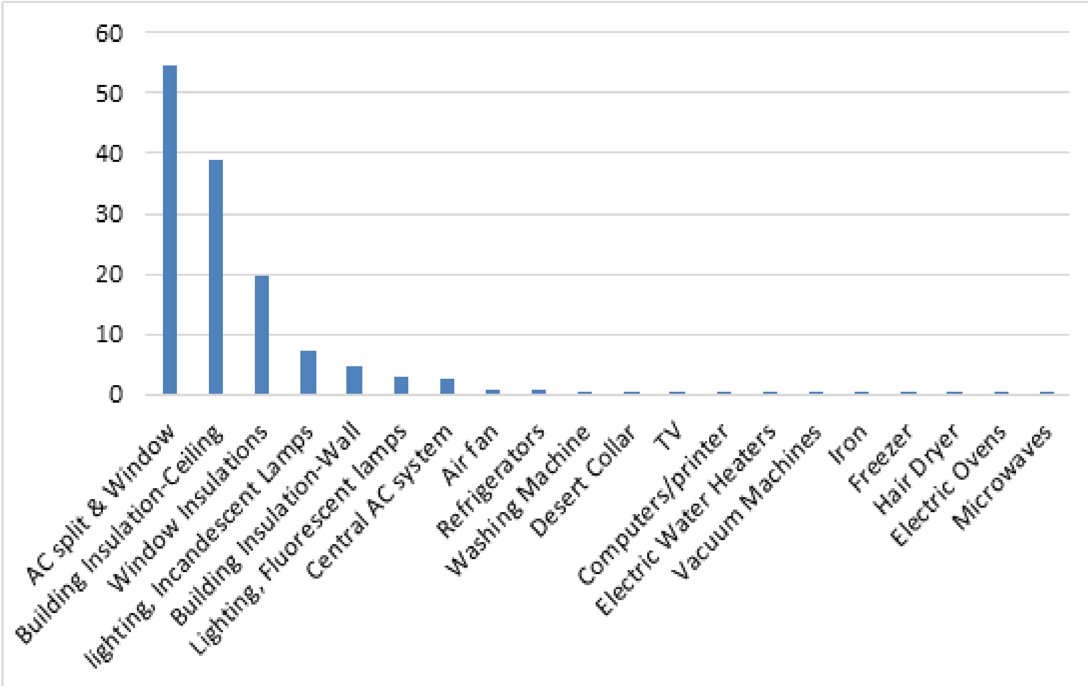

Figure 2.22 Market potential of residential EE measures, 2040 (in TWh)

2.2.4 EE Measures in the Commercial, Governmental, and Industrial Sectors

Since no end-use model is available for commercial, governmental, and industrial sectors, Faruqui and Hledik's (2011) analysis of each EE measure's share of electricity savings in the total energy consumption of each sector was used in the current analysis. As shown in Equation 2.4, the number of customers is critical for calculating the demand savings and analyzing the demand-side measures in these three sectors. As the literature review did not reveal any published projections concerning the future number of customers for these three sectors in Saudi Arabia, econometric models have been created to forecast these figures (see Figure 2.23). The details of these models are shown in Appendix A. Table 2.5, Table 2.6, and Table 2.7 show an example of input data used in analyzing the EE measures in the commercial sector; relevant input data has been used for the governmental and commercial sectors.

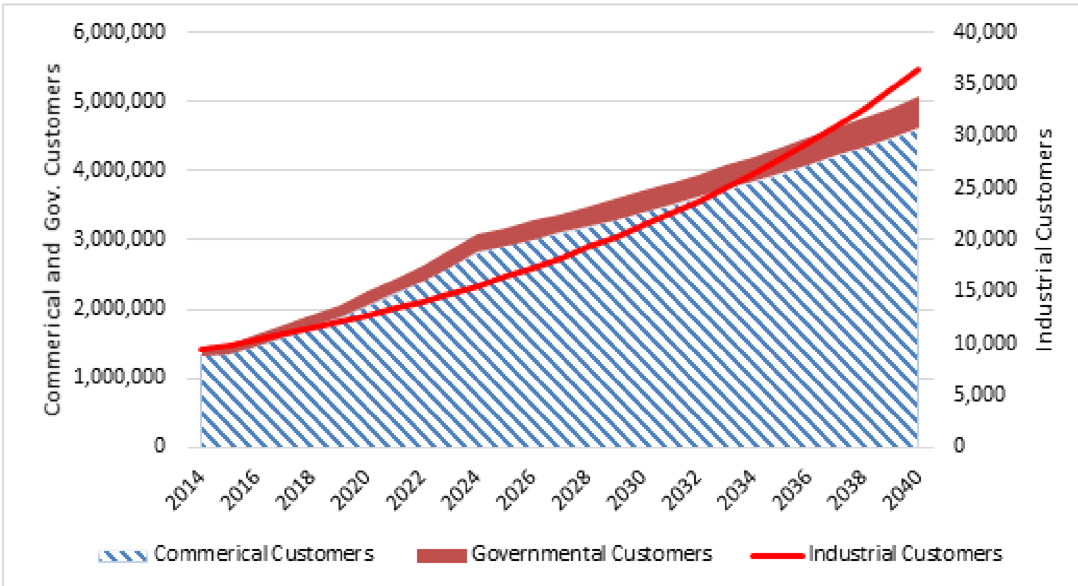

Figure 2.23 Projected number of electricity customers in the commercial, governmental, and industrial sectors in Saudi Arabia (up to 2040)

Table 2.6 Input data for the evaluation of cooling EE measures in the commercial sector

End-Use	EE Measure	Unit	LT	Electric Savings (kWh)	EE Measure Cost (SR/Unit)	Cost Type	Building Footage
Cooling	Split AC, high efficiency	ft^2	14	1.840	1.30	I	5,000
	Packaged AC, high efficiency	ft^2	14	0.770	1.20	I	25,000
	Chiller, high efficiency	ft^2	20	0.620	1.40	I	50,000
	District cooling	ft^2	20	0.620	5.60	I	50,000
	Chiller, variable speed drive (VSD)	ft^2	20	0.830	0.20	I	50,000
	Cooling tower, high efficiency	ft^2	10	0.001	1.10	I	50,000
	Condenser water, temperature reset	ft^2	15	0.230	0.90	I	50,000
	Economizer, installation	ft^2	15	0.310	0.70	I	50,000
	HVAC retro-commissioning	ft^2	4	0.300	2.10	I	50,000
	Pumps, variable speed control	ft^2	10	0.010	0.60	I	50,000
	Thermostat, clock/program-mable	ft^2	11	0.170	0.02	F	5,000

Data source: Faruqui and Hledik, 2011, p. 102

Table 2.7 Input data for the evaluation of lighting and refrigeration EE measures in the commercial sector

End-Use	EE Measure	Unit	LT	Electric Savings (kWh)	EE Measure Cost (SR/unit)	Cost Type	Building Footage
Lighting	Compact fluorescent lamps	ft²	5	0.03	3.400	F	8,250
	Fluorescent, high bay fixtures	ft²	11	0.06	3.700	F	25,000
	T8 lamps and fixtures	ft²	10	0.18	14.800	F	8,250
	LED lamps	ft²	10	1.19	0.005	F	8,250
	LED exit lighting	ft²	10	0.01	20.400	F	8,250
	Metal halide lighting	ft²	10	1.12	1.400	F	25,000
Refrigera-tion	Refrigerator (Ref.) compressor, high efficiency	ft²	15	0.04	1.400	I	25,000
	Ref. compressor, variable speed	ft²	15	0.02	1.000	I	25,000
	Ref., demand defrost	ft²	15	0.02	1.000	F	25,000
	Ref. controls, anti-sweat heater	ft²	15	0.02	1.700	F	25,000
	Ref. controls, floating head	ft²	15	0.02	0.200	F	25,000
	Ref., evaporator fan control	ft²	5	0.02	0.100	F	25,000
	Ref., strip curtain	ft²	8	0.06	1.200	F	25,000

Data source: Faruqui and Hledik, 2011, p. 102

Table 2.8 Input data for the evaluation of ventilation and building EE measures in the commercial sector

End-Use	EE Measure	Unit	LT	Electric Savings (kWh)	EE Measure Cost (SR/unit	Cost Type	Building Footage
Ventilation	Fans, energy-efficient motors	ft²	10	0.13	1.6	I	50,000
	Fans, variable speed control	ft²	10	0.39	2	I	50,000
Building shell	Insulation, ceiling	ft²	20	0.16	2	F	8,250
	Insulation, ducting	ft²	20	0.16	1.3	F	8,250
	Insulation, radiant barrier	ft²	20	0.05	2.4	F	8,250
	Insulation, wall cavity	ft²	20	0.15	0.4	F	8,250
	Roofs, high reflectivity	ft²	15	0.21	3.8	I	8,250
	Windows, high efficiency	ft²	20	0.25	0.08	I	8,250

Data source: Faruqui and Hledik, 2011, p. 102

The assumptions adopted to convert unit measure savings to aggregate technical potential across the commercial sector are presented in Tables 2.9, 2.10 and 2.11. To calculate the technical potential, market acceptance rates were applied to each EE measure. [29] The same process was used in the governmental and industrial sectors,

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[29] In this analysis, the ARs for cooling and building EE measures have been adjusted by assuming a gradual increase over the planning period until reaching 100% and 75% respectively.

based on an analysis undertaken by Faruqui and Hledik (2011, pp. 102-104) (see Appendix B).

Table 2.9 Applicability factor and acceptance rates assumptions for commercial cooling EE measures

End-Use	EE Measure	Applicability factor (%)	AR (%)
Cooling	Split AC, high efficiency	90	100
	Packaged AC, high efficiency	5	100
	Chiller, high efficiency	3	100
	District cooling	3	100
	Chiller, VSD	3	100
	Cooling tower, high efficiency	3	100
	Condenser water, temperature	3	100
	Economizer, installation	3	100
	HVAC retro-commissioning	3	38
	Pumps, variable speed control	3	38
	Thermostat, clock/programmable	90	38

Source: modified from Faruqui and Hledik, 2011, pp. 122-123

Table 2.10 Applicability factor and acceptance rates assumptions for commercial lighting and refrigeration EE measures

End-Use	EE Measure	Applicability factor (%)	AR (%)
Lighting	Compact fluorescent lamps	50	60
	Fluorescent, high bay fixtures	5	60
	T8 lamps and fixtures	50	60
	LED lamps	10	60
	LED exit lighting	25	60
	Metal halide lighting	5	60
Refrigeration	Ref. compressor, high efficiency	5	35
	Ref. compressor, variable speed	5	35
	Ref., demand defrost	5	35

Source: modified from Faruqui and Hledik, 2011, pp. 122-123

Table 2.11 Applicability factor and acceptance rates assumptions for commercial ventilation and building EE measures

End-Use	EE Measure	Applicability factor (%)	AR (%)
Ventilation	Fans, energy-efficient motors	3	35
	Fans, variable speed control	3	35
Building Shell	Insulation, ceiling	70	75
	Insulation, ducting	70	75
	Insulation, radiant barrier	70	75
	Insulation, wall cavity	70	75
	Roofs, high reflectivity	70	75
	Windows, high efficiency	70	75

Source: modified from Faruqui and Hledik, 2011, pp. 122-123

2.2.4.1 Energy Savings Technical Potential of Commercial, Governmental, and Industrial EE Measures

Figures 2.24, 2.25, and 2.26 respectively present the results of the technical potential analysis for the commercial, governmental, and industrial sectors in Saudi Arabia for the period 2017–2040. Similar to the residential sector, building insulations and cooling measures accounted for 82% and 77% of total technical savings potential in the commercial and governmental sectors, respectively. This was again attributed to the low-efficiency cooling systems and poor building insulations currently being used in these sectors. NEEP (2008) reports that nearly 70% of the Saudi industrial sector's energy consumption is attributable to motors and motor-based compressed air. Based on the technical potential analysis, high-efficiency motors contributed to approximately 50% of electricity savings. Cooling measures still represented a significant portion of the technical potential (around 35%) in the industrial sector. Next to cooling and building insulation, lighting constituted the second largest share in commercial electricity use. Using higher EE measures would represent a 14% electricity savings technical potential in this sector. Similarly, EE lighting measures would represent around 19% and 9% of the total technical potential in the governmental and industrial sectors, respectively.

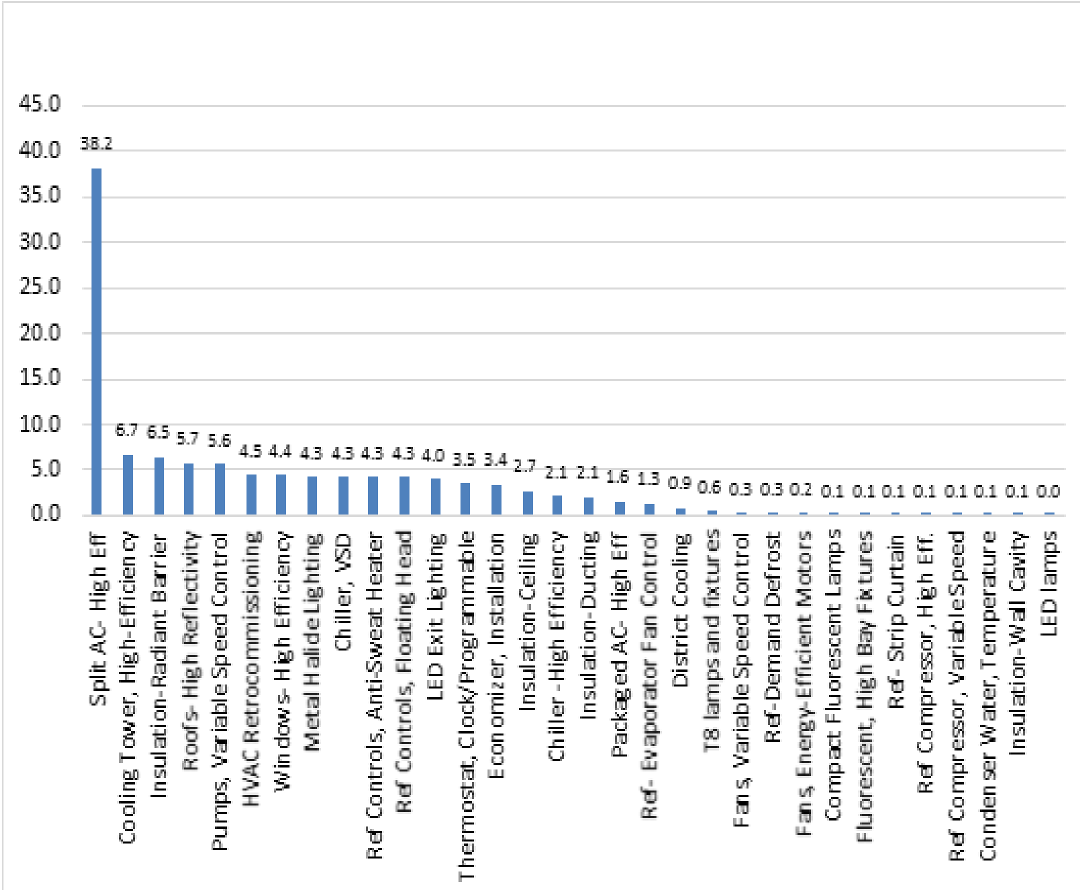

Figure 2.24 Technical potential of commercial EE measures, 2040 (in TWh)

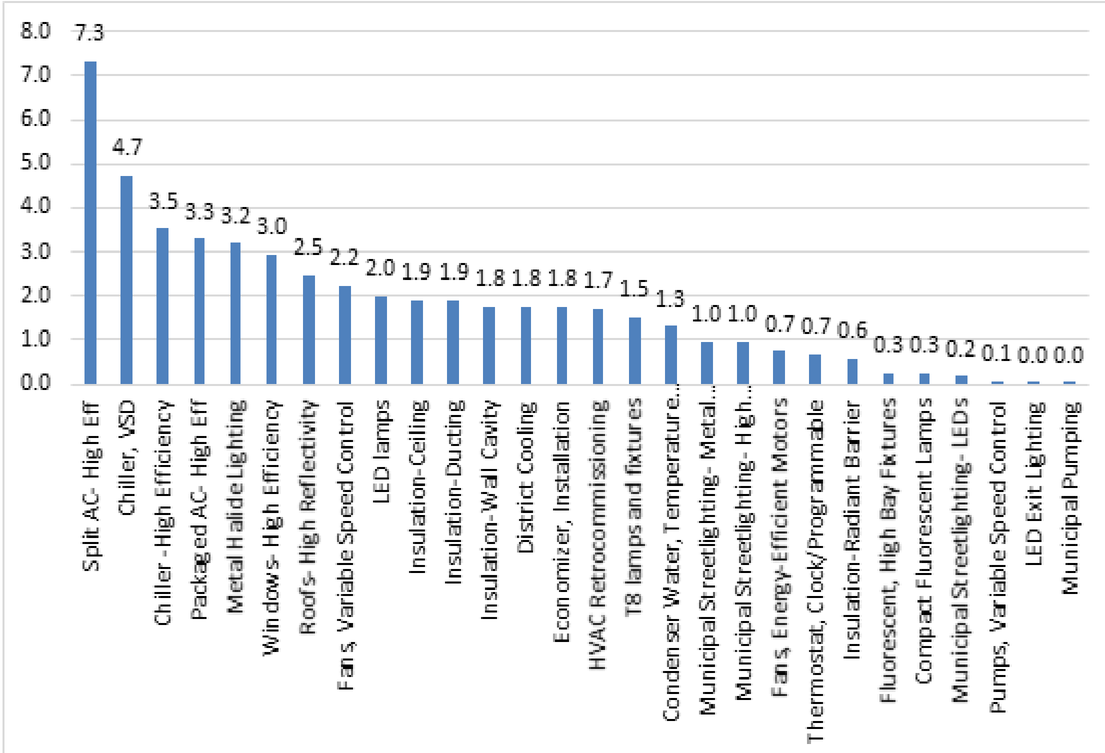

Figure 2.25 Technical potential of governmental EE measures, 2040 (in TWh)

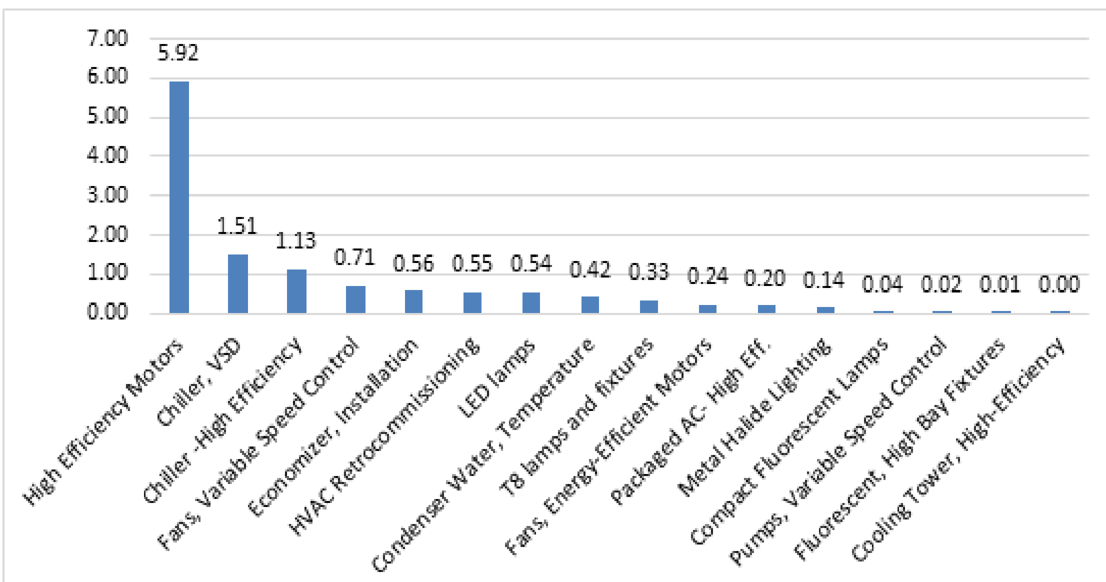

Figure 2.26 Technical potential of industrial EE measures, 2040 (in TWh)

2.2.4.2 Economic Potential of Commercial, Governmental, and Industrial EE Measures

Figure 2.27 shows the B/C ratios of all commercial measures listed in Table 2.6 above. Cooling (except for cooling towers), building, and lighting (apart from fluorescent, high bay fixtures) energy measures emerged as cost-effective for Saudi Arabia, even at the current avoided electricity cost. The primary reason for this was due to lower peak demand resulted from deploying cooling and building insulation measures. On the other hand, the results showed poor cost-effectiveness in the majority of refrigeration measures. This was due to the significant incremental costs involved in enhancing the efficiency of associated equipment.

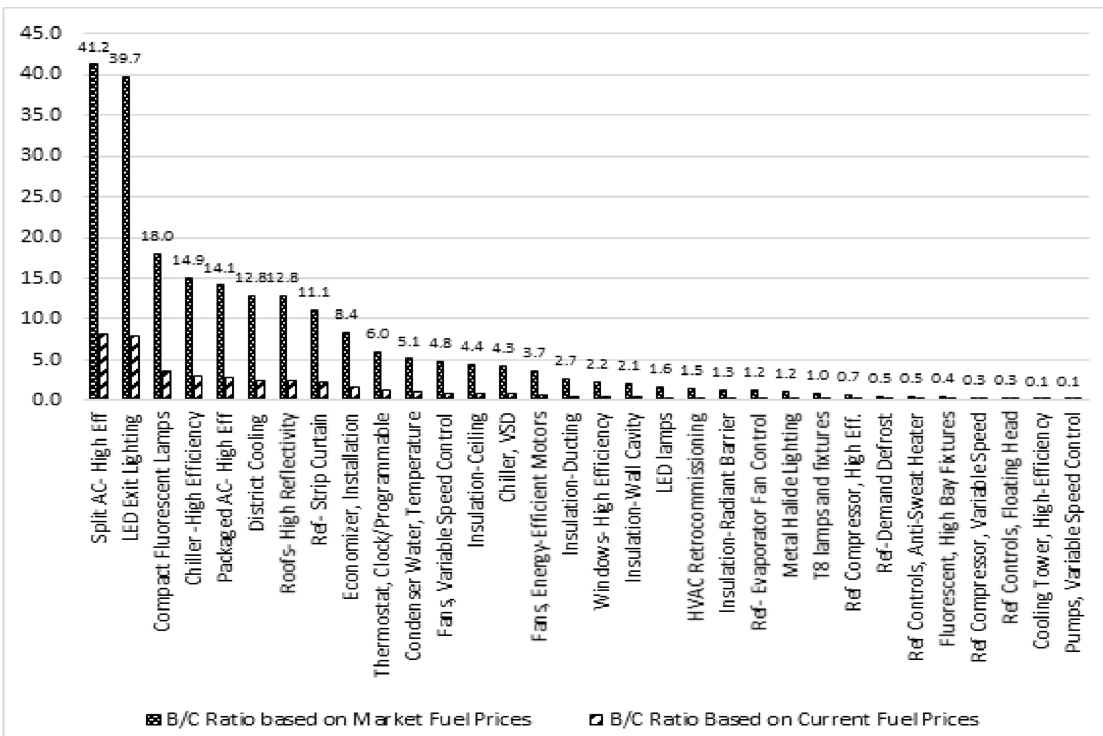

Figure 2.27 B/C analysis results for commercial EE measures, 2040

Figure 2.28 indicates the levelized costs associated with all measures in Saudi Arabia's commercial sector. The current average retail price is around USD 0.064/kWh (SEC, 2016). The analysis revealed that the major potential EE measures, such as the AC split package, appeared to have a levelized cost that is substantially lower than the retail rate of electricity.

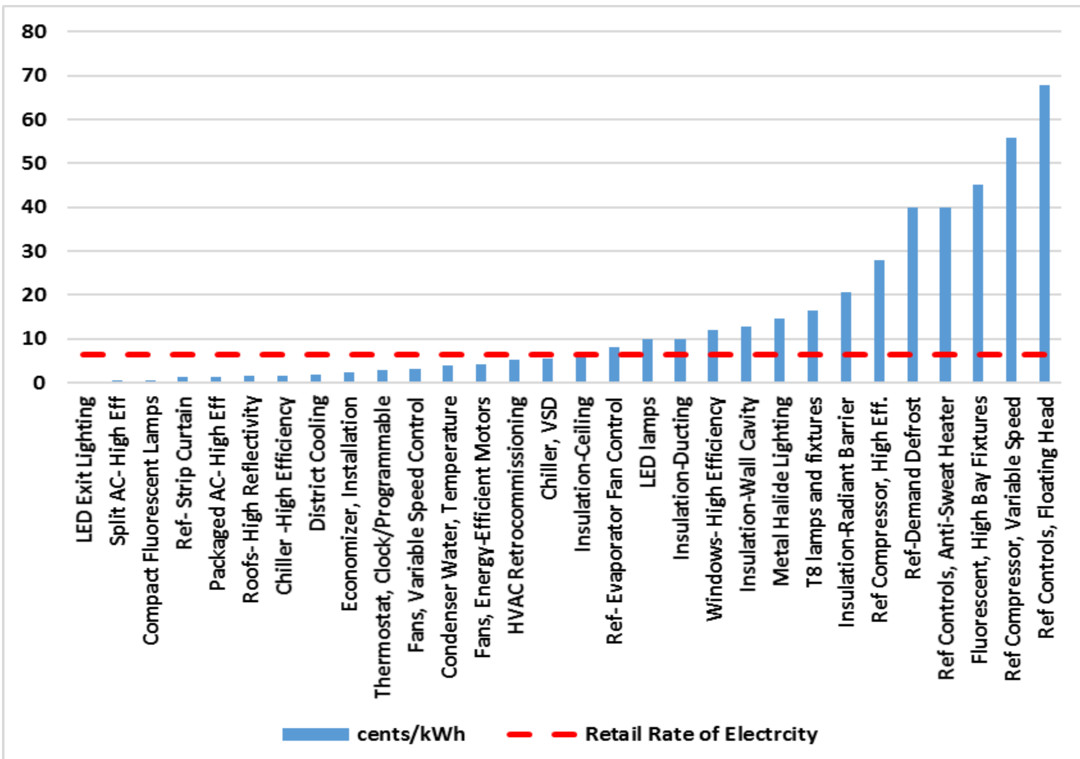

Figure 2.28 Levelized costs for commercial EE measures (in cents/kWh)[30]

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[30] Levelized costs for high-efficiency cooling tower and variable speed control pumps (not shown in Figure 2.27) were found the most expensive EE measures with 160 and 168 cents/kWh respectively.

Figure 2.29 shows the B/C ratios of all commercial measures in Saudi Arabia. Similar to the residential and commercial sectors, cooling, building, and lighting (except for fluorescent, high bay fixture, and LED street lighting) energy measures emerged as cost-effective for the country, even at the current avoided electricity cost. As a result of the significant incremental costs involved in enhancing the efficiency of certain pieces of equipment, fluorescent/LED streetlamps and water pumps were shown to be poor in cost-effectiveness.

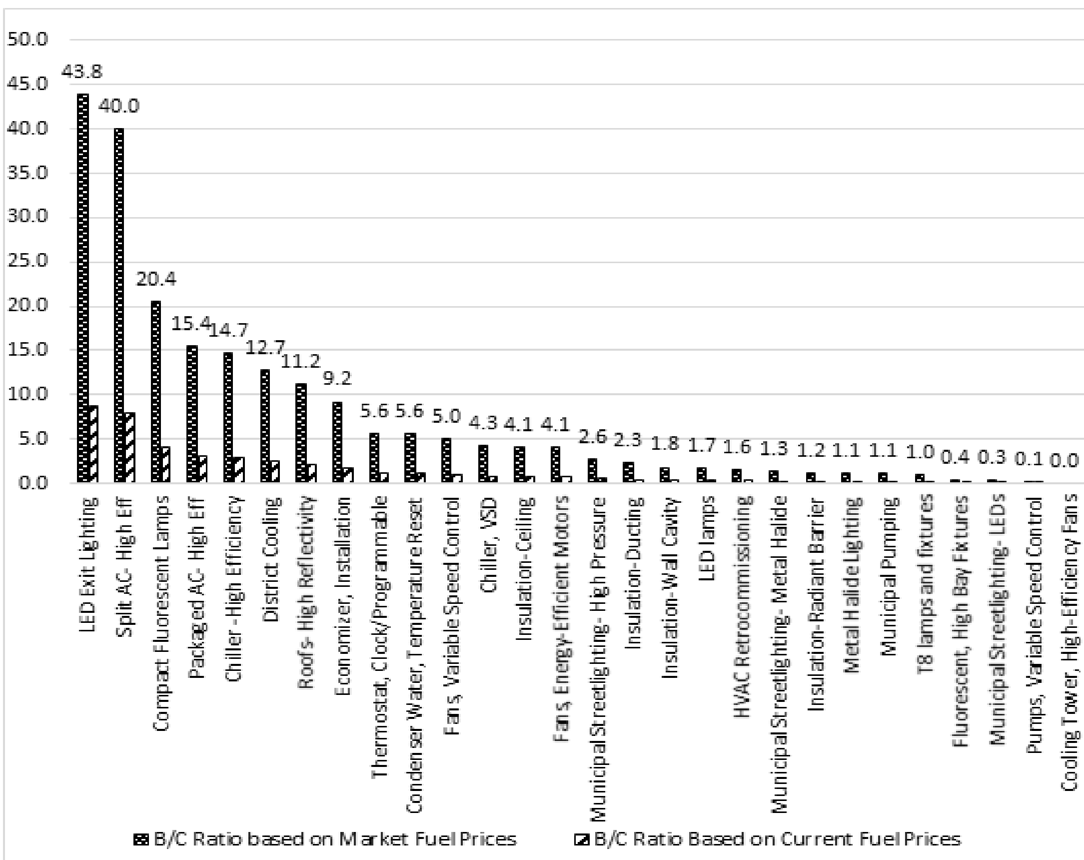

Figure 2.29 B/C analysis results for governmental EE measures, 2040

Figure 2.30 indicates the levelized costs associated with all measures in Saudi Arabia’s governmental sector. The current average retail price is around USD 0.085/kWh (SEC, 2016). The analysis revealed that the major potential EE measures, such as cooling systems, appeared to have a levelized cost that is substantially lower than the retail rate of electricity.

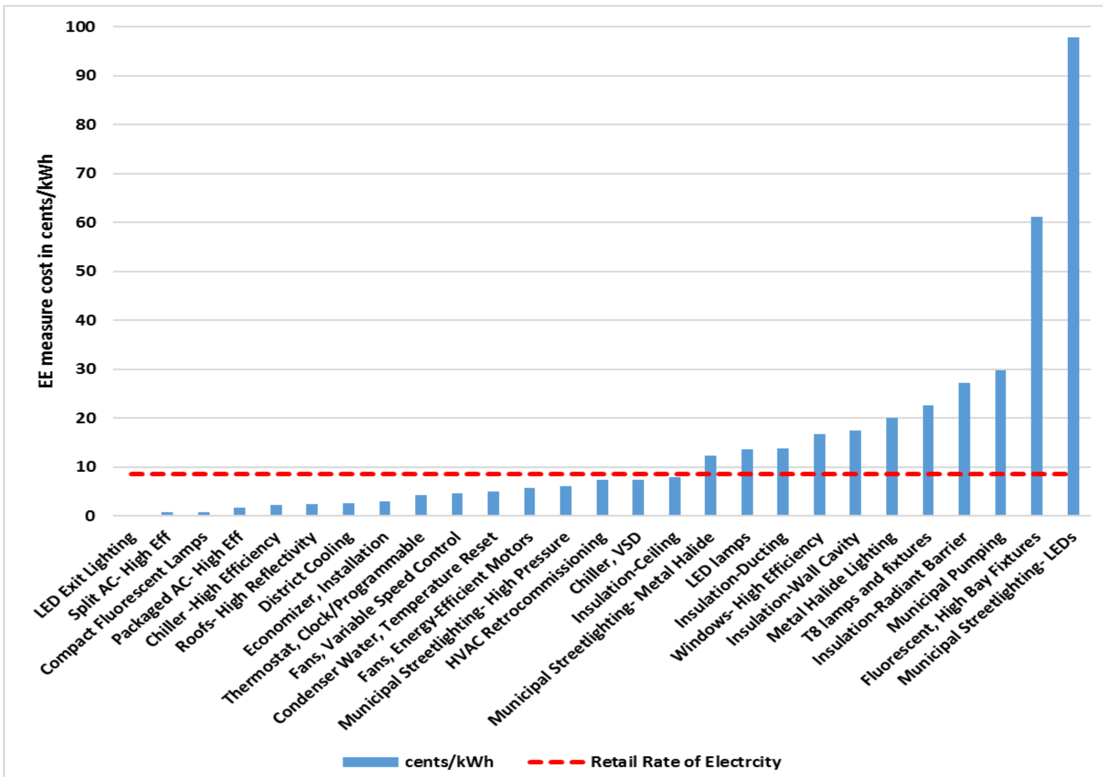

Figure 2.30 Levelized costs for governmental EE measures (in cents/kWh)[31]

[31] Levelized costs for variable speed control pumps (not shown in Figure 2.29) was found the most expensive EE measures with 230 cents/kWh.

Figure 2.31 shows the B/C ratios of all industrial measures. High potential electricity saving EE measures such as cooling (with an exception of cooling tower) and motors emerged as cost-effective for Saudi Arabia, even at current avoided electricity cost. Nonetheless, cooling towers, fluorescent lighting and water pumping were not found to be cost-effective. Again, this was because of the significant incremental costs involved in making these pieces of equipment more efficient.

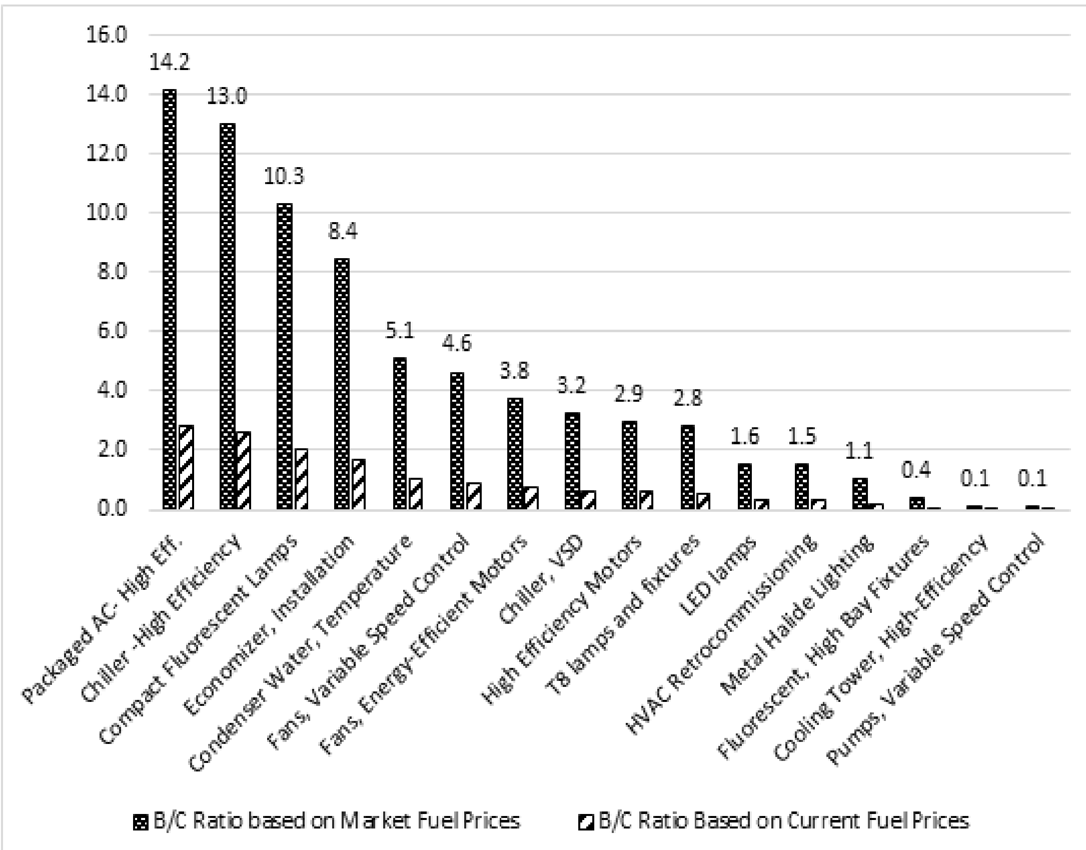

Figure 2.31 B/C analysis results for industrial EE measures, 2040

Figure 2.32 indicates the levelized costs associated with all measures in the governmental sector. The current average retail price is around USD 0.048/kWh (SEC, 2016). The results show that the levelized costs of the potential EE cooling and lighting measures are significantly lower than the retail rate of electricity. However, high-efficiency motors have significantly higher levelized cost than the retail rate of electricity in Saudi Arabia.

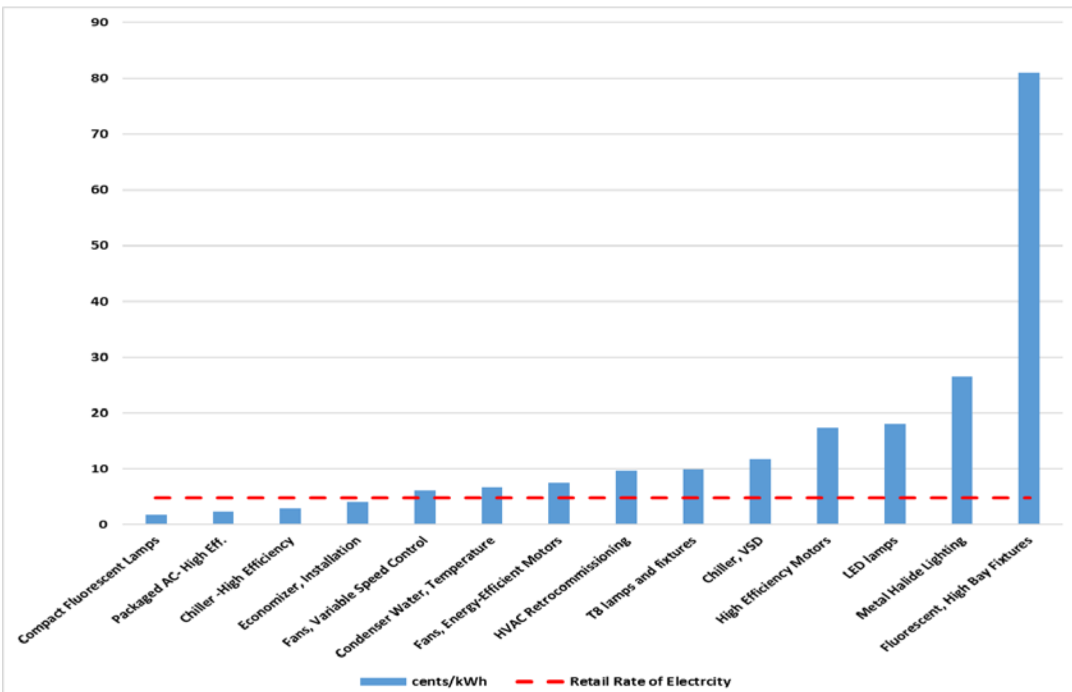

Figure 2.32 Levelized costs for industrial EE measures (in cents/kWh)[32]

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32 Levelized costs for efficient high bay fluorescent lamb fixtures and high efficiency cooling towers (not shown in Figure 2.31) were found the most expensive EE measures with 278 and 305 cents/kWh respectively.

2.2.4.3 Market Potential of Commercial, Governmental, and Industrial EE Measures

Figures 2.33 through 2.35 indicate a market potential of 75 TWh, 30.3 TWh, and 9.4 TWh for Saudi Arabia's commercial, governmental, and industrial sectors by 2040. Due to the expected implementation of cooling and building standards (as mentioned in Section 2.2.2), it was anticipated that these measures would represent more than 88% of the achievable market potential for the three sectors by 2040.

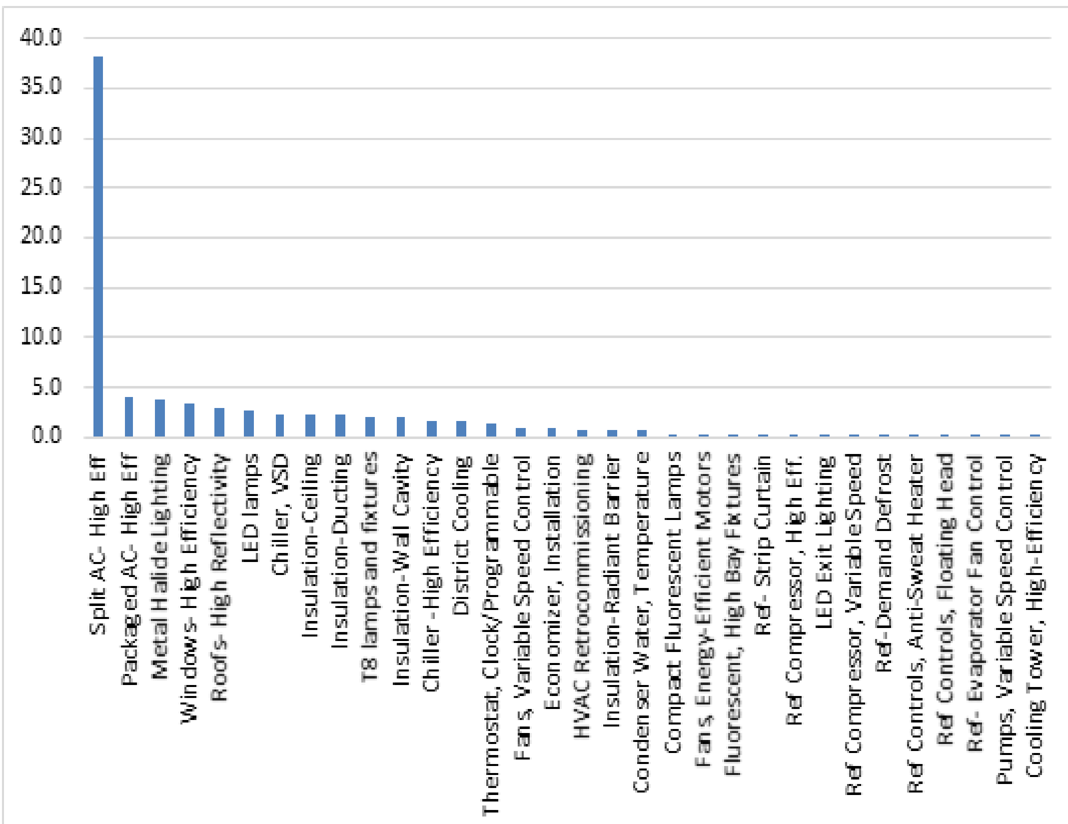


Figure 2.33 Market potential of commercial EE measures, 2040 (in TWh)

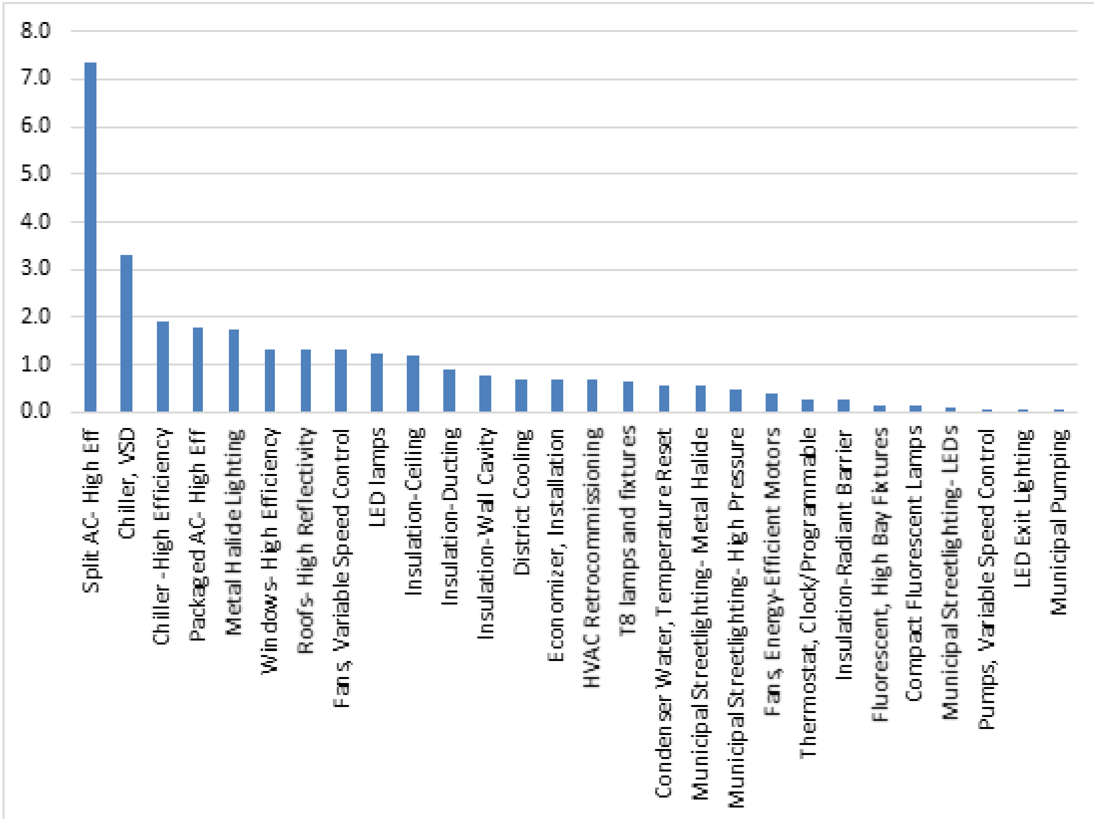


Figure 2.34 Market potential of governmental EE measures, 2040 (in TWh)

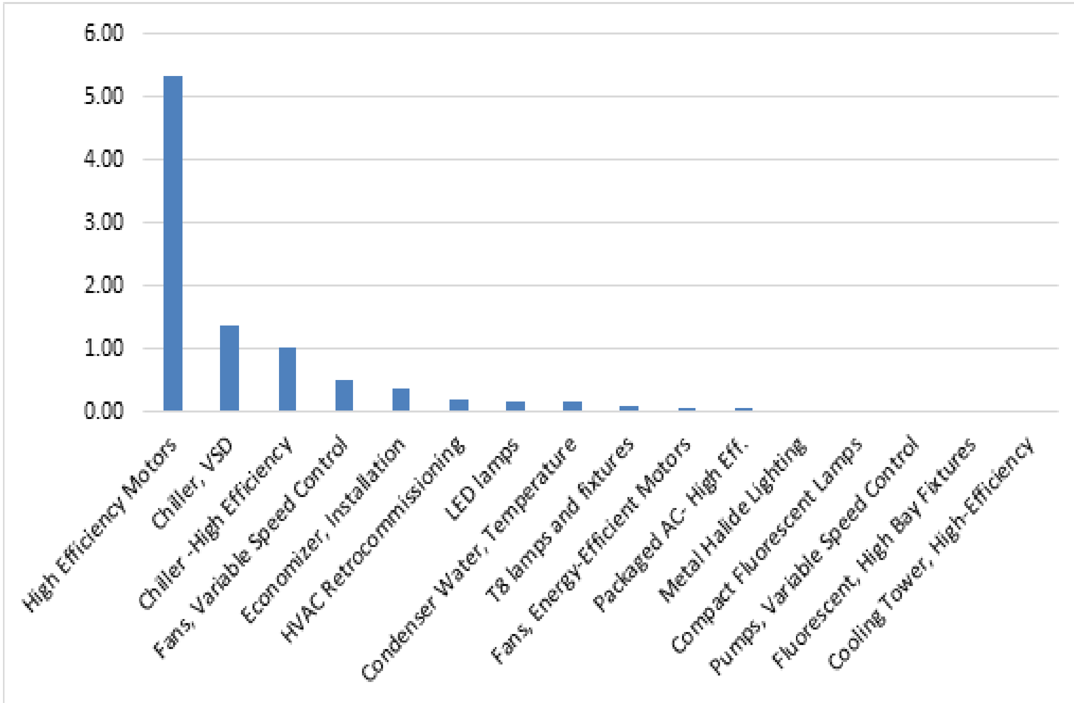


Figure 2.35 Market potential of industrial EE measures, 2040 (in TWh)

2.2.5 Load Management/Demand Response Measures

In evaluating the potential of LM/DR measures in Saudi Arabia, a wide range of measures was considered in the analysis. The measures focused on both event-peak reduction and permanent load shifting programs. Table 2.12 describes each LM/DR measure in detail.

Table 2.12 LM/DR measures and their definitions

Measure	**Definition from the literature**	**Targeted sector**
Direct load control (DLC)	Demand is lowered by the utility through the direct modification, reconnection or disconnection of the end-use device in order to tackle reliability or system issues, with a credit or incentive payment offered to the customer (Bhattacharyya, 2011, p. 140).	Residential & commercial
Interruptible tariff	The customer is subject to tariffs for interruptible loads and acknowledges that the utility has the right to implement a partial load disconnection during peak months without providing advance warning (Bhattacharyya, 2011, p. 141).	Commercial & industrial
Curtailable load management (CLM)	CLM is comparable to an interruptible tariff, with the main difference being that customers only receive payment for unit reductions that occur during event periods. Because customers only receive payment if they make a reduction and do not receive a penalty if no reduction is made, CLM lacks the reliability of other methods, from a system operation point of view (Faruqui & Hledik, 2011, p. 72).	Residential, commercial, & industrial
Dynamic pricing	Customers receive price signals as incentives to lower their bills by curtailing peak usage and shifting usage to less expensive off-peak periods (Faruqui, Sergici, & Wood, 2009, p. 3).	Residential, commercial, & industrial
Demand subscription service (DSS)	DSS is much like dynamic pricing. However, customers are able to decide how much price variation they wish to access. Customers can make a fixed payment to purchase a baseline amount of energy. In this case, they are charged for the remainder of their energy consumption based on the time-based prices at the dynamic rate (Faruqui & Hledik, 2011, p. 73).	Residential, commercial, & industrial
Dynamic pricing with advance DLC	Automatic responses to critical peak prices can be achieved by incorporating automated demand response, customer-programmed automation and other technologies into programmable communicating thermostats (PCTs) (Faruqui & Hledik, 2011, p. 73).	Residential, commercial, & industrial
(continued)		

(Continuation of Table 2.12)		
TOU rates	TOU often refers to prices that are set in advance but vary over the day to capture the expected impacts of changing electricity conditions (Faruqui, Hledik, & Lessm, 2014).	Residential & commercial
In-home information display (IHD)	IHD provides means of providing consumers with meaningful feedback about their energy consumption patterns (Ehrhardt-Martinez, Donnelly, & Laitner, 2010).	Residential
Web portals	Web portals are an internet-based IHD that enable users to monitor their energy consumption via devices such as smartphones and computers. This allows customers to change their approach to energy consumption based on real-time information (Faruqui & Hledik, 2011, p. 74).	Residential
Social norming	Social norming compares customers' energy consumption to that of neighbouring customers and is an approach that has emerged only recently. This is an effective method that encourages customers to improve their energy usage behavior based on competition (Faruqui & Hledik, 2011, p. 75).	Residential

Since no data is available specifically about the potential of LM/DR measures in Saudi Arabia, this study used general data provided by Faruqui and Hledik (2011) about LM/DR measures in Saudi Arabia. Table 2.13 shows input data (including cost per customer, peak reduction, and the assumed participation rates) for each measure used in evaluating the economic and market potentials for LM/DR measures in Saudi Arabia. Faruqui and Hledik (2011) used the best available data based on similar international experiences and adjusted as possible to reflect conditions in Saudi Arabia.

Table 2.13 Input data for evaluating LM/DR measures

Sector	LM/DR Measure	Peak Reduction (%)	Cost [33] USD	Eligible Customer (%)	Partic. (%)	Total Partic. (%)
Resid	DLC (traditional)	22	260	5	20	1
Resid	Advanced DLC+price signal	12	260	5	20	1
Resid	CLM	11	325	100	17	17
Resid	Dynamic pricing	16	325	100	17	17
Resid	DSS	11	325	100	17	17
Resid	TOU	10	325	100	17	17
Resid	IHD	7	130	100	17	20
Resid	Web portals	1	17	30	20	23
Resid	Social norming	3	53	100	75	80
Comm	DLC (traditional)	41	455	90	10	9
Comm	Advanced DLC+price signal	5	455	90	10	9
Comm	Interruptible tariff	45	325	100	11	5
Comm	CLM	3	300	100	75	75
Comm	Dynamic pricing	5	300	100	75	75
Comm	DSS	3	300	100	75	75
Comm	TOU	3	300	100	75	75
Indus	Advanced DLC+price signal	10	17550	90	20	18
Indus	Interruptible tariff	45	9333	100	25	25
Indus	CLM	45	9333	100	20	20
Indus	Dynamic pricing	10	9333	100	75	75
Indus	DSS	7	9333	100	75	75

Data source: Faruqui and Hledik, 2011, pp. 86-94

[33] In Faruqui and Hledik's (2011) study, costs were calculated based on a summary of data from experts, case studies and utility regulatory documents. Importing costs were represented using a 15% adder on equipment costs with around 2-15% representing administration and other program costs.

2.2.5.1 Economic Potential of LM/DR Measures

Figure 2.36 shows the B/C ratios of all LM/DR measures indicated earlier in Table 2.7. It was found that the most economically attractive LM/DR measures in Saudi Arabia included the interruptible tariff (for the industrial and commercial sectors) and CLM (for the industrial sector). Faruqui and Hledik (2011) explained the reason behind this finding:

> The reason for this is that these programs historically have tended to produce very large impacts among participants. In fact, many programs report 100 percent load curtailment among participants, suggesting that the enrolled participants simply shut down their operations during the critical event. Utilities operating these programs have not typically utilized them very often, so participants are not forced to take these measures on a regular basis. Knowing this, they enroll at the maximum level of load curtailment in order to receive the full participation incentive. These programs also produce significant impacts because they often include non-compliance penalties. If the programs were utilized more regularly, the expected impacts (and therefore benefits) would likely be smaller.

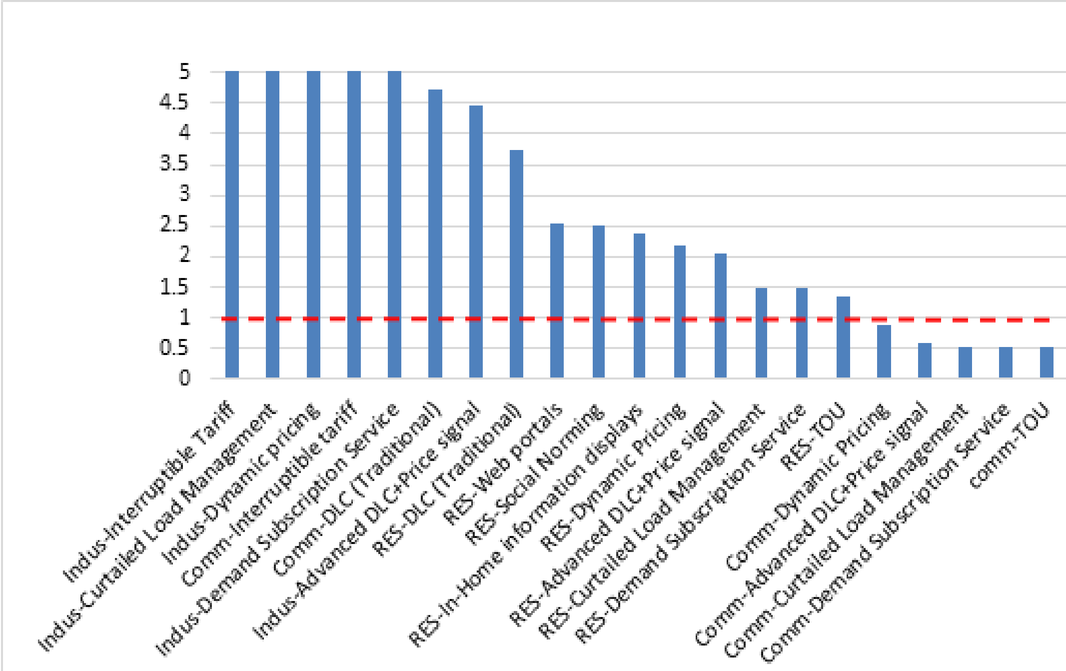


Figure 2.36 B/C analysis results for LM/DR measures, 2040

It was also found that DLC was economically attractive for all sectors in the country, as it would have a major impact on reducing the share of air conditioning load during peak demand. Advanced DLC with signal pricing measures was found more attractive in the industrial and residential sectors, as residential and industrial customers are typically more price-sensitive than commercial customers. Information measures, such as web portals, IHD, and social norming were also found attractive, especially if used with smart grid meters that can provide real-time consumption data to end-users in the residential sector. In the commercial sector, pricing options (e.g., TOU, DSS, and dynamic pricing) were found among the least economically attractive options for Saudi Arabia.

2.2.5.2 Market Potential of LM/DR Measures

Figure 2.37 presents the results of the market potential analysis of LM/DR measures for the residential, commercial, and industrial sectors by 2040. The forecasted growth of a number of customers in all sectors was used to calculate the potential. Dynamic pricing, CLM and the industrial interruptible tariff were the most cost-effective measures. These measures also demonstrated the greatest potential. In the residential sector, LM/DR measures (including pricing and information measures) represented another large potential of a total reduction of 9.8 GW peak. The limited effect of DLC in the residential sector was due to the consideration of the direct control of central air-conditioning systems. The potential of DLC in the residential sector would therefore be more significant if this measure was applied to window air-conditioning units and split-system air-conditioning units in Saudi Arabia.

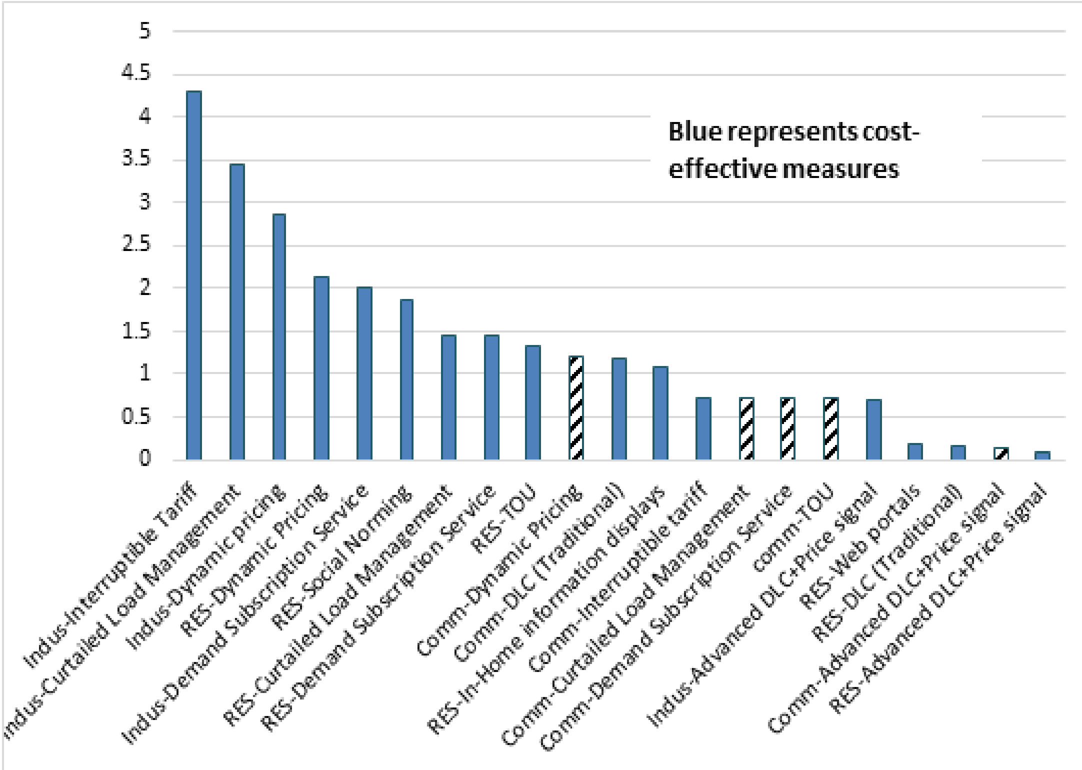


Figure 2.37 Market potential of LM/DR measures, 2040 (in peak reduction GW)

2.3 Chapter Summary

Supply- and demand-side potentials in Saudi Arabia have been comprehensively evaluated in this chapter. On the supply-side, the greatest renewable energy potential is found in solar energy sources, with the second largest being wind energy. On the basis of an analysis of varioues solar technologies, it has been concluded that Saudi Arabia can generate electricity from these technologies at a very low price. These electricity generationsors are also associated with a potentially dramatic improvement of fossil fuel-based generation efficiency as a result of retiring and/or replacing old generation with higher efficiency generation. On the demand-side, EE measures (especially in cooling systems, building insulations, and industrial motors) are proven to offer significant electricity savings and substantial economic benefits. In addition, LM/DR measures would result in significant peak reductions in various sectors.

In next chapter, a detailed demand forecasting model is developed to project electricity demand for different scenarios, including EE scenarios based on the comprehensive demand-side savings results obtained in this chapter.

Chapter 3

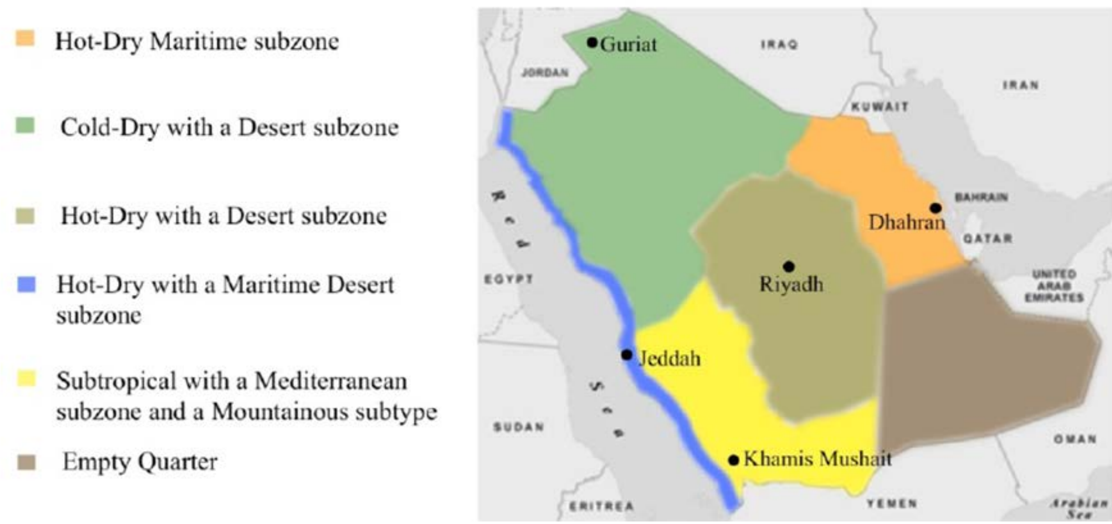
LONG-TERM ELECTRICITY DEMAND FORECASTING

The potential of supply-side resources and demand-side measures in the utility sector were assessed in the previous chapter. In the context of the IRSP model, this chapter addresses the demand forecast as a first basic step required for building an EWS IRSP model for Saudi Arabia. Evaluating the required generation capacity depends greatly upon the results of the demand forecast analysis. These results are a key element in determine the type of generation resources that can be deployed, the ways in which distribution and transmission systems should be expanded, and the locations and customers to be targeted. In the previous chapter, the analysis identified which DSM measures are worth implementation and when, in addition to in which consuming sectors and for what end-uses they should be executed. Based on this analysis of all achievable EE and LM/DR measures, a demand forecasting model is developed to forecast the electricity demand for all regions in Saudi Arabia, taking into consideration various EE scenarios. The forecasting model incorporates all four electricity network operating areas (i.e. the COA, EOA, WOA, and SOA) and all six customer categories (i.e. residential, commercial, governmental, industrial, agricultural, and others).

3.1 Data Description and Assumptions

3.1.1 Load and Temperature Data

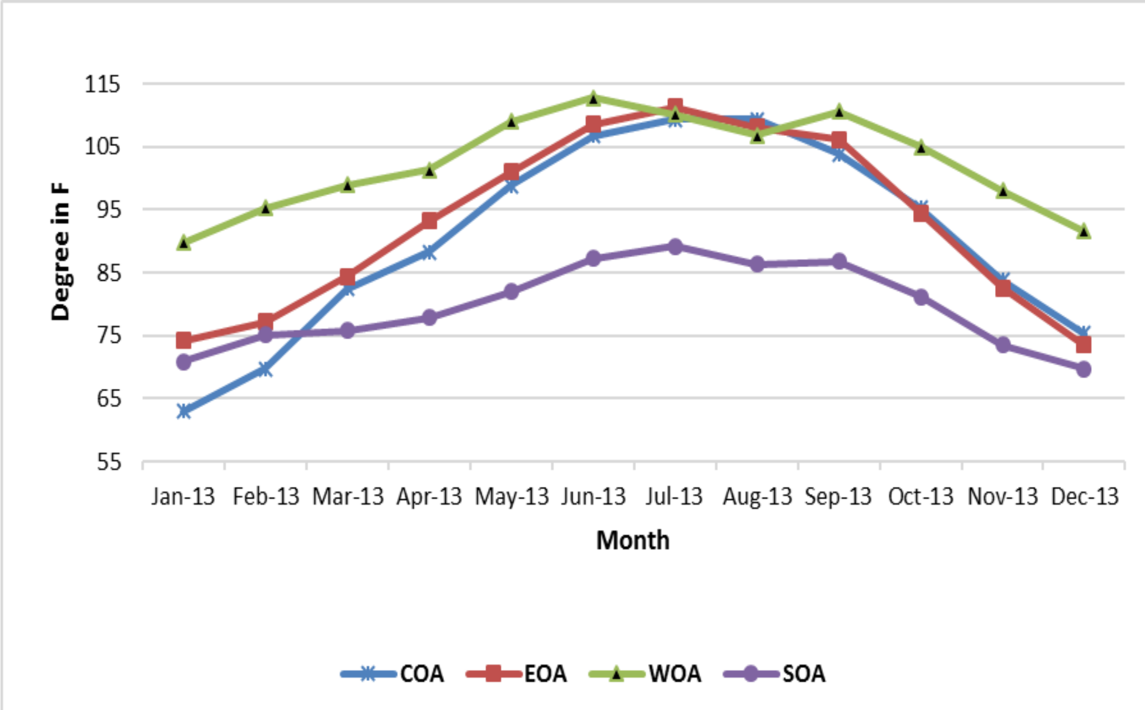
As explained by Said, Habib and Iqbal (2003), the KSA has five distinct inhabited clamtic regions: hot-dry with desert areas, such as Riyadh; cold-dry with desert areas, such as Quriat; hot-dry with maritime desert areas, such as Makkah; and hot-dry with a maritime area, such as Dhahran; and subtropical with Meditteranean and mountainous, such as Khamis Mushait (see Figure 3.1). Riyadh, Makkah, Khamis Mushiat, and Dhahran (and their surrounding cities) are the main representative urban areas in the four electricity network operating areas, as they represented 91% of Saudi Arabia's total electricity consumption and 73% of its total population in 2013 (SEC, 2014; CDSI, 2015). Although Quriat has a different climate zone, it was excluded from the analysis since it represented only 0.6% of the country's total electricity consumption and 1% of its population in 2013 and thus has a minimal impact on electricity demand forecasting (SEC, 2014; CDSI, 2015).



Source: Alrashed and Asif, 2015, p. 1429

Figure 3.1 Saudi Arabia’s climate zones

For analyzing the effects of weather on electricity demand in Saudi Arabia, historical hourly weather data was obtained for the period from 1992 to 2014. The data included temperature and humidity readings for the four selected cities (Weatherbase, 2015). It is evident from Figure 3.2 that the monthly maximum temperatures in 2013 had a clear seasonal trend, with higher summer values and lower winter values; the highest seasonal range was in the COA, with the lowest ranges in the SOA and WOA. Monthly average temperature and minimum temperature followed the same patterns.



Data source: Weatherbase, 2015

Figure 3.2 Monthly maximum temperatures for the four main cities in Saudi Arabia's four electricity network operating areas, 2013

The cooling degree days (CCD) and heating degree days (HDD) methodology is also regarded as a reliable tool for appropriately accounting for the effect of weather on energy demand. Researchers commonly use degree days methodologies to calculate seasonally adjusted energy consumption in a variety of discrete geographies (Atallah, Gualdi, & Lanza, 2015, p. 3); among others, they include Dombayci (2009) for Turkey, Arguez, Karl, Squires, & Vose (2013) for the United States, Badescu (1999) for Romania, You (2013) for China, Matzarakis (2004) for Greece, and Eurostat (2011) for selected European countries. This approach is defined as follows by Atallah, Gualdi, and Lanza (2015, p. 13):

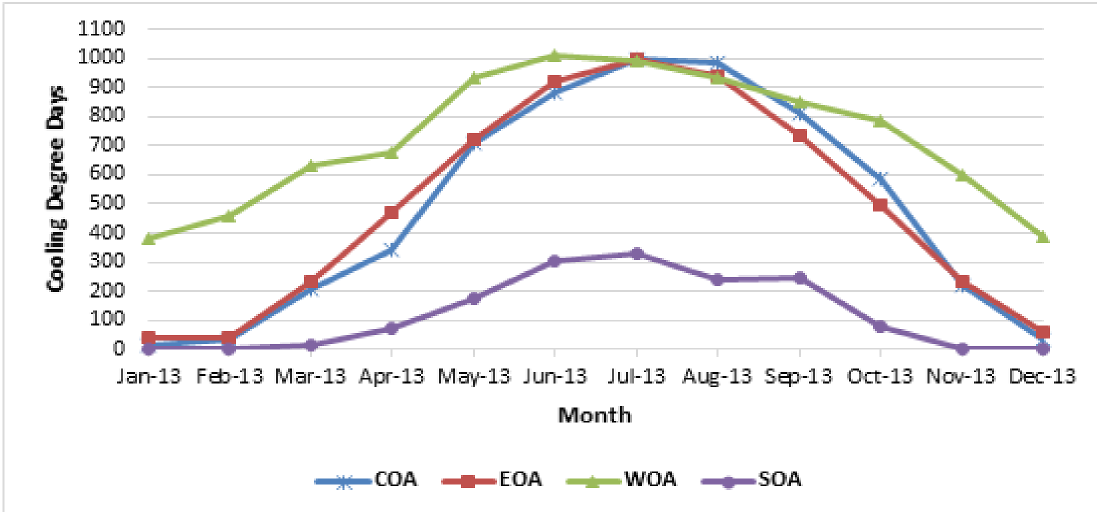
> Degree day is calculated as the difference between a reference temperature (T_{ref}) and the average of the maximum and minimum temperature ($T_{mean)}$). If the difference is positive it is counted as HDD, if it is negative it is represented as CDD. Values for CDD and HDD are typically summed on a monthly or yearly basis, with the most commonly used reference temperature being 65°F (18°C).

Monthly CDD and HDD were computed for the period from 1992 to 2014 for Saudi Arabia's four electricity network operating areas using the following formulas (Atallah, Gualdi, & Lanza, 2015, p. 13; Crowley & Joutz, 2005, p. 3):

$$HDD_I = \sum_{0\ days}^{i\ days}(T_{ref} - T_{daily\ mean}) \tag{3.1}$$

$$CDD_I = \sum_{0\ days}^{i\ days}(T_{daily\ mean} - T_{ref)} \tag{3.2}$$

Strong seasonal variance was evident once again, as shown in Figure 3.3, with higher temperatures during the summer and lower temperatures during the winter, with the smallest range in the WOA and SOA and largest range in the COA.



Data source: Weatherbase, 2015

Figure 3.3. Monthly cooling degree days for the main four cities in Saudi Arabia's four electricity network operating areas, 2013

Table 3.1 presents the calculated annual average weather variables for the four key main representative cities in Saudi Arabia for the period from 1992 to 2013. It indicates that in the four main climate zones, Makkah had the highest annual average temperature and CDD while Khamis Mushait had the lowest annual average temperature and CDD.

Table 3.1 Weather data comparison between cities representing Saudi Arabia's climate zones

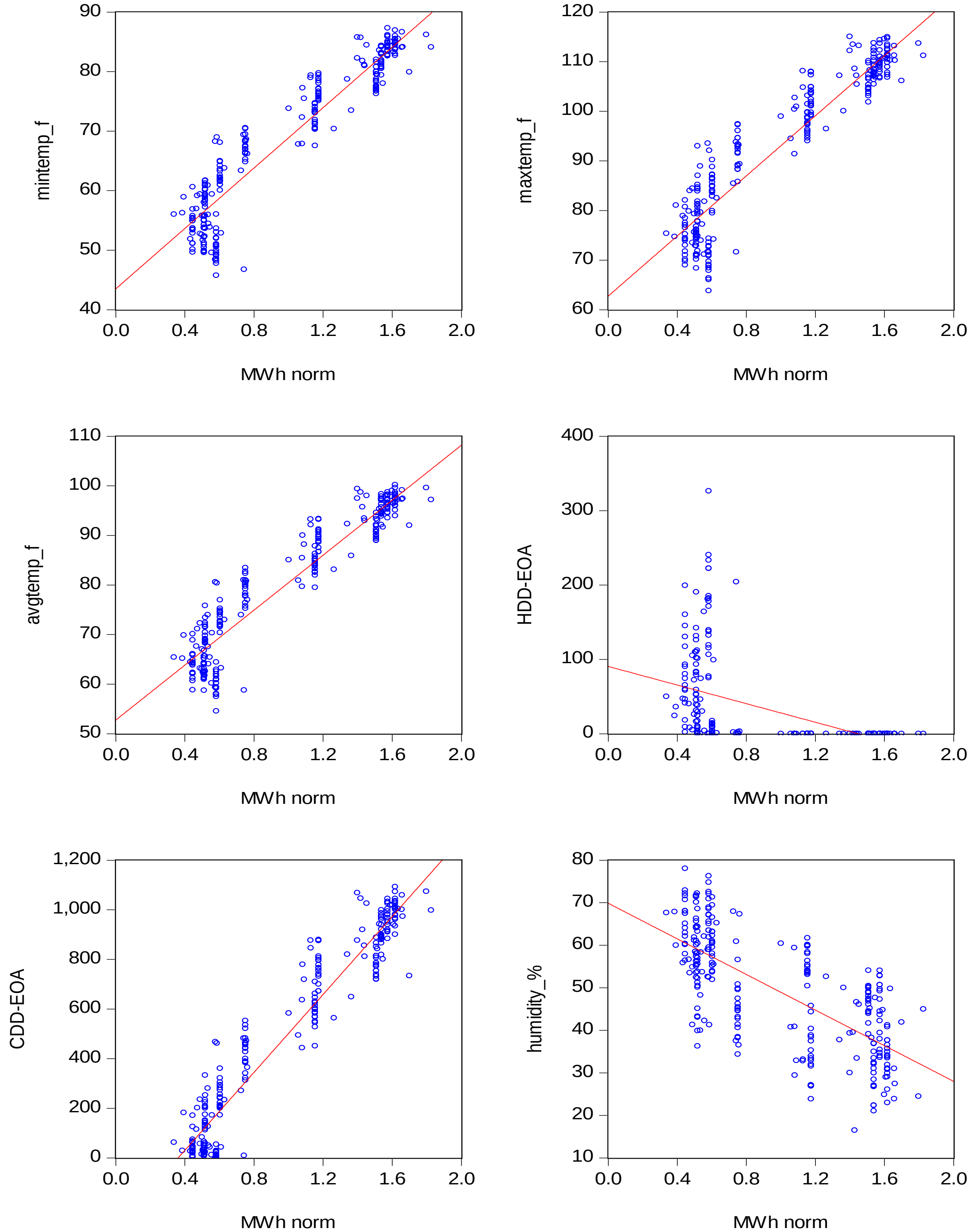
City	**Area**	**Average (1992–2013)**		
		Avg. Temp in ˚F	**Annual HDD**	**Annual CDD**
Riyadh	COA	80.7	468.0	6506.2
Dhahran	EOA	80.5	340.2	6034.2
Makkah	WOA	87.8	0.0	8304.0
Khamis Mushiat	SOA	66.2	912.8	1370.5

Data source: Weatherbase, 2015

Many studies have examined the response of electricity consumption to changes in weather variables and proven that higher temperatures influence the annual electricity demand pattern (Crowley & Joutz, 2005; Feinberg & Genethliou 2005). Furthermore, quantifying the relationship between climate conditions and electricity consumption can raise awareness of climate change's effect on future heating and cooling equipment investments (Atallah, Gualdi, & Lanza, 2015, p. 3). For example, after investigating how climate change influence electricity demand in the Pennsylvania-New Jersey-Maryland (PJM) network in the United States, Crowley and Joutz (2005, p. 3) concluded:

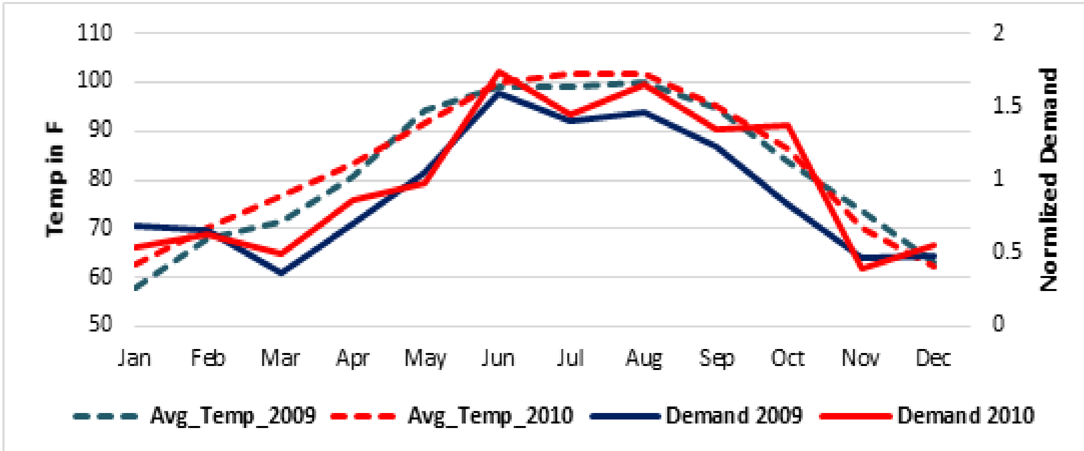
> The impact of temperature warming in the summer scenario had two important effects. First, average load demand was about 2.7 percent higher in the summer months. Second, peak demand was 5.4 percent higher. Thus, the results suggest an important impact on the load shape.

The relationship between monthly weather variables (i.e. maximum temperature, minimum temperature, average temperature, HDD, and CDD) and monthly normalized residential electricity demand in Saudi Arabia is presented in Figure 3.4, which reveals that electricity demand strongly correlates with these weather variables in the EOA. Within this specific operating area, humidity and HDD were found to be not significantly correlated with electricity demand. The same was investigated for the other three operating areas. Figure 3.5 shows the effect of changes in average temperature on the residential electricity demand for two different years (namely 2009 and 2010) in the COA. It can be observed that the annual electricity demand shape/pattern would change from the winter to summer months. Similarly, Figure 3.6 illustrates the impact of CDD and HDD in 2003 and 2004 in the COA. It was very evident that the demand shape strongly follows the total degree days curve.



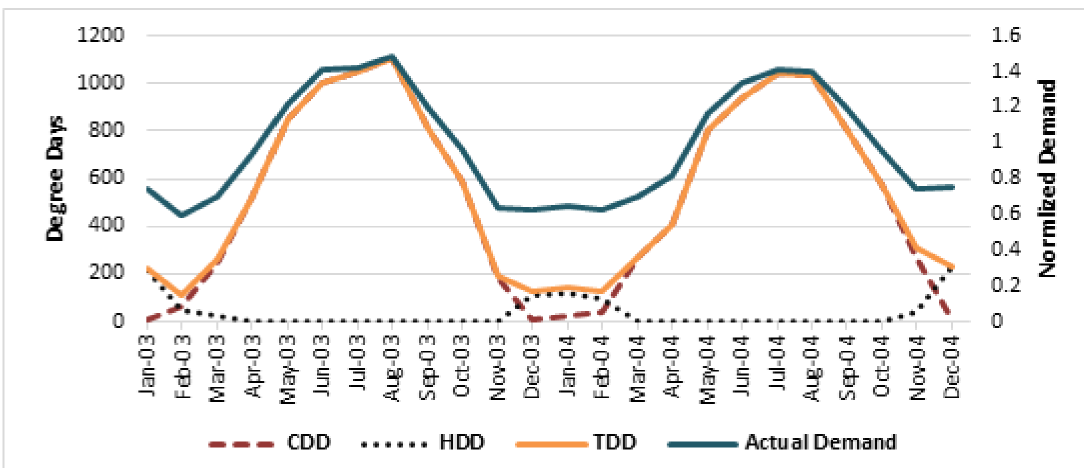
Data source: Weatherbase, 2015; SEC, 2014

Figure 3.4 Monthly normalized electricity demand versus normalized monthly weather variables in the EOA's residential sector



Data source: Weatherbase, 2015; SEC, 2014

Figure 3.5 Effect of average temperature changes on electricity demand in the COA's residential sector, 2009 and 2010



Data source: Weatherbase, 2015; SEC, 2014[34]

Figure 3.6 Effect of average monthly HDD and CDD changes on electricity demand in the COA's residential sector, 2003 and 2004

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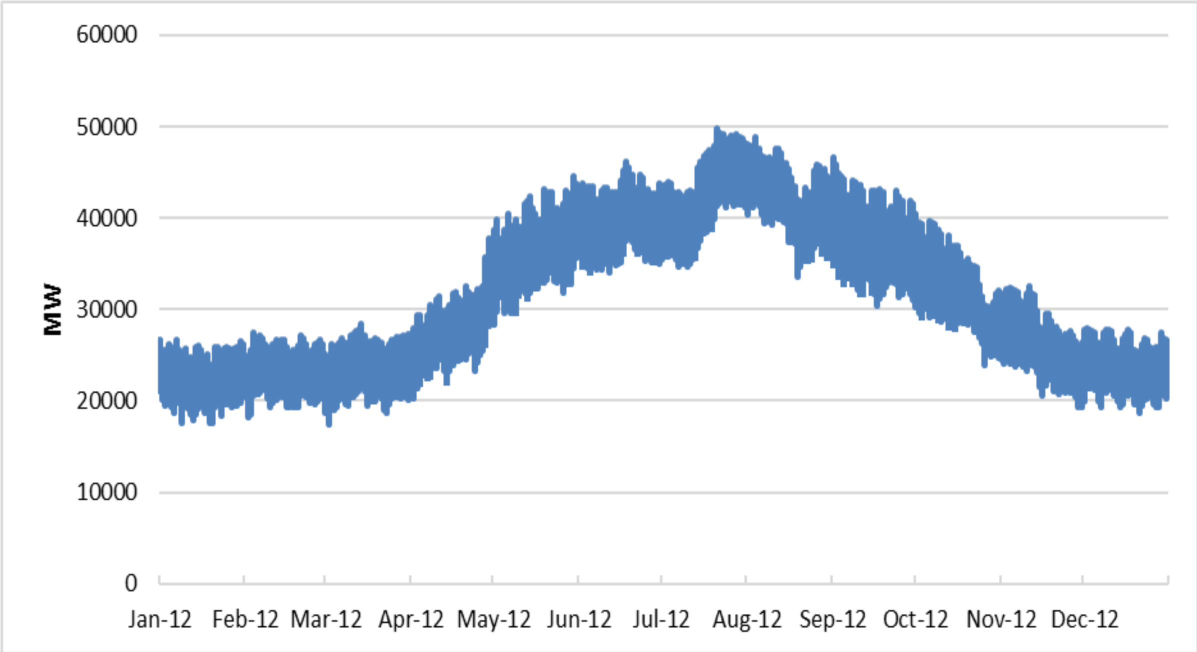
[34] Total degree days (TDD) was calculated as the difference between CCD and HDD.

Historical hourly electricity demand was obtained for the period from 2005 to 2013 for the dispatched hourly data (at an aggregated level) in each operating area. The data represented the overall electric consumption (or electricity requirements) for Saudi Arabia, including the total of all sales to the various customer categories and losses at different voltage levels. The electricity consumed by power plants to power their auxiliaries and controls, which is referred to as station service or own-use, was also included. Figure 3.7 shows an hourly demand curve for Saudi Arabia in 2012. Due to electricity transfer between different operating areas, the data is effectively used to convert the historical electricity sales to the energy required in each region by calculating the ratio of the sales to the aggregated hourly demand measurements. The details of this conversion are addressed in the next sections.

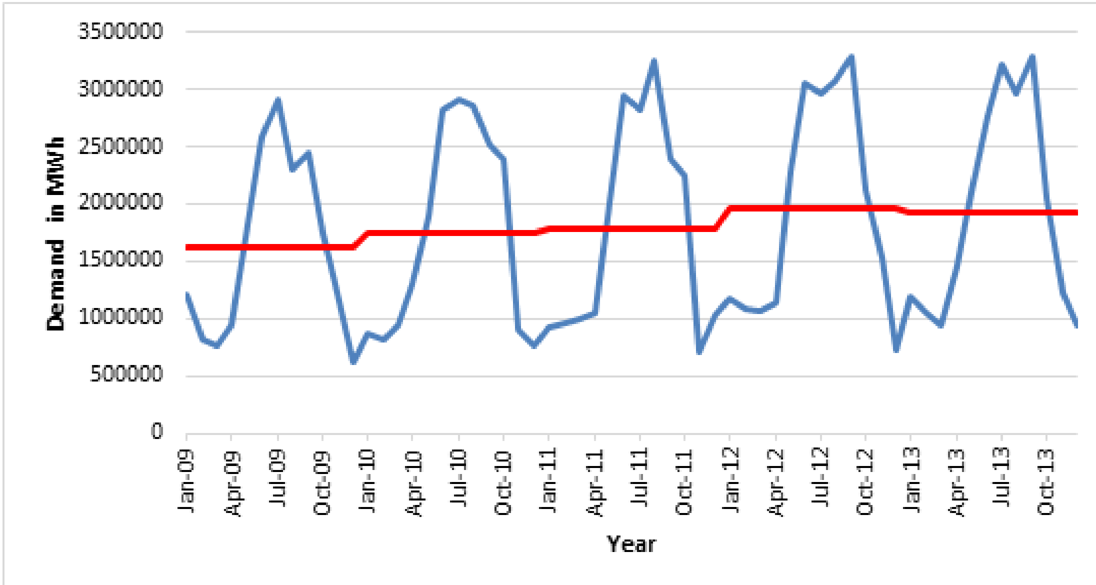


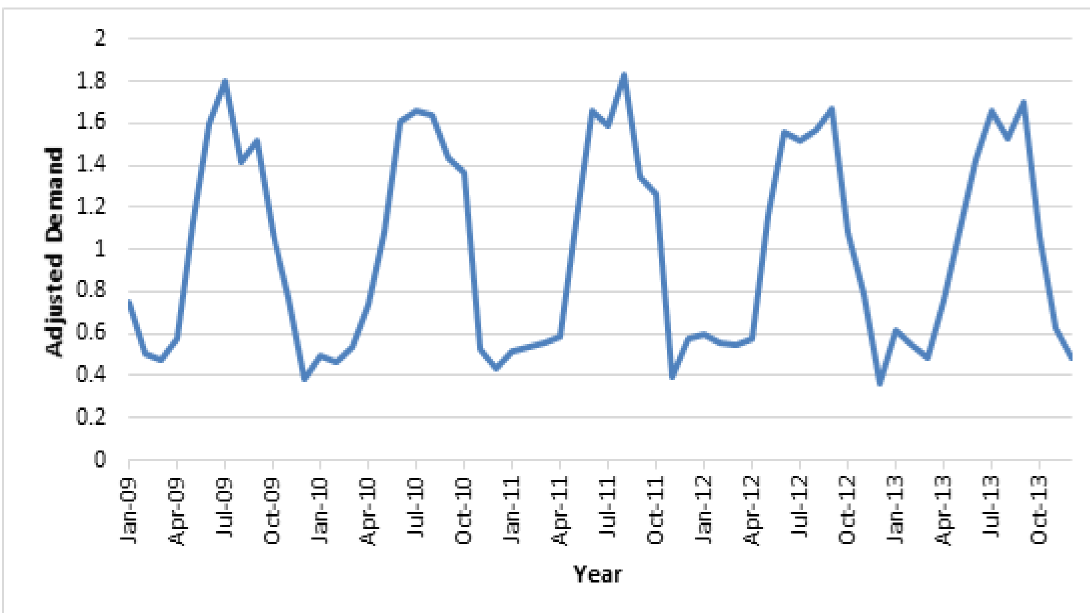
Data source: SEC, 2013

Figure 3.7 Hourly electricity demand for Saudi Arabia, 2012

Since historical hourly demand data at the disaggregated level (namely for each consumer category in each area) was not available, historical monthly and annual demand data for each consumer category in each operating area was obtained from SEC annual reports for use in the long-term demand forecasting model. For example, Figure 3.8 shows the monthly electricity sales data collected for the EOA's residential sector for the period from 2009 to 2013. In addition, Figure 3.9 shows the historical electricity sales for various consumer categories in Saudi Arabia.[35] Electricity sales in the country have grown steadily from 66 TWh in 1992 to 275 TWh in 2014, with an annual average growth rate of 6.6%. Residential and commercial consumers have also clearly increased their relative demand shares from 44% and 7% respectively in 1992 to 50% and 16% respectively in 2014.

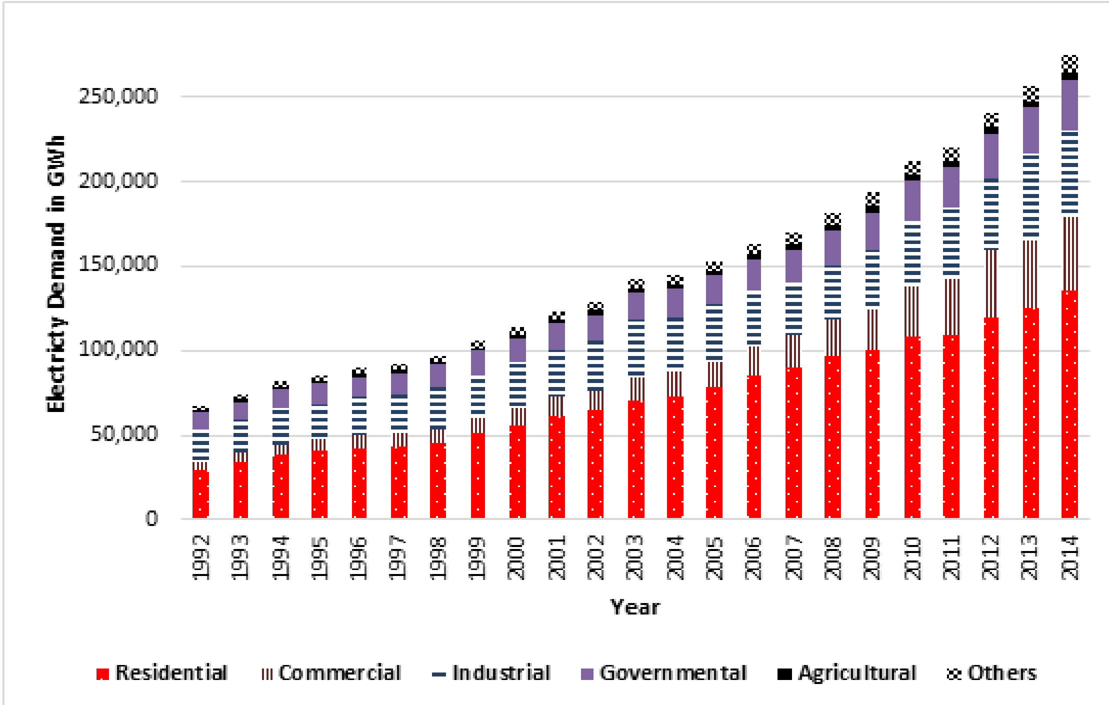
[35] In this chapter, "electricity sales" refer to the demand at the end-use of each consumer category, while "electricity demand" accounts for the electricity sales plus transmission losses and electricity used in power generation stations.





Data source: SEC, 2014

Figure 3.8 Top: Monthly EOA's residential electricity sales 2009-2013 (red line = median annual demand). Bottom: Adjusted monthly electricity sales (median = 1 for each year)



Data source: SEC, 2014

Figure 3.9 Electricity sales in Saudi Arabia by customer category, 1992–2014

3.1.2 Demographic and Economic Data

Tellus (2000, p. 9) and Hyndman and Fan (2009, p. 5) report that economic and demographic factors are largely responsible for the long-term growth of electricity demand. The following economic and demographic data have been highlighted in the CDSI and SEC reports from 1992-2014:

- Residential population;
- Number of residential customers; and
- GDP at 1999 constant prices, with the following components described in Table 3.2:
    - Primary sector: oil and non-oil

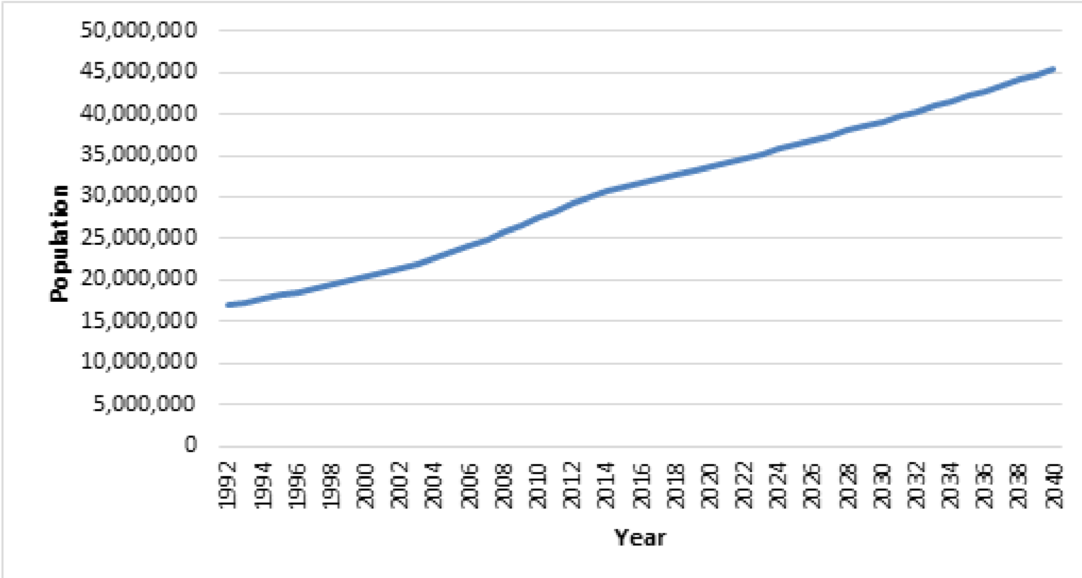
- o Secondary sector: construction, oil, and non-oil
- o Tertiary sector

Table 3.2 GDP definitions for various sectors in Saudi Arabia

Sector	**Sub-Sector**	**Activity**
Primary	**Oil**	Mining and quarrying: crude petroleum and natural gas
	Non-oil	Agriculture Forestry and fishing Electricity, gas, and water Mining and quarrying: other
Secondary	**Construction**	Construction
	Oil	Manufacturing: petroleum refining
	Non-oil	Manufacturing: other
Tertiary		Wholesale and retail trade Restaurants and hotels Transport, storage, and communication Finance Insurance Real estate and business services Community, social and personal services Producers of government services Import duties

Data source: MEP, 2014

As shown in Figure 3.10, Saudi Arabia's total population has grown from less than 17 million in 1992 to more than 30 million in 2014, with an annual growth rate of 2.7%. The population forecast until 2040 was provided by CDSI, with an annual growth rate of 1.5%. The sensitivity of the electricity demand when varying the population forecast by +/-0.5% is investigated.

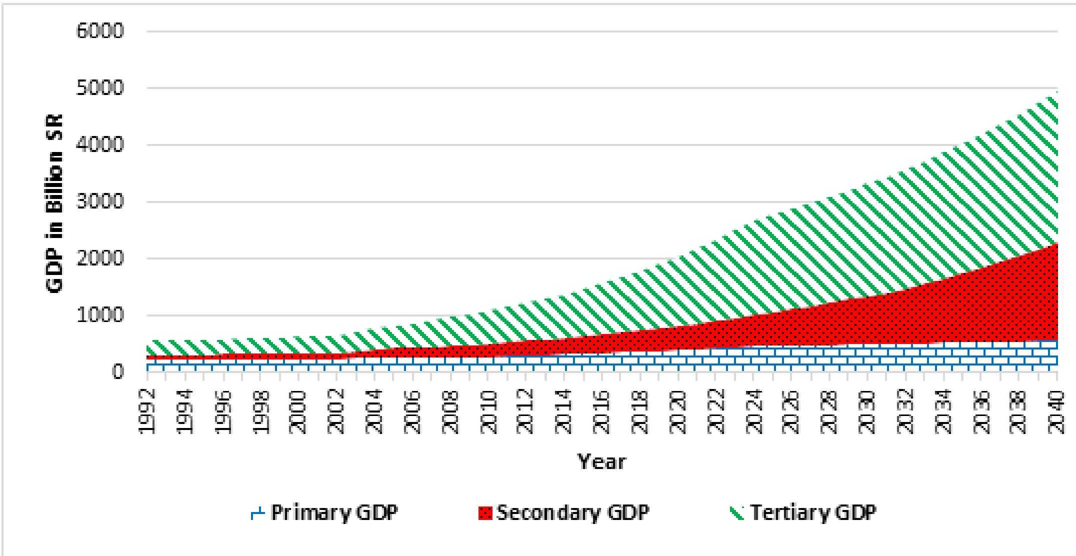


Data source: CDSI

Figure 3.10 Historical data and forecasts for Saudi Arabia's population, 1992–2040

Figure 3.11 presents historical and forecast data for Saudi Arabia's GDP. It reveals that the country's total GDP value reached SAR 1.27 trillion (in 1999 constant price terms) in 2013, with an average annual growth of 4.1%. Between 2006 and 2014, the average annual growth increased to 6%. For future GDP projections, the Ministry of Planning provided forecasts up to 2024 with a 6.6% average annual growth in total GDP. As part of the economic diversification strategy by the government, tertiary GDP and non-oil primary and secondary GDP are expected to grow in this period at 8.8% and 7.1%, respectively; their share of total GDP will increase respectively to 41.9% and 24.9% by 2024. No publications on future Saudi GDP growth were found from other institutions for the period beyond 2024. While other entities in Saudi Arabia do produce their own forecasts, they either do not publish the results or provide only summaries (without detailed data). The King Abdullah University of Science and

Technology (KAUST, 2014) made a time-series GDP forecast for the remaining period; the assumptions in this dissertation analysis follow the same projections for the period from 2025 to 2040. The sensitivity of the electricity demand when varying the GDP forecast by +/-0.5% and +/-1% is investigated.



Data source: MEP[36]

Figure 3.11 Historical data and forecasts for Saudi Arabia's GDP, 1992–2040

3.1.3 Other Assumptions

The historical patterns of Saudi Arabia's network operating areas for the period 2008–2014 indicate a reasonably stable trend for the relative weight in each consumer category. It is therefore justifiable to assume that the same trend will continue in the future when transferring the demand forecast from the sales consumer category level

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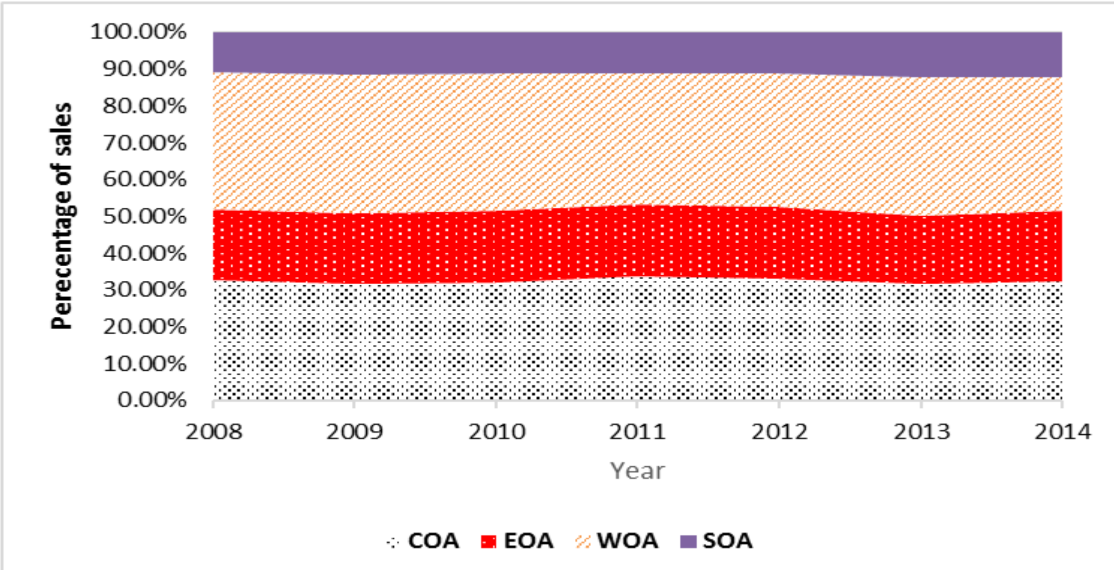
36 The CDSI forecast of GDP was available only until 2024; figures for the remaining years follow forecasts made by KAUST (2014).

to the network area level. For example, Figure 3.12 shows the relative weights of the residential sector in each operating area for the period from 2005 to 2013.



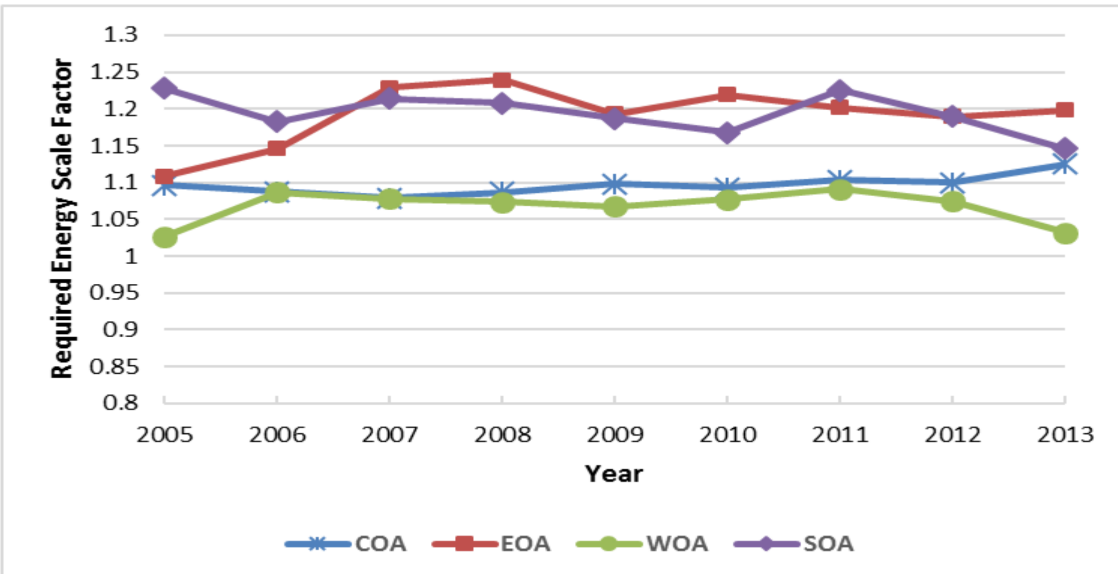
Data source: SEC, 2014

Figure 3.12 Each Saudi operating area's share of the country's residential sector, 2008–2014

As indicated earlier, sales demand does not include network losses and generation stations' own-use. It also does not capture the impact of demand due to interregional transfers. An adjustment is therefore required when transferring the forecasted sales demand at the consumer category level to network operating areas to calculate generation requirements. Since historical aggregated hourly data of dispatched power at each operating area is available, an energy required scale factor can be used as follows:

$$\text{Energy Required Scale Factor} = \frac{\text{Aggregated dispatched Electricity}}{\text{Electricity Sales}} \tag{3.3}$$

Figure 3.13 shows the sales and energy required scale factor based on historical data for period from 2005 to 2013. The average scale factor for each area is used to calculate the energy demand required for each operating area based on the forecasted electricity sales. The high average scale factor values of EOA and SOA are due to the transfer of electricity from these two areas to the other areas.



Data source: SEC, 2014

Figure 3.13 Historical required energy scale factor for all Saudi operating areas, 2005–2014

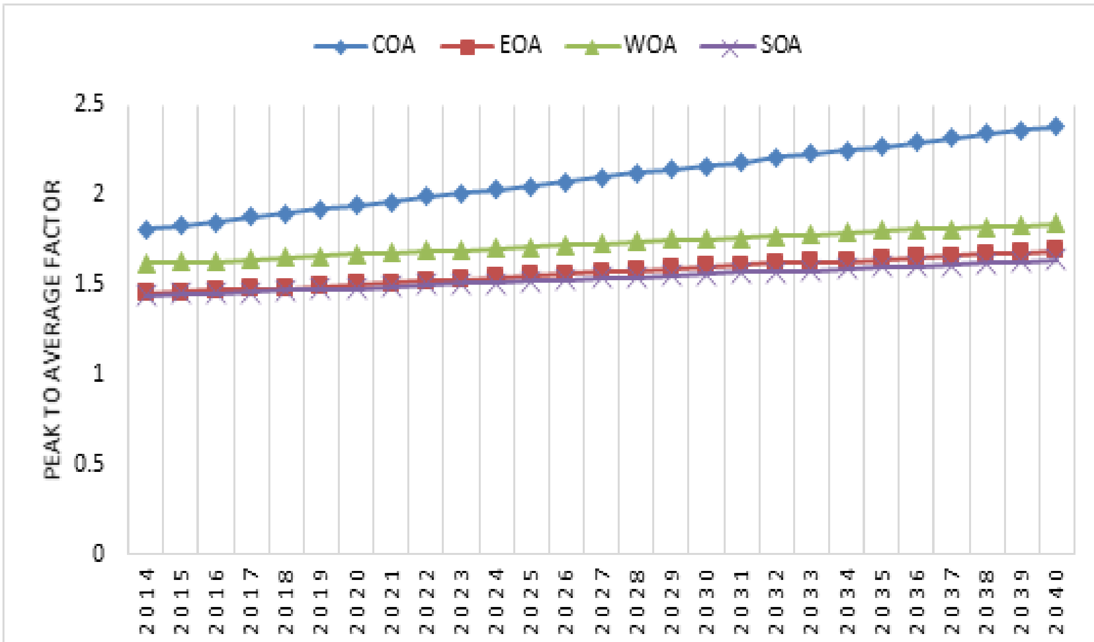
The conversion of average demand to peak demand requires a peak to average demand factor, which is defined as the ratio between the peak and average demands (in GW).[37] Historical factors using hourly dispatched electricity readings for the period from 2005 to 2013 have been obtained and show rising trends throughout the period. The U.S. Energy Information Administration (EIA) investigated the growth of the peak to average electricity demand ratio in various U.S. regions and concluded that the ratio has been rising linearly over the years; for example, New England's (ISO-NE) peak to average ratio rose from 1.52 in 1993 to 1.78 in 2012. Although the U.S. EIA (2014) does not know the exact reasons for this change, likely candidates include:

- Increasing the share of climate-driven appliances causing thee electricity consumption to become more sensitive to weather conditions, thus resulting in higher peak demand during the summer months compared to the annual average;
- Lowering demand for electricity due to advancements in consumption technologies such as energy-efficient lightbulbs and appliances such as refrigerators, as well as higher EE and changes in consumption behaviors; and;
- Moving away from an industry-driven economy, which is associated with steady annual energy consumption, towards a service-based economy.

Figure 3.9 suggests that service consumer categories (such as the residential, commercial, and governmental sectors) increased their shares in electricity sales to reach 77% of Saudi Arabia's total consumption in 2014. This resulted in raising the climate control loads share (i.e. air conditioning in the Kingdom) and therefore increasing the peak to average ratio. A linear extrapolation of the growth rate from the historical peak to average factors is therefore considered as shown in Figure 3.14 for

[37] The peak to average factor is the reciprocal of the load factor.

each network operating area. These factors are used for calculating the peak demand in the forecasting analysis later in this chapter.



Data source: SEC, 2014

Figure 3.14 Extrapolated peak to average factors for all Saudi network areas, 2014–2040

3.2 Methodology Framework

Although KAUST (2014) published aggregated time-series forecasting analyses for the electricity demand in Saudi Arabia, it did not provide load forecasting at disaggregated sector and operating area levels. Another study was conducted by ECRA in 2008 to forecast demand until 2023 using simple econometric analysis (ECRA, 2008). Neither study took the effect of weather on electricity demand into consideration. No other publications on Saudi Arabia's future electricity demand were found from institutions. While other entities in the Kingdom do produce their own forecasts, they either do not publish the results or only provide summaries (without detailed data). The SEC has undertaken 10-year forecasting on power demand and capacity for the electricity sector, but it has not published the results (KAUST, 2014, pp. 1-8).

This research used data outlined earlier to present a methodology (Figure 3.15) for predicting long-term electricity demand until 2040 in the KSA This methodology is comprised of a modeling stage, simulation and forecasting stage, and evaluation stage. The model can be split into two econometric sub-models: an annual demand growth (or long-run) sub-model based on demographic and economic variables and a monthly weather-demand (or short-run) sub-model based on weather variables. Similar approaches to short- and long-run forecasting models have been applied in different countries, such as the United States (Crowkey & Joutz, 2005, p. 3) and Australia (Hyndman & Fan, 2009, p. 4). However, the model in the current study was modified based on available data and its applicability to Saudi Arabia; for example, the proposed methodology utilizes monthly data for the short-run sub-model and an end-use forecasting model for the residential sector.

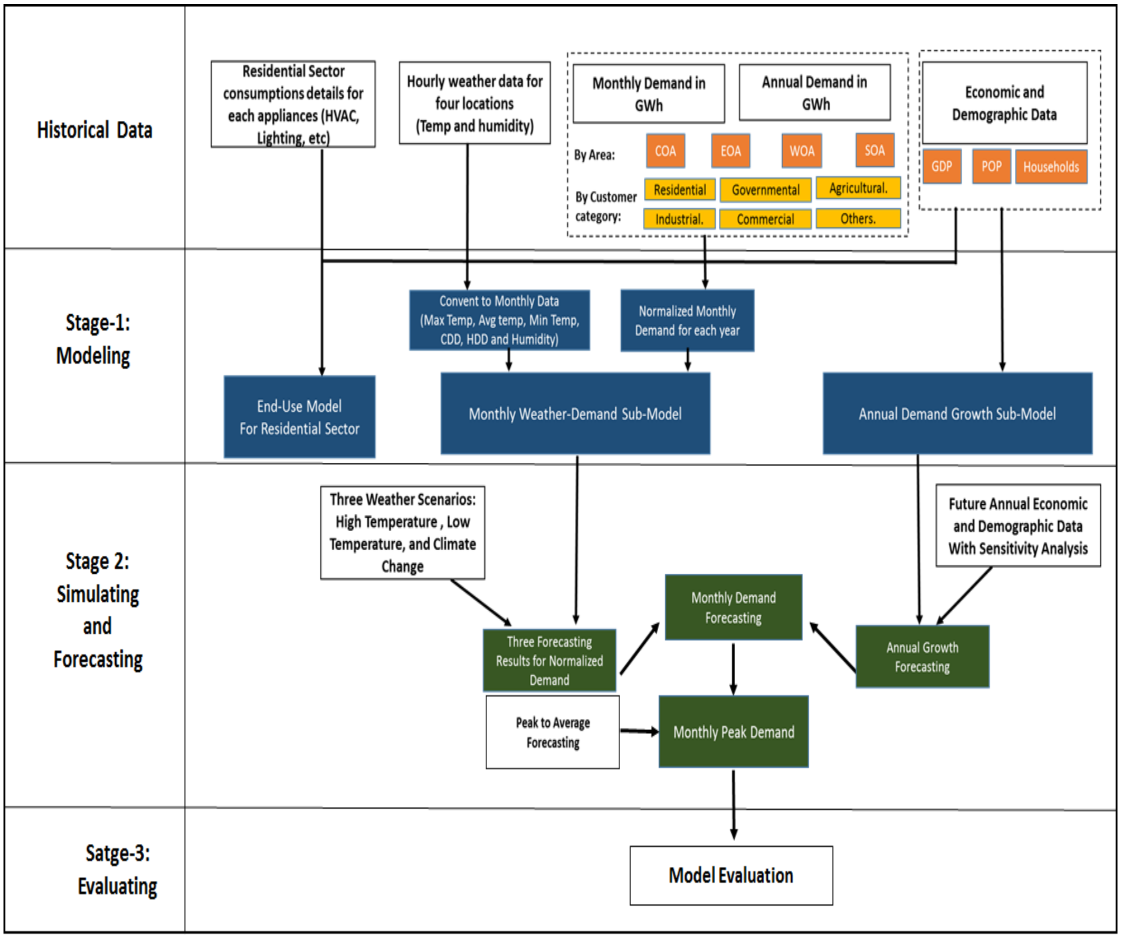


Figure 3.15 Block diagram for the proposed demand forecasting methodology

The first step in this methodology was to select the input variables for both sub-models by minimizing the mean square error (MSE) and ensuring that all models were statistically valid (using EViews software tool). As per the SEC's consumer classifications, the electricity demand (or electricity sales) were grouped into six consumer categories: residential, commercial, industrial, governmental, agricultural, and others. Other consumers include charitable organizations, streets, hospitals, and international and diplomatic organizations. This grouping of customers is used throughout the chapter to report on and to develop the demand forecast for different customer categories in the four network operating areas. While the annual demand growth sub-model (which is based on an econometric approach) was used for all sectors, an end-use (bottom-up) model was used for the residential sector to estimate demand taking a detailed understanding of appliance demand into account.

In the second stage, the estimated models were used to generate forecasts based on three future extreme scenarios of weather variables to account for the impact of changes in weather on electricity demand. The first two scenarios were constructed based on the warmest and coolest summers in the four major cities related to Saudi Arabia's four electricity network operating areas. The third scenario addressed the climate change impact of a two-degree Fahrenheit increase in temperatures over the high temperature scenario. This was similar to the approach adopted in the study of weather effects on electricity loads in the PJM network to investigate how electricity demand is influenced by climate change (Crowkey & Joutz, 2005, p. 3). The forecast was also obtained using the future assumed demographic and economic scenarios, with sensitivity cases based on changes to the growth rates of the variables underlying these forecasts. Existing models, such as DTI energy forecast model[38], use weather variables for forecasting demand in the residential and commercial sectors only, given that their demand is strongly influenced by weather (DTI, 2000); demand in other sectors, such as industrial and agricultural, was not strongly influenced by weather variables. For example, Figure 3.16 shows that the industrial electricity demand in the EOA is not correlated with the average temperature. This stage involved forecasting

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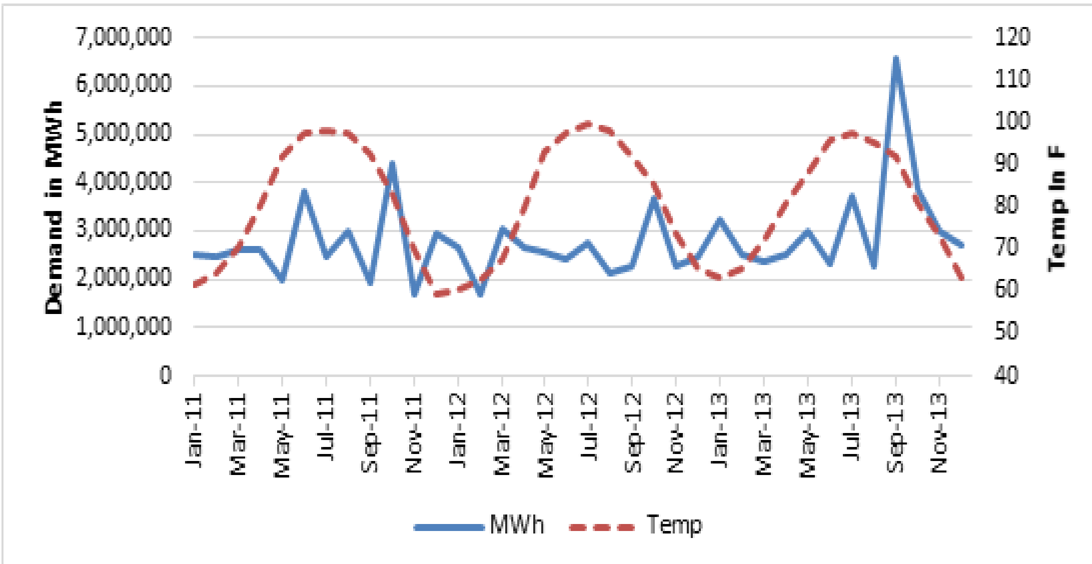
[38] DTI refers to the Department of Trade and Industry in the United Kingdom (now called Department for Business, EEnterprise and Regulatory Reform, BERR).

demand (in GWh) at consumer category and operating area levels. The peak electricity forecasts were also obtained accordingly.



Data source: Weatherbase, 2015; SEC, 2014

Figure 3.16 Industrial demand versus average temperature in Saudi Arabia's EOA, 2011–2013

Finally, the following points were considered when evaluating the model's forecasting performance:

- The year 2014 was included in the forecast and is compared with the actual demand data based on actual weather data; and
- The models were tested using in- and out-of-sample evaluations to ensure the accuracy of the model.

The following section explains the theory behind and implementation of each stage in greater detail.

3.3 Model Establishment

3.3.1 Model Description

As explained earlier, the forecasting model consists of two econometric sub-models: the annual demand growth sub-model (which is based on economic and demographic variables) and the monthly weather-demand sub-model (which is based on weather variables). Following the same approach used by Hyndman and Fan (2009), the forecasting model can be written as follows:

$$y_{t,p} = f_t(w_p) + \sum_{j=1}^{j} C_J Z_{J,t} + n_{t,p} \tag{3.4}$$

Where:

- $y_{t,p}$ denotes monthly electricity sales on year t (measured in GWh) during a month period (p=1, 2, 3,……12);
- $f_t(w_p)$ models all weather effects within each network operating area using econometric analysis;
- $Z_{J,t}$ is the annual demographic and economic variable at time t and its effect on monthly demand as a result of coefficient Cj (irrelevant to period p) through the application of multivariable econometric analysis; and
- $n_{t,p}$ denotes the demand that is left unexplained by the model (i.e. the model residuals) at time t.

Equation 3.4 can be re-written as follows to split between the two sub-models:

$$y_{t,p} = \dot{y}_{t,p} \ \bar{y}_t \tag{3.5}$$

Where $\bar{y}_t$ is the annual average electricity sales for year t in GWh and $\dot{y}_{t,p}$ is the normalized demand for year t in month p. The monthly demand weather sub-model therefore addresses the impact of weather on normalized electricity demand, as shown in Equation 3.6:

$$\dot{y}_{t,p} = f_t(w_p) + n_{t,p} \tag{3.6}$$

To estimate the weather factor$f_p(w_t)$, we can use the following regression model:

$$f_t(w_p) = \beta_0 + \sum_{p=1}^{12} \beta_p W_{t,p} \tag{3.7}$$

Where $W_{p,t}$ are explanatory weather variables that are nonlinear functions of historical weather parameters and β_0, β_p are the regression coefficients.

The model's second component is the annual demand growth sub-model, which examines the annual demographic and economic effects on electricity growth using the following summation term:

$$\sum_{j=1}^{j} C_j Z_{J,t} \tag{3.8}$$

Each of these variables is thus assumed to have a linear relationship with the demand coefficients c_1, …., c_j. Since an end-use model is used for the residential sector, Equation 3.4 can be re-written, using annual end-use demand equation 2.4, as follows:

$$y_{t,p} = f_t(w_p) + \sum_{i=1}^{n} N_i P_i M_i I_i + n_{t,p} \tag{3.9}$$

Since $y_{t,p}$ represents the electricity sales in GWh, the average demand ($Y_{t,p}$) for each consumer category (in GW) can be calculated as follows:

$$\text{Average demand } (Y_{t,p}) = y_{t,p} / \, hours_p \tag{3.10}$$

In order to convert the sales demand from the consumer category level to the network operating area level, the average demand can be calculated as follows:

$$Y_{t,p(Area)} = Y_{t,p} \;\; SF \;\; F_{peak\ to\ average} \tag{3.11}$$

Where SF and $F_{peak\ to\ average}$ are respectively the required energy scale factor and peak to average factor, as defined in the previous assumption section.

3.3.2 Selection Criteria for the Independent Variables

To have the best forecasting model, a highly significant model term along with the optimal combination of independent variables generating an accurate demand forecast must be found. For each sub-model, the electricity sales (dependent variable) was fitted against all possible combinations of independent variables using regression analysis (Hyndman & Fan, 2009, p. 4). Careful consideration was made to avoid imperfect multicollinearity in which one or two regressors were found to be highly correlated (Stock & Watson, 2011, p. 766). Tables 3.3 and 3.4 list the sets of independent variables that were used to explain the electricity sales in the two sub-models. The details of all combinations are shown in the next section.

Table 3.3 Annual demand growth econometric (long-run) sub-model

Dependent Variables[39]	**Independent Variables**[40]
Commercial electricity sales Governmental electricity sales Agricultural electricity sales Others sales	Population Total GDP or sector GDP categories[41]

Table 3.4 Monthly demand weather econometric (short-run) sub-model

Dependent Variables	**Independent Variables**
Residential normalized electricity sales Commercial normalized electricity sales	Monthly maximum temperature Monthly minimum temperature Monthly average temperature Monthly CDD Monthly HDD Monthly average humidity

Selection criteria were used to choose from all possible regression models. Stock and Watson (2011), AEMO (2012, p. 3-5), and MRES (2010, p. F9) summarized statistical criteria for selecting models as follows:

- Greater significance is associated with coefficients that are markedly higher than their standard error terms. Therefore, it is more likely that these coefficients will provide an accurate picture of the real correlation between the dependent (i.e. energy sales) and independent variables. On the other hand, if the coefficient is much smaller than the standard error, there may be a high

[39] For the residential sector, the end-use model was used instead of the econometric model; as a result, the residential sales variable is not included in the table.

[40] Since the electricity price is relatively low and has not changed significantly in the past 25 years (Hagihara, 2013), the price variable was not considered in the analysis.

[41] The GDPs for various sectors and subsectors are defined in Table 3.1.

probability that the true coefficient is zero and that this variable is not significant.

- When accounting for the variation of the dependent variable, its statistical significance is tested with the *t* statistic, which also largely determined the selection of independent variables. The probability that a given variable is a reliable indicator of the dependent variable increases in line with the value of the *t* statistic. Typically, when a *t* statistic has a value higher than 2, it is clear that the variable is appropriate (i.e. statistically significant).
- The *p* value is also helpful in indicating the accuracy of a particular variable as an indicator of the dependent variable. In this case, the strength of the variable for predicting the dependent variable increases as the *p* value decreases.
- The R^2 value reflects the degree of variation in the dependent variable that the model can account for. The R^2 value ranges between 0 and 1, with the latter being the ideal result.
- The adjusted R^2 takes the degrees of freedom into account to modify the R^2. The degrees of freedom represent the amount of observations utilized to make a particular calculation, minus the quantity of variables. As the number of independent variables increase, R^2 also rises. On the other hand, the adjusted R^2 can increase or decrease based on the impact of each new variable
- The *F* statistic statistically assesses the 'fit' of the estimated equation, with a good fit denoted by an *F* statistic that is greater than another critical value, which is determined by the quantity of observations and variables included in the model.
- If all conditions above are satisfied, the model with the least MSE is selected.

- As a final step in the selection criteria, a variable combination that yields an equation where one or more of the fitted coefficients displays a (negative or positive) sign that is contrary to mathematical logic is rejected. It would not be acceptable that electricity sales are viewed as decreasing when GDP is increasing, which would be the case if the output coefficient of the GDP is negative in the derived equation.

3.3.3 The Monthly Demand Weather Sub-Model

A separate model of the form in Equation 3.7 was fitted for each network operating area. The research began with a full model that included all weather variables (as presented in Table 3.4) for input variable selections. The aforementioned selection guidelines were followed to exclude each term from the model one at a time in order to test the predictive capability of each of the variables. In a subsequent test, variables that resulted in decreased MSE were excluded, as were those that failed to fulfill the aforementioned criteria. Consequently, as per the work of Hyndman and Fan (2009, p. 4), a step-wise variable selection process was carried out with consideration of out-of-sample forecasting accuracy.

In order to avoid imperfect multicollinearity that leads to an imprecise estimation of coefficients on at least one individual weather regressor (Stock & Watson, 2011, p. 202), a correlation matrix was developed (see Table 3.5). It shows that weather independent variables (namely maximum temperature, average temperature, minimum temperature, and CDD) were as epxected highly correlated.

Table 3.5 Correlation analysis for weather independent variables, EOA

Covariance Analysis: Ordinary

Sample: 1992M01 2013M12
Included observations: 264

		Correlation
AVGTEMP_F	AVGTEMP_F	1.000000
MAXTEMP_F	AVGTEMP_F	0.996206
MAXTEMP_F	MAXTEMP_F	1.000000
MINTEMP_F	AVGTEMP_F	0.995657
MINTEMP_F	MAXTEMP_F	0.985691
MINTEMP_F	MINTEMP_F	1.000000
HUMIDITY__	AVGTEMP_F	-0.791892
HUMIDITY__	MAXTEMP_F	-0.794537
HUMIDITY__	MINTEMP_F	-0.763756
HUMIDITY__	HUMIDITY__	1.000000
HDD_EOA	AVGTEMP_F	-0.713214
HDD_EOA	MAXTEMP_F	-0.717443
HDD_EOA	MINTEMP_F	-0.709322
HDD_EOA	HUMIDITY__	0.551511
HDD_EOA	HDD_EIOA	1.000000
CDD_EOA	AVGTEMP_F	0.993778
CDD_EOA	MAXTEMP_F	0.988799
CDD_EOA	MINTEMP_F	0.989985
CDD_EOA	HUMIDITY__	-0.787602
CDD_EOA	HDD_EIOA	-0.635516
CDD_EOA	CDD_EOA	1.000000

3.3.4 The Annual Demand Growth Sub-Model

When selecting the economic and demographic variables for this study, models based on Equation 3.8 were taken into consideration, with all possible combinations explored similar the selection process used for the demand weather sub-model. Due to availability of small annual data, it was not feasible to select variables using out-of-sample tests in the case of this sub-model (Hyndman & Fan, 2009, p. 4).

3.3.5 Models Fitting

3.3.5.1 Residential Sector

The predictive capacity of the end-use model in Saudi Arabia's residential sector was investigated by looking at the calculated electricity sales values. Figure 3.17 shows the calculated annual electricity demand versus the actual electricity demand for the period from 2007 to 2014. It can be observed that the model captured the actual electricity sales trend quite well and can be effectively used to forecast the future annual residential electricity demand in Saudi Arabia.

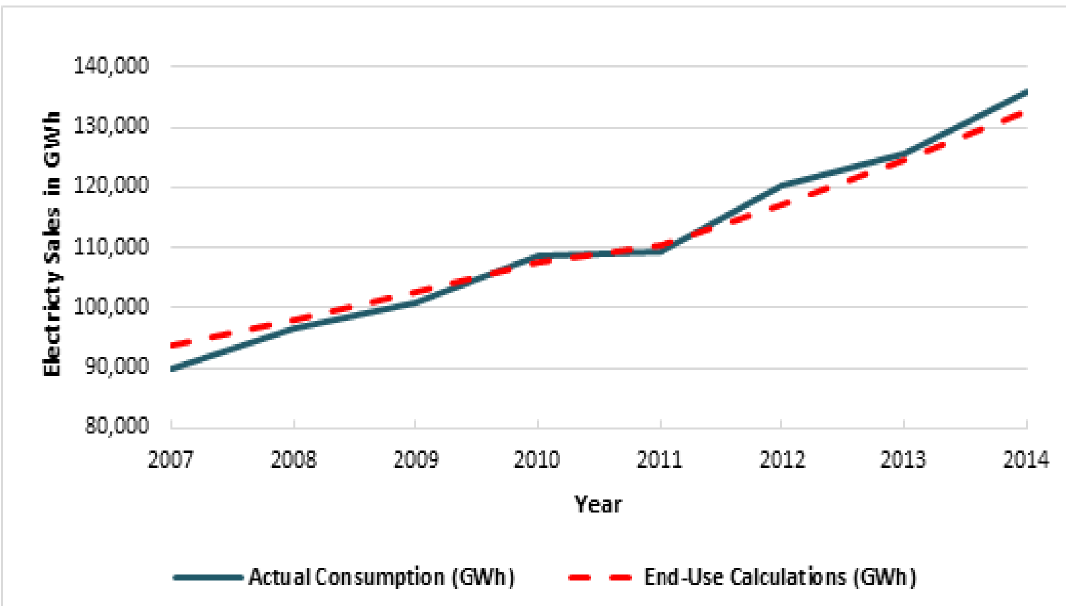


Figure 3.17 Actual annual electricity sales and calculated annual demand from the end-use model, 2007–2014

The monthly demand weather model was selected among all possible combinations of weather independent variables. The model was fitted based on historical monthly data from 1992 to 2010. The predictive capacity was then investigated using out-of-sample forecasting for 2011 to 2013 for all models (as stipulated in Table 3.6 and 3.7) for the EOA. The actual fitted and residual graphs for the best fitted model for the EOA are shown in Figure 3.19. The regression results for the time series data analysis for the best fitted model (Model 4 in Table 3.7) are presented in Table 3.8. Figure 3.18 shows the out-of-sample predicted and actual normalized electricity demand for these years with a minimal root-mean-square error (RMSE) of 0.099776 for the same model. The same was applied to the other three operating areas.[42]

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[42] RMSE is the root mean square error defined as: $\sqrt{\sum_{T+1}^{T+h}(\widehat{y_t} - y_t)^2/h}$ where the forecast sample is represented by *j= T+1, T+2,……, T+ h,* $\widehat{y_t}$ *and* y_t denote the actual and predicted values in period *t.* The use of pseudo out-of-sample forecasting by estimating RMSE is to compare different candidate models that appear to fit the data equally well but can perform quite differently in a pseudo out-of-sample forecasting exercise (Stock & Watson, 2011, p.563)

Table 3.6 Monthly demand weather models fitted to the available data using CDD, HDD, and humidity independent variables in the EOA residential sector[43]

Model 1	CDD	HDD	CDD(-1)	HDD (-1)	Humidity	Avg-CDD (Last 3 Months)	Avg-CDD (Last 6 Months)	Avg-CDD (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	A	A	< t-critical	< t-critical	< t-critical	A	0.963	0.962	0.073261	Rejected
Probability	H	A	A	A	H	H	H	A				
Model 2	CDD								R square	Adjusted R Square	RMSE	Results
t-statistics	A								0.898	0.898	0.153475	Accepted
Probability	A											
Model 3	CDD	HDD							R square	Adjusted R Square	RMSE	Results
t-statistics	A	A							0.92	0.92	0.1056	Accepted
Probability	A	A										
Model 4	CDD	HDD	CDD(-1)	HDD (-1)					R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	< t-critical	A					0.921	0.92	0.136195	Rejected
Probability	A	A	H	A								
Model 5	CDD	HDD	CDD(-1)	HDD (-1)	Humidity				R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	A	A	A				0.931	0.93	0.128366	Accepted
Probability	H	A	A	A	A							
Model 6	CDD	HDD	CDD(-1)			Avg-CDD (Last 3 Months)	Avg-CDD (Last 6 Months)	Avg-CDD (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	< t-critical	A	< t-critical			< t-critical	A	< t-critical	0.955	0.954	0.104367	Rejected
Probability	H	A	A			H	H	A				
Model 7	CDD	HDD	CDD(-1)			Avg-CDD (Last 3 Months)			R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	A			A			0.94	0.94	0.118429	Accepted
Probability	A	A	A			A						
Model 8	CDD	HDD	CDD(-1)			Avg-CDD (Last 3 Months)	Avg-CDD (Last 6 Months)		R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	A			A	A		0.951	0.95	0.108625	Accepted
Probability	A	A	A			A	A					
Model 9	CDD	HDD	CDD(-1)			Avg-CDD (Last 3 Months)		Avg-CDD (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	A			A		A	0.955	0.954	**0.102463**	Accepted
Probability	A	A	A			A		A				
Model 10	CDD	HDD	CDD(-1)				Avg-CDD (Last 6 Months)	Avg-CDD (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	A				A	A	0.955	0.954	0.104778	Rejected
Probability	H	A	A				A	A				

[43] "A" means is acceptable when the *t* statistic is higher than two, while "H" indicates high probability when the *p* value is not close to zero.

Table 3.7 Monthly demand weather models fitted to the available data using average temperature, HDD, and humidity independent variables in the EOA residential sector

Model 1	Avg_Temp Sq	HDD	Avg_Temp Sq (-1)	HDD (-1)	Humidity	Avg-Temp Sq (Last 3 Months)	Avg-Temp Sq (Last 6 Months)	Avg-Temp Sq (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	A	A	< t-critical	< t-critical	< t-critical	< t-critical	0.967	0.966	0.090918	Rejected
Probability	H	A	A	A	H	H	H	A				
Model 2	Avg_Temp Sq								R square	Adjusted R Square	RMSE	Results
t-statistics	A								0.884	0.884	0.161578	Accepted
Probability	A											
Model 3	Avg_Temp Sq	HDD							R square	Adjusted R Square	RMSE	Results
t-statistics	A	A							0.926	0.925	0.131413	Accepted
Probability	A	A										
Model 4	Avg_Temp Sq	HDD	Avg_Temp Sq (-1)	HDD (-1)					R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	A	A					0.957	0.957	**0.099776**	Accepted
Probability	A	A	A	A								
Model 5	Avg_Temp Sq	HDD	Avg_Temp Sq (-1)	HDD (-1)	Humidity				R square	Adjusted R Square	RMSE	Results
t-statistics	A	A	A	A	< t-critical				0.957	0.956	0.099655	Rejected
Probability	H	A	A	A	H							
Model 6	Avg_Temp Sq	HDD				Avg-Temp Sq (Last 3 Months)	Avg-Temp Sq (Last 6 Months)	Avg-Temp Sq (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	< t-critical	A				< t-critical	< t-critical	A	0.955	0.955	0.104603	Rejected
Probability	H	A				H	H	A				
Model 7	Avg_Temp Sq	HDD				Avg-Temp Sq (Last 3 Months)			R square	Adjusted R Square	RMSE	Results
t-statistics	A	A				A			0.946	0.945	0.112451	Accepted
Probability	A	A				A						
Model 8	Avg_Temp Sq	HDD				Avg-Temp Sq (Last 3 Months)	Avg-Temp Sq (Last 6 Months)		R square	Adjusted R Square	RMSE	Results
t-statistics	A	A				A	A		0.951	0.951	0.109055	Accepted
Probability	A	A				A	A					
Model 9	Avg_Temp Sq	HDD				Avg-Temp Sq (Last 3 Months)		Avg-Temp Sq (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A	A				A		A	0.956	0.955	0.10456	Accepted
Probability	A	A				A		A				
Model 10	Avg_Temp Sq	HDD					Avg-Temp Sq (Last 6 Months)	Avg-Temp Sq (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A	A					A	A	0.955	0.954	0.104923	Rejected
Probability	H	A					A	A				

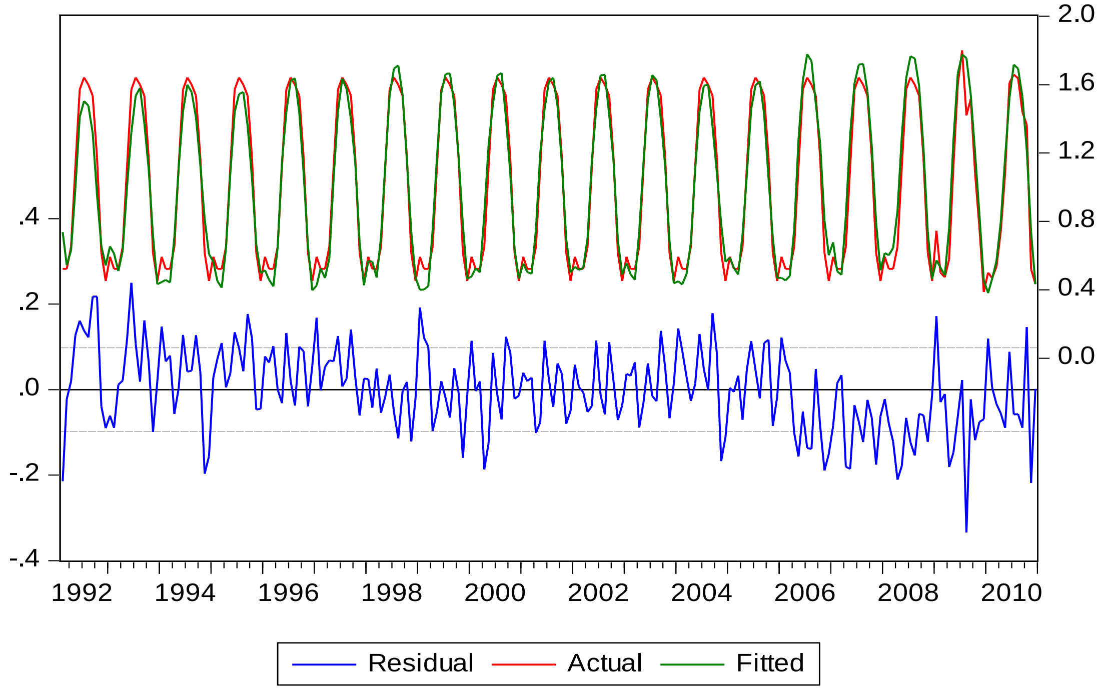


Figure 3.18 The actual, fitted, and residual trends for the residential monthly normalized demand weather sub-model for the EOA, 1992–2010

Table 3.8 Regression analysis of the best fitted monthly demand weather models in the EOA residential sector

Dependent Variable: MWH_NORM
Method: Least Squares
Sample (adjusted): 1992M02 2010M12
Included observations: 227 after adjustments

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-0.865040	0.035420	-24.42257	0.0000
AVG_TEMP_SQ	0.000185	6.73E-06	27.42376	0.0000
HDD_EIOA	0.001835	0.000174	10.52608	0.0000
AVG_TEMP_SQ(-1)	8.28E-05	6.59E-06	12.56050	0.0000
HDD_EOA(-1)	0.001143	0.000162	7.042694	0.0000

R-squared	0.957393	Mean dependent var	1.001793
Adjusted R-squared	0.956625	S.D. dependent var	0.469970
S.E. of regression	0.097879	Akaike info criterion	-1.788385
Sum squared resid	2.126835	Schwarz criterion	-1.712946
Log likelihood	207.9817	Hannan-Quinn criter.	-1.757944
F-statistic	1247.089	Durbin-Watson stat	1.291700
Prob(F-statistic)	0.000000		

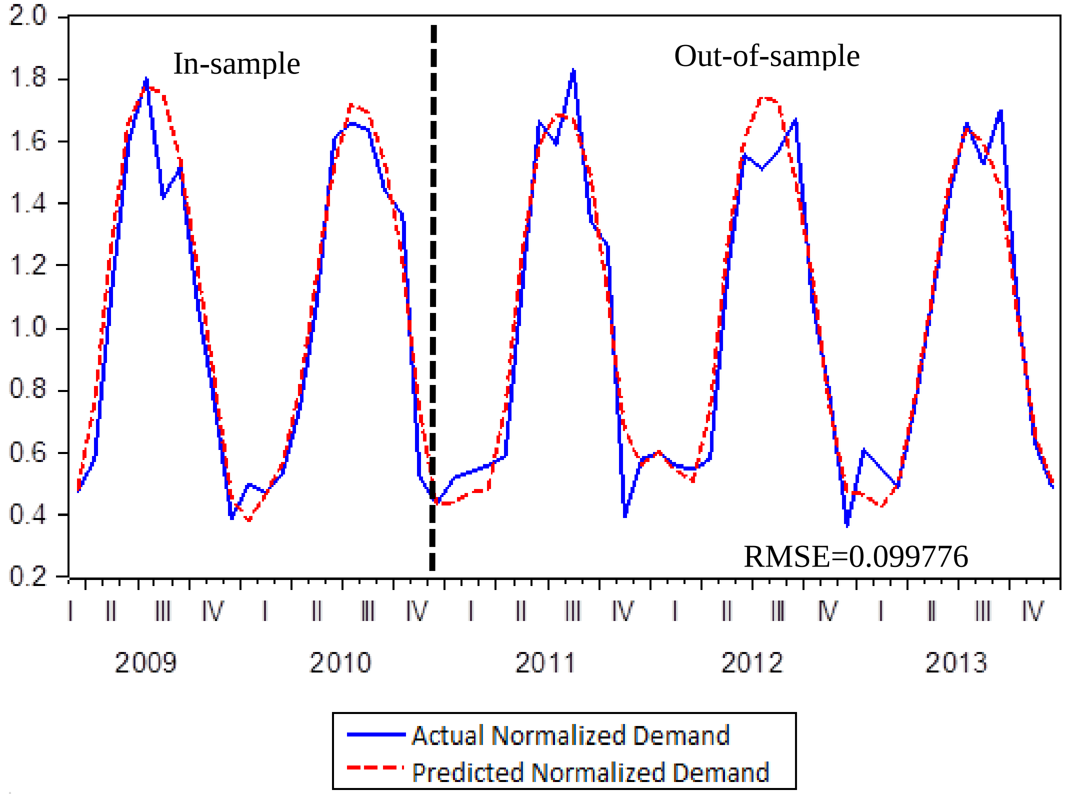


Figure 3.19 Actual versus predicted normalized demand for the residential weather demand sub-model for the EOA, 2009–2013

Figure 3.20 illustrates the estimated EOA's residential electricity demand for each of the data periods. These estimates were generated by integrated the annual fits with those fits from the monthly demand weather sub-model.

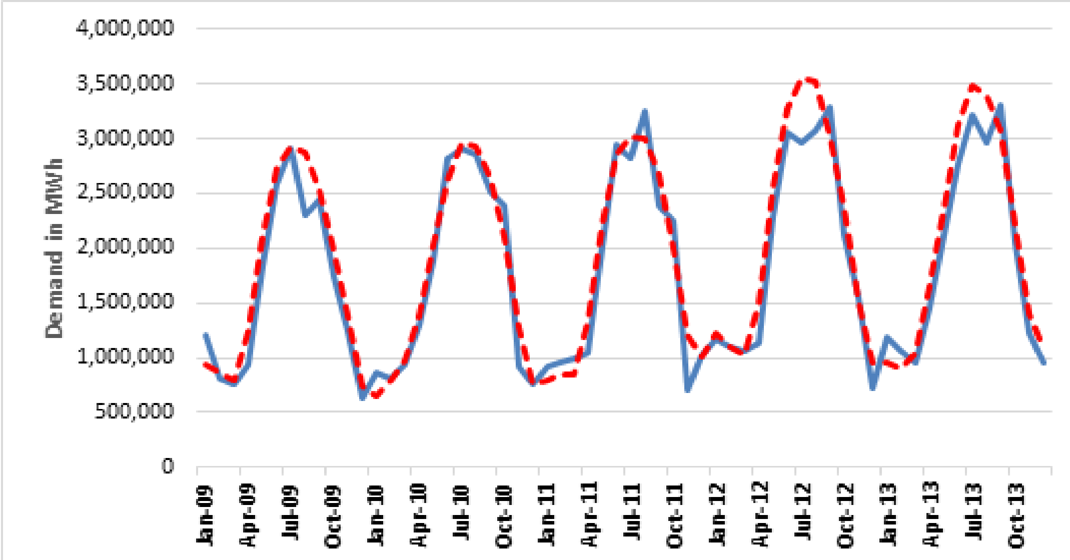


Figure 3.20 Actual versus predicted demand for the residential model for EOA, 2009–2013

3.3.5.2 Commercial Sector

Similar as for the residential sector, the predictive capacity of the annual demand growth econometric sub-model in Saudi Arabia's commercial sector was investigated by looking at the predicted electricity sales values. Table 3.9 shows the results of all possible models that were tested using the selection criteria highlighted earlier and the independent variables listed in Table 3.3. While the population was expected to be a significant explanatory factor, it was found to be statistically irrelevant when combined with GDP. Figure 3.21 shows the fitted annual electricity demand versus the actual electricity demand for the period from 1992 to 2013 for the best fitted model. The regression results for the time series data analysis for this model are presented in Table 3.10. It can be observed that the model captured the actual demand profile remarkably well and can be effectively used to forecast the future annual commercial electricity demand in Saudi Arabia.

Table 3.9 Annual demand growth models fitted to the available data in the commercial sector

Model 1	**Total GDP**	**Population**	R^2	**Adjusted** R^2	**Sum of errors**	**Results**
t statistic	48.0287	-0.456595	0.963	0.962	1690.3	Rejected
Probability	0	0.6529				
Model 2	**Primary GDP**	**Population**	R^2	**Adjusted** R^2	**Sum of errors**	**Results**
t statistic	1.94511	5.71815	0.952	0.947	2723.1	Rejected
Probability	0.0659	0.6529				
Model 3	**Secondary GDP**	**Population**	R^2	**Adjusted** R^2	**Sum of errors**	**Results**
t statistic	6.4111	-1.8756	0.981	0.979	1698.9	Rejected
Probability	0	0.0754				
Model 4	**Tertiary GDP**	**Population**	R^2	**Adjusted** R^2	**Sum of errors**	**Results**
t statistic	6.8289	-0.0829	0.982	0.981	1651.5	Rejected
Probability	0	0.9348				
Model 5	**Total GDP**		R^2	**Adjusted** R^2	**Sum of errors**	**Results**
t statistic	33.2692		0.981	0.98	1658	Accepted
Probability	0					
Model 6	**Primary GDP**		R^2	**Adjusted** R^2	**Sum of errors**	**Results**
t statistic	12.0683		0.963	0.962	4313.6	Accepted
Probability	0					
Model 7	**Secondary GDP**		R^2	**Adjusted** R^2	**Sum of errors**	**Results**
t statistic	30.6311		0.978	0.977	1797.9	Accepted
Probability	0					
Model 8	**Tertiary GDP**		R^2	**Adjusted** R^2	**Sum of errors**	**Results**
t statistic	71.22615		0.982	0.981	1612	Accepted
Probability	0					
Model 9		**Population**	R^2	**Adjusted** R^2	**Sum of errors**	**Results**
t statistic		18.6605	0.963	0.962	2898	Accepted
Probability		0				

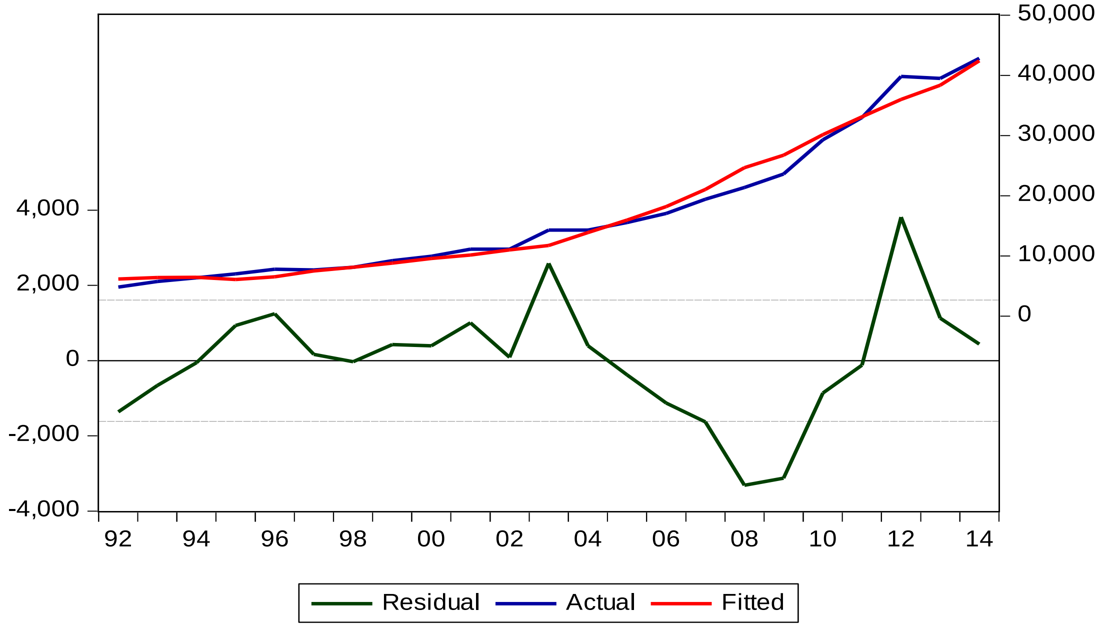


Figure 3.21 Actual, fitted, and residual curves for the annual demand growth sub-model in the commercial sector, 1992–2014 (MWh)

Table 3.10 Regression analysis of the best fitted annual demand growth model for the commercial sector

Dependent Variable: COMM_SALES
Method: Least Squares
Sample: 1992 2014
Included observations: 23

Variable	Coefficient	Std. Error	t-Statistic	Prob.
TERTIARY_GDP	71.22615	2.080287	34.23862	0.0000
C	-12235.22	927.3555	-13.19367	0.0000

R-squared	0.982401	Mean dependent var	17357.04
Adjusted R-squared	0.981563	S.D. dependent var	11872.17
S.E. of regression	1612.017	Akaike info criterion	17.69130
Sum squared resid	54570599	Schwarz criterion	17.79004
Log likelihood	-201.4500	Hannan-Quinn criter.	17.71613
F-statistic	1172.283	Durbin-Watson stat	0.893376
Prob(F-statistic)	0.000000		

To examine the weather effects on the commercial sector, the best fitted monthly demand weather model was selected among all possible combinations of weather independent variables. The model was fitted based on monthly historical data from 1992 to 2010. The predictive capacity was then investigated using out-of-sample forecasting for 2011 to 2013 for all models. Tables 3.11 and 3.12 show the results of the models tested for the EOA using the criteria highlighted earlier. The actual, fitted, and residual graphs for the best-fitted model for the EOA are shown in Figure 3.22. The regression results for the time series data analysis for the best fitted model are presented in Table 3.13. Figure 3.23 shows the out-of-sample predicted and actual normalized electricity demand for 1992 to 2010 with a minimal RMSE of 0.0724 for the same model. The same process has been applied to the other three areas.

Table 3.11 Monthly demand weather models fitted to the available data using CDD, HDD, & humidity independent variables in the EOA commercial sector

Model 1	**CDD**	**HDD**	**CDD(-1)**	**HDD (-1)**	**Humidity**	**Avg-CDD (Last 3 Months)**	**Avg-CDD (Last 6 Months)**	**Avg-CDD (Last 12 Months)**	**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A	A	< t-critical	< t-critical	< t-critical	A	< t-critical	< t-critical	0.957	0.956	0.073261	Rejected
Probability	A	A	H	H	H	A	A	H				
Model 2	**CDD**								**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A								0.926	0.926	0.104461	Accepted
Probability	A											
Model 3	**CDD**	**HDD**							**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A	< t-critical							0.926	0.926	0.076692	Rejected
Probability	A	H										
Model 4	**CDD**		**CDD(-1)**						**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A		A						0.945	0.944	0.092907	Accepted
Probability	A		A									
Model 5	**CDD**	**HDD**	**CDD(-1)**	**HDD (-1)**					**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A	< t-critical	A	< t-critical					0.946	0.945	0.092469	Rejected
Probability	A	H	A	H								
Model 6	**CDD**	**HDD**	**CDD(-1)**	**HDD (-1)**	**Humidity**				**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A	A	A	< t-critical	< t-critical				0.931	0.93	0.092629	Rejected
Probability	H	H	A	H	H							
Model 7	**CDD**		**CDD(-1)**			**Avg-CDD (Last 3 Months)**	**Avg-CDD (Last 6 Months)**	**Avg-CDD (Last 12 Months)**	**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	< t-critical		< t-critical			< t-critical	A	< t-critical	0.955	0.954	0.08873	Rejected
Probability	H		A			H	H	A				
Model 8	**CDD**		**CDD(-1)**			**Avg-CDD (Last 3 Months)**			**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A		A			< t-critical			0.946	0.945	0.092579	Rejected
Probability	A		A			H						
Model 9	**CDD**		**CDD(-1)**			**Avg-CDD (Last 3 Months)**	**Avg-CDD (Last 6 Months)**		**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A		< t-critical			A	A		0.954	0.953	0.088856	Rejected
Probability	A		H			A	A					
Model 10	**CDD**		**CDD(-1)**			**Avg-CDD (Last 3 Months)**		**Avg-CDD (Last 12 Months)**	**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A		< t-critical			< t-critical		A	0.953	0.952	0.089696	Rejected
Probability	A		H			H		A				
Model 11	**CDD**		**CDD(-1)**				**Avg-CDD (Last 6 Months)**	**Avg-CDD (Last 12 Months)**	**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A		A				< t-critical	A	0.953	0.952	0.0896	Rejected
Probability	A		A				H	A				
Model 12	**CDD**		**CDD(-1)**					**Avg-CDD (Last 12 Months)**	**R square**	**Adjusted R Square**	**RMSE**	**Results**
t-statistics	A		A					A	0.953	0.952	0.089659	Accepted
Probability	A		A					A				

Table 3.12 Monthly demand weather models fitted to the available data using average temperature, HDD, & humidity independent variables in the EOA commercial sector

Model 1	Avg_Temp Sq	HDD	Avg_Temp Sq (-1)	HDD (-1)	Humidity	Avg-Temp Sq (Last 3 Months)	Avg-Temp Sq (Last 6 Months)	Avg-Temp Sq (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A	< t-critical	< t-critical	A	< t-critical	A	< t-critical	< t-critical	0.954	0.952	0.08928	Rejected
Probability	A	H	H	H	H	H	H	A				
Model 2	Avg_Temp Sq								R square	Adjusted R Square	RMSE	Results
t-statistics	A								0.921	0.92	0.106127	Accepted
Probability	A											
Model 3	Avg_Temp Sq	HDD							R square	Adjusted R Square	RMSE	Results
t-statistics	A	< t-critical							0.922	0.921	0.105919	Rejected
Probability	A	H										
Model 4	Avg_Temp Sq	HDD	Avg_Temp Sq (-1)	HDD (-1)					R square	Adjusted R Square	RMSE	Results
t-statistics	A	< t-critical	A	A					0.943	0.942	0.093728	Rejected
Probability	A	H	A	H								
Model 5	Avg_Temp Sq	HDD	Avg_Temp Sq (-1)	HDD (-1)	Humidity				R square	Adjusted R Square	RMSE	Results
t-statistics	A	< t-critical	A	A	< t-critical				0.943	0.942	0.093714	Rejected
Probability	H	H	A	H	H							
Model 6	Avg_Temp Sq	HDD				Avg-Temp Sq (Last 3 Months)	Avg-Temp Sq (Last 6 Months)	Avg-Temp Sq (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A	< t-critical				A	A	< t-critical	0.953	0.952	0.089615	Rejected
Probability	A	H				A	A	H				
Model 7	Avg_Temp Sq	HDD				Avg-Temp Sq (Last 3 Months)			R square	Adjusted R Square	RMSE	Results
t-statistics	A	< t-critical				A			0.941	0.94	0.094874	Rejected
Probability	A	H				A						
Model 8	Avg_Temp Sq					Avg-Temp Sq (Last 3 Months)			R square	Adjusted R Square	RMSE	Results
t-statistics	A					A			0.941	0.94	0.094876	Accepted
Probability	A					A						
Model 9	Avg_Temp Sq					Avg-Temp Sq (Last 3 Months)	Avg-Temp Sq (Last 6 Months)		R square	Adjusted R Square	RMSE	Results
t-statistics	A					A	A		0.952	0.952	**0.089632**	Accepted
Probability	A					A	A					
Model 10	Avg_Temp Sq					Avg-Temp Sq (Last 3 Months)		Avg-Temp Sq (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A					A		A	0.949	0.948	0.091323	Accepted
Probability	A					A		A				
Model 11	Avg_Temp Sq						Avg-Temp Sq (Last 6 Months)	Avg-Temp Sq (Last 12 Months)	R square	Adjusted R Square	RMSE	Results
t-statistics	A						A	A	0.947	0.946	0.092567	Accepted
Probability	A						A	A				

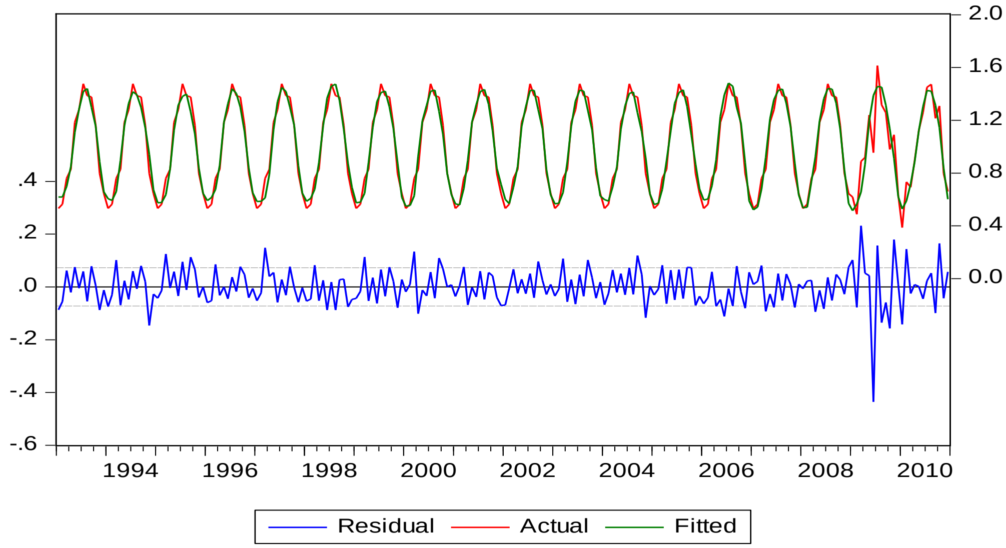


Figure 3.22 The actual, fitted, and residual trends for the commercial monthly normalized demand weather sub-model in the EOA, 1992–2010

Table 3.13 Regression analysis of the best fitted monthly demand weather models in the EOA commercial sector

Dependent Variable: MWH_NORM
Method: Least Squares
Sample (adjusted): 1993M01 2010M12
Included observations: 216 after adjustments

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.923213	0.074294	12.42654	0.0000
CDD_EOA	0.000642	2.50E-05	25.67029	0.0000
CDD_EOA(-1)	0.000246	2.51E-05	9.780837	0.0000
CDD_12MONTHS	-0.000741	0.000148	-5.006511	0.0000

R-squared	0.953030	Mean dependent var	1.000000
Adjusted R-squared	0.952365	S.D. dependent var	0.331817
S.E. of regression	0.072420	Akaike info criterion	-2.394318
Sum squared resid	1.111874	Schwarz criterion	-2.331812
Log likelihood	262.5863	Hannan-Quinn criter.	-2.369065
F-statistic	1433.841	Durbin-Watson stat	2.599339
Prob(F-statistic)	0.000000		

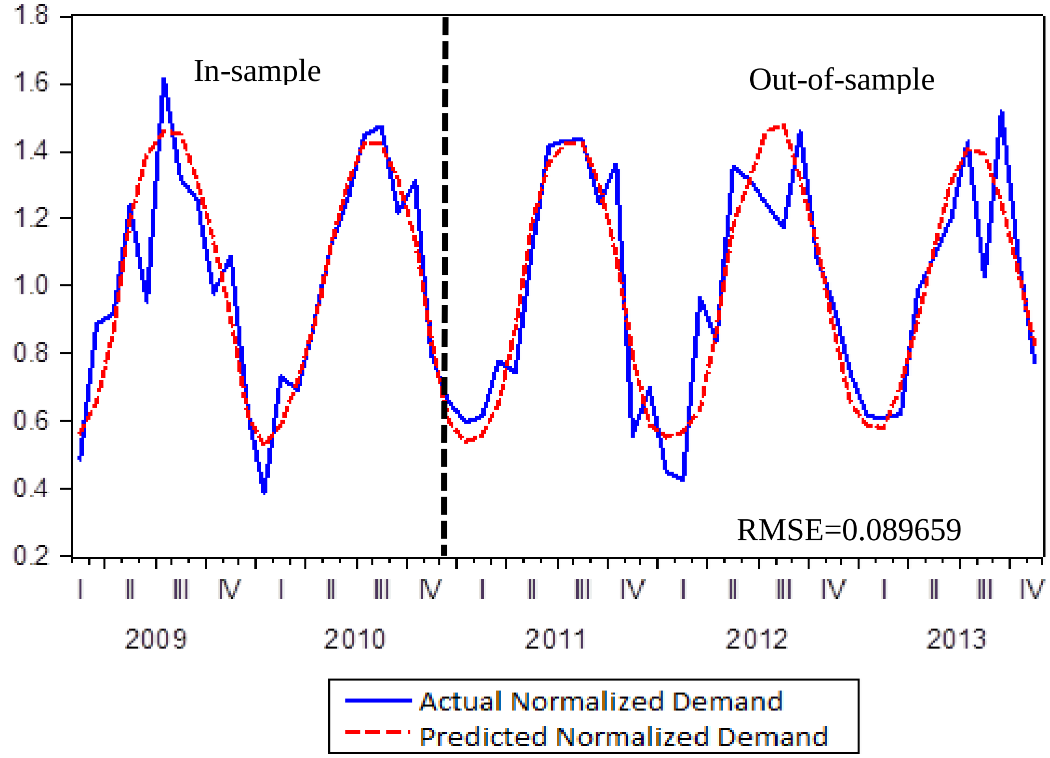


Figure 3.23 Actual versus predicted normalized demand for the commercial weather demand sub-model for EOA, 2009–2013

Figure 3.24 illustrates the estimated EOA's commercial electricity demand for each of the data periods. These estimates were generated by integrated the annual fits with those fits from the monthly demand weather sub-model.

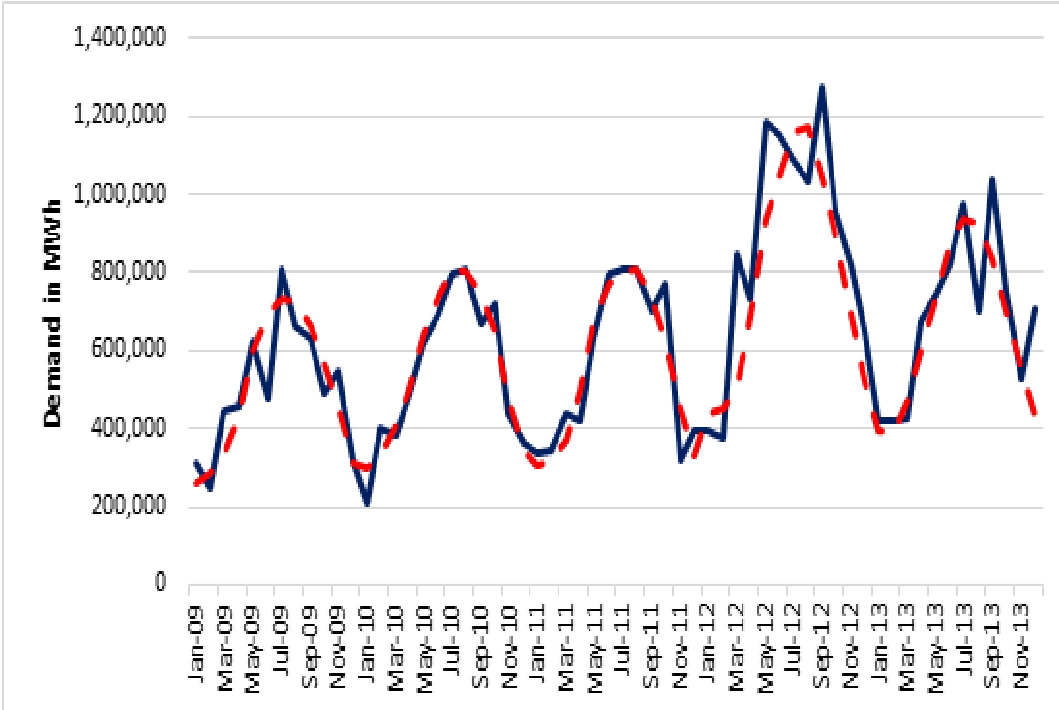


Figure 3.24 Actual versus predicted demand for the commercial model for the EOA, 2009–2013

3.3.5.3 Governmental Sector

Figure 3.25 shows the fitted annual electricity demand versus the actual electricity demand for the period from 1992 to 2013 for the best model for the governmental sector. The regression results for the time series data analysis for the best fitted model are presented in Table 3.14. It can be observed that the model captured the actual demand profile remarkably well and can be effectively used to forecast the future annual governmental electricity demand in Saudi Arabia. The best fitted models for the industrial, agricultural, and others sectors have been selected and tested in the same fashion.

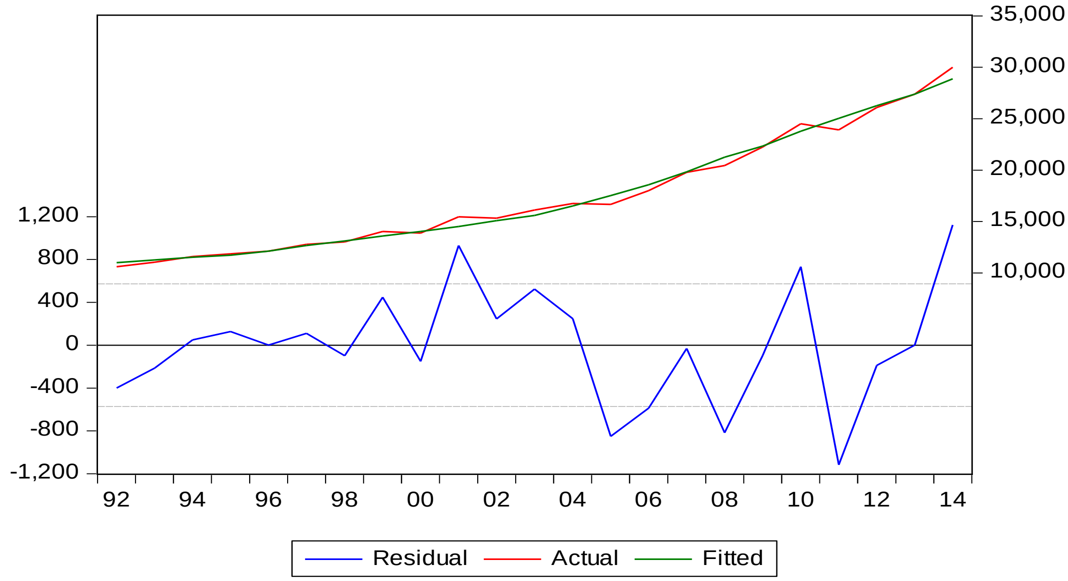


Figure 3.25 The actual, fitted, and residual trends for governmental annual demand model, 1992–2014 (GWh)

Table 3.14 Regression analysis of the best fitted monthly demand weather models in the governmental sector

Dependent Variable: GOVERN_SALES
Method: Least Squares
Sample: 1992 2014
Included observations: 23

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-4445.819	1755.000	-2.533230	0.0198
TOTAL_POP	0.000640	0.000142	4.502848	0.0002
TERTIARY_GDP	17.75924	3.741961	4.745970	0.0001

R-squared	0.990870	Mean dependent var	17557.04
Adjusted R-squared	0.989957	S.D. dependent var	5715.626
S.E. of regression	572.7981	Akaike info criterion	15.66005
Sum squared resid	6561954.	Schwarz criterion	15.80816
Log likelihood	-177.0906	Hannan-Quinn criter.	15.69730
F-statistic	1085.260	Durbin-Watson stat	1.771080
Prob(F-statistic)	0.000000		

Figure 3.26 and Table 3.15 show that the historical monthly normalized demand of governmental sector in the EOA was not highly correlated with weather variables (i.e. average monthly temperature and average monthly CDD). Except for the residential and commercial sectors, the SEC annual reports noted that monthly electricity sales did not necessarily represent actual consumption, as they included the settlement of unbilled sales from previous months. The historical monthly sales for these sectors could therefore not be used in our forecasting model. For the purpose of demand forecasting in this chapter, the monthly demand weather sub-model was applied strictly to the residential and commercial sectors.

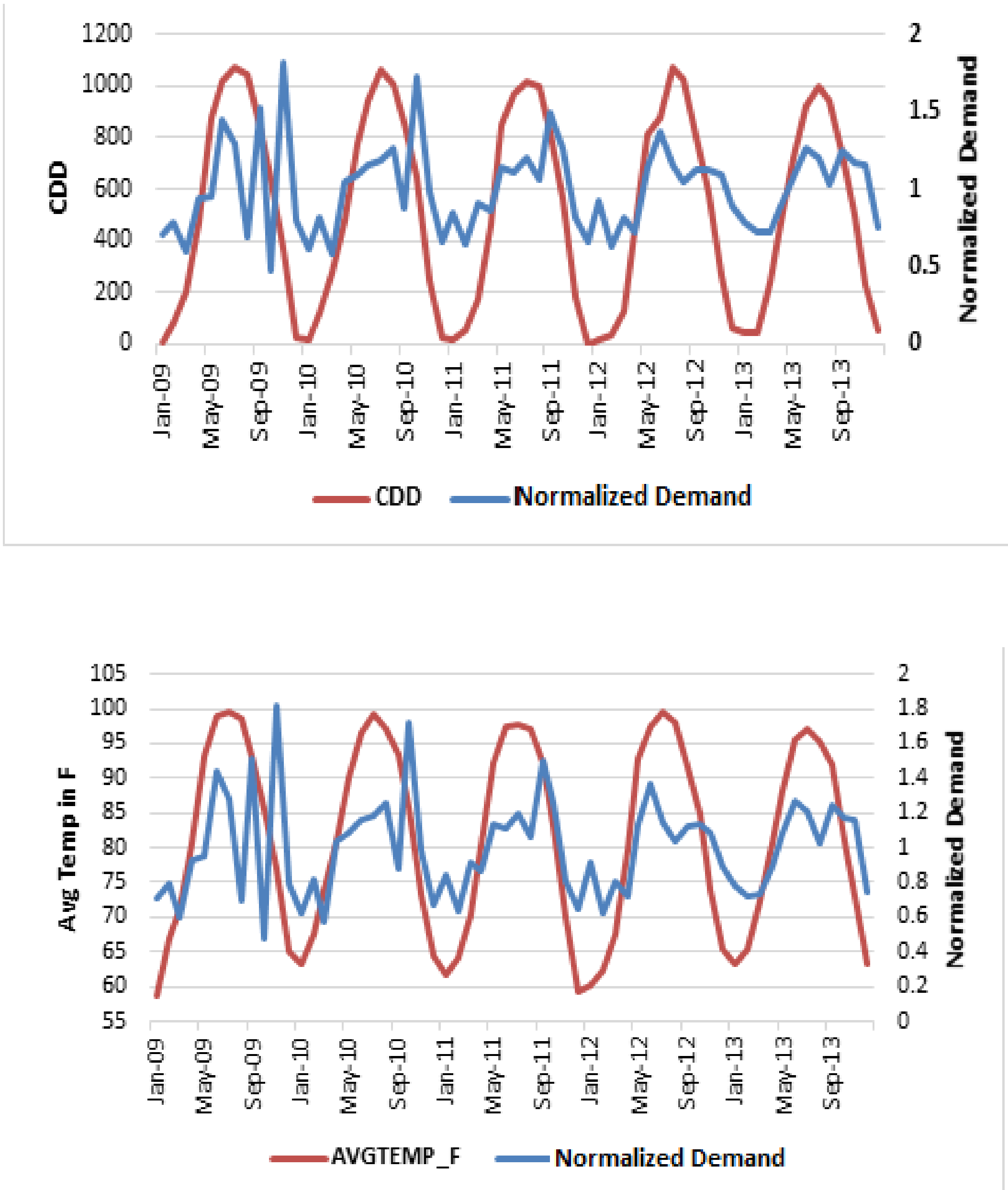


Figure 3.26 Normalized demand versus average temperature and CDD in the governmental sector in the EOA, 2009–2013

Table 3.15 Correlation analysis between the normalized demand and weather independent variables in the governmental sector in the EOA

Covariance Analysis: Ordinary
Sample: 1992M01 2013M12
Included observations: 264
Balanced sample (listwise missing value deletion)

Correlation	MWH_NORM	AVGTEMP_F
MWH_NORM	1.000000	
AVGTEMP_F	0.749581	1.000000
CDD_EOA	0.737410	0.993778

3.4 Forecasting and Evaluations

3.4.1 Forecasting Scenarios

3.4.1.1 Frozen Energy Scenario

As noted in the previous chapter, the frozen scenario represents the first step in the forecasting process. It entails making an abstraction of new load requirements by assuming historical factors and their relationship to key economic and demographic variables (such as GDP, population, and number of households) from 1992 to 2013 as well as into the future.

3.4.1.2 Limited Energy Efficiency Scenario

In the limited energy efficiency (LEE) scenario, savings were attributed to regulatory and policy reforms that have already been enacted in Saudi Arabia. The minimum efficiency standards for ACs sold in the domestic market, which went into effect in 2014, currently require all windows ACs to have an EER of at least 9.5 Btu/watt and all split-cycle ACs to have an EER of 11.5 Btu/watt (up from the current average EER of about 7.5) (SASO 2663, 2014. P. 8). In this scenario, no further measures are assumed beyond 2015. It was also assumed that existing air conditioning devices, which have an average lifetime of 14 years, will become obsolete and gradually be replaced during the planning horizon (2015–2040).

3.4.1.3 High Energy Efficiency Scenario

Starting in 2017, the standards are being extended to cover lighting and white goods as well as building insulation. Based on analysis made in the previous chapter, LM/DR measures were also considered. Furthermore, the EER for all ACs will be raised to a value of at least 12 by the end of the modeling timeframe in this scenario (namely 2040). All new residential buildings were required to have roof, wall, and window insulation. Saudi Arabia’s current average household size of 200 m^2 is assumed to continue in the future, and calculations have been made accordingly. A penetration level of 20% is assumed for building insulation in the first five years, reaching 50% by the end of 2040. A recent study conducted on various buildings in the EOA concluded that implementation of the International Energy Conservation Code for building envelope design can result in 55% less energy consumption for cooling (Abdul-ur-Rehman, Al-Sulaiman, Budaiwi, & Shakir, 2015, p. 27). The SEEP will start mandating new thermal insulation regulations for residential buildings effective January 2017 (SEEP, 2015, p. 17). White goods improve their efficiency over time, reflecting changes across a number of different end-use types (such as refrigeration and washing machines). Lighting improves substantially through the adoption of LED technologies. With the exception of existing building insulation, it is assumed that other appliances (with an average lifetime between 4 years and 20 years) will become obsolete and gradually be replaced during the planning horizon (2015–2040).

As explained in Chapter 2, the end-use model was used to estimate demand for the LEE and HEE scenarios for the residential sector. Electric saving values, based on achievable market potential, over baselines (i.e. the frozen scenario) for each type of DSM measure estimated in Chapter 2, for each sector was used to assess the energy savings and adjust the forecasting results.

3.4.1.4 Weather Effects Scenarios

For the above three scenarios, weather effects scenarios were considered in this study to account for the impact of weather changes on electricity demand. The first two scenarios were constructed based on the warmest and coolest summer in each of the four major cities related to Saudi Arabia's four electricity network operating areas. This was similar to the approach adopted in the study of weather effects on electricity loads in the PJM network, which was conducted to investigate how electricity demand in the PJM network was influenced by climate change (Crowkey & Joutz, 2005, p. 3). The third scenario, which was called the climate change temperature scenario, was used to present the impact of a two-degree Fahrenheit increase in temperatures. Table 3.16 summarizes the details of these three scenarios. It was observed that the average temperatures in the low temperature scenario were almost the same as the average annual temperature of the historical data collected for the period 1992–2013 (Table 3.1). This was applicable to all areas, except for the EOA. For simplicity, average temperature and low temperature scenarios were considered to be the same in this chapter.

Table 3.16 Summary of weather variables in the low temperature, high temperature, and climate change scenarios for the COA, EOA, WOA, and SOA

Low Temp. Scenario			High Temp. Scenario			Climate Change Scenario		
Avg. Temp	Annual HDD	Annual CDD	Avg. Temp	Annual HDD	Annual CDD	Avg. Temp	Annual HDD	Annual CDD
79.8	480.0	5928.0	83.5	264.0	7066.0	85.5	154.4	7675.4
79.0	327.0	5530.0	82.4	265.0	6649.0	84.4	164.3	7267.7
87.2	0.0	8151.0	89.2	0.0	8598.0	91.2	0.0	9325.7
65.9	971.0	1341.0	67.1	835.0	1627.0	69.1	568.9	2085.8

Data source: WeatherBase, 2015

3.4.2 Frozen Energy Efficiency Scenario Forecasting Results

3.4.2.1 Electricity Sales Forecasting Results at the Consumer Category Level

In Saudi Arabia's residential sector, the annual electricity sales were projected to grow at an average rate of 2.9% from 148 TWh in 2015 to 284 TWh and 297 TWh in 2040 for the high and low temperature scenarios respectively, as shown in Figure 3.27. In 2040, the annual residential sales in the climate change scenario were projected to reach 313 TWh, which is 10.2% and 5.2% higher than sales in the low and high temperature scenarios, respectively. Figure 3.28 shows the monthly residential sales for the high and low temperature scenarios. The annual residential growth rate was higher than the population growth rate over the same period, which was around 1.5%. The end-use model was established based on the number of customers, as forecasted using future population growth. This was in line with the historical growth rates of both parameters, where the residential sales growth rate was higher than the population rate.

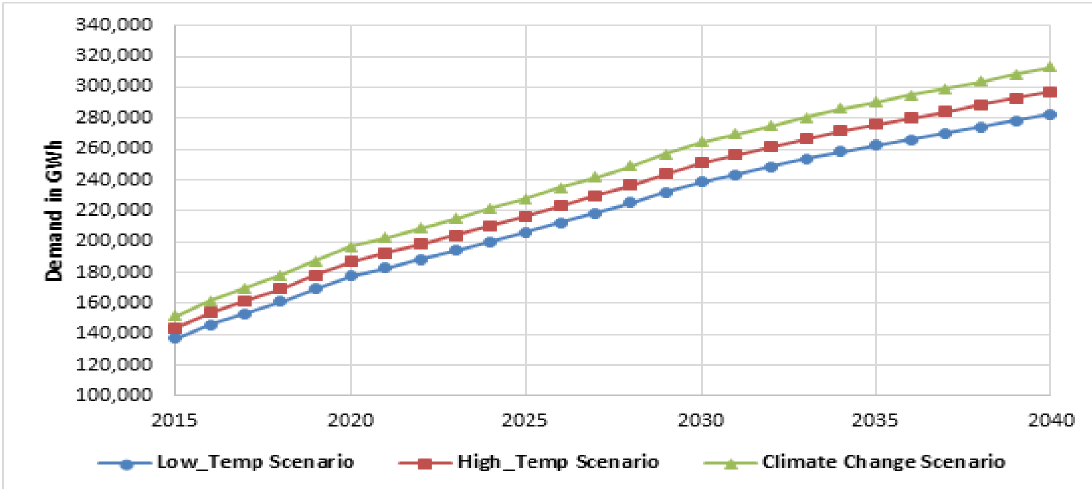


Figure 3.27 Annual electricity sales forecasts for the residential sector for the low and high temperature scenarios, 2015–2040

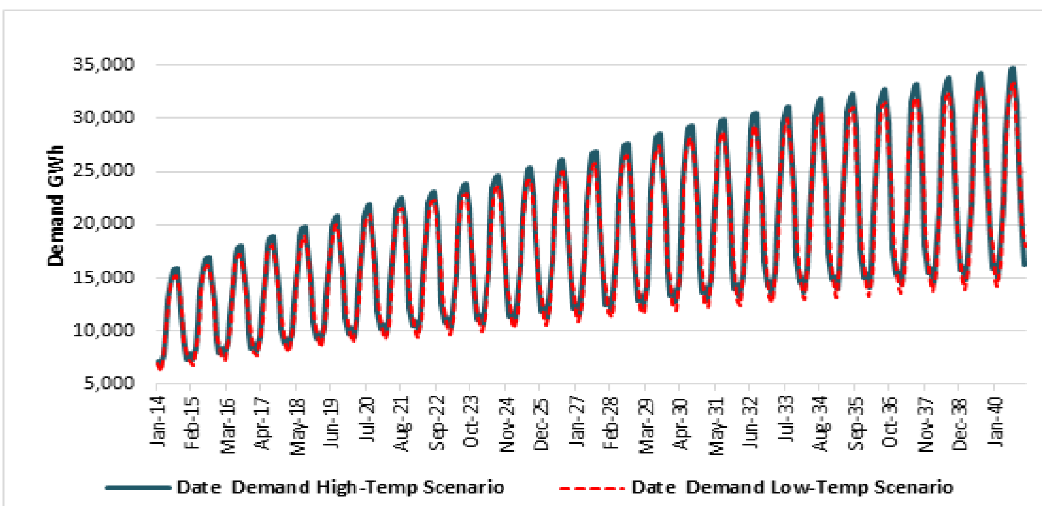


Figure 3.28 Monthly electricity sales forecasts for the residential sector for the low and high temperature scenarios, 2014–2040

Under the sensitivity case (which sees households increasing at an additional 0.5% above the FEE scenario), the residential sales were projected to reach 322 TWh and 338 TWh for the low and high temperature scenarios, respectively. For the cases with residential customer growth reduced by -0.5%, residential sales were projected to respectively reach 251 TWh and 264 TWh for the low and high temperature scenarios (Figures 3.29 and 3.30).

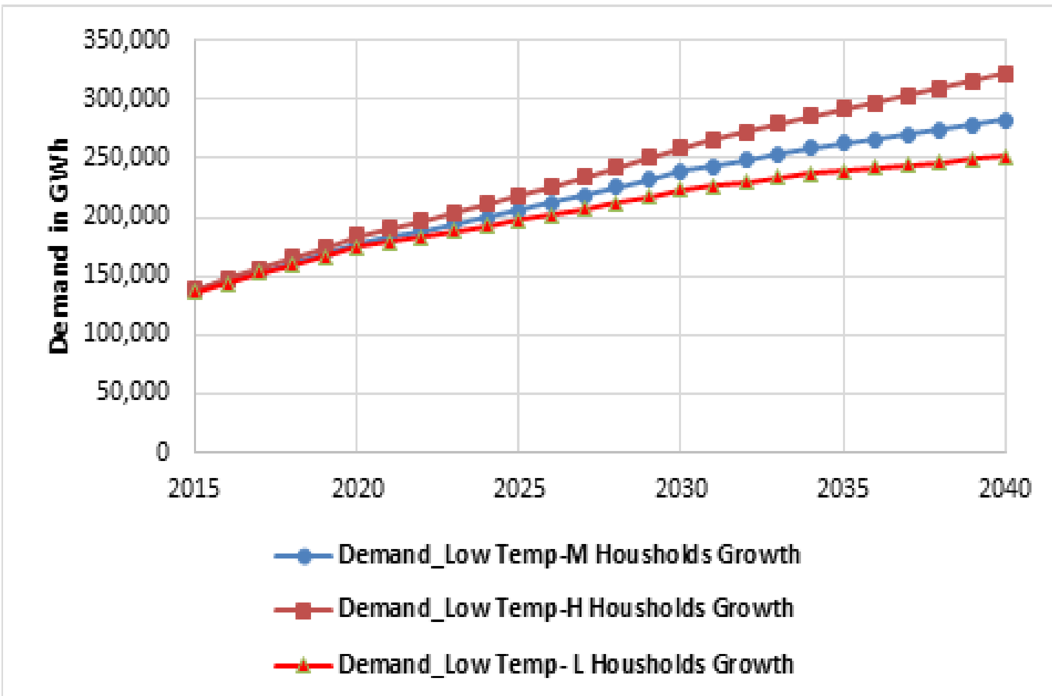


Figure 3.29 Annual electricity sales forecasts for the low temperature scenario and households sensitivity cases, 2015–2040

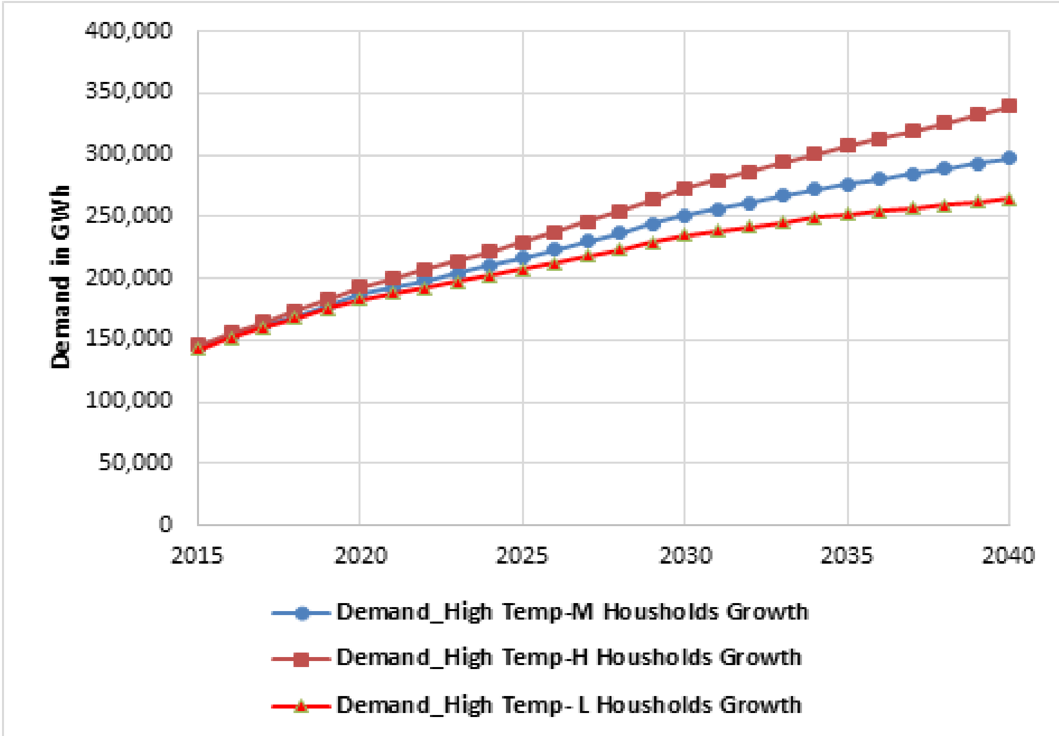


Figure 3.30 Annual electricity sales forecasts for the high temperature scenario and households sensitivity cases, 2015–2040

As shown in Figure 3.31, a maximum difference of 9.7% occurred between the residential sales of the high and low temperature scenarios during peak summer (i.e. July). Similar to the observation made for the relationship between the actual demand in 2004 and degree days in Figure 3.5, Figure 3.32 examines the relationship between the forecasted residential sales in the COA and the monthly difference of degree days for two years (namely 2015 and 2016) in both the high and low temperature scenarios. The two demand curves closely followed the degree days difference curve. During summer, the demand in the high temperature scenario exceeded the demand in the low temperature scenario, since the CDDs were higher. As the HDDs went higher in the low temperature scenario during winter, demand was higher than in the high temperature scenario.

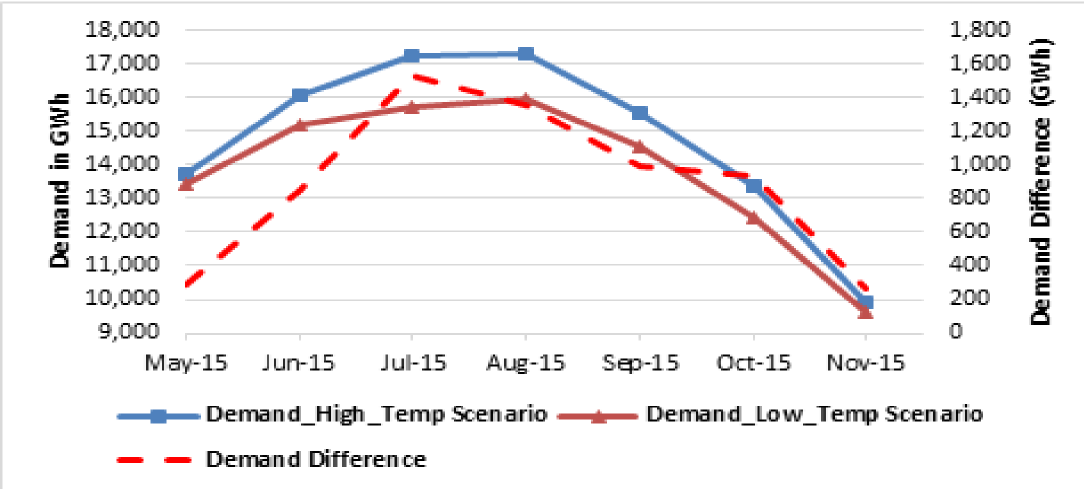


Figure 3.31 Annual electricity sales forecasts comparison between high and low temperature scenarios during summer months in the residential sector, 2015

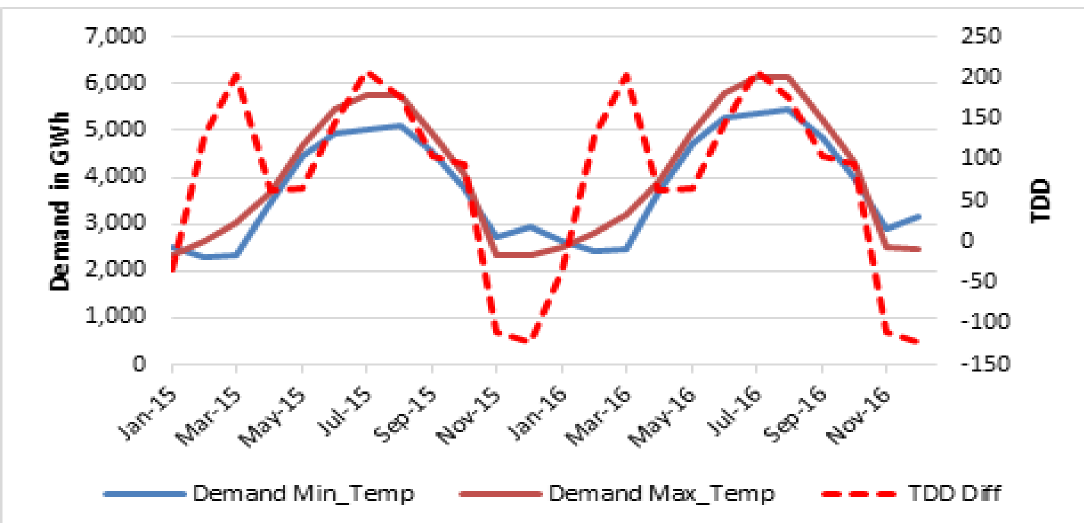


Figure 3.32 Annual electricity sales forecasts for high and low temperature scenarios versus total cooling degree days, 2015 and 2016

In the commercial sector, annual electricity sales were projected to grow at an average rate of 5.69% from 44 TWh in 2014 to 180 TWh and 170 TWh in 2040 for the high and low temperature scenarios, respectively (see Figure 3.33). The high increase in electricity sales in this sector was due to the high growth of tertiary GDP as Saudi Arabia's economy shifts toward a more diverse portfolio over the long-term. In 2040, the annual residential sales in the climate change scenario were 188 TWh, which is respectively 4.7% and 10.9% higher than sales in the low and temperature scenarios. Figure 3.35 shows the monthly residential sales for both scenarios.

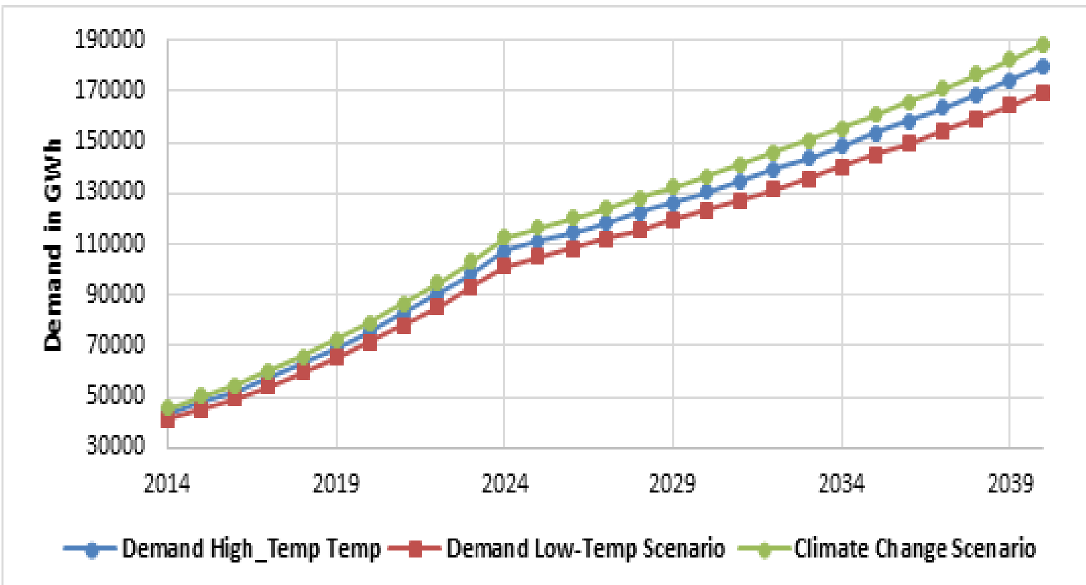


Figure 3.33 Annual electricity sales forecasts for the commercial sector for the low, high temperature, and climate change scenarios, 2014–2040

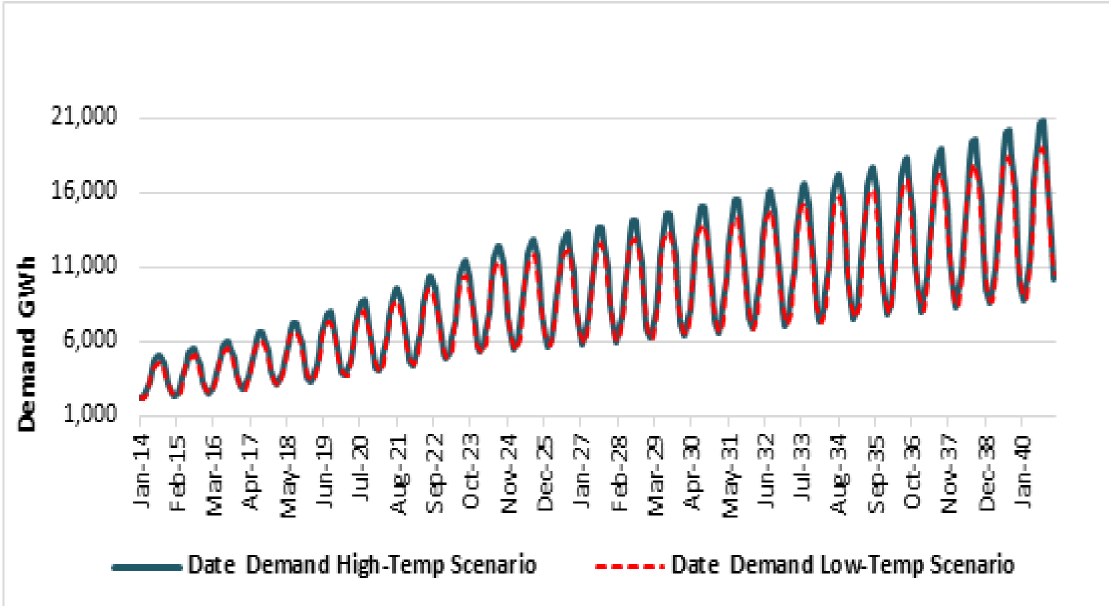


Figure 3.34 Monthly electricity sales forecasts for the commercial sector for the low and high temperature scenarios, 2014–2040

Similar to the observation made for the relationship between the actual demand in 2004 and degree days in Figure 3.5, Figure 3.35 examines the relationship between the forecasted commercial sales in the COA and the monthly difference of degree days for two years (i.e. 2015 and 2016) in both the high and low temperature scenarios. The two demand curves closely followed the degree days difference curve. During summer, demand in the high temperature scenario exceeded demand in the low temperature scenarios, since the CDD are higher. As HDD went higher in the low temperature scenario during winter, demand was higher than in the high temperature scenario.

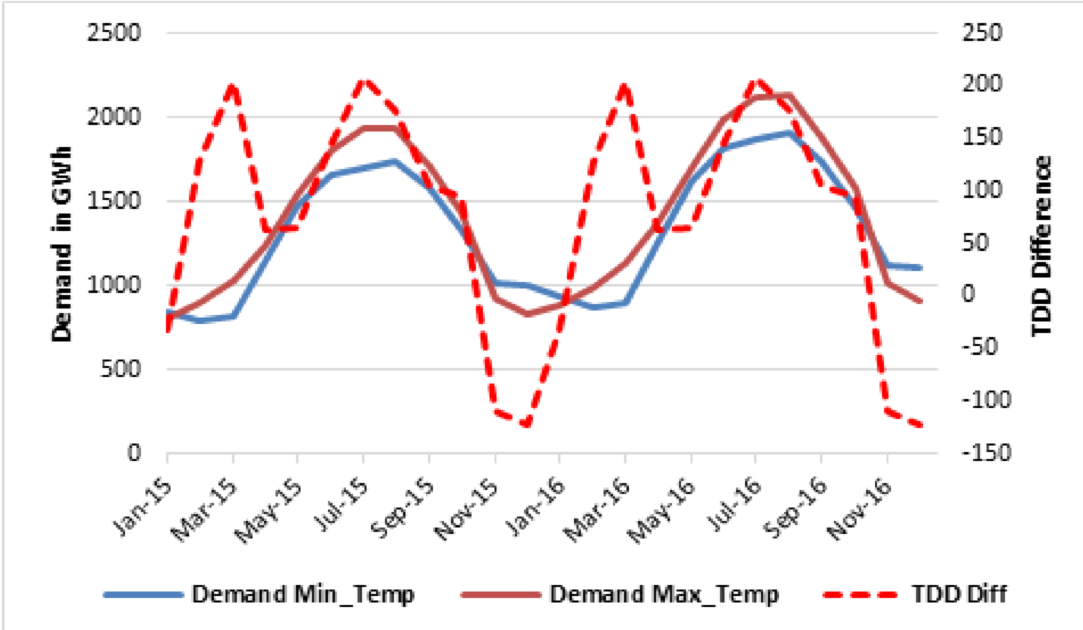


Figure 3.35 Annual electricity sales forecasts for the high and low temperature scenarios versus total cooling degree days, 2015 and 2016

Under the sensitivity case (which sees GDP increasing by an additional 0.5% and 1% above the FEE scenario), commercial sales were projected to reach 196 TWh and 224 TWh respectively for low temperature scenarios and 207 TWh and 237 TWh respectively for high temperature scenarios. For the cases with GDP growth reduced by -0.5% and -1%, commercial sales were projected to reach 130 TWh and 150 TWh respectively for low temperature scenarios and 158 TWh and 138 TWh respectively for high temperature scenarios (Figures 3.36 and 3.37).

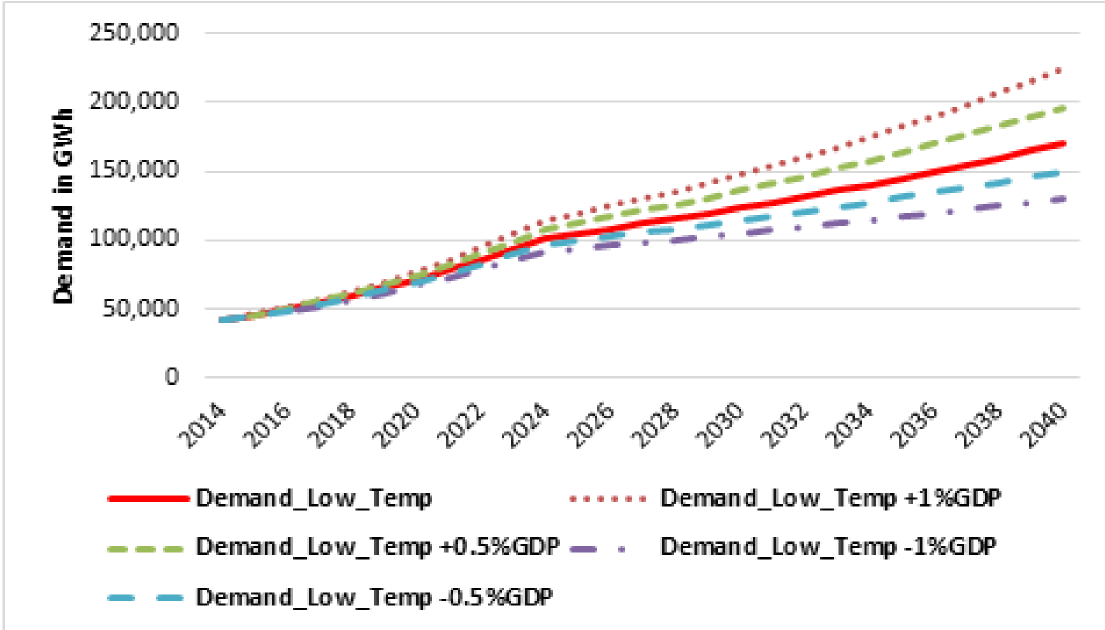


Figure 3.36 Annual electricity sales forecasts for the low temperature scenario and GDP sensitivity cases for commercial cases, 2014–2040

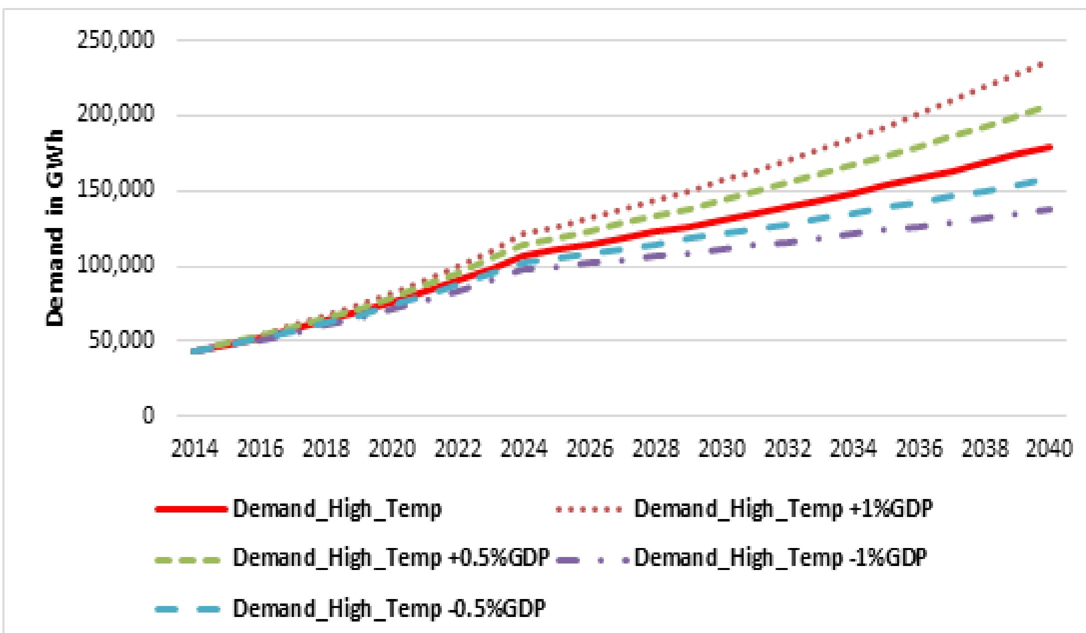


Figure 3.37 Annual electricity sales forecasts for the high temperature scenario and GDP sensitivity cases for commercial cases, 2014–2040

In the governmental sector, annual electricity sales were projected to grow at an average rate of 3.5% from 30 TWh in 2014 to 72 TWh in 2040. Under the sensitivity case (which sees GDP increasing by an additional 0.5% and 1% above the FEE scenario), governmental sales were projected to reach 79 TWh and 86 TWh respectively. For the cases with GDP growth reduced by -0.5% and -1%, governmental sales were projected to respectively reach 67 TWh and 62 TWh (Figure 3.38).

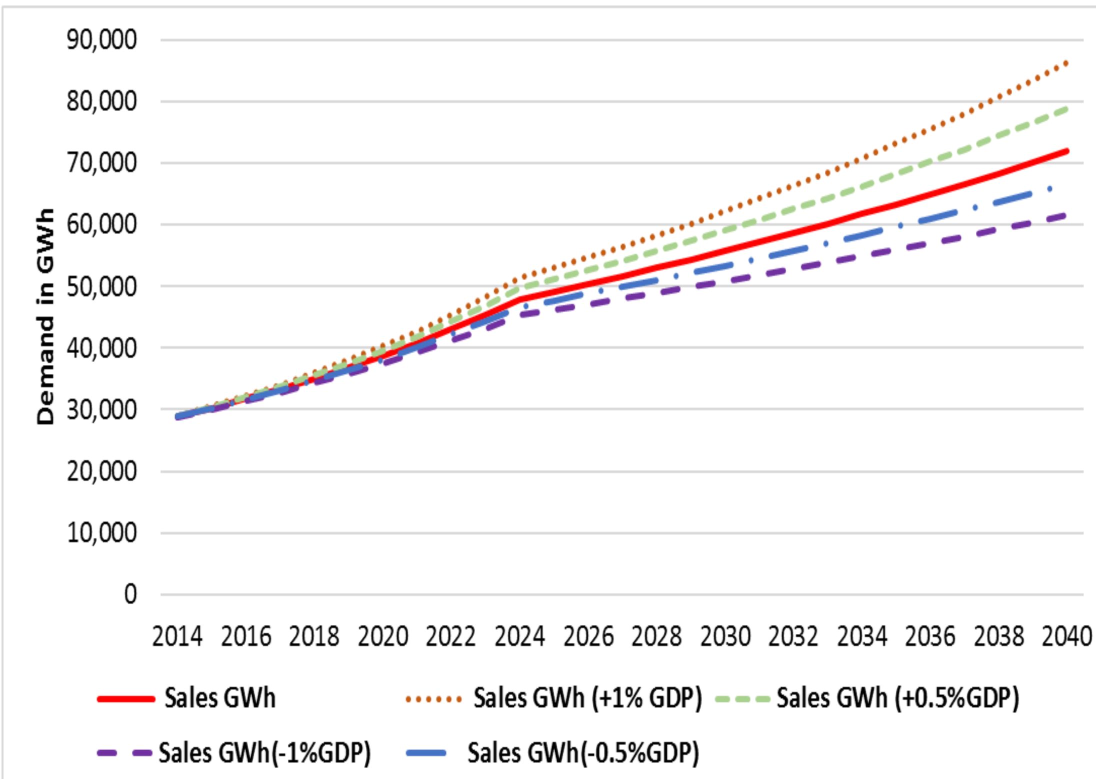


Figure 3.38 Annual electricity sales forecasts and GDP sensitivity cases for the governmental sector, 2014–2040

In the industrial sector, the annual electricity sales were projected to grow at an average rate of 4.3% from 56 TWh in 2014 to 153 TWh in 2040. Under the sensitivity case (which sees GDP increasing by an additional 0.5% and 1% above the FEE scenario), industrial sales were projected to reach 166 TWh and 179 TWh respectively. For the cases with GDP growth reduced by -0.5% and -1%, industrial sales were projected to respectively reach 130 TWh and 142 TWh (Figure 3.39).

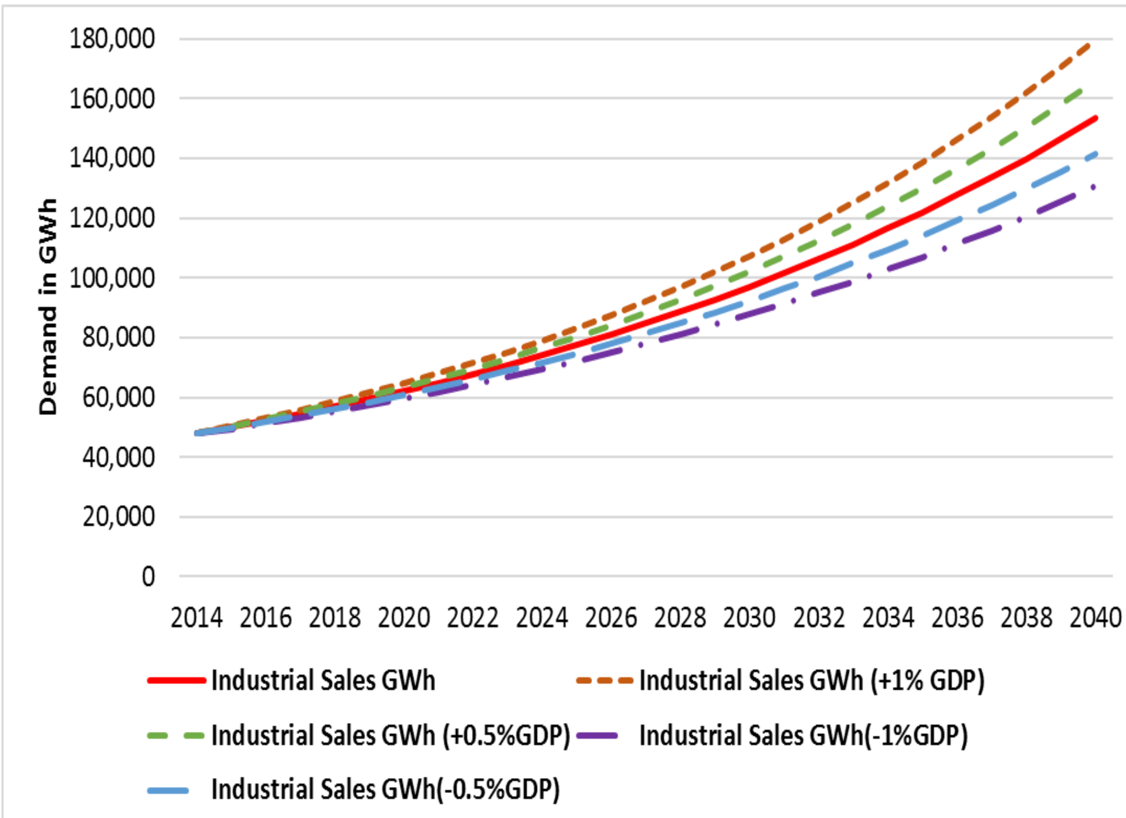


Figure 3.39 Annual electricity sales forecasts and GDP sensitivity cases for the industrial sector, 2014–2040

In the agricultural sector, the annual electricity sales are projected to grow at an average rate of 5.2% from 5 TWh in 2014 to 17 TWh in 2040. Under the sensitivity case (which sees GDP increasing by an additional 0.5% and 1% above the FEE scenario), agricultural sales are projected to reach 20 TWh and 23 TWh respectively. For the cases with GDP growth reduced by -0.5% and -1%, agricultural sales are projected to respectively reach 15 TWh and 13 TWh (Figure 3.40).

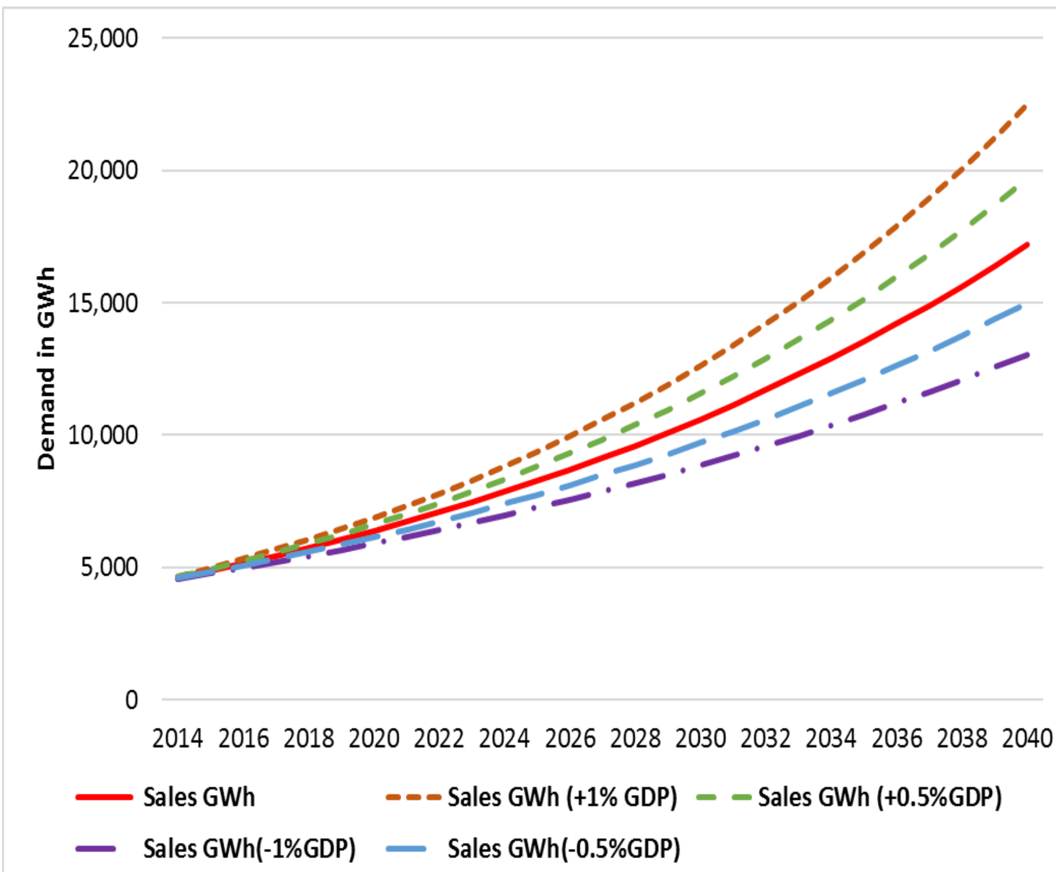


Figure 3.40 Annual electricity sales forecasts and GDP sensitivity cases for the agricultural sector, 1992–2040

In the “others” consumer category, annual electricity sales were projected to grow at an average rate of 4.8% from 10 TWh in 2014 to 33 TWh in 2040. Under the sensitivity case (which sees GDP increasing by an additional 0.5% and 1% above the FEE scenario), “others” sales were projected to reach 37 TWh and 42 TWh respectively. For the cases with GDP growth reduced by -0.5% and -1%, “others” sales were projected to respectively reach 29 TWh and 26 TWh (Figure 3.41).

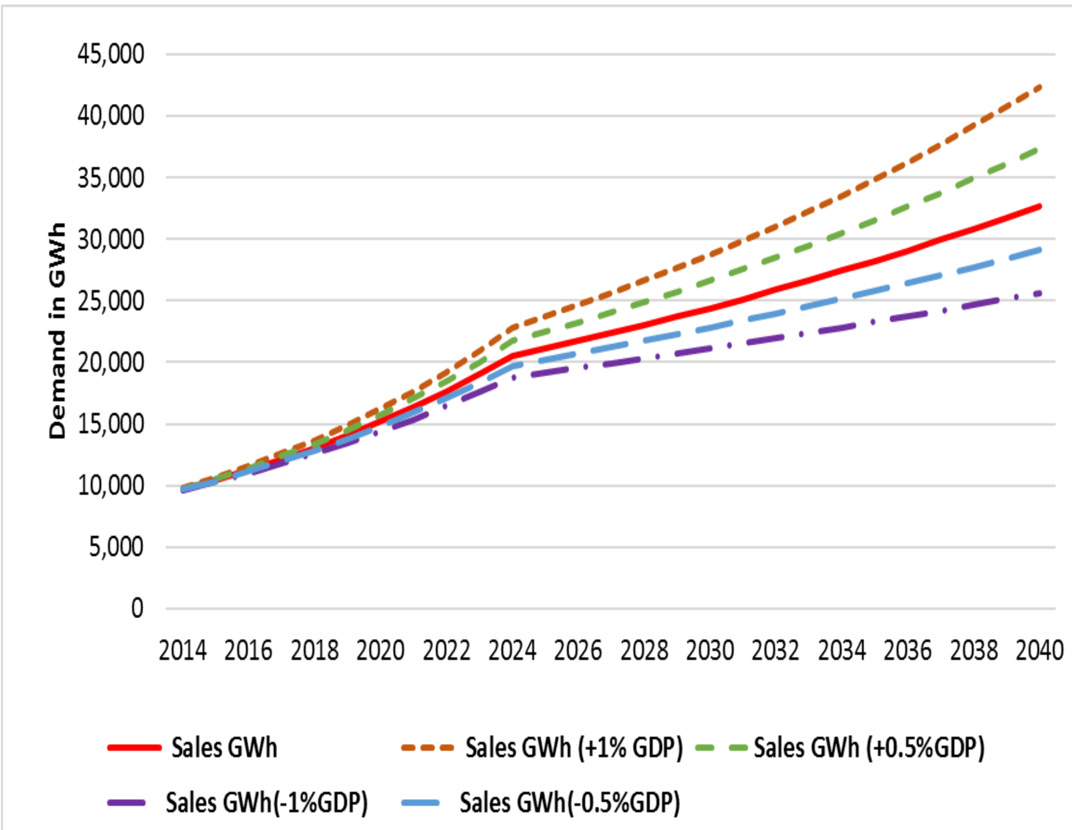


Figure 3.41 Annual electricity sales forecasts and GDP sensitivity cases for the “others” consumer category, 2014–2040

Table 3.17 presents a summary of the outcomes described above for the six sales categories for the FEE scenario. Recently implemented policies (such as building and appliance standards) are not taken into account; it has instead been assumed that the future was related to actions taken from 1992 to 2013. The sharpest growth (6%) was expected during the initial period from 2015 to 2020, with growth then being predicted to stabilize at 2.8% in the last forecasted period of 2035–2040 primarily as a result of declining population and moderated GDP growth.

Table 3.17 Forecasted electricity sales summary (in GWh)

Sector/Year	2015	2020	2025	2030	2035	2040
Residential-high temp	144370	186889	216655	251163	275944	297271
Residential-low temp	137252	177674	205973	238780	262340	282614
Commercial-high temp	47866	75621	110953	130603	153383	179791
Commercial-low temp	45237	71436	104811	123374	144893	169840
Industrial	50010	62134	77569	97172	122028	153511
Governmental	28257	36156	45822	52015	59057	67072
Agricultural	4787	6263	8106	10409	13285	16876
Others	10439	15167	21107	24411	28240	32680
Total sales-high temp	285728	382230	480212	565772	651937	747200
Total sales-low temp	275981	368830	463389	546160	629842	722593
Average annual growth		6.0%	4.7%	3.3%	2.9%	2.8%

3.4.2.2 Energy Demand Forecasting Results at Network Operating Areas Levels

In order to estimate energy requirements (demand) for each region an appropriate conversion factor is required. As explained in Section 3.1.3 (equation 3.3), this factor was derived by taking a ratio of historical sales with historical hourly data of dispatched power at each operating area to account for losses and inter-regional transfers in the system for each hour of the year. Figures 3.42 and 3.43 show the annual energy requirement for each operating area in the forecasted period for low and high temperature scenarios. The energy required in Saudi Arabia was expected to grow at an average annual rate of 3.9% to reach 813 TWh and 841 TWh for the low and high temperature scenarios, respectively. In relation to Saudi Arabia's energy required, a maximum difference of 6.9% occurred between the high and low temperature scenarios during peak summer (i.e. July), as shown in Figure 3.44. The effect of the two temperature scenarios varied in the four operating areas. During peak summer, energy requirement differences of 11.1%, 4.5%, 6.8%, and 5.6% were observed respectively in the COA, EOA, WOA, and SOA. The relatively low energy requirement variation as a result of weather change in the EOA was attributed to the fact that 76% of the forecasted demand was used for the industrial sector which is generally temperature invariant.

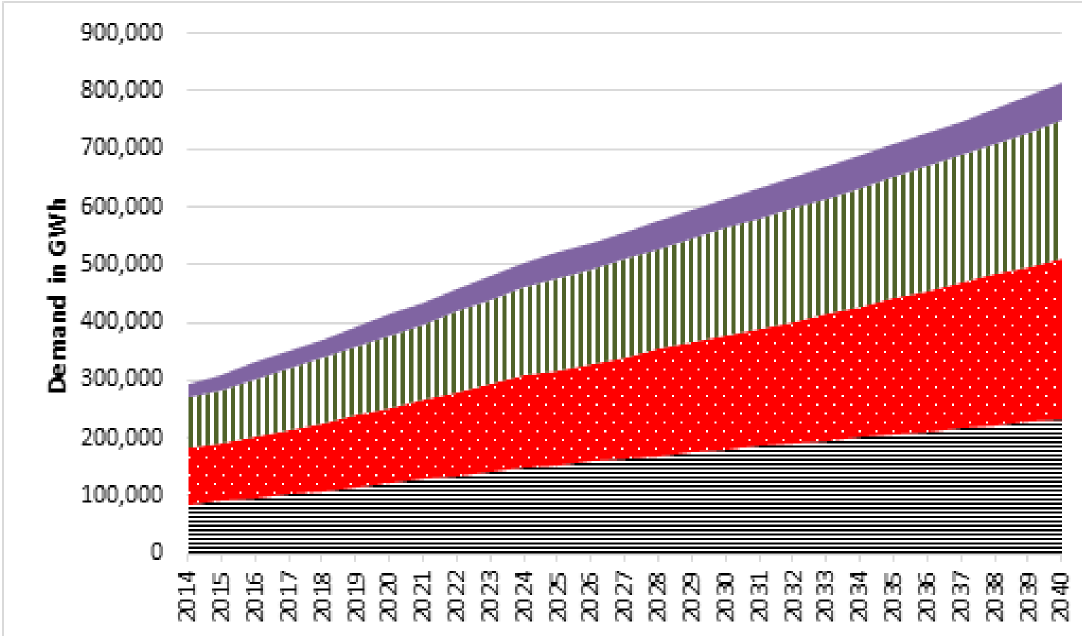


Figure 3.42 Annual energy requirement forecasts for the low temperature scenario in all network operating areas, 2014–2040

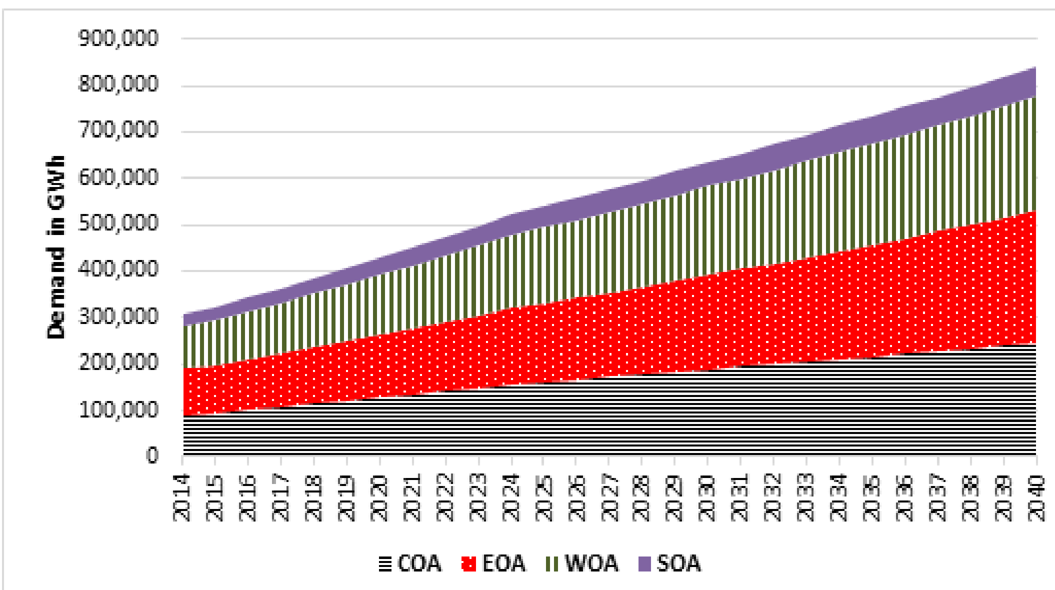


Figure 3.43 Annual energy requirement forecasts for the high temperature scenario in all network operating areas, 2014–2040

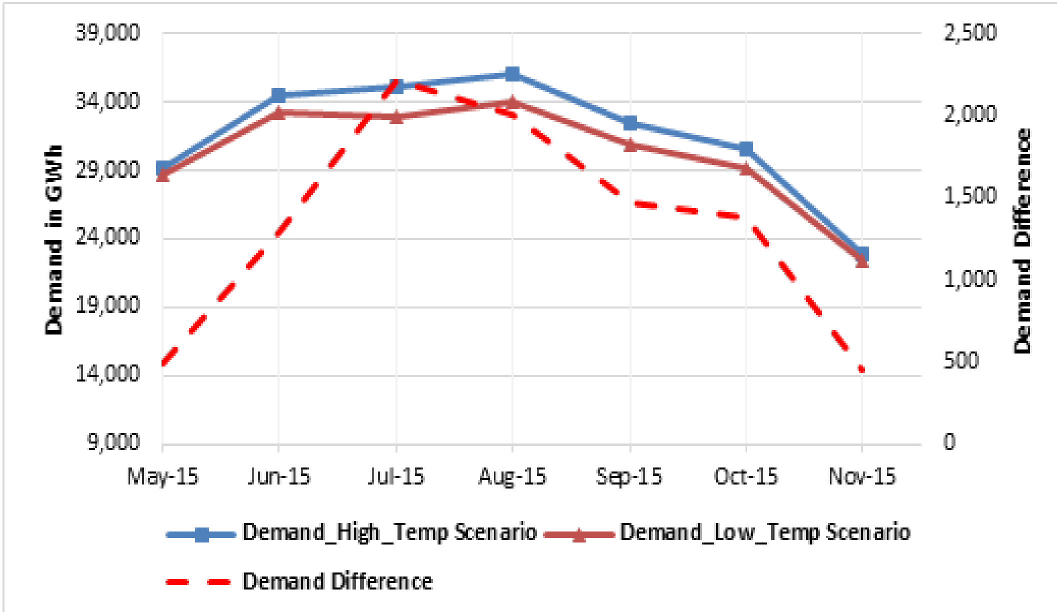


Figure 3.44 Annual energy requirements forecasts comparison between the high and low temperature scenarios during summer months in Saudi Arabia, 2015

In the climate change scenario (Figure 3.45), the energy required increased by 6.7% in comparison to the low temperature scenario. During peak summer, the climate change scenario resulted in increasing Saudi Arabia's demand by 9.4% in comparison with the low temperature scenario (see Figure 4.46). The energy required also increased in each area, by respectively 14.1%, 7.2%, 9.3%, and 9.2% in the COA, EOA, WOA, and SOA. The relatively low energy requirements variation as a result of weather change in the EOA was attributed to the fact that 76% of the forecasted demand was used for the industrial sector.

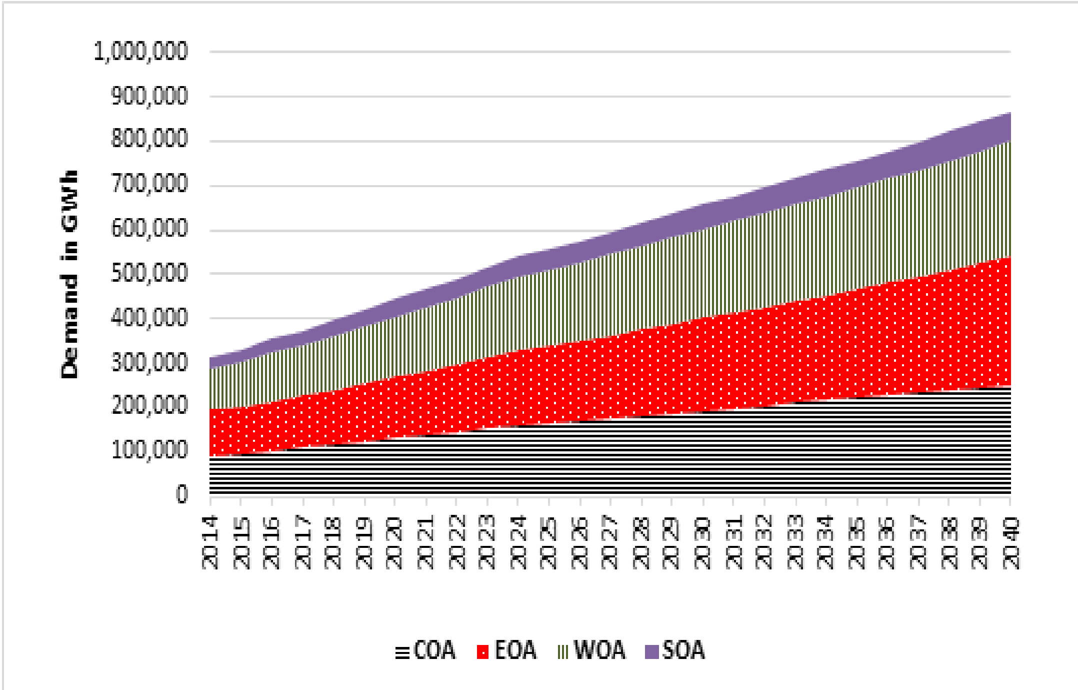


Figure 3.45 Annual energy requirement forecasts for the climate change scenario in all network operating areas, 2014–2040

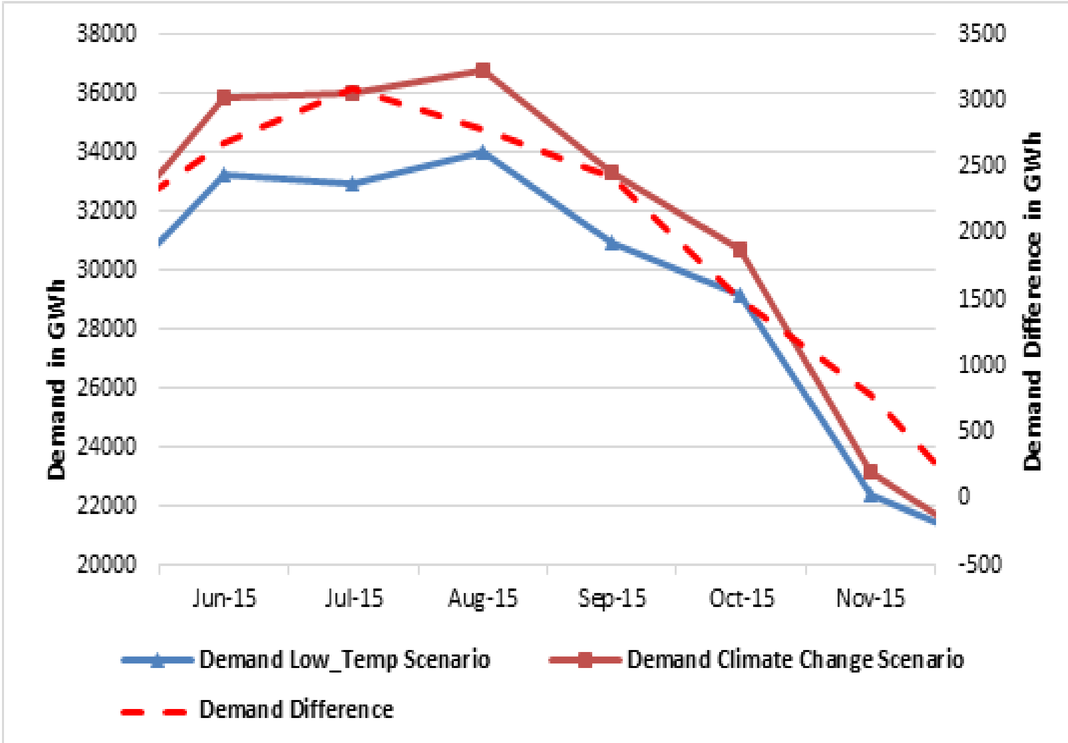


Figure 3.46 Energy requirement forecasts comparison between the climate change and low temperature scenarios during summer months in Saudi Arabia for a forecasted year (2015)

Under the sensitivity case (which sees GDP increasing by an additional 0.5% and 1% above the FEE scenario), Saudi Arabia's energy required was projected to reach 872 TWh and 936 TWh respectively for low temperature scenarios and 902 TWh and 967 TWh respectively for high temperature scenarios. For the cases with GDP growth reduced by -0.5% and -1%, commercial sales were projected to reach 743 TWh and 691 TWh respectively for low temperature scenarios and 769 TWh and 716 TWh respectively for high temperature scenarios (Figures 3.47 and 3.48).

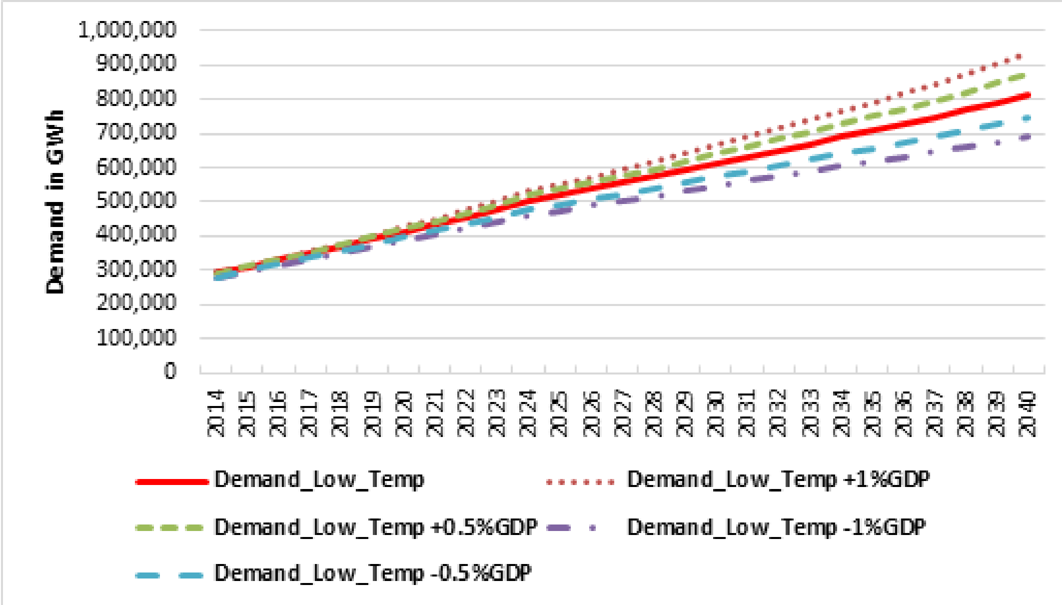


Figure 3.47 Annual energy required forecasts for the low temperature scenario and GDP sensitivity cases for Saudi Arabia, 2014–2040

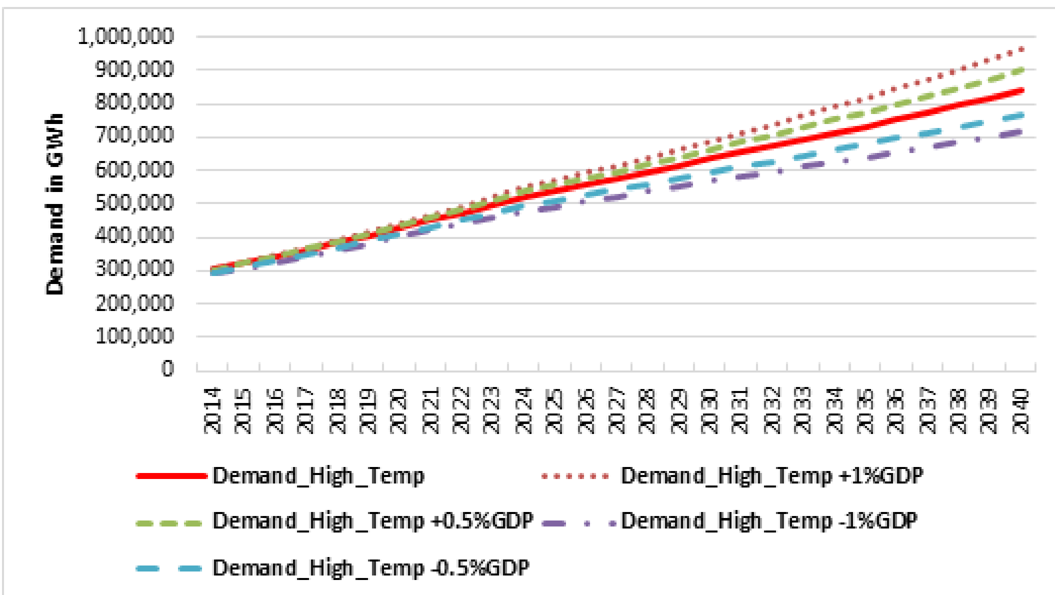


Figure 3.48 Annual energy required forecasts for the high temperature scenario and GDP sensitivity cases for Saudi Arabia, 2014–2040

3.4.2.3 Peak Demand Forecasting Results at Network Operating Areas Levels

In accordance with the methodology explained in Section 3.3, the peak demand (in GW) was calculated for each operating area using the peak to average factor. Figure 3.48 shows the peak demand for Saudi Arabia in the forecasted period for low and high temperature scenarios. The country's peak electricity demand was expected to grow at an annual average rate of 4.7% to reach 182 GW and 172 GW for the high and low temperature scenarios. The difference between Saudi Arabia's peak demand in the high and low temperature scenarios was expected to exceed 10 GW in 2040 (or 5.6% of peak load), as shown in Figure 3.49. The effect of the two temperature scenarios varies in the four operating areas. For example, in 2040 a peak demand difference of 8.3%, 3.7%, 5.6%, and 5.2% was observed respectively in the COA, EOA, WOA, and SOA. In the climate change scenario, the peak demand was found to be 15 GW (or 8.5%) higher than the low temperature scenario. At the areas level, 2040 saw a peak demand difference that increased to 11.1%, 6.3%, 8.1%, and 8.7% in comparison with the low temperature scenario. The highest demand difference took place in the COA due to the high growth of peak to average ratio, which was attributed to the area's relatively high share of residential and commercial demand in comparison to other areas. The EOA had the lowest difference, as most of its demand was used for the industrial sector (which is not highly sensitive to weather changes).

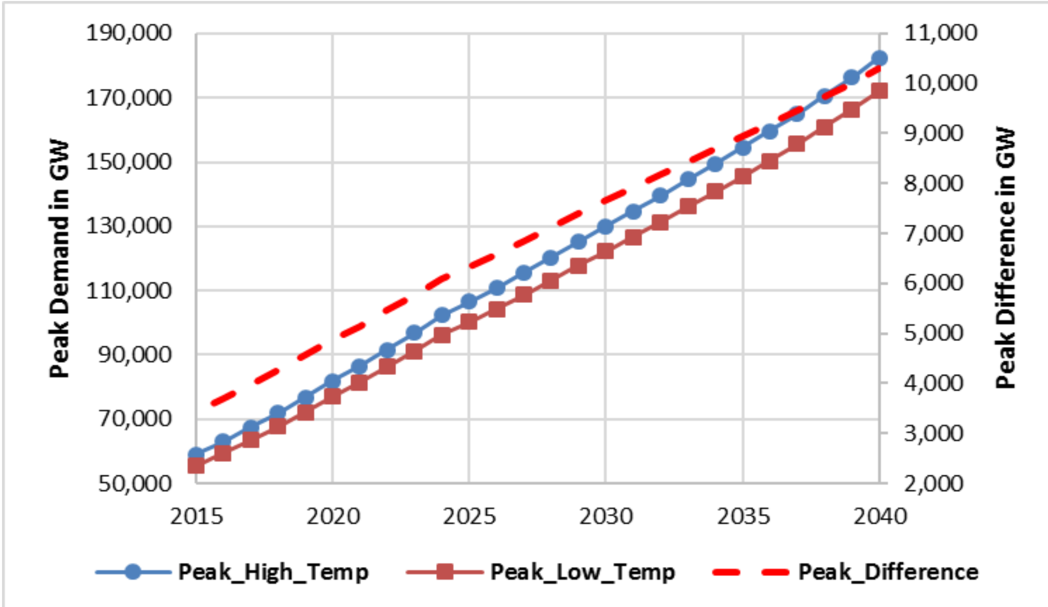


Figure 3.49 Annual peak demand forecasts comparison between high and low temperature scenarios during summer months in Saudi Arabia, 2015–2040

Under the sensitivity case (which sees GDP increasing by an additional 0.5% and 1% above the FEE scenario), the peak demand in Saudi Arabia was projected to reach 185 GW and 197 GW respectively for low temperature scenarios and 196 GW and 209 GW respectively for high temperature scenarios. For the cases with GDP growth reduced by -0.5% and -1%, the peak demand was projected to reach 157 GW and 150 GW respectively for low temperature scenarios and 167 GW and 156 GW respectively for high temperature scenarios (Figures 3.50 and 3.51).

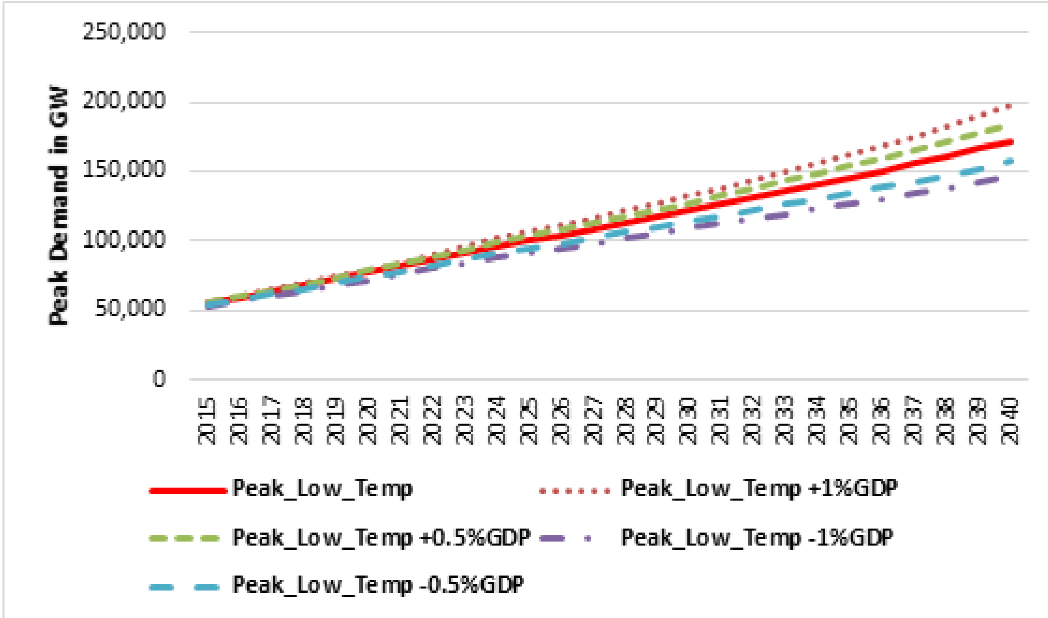


Figure 3.50 Annual peak demand forecasts for the low temperature scenario and GDP sensitivity cases for Saudi Arabia, 2015–2040

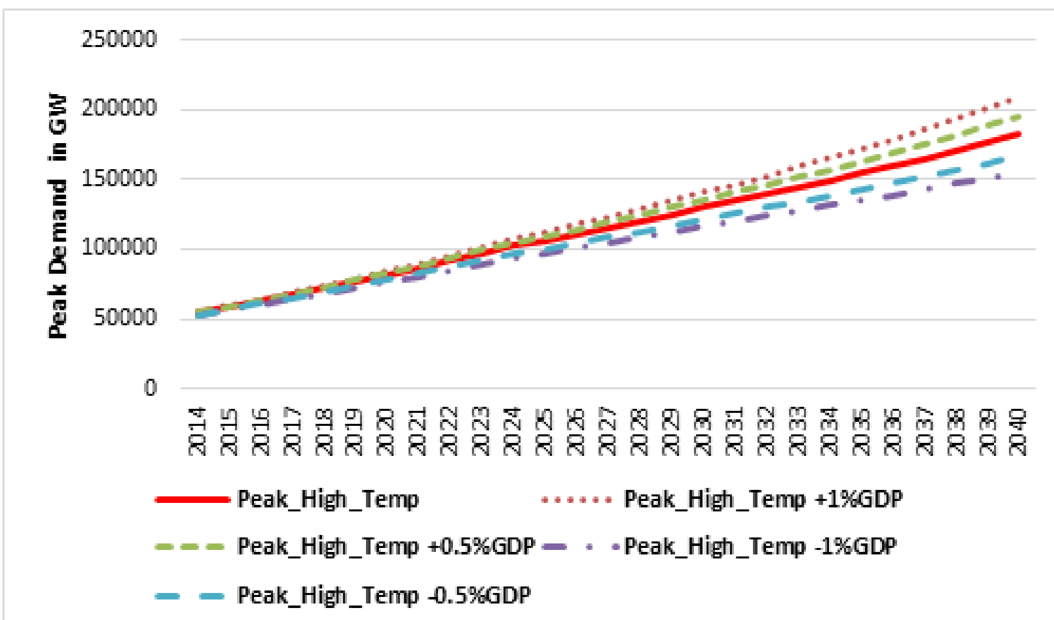


Figure 3.51 Annual peak demand forecasts for the high temperature scenario and GDP sensitivity cases for Saudi Arabia, 2014–2040

Under the sensitivity case and a household variation that is +0.5% above and -0.5% below the FEE scenario, Saudi Arabia's peak demand was projected to reach 193 TW and 174GW for high temperature scenarios, respectively (Figure 3.52).

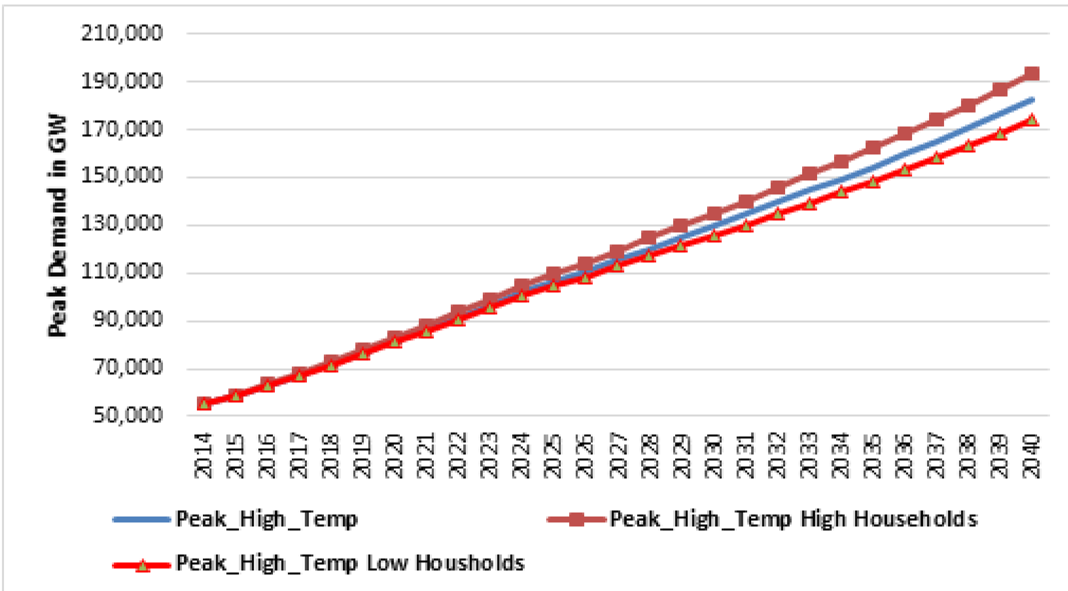
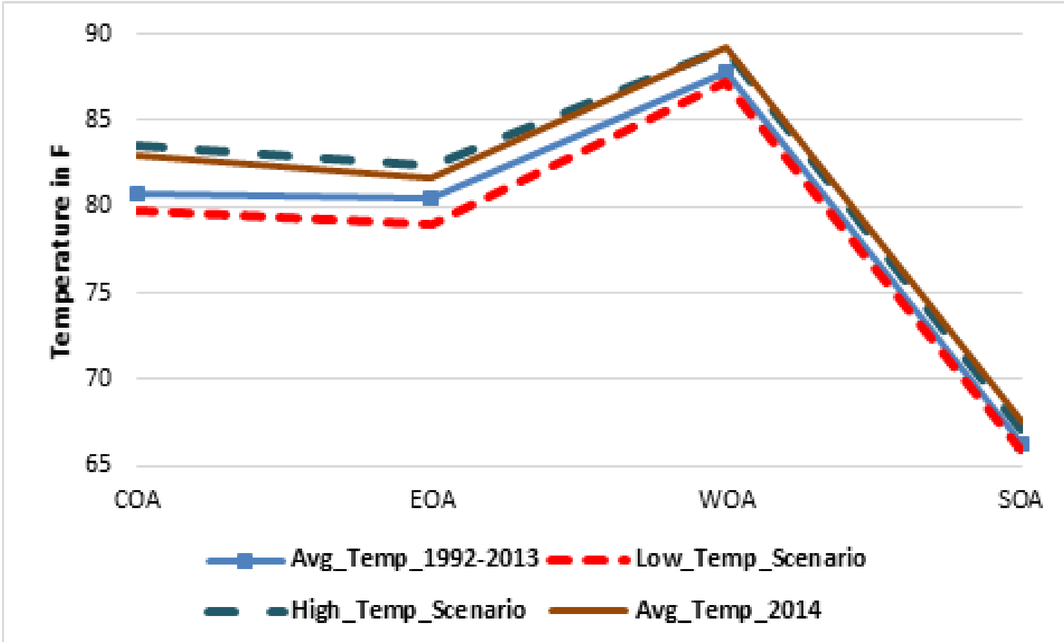


Figure 3.52 Annual peak demand forecasts for the high temperature scenario and households sensitivity cases for Saudi Arabia, 2014–2040

3.4.2.4 Forecasts Evaluation

To evaluate the accuracy of the FEE scenario forecasts, actual weather variables were input to estimate the demand during 2014, which was then compared with the actual demand values. Figure 3.53 shows the average annual temperature for all operating areas in Saudi Arabia for 2014 in comparison with high and low temperature scenarios and average temperature (1992–2013). It is evident that the 2014 annual temperature almost matched the high temperature scenario.



Data source: WeatherBase, 2015

Figure 3.53 Average temperature in 2014 in comparison with high and low temperature scenarios

Figure 3.54 shows that the model accurately predicted electricity sales in each sector with a minimal error of less than 1% in all sector, with the exception of the governmental sector. The error in the governmental forecasts resulted from the model not considering the impact of weather variables on governmental sectors, since these variables were not found to be highly correlated. Nonetheless, 50% of the demand in the governmental sector was consumed for cooling during summer (Faruqui & Hledik, 2011, p. 42). Due to the extreme weather condition in 2014 (close to the high temperature scenario, as shown in Figure 3.42), governmental sales in 2014 grew by 9.5% in comparison to a growth of less than 5% in 2013. Thus, the actual demand for this sector was found to be higher than the demand forecasted using econometric analysis, which did not take the impact of weather changes on electricity demand into consideration. One area of improvement in the forecasting model was to consider governmental demand weather forecasting sub-model even though the correlation of demand and weather variables were not relatively high (i.e., 77%). Nonetheless, the current forecast was considered adequate to meet the objectives of IRSP modeling given the size of the government sector to the other sectors.

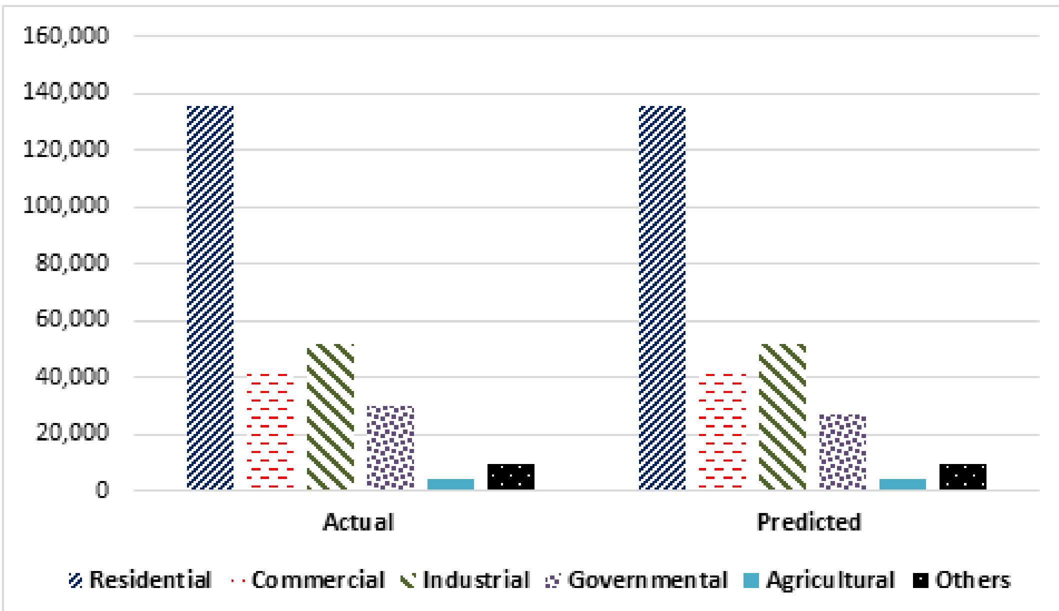


Figure 3.54 Actual versus predicted electricity sales for 2014 (in GWh)

In order to compare the results of the proposed forecasting model with those of other forecasting models, the results of the three main weather scenarios considered in this chapter were compared to a simple annual econometric model for each sector (see Figure 3.55). The future forecasts for demographic and economic variables were assumed to be the same in both models. A similar annual econometric model was used for forecasting in ECRA's Generation Planning for Electricity Sector Study (ECRA, 2008).

The comparison made it evident that the proposed model had the capability to incorporate monthly weather effects, using multivariable econometric analysis for residential and commercial sectors. The annual econometric model clearly underestimated the potential impact of weather related phenomena and potential climate change impacts on the overall demand compared to the techniques used here. For example, in 2040 the demand was forecasted to be 770 TWh, which is respectively 5.6%, 9.1%, and 12.7% lower than the low temperature, high temperature, and climate change scenarios. Furthermore, unlike the simple econometric model, an end-use model was used for calculating annual demand growth in the residential sector, which was helpful when analyzing the impact of implementing various demand-side technologies.

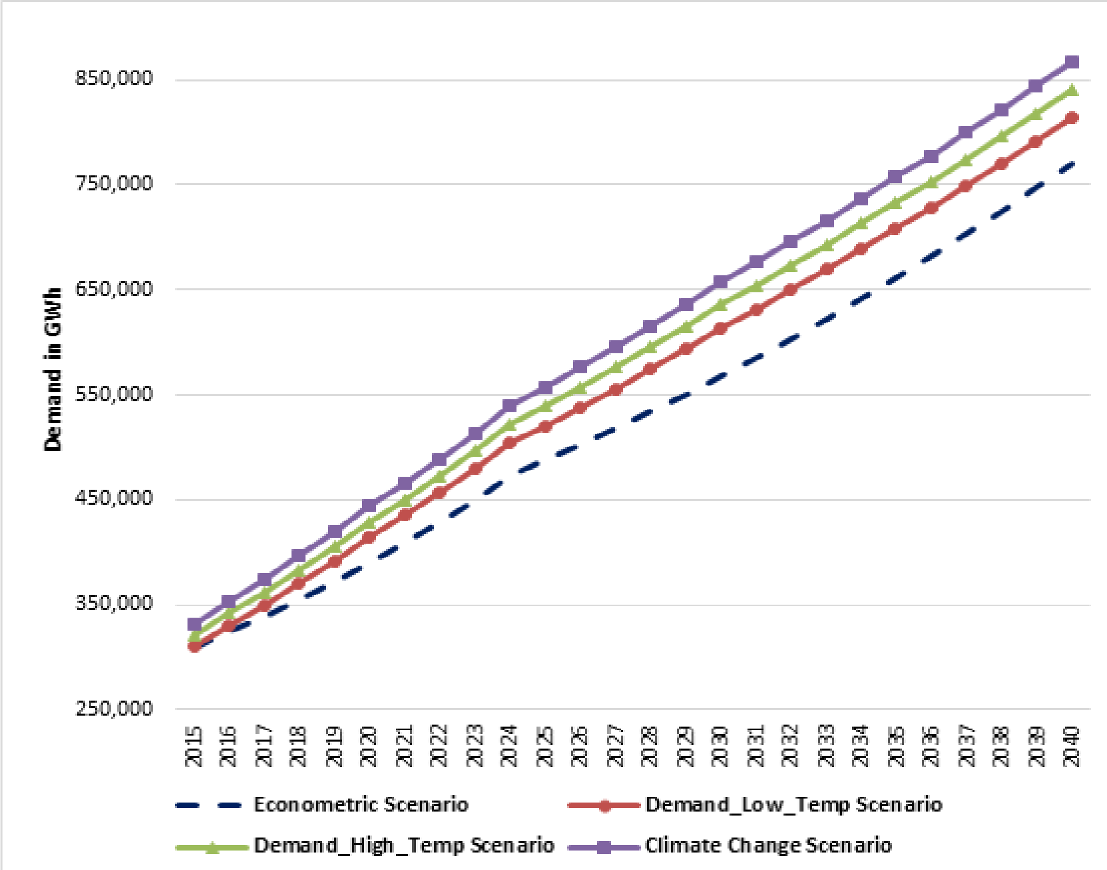


Figure 3.55 Comparison of the proposed forecasting model with a simple annual econometric model, 2015–2040

3.4.3 Energy Efficiency Scenario Forecasting Results

The energy demand and peak demand forecasts for the EE scenarios in comparison with the FEE scenario are presented in Figure 3.56 through Figure 3.59. In the high temperature scenario, energy dropped to 751 TWh for the LEE scenario and 660 TWh for the HEE scenario; furthermore, coincident peak demand dropped to 162 GW for the LEE scenario and 140 GW for the HEE scenario. In the low temperature scenario, energy dropped to 728 TWh for the LEE scenario and 640.1TWh for the high efficiency scenario; in addition, coincident peak demand dropped to 153 GW for the LEE scenario and 134 GW for the HEE scenario.

In comparison with the frozen scenario, an energy demand saving of 11.7% and 27.4% was achieved respectively in the LEE and HEE scenarios. In addition, a peak demand savings of 12.3% and 30.0% was achieved respectively in the LEE and HEE scenarios. Considering the weather effect, the high temperature scenario resulted in an increase of 3.1% in energy demand and 5.2% in peak demand in both the LEE and HEE scenarios in comparison with the low temperature scenario.

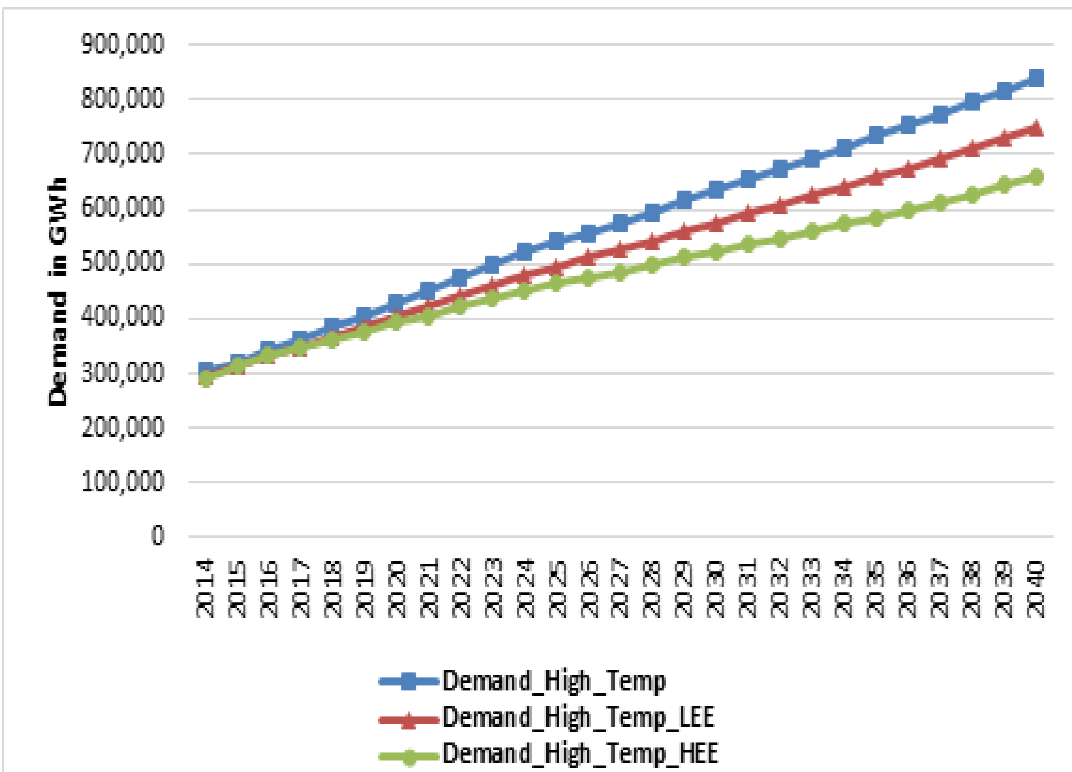


Figure 3.56 Annual energy demand forecasts for all scenarios with the high temperature case for Saudi Arabia, 2014–2040 (in GWh)

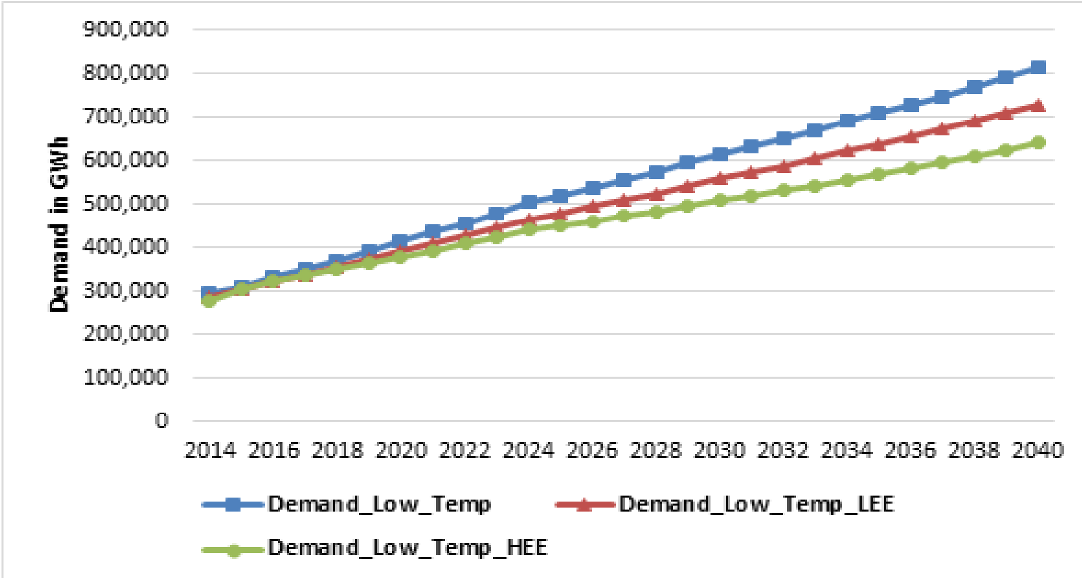


Figure 3.57 Annual energy demand forecasts for all scenarios with the low temperature case for Saudi Arabia, 2014–2040 (in GWh)

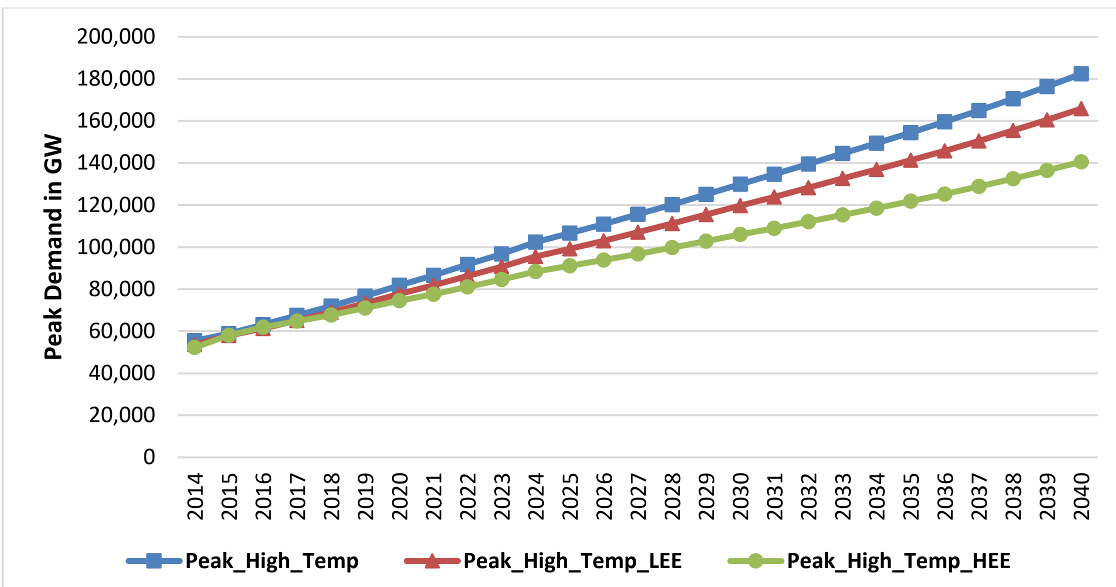


Figure 3.58 Annual peak demand forecasts for all scenarios with the high temperature case for Saudi Arabia, 2014–2040 (in GW)

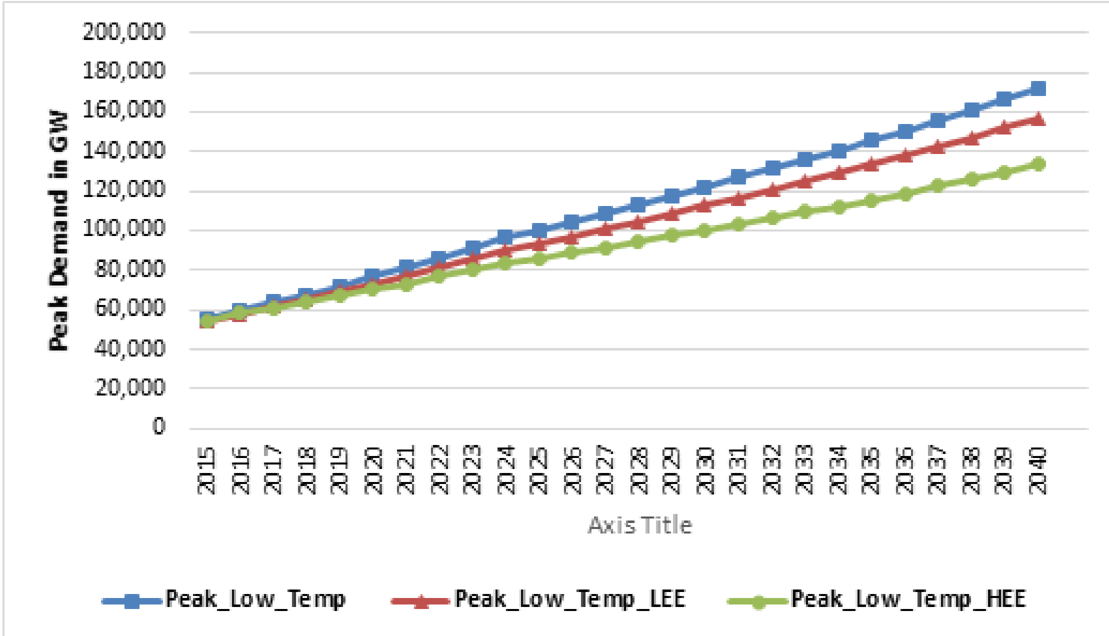


Figure 3.59 Annual peak demand forecasts for all scenarios with the low temperature case for Saudi Arabia, 2015–2040 (in GW)

3.4.4 Consideration of Self Consumption in the Demand Forecasting Results

The forecasting results presented in the previous sections accounted for electricity demand of the end-users; it did not take industrial and desalination facilities' self-consumption into account. Scale factors were therefore developed to deal with own-use through a detailed examination of monthly data at each major point of generation in the Kingdom. The subsequently adjusted estimates of total electricity demand are shown in Figure 3.60. Details of the peak demand forecasting results for each area are shown in Appendix C.

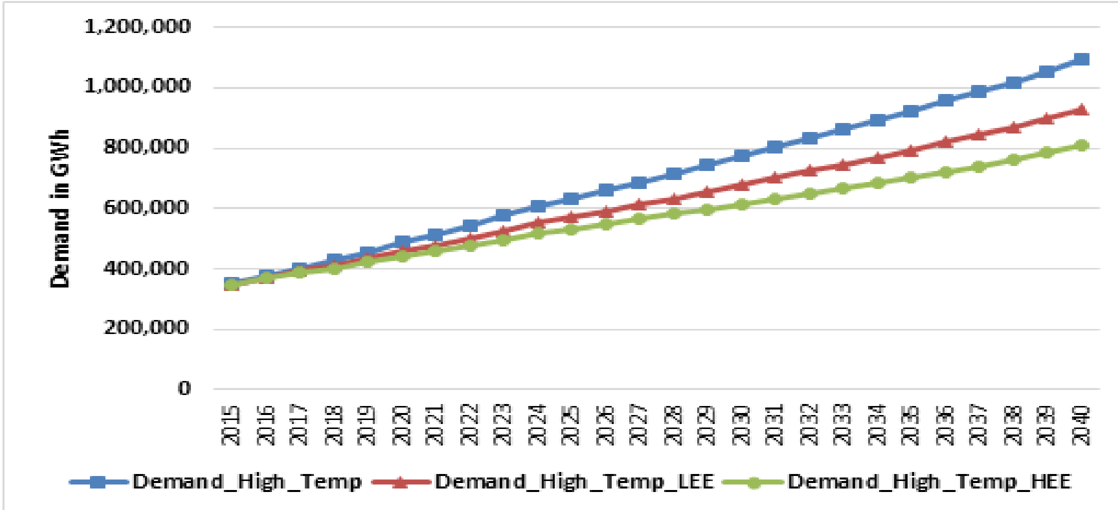


Figure 3.60 Annual energy demand forecasts for all scenarios with the high temperature case for Saudi Arabia, 2015–2040 (in GWh, and adjusted for own-use demand)

3.4.5 Conversion of the Monthly Forecasted Demand to Hourly Demand Data

The proposed forecasting model provided average monthly demand results for each sector and operating area. The annual peak demand was then calculated using the peak to average ratio for each area, as explained in Section 3.1.1. To use the forecasted demand in the EWS IRSP model in the PLEXOS software, the monthly data had to be converted to hourly data for the period 2016–2040. A historical hourly normalized demand curve for each area for one year (i.e. 2012) was thus used to convert the forecasted average monthly demand, taking the extrapolated peak to average ratio (as presented in Figures 3.7 and 3.14) into consideration.[44] The normalized demand

[44] This method of converting the forecasted monthly data to hourly data may not accurately differentiate between weekend days and weekdays. However, it provides a reasonable estimation of hourly demand in the future that is adequate to meet the long-term planning expansion objectives of this research.

curves for each area were calculated as ratios between the hourly demand and average monthly demand. The results for these series were used as a key input to the EWS IRSP model for Saudi Arabia, which is discussed in detail in the next chapter.

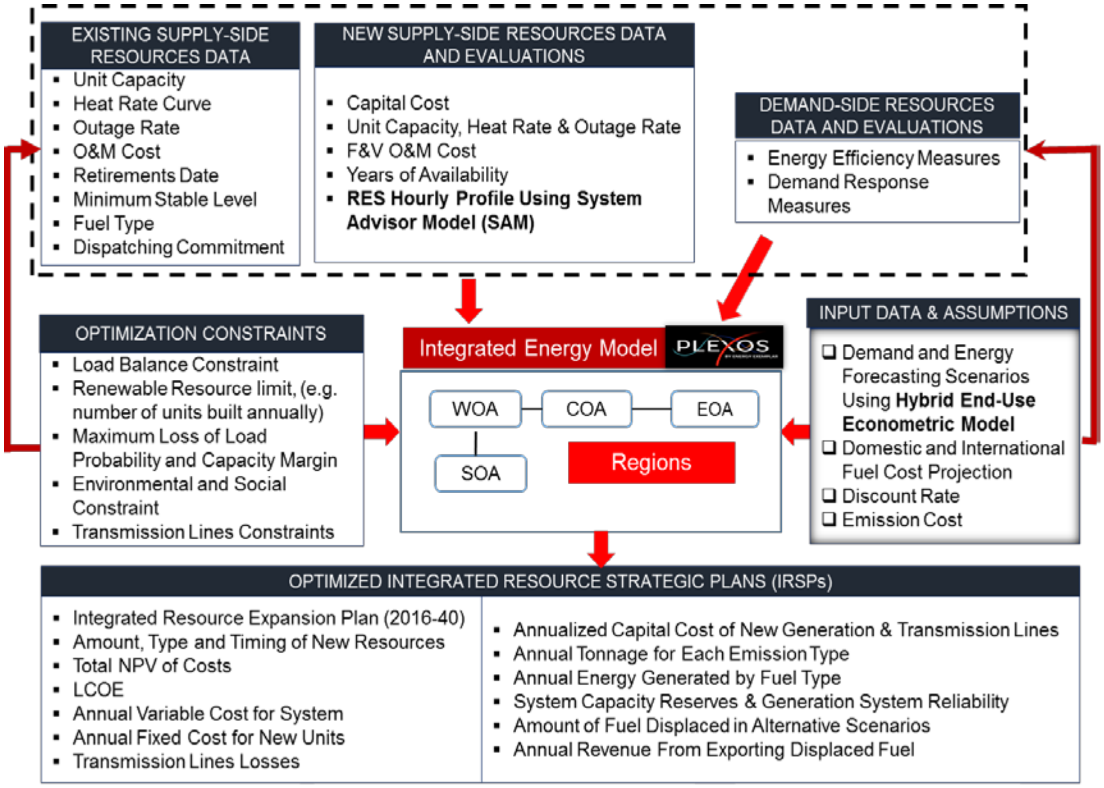
Chapter 4

ESTABLISHING AN IRSP MODEL FOR SAUDI ARABIA's UTILITY SECTOR

The urgency of formulating a comprehensive energy-mix plan in the Saudi utility sector and aligning it with the country's long-term national development plan is strongly recognized and discussed in Chapter 1. Establishing an IRSP model for the electricity and water sectors will help to align fragmented energy policies among various entities with overall economic, social, and environmental objectives. With all of its components and details, the IRSP will clearly determine the Kingdom's future vision of its utility sector, including goals, policies, programs, and a timetable for execution. This chapter introduces a new IRSP model for the utility sector in Saudi Arabia that uses PLEXOS software as an integrated energy tool. The next section provides a detailed description of the framework of the IRSP methodology. The subsequent sections then describe the input data, assumptions, formulations, and objectives developed in conjunction with the IRSP model.

4.1 Overview of the Methodology Framework

The IRSP model is designed to co-optimize supply-side resources, transmission, and demand-side resources to (1) achieve optimal and sustainable economic generation fuel-mix options that minimize fuel consumption and decarbonize the energy sector (i.e. reduce CO_2 emission), and (2) maximize other social and environmental benefits of the utility sector. Chapter 1 provided details about this methodology and the tool applied in the optimal system modeling and design of the Kingdom's electricity and water resources which uses PLEXOS software. Figure 4.1 shows an overview of the PLEXOS regional representation of the IRSP model of Saudi Arabia's utility sector, along with various inputs to and expected outputs from the model. Each region was implemented as a node connected radially by interconnected 380kV transmission lines. Based on the analysis made in Chapters 1 and 2, DSM market potentials, renewable energy resources hourly profiles, and Chapter 3's forecasting demand results for each region and consuming category for various EE scenarios were used as inputs to the IRSP model. The model will integrate the supply-side and demand-side side into candidate integrated plans though an iteration process of varying key input-date and assumptions, and objective functions in various scenarios.



Source: modified from EPRI, 2015, p.36

Figure 4.1 IRSP model: Regional representation, input data, and output

4.2 Input Data and Assumptions

The section presents the sets of assumptions and input data that were used for creating an integrated EWS model for Saudi Arabia.

4.2.1 IRSP Model Study Period

The IRSP model examines a period of 24 years (2016–2040). For validation purposes, the IRSP model was established based on up-to-date data from 2015.

4.2.2 Discount Rates

The discount rate is used to analyze economic costs and benefits at different times. It also represents the minimum rate of return on new investments. In most of the countries in the world, the social discount rate is used in public development activities such as infrastructure projects, for public projects.[45] The social discount rate depends upon the specific conditions within the country in question. For instance, as Zhuang, Liang, Lin and De Guzman (2007, p. 17) report, the United Kingdom had a social discount rate of 10% in 1969, which dropped to 6% in 1989 before further decreasing to 3.5% in 2003 based on the conditions within the United Kingdom at these times. A 3% social discount rate was assumed in this analysis, as it reflects a median discount rate level within Saudi Arabia from 1992 to 2015 (Trading Economics, 2016). It is also in line with the rate assumption of electricity generating cost (EGC) groups in relation to the social cost of capital (IEA & NEA, 2015, p. 27). Furthermore, it was also assumed that this discount rate is stable and does not vary during the planning period. Sensitivity to the discount rate was analyzed by applying higher discount rates to reflect the market rate and high-risk investment environment.

4.2.3 Demand Forecasting Input

4.2.3.1 Electricity Demand

Hourly electricity demand forecasting results for the FEE scenarios for the period 2016–2040 were obtained using the demand forecasting and EE methodologies explained in Chapter 3. The forecasting results include a sensitivity analysis of

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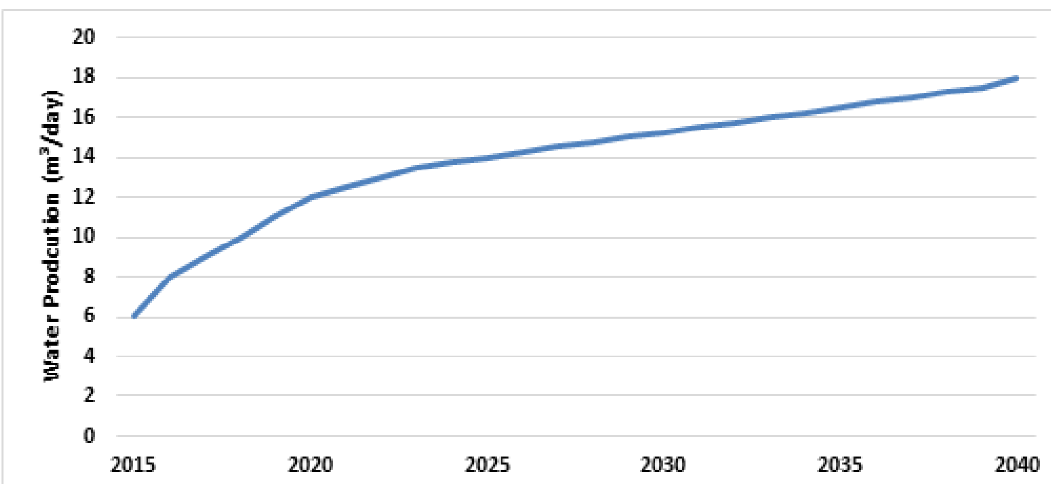
[45] Tellus (2000, p. 56) defines the social discount rate as an indicator of the rate of time preferences for evaluating investments from a societal standpoint.

demand profiles that examines the impacts of key variables, such as GDP and household growth levels.

4.2.3.2 Desalinated Water Demand

The water production capacity of desalination plants in Saudi Arabia is expected to grow from 6 million m³/day in 2015 to approximately 18 million m³/day in 2040 (Figure 4.2). In the EWS IRSP model, the existing desalination technologies are modeled using their technical details, such as unit heat rates, fuel consumption, operation and maintenance (O&M) costs. The model utilizes PLEXOS software to integrate the desalinated water and electricity sectors into one model. For future desalination plants, high efficiency RO desalination plants are modeled as an electrical load in the IRSP model based on their electricity requirements for producing desalinated water.



Data source: ECRA, 2014; World Bank, 2011, p. 36

Figure 4.2 Projected desalinated water production in Saudi Arabia until 2040

4.2.4 Supply-Side Resource Assumptions

4.2.4.1 Existing Supply-Side Resource Classifications

The existing power plants in each of Saudi Arabia's four electricity operating areas were classified by technology type into five main categories, as shown in Table 4.1.

Table 4.1 Existing supply-side resource classifications used in the IRSP model

Generation Class	Description
Combined cycle (CC)	This technology represents the most efficient and advanced technology in the generation mix, with an efficiency of 50–60%; it entails exhaust heat being recycled and used to run steam turbines to generate electricity.
Simple cycle (SC)	This technology uses fuel-fired turbines that are turned by gas produced from burning fuel. Typically, its efficiency is low (around 34.6% at the average air temperature of 32-degree C in Saudi Arabia).
Steam turbines (ST)	This technology uses fuel to turn water into steam, which is then used to turn a generation's turbines.
Combined heat and power (CHP)	These generators are mainly owned by industrial facilities to cogenerate electricity and steam.
Distributed diesel generation	This technology involves small-size generators that are fueled by diesel to supply isolated areas where the grid is not connected.
Desalination plants	This class represents the water technologies currently in service (i.e. RO, MSF, and MED), which are modeled to account for their water production, electricity generation, and fuel and electricity consumption. Future desalination plants will consider only efficient RO plants and are represented in the IRSP model as an electrical load.

Source: ECRA, 2014, p. 47

4.2.4.2 New Supply-Side Resource Options and Their Costs Assumptions

The new power plant candidates used in the EWS IRSP model were classified by technology, as shown in the Table 4.2.

Table 4.2 New supply-side resource options used in the IRSP model

Technology	**Assumed Unit Capacity (MW)** [46]
Natural gas-fired CC	344
Natural gas- and diesel-fired SC	203
Steam turbines ST operating on HFO and Arab light oil	748
New wind (1 MW each)[47]	1
Utility-scale PV (1 MW each)	1
CSP with 8 &12 hours TES (215 MW each) [48]	215
Nuclear power plant (1425 MW each)	1425

Information concerning new fossil fuel-based candidate generation used in the IRSP model (including efficiency, capital costs, fixed and variable O&M costs, and project lead times) is presented in Table 4.3

[46] The unit capacity for each technology is assumed based on unit capacity ranges stipulated in the Electricity Generating Cost (EGC) group 2015 dataset for a wide range of generating technologies (IEA and NEA, 2015, p.37). For PV and wind, flexible unit size for each year has been considered using a typical unit size of 1MW. However, the annual installed capacity was determined based on the calculated potential for each technology.

[47] The widely used wind size turbine is 1 to 1.5 MW model, (for example in GE turbines), which consists of 116-ft blades atop a 212-ft tower for a total height of 328 feet (or 100 meters) (National Wind Watch, 2017)

[48] CSP unit capacity based on the average rating of recently installed large ST CSPs worldwide (110MW-377MW) (NREL, 2017).

Table 4.3 Real costs and data for power generation technologies in 2015

Power Technology	Efficiency[49] (%)	Capital Cost ($/kW)	Fixed O&M Cost ($/kW/year)	Non-Fuel Variable O&M Cost	Project Lead Time[50]
Combined cycle (gas)	58	1021	20.0	3.4	2
Simple cycle	35	708	10.0	5.2	2
Steam turbine	43	1600	40.0	2.5	2
Nuclear power plant	43	5026	109.9	9.4	7

Data source: IEA and NEA, 2015; IRENA, 2015; Matar et al., 2015

A technology roadmap prepared by the International Energy Agency (IEA) provides cost projections for renewable energy sources (namely PV, CSP, and wind), as shown in Figure 4.3. The upper and lower cost projections of these three energy sources are presented in Figures 4.4, 4.5, and 4.6. These limits are used in the sensitivity analysis later in this chapter. Figure 4.7 shows the projected fixed O&M for these technologies based on projections from the International Renewable Energy Agency (IRENA).[51]

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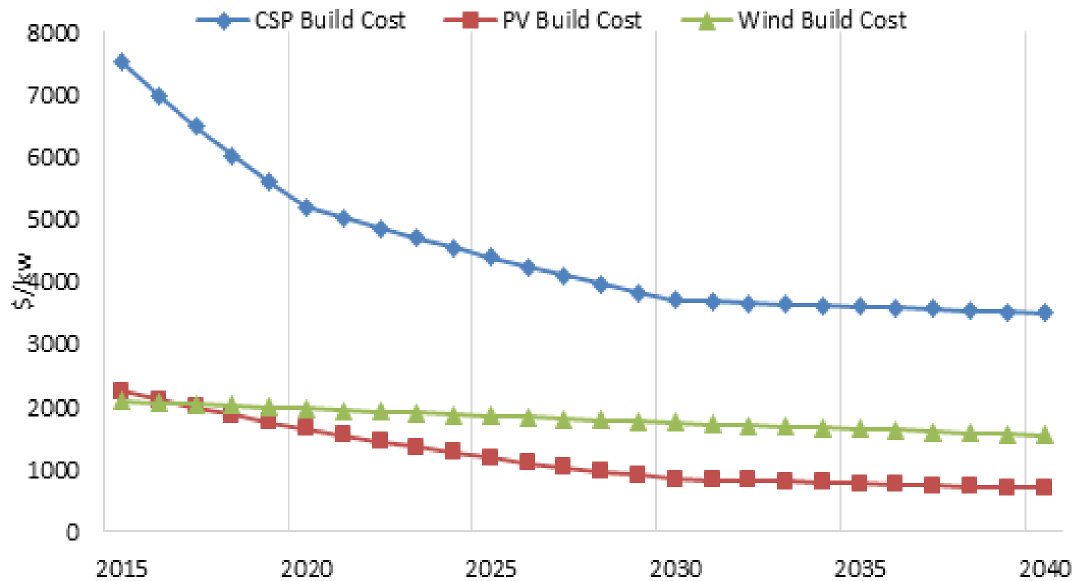
[49] The prevailing ambient conditions in KSA influence the performance of these technologies. Therefore, the efficiencies listed in the table takes into consideration these conditions. In addition, the efficiency of generation in non-coastal areas (i.e. the COA) was reduced due to the impact of using air-cooling technology. For instance, CCGT suffers from additional 2% loss under the average air temperature conditions (32-degree C)

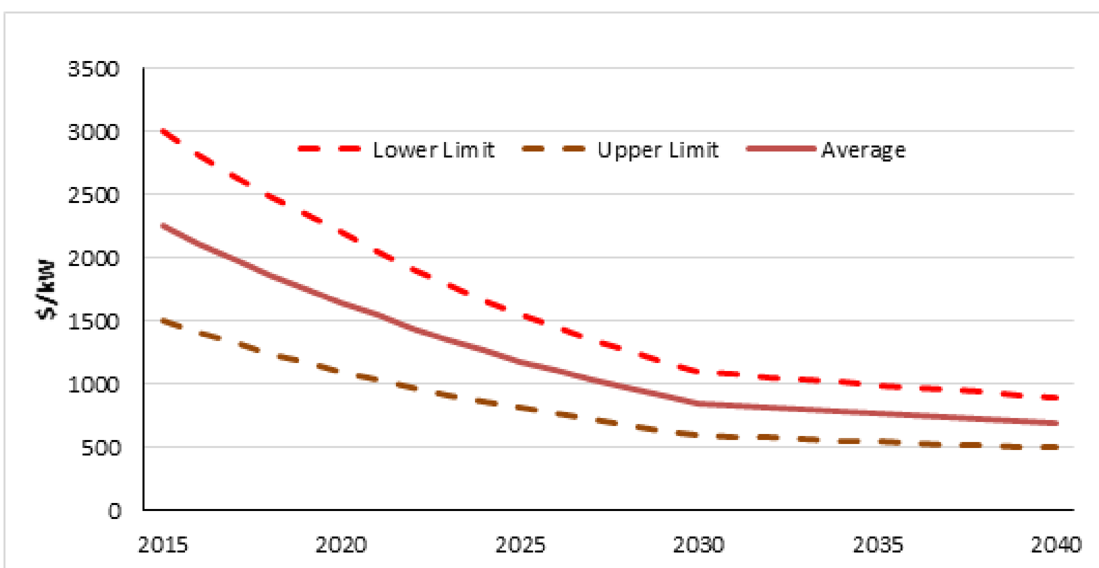
[50] New generation installations were assumed to start in 2018, considering their requisite construction lead-times.

[51] IEA has been criticized for publishing conservative estimates that failed to predict the rapid growth of renewable energy sources in the world (Shankleman, 2016). For the purpose of this dissertation, IEA cost projections have been used as a conservative assumption. Nonetheless, cost variations have been also considered to conduct sensitivity analysis and evaluate the impact of this conservative assumption.



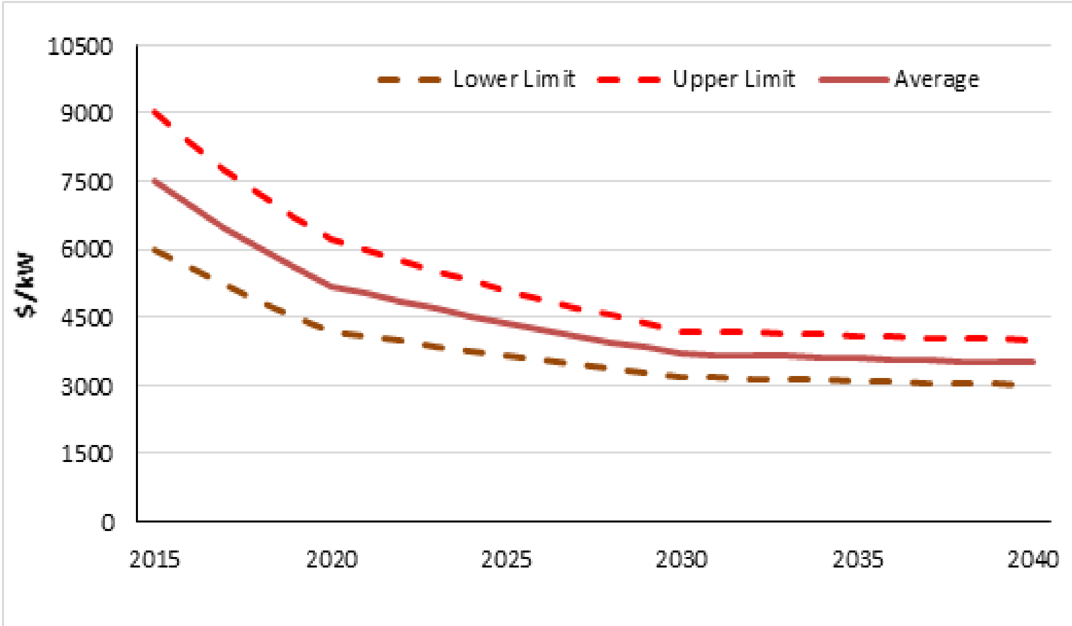
Data source: IEA, 2013b; IEA, 2014b; IEA, 2014c

Figure 4.3 Profile of capital costs for renewable technologies, 2015–2040



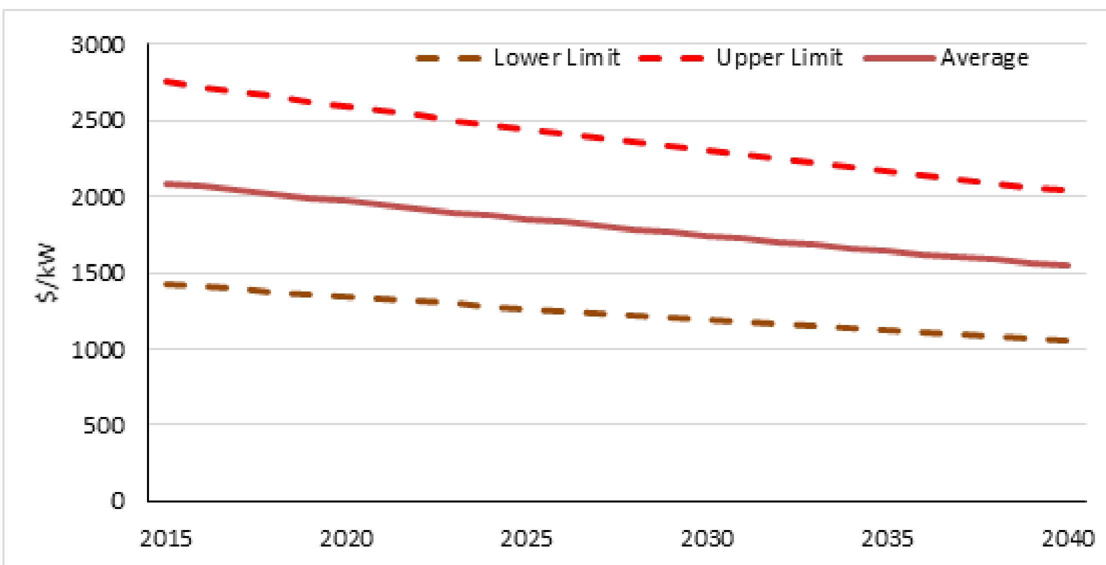
Data source: IEA, 2014b, p. 23

Figure 4.4 Upper and lower cost projections for utility-scale solar PV, 2015–2040



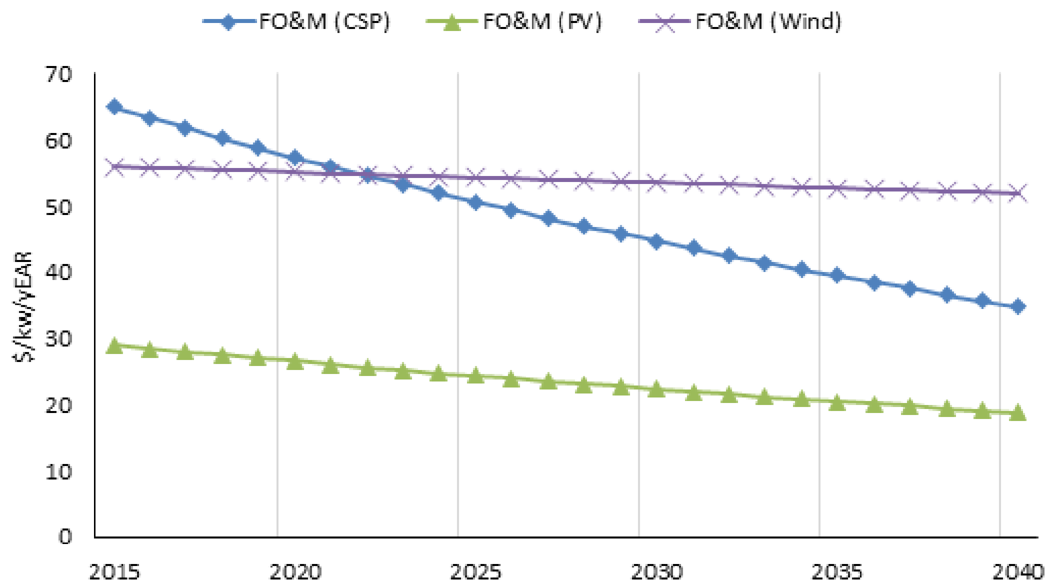
Data source: IEA, 2014c, p. 23

Figure 4.5 Upper and lower cost projections for CSP, 2015–2040



Data source: IEA, 2013b, p. 23

Figure 4.6 Upper and lower cost projections for wind, 2015–2040



Data source: IRENA, 2014, pp. 93&109

Figure 4.7 Profiles of fixed operation and maintenance (FO&M) costs for renewable technologies, 2015–2040

4.2.4.3 Water Consumption for Electricity Generation

Water scarcity has triggered Saudi Arabia to install vast water desalination plants and become the largest producer of desalinated water in the world (Aljarboua, 2009, p. 1). Spnag, Moomaw, Gallagher, Kirshen, and Marks (2014), indicated that Saudi Arabia was ranked among the top six consumers of water used for energy production, including electricity generation. This research calculated water consumption at the power plant-level, taking cooling type, fuel type and generation technology into account. Table 4.4 highlights the water consumption (in m^3 per MWh) for each generation technology.

Table 4.4 Water consumption for various generation technologies

Generation Technology	**Cooling**	**Water Consumption (m^3/MWh)**
Natural gas and oil CCGT[52]	Air	0.01
	Cooling tower	0.80
Natural gas and oil steam turbines	Cooling tower	2.76
Nuclear	Cooling tower	2.73
PV and wind[53]	Not required	0.02
CSP[54]	Air[55]	0.19

Data source: Spang et al., 2014, p. 6; Bracken et al., 2015, p. 8

4.2.4.4 Desalination Technology Type and Cost

As explained in Section 2.1.1, RO technology was selected as the thermal desalination technology throughout the research due to the several advantages (e.g., low electricity consumption cost) that it offers over options such as MED and MSF. The capital and variable O&M costs for the proposed new RO desalination plants are summarized in Table 4.5 below.

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52 In current installations, air-cooled CCGTs are used for in-land areas (i.e. the COA) while cooling tower systems are used in coastal areas (e.g., the EOA and WOA). This assumption is maintained for future installations.

53 As explained by Meldrum, Nettles-Anderson, Heath and Machnick (2013), water is primarily used for cleaning the blades of wind turbines and PV panels. Therefore, minimal water consumption is associated with PV and wind power production.

54 Due to water scarcity in Saudi Arabia and the availability of the highest potential CSP with the highest DNI values inland, CSP with air-cooled systems were used in this research.

55 A dry-cooled CSP system adds no additional water consumption. The assumed water consumption is for mirror washing and makeup water for the steam cycle process. The estimate for CSP water consumption is based on calculations made by Bracken et al., 2015, p. 8.

Table 4.5 The capital and variable O&M costs for the proposed new RO desalination plants

Capital cost in ($/m³/day)	Variable O&M ($/m³)	Water Production Capacity (m³/day)
1100	0.07	250,000

Data source: ACWA, 2014; Napoli and Rioux, 2015, p. 16

4.2.4.5 CSP Profile Assumptions

Concentrated solar power deployed with thermal energy storage (TES) provides a flexible renewable energy source that can dispatch electricity during periods of high demand and displace more (and higher-cost) fuel than other renewables without storage (Denholm & Hummon, 2012). For the purpose of the analysis in this research, various profiles of CSP with TES of 8 Hours (SM-2) and 12 hours (SM-2.5) were considered based on different thermal storage dispatch schedule. Based on the hourly forecasted demand of Saudi Arabia, two peaks normally occur at approximately 14:00 hours and 20:00 hours. Figure 4.8 shows the daily CSP normalized power output profiles obtained using SAM in a peak summer day. CSP with 8 hours of TES (profile-1) peaks during the day time and then it reduces its output during night time. CSP with 12 hours of TES (profile-1) peaks during day and continue to dispatch power at the same rating during evening until early morning to support during both day-time and evening peaks in the summer. For the most part, CSP with 8 hours of TES (profile-1) can replace peaking and intermediate fossil fuel generation while CSP with 12 hours of TES (profile-1) can replace a large portion of fossil fuel base-load generation (DCSP, 2015). CSP with 8 hours of TES (profile-2) and 12 hours of TES (prfile-2) generate power mostly during night to replace fossil fuel base-load generation while other cheaper renewables, such as PV, can be used during daytime. The IRSP model entailed undertaking comprehensive investigations based on using either one of these profiles or combination of all profiles in order to reach to the optimal option.

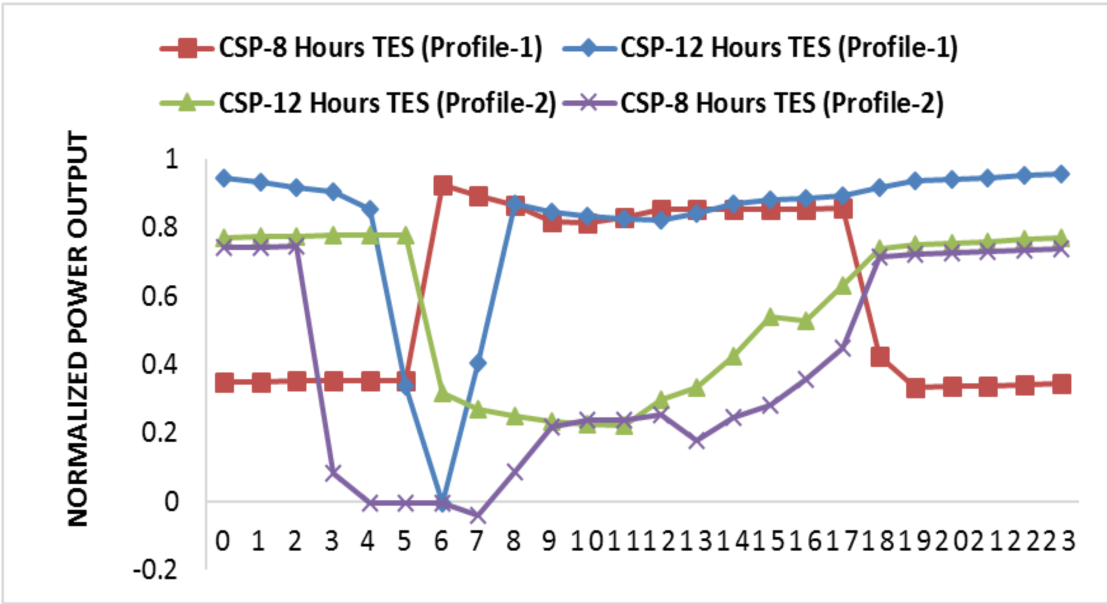


Figure 4.8 Proposed CSP profiles with 8- and 12-hour TES during peak summer day (for WOA area)

4.2.4.6 Plant Commissioning and Retirement

It was assumed that the new power plants were commissioned at the beginning of each year. For existing power plants, the retirement data were determined based on the technical life of these units and it was assumed that they were forced to retire in their retirement month during the year.

4.2.4.7 Maintenance and Forced Outage Rates

The maintenance rate refers to the fraction of time annually that units are expected to be out-of-service due to scheduled maintenance events. The maintenance rate in the IRSP model was set at 7% or 613 hours annually. Furthermore, the forced outage rate is calculated based on the level of unplanned outages that may lead to a full or partial loss of generating capability for a specific period. In the IRSP model, the forced outage rates for fossil fuel-based generation were set at 3% or 262 hours per year. The mean time to repair and restore the generation was assumed to be 24 hours.[56]

4.2.5 Fuel Classification and Cost Assumptions

4.2.5.1 Fuel Classifications and Data

As explained earlier, the electricity and desalination sectors rely on two main types of fuels: liquid fuel and natural gas. Liquid fuels were further classified into three categories: (1) diesel, (2) heavy fuel oil (HFO), (3) crude oil of Arab heavy oil (AH) and Arab light oil (AL) (ECRA, 2014, p. 85). Fuel heat rates, efficiency level, and emission values were obtained from reputable sources (EIA, 2016; Hussy, Klaassen, Koornneef, & Wigand, 2014; Black & Veatch, 2012).

4.2.5.2 Natural Gas Network Assumptions

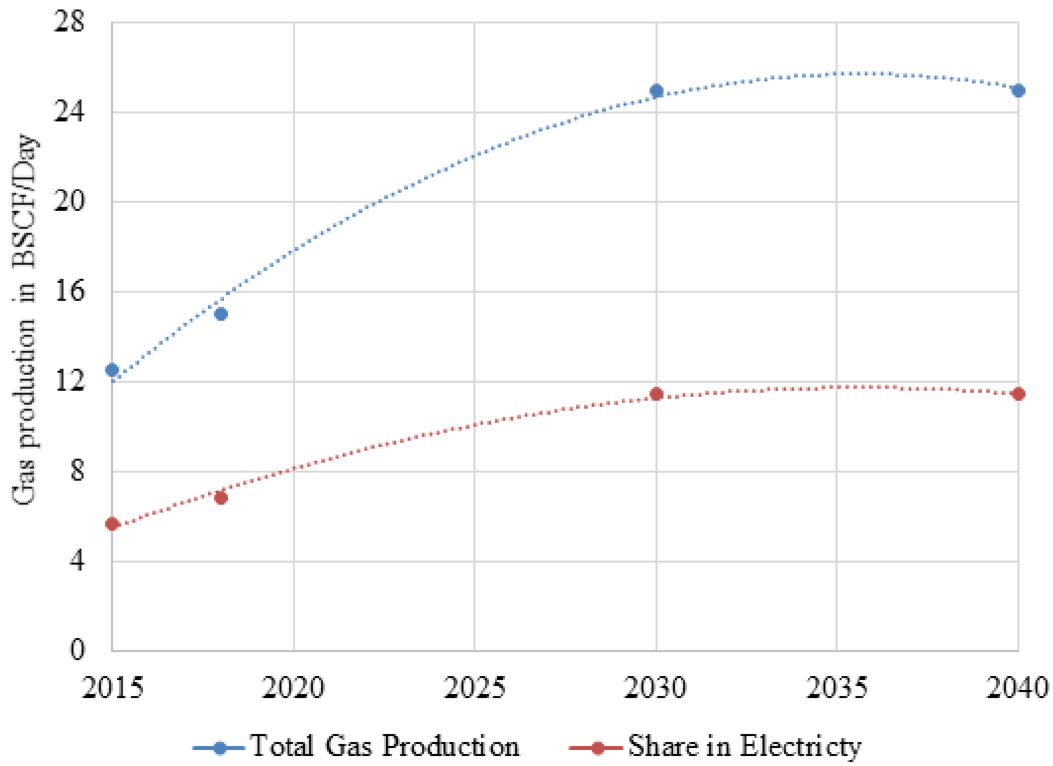
Natural gas is the dominant fuel for power generation in Saudi Arabia's eastern and central regions. However, it does not constitute the fuel mix in the western and southern regions, where oil and diesel are respectively the dominant fuels due to a lack of infrastructure capable of transporting natural gas to them from the production and

[56] These values are based on the median maintenance and forced outage rates for all generators in Saudi Arabia (ECRA, 2009b). In addition, these values are in line with the recommended default values in PLEXOS database (Energy Exemplar, 2016).

processing centers primarily in the east of the country (Fattouh, 2013). Our analysis therefore assumed that oil would be gradually phased out of these two areas by retiring existing oil-based generation and installing more natural gas generators. Relatively new oil-based generation (i.e. five years or newer) in the western and southern regions are estimated to be more than 11 GW; they are not scheduled for retirement during the planning period 2016–2040.

4.2.5.3 Current and Forecasted Domestic Natural Gas Production

Natural gas shortages have prompted oil substitution in Saudi Arabia in the past decade. As a result, the trend has dramatically changed and all Kingdom's natural gas production is consumed in the domestic market. The natural gas shortages have led to more oil being burned, mainly due to the high electricity demand for cooling during summer. The domestic national energy fuels mix in 2012 saw an increase in the share of oil to approximately 66% (IEA, 2013). Natural gas production is now 12.5 billions of standard cubic feet (BSCF)/day, although the current plan is to increase this capacity to 15 BSCF/day in 2018 (IEA, 2014d) and 25 BSCF/day in 2030 (Reuters, 2014b). The current allocation of natural gas in the electricity sector (47%) was maintained during the planning period, especially with the Kingdom's goal to shift natural gas consumption to the petrochemical sector and towards other sectors with greater added-value (Nachet & Aoun, 2015, p. 20). Moreover, since no further data is available about gas production expansion plans beyond 2030, gas production was capped at 25 BSCF/day in the IRSP model. In our analysis, the gas supply constraint for electricity generation was assumed as shown in Figure 4.9.

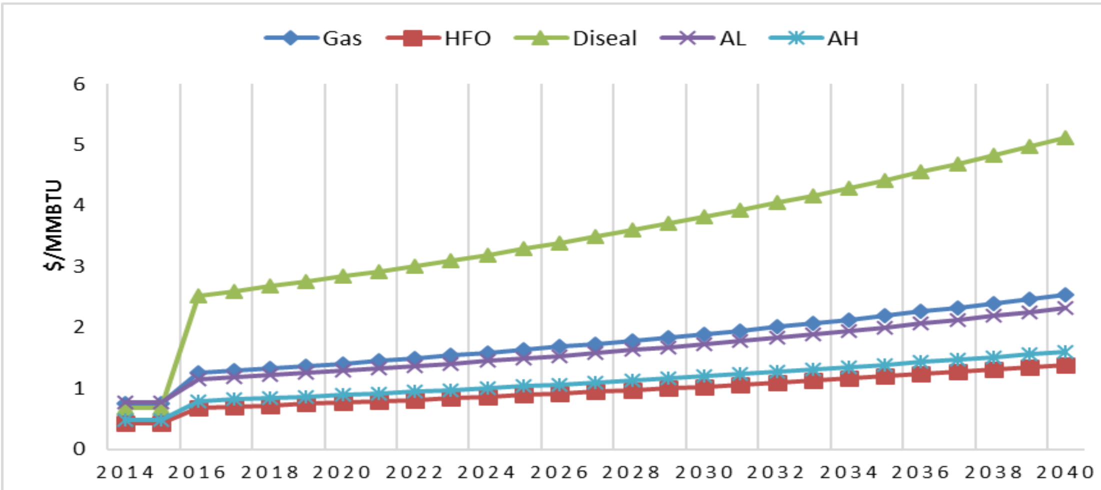


Data source: IEA, 2014; Reuters, 2014b

Figure 4.9 Assumed natural gas supply limits in electricity generation, 2015–2040

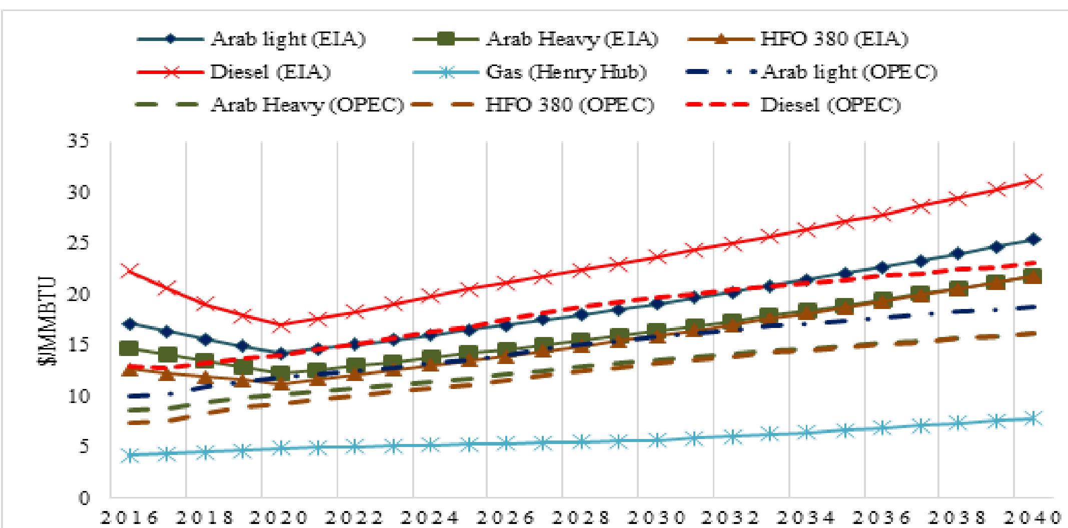
4.2.5.4 Current and International Fuel Prices

Figure 4.10 shows current fuel prices for Saudi Arabia for the period 2016–2040 with a 3% escalation cost rate. These prices represent the subsidized domestic fuel prices following a price increase in early 2016. International fuel costs based on projections of OPEC basket prices (reference case) for oil products and EIA Henry Hub for gas-linked prices (reference case) are shown in Figure 4.11. It should be noted that OPEC basket price projections have been used in this research given that they are more conservative than EIA reference fuel projections. Nonetheless, EIA projections, as shown in Figures 4.12 and 4.13, were used to undertake a sensitivity analysis of IRSP results.



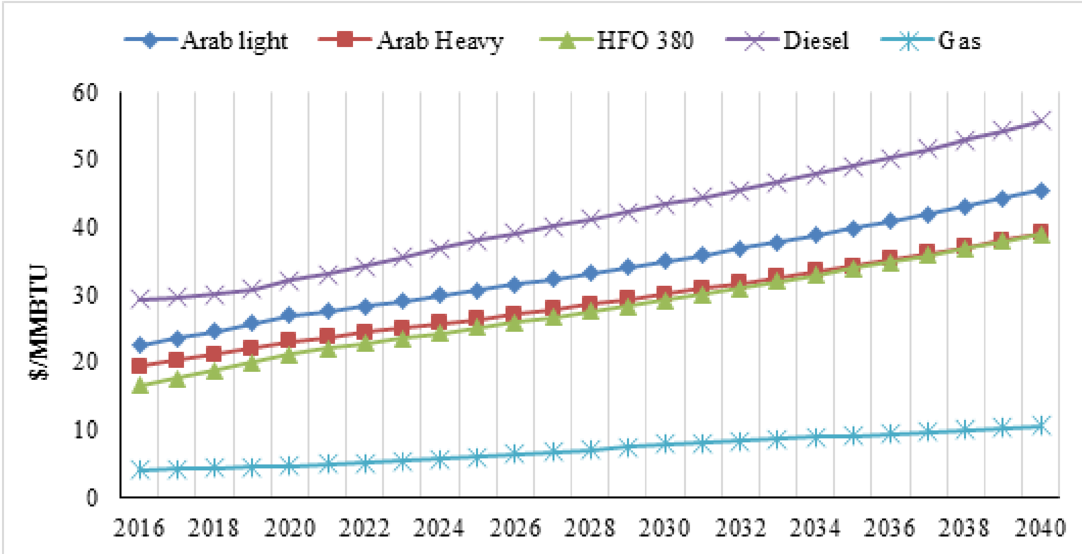
Data source: ECRA, 2014, p. 86

Figure 4.10 Current fuel prices for electricity usage in Saudi Arabia, 2014–2040



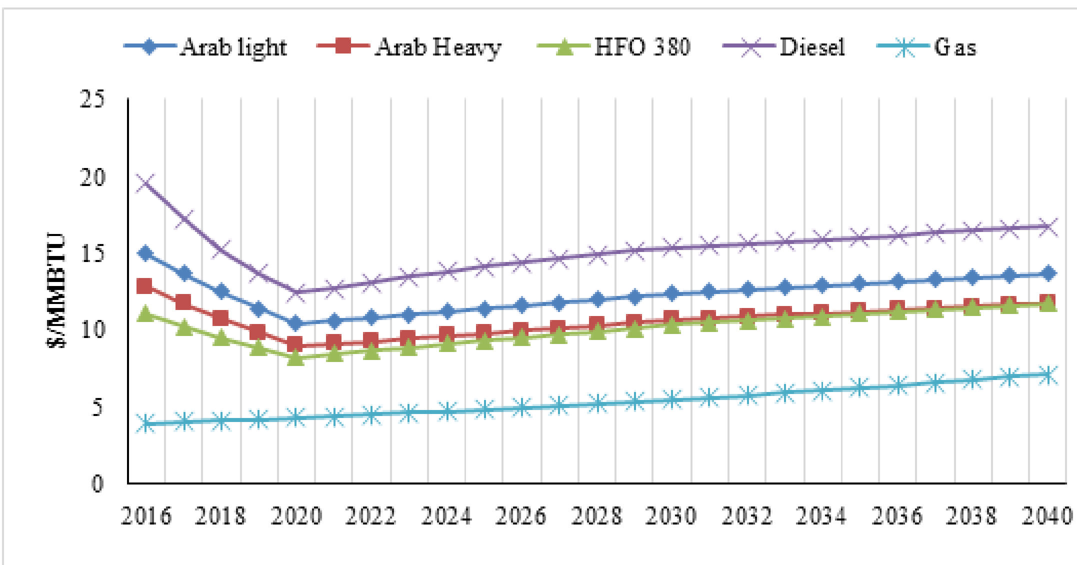
Data source: OPEC, 2015, p. 48; EIA, 2015, p. 6

Figure 4.11 International fuel prices, 2016–2040



Data source: EIA, 2015, pp. 5&6

Figure 4.12 High international fuel prices, 2016–2040 (based on EIA projections)



Data source: EIA, 2015, pp. 5&6

Figure 4.13 Low international fuel prices, 2016–2040 (based on EIA projections)

4.2.6 Reliability Index Assumptions

Loss of load probability (LOLP) is a reliability index that is defined as the percentage of time that the system load exceeds the system's available generation capacity. The target sets an upper bound on each region's LOLP (for each period) in the long-term plan. The expansion solution will attempt to meet the required LOLP target through new builds, restricted plant retirements, or both. In the IRSP model, LOLP was set to 0.001 %.[57] This is in line with the most resource adequacy standards of North American Systems (Pfeifenberger et al. 2013).

4.2.7 Social Benefits Analysis

4.2.7.1 Description of the Methodology

One quantitative method for evaluating the social benefits of IRSP results is to create jobs and increase local employment related to the EWS as well as in the Saudi economy at large. For the purpose of the analysis conducted in this research, a proxy of jobs per annual GWh produced was used to convert various job types to single long-term, full-time jobs. The original job types included long-term maintenance and operatoin jobs, short-term construction and manufacturing jobs, and so on. (Blyth, Gross, Speirs, Sorrell, Nicholls, Dorgan, & Hughes, 2014). Full-time equivalent (FTE) assumes that "1" job lasts for a plant's entire lifetime (Wei, Patadia, & Kammen, 2010) and allows generation sources to be compared on a like-for-like basis. This indicator was used to calculate the following three types of jobs:

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[57] Some areas may have LOLP values higher than 0.1%, but the target is to maintain a balance between the total demand and total supply of all areas so that the LOLP will be maintained at 0.1% at the Kingdom level.

- Direct jobs, which are defined by Wei et al. (2010) as “jobs created in the design, manufacturing, delivery, construction, installation, project management and operation and maintenance of the different components of the technology, or power plant, under consideration.”;
- Indirect jobs, which are designed to facilitate one particular project and are generated within the supply chain: and
- Induced jobs, which are generated due to a rise in employees’ household expenditure. This includes both indirect and direct employees.

4.2.7.2 Gross Jobs Calculations

Jobs related to the O&M of generation technologies are usually reported for the duration of a project. Short-term jobs related to the manufacturing and construction phase are reported in job-years, which are converted by dividing by the job-years by the project’s lifetime. Table 4.6 shows the average gross numbers of jobs created per unit of electricity generated, which are used to calculate the social impact of different scenarios in this research.

Table 4.6 Gross jobs per annual GWh generated for various technologies

Type of Generation	Direct Jobs	Indirect Jobs	Induced Jobs	Number of Studies [58]
PV	1.8	0	4.5	5
CSP	0.3	2	1.0	3
Wind	0.5	0.6	0.8	15
EE	0.3	0	4.1	3
Fossil fuel	0.2	0.2	0.3	4

Data source: Blyth et al., 2014, p. 34

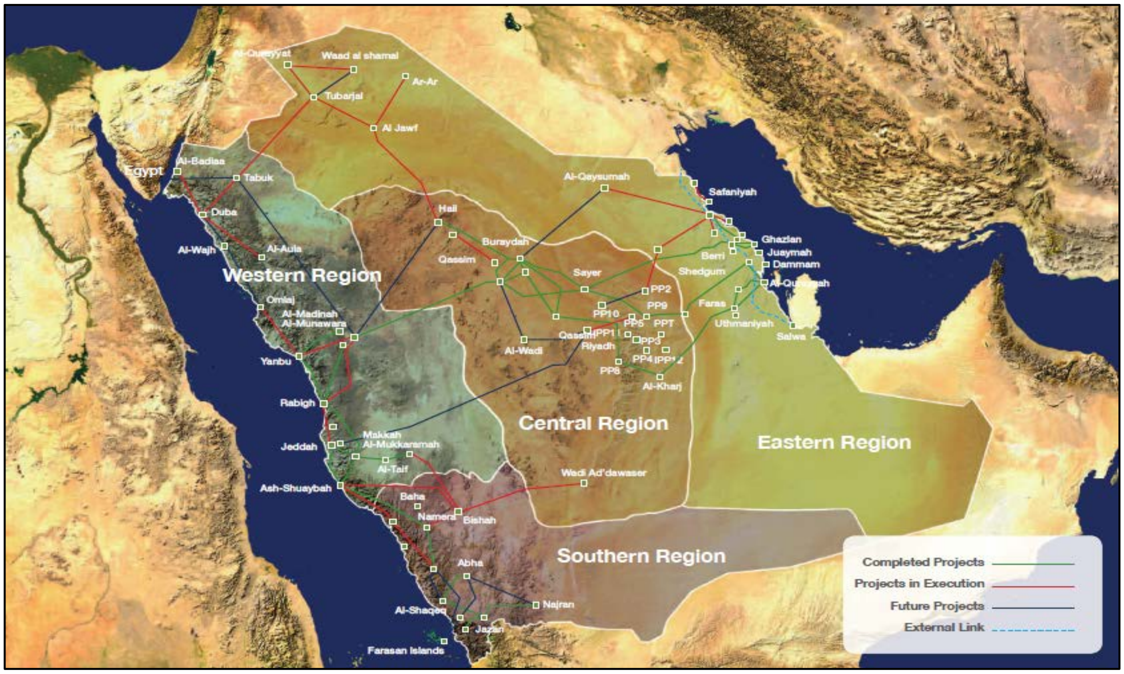
4.2.8 Transmission Line Assumptions

Based on the analysis of potential renewables, it is assumed that the renewable energy resources would be installed in the vicinity of major cities to minimize the costs of undertaking significant transmission expansions. In this research, only 380kV interregional transmission lines (TLs) were modeled in the EWS IRSP model to address electricity import and export between the four electricity operating areas.

4.2.8.1 Existing and Planned 380kV Interregional TLs

Figure 4.14 shows the Kingdom's four main electricity regions, namely the COA, EOA, WOA, and SOA; it also illustrates the 380kV TLs that interconnect them with an existing total transfer capacity of around 10 GW. Planned TLs will add around 2.6 GW transfer capacity to the grid.

[58] The average gross jobs were calculated based on the number of publications that provided data in each particular category.



Data source: SEC, 2015, p. 16

Figure 4.14 380kV power grid and operating areas in Saudi Arabia

4.2.8.2 New TL Candidates and Cost

Existing 380kV transmission lines interconnecting between the main four electricity regions (Central Operating Area (COA), Western Operating Area (WOA), Eastern Operating Area (EOA), and Southern Operating Area (SOA)) in Saudi Arabia were modelled in the IRSP model. These transmission lines interconnect the four areas with an existing total transfer capacity of around 10 GW. Planned transmission lines will add around 2.6 GW transfer capacity to the grid. All new TL's are assumed to be High-Voltage Direct Current (HVDC) due to the long distance between the operating areas (i.e., 900 km between COA and WOA and 400 km between COA and EOA). The capacity of each line is assumed to be 1000 MW. HVDC TL's costs are significantly reduced and losses can be reduced at long distances (above 350km) in comparisons with HVAC TL’s (MacDonald, Clark, Alexander, Dunbar, Wilczak and Xi 2015; Behravesh and Abbaspour, 2012 303; Nguyen and Saha, 2009, 310). TL's technical data (i.e., impedance) and costs were obtained from Black & Veatch (2014). The assumed cost is inclusive of other components, such as substations and, HVDC converter station.

4.2.8.3 Network Limitations

While the IRSP model addressed physical limitations (including the thermal limit of interregional TLs between Saudi Arabia’s four operating areas), it does not explicitly consider intra-regional power flows, either as a model result or for modeling the power system’s physical limitations (including its stability limits). Concerns have repeatedly been raised about the impact of high renewable energy sources penetration on grid stability. Nonetheless, this situation does not cause problems in countries with high renewable energy resources (such as Germany, where PV already contributed about 40% of the peak demand in the summer during some hours) (Appen, Braun, Stez, Diwold, & Geibel, 2013, p. 55).

4.3 Model Formulation and Constraints

4.3.1 The Least Cost Optimization Formula

The long-term plan simulator of PLEXOS expands the generation capacity in each region over the planning horizon such that the net present value (NPV the capital cost, fixed O&M cost, and production cost are minimized over the planning horizon. This is mathematically represented by the following least-cost linear optimization equation:

$$\sum_{(y)} \sum_{(g)} DF_y \times (BuildCost_g \times GenBuild_{(g,y)})$$
$$+\sum_{(y)} DF_y \; [\text{FOMCharge}_g \times 1000 \times \text{PMAX}_g (\text{Units}_g + \sum_{i \leq y} GenBuild \; \text{Units}_{g,i}) \quad (4.1)$$

These variables and other parameters are defined in Table 4.7.

Table 4.7 Definitions of variables and other parameters

Variable	Description	Type/Unit
$GenBuild_{(g,y)}$	Number of generating units built in year *y* for generator *g*	integer
$GenLoad_{(g,t)}$	Dispatch level of generating unit *g* in period *t*	continuous
$CapShort_y$	Capacity shortage in year *y*	continuous
D	Discount rate. $DF_y = 1/(1 + D)^y$ (which is the discount factor applied to year) and DF_t (which is the discount factor applied to dispatch period *t*)	%
L_t	Duration of dispatch period *t*	Hours
$BuildCost_g$	Overnight build cost of generator *g*	$
$\text{MaxUnitsBuilt}_{(g,y)}$	Maximum number of units of generator *g* allowed to be built by the end of year *y*	each
PMAX_g	Maximum generating capacity of each unit of generator *g*	MW
Units_g	Number of installed generating units of generator *g*	each
FOMCharge_g	Fixed O&M charge of generator *g*	$
$Load_t$	Average power demand in dispatch period *t*	MW
PeakLoad_y	System peak power demand in year *y*	MW
ReserveMargin_y	Margin required over maximum power demand in year *y*	MW

Source: Energy Exemplar, 2016

4.3.2 General Constraints

According to the guidelines for using PLEXOS software (Energy Exemplar, 2016), least-cost generation expansion in the software is subject to the seven equations listed below.

1. Energy balance constraint:

$$\sum_{(g)} GenLoad_{(g,y)} + USE_t = \text{Demand}_t \ \forall_t \tag{4.2}$$

2. Feasible energy dispatch constraint:

$$GenLoad_{(g,t)} \leq \text{PMAX} \ (\text{Units}_g + \sum_{i \leq y} GenBuild \ \text{Units}_{g,i} \ ) \tag{4.3}$$

3. Feasible builds constraint:

$$\sum_{i \leq y} GenBuild_{\ g,i} \leq \text{MaxUnitsBuilt}_{g,y} \tag{4.4}$$

4. Integrity constraint:

$$GenBuild_{(g,y)} \text{ integer} \tag{4.5}$$

5. Capacity adequacy:

$$\sum_{(g)} \text{PMAX}_g \ (\text{Units}_g + \sum_{i \leq y} \text{GenBuild}_i) + \text{CapShort}_y \geq \text{PeakLoad}_y + \text{ReserveMargin}_y \ \forall_y \tag{4.4}$$

6. Energy dispatch feasibility accounting for outages rates constraint:

The LT plan formulation includes the generator forced outage rate (FOR) and maintenance rate (MOR). Both the MOR and FOR decrease generators' energy contribution. Therefore, Equation 4.3 becomes:

$$GenLoad_{g,t} \leq (1 - \text{MOR}_g \times \text{MF}_t - \text{FOR}_g) \times \text{PMAX}_g \times (\text{Units}_g + \sum_{(i \leq y)} (GenBuild_i)) \ \forall \ g,t \tag{4.7}$$

Where MF_t is the Region Maintenance Factor in period t.

7. Capacity constraint:

Since forced outages are accounted for by the input reserve margin, forced outage and maintenance are not considered when totaling the generation capacity in terms of determining the capacity available to fulfil a capacity margin constraint.:

$$\sum_{(g)} \text{PMAX}_g \times (\text{Units}_g + \sum_{(i \le y)} (\text{GenBuild}_i)) + \text{CapShort}_y \ge \text{PeakLoad}_y + \text{ReserveMargin}_y \; \forall y \quad (4.8)$$

4.3.3 Additional Constraints Defined for the Model

Additional constraints are defined exclusively for the IRSP model for Saudi Arabia's utility sector to address the issues discussed in the subsections that follow.

4.3.3.1 Annual Generation Capacity Build

This constraint defines the maximum capacity of generation that needs to be built annually based on the total required new generation capacity. It allows PLEXOS to choose the technology and its geographical operating area based on the least cost formula in equation (4.2). The formula for this constraint is as follows:

$$\sum (New\ CC_{(i,COA)} + New\ CC_{(i,EOA)} + New\ CC_{(i,SOA)} + New\ SC_{(i,WOA)}) + (New\ SC_{(i,COA)} + New\ SC_{(i,EOA)} + New\ SC_{(i,SOA)} + New\ SC_{(i,WOA)}) + (New\ ST_{(i,EOA)} + New\ ST_{(i,SOA)} + New\ ST_{(i,WOA)}) \le \text{Total Required New Gen Capacity } (NewGenCap_i) \quad (4.9)$$

Where:

$$(NewGenCap_i) = (Added\ Peak\ Load_i - Retired\ generation_i - Existing\ Generation_i) \quad (4.10)$$

4.3.3.2 Annual Renewable Capacity Build

This constraint defines the maximum capacity of generation that needs to be built annually based on the capacity target for each technology. These targets are defined for different cases simulated by PLEXOS to investigate the impacts of various penetration percentages on the model. As renewable resources are not uniform across the country, the constraint allows PLEXOS to choose the technology and its geographical operating area based on the least cost formula in equation (4.2).

For PV technology, the following constraint is defined:

$$\sum (New\ PV_{(i,COA)} + New\ PV_{(i,EOA)} + New\ PV_{(i,SOA)} + New\ PV_{(i,WOA)}) \leq \text{Annual Capacity Target } (PV\_CapTarget_i) \quad (4.11)$$

For CSP technology, the following constraint is defined, taking different thermal storage durations (8 and 12 hours) into consideration:

$$\sum (New\ CSP_{(i,COA,8hours)} + New\ CSD_{(i,EOA,,8hours)} + New\ CSP_{(i,SOA,8hours)} + New\ CSP_{(i,WOA,8hours)}) + New\ CSP_{(i,COA,12hours)} + New\ CSP_{(i,EOA,12hours)} + New\ CSP_{(i,SOA,12hours)} + New\ CSP_{(i,WOA,12hours)} \leq \text{Annual Capacity Target } (CSP\_CapTarget_i) \quad (4.12)$$

For wind technology, the following constraint is defined:

$$\sum (New\ Wind_{(i,COA)} + New\ Wind_{(i,EOA)} + New\ Wind_{(i,SOA)} + New\ Wind_{(i,WOA)}) \leq \text{Annual Capacity Target } (Wind\_CapTarget_i) \quad (4.12)$$

For nuclear energy, the following constraint is defined, such that these nuclear plants will be constructed only in coastal areas:

$$\sum (New\ Nucl_{(i,EOA)} + New\ Nucl_{(i,WOA)}) \leq \text{Annual Capacity Target } (Wind\_CapTarget_i) \quad (4.13)$$

4.3.3.3 Daily Gas Supply Constraint

As explained concerning maximum natural gas production in Section 4.2.5.3, a daily gas supply constraint for each area is defined using the following equation:

$$Daily\_Gas\_Consumption_{\ (i,area)} \leq Daily\_Gas\_Supply_{(i,area)} \qquad (4.14)$$

4.3.4 Levelized Cost of Electricity Calculations

Annual levelized cost is calculated using the following formula (Energy Exemplar, 2016):

$$LCOE\ (in\ \$/MWh) = \frac{Total\ Cost}{Total\ Generation\ in\ MWh} \qquad (4.15)$$

The total generation cost is achieved as below:

$$Total\ Cost = Total\ Generation\ cost + FO\&M\ Cost + Annualized\ Build\ Cost \qquad (4.16)$$

Where total generation cost and annualized build cost are calculated respectively by Formulas 4.17 and 4.18:

$$Total\ Generation\ Cost = (Running\ Cost \times Units\ Generating + Fuel\ Offtake \times Fuel\ Price + Generation \times VOM\ Charge) + Start\ \&\ Shutdown\ Cost + Emissions\ Cost + Abatement\ Cost) \qquad (4.17)$$

$$Annualized\ Build\ Cost = \mathrm{BuildCost}_g \times \mathrm{PMAX}_g \times \mathrm{D} / \left(1 - \left[1 / (1 + \mathrm{D} \right]^{\mathrm{EconomicLife}} \right) \qquad (4.18)$$

Therefore, the total discounted annual charges, beginning in the chosen year y and ending at the end of the economic using discount rate (D) of the unit, replace the build cost coefficient in the objective function (BuildCostg).

An IEA report on the projected costs of generating electricity (2015) used an approach to calculate average lifetime levelized costs that entailed dividing the present value of the sum of discounted costs (which covers all related costs) by the present sum of discounted revenues (expressed in MWh) (IEA, 2015, p. 28). Following the same approach, the average levelized cost in the planning period can be calculated using Equation 4.15 and the discount rate (D):

$$LCOE\ (in\ \$/MWh) = \frac{\sum Total\ Cost\ X\ (1+D)^{-t}}{\sum Total\ Generation\ in\ MWh\ X\ (1+D)^{-t}} \qquad (4.19)$$

4.3.5 Optimal Power Flow Formulations

DC-optimal Power flow also becomes commonly utilized perform real-time dispatch and techno-economic analysis of power systems as a result of its robust, basic structure. It can also easily integrate HVDC and HVAC transmission lines in one model. This section highlights the derivations for the linearized DC-optimal power flow (OPF) as stipulated in the PLEXOS help guide. The main power flow parameters are defined in Table 4.8.

Table 4.8 Definitions of power flow parameters

r + jx	Impedance, represented respectively by resistance and reactance
G+jB	Real and imaginary terms of admittance (inverse of impedance). Note that the approximations of the imaginary term, 1/x, is called susceptance.
bus	Constant voltage construction to which TLs are connected.
|V|q	Indicates voltage magnitude and phase angle at a system bus.
p.u.	"Per unit" indicates that the quantity has been scaled down for power calculations, where the scaling is specified by both a kV and MW rating for any given section of the power system.

Source: Energy Exemplar, 2016

The linearized DC load flow model is driven by the following points in regard to large-scale, high-voltage power systems (Energy Exemplar, 2016):

- Line reactance is significantly greater than line resistance x/r 1.0;
- There is little variances between bus voltage levels |V| 1.0 p.u.; and
- There is only a minimal phase angle difference over TLs (e.g. all lines are likely to have an angular difference of less than 30°).

Therefore, the following approximations are presented:

- G= $\frac{r}{(r^2+x^2)} \cong 0$;
- B= $\frac{-x}{(r^2+x^2)} \cong 1/x$: the term g=1⁄x (susceptance) is frequently used in power equations;
- cos(q_k - q_1) ≅ 1: the first term of the power series equivalent of cos(); and
- sin(q_k - q_1) ≅ q_k - q_1: the first term of the power series equivalent of sin().

The following equation for power flow on a line is therefore presented (Broad, 1996):

$$f_{kl} = -B_{kl}(q_k - q_l) = g_{kl}(q_k - q_l) \qquad (4.18)$$

where g_{kl} is the susceptance in that g_{kl}=-− B_{kl}=1⁄ x.

Therefore, complete linearity is demonstrated in the power flow equations, meaning that they can be reflected accurately within a linear programming (LP) framework. In the case of Equation 4.18, $q_k - q_l$ represents the phase angle difference (in radians) between buses at each end of the line.

4.3.6 Definitions of the Objectives

In general, IRSP modeling requires setting explicit objectives for the planning process. These objectives should reflect the country in question's national strategies for energy resources. After defining these planning objectives, metrics must be assigned to each objective. These metrics can be either quantitative or qualitative, according to how they are measured. For example, cost objectives lend themselves well to quantitative measures of performance while other metrics may entail a mix of quantitative and qualitative measures (Tellus, 2010, p. 6; Hawaiian Electric Companies, 2013).

In relation to the EWS IRSP model for Saudi Arabia, the following four objectives were defined in line with this study's main questions:

- Minimize domestic fossil fuel consumption in the utility sector. This requires a fundamental change in the supply-side sources mix and high implementation of EE measures on the demand-side.
- Maximize penetration of sustainable energy sources. This requires incorporating a diverse portfolio of renewables to support the transition toward a sustainable supply of electricity.
- Minimize environmental impact. This requires an aggressive move away from fossil-fuel based electricity generation toward diverse and renewable energy generation to reduce emissions and lower greenhouse gasses.

- Maximize social benefits. This requires choosing resources that create both local jobs related to the utility sector and jobs in the economy at large. It also targets reducing end-users' electricity bills as well as securing a reliable supply that has minimal interruptions throughout the year.

4.3.7 Metrics Development

4.3.7.1 Metrics Definition

Hawaiian Electric Companies (2013, p. 3-2) developed a number of IRSP objectives along with detailed qualitative and quantitative metrics, which it defined as follows:

> Qualitative metric measures the quality or characteristic of an objective. Qualitative metrics measure direction — for instance: up, down, or the same — rather than the size of the movement (which would be a hard number). While the description of a qualitative metric can be expanded beyond the simple "up, down, the same", this additional information is inherently subjective because they are based on personal opinion. On the other hand, a quantitative metric uses hard numbers to measure the movement of an objective. Quantitative metrics provide the actual number of a movement. Rather than indicating that sales went up, a quantitative measure would state the actual amount sales rose, such as "12% over the same time last year". While opinions might vary over what such a number means, the number itself — and thus all quantitative metrics — are objective. Thus, quantitative metrics have computable results.

The below tables define quantitative and qualitative metrics (where applicable) for the IRSP model of the Saudi utility sector to assess how well each objective is being met. Tables 4.9 to 4.13 provide detailed definitions of each metric for the four main objectives identified earlier.

Table 4.9 Quantitative metrics of objective 1: Minimize domestic fossil fuel consumption in the utility sector

Quantitative Metric	Units	Formula
Share of delivered electricity from fossil fuels	%	$\frac{\sum \text{electricty generated by fossil fuel in GWh}}{\text{Total generation in GWh}}$
Share of the resource plan cost in relation to fossil fuel	%	$\frac{\text{Total fossil fuel} - \text{based resource cost}}{\text{Total resource cost}}$
Amount of liquid fuel used in the utility sector	BOE	∑ Crude Oil + Diesel + HFO
Amount of natural gas used in the utility sector	BOE	∑ Natural Gas
EE savings	GWh	∑ EE measures savings
Estimated revenue from exporting displaced fuel	$	∑ fuel displaced x fuel price

Table 4.10 Quantitative metric of Objective 2: Maximize penetration of sustainable energy sources

Quantitative Metric	Units	Formula
Renewable share	%	$\frac{\sum \text{Renwable energy in GWh}}{\text{Net generation in GWh}}$
Renewable energy curtailed	GWh	Non-dispatched energy in GWh due to system constraints
Resource diversity index[59]	Range from 0 to 1	α = 1- $\sum(x_i)^2$ where α is the resource diversity and *x* is the generation share from a given resource across all generation types
Estimated cost saving	$	∑ Total resource cost in frozen scenario - ∑ Total resource cost in RES scenario

59 As Wang and Shahidehpour (2009) and Hovacheck (2014) explain, the Herfindahl-Hirschman Index (HHI) has long been adopted in order to measure the competitiveness of given markets based on the identification of market shares. Additionally, the HHI has been used to determine intra-regional differences in terms of power capacity). In this analysis, the diversity index is used to assess generation resource diversity in the generation mix.

Table 4.11 Quantitative metrics of objective 3: Minimize environmental impact

Quantitative Metric	Units	Formula
CO_2 emissions	Tons	$\sum CO_2$ emissions
Sulfur oxides (SO_X) emission intensity	kg/MWh	$\frac{\sum SOx\ emissions}{Net\ generation\ in\ MWh}$
Nitrous oxides (NO_X) emission intensity	kg/MWh	$\frac{\sum NOx\ emissions}{Net\ generation\ in\ MWh}$
Water consumption in generation	m^3/MWh	$\frac{\sum Net\ water\ consumption}{Net\ generation\ in\ MWh}$

Table 4.12 Quantitative metrics of objective 4: Maximize social benefits

Quantitative Metric	Units	Formula
Create local jobs (direct, indirect, and induced)	Number of jobs	$\sum$ jobs created by each supply/demand resource
Reduce nominal price of electricity	Cent/kWh	Levelized cost of electricity
Provide reliable supply by increasing the reserve margin	%	$\frac{System\ generation\ capacity - Peak\ load}{Peak\ load}$
Reduce loss of load probability	Days/year	In the IRSP model, this metric is set as a constraint to have LOLP at 0.001%.

Table 4.13 Qualitative metrics of objective 4: Maximize social benefits

Qualitative Metric	Comment
Geographic diversity of generating resources	System reliability and security is positively correlated to regional resource diversity

4.3.7.2 Existing Metrics in Saudi Arabia

In early in 2016, Saudi Arabia launched “Saudi Arabia’s Vision 2030” as a roadmap and guide for future economic development in the Kingdom. This vision is targeted to identify the nation's overall objectives, policies and plans. In order to build the institutional capacity with the necessary capabilities to accomplish the vision's ambitious goals, in 2016 the National Transformation Program (NTP) 2020 was also launched across 24 government bodies operating in the economic and development sectors. The objectives outlined under the NTP are clearly and explicitly associated with interim metrics for 2020. Implementation began last year and will continue to garner support from a greater number of government entities over the next few years. Many of these strategic objectives have an impact on the utility sector. Table 4.14 identifies all relevant strategic objectives and metrics (against the baseline of year 2016) in the NTP 2020 and links all applicable metrics to the above four objectives of the current research.

Table 4.14 Summary of the Saudi National Transformation Program's objectives relevant to the electricity and water sector

Relevant Research Objective No.	**Metric/Target**	**Target for 2020**
1	Energy efficiency: Efficient utilization of fuel in electricity power generation	40%
2	Renewable energy resources share: Percentage of renewable energy to total energy used	4%
3	Reduce CO_2 emissions from 2016 levels	7.2%
4	Reliability of supply: Average number of outages for more than 5 minutes in the electricity power grid annually	3 outages
	Reliability of supply: Percentage of electricity generation capacity reserve	12%
	Job creation: Percent of localized technologies out of total targeted	100%
	Job creation: Number of available direct job opportunities for citizens in both the atomic and renewable energy sectors	7774

Data source: Saudi Arabia's Vision 2030, 2016

4.3.7.3 Comparisons of Metrics with Global Results

In addition to evaluating metrics related to each IRSP objective defined in the previous section, the metrics for each scenario in the IRSP were also compared with global metric results related to the same objectives (Tables 4.15 to 4.18). This comparison was made with the goal of analyzing the performance of the IRSP model with respect to various international plans containing similar objectives and nations in different geographical locations and with diverse development levels. For the purpose of the comparisons, results related to different metrics were aggregated at four levels: (1) the world, (2) the Middle East, (3) developed regions/countries (e.g., the EU and the United States), and (4) developing countries (e.g., China). The following three main scenarios were identified:

- The new policies scenario (NPS) in the World Energy Outlook prepared by the IEA (2015) and defined as follows:

  > In addition to incorporating the policies and measures that affect energy markets that had been adopted as of mid-2015, the NPS also takes account of other relevant intentions that have been announced, even when precise implementing measures have yet to be fully defined. This includes the energy-related components of the intended nationally determined contributions submitted by national governments by October 1, 2015 as pledges in the run-up to the United Nations Framework Convention on Climate Change's 21st Conference of the Parties.

- China's 2050 high renewable energy (REN) penetration scenario. This scenario, which sees renewable energy accounting for 85.8% of China's total power generation in 2050, will enable the country to rely solely on its domestic energy resources and realize the sustainable utilization of natural resources as well as ecologically and environmentally friendly energy development (Energy Research Institute (ERI), 2015).

- The EU green scenario. This scenario aims to bring about a decrease of 95% in the power sector's GHG emissions by 2050 based on figures from 1990. Renewable generation will achieve a predefined target of 80% by 2050 with the assumed completion of the Desertec project, which will make power from solar fields in the Middle East and North Africa accessible (McKinsey&Company, 2015).

Table 4.15 Global metrics results of the IRSP objective-1 in 2040

The IEA New Policies Scenario					**The EU Green Scenario**	**China's High REN Scenario**
World	**Middle East**	**USA**	**EU**	**China**		
Share of delivered electricity from fossil fuel (%)						
62	86	72	49	68	29	22
Fossil fuel consumption (except gas) (Mtoe)						
2848	61	244	61	1188	NA	NA
Natural gas consumption (Mtoe)						
1681	257	250	134	158	NA	NA
Energy efficiency savings (%)[60]						
8.5	8.6	8.6	11.0	11.7	16.9	11.0

[60] Energy efficiency savings were determined by calculating the difference between electricity demand in the new and current IEA policy scenarios.

Table 4.16 Global metrics results of the IRSP objective-2 in 2040

The IEA New Policies Scenario					The EU Green Scenario	China's High REN Scenario
World	Middle East	USA	EU	China		
Renewable share (%)						
3	14	28	51	32	71	78
Resource diversity index						
0.71	0.26	0.72	0.93	0.68	0.99	0.95

Table 4.17 Global metrics results of the IRSP objective-3 in 2040

The IEA New Policies Scenario					The EU Green Scenario	China's High REN Scenario
World	Middle East	USA	EU	China		
CO_2 emissions (millions of tons)						
15060	796	1537	531	4995	255	2900
SO_X emissions (millions of tons)[61]						
NA	NA	500	NA	NA	NA	2500
NO_X emissions (millions of tons)						
NA	NA	800	NA	NA	NA	2500
Water consumption in generation (m^3/MWh)[62]						
1.18	0.92	1.26	1.03	1.39	0.77	0.57

[61] NO_X and SO_X emissions were only available in the report developed by the Energy Research Institute (ERI, 2015, p. 8).

[62] Water consumption was calculated based on operational water consumption for thermal and non-thermal electricity generation technologies as defined in European Wind Energy Association (2014) and projected generated electricity in 2040 for all scenarios.

Table 4.18 Global metrics results of the IRSP objective-4 in 2040

The IEA New Policies Scenario					The EU Green Scenario	China's High REN Scenario
World	**Middle East**	**USA**	**EU**	**China**		
Jobs created (millions of jobs)[63]						
48.15	2.62	6.52	5.58	14.16	7.78	30.57
Price of electricity ($/MWh)						
NA	NA	NA	NA	NA	NA	120

Using the input data and assumptions to establish the IRSP model in this chapter, next chapter presents the scenario analysis and results from 2016 to 2040 based on an in-depth analysis of the interrelations between energy, economics, environment, and society. It also undertakes a sensitivity analysis of different variables that are likely to have a major impact on the results of the scenario analysis.

[63] The number of jobs created was calculated based on the methodology defined in Section 4.2.7.

Chapter 5

THE IRSP MODEL RESULTS

5.1 Development of the Scenarios

Scenario analysis is an effective method to evaluate alternative technological options mix of technological options that deliver the same energy services level. This dissertation has proposed alternatives based on various factors including significant social advantages, high alternative energy source, CO_2 emissions minimization, least-cost and other energy supply and demand strategies. Figure 5.1 shows the schematics of the following four main scenario families that were considered, namely:

- EE scenarios,[64] including (1) a FEE case or baseline case and (2) EE cases;
- Renewable scenarios[65], which envision the highest possible level of renewable energy source penetration throughout the planning horizon;
- Environmental scenarios, which target the highest emission reduction in the utility sector; and
- Social scenarios, which target maximizing a net increase in the creation of jobs based on the influence of relevant policies for EE and renewable energy.

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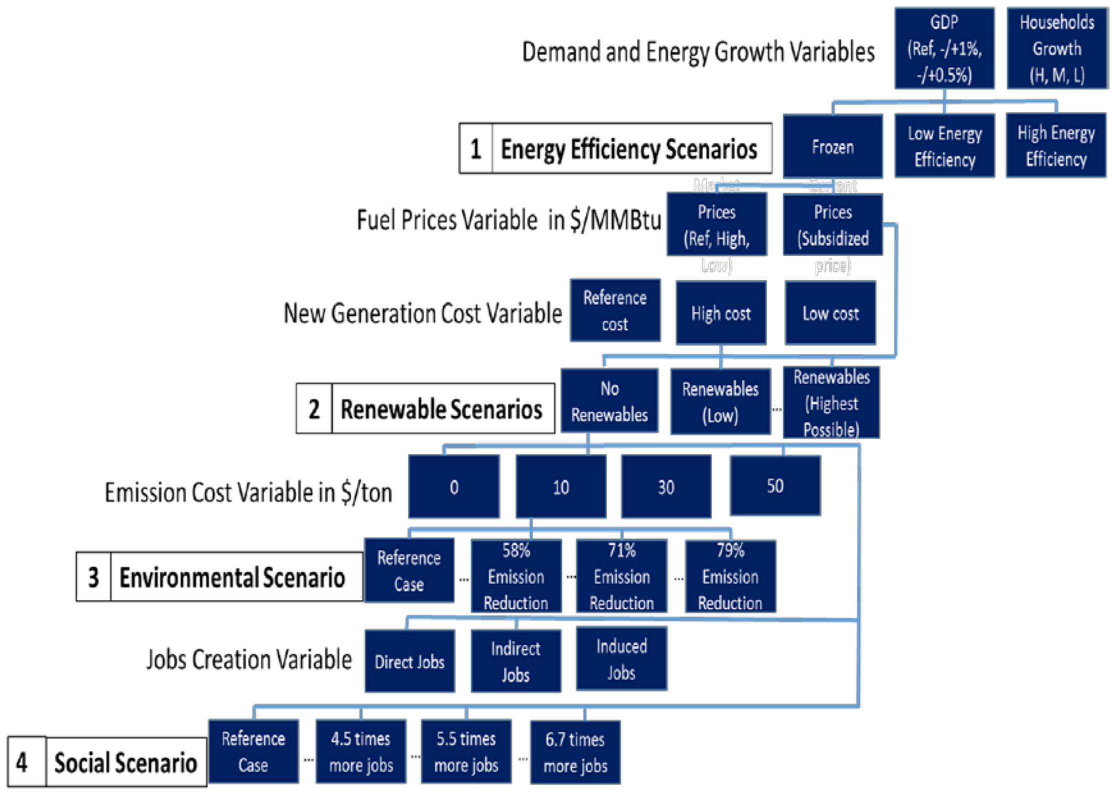
[64] Cases under this scenario were defined and discussed in detail in Section 2.2.1.

[65] The highest possible level of renewable energy source penetration was defined as the optimum amount of renewable energy determined by the economic and technical rationales.



Source: modified from EPRI, 2015, p.38

Figure 5.1 Schematics of modeled scenarios with different policy and economic sensitivities

The schematics list the most significant and uncertain key variables that represent the main axis along which scenarios differ and are characterized. These variables were classified into three main categories: (1) demand forecasting variables (i.e. GDP growth and household growth), (2) supply technologies variables (i.e. fuel prices and generation costs), and (3) EE variables. A list of cases has been created to examine the impact of differing these variables and identify the optimal option for each main scenario. Appendix D lists a sample list of the 162 cases simulated in the EWS IRSP model using the PLEXOS tool.

5.2 Economic and Technical Limits of Renewable Energy Sources in KSA

5.2.1 The Economic Rationale for Renewable Energy

Successful renewable energy policies need to be grounded in economic analysis to ensure economic efficiency (Meier, Vagliasindi, & Imran, 2015, p.13). Therefore, the economic analysis for renewable energy in Saudi Arabia was used to determine the optimum amount or the maximum limit of renewable energy for grid-connected generation. In this analysis, the renewable energy supply curve was estimated using cases simulated by EWS IRSP model for the Kingdom as shown in Figure 5.2. The cost was calculated in $/MWh using LCOE formula, described in details in equation 4.17. The point at which the renewable energy supply curve meets the avoided cost of thermal electricity generation represents the optimum level of renewable energy. Renewable energy will not be competitive if thermal generation cost is based on financial prices (P_{FIN}) or subsidized prices of fuel in the Kingdom. However, if thermal energy is correctly valued at the (P_{ECON}), which represent the prices with no fuel subsidies, the optimum quantity of renewable energy increases to almost 70% as shown in Figure 5.2. Furthermore, if the thermal generation cost is adjusted to reflect the local environmental damage (P_{ENV}) [66], RE optimum quantity will increase to 75%.

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[66] The environmental damage was assumed to be USD 33.7 per ton of CO_2 carbon price rate (which was the highest carbon price realized in 2008 under the EU Emission Trading System) (Carbon Market Watch, 2014).

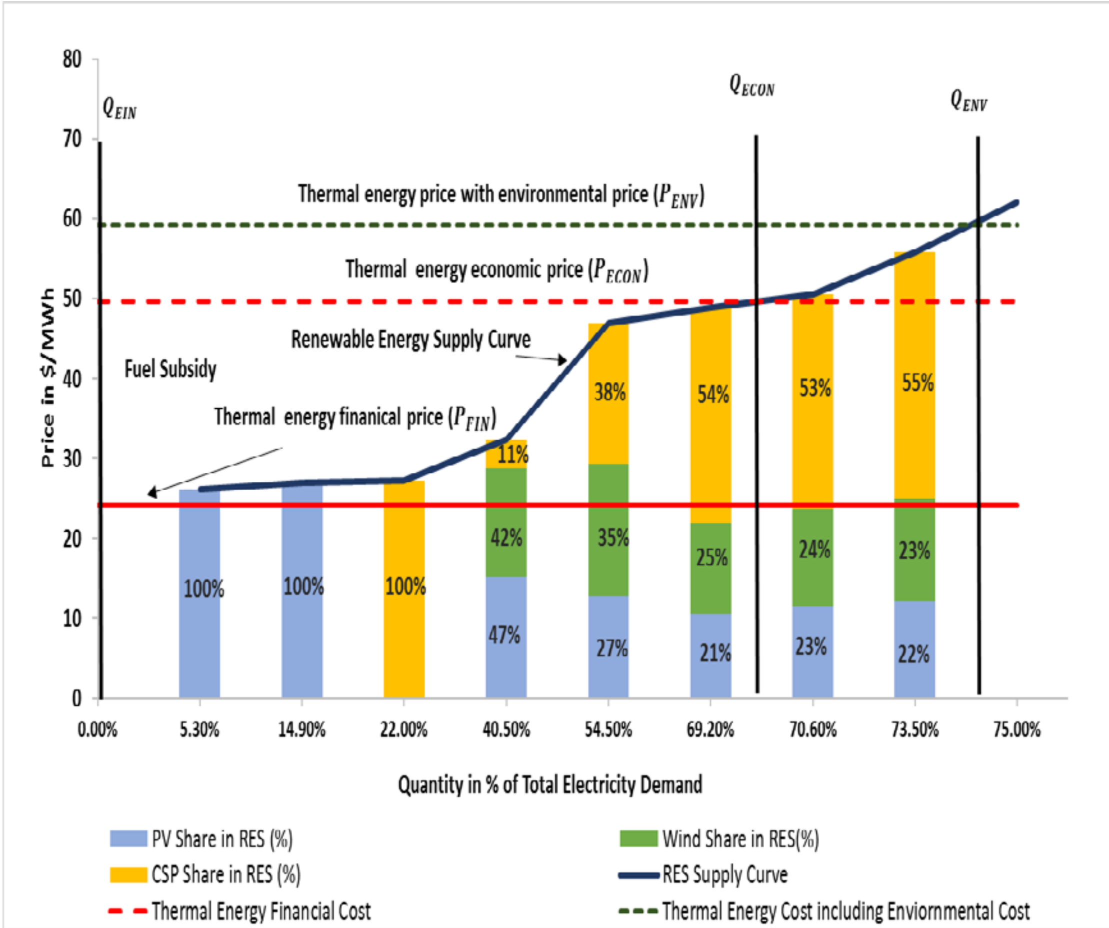

Figure 5.2 Optimum quantity of renewable energy at thermal energy financial, economic, and environmental damage costs for the period 2017-2040[67]

5.2.2 Technical Limit of Renewable Energy

Due to the seasonal variation of the demand between summer and winter (estimated at around 43%), it sets a dispatchability technical limit of renewable energy resources penetrations. The dispatchability limit was defined such that the

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[67] The renewable cases shown in the figure represent only a small sample for all EWS IRSP model cases that are used to establish the renewable energy supply curve for Saudi Arabia.

curtailment[68] of renewables is kept at the minimum level. Table 5.1 defines the limit each renewable technology, renewable share of the total demand in the country, and the curtailment level for four main renewable scenarios. With the first two scenarios, the curtailment levels were kept at zero with the highest possible installations of PV only, and PV with CSP. However, curtailment level increased as renewable penetrations increased to achieve the targeted optimum economic quantity (($Q_{ECON} = 70\%$) and ($Q_{ENV} = 75\%$)) of renewables defined in the previous section.

Table 5.1 Renewable technologies maximum Installed capacities and demand shares considering different dispatchability limits

No	**Scenario**	**Installed capacity limit (GW)**	**Renewable Share of Demand (%)**	**Curtailment % at 2040[69]**
1	PV only	PV= 61	22.5%	PV= 0%
2	PV and CSP	PV= 61 CSP= 61	57%	PV= 0%
3	PV, CSP, and Wind	PV= 61 CSP= 74 Wind = 42	70%	PV=4.5%, CSP=1.7%, Wind =2.9%
4	PV, CSP, and Wind	PV= 61 CSP= 106 Wind = 42	75%	PV=4.5%, CSP=4% Wind =2.9%

Figure 5.3 presents an example of renewable limit analysis for the first scenario, in which the technology mix for a typical peak summer and winter days are

68 Curtailment refers to the (often forced) decrease of a generator's output compared to what it could otherwise produce given available resources (Bird, Cochran & Wind, 2014).

69 Curtailment percentages of CSP in scenarios 3 & 4 was calculated during the high peak months (June-September). Higher curtailment was calculated during the year.

shown. Due to the huge reduction of demand in winter, the amount of installed PV was limited to 61 GW by the EWS IRSP model to avoid any renewable curtailment.

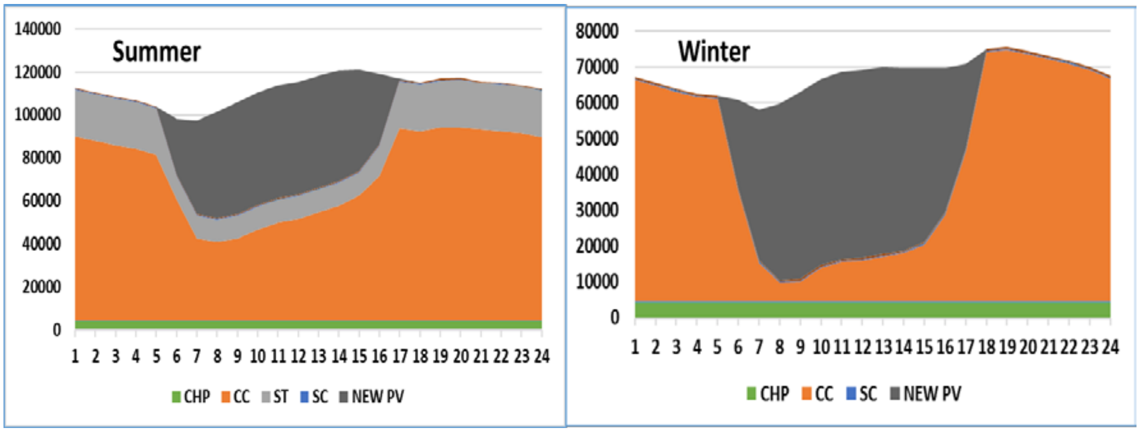

Figure 5.3 Technology mix for typical peak summer and winter says with PV limit of 61 GW

5.3 Scenario-Based Analysis

A scenario-based approach was employed to ensure a clear interpretation of the results. Figure 5.1 presented the four main scenarios simulated by the established EWS IRSP model. In this analysis, 12 capacity expansion cases were considered. These cases represented three different levels of meeting each main scenario's objectives. Frozen, limited and high energy efficiency cases were considered for the EE scenario, while low, moderate and high cases were considered for the renewable (RES), environmental (ENV), and social (SOC) scenarios (see Table 5.2). Table 5.3 provides more details about these cases by indicating the generation technology share percentage in the generation mix by 2040.

Table 5.2 Descriptions of the cases considered in the results analysis (by scenario)

Scenario	Case	Description
Energy efficiency	Frozen	Projected growth in energy consumption is the same as energy service growth and the technological structure of energy demand (including end-use efficiency) stays the same.
	Limited (LEE)	Only EE measures related to the existing regulatory and policy reforms related to cooling systems and building insulation are considered.
	High (HEE)	All market potentials of EE measures are implemented (the highest EE case).
Renewable energy[70]	Low (RES-L)	A renewable portfolio is supplying 37% of total electricity generation by 2040.
	Moderate (RES-M)	A renewable portfolio is supplying 45% of total electricity generation by 2040.
	High (RES-H)	A renewable portfolio is supplying 74% of total electricity generation by 2040 (the highest share).
Environmental impact minimization[71]	Low (ENV-L)	A 58% reduction of CO_2 emissions against the frozen case.
	Moderate (ENV-M)	A 71% reduction of CO_2 emissions against the frozen case.
	High (ENV-H)	A 79% reduction of CO_2 emissions against the frozen case (the highest reduction).
Social benefits maximization	Low (SOC-L)	3.3 times more job creation than in the frozen case.
	Moderate (SOC-M)	5 times more job creation than in the frozen case.
	High (SOC-H)	6.7 times more job creation than in the frozen case

[70] The simulated cases were classified in three levels of renewable penetrations, measured in percentage of electricity generated by renewables sources: (1) 8.4%–40%, (2) 41%–60%, and (3) 61%–74%. The RES-L, RES-M, and RES-H cases were selected such that they have the lowest NPV cost and highest fuel displacements in their corresponding penetration level. In addition, RES-H represents the optimum economic limit defined in section 5.3.

[71] The ENV-L, ENV-M, and ENV-H cases were selected such that they have the lowest emissions in their corresponding low carbon energy resources level, including nuclear power.

Table 5.3 Electricity generation by technology for cases considered in the results analysis

Case	Electricity Generation Share (%)					RES % Share	Low Carbon % Share	Total Gener. (TWh)
	Fossil fuel generation	PV	CSP	Wind	Nuclear			
Frozen	100	0	0	0	0	0	0	1094.2
LEE	100	0	0	0	0	0	0	930.5
HEE	100	0	0	0	0	0	0	807.0
RES-L	63	21	0	0	16	37	21	807.0
RES-M	55	19	5	17	4	45	41	807.0
RES-H	25	21	34	20	0	75	75	807.0
ENV-L	62	0	0	21	17	21	38	807.0
ENV-M	40	15	25	21	0	60	60	807.0
ENV-H	25	4	40	17	15	60	75	807.0
SOC-L	92	0	0	8	0	8	8	807.0
SOC-M	50	5	26	19	0	50	50	807.0
SOC-H	42	21	37	0	0	58	58	807.0

The results evaluation for each case were evaluated based on the following factors, in line with the objectives defined in Section 4.3:

- Generation technology mix and resource diversity mix factor;
- Fuel consumption analysis;
- Environmental impacts analysis, including calculations of total emissions (i.e. CO_2, NO_X, and SO_X);
- Social benefits analysis, addressing the number of direct, indirect, and induced jobs; and
- Economic analysis, including calculation of the present value of total resource planning costs, revenue from exporting/utilizing displaced fuels, and fuel subsidies.

To further simply their interpretation, the results are presented in the following order: the EE scenario, the renewable scenario, the environmental impact minimization scenario, and the social benefits maximization scenario.

5.3.1 Energy Efficiency Scenario Results

5.3.1.1 Electricity Generation Mix Analysis

As shown in the results of the demand forecasting model in Chapter 3, under the frozen case an installed capacity of 207 GW by 2040 is expected to generate approximately1096 TWh (see Figure 5.4). The bulk of the total generated electricity (i.e. 55%, or 605 TWh) is expected to come from CCGTs, which is in line with the current policy of increasing the share of the most efficient generation. Steam turbine generation is expected to produce 430 TWh by 2040 from their installed capacity of 83 GW. Steam turbines' share in the generation mix grows slightly by 3% to reach 43% of total generation. Simple cycle generation is expected to represent less than 2% of generated electricity. Finally, off-grid diesel generators were assumed to be gradually eliminated as the grid will be expanded to connect all of Saudi Arabia's isolated areas.

Consideration was given to more EE measures on the demand-side in the LEE case, as described in Table 5.2. The total electricity generated in this case accounted for 930 TWh from an installed capacity of 176 GW by 2040. While CCGTs will account for 598 TWh (64%), less efficient generation (e.g., steam turbines) will generate 285 TWh (30%) by 2040, as shown in Figure 5.4. Other generation represents the rest of the electricity generation mix. In comparison with the frozen scenario, both generated electricity and installed capacity are reduced by 15%. Thus, the electricity produced through lower efficiency generation fueled by liquid fuels (such as steam turbines) is reduced by 34%.

In the HEE case, consideration was given to the highest implementation of market potential EE measures on the demand-side (see Table 5.2). The total electricity generated in this case accounted for 807 TWh from an installed capacity of 143 GW by 2040. While CCGTs account for 574 TWh (71%), less efficient generation (e.g., steam turbines) will generate 185 TWh (23%) by 2040, as shown in Figure 5.4. Other generation represents the rest of the electricity generation mix. In comparison with the frozen scenario, generated electricity and installed capacity are respectively reduced by 26% and 31%. As a result, electricity produced through lower efficiency generation fueled by liquid fuels (such as steam turbines) is reduced even further in this case by 57%.

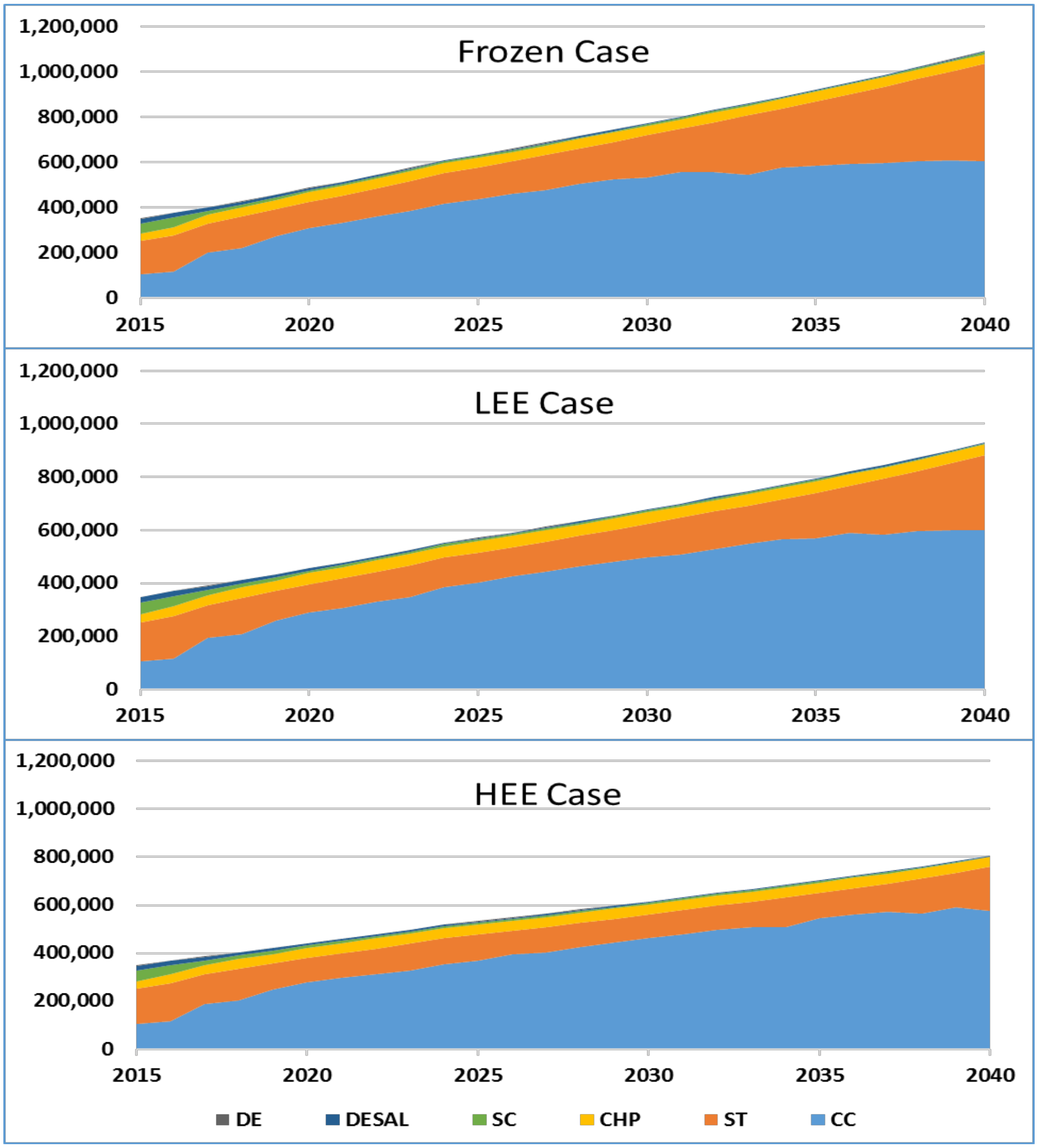

Figure 5.4 Growth of electricity supply by type of technology for the frozen, LEE, and HEE cases, 2015–2040 (in GWh)

5.3.1.2 Fuel Consumption Analysis

The total fuel demand under the frozen case was observed to be more than 6.8 million GBTU by 2040 (Figure 5.5). This amount of fuel is equivalent to 3.4 million barrels of equivalent oil per day (MBOED), which is two times more than the utility sector's current fuel consumption or more than 27% of Kingdom's present domestic total oil production capacity. Due to the limitation of natural gas availability for electricity generation, the maximum allocated natural gas for the utility sector (which represents 52% of total fuel consumption)[72] is used to fuel the generation. The remaining fuel consumption came from burning liquid fuels (i.e. crude oil, diesel, and HFO) to generate electricity and satisfy the utility sector's demand.

Due to the application of various EE measures that resulted in lower electricity demand, fuel consumption was reduced by 15% (2.9 MBOED) in the LEE cases and 25% (2.5 MBOED) in the HEE cases by 2040 in comparison with the frozen case (see Figure 5.5). This fuel consumption savings contributed to reducing the burning of valuable liquid fuel in electricity generation by 32% and 52%, respectively. Cumulatively, the amounts of fuel displaced during the planning period were calculated to be 2,136 MBOE for LEE and 3,519 MBOE for HEE. Such reduction in fuel burning will also reduce emissions, as discussed in the next section.

[72] Natural gas use in the utility sector is assumed to be 10 BSCF/day, as explained in Section 4.2.5.3. This is equivalent to approximately a maximum annual production of 3,600,000 GBTU.

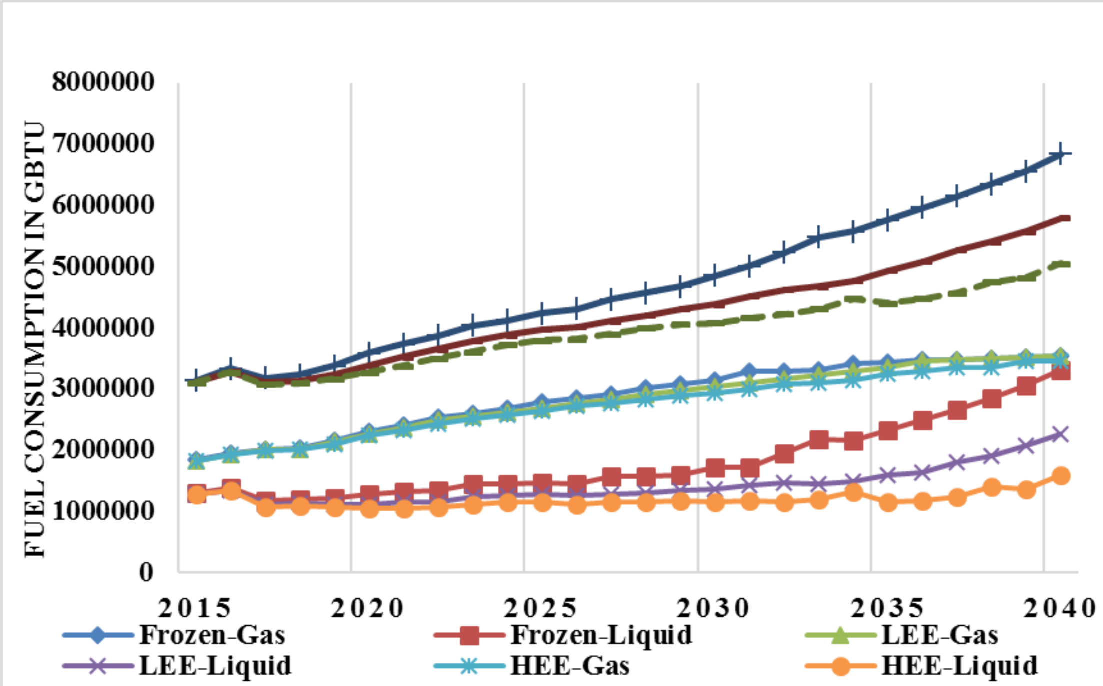

Figure 5.5 Fuel consumption analysis for energy efficiency cases, 2015–2040

5.3.1.3 Environmental Impact Analysis

The rapid growth of electricity demand in the frozen case assures the rise of CO_2 emissions level from 224 million tons in 2015 to more than 480 million tons in 2040, which is more than twice the current emissions level (see Figure 5.6). Burning liquid fuels contributed to 57% of the total emissions, with natural gas accounting for the remaining emissions. The main motive behind the development of the LEE and HEE cases was to reduce demand by adopting more EE measures, increasing energy supply through the use of more efficient generation on the supply-side, and reducing emissions by 2040. As discussed in the previous section, the reduced demand in the LEE and HEE cases resulted in a lower burning of liquid fuel and thus lowered the total CO_2 emissions level by 18% and 31% respectively (see Figure 5.6).

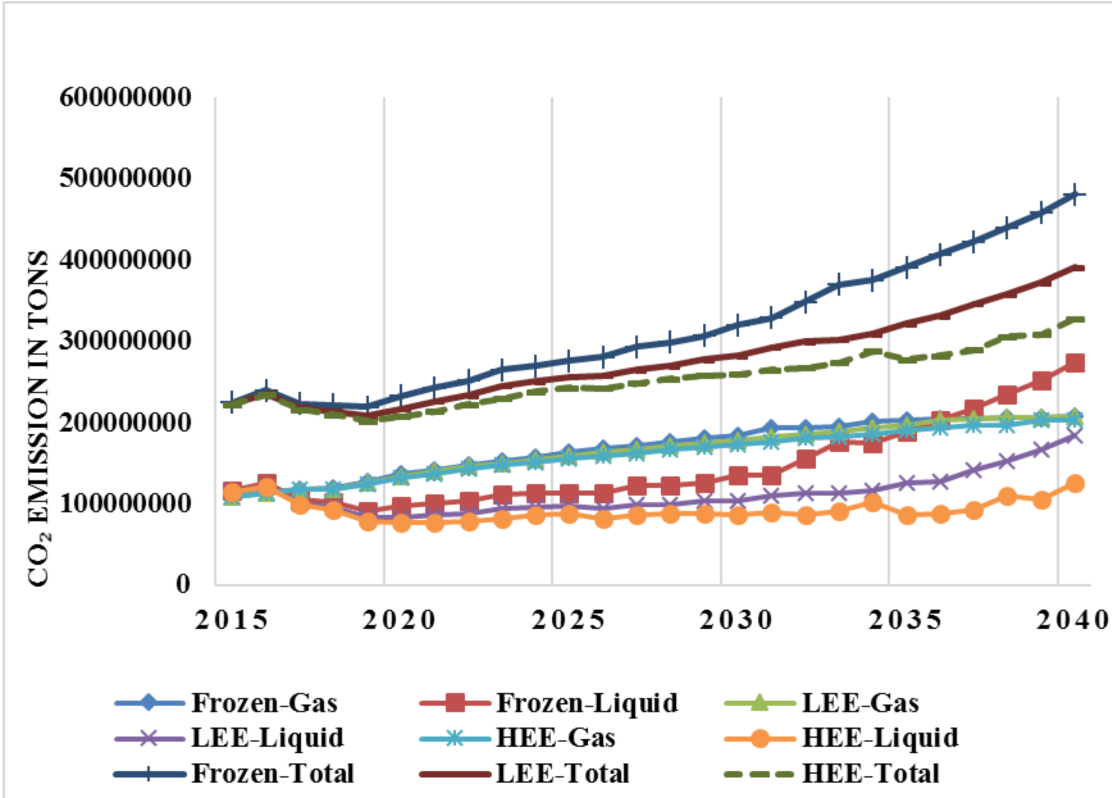

Figure 5.6 CO_2 emission analysis for energy efficiency cases, 2015–2040

Electricity generation produces NO_X and SO_X emissions. Table 5.4 shows that the NO_X and SO_X emissions respectively amount to approximately 1.5 and 3.5 million tons by 2040 in the frozen case. The LEE cases will result in NO_X and SO_X emissions that are respectively reduced by 16% and 15%, while the HEE cases will lead to reductions of 28% and 26%. However, NO_X and SO_X intensity (in MWh/lb) remains almost constant in the three scenarios since the emissions and demand are reduced at almost the same rate in the LEE and HEE cases.

Table 5.4 NO_X and SO_X emissions for the energy efficiency cases[73]

Case	NO_X (total in million tons)	SO_X (total in million tons)	NO_X (million tons in 2040)	SO_X (million tons in 2040)	NO_X Intensity (MWh/lb (2040)	SO_X Intensity (MWh/lb) (2040)
Frozen	12.7	62.7	1.5	3.5	2.8	6.5
LEE	10.5	56.5	1.3	3.0	2.7	6.4
HEE	9,.2	52.5	1.1	2.6	2.7	6.4

5.3.1.4 Economic Analysis

One important factor in evaluating and comparing various alternatives is calculating the present value of total costs for all cases, as shown in Table 5.5. The cost avoidance was calculated with respect to the frozen case by subtracting all discounted costs (i.e. fuel cost, fixed and variable O&M costs, and annualized build cost) in the alternative cases from the discounted costs of the frozen case. From Table 5.5, it can be observed that implementing the LEE and HEE cases will result in a significant cost avoidance of more than USD 123 and 200 billion, respectively. The major contributor to these savings is the reduction of fuel consumption, which resulted in 81% of total cost avoidance; capital cost also contributed approximately to 10%.

[73] Total NO_X and SO_X emissions refer to the cumulative emission during the period (2016-2040).

Table 5.5 Results of the cost analysis for energy efficiency cases using market fuel prices (in billions of USD)

	Present Value of Generation Cost (2016–2040)			**Cost Avoidance**	
	Frozen Case	**LEE Case**	**HEE Case**	**LEE**	**HEE**
Fuel cost	667.44	567.39	504.38	100.05	163.06
Variable O&M (VO&M)	39.94	36.54	34.12	3.40	5.81
Fixed O&M (FO&M)	64.68	57.61	53.53	7.07	11.16
Annualized build cost	44.04	31.00	23.44	13.04	20.60
Total	816.10	692.55	615.47	123.56	200.64

While the results in Table 5.5 were calculated based on market (international) fuel prices, Table 5.6 summarizes the same calculations by considering the current (domestic) fuel prices. Even though the Saudi government heavily subsidizes the current fuel prices, it was observed that implementations of LEE and HEE with EE measures still result in a cost avoidance of more than USD 30 and 50 billion, respectively. Another advantage of deploying EE measures is the reduction of fuel subsidies as a result of the decrease in fuel consumption. In the frozen scenario, the total amount of fuel subsidies (2016–2040) exceeded USD 540 billion. In this analysis, LEE and HEE contributed to reducing these subsidies respectively by approximately 20% and 27%.

Table 5.6 Results of the cost analysis for energy efficiency cases using current fuel prices (in billions of USD)

	Present Value of Generation Cost (2016–2040)			**Cost Avoidance**	
	Frozen Case	**LEE Case**	**HEE Case**	**LEE**	**HEE**
Fuel cost	124.82	120.10	106.76	4.72	18.06
VO&M	40.54	37.08	34.62	3.46	5.91
FO&M	57.77	52.37	48.66	5.40	9.11
Annualized build cost	30.55	17.18	12.99	13.37	17.56
Total	253.68	228.46	203.03	25.22	50.64

An analysis was also undertaken to estimate the total present value of revenue as a result of exporting or utilizing the displaced fuels in the LEE and HEE cases in the period 2016–2040; the total revenue was calculated to be USD 100 and 163 billion, respectively.

5.3.1.5 Social Benefits

It was observed that LCOE in 2040 for LEE and HEE was reduced by more than 8% and 13%, respectively (Table 5.7). The LEE and HEE cases also increased the total number of created jobs by more than respectively 2.2 and 3.2 times the jobs created in the frozen case. The minimum reserve margin increases as the level of EE implementation increases (6.6% in the LEE cases and 10.2% in the HEE cases, in comparison with 5.4% in the frozen cases). During the summer months, peak demand levels will decrease compared to the annual average when cooling systems and other efficient measures are utilized, and consequently increase the minimum reserve margin in comparison with the frozen case.

Table 5.7 Social benefits analysis of the energy efficiency cases

Factor	Frozen	LEE	HEE
LCOE ($/MWh) in 2040	92.4	84.9	79.7
Jobs created 2016–2040 (millions of jobs)	0.5	1.1	1.6
Provide reliable supply by increasing the reserve margin (%)	5.4	6.6	10.2

5.3.1.6 Evaluation of the IRSP Objectives

As discussed in Section 4.3, metrics are defined to evaluate the effectiveness of implementing the six objectives for each IRSP scenario. Tables 5.8 to 5.11 summarizes the results of evaluating these objectives using the metrics defined earlier. These results are evaluated comprehensively in the previous sections for the three efficiency cases

.

Table 5.8 Evaluation of the IRSP objective-1 for energy efficiency cases

Objective	**Metric**	**Unit**	**Evaluation Results**		
			Frozen	**LEE**	**HEE**
Minimize domestic fuel consumption	Share of delivered electricity from fossil fuels	%	100	100	100
	Resource plan cost share in relation to fossil fuel	%	100	100	100
	Amount of liquid fuel used in utility sector	MBOE	13410	13139	12814
	Amount of natural gas used in utility sector	MBOE	8487	6621	5563
	Energy efficiency savings	TWh	0	163	286
	Estimated revenue from exporting displaced fuel	Billions of USD	0	100	163

Table 5.9 Evaluation of the IRSP objective-2 for energy efficiency cases

Objective	**Metric**	**Unit**	**Evaluation Results**		
			Frozen	**LEE**	**HEE**
Maximize penetrations of sustainable energy	Renewable share	%	0	0	0
	Renewable energy curtailed	GWh	0	0	0
	Resource diversity index	Range from 0 to 1	0	0	0

Table 5.10 Evaluation of the IRSP objective-3 for energy efficiency cases

Objective	Metric	Unit	Evaluation Results		
			Frozen	**LEE**	**HEE**
Minimize environmental impacts	CO_2 emissions	Millions of tons	8179	7196	6579
	Sulfur oxides (SO_X) emissions intensity	Pounds/MWh	2.8	2.7	2.7
	Nitrous oxides (NO_X) emissions intensity	Pounds/MWh	6.5	6.4	6.4
	Water consumption for generation	m^3/MWh	1.386	1.150	1.051

Table 5.11 Evaluation of the IRSP objective-4 for energy efficiency cases

Objective	Metric	Unit	Evaluation Results		
			Frozen	**LEE**	**HEE**
Maximize social benefits	Create local direct jobs	Millions of jobs	0.167	0.189	0.202
	Create local indirect jobs		0.167	0.137	0.116
	Create local induced jobs		0.167	0.810	1.293
	Reduce nominal price of electricity	$/MWh	69.3	65.7	63.3
	Provide reliable supply by increasing the reserve margin	%	5.79	6.99	11.02

5.3.2 Renewable Energy Scenario Results

5.3.2.1 Electricity Generation Mix Analysis

The RES scenario presented the highest share of renewables in the electricity generation mix of Saudi Arabia's utility sector. Three cases were selected in renewable penetration levels of (1) 8.4%–40%, (2) 41%–60%, and (3) 61%–75%, such that these cases represented the lowest present value of the total cost of the resource plans and the maximum fuel displacements in their corresponding penetration level. Figure 5.7 presents the generation mix for the three RES cases, classified by electricity generation (in GWh) and installed generation capacities (in MW); it reveals that RES-L, RES-M, and RES-H represented 37%, 45%, and 75% of the electricity generation mix in 2040, respectively. In RES-L, the 59.9 GW installed capacity of PV generated 21% of the electricity in 2040, while 17.1 GW of nuclear power plant capacity generated approximately 16%. In RES-M, the installed capacities of PV (50.9 GW) produced 19% of Saudi Arabia's total generated electricity, while the CSP capacity (7.7 GW) generated 5%, the wind capacity (36.8 GW) generated 17%, and the nuclear power capacity (4.3 GW) generated 4%. The RES-H represented the highest possible renewable generation in the country. The installed capacities of PV (61 GW), CSP (106 GW), and wind (42.4 GW) respectively represented shares of 21%, 34%, and 20% of the total electricity generated in 2040.

In the renewable energy mix in the RES-H, CSP technology was the dominant due to its thermal storage capability to dispatch electricity at night. Thermal energy storage enabled CSP to serve as a base-load (replacing the fossil fuel-based generation) and act as a peaking generation during the peak load time during the day. The CCGT share represented only 14% of total generated electricity in 2040; this was more than an 80% reduction in comparison to the frozen scenario. In the other RES-L and RES-M cases, the CCGT share represented 49% and 40% of the total generated electricity, respectively. Detailed results of electricity generation under these three cases are shown in Figure 4.18. A high level of diversity between generation resources was achieved; for example, in RES-H the resource diversity index was raised to above 0.88 for all installed renewables and fossil fuel generation.

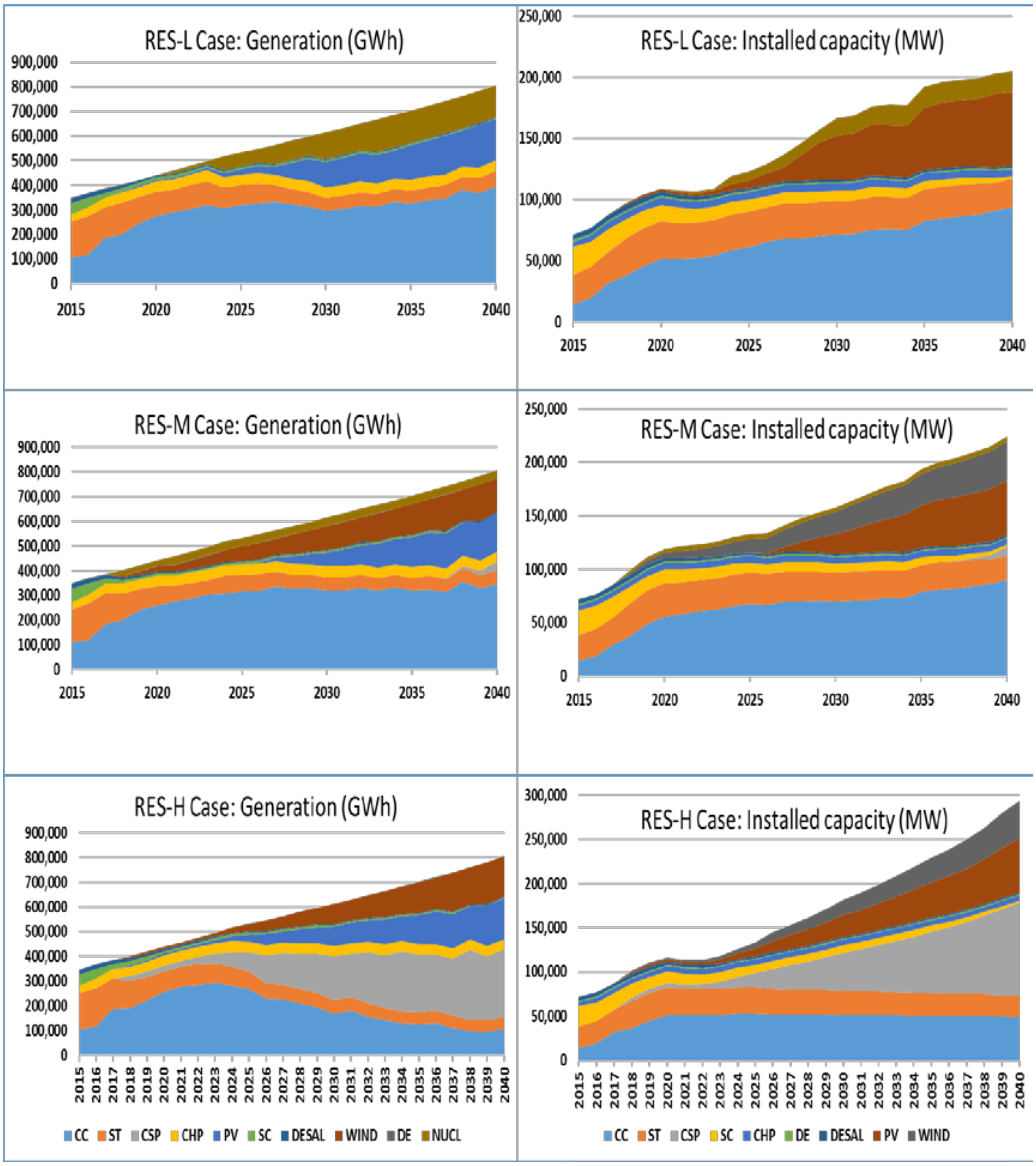

Figure 5.7 Technology mix for the renewables cases (by electricity generation and installed capacity)

Figure 5.8 shows the modeled dispatch for a day in summer with high electricity demand and a day in winter with relatively low electricity demand. With nuclear power plants serving as a base load, PV generation in the RESL-L reaches its peak around midday before decreasing through the peak hours of the afternoon. During winter, PV supplies around 60% of the total load during the daytime. In RES-M, wind is added to the generation mix, producing most strongly at night and during the morning (proceeding peak demand). In this case, renewable energy resources supplied almost 90% of the demand in the winter during the daytime. In the RES-H, CSP with storage provides ramped up during early morning to late afternoon and act as baseload during night time, along with nuclear while the wind generation is highest overnight and in the morning prior to peak demand time. In the high RES, at noontime, 90% of demand is supplied by renewables. Thus, CSP displaced a significant portion of baseload CC. CSP and PV primarily displace natural gas CC generation on peak days and thus natural gas generation increases from the middle of the day through the afternoon until the early hours of evening. During winter, almost 90% of electricity demand is supplied by RES throughout the day in the RES-H case. During the early hours of the evening, a very minor increase in steam turbine generation is demonstrated across all RES cases.

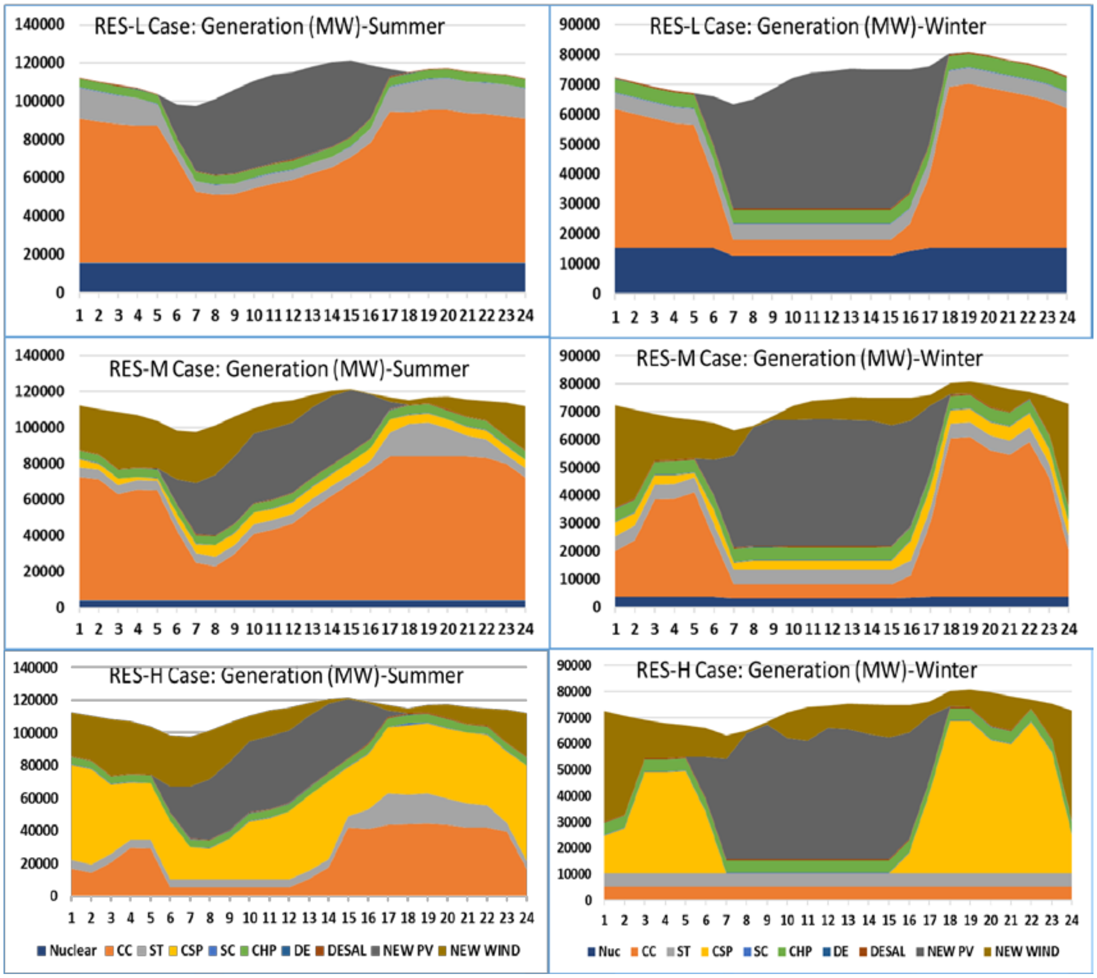

Figure 5.8 Typical daily generation dispatch in summer and winter for renewable cases

5.3.2.3 Fuel Consumption Analysis

In relation to the Saudi utility sector's fuel consumption, the presence of renewables in the energy mix has a greater impact in the RES scenario than in the FEE case. In comparison with the frozen case, fuel consumption in 2040 was reduced by 51, 56%, and 76% respectively for RES-L, RES-M, and RES-H (Figure 5.9). Furthermore, RES-M stabilized the current fuel consumption of approximately 1.5 MBOED throughout the planning period, even though the electricity demand grew by

2.3 times. As an example of the potential fuel consumption reduction, in the RES-H case the gas and liquid fuel displaced by deploying renewable energy resources was calculated to respectively be more than 5.4 billion BOE and 5 billion BOE for the period from 2016 to 2040.

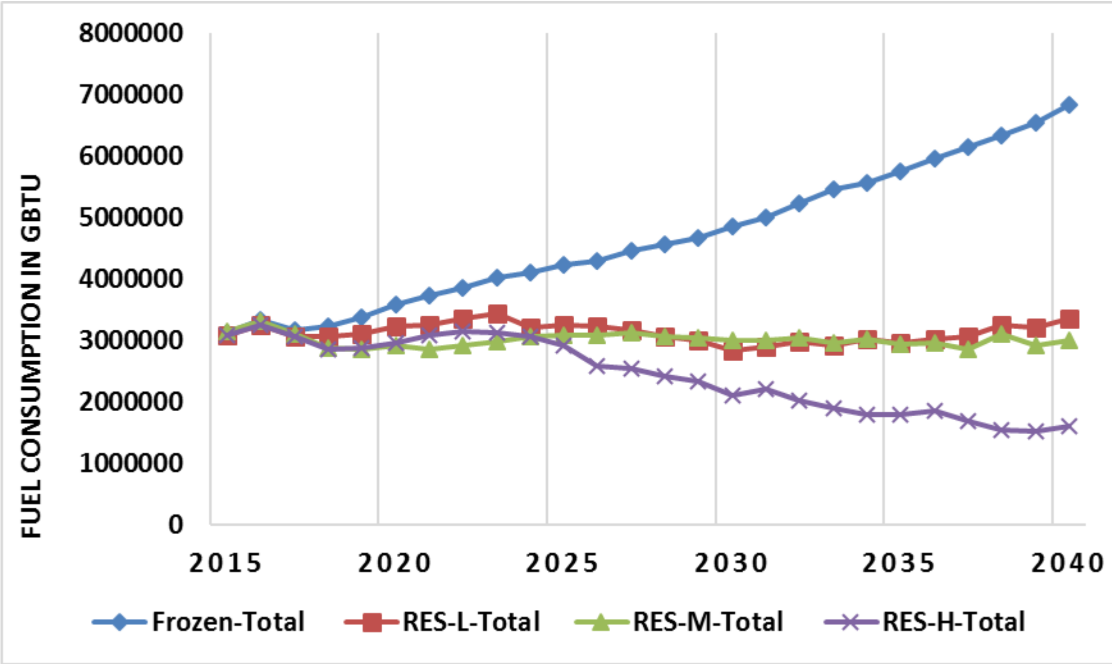

Figure 5.9 Fuel consumption analysis for the renewable energy cases, 2015–2040

5.3.2.4 Environmental Impact Analysis

Considering that the RES scenario emphasizes the expansion of renewables, much lower CO_2 emissions were expected to result. In comparison with the frozen case, CO_2 emissions in 2040 were reduced by 57, 62%, and 78% respectively for RES-L, RES-M, and RES-H (Figure 5.10). Furthermore, RES-M stabilized the current emissions level throughout the planning period, even though the electricity demand grew by 2.3 times. To illustrate the environmental benefits of the RES scenario, the total emissions reduction by deploying renewable energy resources was calculated to be more than 4183 million tons for the period from 2016 to 2040 in the RES-H case.

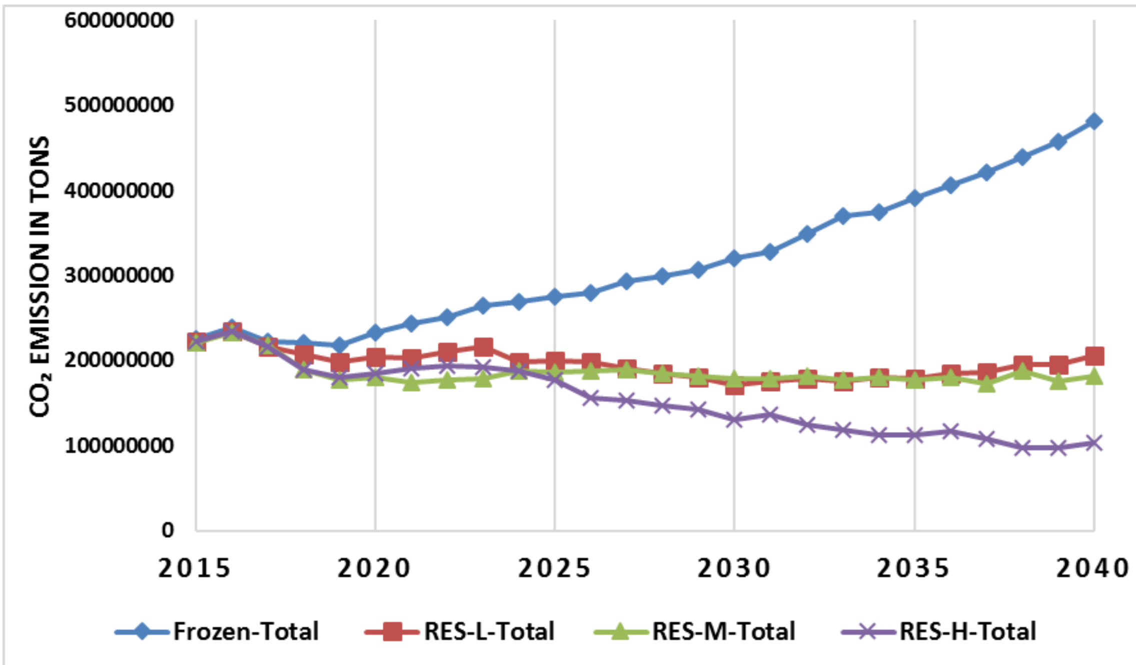

Figure 5.10 CO_2 emission analysis for the renewable energy cases, 2015–2040

Table 5.12 shows the NO_X and SO_X emissions for the frozen and RES cases. Deploying renewable energy resources led to a significant reduction of both kinds of emissions. For example, RES-H resulted in a reduction of total NO_X and SO_X by 55% and 48% respectively in comparison with the frozen case; NO_X and SO_X intensities were also reduced significantly (respectively by 68.5% and 67.6%).

Table 5.12 NO_X and SO_X emissions for the renewable energy cases

Case	NO_X (total in million tons)	SO_X (total in million tons)	NO_X (million tons in 2040)	SO_X (million tons in 2040)	NO_X Intensity (MWh/lb (2040)	SO_X Intensity (MWh/lb) (2040)
Frozen	12.7	62.7	1.5	3.5	2.8	6.5
RES-L	6.8	41.9	0.7	1.7	1.8	3.7
RES-M	6.4	40.2	0. 6	1.5	1.6	3.8
RES-H	5.7	32.4	0.4	0.8	0.9	2.1

5.3.2.5 Economic Analysis

Table 5.13 reveals that the benefits of implementing the RES-L, RES-M, and RES-H cases include a significant cost avoidance of more than USD 269, 278, and 235 billion, respectively. The capital and FO&M costs for the RES cases were higher than for the frozen case, but they were offset by the reduction of fuel consumption. Given that the RES-M case was modeled with flexibility in selecting renewables based on the least cost calculations, it had the lowest total cost and highest cost saving; in contrast, RES-L and RES-H were constrained to a minimum number of renewable energy resources installations per year, irrespective of related technology costs. Furthermore, the resource plan cost share in relation to fossil fuel was reduced to only 64% in the RES-H case, in comparisons with 100% in the frozen case.

While results in Table 5.13 were calculated based on market (international) fuel prices, Table 5.14 shows that RES-L and RES-M still result in a cost avoidance of more than USD 10 billion. Based on current fuel prices, the RES-H high capital cost (which is mainly attributed to CSP with TES installation) contributed to additional costs in comparison with the frozen case. Nonetheless, it was estimated that exporting displaced fuel or utilizing it locally at local sectors with higher added value (based on the international fuel prices), such as petrochemical industries, generates a revenue of USD 299, 319, and 369 billion for RES-L, RES-M, and RES-H, respectively (Table 5.10). Another advantage of deploying renewable energy resources is the reduction of fuel subsidies as a result of decreasing fuel consumption. In the frozen scenario, the total amount of fuel subsidies (2016–2040) exceeded USD 540 billion; in this analysis, RES-H, RES-M, and RES-L contributed to the reducing these subsidies by circa 58%, 53%, and 49%, respectively.

Table 5.13 Results of the cost analysis for the renewable energy cases using market fuel prices (in billions of USD)

	Present Value of Generation Cost (2016–2040)			**Cost Avoidance**		
	RES-L	**RES-M**	**RES-H**	**RES-L**	**RES-M**	**RES-H**
Fuel cost	368.94	348.17	298.72	298.50	319.28	368.72
VO&M cost	36.87	30.62	26.91	3.06	9.31	13.02
FO&M cost	72.91	76.49	86.45	(8.23)	(11.81)	(21.77)
Annualized build cost	68.17	72.71	187.16	(24.13)	(28.67)	(143.12)
Total	546.90	537.18	608.25	269.20	278.93	207.86
				NPV of Revenue from Displaced Fuel (2016–2040)		
				RES-L	**RES-M**	**RES-H**
				299	319	369

Table 5.14 Results of the cost analysis for the renewable energy cases using current fuel prices (in billions of USD)

	Present Value of Generation Cost (2016–2040)			**Cost Avoidance**		
	RES-L	**RES-M**	**RES-H**	**RES-L**	**RES-M**	**RES-H**
Fuel cost	84.55	81.83	$64.41	40.27	42.99	$60.41
VO&M cost	36.87	30.62	$26.91	3.06	9.31	$13.02
FO&M cost	72.91	76.49	$86.45	(8.23)	(11.81)	($21.77)
Annualized build cost	68.17	72.71	$187.16	(24.13)	(28.67)	($143.12)
Total	262.50	261.65	$364.93	10.97	11.82	($91.45)
				NPV of Revenue from Displaced Fuel (2016–2040)		
				RES-L	**RES-M**	**RES-H**
				299	319	369

5.3.2.6 Social Benefits Analysis

It was observed that LCOE in 2040 was reduced by more than 34.5%, 34.2%, and 20.2% respectively for RES-L, RES-M, and RES-H. In addition, the total number of jobs created was respectively increased by more than 5.1, 5.3, and 6.8 times the number created in the frozen case. Table 5.18 (which is presented in the below subsection) shows the breakdown of the jobs classifications. The minimum reserve margin also increases as the level of EE implementation increases (by 19% in RES-L, 14.5% in RES-M, and 19.2% in RES-H in comparison with 5.4% in frozen case).

5.3.2.7 Summary of the Evaluation of the IRSP Objectives

Tables 5.15 to 5.18 summarizes the results of evaluating the IRSP objectives for the three renewable energy cases using the metrics defined earlier.

Table 5.15 Evaluation of the IRSP objective-1 for the renewable energy cases

Objective	Metric	Unit	Evaluation Results		
			RES-L	**RES-M**	**RES-H**
Minimize domestic fuel consumption	Share of delivered electricity from fossil fuels	%	63	55	25
	Resource plan cost share in relation to fossil fuel	%	85	84	63
	Amount of liquid fuel used in the utility sector	MBOE	3799	3440	3339
	Amount of natural gas used in the utility sector	MBOE	10867	10674	8098
	Energy efficiency savings	TWh	286	286	286
	Estimated revenue from exporting displaced fuel	Billions of USD	299	319	369

Table 5.16 Evaluation of the IRSP objective-2 for the renewable energy cases

Objective	Metric	Unit	Evaluation Results		
			RES-L	**RES-M**	**RES-H**
Maximize penetrations of sustainable energy	Renewable share	%	37	45	75
	Renewable energy curtailed	TWh (2016–2040)	85.50	58.30	1066.40
		TWh (2040)	8.90	17.96	203.70
	NPV cost avoidance	Billions of USD	269.20	278.93	207.86
	LCOE of RES (2040)	$/MWh	37.2	35.6	66.6
	Resource diversity index	Range from 0 to 1	PV= 0.96	PV= 0.964	PV= 0.956
			CSP= N/A	CSP= 0.998	CSP= 0.884
			Wind = N/A	Wind= 0.971	Wind= 0.961
			Nuc= 0.97	Nuc= 0.998	Nuc= N.A
			Fossil gen= 0.605	Fossil gen= 0.693	Fossil gen= 0.932

Table 5.17 Evaluation of the IRSP objective-3 for the renewable energy cases

Objective	Metric	Unit	Evaluation Results		
			RES-L	**RES-M**	**RES-H**
Minimize environmental impacts	CO_2 emission	Millions of tons	5095	4838	4020
	Sulfur oxides (SOx) emission intensity	Pounds/MWh	1.77	1.58	1.58
	Nitrogen oxides (NOx) emissions intensity	Pounds/MWh	3.71	3.82	2.10
	Water consumption for generation	m^3/ MWh	0.582	0.497	0.367

Table 5.18 Evaluation of the IRSP objective-4 for the renewable energy cases

Objective	Metric	Unit	Evaluation Results		
			RES-L	**RES-M**	**RES-H**
Maximize social benefits	Create local direct jobs	Millions of jobs	0.473	0.496	0.591
	Create indirect local jobs		0.834	0.211	0.682
	Create induced local jobs		2.020	1.986	2.275
	Reduce nominal price of electricity	$/MWh	56.2	55.2	59.4
	Provide reliable supply by increasing the reserve margin	%	19.00	14.50	19.20

5.3.3 Environmental Impact Minimization Scenario

The environmental impact minimization scenario targeted the highest emission reduction in the Saudi utility sector by aggressively deploying both EE measures on the demand-side and renewable energies on the supply-side. This was accompanied by increasing the efficiency of the fossil fuel generation by introducing high efficiency natural gas CCGTs.

5.3.3.1 Electricity Generation Mix Analysis

Figure 5.11 shows the generation mix (in GWh) and installed capacity (in MW) for the three cases in the environmental scenario (ENV-L, ENV-M, and ENV-H). The three cases were selected in renewable penetration levels of (1) 8.4%–40%, (2) 41%–60%, and (3) 61%–75%, such that they represented the highest emission reduction in their corresponding penetration level. The electricity supplied from renewable energy resources was increased to reach to 38%, 60%, and 75% respectively.

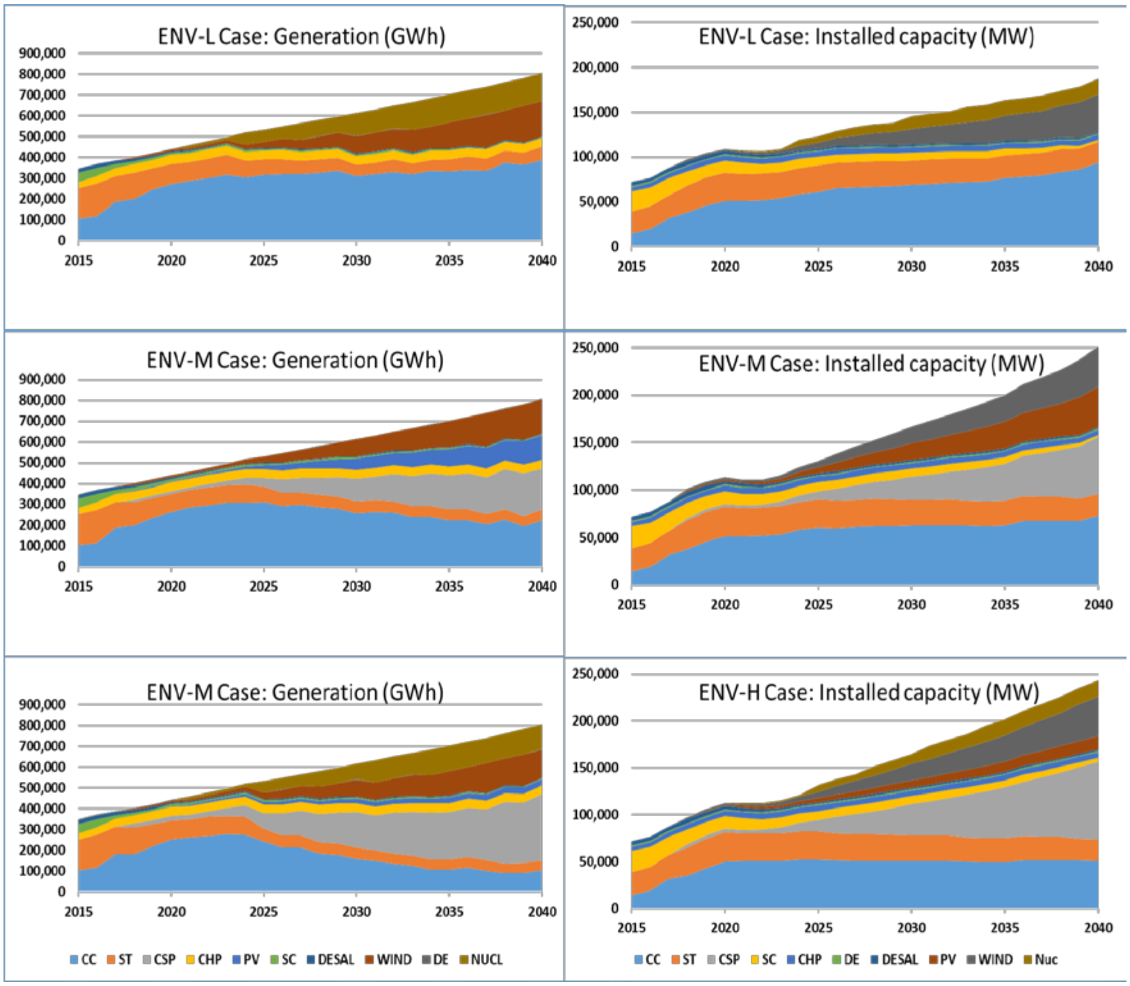

Figure 5.11 Technology mix for the environmental impact minimization cases (by electricity generation and installed capacity)

5.3.3.2 Fuel Consumption Analysis

In comparison with the frozen case, fuel consumption in 2040 was reduced by 51, 66%, and 77% respectively for ENV-L, ENV-M, and ENV-H (Figure 5.12). It can be observed that the fuel consumption in the ENV-M and ENV-H cases was even lower than the current fuel consumption, despite demand growth in the utility sector.

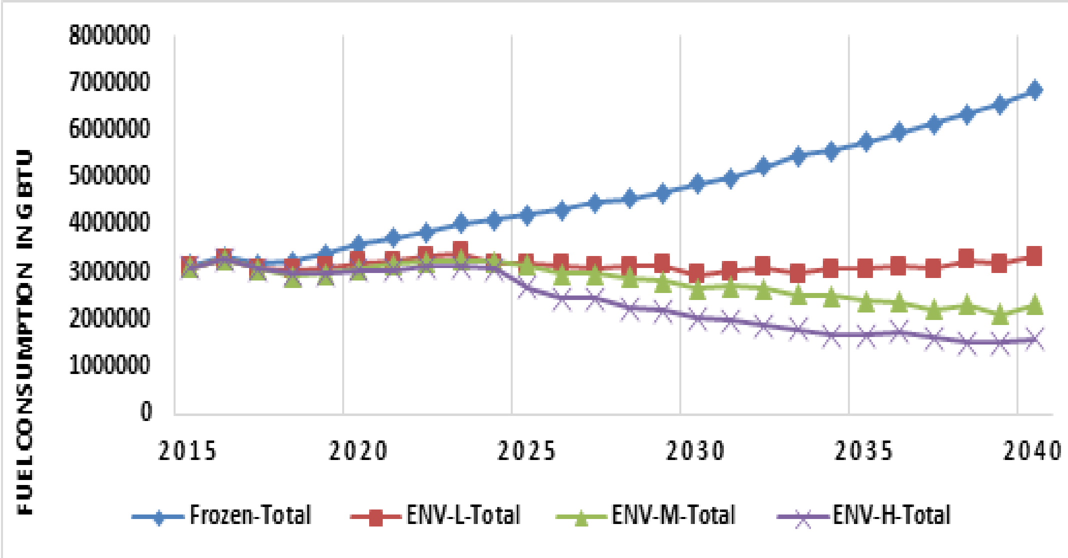

Figure 5.12 Fuel consumption analysis for the environmental impact minimization cases, 2015–2040

5.3.3.3 Environmental Impact Analysis

In comparison with the frozen case, CO_2 emissions in 2040 were reduced by 58%, 71%, and 79% respectively for ENV-L, ENV-M, and ENV-H (Figure 5.13). The total emission reduction achieved by deploying renewable energy resources was calculated to be more than 4259 million tons for the period from 2016 to 2040 in the ENV-H case. Furthermore, the NO_X and SO_X intensities were reduced significantly (by 68.5% and 67.6%, respectively). The details of the NO_X and SO_X emissions are shown in Table 5.19.

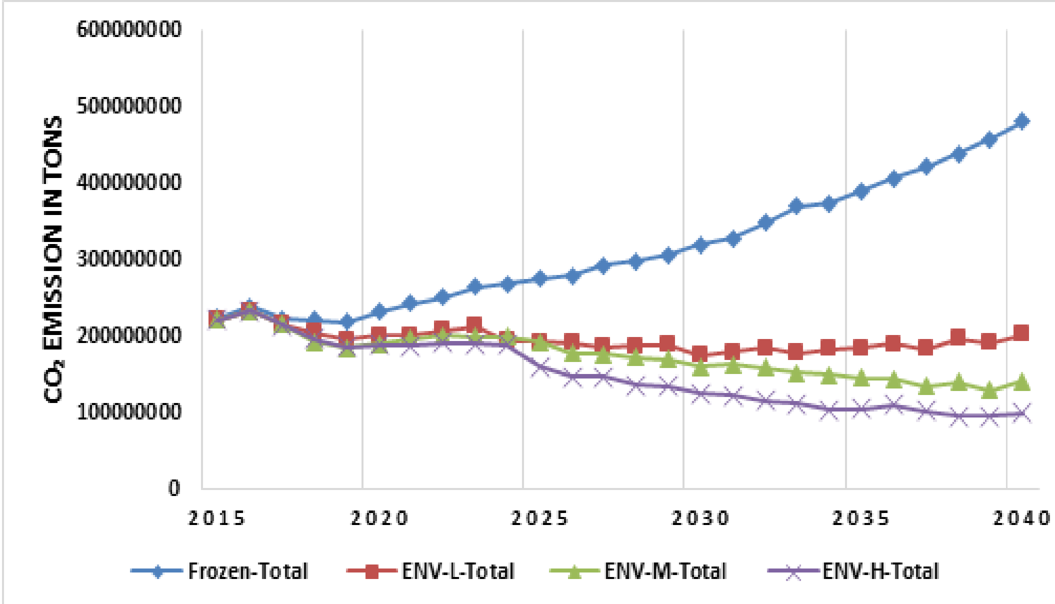

Figure 5.13 CO_2 emission analysis for the environmental impact minimization cases, 2015–2040

Table 5.19 NO_X and SO_X emissions for the environmental impact minimization cases

Case	**NO_X (total in million tons)**	**SO_X (total in million tons)**	**NO_X (million tons in 2040)**	**SO_X (million tons in 2040)**	**NO_X Intensity (MWh/lb (2040)**	**SO_X Intensity (MWh/lb) (2040)**
Frozen	12.7	62.7	1.5	3.5	2.8	6.5
ENV-L	6.8	41.9	0.7	1.7	1.8	3.7
ENV-M	6.2	37.4	0.5	1.2	1.2	2.9
ENV-H	5.6	32.6	0.4	0.9	0.8	2.0

5.3.3.4 Economic Analysis

Based on market fuel prices, cost avoidance was realized in the ENV-L, ENV-H, and ENV-L in comparison with the frozen scenario. The benefits of ENV-H would be more significant if revenue from displaced fuels was taken into consideration

(Table 5.20). Furthermore, while the ENV-M and ENV-H cases were more expensive than the frozen case based on current fuel prices, the cost difference was offset by the revenue from displaced fuel (Table 5.21).

Table 5.20 Results of the cost analysis for the environmental impact minimization cases using market fuel prices (in billions of USD)

	Present Value of Generation Cost (2016–2040)			**Cost Avoidance**		
	ENV-L	**ENV-M**	**ENV-H**	**ENV-L**	**ENV-M**	**ENV-H**
Fuel cost	369.03	333.29	292.97	298.41	334.15	374.47
VO&M cost	37.10	28.10	34.77	2.84	11.84	5.17
FO&M cost	76.50	77.34	90.64	(11.81)	(12.65)	(25.95)
Annualized build cost	68.60	124.24	170.97	(24.56)	(80.20)	(126.93)
Total	551.23	562.97	589.35	264.87	253.14	226.76
				NPV of Revenue from Displaced Fuel (2016–2040)		
				ENV-L	**ENV-M**	**ENV-H**
				298	342	374

Table 5.21 Results of the cost analysis for the environmental impact minimization cases using current fuel prices (in billions of USD)

	Present Value of Generation Cost (2016–2040)			**Cost Avoidance**		
	ENV-L	**ENV--M**	**ENV-H**	**ENV-L**	**ENV-M**	**ENV-H**
Fuel cost	84.39	75.12	62.99	40.43	49.70	61.83
VO&M cost	37.10	28.10	34.77	2.84	11.84	5.17
FO&M cost	76.50	77.34	90.64	(11.81)	(12.65)	(25.95)
Annualized build cost	68.60	124.24	170.97	(24.56)	(80.20)	(126.93)
Total	266.59	304.79	359.36	6.89	(31.32)	(85.88)
				NPV of Revenue from Displaced Fuel (2016–2040)		
				ENV-L	**ENV-M**	**ENV-H**
				298	342	374

5.3.3.5 Social Benefits Analysis

It was observed that LCOE in 2040 was reduced by more than 34.9%, 30.8%, and 24.3% for ENV-L, ENV-M, and ENV-H, respectively. In addition, the ENV-L, ENV-M, and ENV-H cases respectively increased the total number of jobs created by more than 5.2, 5.9, and 5.2 times the jobs created in the frozen case. The breakdown of the jobs classifications is shown in Table 5.25 (which is presented in the below subsection).

5.3.3.6 Evaluation of the IRSP Objectives

Tables 5.22 to 5.25 summarizes the results of evaluating the IRSP objectives for the three environmental impact minimization cases using the metrics defined earlier.

Table 5.22 Evaluation of the IRSP objective-1 for the environmental impact minimization cases

Objective	**Metric**	**Unit**	**Evaluation Results**		
			ENV-L	**ENV-M**	**ENV-H**
Minimize domestic fuel consumption	Share of delivered electricity from fossil fuels	%	62	40	25
	Resource plan cost share in relation to fossil fuel	%	84	74	62
	Amount of liquid fuel used in the utility sector	MBOE	3872	3559	3321
	Amount of natural gas used in the utility sector	MBOE	10829	9546	7870
	Energy efficiency savings	TWh	286	286	286
	Estimated revenue from exporting displaced fuel	Billions of USD	298	342	374

Table 5.23 Evaluation of the IRSP objective-2 for the environmental impact minimization cases

Objective	Metric	Unit	Evaluation Results		
			ENV-L	**ENV-M**	**ENV-H**
Maximize penetrations of sustainable energy	Renewable share	%	21	60	60
	Renewable energy curtailed	TWh (2016–2040)	478.00	260.20	992.50
		TWh (2040)	16.00	63.50	159.10
	NPV cost avoidance	Billions of USD	264.87	253.1	226.7
	Resource diversity index	Range from 0 to 1	PV= n/a	PV= 0.978	PV= 0.999
			CSP= N/A	CSP= 0.94	CSP= 0.843
			Win= 0.95	Wind= 0.958	Wind= 0.972
			Nuc= 0.97	Nuc= N/A	Nuc= 0.978
			Fossil gen= 0.614	Fossil gen= 0.84	Fossil gen= 0.993

Table 5.24 Evaluation of the IRSP objective-3 for the environmental impact minimization cases

Objective	Metric	Unit	Evaluation Results		
			ENV-L	ENV-M	ENV-H
Minimize environmental impacts	CO_2 emissions	Millions of tons	5093	4555	3920
	Sulfur oxides (SOx) emission intensity	Pounds/MWh	1.75	1.21	0.93
	Nitrogen oxides (NOx) emissions intensity	Pounds/MWh	3.67	2.92	2.22
	Water consumption for generation	m^3/MWh	0.549	0.497	0.364

Table 5.25 Evaluation of the IRSP objective-4 for the environmental impact minimization cases

Objective	Metric	Unit	Evaluation Results		
			ENV-L	ENV-M	ENV-H
Maximize social benefits	Create local direct jobs	Millions of jobs	0.256	0.469	0.335
	Create indirect local jobs		0.187	0.519	0.750
	Create induced local jobs		1.290	1.975	1.692
	Reduce nominal price of electricity	$/MWh	56.7	57.9	60.6
	Provide reliable supply by increasing the reserve margin	%	14.8	27.0	9.97

5.3.4 Social Benefits Maximization Scenario

The social benefits maximization scenario targeted the highest job creation in Saudi Arabia's utility sector by aggressively deploying both EE measures in the demand-side and renewable energies in the supply-side.

5.3.4.1 Electricity Generation Mix Analysis

Figure 5.14 shows the generation mix (in GWh) and installed capacity (in MW) for the three cases in the social scenario (SOC-L, SOC-M, and SOC-H). The three cases were selected in renewable penetration levels of (1) 8.4%–40%, (2) 41%–60%, and (3) 61%–75%, such that they represented the highest jobs creation in their corresponding penetration level. The electricity supplied from renewable energy resources was increased to reach to 8%, 50%, and 58% for SOC-L, SOC-M, and SOC-H, respectively.

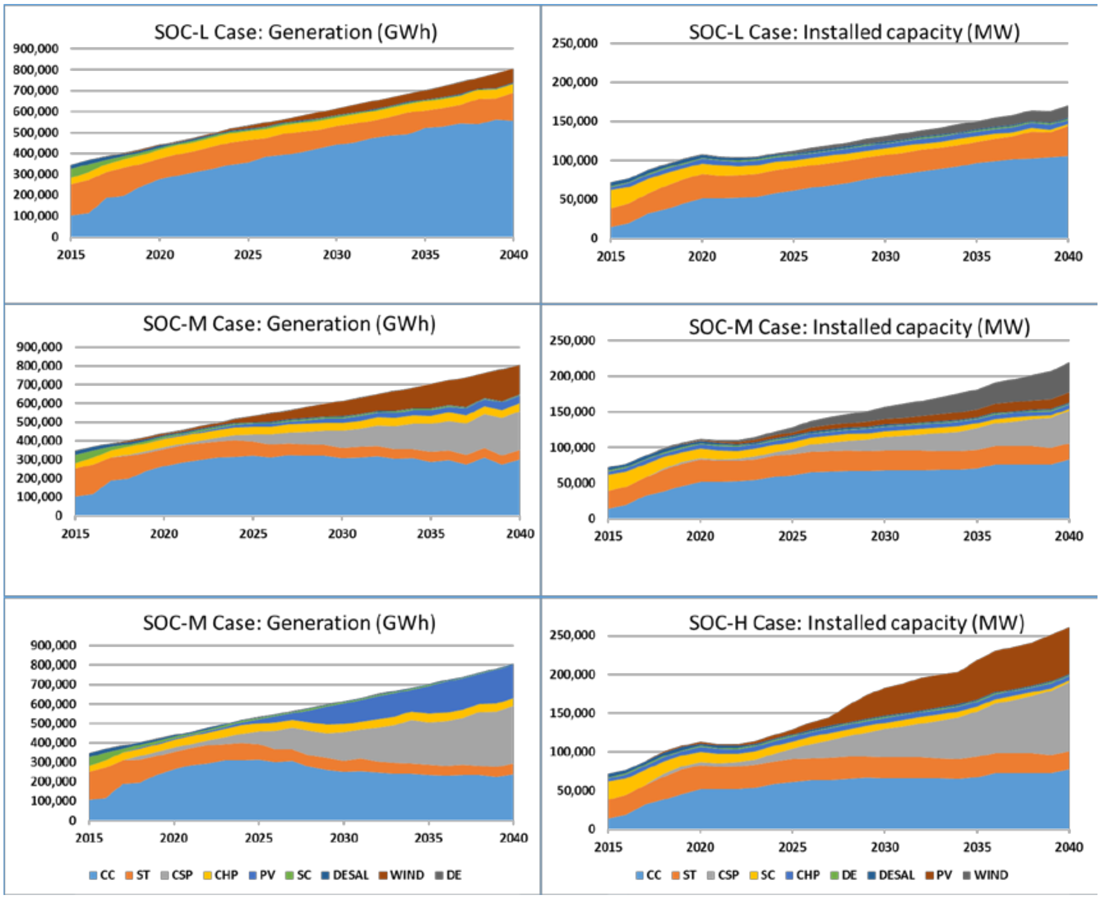

Figure 5.14 Technology mix for the social benefits maximization cases (by electricity generation and installed capacity)

5.3.4.2 Fuel Consumption Analysis

In comparison with the frozen case, fuel consumption in 2040 was reduced by 33%, 60%, and 65% for SOC-L, SOC-M, and SOC-H, respectively (Figure 5.15). It can be observed that the fuel consumption in the SOC-M and SOC-H cases was even lower than the current fuel consumption, despite the demand growth in the Saudi utility sector.

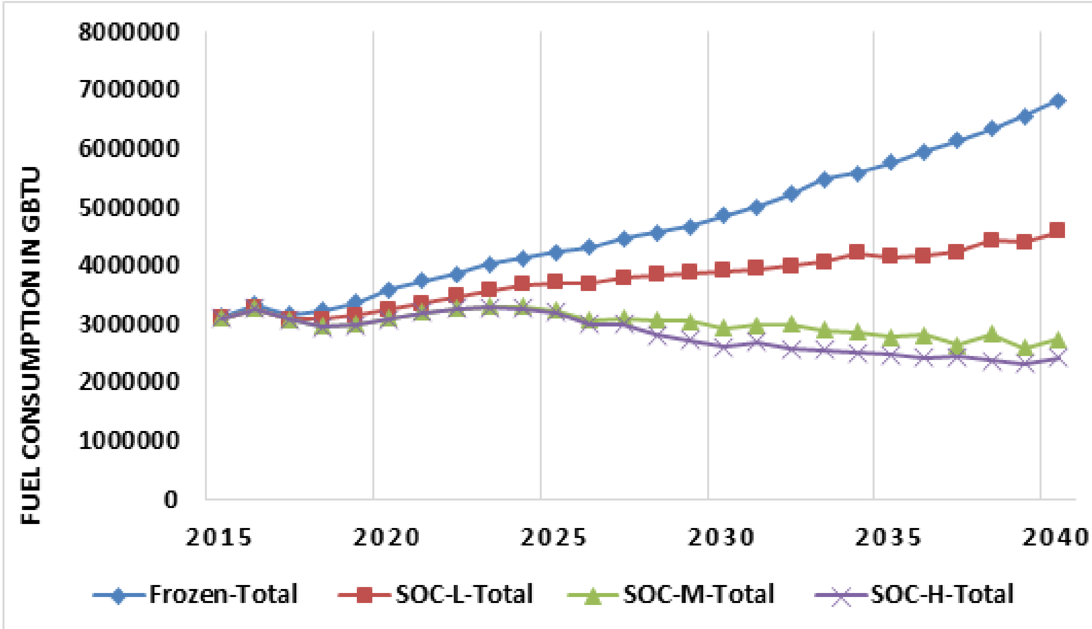

Figure 5.15 Fuel consumption analysis for the social benefits maximization cases, 2015–2040

5.3.4.3 Environmental Impact Analysis

In comparison with the frozen case, CO_2 emissions in 2040 were reduced by 40, 65%, and 69% for SOC-L, SOC-M, and SOC-H, respectively (Figure 5.16). The total emissions reduction achieved by deploying renewable energy resources was calculated to be more than 3561 million tons for the period from 2016 to 2040 in the SOC-H case; the NO_X and SO_X intensities were also reduced significantly (by 53% and 52%, respectively). The details concerning the NO_X and SO_X reductions in all three cases are shown in Table 5.26.

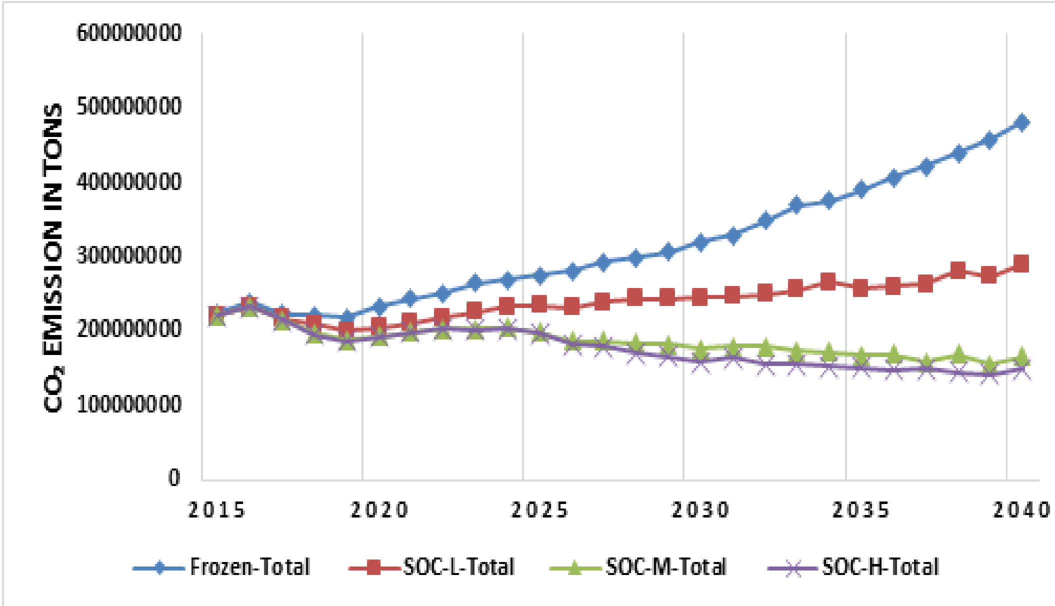

Figure 5.16 CO_2 emissions analysis for the social benefits maximization cases, 2015–2040

Table 5.26 NO_X and SO_X emissions for the social benefits maximization cases

Case	NO_X (total in million tons)	SO_X (total in million tons)	NO_X (million tons in 2040)	SO_X (million tons in 2040)	NO_X Intensity (MWh/lb (2040)	SO_X Intensity (MWh/lb) (2040)
Frozen	12.7	62.7	1.5	3.5	2.8	6.5
SOC-L	8.7	50.3	1.0	2.4	2.4	5.1
SOC-M	6.6	40.1	0.6	1.4	1.4	3.5
SOC-H	6.3	37.8	0.5	1.2	1.3	3.1

5.3.4.4 Economic Analysis

Based on market fuel prices, cost avoidance was realized in the SOC-L, SOC-M, and SOC-H cases in comparison with the frozen scenario. The benefits of SOC-H would be more significant if revenue from displaced fuels was taken into consideration (Table 5.27). Nonetheless, while the SOC-M and SOC-H cases were more expensive than the frozen case based on current fuel prices, this cost difference was offset by the revenue from displaced fuel (Table 5.28).

Table 5.27 Results of the cost analysis for the social benefits maximization cases using market fuel prices (in billions of USD)

	Present Value of Generation Cost (2016–2040)			**Cost Avoidance**		
	SOC-L	**SOC-M**	**SOC-H**	**SOC-L**	**SOC-M**	**SOC-H**
Fuel cost	**475.05**	**352.90**	**337.83**	**192.39**	**314.54**	**329.61**
VO&M cost	32.92	29.43	29.90	7.02	10.51	10.04
FO&M cost	57.51	72.92	75.35	7.18	(8.24)	(10.67)
Annualized build cost	31.42	102.22	146.32	12.62	(58.18)	(102.28)
Total	596.90	557.47	589.40	219.20	258.64	226.70
				NPV of Revenue from Displaced Fuel (2016–2040)		
				SOC-L	**SOC-M**	**SOC-H**
				192	315	330

Table 5.28 Results of the cost analysis for the social benefits maximization cases using current fuel prices (in billions of USD)

	Present Value of Generation Cost (2016–2040)			Cost Avoidance		
	SOC-L	**SOC-M**	**SOC-H**	**SOC-L**	**SOC-M**	**SOC-H**
Fuel cost	102.50	80.80	76.08	22.32	44.02	48.74
VO&M cost	32.92	29.43	29.90	7.02	10.51	10.04
FO&M cost	57.51	72.92	75.35	7.18	(8.24)	(10.67)
Annualized build cost	31.42	102.22	146.32	12.62	(58.18)	(102.28)
Total	224.34	285.37	327.65	49.13	(11.89)	(54.18)
				NPV of Revenue from Displaced Fuel (2016–2040)		
				SOC-L	**SOC-M**	**SOC-H**
				192	**315**	**330**

5.3.4.5 Social Benefits Analysis

The SOC-L, SOC-M, and SOC-H cases achieved the highest number of created jobs in their corresponding renewable penetration level; they increased the total number of created jobs by more than 3.3, 5, and 6.7 times the number created in the frozen case. The breakdown of the jobs classifications is shown in Table 5.32 (which is presented in the following subsection).

5.3.4.6 Evaluation of the IRSP Objectives

Table 5.29 to 5.32 summarizes the results of evaluating the IRSP objectives for the three social benefits maximization cases using the metrics defined earlier.

Table 5.29 Evaluation of the IRSP objective-1 for the social benefits maximization cases

Objective	**Metric**	**Unit**	**Evaluation Results**		
			SOC-L	**SOC-M**	**SOC-H**
Minimize domestic fuel consumption	Share of delivered electricity from fossil fuels	%	92	50	43
	Resource plan cost share in relation to fossil fuel	%	98	80	72
	Amount of liquid fuel used in the utility sector	MBOE	5089	3682	3559
	Amount of natural gas used in the utility sector	MBOE	12548	10377	9546
	Energy efficiency savings	TWh	286	286	286
	Estimated revenue from exporting displaced fuel	Billions of USD	192	315	330

Table 5.30 Evaluation of the IRSP objective-2 for the social benefits maximization case

<table>
<tr><th rowspan="2">Objective</th><th rowspan="2">Metric</th><th rowspan="2">Unit</th><th colspan="3">Evaluation Results</th></tr>
<tr><th>SOC-L</th><th>SOC-M</th><th>SOC-H</th></tr>
<tr><td rowspan="10">Maximize penetrations of sustainable energy</td><td>Renewable share</td><td>%</td><td>8</td><td>50</td><td>58</td></tr>
<tr><td rowspan="2">Renewable energy curtailed</td><td>TWh (2016–2040)</td><td>0.00</td><td>89.50</td><td>694.00</td></tr>
<tr><td>TWh (2040)</td><td>0.00</td><td>23.30</td><td>108.00</td></tr>
<tr><td>NPV cost avoidance</td><td>Billions of USD</td><td>219.20</td><td>258.64</td><td>226.70</td></tr>
<tr><td rowspan="5">Resource diversity index</td><td rowspan="5">Range from 0 to 1</td><td>PV= N/A</td><td>PV= 0.997</td><td>PV= 0.956</td></tr>
<tr><td>CSP= N/A</td><td>CSP= 0.934</td><td>CSP= 0.866</td></tr>
<tr><td>Wind= 0.992</td><td>Wind= 0.962</td><td>Wind= N/A</td></tr>
<tr><td>Nuc= N/A</td><td>Nuc= N/A</td><td>Nuc= N/A</td></tr>
<tr><td>Fossil gen= 0.161</td><td>Fossil gen= 0.755</td><td>Fossil gen= 0.819</td></tr>
</table>

Table 5.31 Evaluation of the IRSP objective-3 for the social benefits maximization cases

Objective	**Metric**	**Unit**	**Evaluation Results**		
			SOC-L	**SOC-M**	**SOC-H**
Minimize environmental impacts	CO_2 emissions	Millions of tons	6258	4862	4618
	Sulfur oxides (SOx) emission intensity	Pounds/MWh	2.43	1.44	1.28
	Nitrogen oxides (NOx) emissions intensity	Pounds/MWh	5.06	3.49	3.08
	Water consumption for generation	m^3/MWh	0.864	0.490	0.490

Table 5.32 Evaluation of the IRSP objective-4 for the social benefits maximization case

Objective	**Metric**	**Unit**	**Evaluation Results**		
			SOC-L	**SOC-M**	**SOC-H**
Maximize social benefits	Create local direct jobs	Millions of jobs	0.225	0.341	0.505
	Create indirect local jobs		0.145	0.546	0.618
	Create induced local jobs		1.295	1.650	2.258
	Reduce nominal price of electricity	$/MWh	61.4	61.4	60.6
	Provide reliable supply by increasing the reserve margin	%	19.30	7.60	32.00

5.4 Summary and Evaluation of the IRSP Results

5.4.1 Electricity Sector

This section summarizes the results of the main four scenarios, taking into consideration the three EE cases, and the cases from renewable, environmental, and social scenarios that achieve the highest level of optimization objectives related to renewable penetrations maximization, environmental impact minimization, and social benefits maximizations. Figure 5.17 summarize all cases in the four main scenarios presented in the previous sector, taking into considerations, renewable penetrations, economic, environmental and social benefits. the economic analysis of each case was undertaken by subtracting the present value of the TRC of each alternative from the frozen case to calculate the avoided cost. These alternative cases were found economically feasible when compared to the frozen scenario.

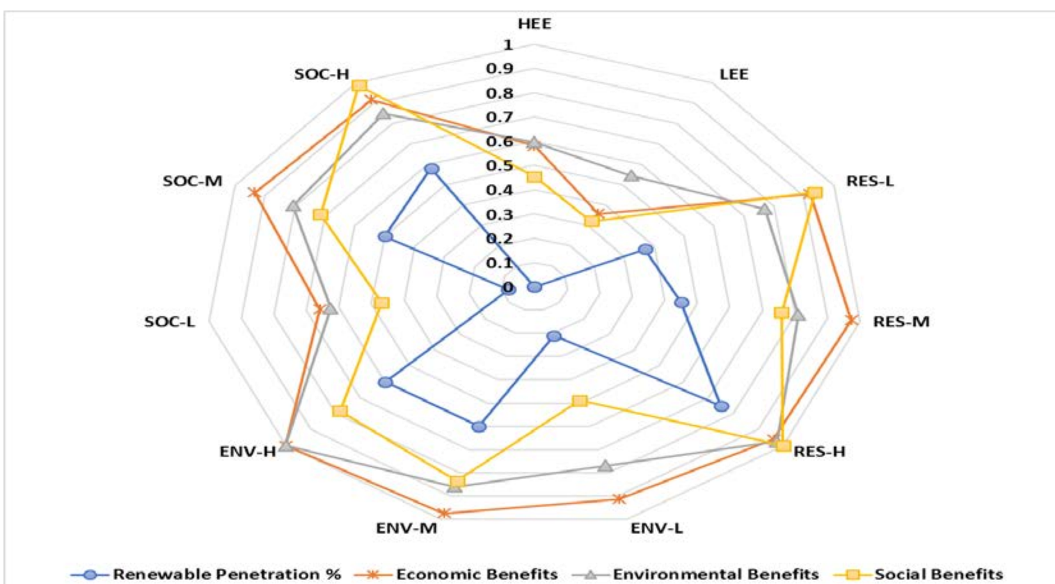

Figure 5.17 Summary of results for energy efficiency, renewable, environmental and social scenarios.

Figures 5.18 and 5.19 show the generation technology mix in GWh and MW, respectively. While the generated electricity from low carbon sources was almost the same in RES-H (75% from renewables) and ENV-H (60% from renewables and 15% from nuclear), the installed capacity of renewable energy resources in RES-H. The capacity factors of renewable energy resources in RES-H were higher in comparison with ENV-H (52.4% versus 49.7%). Although the generated electricity from renewables in SOC-H represented 58% of total generated electricity (against 74% and 60% for RES-H and ENV-H), SOC-H had 2.2% and 8.1% more renewable energy resources installed capacity than RES-H and ENV-H, respectively. This was due to the lower capacity factor of renewable energy resources (around 35%), which was attributed to the deployment of CSP technology with TES of 8 hours (with SM-2). In contrast, RES-H and ENV-H maintained a mix of CSP technology with TES of 8 hours (with SM-2) and TES of 12 hours (with SM-2.5).

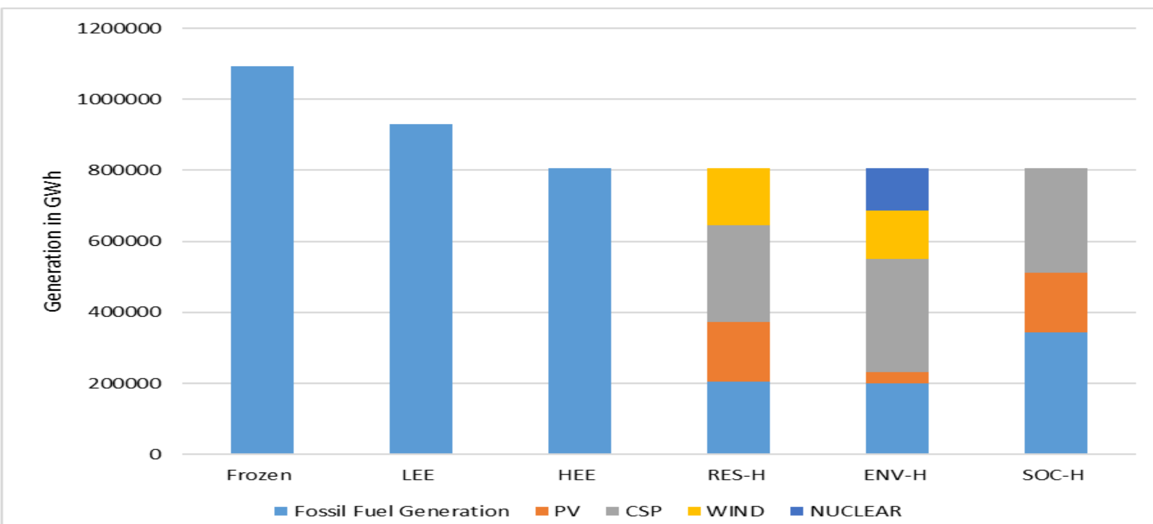

Figure 5.18 Technology mix by generated electricity for the high cases in the energy efficiency, renewables, environmental, and social scenarios (in GWh)

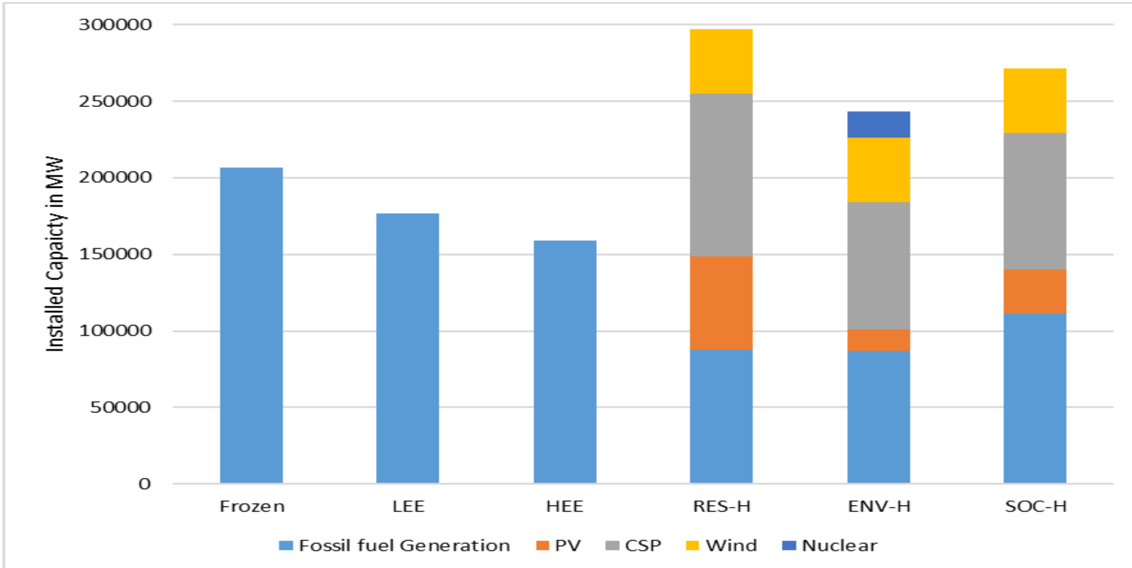

Figure 5.19 Technology mix by installed capacity for the high cases in the energy efficiency, renewables, environmental, and social scenarios (in MW)

In Table 5.33, a benefit-cost analysis was conducted independently for the six cases to quantify the NPV total benefits, considering the following two calculation criteria:

- Criterion 1: (Total NPV benefits from electricity sales revenue, and emission trading revenue) – (total NPV resource cost); assuming that the fuels supplied to electricity generation plants are priced based on market fuel prices and that retail electricity prices remain constant throughout the planning period.

- Criterion 2: (Total NPV benefits from electricity sales revenue, revenue from displaced fuel sales and emission trading revenue) – (total NPV resource cost); assuming that the fuels supplied to electricity generation plants are priced based on market fuel prices and that retail electricity prices remain constant throughout the planning period.

Based on the results in Table 5.33, the NPV of RES-H, ENV-H, and SOC-H (ordered from the highest to the lowest cost option) were found lower than in the frozen case in all benefit-cost analysis criteria, even when electricity was priced based on the current subsidized prices. The LEE and HEE scenarios were attractive only when the second benefit analysis criterion was considered, while the frozen scenario was not economical in any benefit-cost analysis. In these cases, the fuel subsidies can be removed while maintaining electricity sector profitability. If the Saudi government decides to continue these subsidies, it was found that RES-H, ENV-H, and SOC-H reduced them respectively by 56.9%, 57.6%, and 51.7%, due to the high reduction of fuel consumption (Table 5.34).

Fuel consumption in the utility sector was minimized in the five cases in comparison with the frozen case (Table 5.34 and Figure 5.20). For example, the natural gas and liquid fuel consumption in RES-H was reduced by approximately 40% and 60%, respectively. This represents 47% reduction of the current total fuel consumption in the utility sector. The environmental impact was minimized in the five cases, with the highest emissions reduction (i.e. more than 50%) in the ENV-H case. Socially, the RES-H case represented the lowest LCOE, which would minimize the overall electricity retail price for the end-users. However, the SOC-H case had the highest total job creation of all the cases, with 6.7 times more jobs being created than in the frozen scenario. This was due mainly to the high number of PV installations, which are more labor intensive than other technologies.

Table 5.33 Summary of the benefit-cost analysis of the high cases in the energy efficiency, renewables, environmental, and social scenarios[74]

	Frozen	LEE	HEE	RES-H	ENV-H	SOC-H
Total cost (billions of USD), market fuel prices	816	693	615	608	589	589
Total revenue from displaced fuel (billions of USD)[75]	0	100	163	369	374	227
Total revenue from emission trading (billions of USD)[76]	0	17	28	72	74	62
Total electricity sales revenue (billions of USD)[77]	713	637	586	586	586	586
NPV of benefit-cost (Criterion 1)[78]	**(103)**	**(39)**	**(2)**	**55**	**71**	**58**
NPV of benefit-cost (Criterion 2)	**(103)**	**61**	**162**	**424**	**445**	**285**

[74] All costs were discounted using a social discount rate of 3%.

[75] The total revenue was calculated as the present value of exporting/utilizing the displaced fuel based on international fuel market prices for the period 2016–2040.

[76] The CO_2 reduction yielding revenue was calculated by the end of 2040 assuming a USD 33.7 per ton of CO_2 carbon price rate (which was the highest carbon price realized in 2008 under the EU Emission Trading System) (Carbon Market Watch, 2014).

[77] The electricity sales revenue was calculated based on the current electricity retail price with a conservative assumption that this price will remain.

[78] The revenue from exporting displaced fuels was not included in this calculation.

Table 5.34 Summary of other economic, environmental, and social analysis of the high cases in the energy efficiency, renewables, environmental, and social scenarios

	Frozen	**LEE**	**HEE**	**RES-H**	**ENV-H**	**SOC-H**
Total fuel subsidies (billions of USD)	543	464	412	234	230	262
Natural gas consumption (MBOE)	13410	13139	12814	8098	7870	9546
Liquid fuel consumption (MOBE)	8487	6621	5563	3339	3321	3559
Emissions (millions of tons)	8179	7196	6579	4020	3920	4618
LCOE ($/MWh)-nominal	69.3	65.7	63.3	59.4	60.6	60.6
Jobs created (millions of jobs)	0.50	1.14	1.61	3.30	2.78	3.38

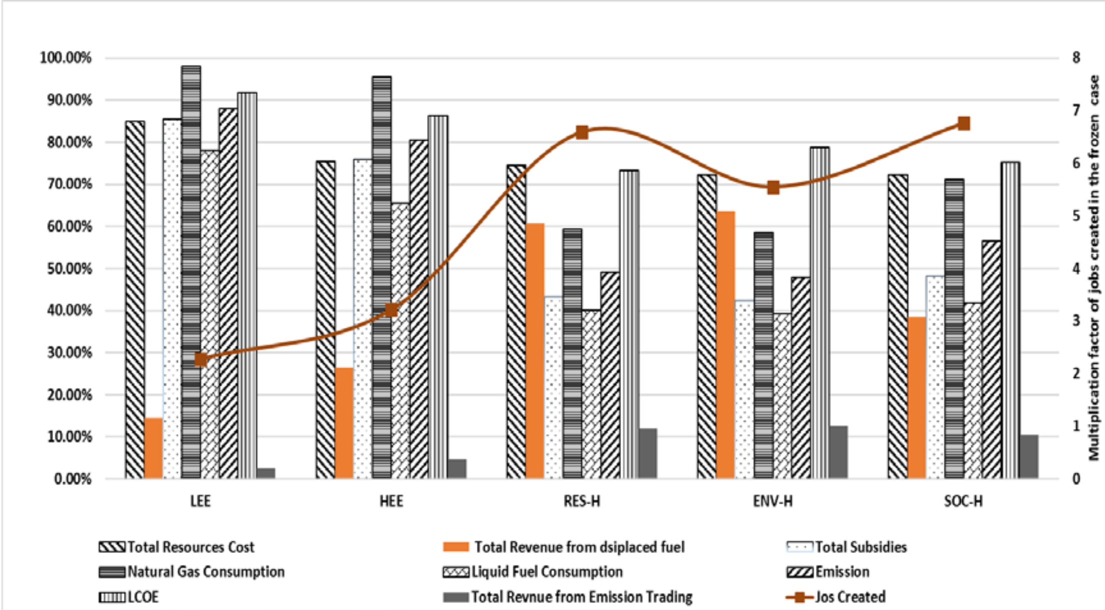

Figure 5.20 Summary of the results for the high cases in the energy efficiency, renewables, environmental, and social scenarios[79]

5.4.2 Water Sector

5.4.2.1 Electricity Consumption in the Desalination Plants

Based on the existing desalination plant capacities, planned retirement, and planned new installations, Figure 5.21 highlights the additional desalination plants required for each year given projected desalinated water consumption (as presented in Figure 4.2). The electricity consumption of these plants is expected to grow from the current level of approximately 16 GWh to more than 32 GWh in 2040. The electricity consumption calculations are based on 7 kWh/m^3 for existing plants and 3.6 kWh/m^3

[79] The results of these scenarios were compared with those of the frozen scenario. In this figure, the values are presented as percentages of the results of the frozen scenario for each corresponding factor. The percentages of total subsidies and revenues from emissions trading were calculated with respect to the total cost of each case.

for efficient new RO desalination plants (Sood, 2014; Masdar, 2014, p. 9). While the water production is tripled, the electricity demand in these desalination plants was only doubled due to the use of efficient RO plants.

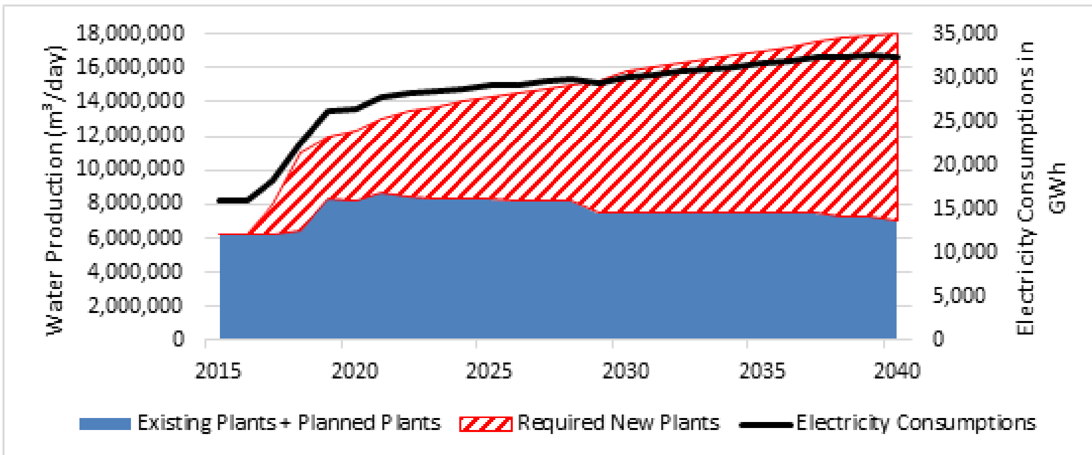

Figure 5.21 Calculated additional desalination plants and their electricity consumption (based on projected desalinated water consumption), 2015–2040

5.4.2.2 CSP and other Renewable Energy Application in Desalination Plants

As investigated in Chapter 2, CSP technology has the potential for deployment in Saudi Arabia's water desalination plants to efficiently produce water and reduce the current reliance on oil and gas in the water sector. However, CSP performance depends on the DNI level. As such, geographic location is a key factor to consider in designing CSP plants. An additional case investigating the option of using integrated CSP-RO plants in the Kingdom's coastal areas was thus also considered in the desalinated water sector analysis, in addition to the four high cases from the four main scenarios considered in the EWS IRSP model. Table 5.35 describes all of these cases.

Table 5.35 Cases considered in the desalinated water sector analysis

Case	Description
Frozen	Addresses the RO plants that are supplied from the grid based on the frozen case, using only fossil fuel generation.
RES-H	Considers a decoupled combination of RO and a mix of renewable technologies including a dry-cooled CSP plant located inland (which has the best DNI values and lowest diffusion factor, as explained in detail in Chapter 2).
Integrated CSP-RO plants	Considers coastal RO plants with dry-cooled CSP technology. The generated hourly electricity profile for CSP is calculated by SAM using DNI values in the city of Dammam (located on the Arabian Gulf).

5.4.2.3 Desalination Analysis

Table 5.36 provides the present value of the TRCs of desalinated water in Saudi Arabia for the period 2016–2040. The present value of the TRC compromises a desalination plant's capital cost, VO&M cost, fuel cost (in the case of non-RO desalination plants), and electricity cost. An integrated RO-CSP coastal desalination plant was found to be the most expensive option due to the relatively low DNI values (which had an approximate average monthly DNI of 3500Wh/m^2 in winter and 6500Wh/m^2 in summer) as it resulted in a higher electricity cost of CSP. The RO-CSP option was identified as being even more expensive than the frozen scenario. The RES-H case optimized the location of renewable technology based on available renewable resources and lowest cost; as a result, it provided lower cost for expansions in desalination plants.

Table 5.36 Results of the total cost analysis for the desalinated water cases (in billions of USD)

Scenario		Frozen	RES-H (inland RES)	RO-CSP (Coastal)
New RO plants	Capital cost (billions of USD)	9.46	9.46	9.46
	VO&M cost (billions of USD)	8.74	8.74	8.74
	Electricity cost[80] (billions of USD)	10.42	8.89	10.59
	Total cost (billions of USD)	28.61	27.50	28.79
Existing	Total cost (billions of USD)	22.91	21.4	22.91
Total cost, new and existing desalinization facilities (billions of USD)		51.52	49.00	51.69

The water production cost (i.e. the levelized water cost, or LWC) was calculated similarly to the electricity cost (Moser, Terib, & Fichter, 2013, p.131). Table 4.5 provides the main economic assumptions for the desalination technologies. The water production costs estimations were based on the calculation of the annual costs, which included annual capital costs, annual operational costs, and electricity costs. In each case, the cost of electricity was calculated using the LCOE calculations made for the five cases (Figure 5.22). The nominal LWC from integrated RO-CSP in coastal areas was higher than RES-H, given that coastal areas have DNI values that are relatively lower in comparison to those in inland locations in Saudi Arabia. The RES-H case provided the lowest LWC of new and total water desalination plants (USD

[80] The electricity cost was calculated based on the LCOE of each case, not on retail electricity prices. The purpose of using LCOE was to investigate the effect of deploying various renewable energy resources in each case on the PV total cost.

0.312/m³ and USD 0.857/m³, respectively), due to the reduced electricity price resulting from the high deployment of renewables. Since the new RO plants are more efficient than other existing desalination plants, their LWC is significantly (almost 63%) lower than the total LWC. Thus, the integrated RO-CSP coastal desalination plants option was excluded from the IRSP model.

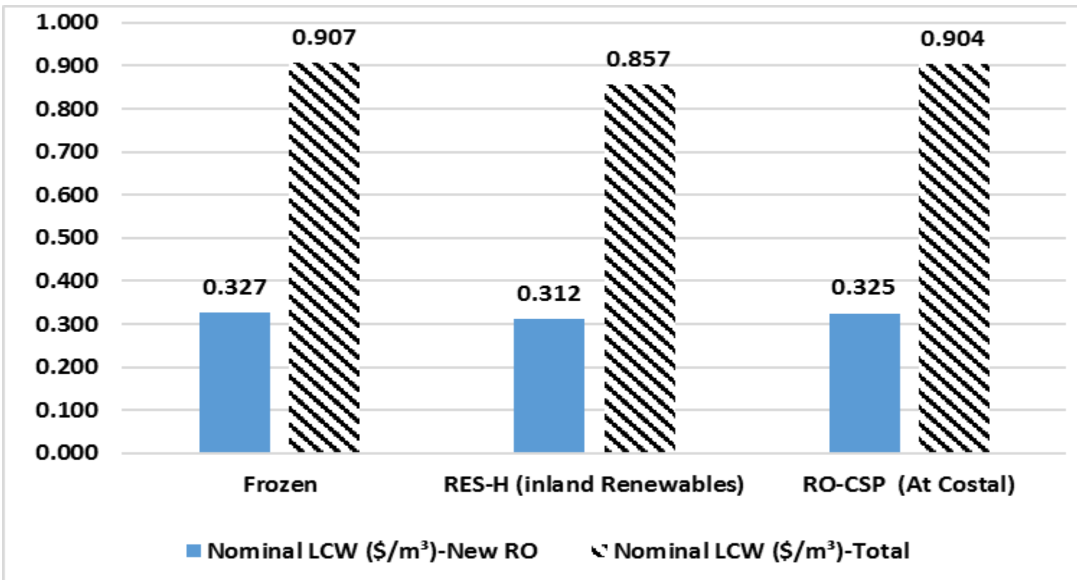

Figure 5.22 Levelized water costs for all cases (in $/m³)

As shown in Figure 5.23, the fuel consumption savings in RES-H was calculated to be 301 MOBE in comparison with the frozen case for the period 2016–2040. Moreover, the CO_2 emissions reductions were estimated to be 123.9 million tons for RES-H.

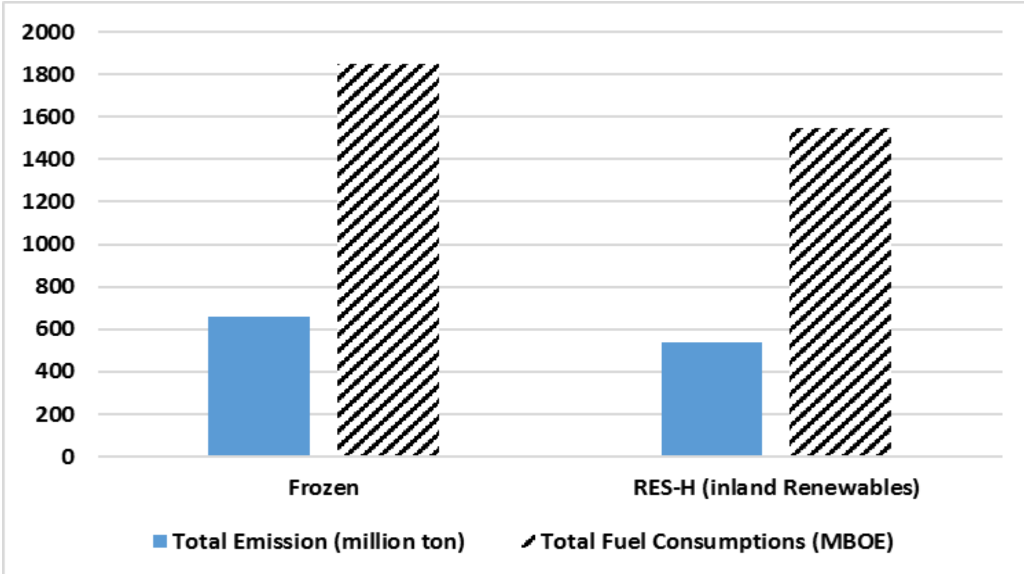

Figure 5.23 CO_2 emissions and fuel consumption in the desalinated water cases

5.4.3 Comparison of the EWS IRSP Scenario Results with Global Sustainable Scenarios

In order to evaluate the various metric of the EWS IRSP scenarios, comparisons were made with various global sustainable scenarios that use different regions and scenarios assumptions (as presented in Table 4.13).

In relation to the first objective (namely to minimize fossil fuel consumption in electricity generation), Figure 5.24 indicates that liquid fuel consumption in the RES, ENV, and SOC cases was lower than the projected consumption in the NPS scenario (except for the SOC-L case). Gas consumption was lower in the IRSP cases than in the NPS for the Middle East region. The high consumption of gas in the low and moderate IRSP cases in comparison with consumption in other regions was due to the increase the gas share in generating electricity; in contrast, other regions still relied on other fossil fuel (i.e. coal) for generating electricity. Nonetheless, RES-H and ENV-H had the lowest gas consumption among all regions (except for NPS for China). The share of delivering electricity from fossil fuel in RES-H and ENV-H was among the lowest of the selected regions.

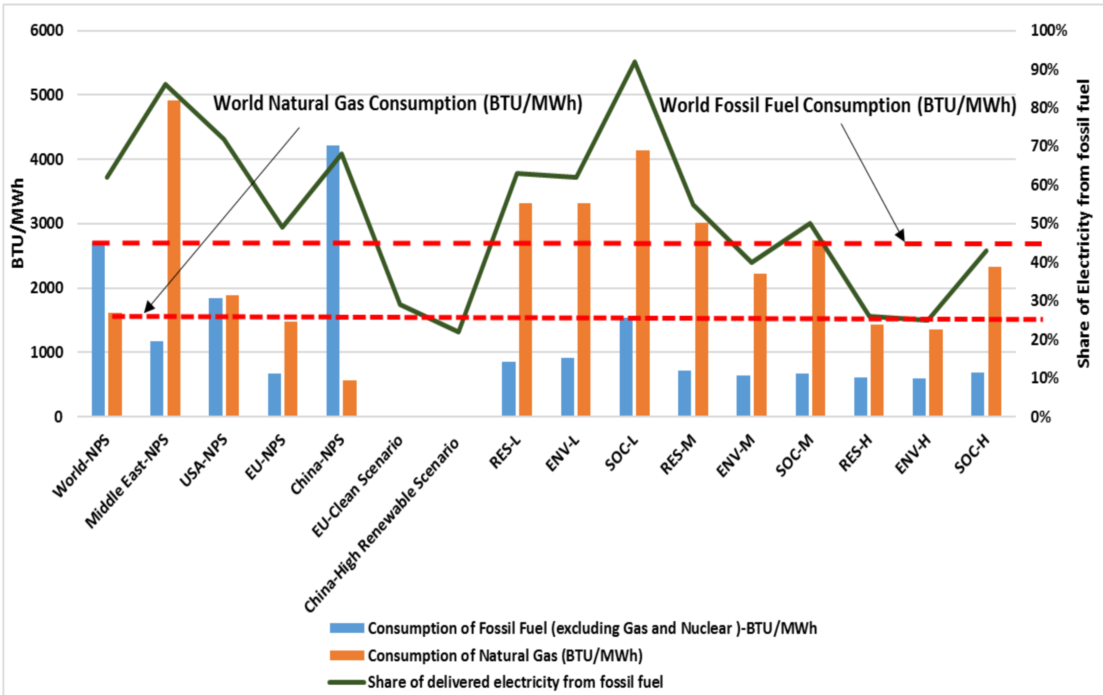

Figure 5.24 The IRSP and global metrics to minimize domestic fossil fuel consumption in the utility sector[81]

Analyzing the second objective, the renewable shares in the moderate and high IRSP cases were higher than in all other regions. Moreover, the RES-H and ENV-H cases shared almost the same high renewable penetration share as the EU-green and China-REN scenarios, as shown in Figure 5.25. The resource diversity index, which

[81] For comparison purposes, fuel consumption was calculated in BTU per total electricity demand in 2040 for all scenarios. The share of delivered electricity included nuclear power.

measures independency on fossil fuel to generate electricity, saw a high increase in the moderate and high cases in comparison to other regions; for example, the diversity index for fossil fuels increased to 0.93 in RES-H and 0.99 in ENV-H.

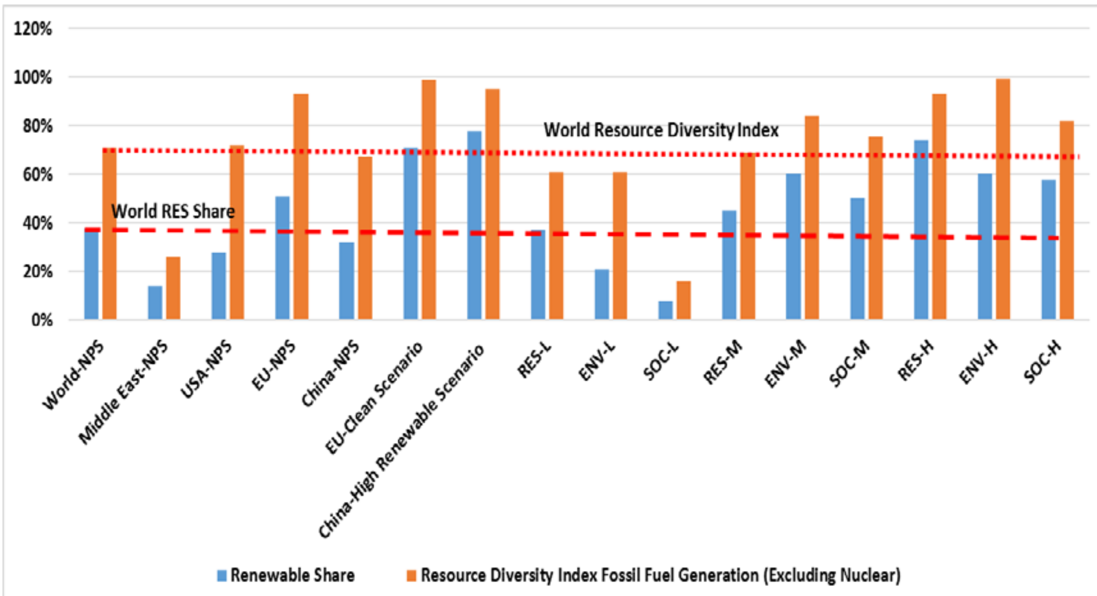

Figure 5.25 The IRSP and global metrics to maximize the penetration of sustainable energy sources

The third IRSP objective is to minimize both the environmental impact and water consumption in the utility sector. In the nine IRSP cases, emission intensity (in ton/MWh) was found to be lower than in most of the regions in the NPS scenario (Figure 5.26). Moreover, RES-H and ENV-H had the lowest energy intensity in all regions, with an exception of the EU-green scenario. Regarding water consumption (in m^3/MWh), all nine IRSP cases were the lowest among all regions. The reductions in Saudi Arabia were mainly due to the adoption of dry-cooled CSP technologies; in contrast, the increase of water consumption in other regions was due to high water consumption in coal and nuclear generation (i.e. coal and nuclear in China, the EU, and the United States, which respectively represented 41%, 29%, and 41% in the NPS).

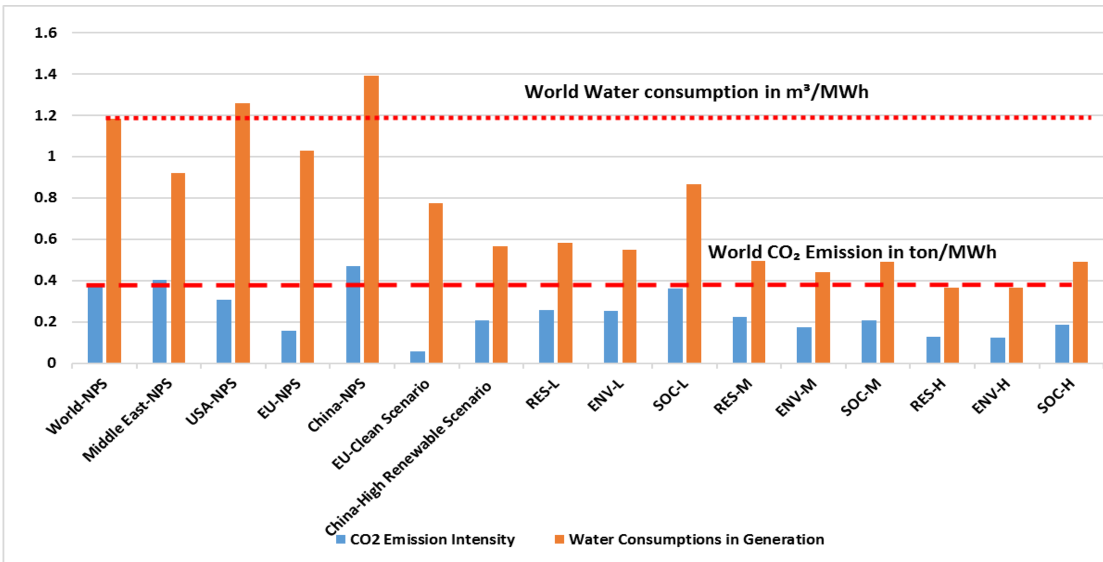

Figure 5.26 The IRSP and global results to minimize environmental impacts[82]

In maximizing social benefits in the fourth objective, job creation was a key metric for evaluating the IRSP scenarios. The IRSP results revealed that in comparison with other regions, Saudi Arabia would have the job creation rate per GWh. This was due to the country's heavy deployment of solar and EE measures, which are more labor intensive than other renewables and generation technologies. For example, solar

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[82] Since Saudi Arabia does not have hydro-power generation, the water consumption for other regions excluded this category of generation.

generation in the EU's NPS and the RES-L were 6% and 20%, while EE savings were respectively 11% and 24% (Figure 5.27).

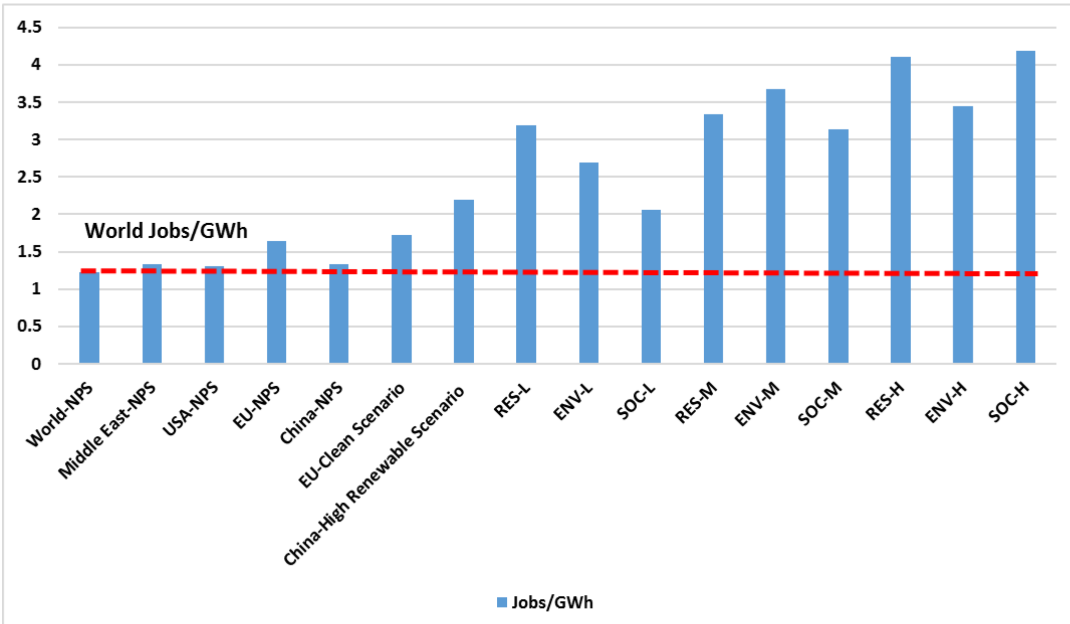

Figure 5.27 The IRSP and global metrics to maximize social benefits

5.5 Sensitivity Analysis

A vital part of an IRSP analysis is performing a sensitivity analysis on different variables that are likely to pose a major impact on the results. In this regard, a sensitivity analysis may result in re-ordering the integrated plan ranks or excluding specific resources from it (Swisher et al., 1997, p. 166). For example, electricity forecasting cases make it possible to evaluate whether or not a potential IRSP could be applicable to a certain situation wherein demand levels are different whilst still maintaining cost-effectiveness. (Tellus, 2000, p. 11).

In this study, the sensitivity analysis explored the impacts of the following factors:

- The life-cycle cost (present value) of generation and transmission options, and
- The levelized cost of energy.

The analysis was conducted by altering each of the following variables while adjusting others so that the relative impact of the candidate variable could be compared:

- International fuel prices (with EIA high, reference, and low price projections being considered);
- Discount rate (with 5%, 7%, and 10% being considered and compared to the reference 3% value).
- Generation cost (with three high, reference, and low cost levels being considered);
- Transmission augmentation (with the building of new 380 kV TLs versus utilizing the existing TLs being considered);
- GDP (with +1% and -1% the reference GDP being considered);
- Effect of number of household growth in electricity demand in the residential sector (with higher and lower household growth being considered); and
- Effects of weather variables (the reference weather case in the IRSP analysis was based on the high temperature case; as such, the sensitivity analysis was made by considering the low temperature case).

The sensitivity of the NPV TRC and LCOE for 2040 for three cases (frozen, HEE, and one of high renewable cases (RES)) to changes in the above input variables was computed, as shown in Figures 5.28 and 5.29.

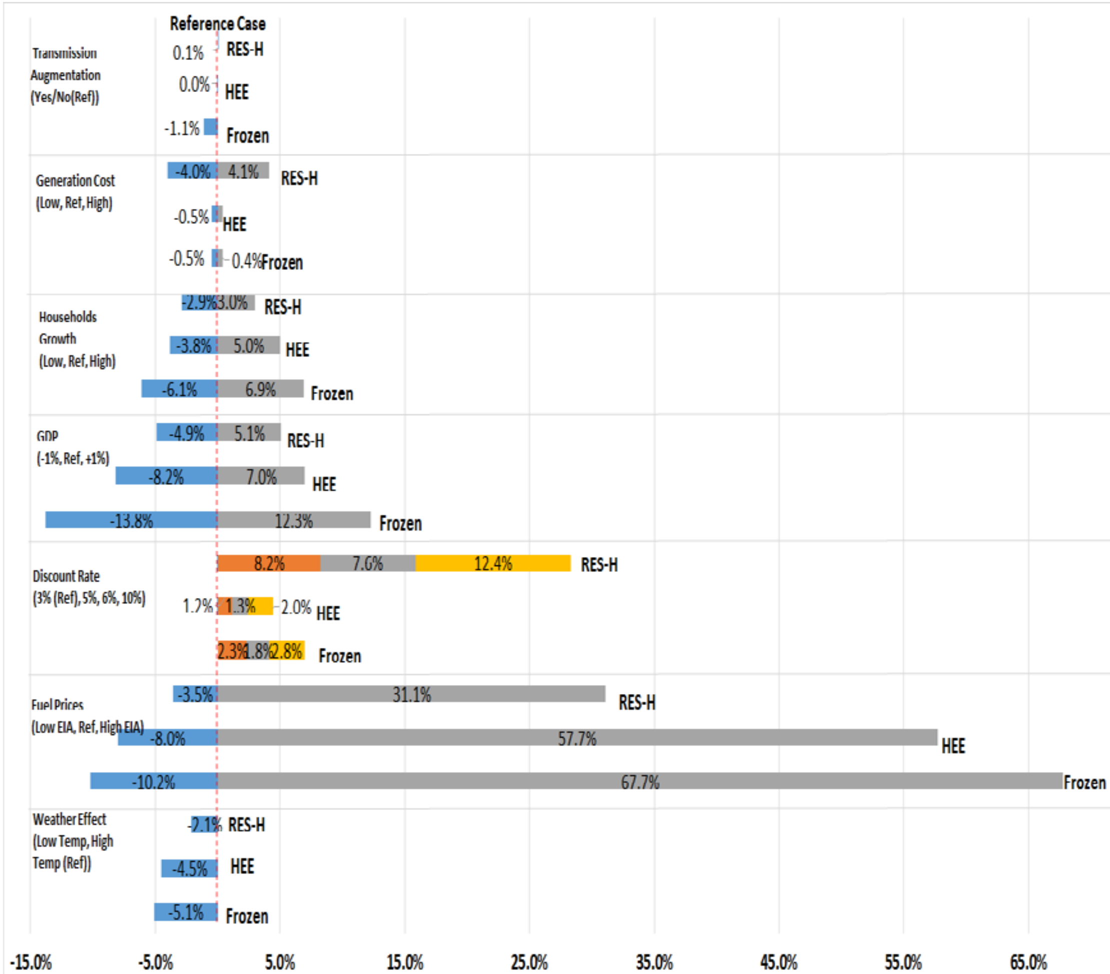

Figure 5.28 Sensitivity analysis of the total resources cost for the frozen, HEE, and RES-H cases in 2040

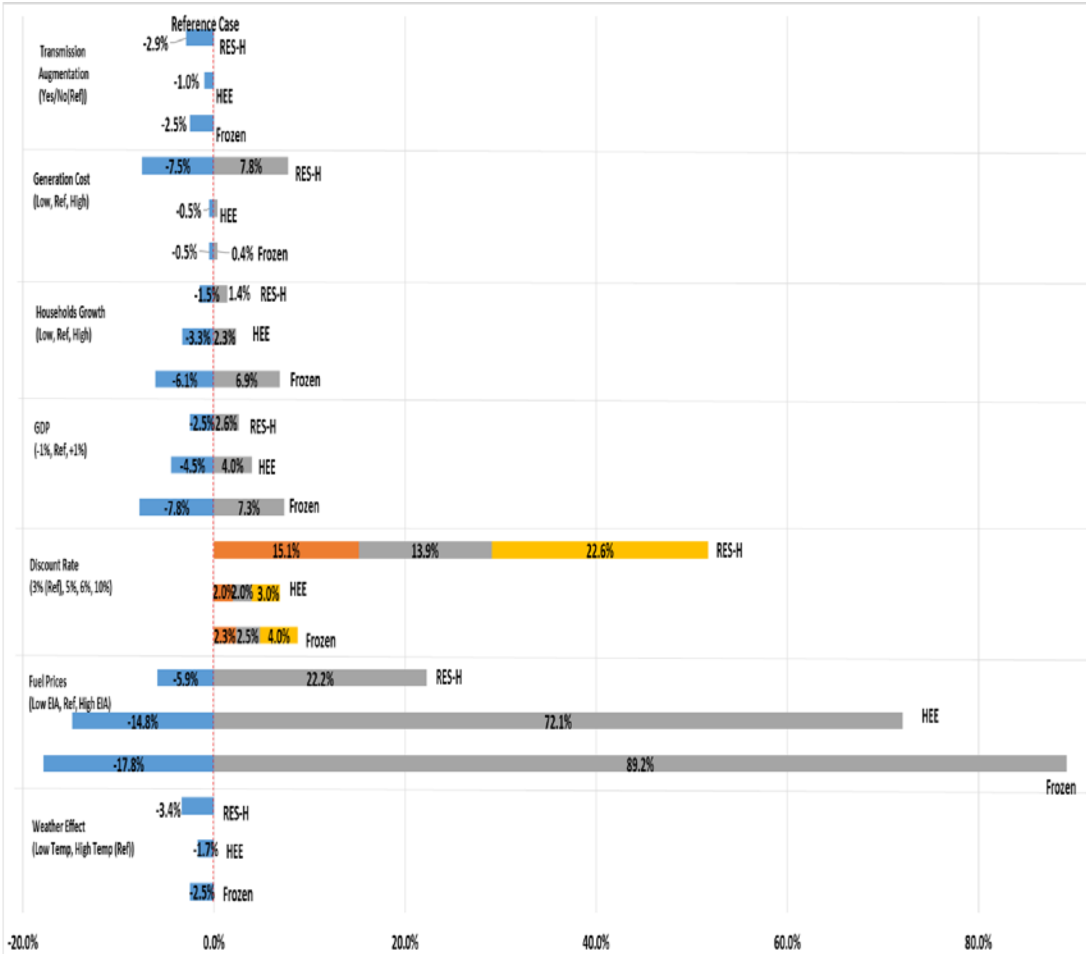

Figure 5.29 Sensitivity analysis of LCOE for the frozen, HEE, and RES-H cases in 2040

5.5.1 The Effects of Fuel Price on TRC and LCOE

Fuel price is one of the largest factor influencing TRC and LCOE values. In the frozen case, total cost varied from -10.2% to 67.7% for low and high EIA fuel price projections, respectively; similarly, the LCOE ranged from USD 76.0/MWh to USD 174.9/MWh in 2040. In the HEE case, fuel consumption was reduced as a result of applying EE measures; the impact of varying fuel prices was therefore slightly lower than in the frozen case. In this case, the total cost ranged from -8% to 57.7% for the low and high EIA fuel price projections; the LCOE also ranged from USD 68.0/MWh to USD 137.0/MWh. However, as fuel costs were a relatively small component of the total cost and LCOE calculations in the RES-H case, variations in these costs had less influence. This was due to the dramatic reduction in fuel consumption in this case. The least impact of varying the fuel prices was thus realized in RES-H, with a total cost range of -3.5% to 31.1% and an LCOE range of USD 61.3/MWh to USD 97.7/MWh.

5.5.2 The Effects of the Discount Rate

Changing the discount rate value had a significant impact on the RES-H case, since the capital cost of new renewable generation was the dominant factor in calculating the LCOE (which increased by approximately 23% when the discount rate was raised to 10%). Discount rate had less of an impact in the frozen and HEE cases, since the LCOE values were mostly driven by fuel prices. For example, the LCOE was increased by only 4% in the frozen case.

Since fuel prices and discount rates are the two most important factors influencing the results of the IRSP model, a further analysis was conducted to investigate the effects that varying them simultaneously had on the TRC. Figure 5.30 shows that the total cost of the HEE case was much lower than the frozen case at all sensitivity cases. Moreover, RES-H was found to be much lower than the frozen case, even when the two factors were tested at the highest discount rate (i.e. 10%) and the lowest EIA fuel price projections. Totals costs of RES-H became higher than those of HEE when discount rates increased and fuel prices decreased. Nonetheless, RES-H became the least cost option when accounting for revenues from displaced fuels, as these revenues offset the RES-H case’s increase in TRC. For example, in the worst scenario (i.e. a 10% discount rate and EIA low fuel prices), the total costs of HEE and RES-H were found to be USD 223 and 214 billion respectively (Table 5.37). Using the reference discount rate (3%) and reference fuel prices, the total cost of RES-H became even lower than the cost of the HEE case, with a cost avoidance of USD 258 billion.

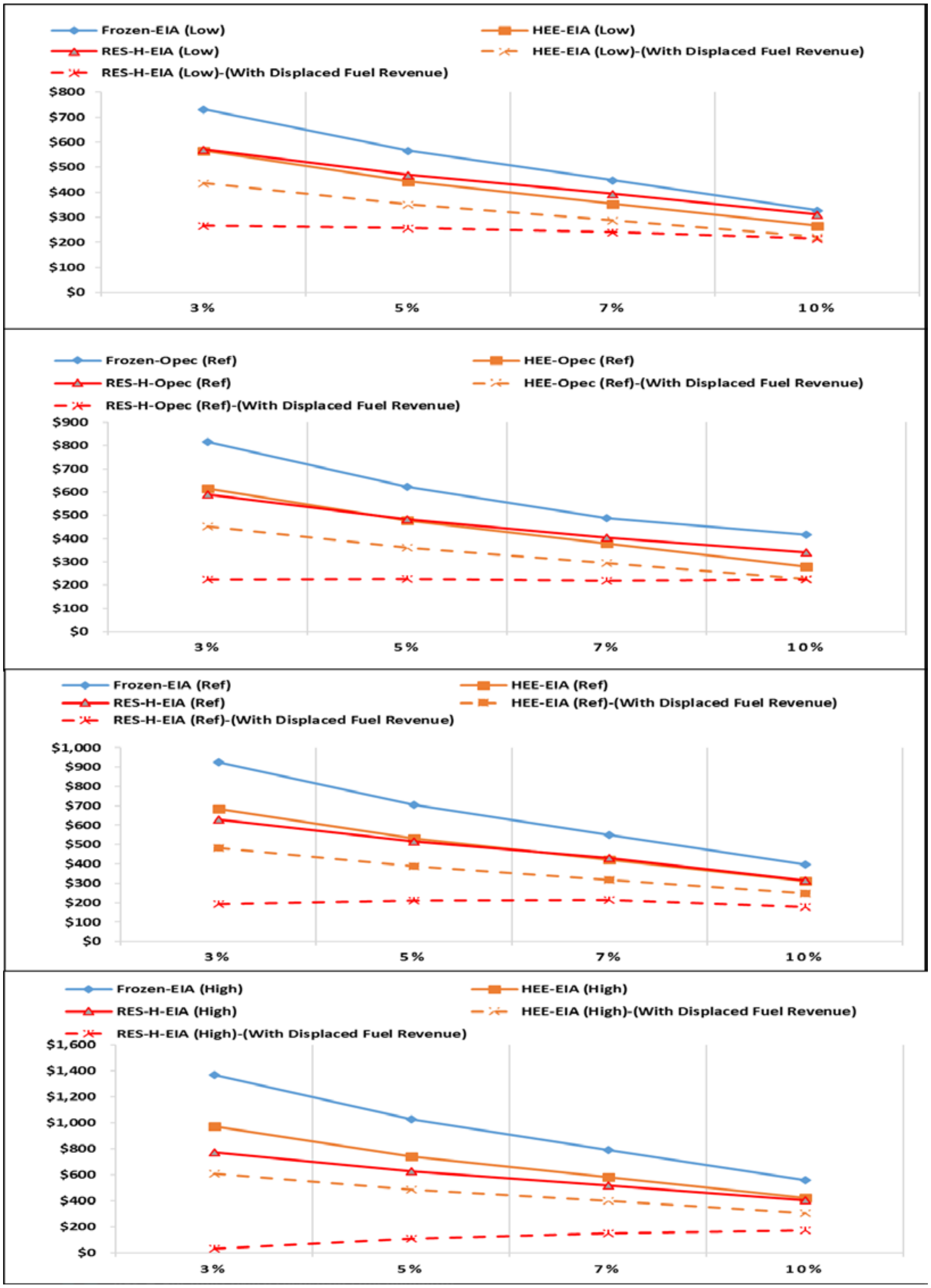

Figure 5.30 Total resource cost as a function of fuel prices and discount rates for the frozen, HEE, and RES-H cases (in billions of USD)

Table 5.37 Cost analysis based on a discount rate of 10% and EIA low fuel prices (in billions of USD)

	Present Value of Generation Cost (2016–2040)			**Cost Avoidance**	
	Frozen Case	**HEE Case**	**RES-H Case**	**HEE**	**RES**
Fuel cost	593.1	459.3	280.3	133.8	312.8
VO&M cost	40.4	34.3	38.9	6.1	1.5
FO&M cost	61.5	52.2	86.8	9.4	(25.3)
Annualized build cost	87.2	46.6	310.7	40.6	(223.5)
Total	782.2	592.3	716.7	189.9	65.5
				NPV of Revenue from Displaced Fuel (2016–2040)	
				133.8	312.8

Further analysis was conducted to investigate the effects of varying the fuel prices and discount rates simultaneously on the LCOE for different renewable energy technologies. These LCOE were compared with the calculated LCOE of new fossil fuel generation in the frozen case at different fuel prices and discount rates. In this analysis, the LCOE was calculated taking the renewable energy resources curtailments into consideration. Figure 5.31 illustrates that curtailing variable renewable generation, specifically solar and wind energy, increases in Saudi Arabia as penetration of more solar and wind energy sources expands in the country (such as in the RES-H case, where 74% of electricity is supplied by renewables). Table 5.38 summarizes the findings of the analysis and indicates the year when renewable energy resources will produce electricity for the same cost as fossil fuel generation.[83] The analysis revealed, unsurprisingly, that renewable energy resources reached grid parity

[83] This is also called “grid parity.” In this analysis, this term refers to the cost at which renewable energy resources will produce electricity at the same LCOE as fossil fuel generation.

faster at a lower discount rate and higher fuel prices. Wind technology attained grid parity earlier than PV and CSP, due to its relatively low capital cost. In the worst case (i.e. a discount rate of 10% and EIA low fuel price projections), wind and PV will reach grid parity respectively in 2026 and 2028 respectively. In contrast, CSP does not reach grid parity during the modeling period in the worst-case scenario, even without curtailment as its high capital cost is not offset by fuel savings with the lower fuel prices.

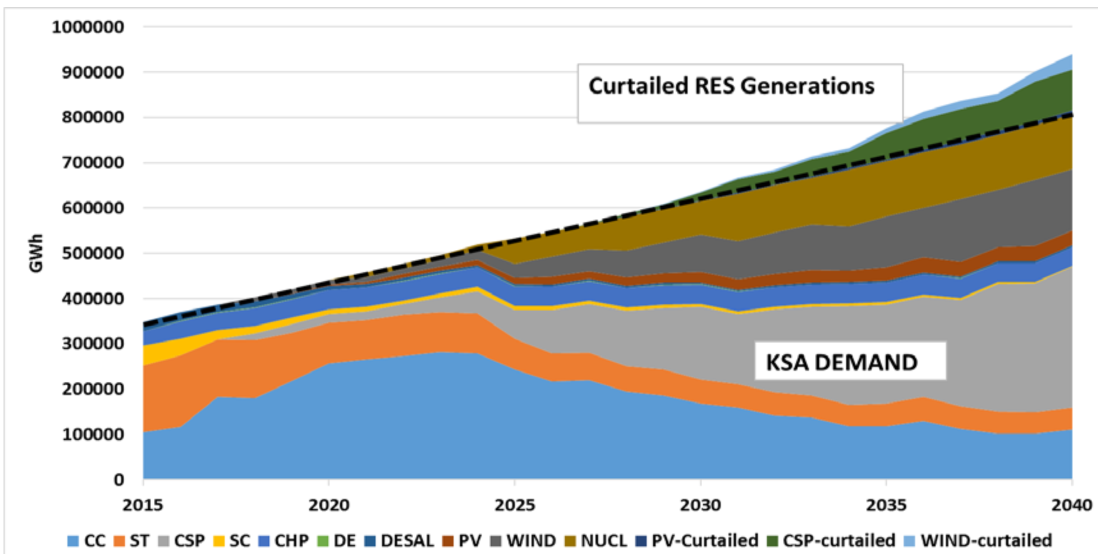

Figure 5.31 Generation mix by technology, including curtailed generation, 2015–2040 (in GWh)

Table 5.38 Summary of the cost parity sensitivity analysis for RES technology[84]

Technology	Fuel Price Projection	Curtailment (Yes/No)	Discount Rate			
			3%	**5%**	**7%**	**10%**
PV	EIA-High	YES	2020	2022	2024	2024
	EIA-Ref.		2022	2022	2025	2026
	OPEC-Ref.		2022	2024	2025	2026
	EIA-Low		2020	2024	2026	2026
	EIA-High	NO	2020	2022	2024	2024
	EIA-Ref.		2022	2022	2025	2026
	OPEC-Ref.		2022	2024	2025	2026
	EIA-Low		2020	2024	2026	2026
Wind	EIA-High	YES	2018	2018	2018	2024
	EIA-Ref.		2018	2018	2021	2025
	OPEC-Ref.		2018	2019	2025	2026
	IEA-Low		2018	2019	2025	2028
	EIA-High	NO	2018	2018	2018	2024
	EIA-Ref.		2018	2018	2021	2024
	OPEC-Ref.		2018	2019	2025	2026
	EIA-Low		2018	2019	2025	2028
CSP	EIA-High	YES	2026	2028	2030	2031
	EIA-Ref.		2032	2038	2037	2038
	OPEC-Ref.		2033	2038	N/A	N/A
	IEA-Low		2038	N/A	N/A	N/A
	EIA-High	NO	2026	2026	2029	2030
	EIA-Ref.		2029	2032	2033	2035
	OPEC-Ref.		2030	2032	2036	2040
	EIA-Low		2032	2033	2036	N/A

Figures 5.32, 5.33, and 5.34 show that the LCOEs of PV and wind were much lower than the LCOE of fossil fuel generation at all discount rates for all fuel price considered. The LCOE of CSP was lower than the LCOE of fossil fuel generation in

[84] The cost of renewable energy resources followed the reference cost case of IEA projections

high and reference EIA fuel prices, but higher at 10% discount rates in low EIA and reference OPEC full prices. If curtailed electricity from CSP is utilized, CSP is lower in the case of low EIA fuel prices (with a 10% discount rate).

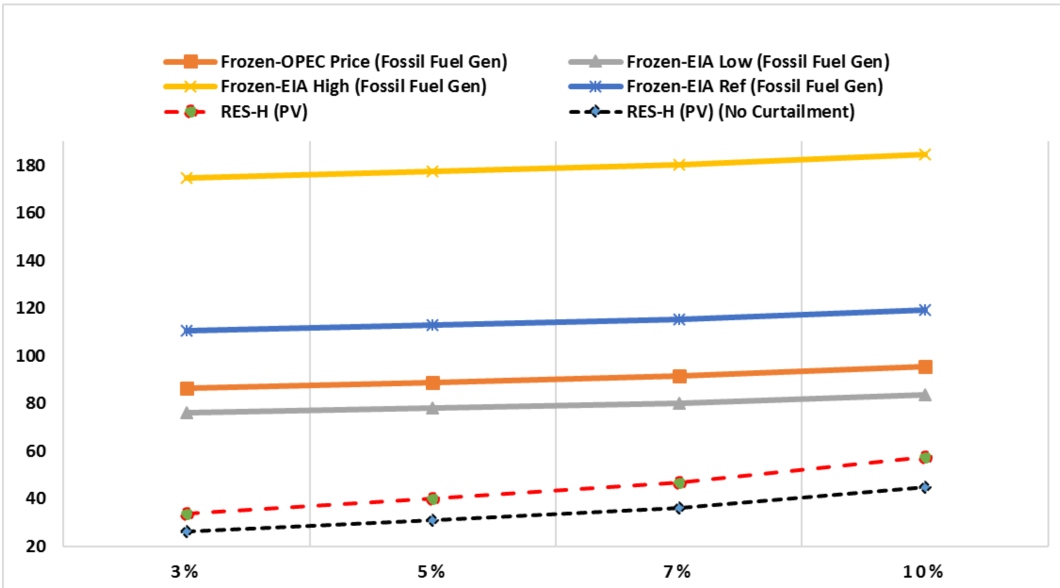

Figure 5.32 The LCOE as a function of fuel prices and discount rates for PV and fossil fuel generation, 2040 (in $/MWh)

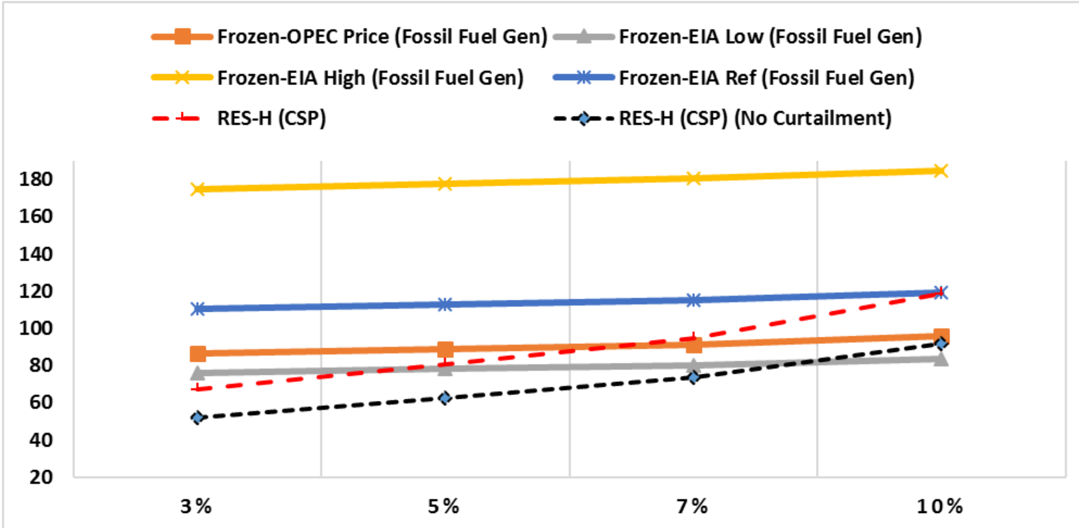

Figure 5.33 The LCOE as a function of fuel prices and discount rates for CSP and fossil fuel generation, 2040 (in $/MWh)

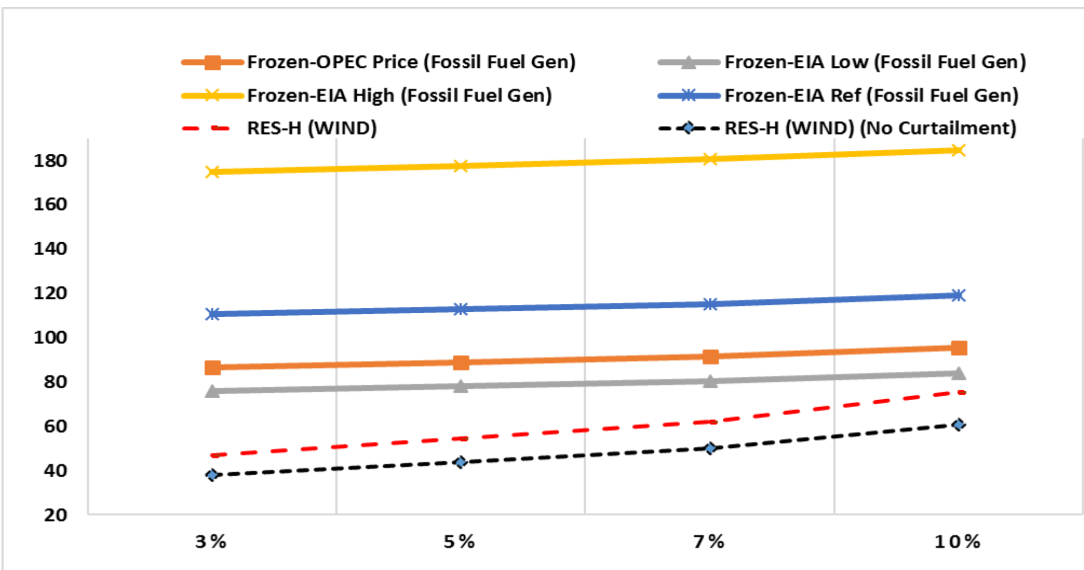

Figure 5.34 The LCOE as a function of fuel prices and discount rates for wind and fossil fuel generation, 2040 (in $/MWh)

5.5.3 The Effects of Generation Cost on LCOE

The generation cost affects mainly RES-H, with a variation of 6% NPV of TRC and 10% LCOE. To evaluate the impacts that each renewable technology has on LOCE, a detailed sensitivity analysis was conducted by varying fuel prices and renewable energy resources costs. Figure 5.34 compares the LCOE of new fossil fuel generation in the frozen case with the LCOE of PV in the RES-H case. The LCOE of PV is lower than the LCOE of fossil fuel generation at all fuel prices projections; the exception is the OPEC reference fuel prices case, in which the LCOE of PV reached cost parity in 2022 and in 2024 for the reference and high renewable energy technologies cost cases. The LCOE of PV attained grid parity from the beginning of the planning period in the low renewable technologies cost case.

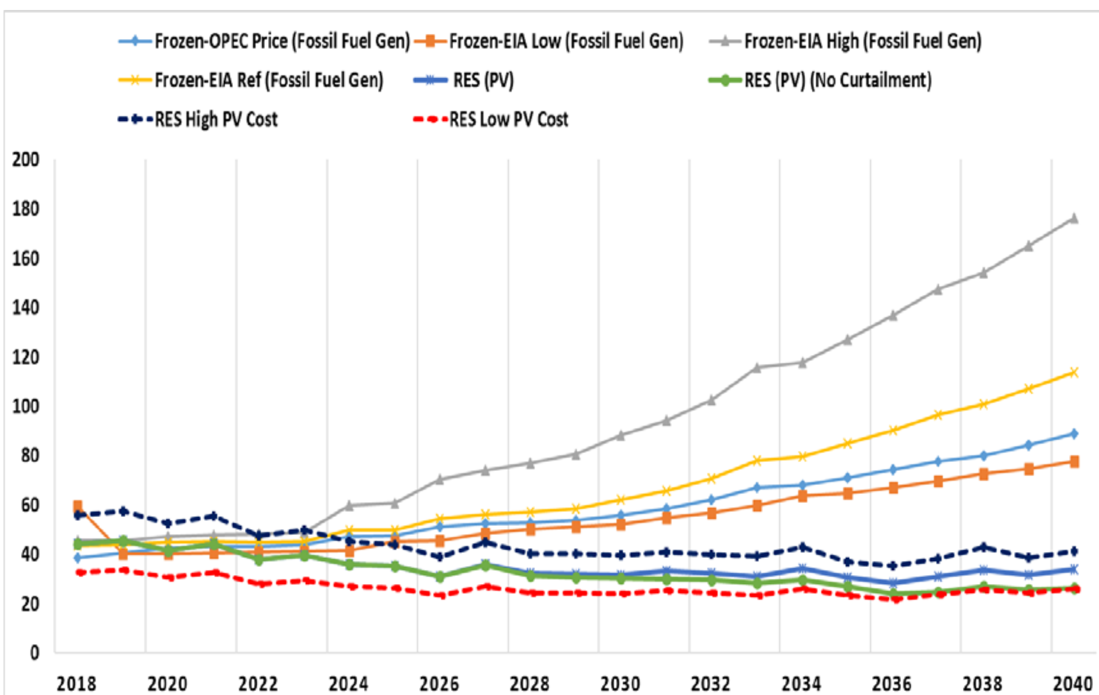

Figure 5.35 The LCOE as a function of fuel prices and generation costs for PV technology 2018–2040, (in $/MWh)

Figure 5.36 compares the LCOE of CSP with the LCOE of fossil fuel generation. At reference cost, CSP reached cost parity in 2032, 2038, and 2033 based respectively on EIA reference, EIA low, and OPEC reference fuel price projections. At its cost, CSP attained cost parity in 2025, 2033, and 2033 based respectively on EIA reference, EIA low, and OPEC reference fuel prices projections. If curtailment of CSP is avoided by exporting the curtailed generation to Saudi Arabia's neighbors (such as other GCC countries), the LCOE of CSP is reduced by 22% in 2040. In the wind reference and low-cost cases, the LCOE of wind is lower than the LCOE of fossil fuel generation at all fuel price projection cases, as shown in Figure 5.37.

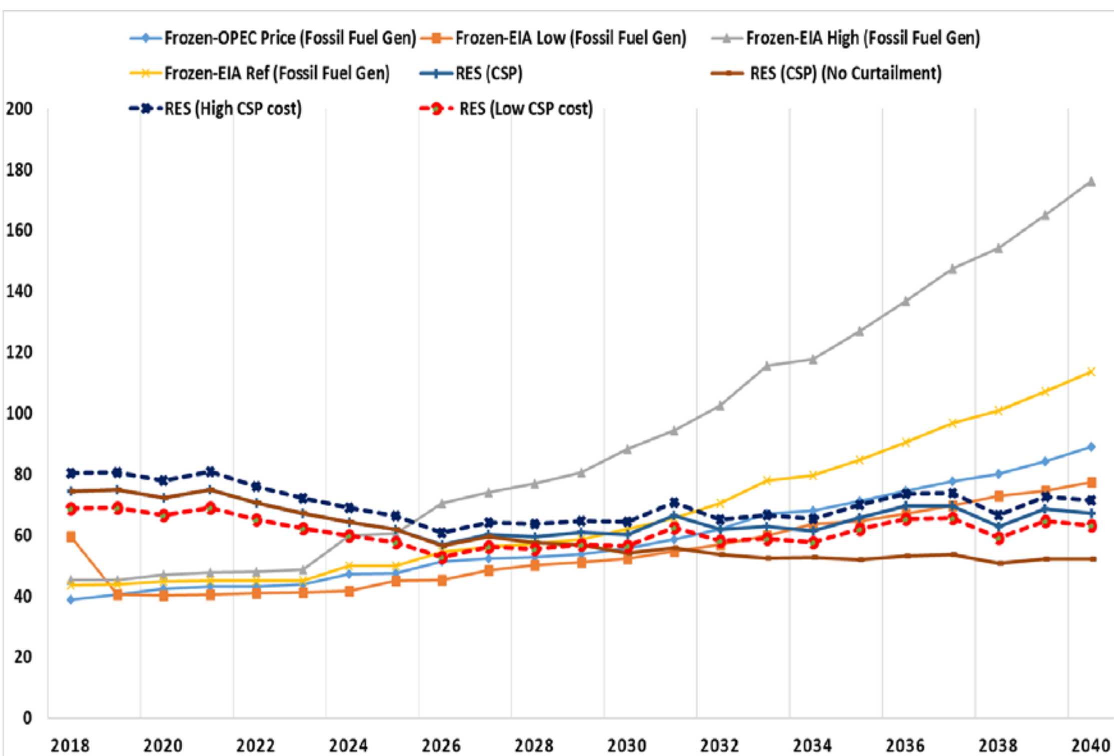

Figure 5.36 The LCOE as a function of fuel prices and generation costs for CSP technology, 2018-2040 (in $/MWh)

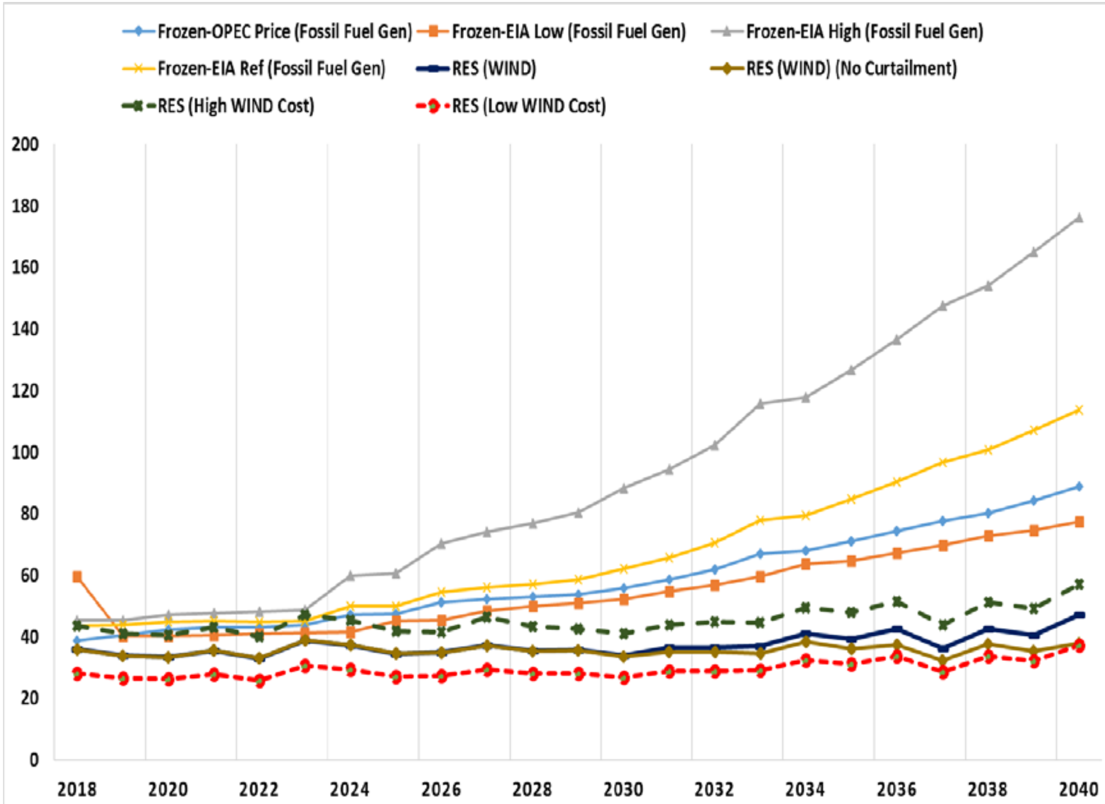

Figure 5.37 The LCOE as a function of fuel prices and generation costs for wind, 2018–2040 (in $/MWh)

5.5.4 The Effects on Transmission Line Augmentation

Another important variable that impacts the TRC and LCOE is allowing for 380kV TL augmentation in the future between Saudi Arabia's four operating regions. Transmission line augmentation resulted in a lower NPV of total generation costs. For example, the NPV of total generation costs were reduced by around USD 9 billion in RES-H; however, this cost savings was offset by the cost of the new TLs, which meant that the NPV of the total costs of cases with and without TL augmentation was almost equal. Nonetheless, this augmentation could provide both better distribution and a higher utilization of generation resources between the four regions and thus more reliable electricity service to the end-users. For instance, the new installed capacity of fossil fuel generation was reduced by 45% in the RES-H case. In addition, due to high penetrations of renewable energy resources, transmission augmentation support citing renewable technologies over a large geographic area resulting in less variability and more dispatching of renewables throughout the day. Table 5.39 shows that renewable energy resources were re-distributed among the four regions as a result of the TL augmentation, which also shifted PV and CSP from areas with lower solar resources (i.e. the EOA) to regions with better solar resources (i.e. the COA and WOA). In addition, more wind was installed in WOA, where Saudi Arabia has the best wind resources.

Table 5.39 The re-distribution of renewable generation as a result of TL augmentation (in GW)

Renewable Technology	**RES-H (with TL)**	**RES-H (without TL)**
New PV-COA	4.2	3.5
New PV-EOA	0.0	4.8
New PV-SOA	0.7	0.6
New PV-WOA	9.2	5.2
New CSP-COA	46.4	41.9
New CSP-EOA	11.2	16.1
New CSP-SOA	4.3	4.3
New CSP-WOA	12.5	12.0
New Wind-COA	13.6	14.8
New Wind-EOA	5.6	12.1
New Wind-SOA	3.2	3.3
New Wind-WOA	20.0	12.2
New Nuclear-EOA	11.4	10.0
New Nuclear-WOA	5.7	7.1

5.5.5 The Effects of Emission Trading on Total Resource Cost

In this analysis, the emission trading price was varied from USD 0/ton to USD 50/ton for the frozen, HEE, and RES-H cases. The previous sensitivity was conducted with an assumption that no emission trading took place. Figure 5.38 indicates a significant reduction in the total cost of RES-H as the emission trading price increases. At a median emission price of USD 30/ton, the total cost was reduced by circa 5% and 12% in the HEE and RES-H cases, respectively; at the higher price (USD 50/ton), the total cost was reduced respectively by 8% and 21%.

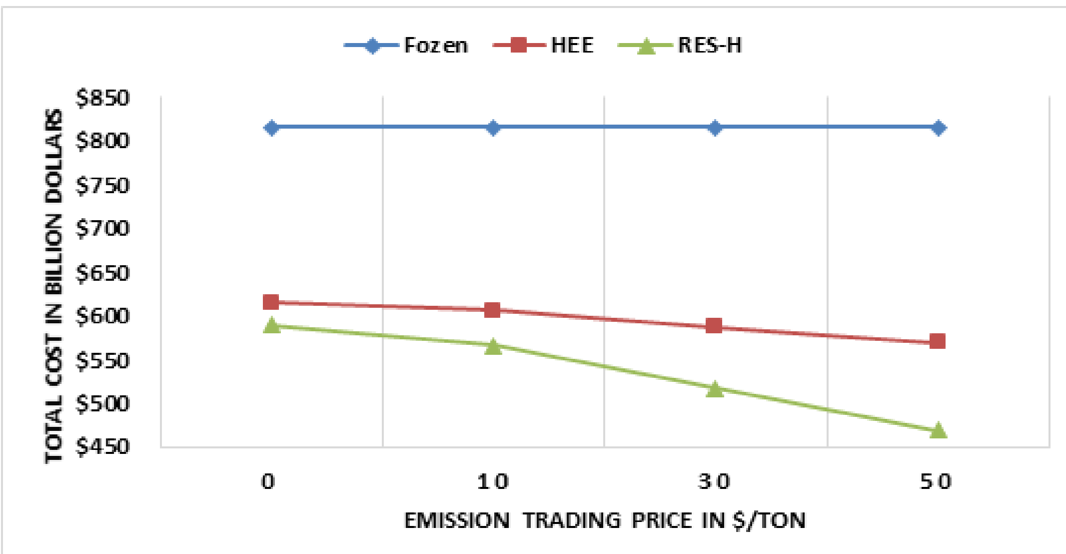

Figure 5.38 Total resource cost as a function of the emission trading price for frozen, HEE, and RES-H cases

5.5.6 The Effects of Weather on the TRC and LCOE

As discussed in chapter 3, the forecasting model shows that weather has a major impact on Saudi Arabia's electricity demand. In this analysis, a temperature variation from a high temperature case to a low temperature case resulted in reducing the NPV and LCOE by circa 5% and 2.5% for the frozen case, and by approximately 4.5% and 3% for the HEE and RES-H cases (Figures 5.28 and 5.29).

5.5.7 The Effects of GDP and Household Growth

Variations of Saudi Arabia's GDP and household growth rate affected the NPV and the LCOE values for the frozen, HEE, and RES-HEE cases. While GDP variations affected the electricity demand in all sectors, the household growth resulted in lower or higher demand for the residential sector and therefore affected the NPV and the LCOE values (Figures 5.28 and 5.29).

5.5.8 Other Sensitivity Analysis

5.5.8.1 The Effects of Renewable Energy Costs on the Renewable Penetration Level

As indicated earlier, the factors influencing the NPV of TRC the most are the fuel prices, discount rates, and generation costs. In this section, the analysis investigates the impacts of these factors on the renewable penetration level. The IRSP was set to freely select the generation resources that can achieve the least cost;[85] the fuel prices were varied based on the main four fuel price projections (namely OPEC reference, EIA low, EIA reference, and EIA high); and discount rates of 3% (as the reference case) and 10% (as the highest case) and three different cases of generation costs (namely high, reference, and low) were used.

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[85] This analysis did not consider additional cost benefits, such as revenue from displaced fuels and the trading of emissions.

Figure 5.39 summarizes the results of the sensitivity analysis in relation to the penetration of renewables. The highest renewable energy resources penetration (i.e. 57% of total electricity generated by 2040) occurred at the highest fuel prices and lowest generation cost; in contrast, the lowest penetration (i.e. 28%) occurred at the lowest fuel prices and highest generation cost. It was also noticed that as the discount rate increased and fuel prices decreased, the high generation cost had the greatest impact on the renewable energy resources penetration level; for example, the penetration level varied between 42% and 27% at a high generation cost and 10% discount rate.

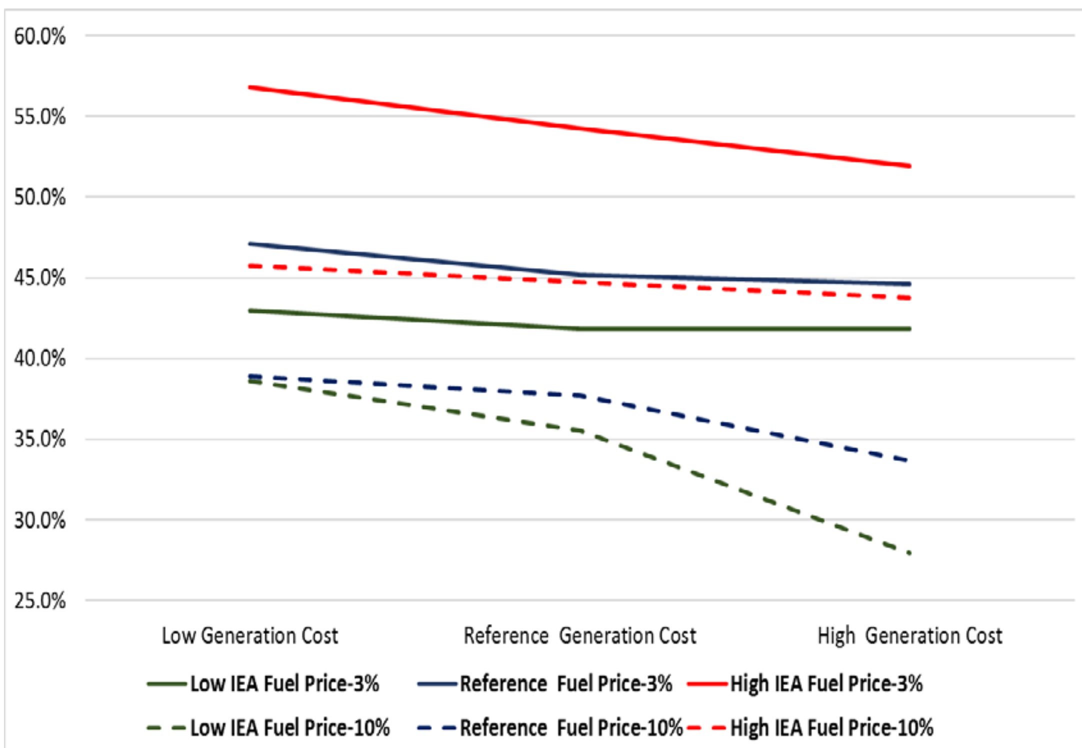


Figure 5.39 Renewable penetration as a function of fuel prices, generation costs, and discount rates

5.5.8.2 The Effects on Eliminating Liquid Fuel from the Utility Sector by 2030

Many actions have the potential to bring significant economic, social, and environmental benefits to Saudi Arabia, including decoupling crude oil from power generation, completely stopping the use of oil for electricity generation, reducing electricity demand, utilizing only natural gas to balance energy demand and supply, and implementing a renewable energy economy. In this section, a sensitivity analysis is conducted to investigate the impacts of forcing all existing oil-based generation to retire before or during 2030; the advantages associated with such a move are presented in Table 6.4. In RES-H, the NPV and LCOE would be reduced by approximately 6% and 10%, respectively; 355.4 MBOE of high-value liquid fuels would also be displaced, which would generate an additional revenue of USD 32.7 billion and reduce emissions by more than 7%. In terms of renewable energy dispatching, retiring oil-based generation would allow more penetrations and thus higher capacity factors, as shown in Table 5.40.

Table 5.40 The RES-H case effects of eliminating liquid fuel by 2030

Factor	**RES-H (With liquid fuel)**	**RES-H (No liquid fuel)**
NPV (billions of USD)	580.4	544.6
LCOE-2040 ($/MWh)	65.2	58.1
Emission (millions of tons)	4015.2	3717.5
Fuel consumption (MBOE)	11052.7	11408.1
RES (capacity factor %)	52.3	56.5
PV (capacity factor %)	26.3	28.5
Wind (capacity factor %)	36.5	39.5
CSP (capacity factor %)	47.7	52.1

The next chapter analyzes the effects of the existing strategic policies on transitioning to sustainable supply and demand-side in Saudi Arabia's utility sector. To meet this study's economic, environmental, and social objectives, it also addresses the methodology necessary for formulation and implementation of specific strategic policies that will be sustainable for Saudi Arabia in the long-term. Based on the results of the EWS IRSP model and an analysis thereof, a set of national renewable energy plans, DSM measures, emissions reduction targets, and social benefits maximization targets is identified. Thereafter national sustainable priority policies and initiatives for the utility sector are identified.

Chapter 6

CONCLUSIONS AND POLICY RECOMMENDATIONS

6.1 Conclusions

The sustainable development of Saudi Arabia is hugely dependent on the nation's ability to curb its overconsumption of energy and break away from its reliance on conventional sources of energy for water desalination production, transportation and electricity. Decades of domestic oil subsidies accompanied by a high population growth rate have encouraged high domestic energy consumption of oil and natural gas, which has led to major economic, social and environmental issues. Furthermore, Saudi Arabia's dependence on oil as an essential pillar of the Saudi economy must be minimized due to oil's exhaustible nature and the country's ever-rising domestic energy consumption levels.

In Saudi Arabia, the electricity and water sectors consume more conventional energy than other sectors. The literature review conducted as part of this dissertation revealed that electricity use in Saudi Arabia is following an unsustainable path: it has increased by around 7-8% over the last 10 years, with a 93% rise in summer peak demand between 2004 and 2013. Due to the country's extremely hot weather during the summer, air conditioning represents 70% of overall annual electricity consumption in the residential sector (ECRA, 2014). The desalinated water sector is another major energy consumer due to elevated demand for water and a general scarcity of natural water sources in the Kingdom. Saudi Arabia's water consumption levels are also highly concerning at double the global average. This is even more alarming given that other countries with greater access to water resources consume significantly less water than the Kingdom. Much of Saudi Arabia's municipal water (59%) is derived from desalination plants (MoWE, 2014), which are currently responsible for producing approximately 18% of world's total desalinated water output.

Since the Kingdom started restructuring its power sector in the 2000's, multiple entities have been involved in fragmented planning activities on the supply-side as well as to a certain extent on the demand-side; moreover, comprehensive integrated resource strategic plans have been lacking at the national level. The "Saudi Arabia's Vision 2030" initiative was launched in April 2016 with the objective of identifying the nation's goals, policies and plans with regards to energy and other important sectors. Additionally, the NTP 2020 was introduced during the same year, supported by 24 government entities and designed to support the government's objectives in this context through the determination of utility-based metrics and strategic objectives for the energy sector. In addition, a new Ministry of Energy, Industry, and Mineral Resources (MEIM) was established as the successor to the Petroleum and Mineral Resources Ministry. The Ministry of Water and Electricity was dismantled and responsibility for electricity (and thus control of SEC) was reassigned to the new energy ministry. To ensure that the Vision 2030 comes to fruition, the government's primary objective is to replace a structure that now includes several competing entities (such as K.A.CARE, SEC, ECRA, and Saudi Aramco) with a central, top-down national governance structure.

This dissertation established an IRSP model for Saudi Arabia's electricity and water sectors (i.e., the EWS model). This model is a useful optimization tool for aligning fragmented energy policies among various entities with overall economic, social, and environmental objectives. With all of its components and details, the IRSP clearly identifies a possible vision of the Kingdom's utility sector, including goals, policies, programs, and an execution timetable. To provide input to the EWS model, a weather-based hybrid end-use econometric demand forecasting model was developed to comprehensively project electricity demand in all sectors and regions until 2040. This proposed forecasting model was used to evaluate weather and climate change impacts on Saudi Arabia's demand.

A concerted effort to implement relevant measures and policies to develop and improve the utility sector's sustainable energy systems is needed, despite the Kingdom's promising renewable energy and demand-side management potential. As such, it is imperative for all governing authorities to take proactive action and facilitate the enforcement of policy that supports renewable energy projects and DSM-based investment where they are socially, economic and technically efficient. In Saudi Arabia, the number of policies designed to incentivize DSM measures has increased in recent years. At the same time, however, policies related to renewable energy are still underdeveloped but improving with the recent announcement of the first phase tenders for the Vision 2030 program of 9.5 GW of solar, PV and CSP by 2023 (Kneller, 2017).

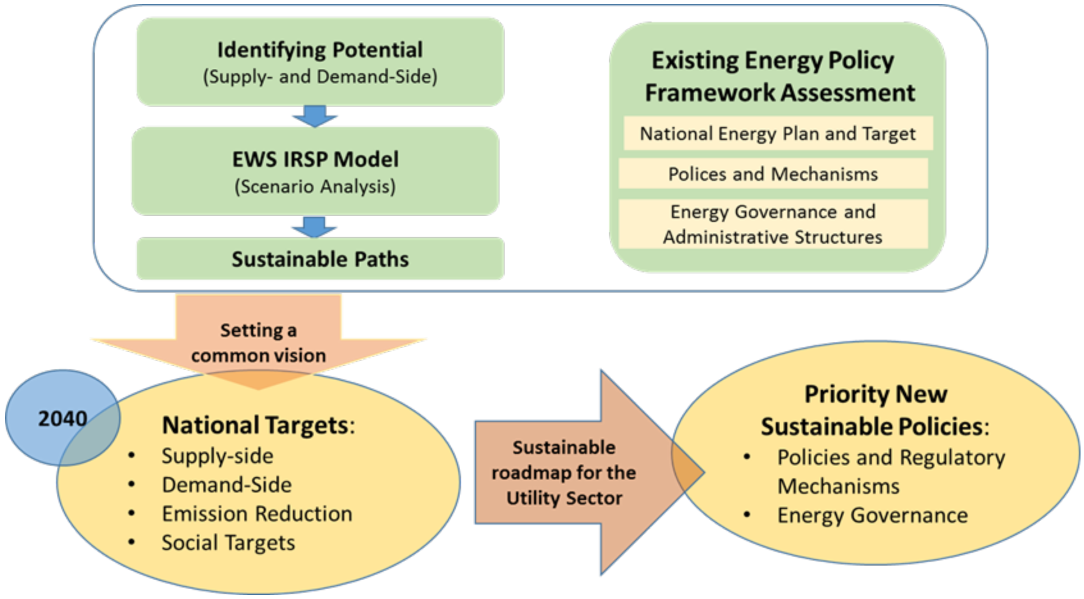
Without a clear long-term plan, well-considered policy and stable regulatory structures and processes along with effective governance models, the transition of the country towards a future of sustainable energy will be difficult due to current institutional, technical, economic, and capacity barriers. The results related to scenarios that this dissertation simulated using the EWS model serve as potential basis for proposing a number of policy recommendations that could foster the development of sustainable strategies and energy policies for the Saudi utility sector, as presented below.

The scenarios and analysis, described in the previous chapters, present possible sustainable pathways and their impacts in terms of energy demand and supply mix, environmental damages, and cost-benefit analysis in Saudi Arabia. These results are very useful for energy planning and the formulation of effective policies. International experience shows that countries that have successfully promoted renewable energy and DSM measures share three common strengths: (1) a long-term targets and objectives as part of a grander overall vision for the future, (2) solid plans in place to realize these objectives, in the form of regulatory mechanisms and sound policies, and (3) effective administration, governance and institutions for implementing and revisiting these mechanisms and policies (Ochs et al., 2015, p.72). This following section evaluates whether the existing energy policy framework is adequate to make Saudi Arabia's utility sector sustainable.

6.2 Review of the KSA's Existing Energy Policy Framework

6.2.1 Methodology for a Sustainable Energy Roadmap, Strategies, and Policy

Figure 6.1 presents the methodology that is proposed for identifying the sustainable energy roadmap, strategies, and policies for Saudi Arabia's utility sector.



Source: modified from Ochs et al., 2015, p.22

Figure 6.1 Methodology for Saudi Arabia's Sustainable Energy Roadmap, Strategies, and Policies

In this dissertation, the EWS IRSP model was established based on a comprehensive analysis of potential in both the supply- and demand-side. The scenarios and results yielded by this model represent possible sustainable pathways and their impacts in terms of the energy demand and supply mix, environmental damages, and cost-benefit analysis. This chapter now identifies the existing regulatory policy framework for Saudi Arabia's utility sector, along with current supply- and demand-side policies. These results are then used as the baseline for developing a broad set of national renewable energy plans, DSM measures, emissions reduction, and social benefit maximization targets as well as recommendations for a series of national sustainable priority policies and initiatives for the utility sector.

6.2.2 National Energy Plan and Targets

Overall, Saudi Arabia is ranked 51st in the energy sustainability index; its global ranking was respectively 45th, 7th, and 120th in relation to the sub-categories of energy security,[86] energy equity,[87] and environmental sustainability[88] (Wyman, 2015, p. 51).[89] While Saudi Arabia has gained 17 places in 2015's index in comparison to 2014, energy security and environmental sustainability still lags severely since the country's energy mix relies entirely on fossil fuels. Its energy equity performance remains in the top ten highest countries due to its high-quality electricity and low domestic energy prices. Consequently, the Saudi utility sector's ability to achieve successful sustainable energy planning depends greatly on its ability to take a long-term perspective regarding sustainable energy development. This plan should clearly define the country's objectives and ensure that government stakeholders are working towards the same mission. The following section outlines the goals already set by the Saudi government in terms of sustainable energy development with regard to social

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[86] One major indicator of energy security is diversity factor of electricity generation defined in section 4.4.2.1.

[87] Energy equity is mainly measured by affordability, level of access, and electricity supply quality.

[88] Environmental sustainability indicators include CO_2 intensity and CO_2 grams/kWh from electricity population.

[89] Hashmi, Abdulghaffar and Edinat (2015, p. 49) explain that energy security fulfils both present and future primary energy demand through effective energy management. Energy equity is the equal access to energy nationwide. Environmental sustainability is the development of energy that has low carbon emissions, and deployment of energy efficiency measures and renewable sources.

objectives, the reduction of carbon emissions and a greater representation of renewable energy in the country's energy mix and DSM measures.

6.2.2.1 Existing Renewable Energy and Electricity Targets

In 2013, Saudi Arabia announced ambitious targets for medium term renewable energy development. However, shortcomings in suitable policy, regulatory, and commercial frameworks prevented the implementation of these targets as only prototype renewable projects has been commissioned to date (Nachet & Aoun, 2015, p. 22). In relation to long-term policy, clarity over the timeline and implementation of Saudi Arabia's NTP is still lacking. This program aims to have power generation from renewable resources, such as solar, up to 4% of the country's energy mix in 2020, which is a reduction from an earlier very ambitious target by 80% (20% in 2020) (Saudi Arabia's Vision 2030, 2016, p.74, & K.A.CARE, 2010, p.28).

In terms of the fuel mix and its efficient utilization in the utility sector, as noted in the NTP report, the Kingdom has set a target for increasing natural gas production by more than 48% (to 17.8 BSCF) in 2020, emphasizing more the need to minimize the firing of diesel and crude oil in the utility sector. The country has also established a target to increase the efficiency of its electricity sector's fuel utilization by increasing power generation efficiency to 40% by 2020 (Saudi Arabia's Vision 2030, 2016). Nonetheless, no specific long-term target exists vis-à-vis natural gas or fuel liquids shares in the utility sector fuel mix.

6.2.2.2 DSM Savings Target

Overall, ECRA plans to achieve energy conservation and peak demand targets reaching 8% and 14% respectively by 2021 (Lahn, Stevens, & Preston, 2013, p. 13).

Existing appliance and building insulation standards can substantially contribute to the electricity demand reduction as indicated in the limited energy efficiency (LEE) scenario in Chapter 2. Nonetheless, Saudi Arabia still fails to implement sustainability measures on a large scale, since these efforts are associated with little public awareness about energy efficiency, higher costs and lower returns on investment. In addition, when regulations (such as in relation to buildings and appliances) do exist, lax enforcement often renders them ineffective. For instance, the Saudi building code mandates using thermal insulation for all new buildings, which has proven to reduce household energy demand by 30–40%. Nevertheless, some new buildings continue to be erected without proper insulation (Lahn, Stevens, & Preston, 2013, p. 23).

6.2.2.3 Emissions Reduction Targets

The actions and plans outlined in the Intended Nationally Determined Contribution (INDC) report that Saudi Arabia submitted to the UNFCCC in 2015 target a reduction of CO_2eq by as much as 130 million tons every year by 2030. The government plans to achieve this through economic adaptation and diversification activities. While this target is not set specifically for the utility sector, the baseline assessment covers only the period 2021 to 2030. As indicated in the INDC report, the assessment's coverage will be expanded until 2050 in the future (UNFCCC, 2015). In terms of environmental sustainability targets, Saudi Arabia has a current CO_2 emissions intensity in the electricity sector of 0.64 ton/MWh with no specific targets for future reductions.

6.2.2.4 Social Targets

Renewable energy and energy efficiency can create more jobs in manufacturing, construction, and operation and maintenance than conventional generation. According to Saudi Arabia's recently announced NTP, it is expected that the number of direct job opportunities available for citizens in both the atomic and renewable energy sectors will be 7,774 in 2020; no specifications are provided for targeted jobs in DSM initiatives, such as energy efficiency (Saudi Arabia's Vision 2030, 2016), which are more labor-intensive when compared to generated electricity by fossil-fuel power plants (Blyth et al., 2014). Moreover, these targets do not address wider macro-economic analysis on employment, which tends to view issues related to a transition to sustainability within a longer-term and wider context. To date no clear implementation localization plan for a strategy to develop value chains and local human resources for renewable energy and DSM measures exists.

A dependence on only fossil fuel to generate electricity has resulted in an undiversified electricity supply in Saudi Arabia, which in turn impacts the country's energy security. No specific target for the level of electricity diversity in the future currently exists. Nonetheless, the NTP targets enhancing the country's primary sources and security of electricity supplies by increasing the electricity generation capacity margin to 12% and reducing the average daily number of outages that exceed five minutes from 6.36 outages to 3 outages by 2020. In addition, Saudi Arabia is ranked high (7^{th} globally) in relation to energy equity, and the NTP targets an increase of electricity access from 99% to 99.5%.

6.2.3 Barriers to Existing Policies and Mechanisms

Energy markets are shaped by supporting or restricting policies, which establishes market rules and conditions. Although certain policies and mechanisms have been implemented across Saudi Arabia’s utility sector, there is still an urgent need for further measures to be implemented, as well as for current policy to be evaluated.

6.2.3.1 Policy Support Related to Renewable Energy

As highlighted earlier, Saudi Arabia has set initial targets for the deployment of renewable energy. To be effective, these targets require concrete policies and measures that guarantee retunes on investment for projects, stabilize the investment environment, and support the elimination of non-economic barriers, such as market and financial barriers (IRENA, 2016, p. 53). Broadly, deployment barriers can be classified as economic regulation and policy, market, and financial, as presented below.

6.2.3.1.1 Economic Regulation and Policy Barriers

Saudi Arabia currently does not support economic mechanisms that aim to directly generate additional revenue for renewable energy development or encourage market participants to deploy specific technologies. Most of the renewables deployment in the Kingdom to date has been state sponsored, without a need for policy support (Kalkman, 2015, p. 6). Globally, such mechanisms are embedded within policies that aim to facilitate the greater deployment of renewable energy through quantity forcing policies (such as tendering schemes and quota systems or renewable energy portfolio standards) and price-setting policies (such as feed-in tariffs).

6.2.3.1.2 Market Barriers

In Saudi Arabia, inconsistent pricing structures currently disadvantage renewables due to the heavy subsidies that exist for fossil fuels and due to current transmission grid connection requirements that lack clarity. Energy prices remain regulated and heavily subsidized. For example, energy subsidies reached almost 8% of the country's GDP in 2014 (IRENA, 2016, p. 39). Although the government historically kept energy prices to a minimum to achieve national economic and social development goals, the ever-increasing energy consumption has become a significant challenge. Energy prices were raised in 2016, however such measures have done little to encourage greater deployment of renewable energy, as explained in Section 5.2.1. Energy subsidies form a sort of “super-barrier” and make it impossible for renewables to compete with these energy prices (Lilliestam & Patt, 2015, p. 8370). The NTP report indicates that the Saudi government targets reducing water and electricity subsidies by SR 200 billion in 2020, with the objective of developing more efficient welfare system. However, these targets are not accompanied by a detailed implementation plan (Saudi Arabia's Vision 2030, 2016).

The private sector's role in the Saudi utility sector remains limited. Currently, only 27% of power plant electricity generation facilities are owned by private investors through strategic partnerships with major companies, such as SEC and Saudi Aramco. Saudi Arabia targets privatizing the remaining power generation facilities by 2020 and to this end is inviting private investors to develop new renewable projects (Saudi Arabia's Vision 2030, 2016). However, infrastructure barriers may affect investors' participation. For example, transmission grid connections pose the most common challenge in terms of an infrastructural barrier to develop renewable energy projects. The current grid code rules, regulations, and performance standards were not designed to promote renewable energy and there remains a lack of clarity on issues such as deep or shallow connection charges. Furthermore, the current electricity law does not provide priority access for renewable developers to connect and dispatch electricity to the grid in preference to fossil fuel generation (IEA, 2011).

6.2.3.1.3 Financial Barriers

The high capital costs of renewable and unexplored markets, such as those found in Saudi Arabia, pose a greater risk that may prevent private investors from entering these markets and raising funds to finance sustainable projects. At present, the private sector remains skeptical about investing when the government does not provide financial support measures such as loan guarantees and grants. However, a survey undertaken by IRENA reveals that commercial banks in Saudi Arabia are willing to offer loans for large-scale renewable energy projects with long tenures and decent interest rates if enabling frameworks are established (IRENA, 2016, p. 64).

6.2.3.2 Policy Support Related to DSM Initiatives

Major DSM measures can be promoted efficiently through fiscal incentives and government regulation. However, barriers to the implementation of DSM measures exist and can again be classified broadly as economic regulation and policy, market, or financial in nature.

6.2.3.2.1 Economic Regulation and Policy Barriers

Unlike other countries, Saudi Arabia offers little or no incentives to deploy DSM measures. Therefore, end-users are largely unmotivated to change their electricity consumption behavior. Currently, the payback period to reach to a breakeven on investments in some energy efficiency technologies is relatively long. In fac, customers in Saudi Arabia often fail to realize any kind of economic return on their investment in the short-term. As per the detailed economic screening analysis conducted using the TRC test (see Chapter 2), most of the major energy efficiency measures are cost effective even at subsidized energy prices. Customers may receive cash incentives to reduce the payback period and make DSM investments more attractive. These incentives are not incorporated in the analysis since they have no effect on the total DSM measure's cost from a societal perspective. In fact, such incentives represent only a transfer of payment between members within the society (Faruqui & Hledik, 2011, p. 99). While SASO has issued detailed standards for new building efficiency (see Section 2.2.2), there is much ambiguity surrounding the entity responsible for administering those standards. In addition, while these energy efficiency standards are applicable to new installations, incentives to accelerate the replacement of current low-efficiency appliances and retrofit existing buildings without insulation are lacking. On the utilities-side, no regulatory incentives have been set to recover the costs of DSM (Faruqui & Hledik, 2011).

6.2.3.2.2 Market Barriers

Due to Saudi Arabia's regulated electricity market and the absence of a national central policy focusing on energy efficiency, DSM implementation is currently limited for residential consumers (Papadopoulou et al., 2013, p. 15). In addition, even following their increase in early 2016, subsidized energy prices create little incentive for consumers to save energy. The lack of smart meter deployment across the country also makes it impossible to implement time-of-use rates in the residential sector, which would promote more economically efficient electricity consumption behavior by enabling greater cohesion between system cost and the price to the customer. In addition, the current utility companies' structure does not support the deployment of DSM, as demand reduction will reduce their revenue (Faruqui & Hledik, 2011).

6.2.3.2.3 Financial Barriers

Without government intervention in relation to subsidies and incentives, it will be risky for financial institutions to finance DSM projects in the Kingdom. As the common approach of a utility spending capital in DSM projects and then recovering the investment through electricity bill surcharges is not desirable in Saudi Arabia, securing public funding for the program should be a better option. Nonetheless, no financing mechanism is in place for DSM in Saudi Arabia (Faruqui & Hledik, 2011).

6.2.4 Energy Governance and Administrative Structures

If the relevant administrative and governance structures are not effective, sustainable energy support policies will not usually succeed. The development and growth of sustainable energy can only be achieved if the functioning institutions are supporting it effectively. Based on global experience, it appears clear that the energy sectors can only be successfully developed if administrative and governance-based reform is achieved. Unfortunately, the Kingdom appears to be lacking both a central agency that is responsible for the country's entire energy sector and an overall energy policy that provides a blueprint for energy efficiency, renewables, and energy diversifications (Silva-Send, 2016, p. 27). Current responsible institutions and agencies for policy making and implementation, institutions for data sharing, utilities structure, and civil society role will be presented in the following sections.

6.2.4.1 Institutional Barriers

Since the mid-2000s, Saudi Arabia has been establishing specialized institutions beyond fossil fuels (i.e., oil and gas) to create a strong and more cohesive policy environment in the areas of renewable energy and DSM initiatives. However, one barrier in the transition to a sustainable utility sector is the perceived overlap between responsibilities and activities that results from the country's present bureaucratic system. This system has been often described as a "hub and spoke" with little coordinated effort between various ministries, agencies and other entities. The overlapping activities include planning and policy making, regulating renewables and DSM measures, and undertaking research and innovation (Lahn & Stevens, 2011, p. 22). In the following sections, existing status of institutions for planning and policy making, and institutions for research and innovation are presented.

6.2.4.1.1 Institutions for Planning and Policy Making

On the supply-side, the quasi-government agency K.A.CARE has dealt with significant challenges in stakeholder management since it was introduced by Royal Decree less than a decade ago. K.A.CARE is responsible for ensuring that alternative energy options are deployed successfully and efficiently. Nonetheless, it essentially has no direct explicit authority over the Ministry of Economy & Planning, the Ministry of Finance, or other important stakeholders and may thus struggle to drive collaborative efforts to achieve the targeted common goal. Moreover, the nature of its collaborations with various existing stakeholders is unclear in its mandate. For instance, SEC is the principal buyer and participates actively in renewable project management and development, while K.A.CARE was originally tasked with similar duties such as the issuance of power purchase agreements, proposal review, and renewable project tender management (Kalkman, 2015, p.7; POYRY, 2016, p.3). In addition, ECRA (an independent agency that regulates Saudi Arabia's electricity and water industry) engages in overlapping activities to develop and implement legal frameworks that address the power industry restructuring, tariffs structure, and licensing framework (including all types of generation).

On the demand-side, the government also created the SEEC in 2010 (following the first NEEP in 2003). The SEEC, which has a goal of reducing energy intensity by 20% between 2005 and 2030, launched the SEEP in 2012. The SEEP focuses on implementing DSM measures (including energy efficiency standards for air conditioners, lighting, refrigerators, washing machines, and building standards) and vehicle fuel economy standards that adhere to US CAFE standards. Among other things, the energy efficiency program is charged with implementing a public awareness program in relation to reducing energy consumption (Silva-Send, 2016, p.25). In addition to its aforementioned duties as a regulator, ECRA is also responsible for DSM activities. Alyousef & Abu-ebid (2012) described the fragmented efforts:

> Although many other national organizations deal with limited aspects of energy efficiency and have sophisticated skill sets, their work is often duplicated, their strategies and policies are limited in scope, and their activities are not coordinated.

For example, despite all of the ongoing effort governmental and non-governmental agencies are undertaking to raise public awareness of rationalization and energy conservation, 150,000 air conditioners not adhering to standards specification for the minimum energy efficiency levels were discovered by authorities in 2015 (Nachet & Aoun, 2015, p. 26). The multiple, yet fragmented, authorities and agencies described above are currently not correlated with economic development plans and the poor coordination of supply- and demand-side management may lead to an inefficient utilization of resources and unnecessary investments. The lack of integrated strategic resource planning in relation to a range of resources will not result in a realistic strategy for Saudi Arabia's utility sector (Lahn, Stevens, & Preston, 2013, p. 18). In May 2016, the Saudi government established a new Ministry of Energy, Industry, and Mineral resources to succeed the former Petroleum and Mineral Resources Ministry. The existing Ministry of Water and Electricity was summarily disbanded, with responsibility for electricity (and thus control of the SEC) being assigned to the new energy ministry. The government's main objective is to replace a structure that previously included a multitude of competing entities (such as K.A.CARE, SEC, ECRA, and Saudi Aramco) with a central, top-down governance structure that will enable the Kingdom's Vision 2030 to become a reality (Borgmann, 2016).

6.2.4.1.2 Institutions for Research and Innovation

Saudi Arabia has increased its research and development (R&D) of renewable and clean energy options and DSM through the establishment of various research and academic institutions. The King Abdullah University of Science and Technology (KAUST) was established with an objective to lead the country in advanced scientific and applied research to deal with four global issues (namely food, water, energy, and environment), while the King Abdulaziz City for Science and Technology (KASCT) is a national science and technology center that proposes national policy for science and development. Moreover, the King Abdullah Petroleum Studies and Research Center (KAPSARC) was established to advance information sharing and knowledge on local and global energy issues and opportunities by conducting high quality and advanced research into the environment, technology, policy, economics and energy humanity propensity and future value (Silva-Send, 2016, pp. 25-26). Taher and Hajjar (2014, p.

17) highlight the significance of the contributions such institutions make to knowledge development. However, they also point out that these institutions are missing a solid and cohesive national strategy providing clear guidance on partnership with each other and with private sector businesses. This is an area that requires further attention, since these partnerships could allow them to commercialize products or apply their research in the private sector. In addition, these institutions have only a very limited involvement in raising awareness; at the moment, their related activities include incorporating energy efficiency and conservation research efforts into brochures, exhibitions, workshops, conferences and expos, training, and educational visits (Al-Ajlan et al., 2004; Alyousef & Abu-ebid, 2012; Lahn & Stevens, 2011).

6.2.4.2 Data and Information Providers

The data required to conduct initial assessments, make projections, and choose the most practical interventions are key for both national energy planning and policy-making institutions and the private sector (Lahn, Stevens, & Preston, 2013, p. 18). In Saudi Arabia, different institutions currently hold this data and no overreaching ministry or agency is responsible for collecting, standardizing, and disseminating various energy-related statistics. For example, the General Authority for Statistics, MEIM, ECRA, SEC, Saudi Aramco, and many other authorities provide fragmented data related to the utility sector. Without reliable data to show baseline consumption and realistic scenarios, it is difficult to make a politically viable case for institutional changes and investments that will enable progress in the utility sector.

6.2.4.3 Utilities

The Kingdom's current setup of having one utility dominating the distribution and transmission of electricity and to a certain extent, generation – presents a potential roadblock to supporting the entry of renewable energy technologies and the implementation of DSM measures. It can be very challenging for private investors to participate in a market in which there is a sole authority in charge for the new generation projects. As highlighted by ECRA, implementation of the first phase of the restructuring plan for the electricity sector and SEC has obviously been delayed; as such, a strict roadmap for moving faster needs to be developed (please see Section 1.3.1).

6.2.4.4 Civil Society

It is very likely that consumers will play a rather different role in new sustainable energy systems than they are playing today. Individuals may be actively involved in the production and trade of energy and will become so-called "prosumers[90]" (Steg, Perlaviciute, & Van der Werff, 2015, p. 2). This shift may not only affect individuals' involvement in energy issues in important ways; it also requires substantial changes in energy demand to increase the efficiency of sustainable energy systems. Individuals and households are thus key, but often neglected, players in the current energy policy framework in Saudi Arabia. Both the general public and

[90] Prosumers refers to customers that are able to choose whether to buy all their electricity from retailer or to produce part of it themselves by benefiting from a guaranteed and continuous supply of electricity through the connection to the grid and accessing to the market, in which the network allows the injection and withdrawal of electricity, while access to the market makes it possible to buy and sell electricity at market prices (Eurelectric, 2015, p.3)

the government in Saudi Arabia are beginning to pay increasing attention to the importance of reducing the consumption of oil in the electricity production sector while also identifying effective ways to fulfil the increasing demand for electricity (Nachat & Aoun, 2015, p. 26).

The previous sections of this chapter have outlined the current regulatory policy framework in Saudi Arabia’s utility sector, along with existing supply- and demand-side policies. This information is used as a baseline for developing a suggested sustainable energy policy framework.

6.3 The Recommended Sustainable Energy Policy Framework

The results of EWS IRSP model presented in the previous chapters identify potential targets related to Saudi Arabia’s renewables, DSM measures, emissions reductions, and social benefits. If the country is to achieve these targets, it needs to undertake national integrated resource strategic planning actions. The ambition to achieve the environmentally, economically and socially sustainable development in the utility sector suggests a bright future for the Kingdom. To meet this goal, however, a great deal of work must be done to develop a robust and dynamic sustainable energy policy framework.

Based on the EWS IRP analysis (see Chapters 5), several important conclusions related to the design of effective intervention policies for the Saudi utility sector are made using the sustainability roadmap methodology (see Figure 6.1). Three major components to success are contained within the methodology: (1) a long-term national target and vision (see Section 6.3.1), (2) sound regulatory mechanisms and policies designed to reach the country’s targets and goals (see Section 6.3.2), and (3) effective governance structures and administrative processes for implementing and revisiting these policies and mechanisms (see Section 6.3.3). It is worth noting that this suggested policy framework in this research does not exhaust all possible polices and, hence more pathways that involve various energy polices could be developed in future studies and identify more effective polices.

6.3.1 National Energy Targets

Energy targets that bear no relationship to economic and technical factors are rarely achieved. The EWS IRSP model utilized in this study, therefore used a broad range of scenarios to identify potential targets based on techno-economic analysis to ensure economic efficiency and technical viability. It also co-optimized resources at the supply-side and demand-side and identified the optimal feasible configuration of the modeled sector from technical, economic, environmental, and social perspectives.

A review of existing targets revealed that they are preliminary and not backed by comprehensive integrated planning studies (see Section 6.2). While more than 140 cases, simulated by EWS IRSP model, were considered in this dissertation, the targets proposed below were developed based on the most ambitious but achievable scenario and address economically rational targets for the highest renewable penetration and highest implementation of DSM measures in the country. Recommended targets based on four main pillars: (1) the supply-side, (2) demand-side, (3) emission reduction, and (4) social benefits maximizations are presented in the following sections.

6.3.1.1 Supply-Side Targets

Based on cumulative renewable energy potential assessments for the highest possible penetration that take economic efficiency and technical limits evaluations into consideration (see Section 5.2.1), the analysis concludes that Saudi Arabia could set the following overall national goals for renewable power capacity: **9%** by 2020, **55%** by 2030, and **75%** by 2040 to maximize social, environmental, economic and technical efficiency given the assumed factors (i.e., fuel prices, demand projections..etc). In addition, the country may post the efficiency of electricity sector's fuel utilization by increasing power generation efficiency to **49%** in 2040.

The total saving of natural gas and liquid fuels could be **5148 MBOE** and **5312 MBOE**, respectively (see Section 5.3.2.3) under the conditions assumed. Natural gas is targeted to substitute the majority of liquid fuel during the early years of the Kingdom's planning period (e.g., up to year 2023); in terms of percentage of total generated power, it could account for **67%** by 2020, **34%** by 2030, and **18%** by 2040. Moreover, liquid fuel consumption as a percentage of total generated power could be reduced to **25%** by 2020, **11%** by 2030, and **7%** by 2040. Thus, the supply of natural gas to utilities could reach its peak and increase by **28% (6.4 BSCF/day)** in 2023; thereafter it would decline by **18%** (**4.2 BSCF/day)** by 2030 and **59%** (**3.1 BSCF/day)** by 2040.[91] These savings would allow for greater natural gas allocations to other sectors, such as petrochemical industries which could drive further economic growth for the economy.

6.3.1.2 Demand-Side Targets

The simulation of the high efficiency scenario of implementing DSM measures revealed that the following national peak demand savings are achievable, respectively:

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[91] The targeted decline in natural gas consumption due to energy efficiency improvement at the demand-side and higher penetration of renewables at the supply-side

9% (or 4.9 GW) by 2020, **21% (or 28.9 GW)** by 2030, and **26% (or 52 GW)** by 2040 (see Section 3.4.4) in comparison with the frozen (BAU) scenario. This scenario considers the deployment of various DSM measures (focused on adopting building insulation standards and raising energy efficiency of air conditioning) and load management/demand response measures. All measures were identified based on the detailed technical, economic, and market potentials calculations presented in Section 2.2.

6.3.1.3 Emission Reduction Targets

The third element of Saudi Arabia's future national plan proposed in this dissertation is a set of CO_2 emission reduction targets. Potential short-, mid-, and long-term targets suggested by the modeling could be the reduction of emissions by **26%** (or **48.5** million tons of CO_2) by 2020, **46%** (or **190** million tons of CO_2) by 2030, and **76%** (or **378** million tons of CO_2) by 2040 (see Section 5.3.2.4). It should be noted that the emissions reduction target proposed for 2030 by this research, is a substantial 46% lower than INDC target for the country's emissions reduction for all sectors (including the utility sector) for the same year. In terms of the environmental sustainability index, the CO_2 emission intensity could be reduced to **0.15 tons/MWh** by **2040**, which is 2.6 times lower than the world average emission intensity level identified in the IEA New Policy Scenario (NPS).

6.3.1.4 Social Targets

Localizing renewable energy and energy efficiency measures can enable industries to create new economic activities. These activities will be further driven by maximizing the local content of employment. This research suggests that the Kingdom could create **0.591, 0.682 and 2.275 million direct, indirect, and induced** jobs for Saudi citizens by 2040 (see Section 5.3.2.7).

In terms of energy security, the generation diversity of electricity could reach **88%** or more for all types of generation, including renewable energy sources. To ensure a reliable electricity supply, electricity reserve capacity is targeted to reach **19%** by 2040 (see Section 5.3.2.7).

6.3.2 Policies and Regulatory Mechanisms

Sound regulatory mechanisms and policies must be put in place in order to support the achievement national targets for specific sectors and subsectors. Demand-side measures and sustainable energy technologies will be deployed and developed through these concreate support systems. Although some measures have already been widely implemented across Saudi Arabia, there is an obvious need for policy assessment and the deployment of more measures. Section 6.2.3 evaluated the policies already in place, both in terms of supply and demand, and demonstrated that additional steps that need to be taken in addition to the early efforts being made to implement sustainability-based policy components. The following subsections outline briefly a number of specific policies that the Saudi government could implement at the supply-side and demand-side:

6.3.2.1 Supply-Side Policies

- **Move fuel pricing toward international market prices to stimulate energy efficiency**

Evidence shows that a move toward international market prices will stimulate energy efficiency, reduce fossil fuel subsidies, and increase economic efficiency by reducing dead-weight welfare losses. Non-targeted subsidies will also be eradicated by applying the market fuel prices. These subsidies are not an efficient mechanism for redistributing income and improving energy access to lower income classes given that they essentially benefit richer households and adversely affect equity. This shift will also adjust the current pricing scheme, which favors liquid fuel and acts as a barrier to investments, and encourage the deployment of sustainable technologies and more efficient measures and practices. Moreover, market fuel prices will allow electricity generation companies to generate revenues proportional to their operating, maintenance and investment costs.

The IRSP model results for the high renewable scenario showed that the forgone revenue from fossil fuel exports and cost avoidance due to eliminating subsidies were respectively estimated to be **USD 369 billion** and **USD 234** billion for the planning period until 2040 (see Section 5.3.2.5). Fuel allocations for future projects should take into account IRSP results to ensure a balance of short and long-term objectives for the Kingdom.

- **Minimum efficiency standards for new power plants**

Long-term fuel efficiency enhancement is an essential component for meeting fuel requirements for expanded power demand within the Kingdom, as well as for achieving a more effective use of valuable natural hydrocarbon resources. This includes phasing out regular crude firing on conventional gas turbines and shifting toward efficient modern combined cycle generation using cleaner natural gas. In addition, simple cycle gas turbines should be utilized for peak/emergency service only and not for intermediate or base-load. The IRSP could serve as a tool to propose minimum efficiency standards, selecting optimal technologies and identifying the most suitable geographical location for installation and allocating fuels, taking economic, environmental, and social objectives into consideration (see Section 5.3.2.7). In addition, annual efficiency performance-based monitoring reporting should be implemented and the system operator should ensure optimum dispatch of generation.

- **Policy deployment to promote sustainable energy**

Moving fuel prices toward international prices offers an economic incentive for the uptake of renewable energy technologies. The results of the EWS IRSP highest renewable penetration scenarios showed that significant amounts of renewables can be deployed based on an economically rational target for the planning period until 2040. While the long-term overall cost of renewables is less than for fossil fuel generation, markets have tended to require incentives to attract investors during the early planning period (when renewables will not meet the grid parity cost).

The proposed incentive mechanisms include two main categories: (1) price incentives, in which the government intervenes to provide renewable energy with preferential output prices (with the result that the market determines the quantity of renewables at the stipulated price), and (2) quantity incentives, in which the government sets a target for the quantity of renewables to be provided, with the result that the marketplace determines the price (Meier, Vagliasindi, & Imran, 2015, pp. 10-

12). In many cases, the following instruments are used for the implementation of such mechanisms:

1. **Feed-in tariffs (FIT):** This regulatory instrument, which is one of the most popular mechanisms used to support the development of new renewable projects, is based on long-term purchase agreements for the sale of renewable electricity (Taher & Hajjar, 2014, p. 106). At the time of writing, FIT policies are being implemented in more than 49 countries, states, and regions, including most EU countries, Japan, South Korea, Thailand, and South Africa (Meier, Vagliasindi, & Imran, 2015, p. 5).
2. **Renewable portfolio standards (RPSs)**: These standards specify a minimum percentage of power generation that renewable energy providers and obligated utilities are required to supply or install. They are designed to encourage new renewable energy development by establishing a target or quota for the proportion of electricity generation that must come from renewable sources by a certain date (Taher & Hajjar, 2014, p. 109). To date, 16 countries (including Australia, Japan, and the UK) and 31 U.S. states have implemented RPS policies (Meier, Vagliasindi, & Imran, 2015, p. 6).
3. **Auction-based procurement through tender mechanisms**: This instrument entails governments requesting competitive bids for electricity from renewables. The auctioned product can be either capacity (MW) or energy (MWh) (IRENA, 2015, p. 53). For example, auctions to build a 350 MW solar plant in Abu Dhabi resulted in the lowest awarded price on record (namely 2.42 cents/kWh) (Dipaola,

2016). Auctions are likely to continue to be implemented in the GCC region to support large-scale renewable energy deployment.

4. **Net-metering**: Under this instrument, utilities must give credits to customers when they generate electricity with an on-site power generation system and then feed excess power into the grid (Taher & Hajjar, 2014, p. 110). For example, net-metering encourages small-scale renewable energy development and has resulted in concrete actions in the UAE (IRENA, 2016, p.54).

- **Carbon pricing systems**

Currently, carbon pricing and trading could be expanded to enable the full implementation of Nationally Determined Contributions (NDC) under Article 6 of the UNFCCC Paris Agreement. An important next step in advancing the Paris Agreement is to accelerate the adoption of carbon pricing. Many business leaders and government officials urge the use of carbon pricing as it appears to be the most effective policy instrument for directly tackling greenhouse gas emissions. With the potential for high renewable deployment in Saudi Arabia that this research demonstrates, the country can develop a local carbon market and can trade “Internationally Transferred Mitigation Outcomes” globally (IETA, 2016). As indicated in the IRSP results for the high renewable scenario, a total revenue of **USD 73 billion** (refer to Section 5.4.1) could be achieved by 2040.

- **Sustainable energy value chain development**

According to the high renewable deployment plans in the EWS IRSP results, any proposed competitive procurement plans should strongly favor local supply chain development in projects and mandate bidders to propose higher levels of local content and employment. This would also allow investors to establish companies capable to supply both the domestic and global markets with products and services. Furthermore, the creation of local manufacturing facilities through technology-based joint ventures must be achieved with clear local content targets. Such development of the sustainable energy sector can support its position as a new vehicle of growth that facilitates national and socio-economic development and economic diversification plans.

- **Interregional transmission lines modernization**

As suggested earlier in this research, increasing the transfer capacity of the TLs that connect Saudi Arabia's four regions will add flexibility to transfer electricity, particularly as more renewable energy is brought into the mix. As shown in the IRSP analysis (see Section 5.5.4), transmission augmentation could improve the distribution and utilization of generation resources between the four regions and provide a more reliable electricity service to end-users. For example, in high renewable scenario, the newly installed capacity of fossil fuel generation was reduced by 45% when transmission augmentation is considered. In addition, due to high penetrations of RES, transmission augmentation supports siting RES over a large geographic area; moreover, it also results in even less variability and a higher dispatch of renewables throughout the day in the four regions.

Furthermore, interconnecting Saudi Arabia with other GCC countries, or even markets further abroad, can generate advantages related to capacity availability. For example, one country can find it advantageous to rent its unused spinning capacity out during peak days (and thereby gain additional revenue), while another country could avoid the expense of building and maintaining planned peak-capacity plants (IRENA, 2016).

6.3.2.2 Demand-Side Policies

- **Existing tariff system modification to reflect the true cost of electricity**

The DSM analysis in this dissertation indicated that the levelized costs of most of the major energy efficiency measures (i.e., cooling and building insulations in the residential sector) are lower than the recently revised tariff. In addition, the TRC analysis revealed that these major energy efficiency measures are attractive even at the current domestic subsidized fuel prices (see Sections 2.2.3.2, 2.2.4.2, and 2.2.5.1). Adopting high energy efficiency measures within the current tariff system in the high renewable scenario would result in a total benefit of **USD 55 billion** during the planning period (2017–2040). In addition, the practices of many countries has proven that end-users will change their consumption behavior by responding actively to price change (Hu et al., 2013, p.155). The structural change of the tariff system would eliminate the low cost of energy as a barrier for DSM implementation (CSIRO, 2009; Crossley, 1999; Vine et al. 2003. In order to not impact low-income populations disproportionately, the tariff could be gradually increased for those who consume 5000 kWh and above.[92]

In addition, full smart meter coverage of the residential sector can reduce consumption during peak demand periods and activate the time-of-use tariff system to

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[92] 95.96% of consumers in Saudi Arabia consumes 76.3% of residential electricity with less than 5000 kWh consumptions.

enable both a better understanding of and response to customer energy demand (Brown, 2011; Uribe-Perez, Hernandez, Bega, & Angulo, 2015, p.5). A study conducted by ECRA indicated that the direct and indirect benefits of installing smart meters was estimated to be USD 0.427 billion and USD 27.2 billion, respectively (ECRA, 2014, p.55).

- **Effective incentive mechanisms deployment**

In general, DSM is essentially considered just as significant as the supply-side resources with high market potential to decrease the peak demand by 26% as shown in this research. Based on DSM program experiences across the United States, a wide range of options of financial and other incentives are available to encourage investments in DSM and particularly energy-efficient technologies, related services, and/or behavior change programs. These incentives range from simple cash rebates (i.e., the purchase of efficient products) to bundled customized financial incentives and non-financial incentives (i.e., technical assistance, education and training, and information sharing). Incentives can be directed to end-users and purchase transactions, or can be used to encourage upstream manufacturers, retailers, or contractors in market supply chains to influence how customers choose appliances, building operating methods, or building designs (EPA, 2010, p.1; Hu et al., 2013, p.174). Nonetheless, due to the lack of DSM incentive and financing programs, enterprises and individuals in Saudi Arabia are not intrinsically motivated to implement DSM (Faruqi & Hledik, 2011). Deploying a portfolio of incentive instruments could therefore expedite the implementation of DSM measures. The following are examples of financial instruments that have used elsewhere to encourage the implementation of DSM programs by end-users.

1. **Energy-efficient equipment leasing programs:** Such programs can remove financial barriers by encouraging energy-efficient technology purchasing and direct supply to end-users, thereby eradicating financial issues preventing greater energy efficiency from being deployed. These programs also recover costs by incorporating lease payments into electricity bills, with lease costs expected to be accounted for by energy savings. A key advantage of these programs is that old equipment can be traded in for new equipment, which prevents inefficient equipment from being sold and subsequently utilized elsewhere (Alyousef & Abu-ebid, 2012, p.298)
2. **Energy service companies (ESCOs):** ESCOs support end-users to participate in “performance contracting” to invest future cash flows from energy saving measures, thereby allowing them to cut costs and improve their existing facilities. Performance contracting is free for the end-user, with energy savings used as investment repayments. Prior to implementation, preparatory work to overcome contractual and legal start-up barriers should be introduced by the concerned entities. In additions, barriers associated with ESCOs projects, such as development risk, design and technology advancement and maturity, tariff price change, and return of investment needs to be eliminated (Hu et al., 2013, p.257)
3. **Cash rebates:** Such programs compensate customers for purchasing energy-efficient goods or for load curtailment. The TRC analysis shows that most

DSM measures are competitive (see Sections 2.2.3.2, 2.2.4.2, and 2.2.5.1), which means that rebates could be financed from the total recourse savings provided the incentive does not exceed or significantly erode the benefits. Priority should be given to measures with the highest benefit-cost ratio. EPA (2010) investigated how difference incentives encourage end-users to change the way they use appliances or operate buildings and concluded that financial incentives, such as cash rebates, may not necessarily be effective and may be unnecessarily costly. In fact, customers are best impacted by information services while technical assistance and bundled were proven to be effective. Although this evaluation depends on the details and the environment in which the incentive is applied in a specific market and program design, it is imperative to evaluate all financial options prior to implementation in Saudi Arabia

- **Building code and appliance standards development**

It is imperative that the Kingdom continues to develop, improve, and enforce standards and codes that prescribe baseline criteria for energy efficiency – particularly in the case of new building and cooling systems (see Section 2.2.2). For example, this research's analysis indicates that mandating more efficient cooling and building insulation standards could alone save **133 TWh** in Saudi Arabia's residential sector by 2040, which represents more than 88% of the energy efficiency saving in the sector (see Section 2.2.3.2). Hu et al. (2013) indicated that around 37 countries and regions have established and implemented energy efficiency standards and labeling systems. Although the methods of determining the energy efficiency standards level vary, these standards are developed based benefit/cost analysis of the investments to calculate the payback period. Some standards have been developed in the Kingdom based on comprehensive technical and economic analysis of different appliances (Alyousef & Abu-ebid, 2012, p.294) but these will need to track and respond to various changes underway in Kingdom such as fuel price reform to remain relevant.

- **Measurement and verification protocols establishment**

Measurement and verification (M&V) protocols are imperative for assessing the effects of DSM programs. Such protocols guarantee that organizations responsible for evaluation and approval will adhere to a more standardized set of guidelines for reporting. The measurement and verification analyses should yield annual reports that document the progress of each program based on key performance indicators (such as peak and energy reduction in each consuming sector). One barrier related to having an effective M&V program is to build capacity and knowledge for M&V auditors (Clean Energy Ministerial, 2014, p. 9). Therefore, the Kingdom needs to address the critical shortage of qualified personnel in M&V as there are presently inadequate suitably skilled and experienced engineers and technicians to perform the essential work on a national scale (Alyousef & Abu-ebid, 2012, p.300). In addition, the weather-based forecasting model (as developed in Chapter 3) can be used to monitor progress on DSM measures and determine whether forecasted demand reductions can be achieved.

6.3.3 Energy Sector Governance and Institutions

Having a functioning energy sector governance structure (and related institutions) is important for the successful implementation of sustainable energy policies and regulatory measures in Saudi Arabia’s utility sector. The following subsections outline a number of potential institutional reforms on planning and policy-making, data-sharing and capacity building, restructuring of the utilities, and role of civil society:

6.3.3.1 Reforms to Planning and Policymaking Institutions

- **Strengthen institutional frameworks in the utility sector by integrating all strategies into a national IRSP**

The traditional fragmented utility planning process should be replaced by IRSP due to the latter's ability to integrate and co-optimize both supply- side and demand-side resources into a comprehensive resource plan. Mandating the preparation of an IRSP will place more emphasis on utility entities studying and exploring cost-effective DSM options. For example, co-optimizing supply- and demand-sides resources by the EWS IRSP model in the high renewable scenario would result in a total cost avoidance of **USD 208 billion** and generate a revenue of **USD 369 billion** from exporting displaced fuels, in comparison to the FEE scenario (see Section 5.3.2.5).

Saudi Arabia's new Ministry of Energy, Industry, and Mineral Resources can align the multitude of traditionally competing interests now under its umbrella (such as K.A.CARE, SEC, ECRA, and Saudi Aramco) by assuming the responsibility for developing the government's national energy policy targets using an IRSP model. Additionally, the ministry must take the necessary steps to ensure that all entities adhere to the guidelines proposed, including the submission of regular performance reports that clearly highlight challenges and areas of progress

- **Recognize that institutional development is imperative for supporting sustainable renewable energy deployment**

One key enabler of renewable energy deployment is to ensure collaboration across government entities taking into consideration a diversity of technical, economic, environmental, and social views. Allison (2005) emphasized the importance of policy networks in shaping public policy related to renewable energy resources. To streamline the fragmented and overlapped activities being undertaken by the institutional players involved in developing renewable energy in Saudi Arabia (see Section 6.2.4.1.1), all relevant stakeholders (e.g., K.A.CARE, SEC, and Saudi Aramco) should strictly follow a proposed IRSP developed by MEIM which should lead the overall IRSP strategies and develop funding mechanisms. A Renewable Energy Project Development Office (REPDO) has been created recently under the umbrella of MEIM. REPDO is responsible for standardizing the procurement process, creating evaluation criteria for tenders, and developing PPAs (Kneller, 2017). As the independent sector regulator, ECRA should oversee technical and regulatory requirements (such as grid code and renewable connection requirements).

- **Revise DSM institutional structures and recognize that their implementation responsibilities are key for DSM successful implementations**

Taylor et al. (2008, p.19) indicated that one of the biggest barriers to the success of DSM projects is the mismatch between the attempted solutions and domestic institutional environments. In Saudi Arabia, the current responsibilities for DSM between various existing entities and institutions are somewhat unclear (Faruqui, & Hledik, 2011, p. 176). The MEIM should lead the overall strategies and polices related to efficiency and DSM initiatives in line with a developed IRSP. It should also conduct advanced researches to evaluate incentive policies based on international best practices to stimulate the implementation of DSM measures for individuals and utilities. Finally, the SEEC/SEEP should administer all energy efficiency programs within Saudi Arabia (which should include enforcing developing, implementing, and monitoring them).

- **Implement measures to streamline activities within R&D institutions**

CSIRO (2009, p. 205) emphasized the important role of R&D as a key enabler for distributed energy (including renewables and DSM measures):

> A comprehensive R&D program that allows for overcoming technology lock-in at a scale in line with the need for efficient uptake of DE and complementary polices/programs structured to move technologies efficiency through their development lifecycle

Saudi industries could benefit greatly from the support of the utility sector in R&D efforts, which could also enable technologies to be adapted to local context as well as increase overall performance. Promoting collaboration among existing universities and research institutions (e.g., K.A.CARE, KAPSARC, KACST, and KAUST) and linking these entities with industries and entrepreneurs can play a significant role in enticing the private sector to take a key role in relation to renewable energy and DSM programs investments (Taher & Hajjar, 2014, p.171). These entities could then further solidify the value chain across all its segments, which will further support the implementation of projects and build a core body of expertise on the topic of sustainable energy and development in Kingdom.

6.3.3.2 Institutions for Data/Information-Sharing and Capacity Building

Policy barriers, design making bias, or an absence of incentives often result from a lack of data/information. Data/information sharing can act as a key enabler for sustainable energy policies as they allow more accurate valuation of various DSM measures and renewable energy sources (CSIRO, 2009, p.210). Currently, entities involved in the KSA utility sector provide fragmented energy-related data (see Section 6.2.4.2). The following information-sharing and capacity building can improve the current situation:

- **Centralize data-sharing to avoid duplication or data conflicts among entities**

A central resource center that holds open-source information about energy profiles, policies, and strategies would allow regulatory engineers, consultants, and academic researchers to provide detailed advice and undertake studies. This center could be established under MEIM, since all of the various entities that relate to the utility sector reside under this ministry. The center should utilize recent demand forecasting models, perform technical evaluations of and energy efficiency and renewable resource potential, and ensure their application in the integrated energy modeling. The availability of such data would allow users to quantify the anticipated benefits, and encourage greater private sector participation in upcoming projects (Lahn, Stevens, & Preston, 2013, p. 18; Papadopoulou et al., 2013, p. 9).

- **Develop a common approach to electricity and water IRSP modeling**

Sharing national assessments and the economic, environmental, and social objectives of a developed national IRSP model would help to generate debate and raise public awareness of both the value of energy resources and the inefficiency of the current resource; it would also enable better cost-benefit analyses. An IRSP model can be also broadly disseminated for use in intense stakeholder and public consultations.

- **Improve capacity building and skills**

One barrier identified by CSIRO (2009, p. 213) was a lack of industry knowledge/skills and the connection between this and industry/cultural bias. In addition, Taher and Hajjar (2014, p. 177) shows that information/data asymmetry acts as a significant barrier to the adoption of otherwise cost effective measures. One method to overcome such barriers could be the development of compressive, informative, and extensive training and materials on energy efficiency topics, including case study documents, websites and databases, in order to improve public awareness. SEEC and K.A.CARE are two entities that would be well positioned to champion greater understanding regarding DSM initiatives and renewable energy projects. This will encourage new and expanding firms to make informed, educated decisions prior to purchasing new equipment and technologies.

6.3.3.3 Electricity Industry Restructuring

In the Saudi Arabia's electricity sector, current structure and government intervention has led tariffs to be divorced from the underlying cost structure. Subsidies and cross-subsidies have been deliberately used to manipulate tariffs for economic development and raising living standards. The utilities (e.g., SEC owing the majority of generation in the Kingdom) do not have any incentive to improve performance when government support is guaranteed (Bhattacharyya, 2011, p. 701). In addition, utilities tend to overinvest in capacity, with little investment being made in more efficient technologies on the supply-side and DSM measures on the demand-side. As indicated in ECRA's annual report, implementing the restructuring plan to establish an independent electric system operator, generation and distribution companies to bolster competition, and improve the efficiency of providing the service to consumers has been delayed (ECRA, 2014) (see Section1.3.1). Expediting the sector's restructuring would therefore promote competition by removing entry barriers for both new producers and the targeted privatized generation facilities. It would also enable the utility sector to achieve greater efficiency, reduce public capital spending in the sector, and promote renewables on the supply-side and DSM measures on the demand-side One obstacle associated with this restructuring is the need for developing technical and managerial skills to introduce this new system (Bhattacharyya, 2011, p. 714-715).

6.3.3.4 A New Role of Civil Society

Individuals involved in sustainable energy governance can be actively engaged in the production and trade of energy and become prosumers (Steg, Perlaviciute, & Van der Werff, 2015, p. 2) (see Section 6.2.4.4). The supportive mechanisms mentioned earlier can enable individuals to help the utility sector transform to being sustainable by investing in small-scale renewable energy deployment and actively participating in the implementation of demand-side measures. The role of the society can be effectively enabled through the following enablers suggested by CSIRO (2009; pp 210-215):

- Long-term stable policy with firmed targets and commitments, and improved certainty can support active participation of individuals in both DSM and distributed renewable energy sources investments.

- A regulatory and policy framework that effectively streamlines the incentives to stakeholders involved in the supply chain would encourage innovation and provide efficient services to end-users. This includes eliminating barriers, such as split of misplaced incentives, and unaligned incentives of supply chain with energy efficiency.
- Effective data sharing/symmetry and education of smart meters, tariff structures, efficient appliances and standards can provide the end-users with accurate understanding for effective behavioral change. Awareness-raising campaigns that address the economic, social, and environmental benefits of such a transition and target the country's whole population will be a key enabler. It is also imperative to feed such initiatives into the education system so that the young Saudi generation can grow up environmentally-conscious, thus creating more lasting change (Al-Ajlan et al., 2004; Alyousef & Abu-ebid, 2012; Lahn & Stevens, 2011).
- A well informed trained skilled workforce that understand DSM and renewable energy sources can inform the end-users with the benefits using decision making science to eliminate cultural bias.
- Technological innovation through R&D on DSM and renewable energy sources can reduce the cost and improve reliability, which would attract more participation by society.

6.4 Directions for Future Research

Some limitations are related to this dissertation and may be considered for future research, as shown below. While the methods in this research provide a significant step forward for the development of IRSP in Saudi Arabia, there are some limitations related to this research that require future research which are described below.

6.4.1 Improving the Electricity and Water Sector Model

6.4.1.1 Modeling Detailed Transmission and Distribution Networks

This research considered interregional 380 kV TLs in the EWS model, using PLEXOS. The regional representation of TLs allows for co-optimization of generation and transmission expansion to identify the optimal distribution of supply resources, taking the cost and losses of TLs into consideration. These analyses were adequate to meet the current research objectives. Nonetheless, modeling the detailed transmission and distribution networks within each region would allow transmission congestion in the electricity network to be explored further which is particularly relevant to transmission congestion from the development of renewable generation under the targeted high renewable penetration. The EWS IRSP model developed in this research could be expanded to address this issue and the potential economic and technical impacts it may have on the study's results.

6.4.1.2 Considering Regional Transmission Interconnections

Saudi Arabia's transmission network is currently connected to the other GCC countries. These interconnections were not reflected in the EWS IRSP model due to the relatively small amount of power transferred through these existing TLs. Efforts to connect the Kingdom to Egypt using HVDC TLs are ongoing. The EWS IRSP model could thus be enhanced to incorporate transmission interconnections with neighboring countries, as such, interconnections may help in minimizing the curtailed renewables through exporting to other countries.

6.4.1.3 Confirming the Impact of Renewable Energy Penetration on the Transient Stability of the Electricity Network

While the EWS IRSP model addresses physical limitations (including the thermal limit of interregional TLs between Saudi Arabia's four operating areas), it does not explicitly consider intra-regional power stability limits. Globally, concerns have repeatedly been raised about the impact of the penetration of high renewable energy sources on grid stability, although this situation does not currently cause significant problems in countries with high renewable energy resources (such as Germany, where PV already contributes about 40% of the peak demand during some summer hours) (Appen, Braun, Stez, Diwold, & Geibel, 2013, p. 55). Future research can utilize detailed power simulation tools (such as ETAP, IPSA, and PSS/E) to validate any other stability limitations in the Saudi electricity network from the IRSP results. In addition, medium-term planning is also recommended to check operational dispatch over shorter periods (i.e., around five years at a time), to account for mid-term inter-temporal constraints such as emission constraints or annual fuel supply constraints.

6.4.1.4 Implementing a Dynamic Model of Concentrated Solar Power

Concentrated solar power deployed with TES provides a flexible source of renewable energy that can dispatch energy during periods of high demand and displace more (and higher-cost) fuel than other renewables without storage (Denholm & Hummon, 2012). For the purpose of the analysis undertaken in this study, several static profiles of CSP with TES of 8 and 12 hours were considered. Based on the hourly forecasted demand of Saudi Arabia, peaks normally occur at approximately 14:00 hours and 20:00 hours. The EWS IRSP model entailed undertaking comprehensive investigations using one of these profiles or a combination of both to identify an optimal option. Based on the results, the curtailment was kept at the minimum, which ensured that the static models of CSP met the objectives of this research. Nonetheless, dynamic CSP modeling in the developed EWS model could further optimize the dispatchability of generated power, which is a topic that could be addressed in future research (Denholm, Wan, Humoon, & Mehos, 2013, p. 2).

6.4.1.5 Evaluating the Impact of Non-Thermal Storage on IRSP Results

While the IRSP model in this research considered CSP with thermal energy storage to overcome renewable energy sources variability and generate power beyond the daytime hours, there is a great interest in a range of other energy storage technologies, such as batteries and flywheels to pumped hydro and compressed air. Currently, batteries are costly and have very low efficiency with a lifespan shorter than the average solar thermal plant. With the rapid technological development of batteries to improve efficiency, reduce cost, and increase lifespan, they may end up being cheaper than TES option (Deign, 2014). In future studies, examining non-thermal storage in the IRSP model, considering various future cost projections and technical improvements may provide a valuable sustainable path for the country.

6.4.1.6 Considering Alternative Water Conservation Scenarios

As a conservative assumption, the EWS model considered existing forecasts for desalinated water demand in Saudi Arabia and did not consider implementation of any conservation programs to reduce this demand. In future studies, identifying and reflecting these programs in water demand forecasts would reduce the water demand and subsequently overall energy consumption.

6.4.2 Improving the Demand Forecasting Model

6.4.2.1 Considering a Bottom-Up Forecasting Model for all Sectors

This research utilized both top-down and bottom-up (end-use) approaches for electricity demand forecasting. Total demand was estimated with a top-down forecasting model, while potential savings from efficiency measures were estimated with a bottom-up forecasting model of the Kingdom's energy sector. Due to limitations in data availability, a detailed end-use forecasting model was only used for the residential sector (which represents the main consumer sector in Saudi Arabia). While a bottom-up model provides the greatest flexibility for examining future policy impacts, it requires an extensive amount of data to accurately build the base level demand (ideally by hour) in each sub-sector. The developed hybrid model of top-down/bottom-up model will remain important for cross checking the outputs of bottom-up models, but the approach used here should be expanded to improve on the key driving factors once detailed data for all sectors are made available in the future.

6.4.2.2 Considering an Hourly Weather-Based Forecasting Model for all Sectors

In this research, monthly consumption data for the two main sectors (residential and commercial) provided an accurate tool for calculating the effect that weather factors have on demand. Monthly demand data (as provided in SEC annual reports) were used due to the unavailability of hourly demand data for the two sectors in question. The SEC annual reports also note that monthly electricity sales do not necessarily represent actual consumption, as they include the settlement of unbilled sales from previous months for other sectors (e.g., governmental, industrial, and other sectors). Thus, the historical monthly sales and consumptions data could not be used in this study's forecasting model. If these data are made available, the accuracy of the forecasting model will be enhanced.

6.4.3 Studying the Macroeconomic Effects of Energy Policies in Saudi Arabia

This research has concluded that introducing measures that regulate the supply and demand-sides could reduce demand significantly and free more fuel for long-term export. Enhancing energy efficiency at the microeconomic level acts at the macroeconomic level on energy productivity through different channels. First, the direct impact of energy efficiency results in both a substitution effect (which lowers energy consumption for a given level of output) and a partially offsetting rebound effect (which due to more available income leads to a higher level of activity and greater energy consumption). A second possible channel is through the impact of energy efficiency and renewable penetration on the financial balance of Saudi Arabia due to increased oil revenues from exporting, at later time, fuel otherwise domestically consumed. A third possible channel involves recycling this higher public oil income through either higher public current expenditures or public investments in infrastructure, both of which – albeit differently – affect the accumulation of capital and thus growth and equity across generations (Gonand, 2016, p. 5). Future research may therefore address the macroeconomic impact of the energy policies proposed in this research.

6.4.4 Conducting Comprehensive Sustainable Energy Policy Analysis

While this research has outlined a potential policy framework for Saudi Arabia's utility sector in the future based on the IRSP analysis, it is imperative to comprehensively examine the suggested set of polices critically from a variety of frameworks and evaluate its effectiveness in achieving intended goals. It is also crucial that policy decision making and various stakeholders in the utility sector are represented in the policy analysis process to create implementable policies. The process of analyzing policy should be initiated by establishing evaluation criteria, and identifying and evaluating a comprehensive set of policy options using recognized policy frameworks, such as those developed by Patton and Sawicki (1993), Popple and Leighninger (2004), Dobelstein (2002), Chambers (2000), and Gilbert and Terrell (2002). This should take into consideration barriers and enablers identified in international sustainable energy policy reviews to determine their relevance to Saudi Arabia's context. International reviews of sustainable energy policies implemented in other comparable countries, especially among resource-rich emerging countries across the world would allow Saudi Arabia to prevent unexpected consequences by overcoming the shortcoming of these policies prior to implementation. Ineffective polices or polices with unintended consequences should be modified without creating disruption to long-term plans (Meier, Vagliasindi, & Imran, 2015; Taher, & Hajjar, p. 180).

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Appendix A

ECONOMETRIC FORECASTING MODELS FOR HOUSEHOLDS AND CUSTOMERS IN THE COMMERCIAL, GOVERNMENTAL, AND INDUSTRIAL SECTORS

Table A.1 Regression analysis of the best fitted model to forecast households in residential sector

Dependent Variable: RESIDENTIAL HOUSHOLDS
Method: Least Squares
Date: 03/17/17 Time: 22:47
Sample: 1992 2014
Included observations: 23

Variable	Coefficient	Std. Error	t-Statistic	Prob.
TOTAL_POP	0.266914	0.003724	71.66853	0.0000
C	-2406327.	86501.63	-27.81828	0.0000

R-squared	0.995928	Mean dependent var	3688407.
Adjusted R-squared	0.995734	S.D. dependent var	1162474.
S.E. of regression	75924.15	Akaike info criterion	25.39580
Sum squared resid	1.21E+11	Schwarz criterion	25.49454
Log likelihood	-290.0517	Hannan-Quinn criter.	25.42063
F-statistic	5136.378	Durbin-Watson stat	0.519298
Prob(F-statistic)	0.000000		

Table A.2 Regression analysis of the best fitted model to forecast commercial customers

Dependent Variable: COMMERCIAL CUSTOMERS
Method: Least Squares
Sample: 1992 2014
Included observations: 23

Variable	Coefficient	Std. Error	t-Statistic	Prob.
TERTIARY_GDP	1782.475	70.37149	25.32951	0.0000
C	-125552.8	31370.38	-4.002272	0.0006

R-squared	0.968306	Mean dependent var	615010.7
Adjusted R-squared	0.966797	S.D. dependent var	299262.6
S.E. of regression	54530.97	Akaike info criterion	24.73387
Sum squared resid	6.24E+10	Schwarz criterion	24.83261
Log likelihood	-282.4395	Hannan-Quinn criter.	24.75870
F-statistic	641.5842	Durbin-Watson stat	0.527724
Prob(F-statistic)	0.000000		

Table A.3 Regression analysis of the best fitted model to forecast governmental customers

Dependent Variable: GOVERNMENTAL CUSTOMERS
Method: Least Squares
Sample: 1992 2014
Included observations: 23

Variable	Coefficient	Std. Error	t-Statistic	Prob.
TOTAL_POP	0.005393	0.000114	47.47100	0.0000
C	-29930.30	2638.884	-11.34203	0.0000

R-squared	0.990767	Mean dependent var	93224.30
Adjusted R-squared	0.990328	S.D. dependent var	23550.88
S.E. of regression	2316.199	Akaike info criterion	18.41618
Sum squared resid	1.13E+08	Schwarz criterion	18.51492
Log likelihood	-209.7861	Hannan-Quinn criter.	18.44102
F-statistic	2253.496	Durbin-Watson stat	1.145584
Prob(F-statistic)	0.000000		

Table A.4 Regression analysis of the best fitted model to forecast industrial customers

Dependent Variable: LOG (NO_INDUSTRIAL CUSTOMERS)
Method: Least Squares
Sample: 1992 2014
Included observations: 23

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	5.170681	0.250555	20.63688	0.0000
LOG(SECOGDP2^2)	0.351712	0.025378	13.85902	0.0000

R-squared	0.901442	Mean dependent var	8.630677
Adjusted R-squared	0.896749	S.D. dependent var	0.316454
S.E. of regression	0.101685	Akaike info criterion	-1.650929
Sum squared resid	0.217137	Schwarz criterion	-1.552190
Log likelihood	20.98568	Hannan-Quinn criter.	-1.626096
F-statistic	192.0726	Durbin-Watson stat	0.340851
Prob(F-statistic)	0.000000		

Appendix B

INPUT DATA FOR THE ENERGY EFFICIENCY MEASURES

Table B.1 Input data for EE measures evaluations in the governmental sector

End-Use	EE Measure	Unit	LT	Electric Savings	EE Measure Cost	Cost Type	Building Footage
Cooling	Split AC- high efficiency	ft²	14	1.84	0.25	I	12,500
Cooling	Packaged AC- high efficiency	ft²	14	0.77	0.16	I	62,500
Cooling	Chiller-high efficiency	ft²	20	0.62	0.13	I	125,000
Cooling	District cooling	ft²	20	0.62	0.13	I	125,000
Cooling	Chiller, VSD	ft²	20	0.83	0.29	I	125,000
Cooling	Cooling tower, high-efficiency fans	ft²	10	0	0.00	I	125,000
Cooling	Condenser water, temperature reset	ft²	15	0.23	0.09	I	125,000
Cooling	Economizer, installation	ft²	15	0.31	0.09	I	125,000
(Continued)							

(Continuation of Table B.1)							
Ventilation	Fans, energy-efficient motors	ft²	10	0.13	0.05	I	125,000
Ventilation	Fans, variable speed control	ft²	10	0.39	0.15	I	125,000
Cooling	HVAC retro-commissioning	ft²	4	0.3	0.09	I	125,000
Cooling	Pumps, variable speed control	ft²	10	0.01	0.01	I	125,000
Cooling	Thermostat, clock/programmable	ft²	11	0.17	0.05	F	12,500
Lighting	Compact fluorescent lamps	ft²	5	0.03	0.67	F	37,000
Lighting	Fluorescent, high bay fixtures	ft²	11	0.06	0.04	F	62,500
Lighting	T8 lamps and fixtures	ft²	10	0.18	0.10	F	37,000
Lighting	LED lamps	ft²	10	1.19	0.88	F	37,000
Lighting	LED exit lighting	ft²	10	0.01	0.94	F	37,000
Lighting	Metal halide lighting	ft²	10	1.12	0.80	F	62,500
Lighting	Municipal street lighting-metal halide	Per lamp	6	657	0.38	F	2,875,000

Continued

(Continuation of Table B.1)							
Lighting	Municipal street lighting-high pressure	Per lamp	6	657	0.43	F	2,875,000
Lighting	Municipal street lighting-LEDs	Per lamp	20	548	0.39	I	2,875,000
Other	Municipal pumping	Per HP	20	45	0.02	F	745,600
Building shell	Insulation-ceiling	ft^2	20	0.16	0.05	F	37,000
Building shell	Insulation-ducting	ft^2	20	0.16	0.05	I	37,000
Building shell	Insulation-radiant barrier	ft^2	20	0.05	0.01	I	37,000
Building shell	Insulation-wall cavity	ft^2	20	0.15	0.05	F	37,000
Building shell	Roofs-high reflectivity	ft^2	15	0.21	0.06	F	37,000
Building shell	Windows-high efficiency	ft^2	20	0.25	0.08	F	37,000

Data source: Faruqui and Hledik, 2011, p. 103

Table B.2 Applicability factors and acceptance rates for Governmental EE Measures[93]

End-Use	EE Measure	Applicability factor (%)	AR (%)
Cooling	Split AC-high efficiency	70	38
Cooling	Packaged AC-high efficiency	15	38
Cooling	Chiller-high efficiency	10	38
Cooling	District cooling	5	38
Cooling	Chiller, VSD	10	38
Cooling	Cooling tower, high-efficiency fans	10	38
Cooling	Condenser water, temperature reset	10	38
Cooling	Economizer, installation	10	38
Ventilation	Fans, energy-efficient motors	10	35
Ventilation	Fans, variable speed control	10	35
Cooling	HVAC retro-commissioning	10	38
Cooling	Pumps, variable speed control	10	38
Cooling	Thermostat, clock/programmable	70	38
Lighting	Compact fluorescent lamps	50	60
Lighting	Fluorescent, high bay fixtures	15	60
Lighting	T8 lamps and fixtures	50	60
Lighting	LED lamps	10	60
Lighting	LED exit lighting	25	60
Lighting	Metal halide lighting	10	60
Lighting	Municipal street lighting-metal halide	45	60
Continued			

[93] In this analysis, the ARs for cooling and building EE measures have been adjusted by assuming a gradual increase over the planning period until reaching 100% and 75%, respectively.

(Continuation of Table B.2)			
Lighting	Municipal street lighting-high pressure	45	60
Lighting	Municipal street lighting-LEDs	10	60
Lighting	Municipal pumping	75	40
Other	Insulation-ceiling	70	23
Building shell	Insulation-ducting	70	23
Building shell	Insulation-radiant barrier	70	23
Building shell	Insulation-wall cavity	70	23
Building shell	Roofs-high reflectivity	70	23
Building shell	Windows-high efficiency	70	23

Source: modified from Faruqui and Hledik, 2011, pp. 130-131

Table B.3 Input data for EE measures evaluations in the industrial sector

End-Use	EE Measure	Unit	LT	Electric Savings	EE Measure Cost	Cost Type	Footage of Building
Cooling	Packaged AC-high efficiency	ft²	14	0.77	0.16	I	50,000
Cooling	Chiller-high efficiency	ft²	20	0.62	0.13	I	100,000
Cooling	Chiller, VSD	ft²	20	0.83	0.29	I	100,000
Cooling	Cooling tower- high efficiency	ft²	10	0.001	0.00	I	100,000
Cooling	Condenser water, temperature	ft²	15	0.23	0.09	I	100,000
Cooling	Economizer, installation	ft²	15	0.31	0.09	I	100,000
Ventilation	Fans, energy-efficient motors	ft²	10	0.13	0.05	I	100,000
Ventilation	Fans, variable speed control	ft²	10	0.39	0.15	I	100,000
Cooling	HVAC retro-commissioning	ft²	4	0.3	0.09	I	100,000
Cooling	Pumps, variable speed control	ft²	10	0.01	0.01	I	100,000
Lighting	Compact fluorescent lamps	ft²	5	0.08	0.67	F	25,000
Lighting	Fluorescent, high bay fixtures	ft²	11	0.06	0.04	F	25,000
Continued							

(Continuation of Table B.3)							
Lighting	T8 lamps and fixtures	ft²	10	0.73	0.20	F	25,000
Lighting	LED lamps	ft²	10	1.19	0.88	F	25,000
Lighting	LED exit lighting	ft²	10	0.01	0.94	F	25,000
Lighting	Metal halide lighting	ft²	10	1.12	0.80	F	25,000
Industrial	High-efficiency motors	ft²	20	45	0.13	I	55,025,280

Data source: Faruqui and Hledik, 2011, p. 104

Table B.4 Applicability factors and acceptance rates for industrial EE measures[94]

End-Use	EE Measure	Applicability factor (%)	AR (%)
Cooling	Packaged AC-high efficiency	14	26
Cooling	Chiller-high efficiency	50	26
Cooling	Chiller, VSD	50	26
Cooling	Cooling tower-high efficiency	50	26
Cooling	Condenser water, temperature	50	26
Cooling	Economizer, installation	50	26
Ventilation	Fans, energy-efficient motors	50	26
Ventilation	Fans, variable speed control	50	26
Cooling	HVAC retro-commissioning	50	26
Cooling	Pumps, variable speed control	50	26
Lighting	Compact fluorescent lamps	50	20
Lighting	Fluorescent, high bay fixtures	14	20
Lighting	T8 lamps and fixtures	50	20
Lighting	LED lamps	50	20
Lighting	LED exit lighting	50	20
Lighting	Metal halide lighting	14	20
Industrial	High-efficiency motors	100	26

Source: modified from Faruqui and Hledik, 2011, pp. 137-138

[94] In this analysis, the ARs for cooling and building EE measures have been adjusted by assuming a gradual increase over the planning period until reaching 100% and 75%, respectively.

Appendix C

REGIONAL DEMAND FORECASTING RESULTS

Table C.1 Regional peak demand for the frozen energy efficiency scenario (in GW)

Year	FEE Scenario			
	COA	EOA	WOA	SOA
2017	22.5	22.1	22.3	5.3
2018	24.2	23.3	23.8	5.7
2019	25.9	24.8	25.4	6.1
2020	27.8	26.3	27.1	6.4
2021	29.5	27.8	28.6	6.7
2022	31.4	29.4	30.3	7.1
2023	33.4	31.0	31.8	7.5
2024	35.5	32.7	33.6	7.8
2025	37.0	34.1	34.9	8.1
2026	38.6	35.6	36.2	8.4
2027	40.4	37.1	37.5	8.7
2028	42.1	38.7	38.9	9.0
2029	43.8	40.4	40.4	9.3
2030	45.7	42.1	41.6	9.7
2031	47.4	43.8	43.0	10.0
2032	49.4	45.5	44.4	10.2
2033	51.2	47.3	45.8	10.5
2034	53.1	48.9	47.2	10.8
2035	54.9	50.8	48.6	11.1
2036	56.8	52.7	50.1	11.4
2037	59.0	54.8	51.3	11.7
2038	61.1	56.9	52.8	12.0
2039	63.2	59.1	54.4	12.3
2040	65.4	61.4	56.0	12.7

Table C.2 Regional peak demand for the limited energy efficiency scenario (in GW)

Year	LEE Scenario			
	COA	**EOA**	**WOA**	**SOA**
2017	22.5	22.1	22.3	5.3
2018	24.2	23.3	23.8	5.7
2019	25.9	24.8	25.4	6.1
2020	27.8	26.3	27.1	6.4
2021	29.5	27.8	28.6	6.7
2022	31.4	29.4	30.3	7.1
2023	33.4	31.0	31.8	7.5
2024	35.5	32.7	33.6	7.8
2025	37.0	34.1	34.9	8.1
2026	38.6	35.6	36.2	8.4
2027	40.4	37.1	37.5	8.7
2028	42.1	38.7	38.9	9.0
2029	43.8	40.4	40.4	9.3
2030	45.7	42.1	41.6	9.7
2031	47.4	43.8	43.0	10.0
2032	49.4	45.5	44.4	10.2
2033	51.2	47.3	45.8	10.5
2034	53.1	48.9	47.2	10.8
2035	54.9	50.8	48.6	11.1
2036	56.8	52.7	50.1	11.4
2037	59.0	54.8	51.3	11.7
2038	61.1	56.9	52.8	12.0
2039	63.2	59.1	54.4	12.3
2040	65.4	61.4	56.0	12.7

Table C.3 Regional peak demand for the high energy efficiency scenario (in GW)

Year	HEE Scenario			
	COA	EOA	WOA	SOA
2017	22.5	22.1	22.3	5.3
2018	24.2	23.3	23.8	5.7
2019	25.9	24.8	25.4	6.1
2020	27.8	26.3	27.1	6.4
2021	29.5	27.8	28.6	6.7
2022	31.4	29.4	30.3	7.1
2023	33.4	31.0	31.8	7.5
2024	35.5	32.7	33.6	7.8
2025	37.0	34.1	34.9	8.1
2026	38.6	35.6	36.2	8.4
2027	40.4	37.1	37.5	8.7
2028	42.1	38.7	38.9	9.0
2029	43.8	40.4	40.4	9.3
2030	45.7	42.1	41.6	9.7
2031	47.4	43.8	43.0	10.0
2032	49.4	45.5	44.4	10.2
2033	51.2	47.3	45.8	10.5
2034	53.1	48.9	47.2	10.8
2035	54.9	50.8	48.6	11.1
2036	56.8	52.7	50.1	11.4
2037	59.0	54.8	51.3	11.7
2038	61.1	56.9	52.8	12.0
2039	63.2	59.1	54.4	12.3
2040	65.4	61.4	56.0	12.7

Appendix D

LIST OF SAMPLE CASES SIMULATED BY THE EWS IRSP MODEL

Table D.1 Cases simulated by the EWS IRSP model

No	Scenario	Temperature	Fuel Price	GDP	Household Growth	Discount Rate	Renewable Shares (% of Peak Load)					TL Augmentation	% of RES Supply
							PV	CSP (% &TES)		WIND	NUC		
1	FROZEN	HIGH	MARKET	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
2	FROZEN	LOW	MARKET	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
3	FROZEN	Climate Change	MARKET	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
4	FROZEN	HIGH	CURRENT	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
5	FROZEN	HIGH	MARKET	1%	REF	3%	0%	0%	0%	0%	0%	NO	0%
6	FROZEN	HIGH	MARKET	0.50%	REF	3%	0%	0%	0%	0%	0%	NO	0%
7	FROZEN	HIGH	MARKET	-0.50%	REF	3%	0%	0%	0%	0%	0%	NO	0%
8	FROZEN	HIGH	MARKET	-1%	REF	3%	0%	0%	0%	0%	0%	NO	0%
9	FROZEN	HIGH	MARKET	REF	HIGH	3%	0%	0%	0%	0%	0%	NO	0%
10	FROZEN	HIGH	MARKET	REF	LOW	3%	0%	0%	0%	0%	0%	NO	0%
11	FROZEN	HIGH	MARKET	REF	REF	5%	0%	0%	0%	0%	0%	NO	0%
12	FROZEN	HIGH	MARKET	REF	REF	7%	0%	0%	0%	0%	0%	NO	0%
13	FROZEN	HIGH	MARKET	REF	REF	10%	0%	0%	0%	0%	0%	NO	0%
14	Frozen	HIGH	MARKET	REF	REF	3%	0%	0%	0%	0%	0%	YES	0%
15	Frozen	HIGH	EIA REF	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
16	Frozen	HIGH	EIA HIGH	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
17	Frozen	HIGH	EIA LOW	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
18	LEE	HIGH	MARKET	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
19	HEE	HIGH	MARKET	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
20	HEE	LOW	MARKET	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
21	HEE	HIGH	CURRENT	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
22	HEE	HIGH	MARKET	1.0%	REF	3%	0%	0%	0%	0%	0%	NO	0%
23	HEE	HIGH	MARKET	0.5%	REF	3%	0%	0%	0%	0%	0%	NO	0%
24	HEE	HIGH	MARKET	-0.5%	REF	3%	0%	0%	0%	0%	0%	NO	0%
25	HEE	HIGH	MARKET	-1.0%	REF	3%	0%	0%	0%	0%	0%	NO	0%
26	HEE	HIGH	MARKET	REF	HIGH	3%	0%	0%	0%	0%	0%	NO	0%
27	HEE	HIGH	MARKET	REF	LOW	3%	0%	0%	0%	0%	0%	NO	0%
28	HEE	HIGH	MARKET	REF	REF	5%	0%	0%	0%	0%	0%	NO	0%
29	HEE	HIGH	MARKET	REF	REF	7%	0%	0%	0%	0%	0%	NO	0%
30	HEE	HIGH	MARKET	REF	REF	10%	0%	0%	0%	0%	0%	NO	0%
31	HEE	HIGH	MARKET	REF	REF	3%	0%	0%	0%	0%	0%	YES	0%
32	HEE	HIGH	EIA REF	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
33	HEE	HIGH	EIA HIGH	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%
34	HEE	HIGH	EIA LOW	REF	REF	3%	0%	0%	0%	0%	0%	NO	0%

Continued

(Continuation of Table D.1)

No	Scenario	Temperature	Fuel Price	GDP	Household Growth	Discount Rate	Renewable Shares (% of Peak Load)					TL Augment	% of RES Supply
							PV	CSP (% &TES)		WIND	NUC		
35	HEE	HIGH	MARKET	REF	REF	3%	0%	0%	N/A	10%	0%	NO	8.4%
36	HEE	HIGH	MARKET	REF	REF	3%	30%	0%	N/A	0%	0%	NO	14.9%
37	HEE	HIGH	MARKET	REF	REF	3%	41%	0%	N/A	0%	0%	NO	21.7%
38	HEE	HIGH	MARKET	REF	REF	3%	0%	20%	12H	0%	0%	**YES**	21.7%
39	HEE	HIGH	MARKET	REF	REF	3%	0%	0%	N/A	30%	0%	NO	22.3%
40	HEE	HIGH	MARKET	REF	REF	3%	0%	30%	N/A	0%	0%	NO	25.7%
41	HEE	HIGH	MARKET	REF	REF	3%	32%	0%	N/A	30%	0%	NO	36.7%
42	HEE	HIGH	MARKET	REF	REF	3%	60%	0%	N/A	0%	11%	NO	37.0%
43	HEE	HIGH	MARKET	REF	REF	3%	0%	0%	N/A	30%	11%	NO	37.8%
44	HEE	HIGH	MARKET	REF	REF	3%	41%	30%	8H	0%	0%	NO	39.5%
45	HEE	HIGH	MARKET	REF	REF	3%	41%	16%	8H	10%	0%	NO	40.3%
46	HEE	HIGH	MARKET	REF	REF	3%	30%	13%	8H	30%	0%	NO	45.0%
47	HEE	HIGH	MARKET	REF	REF	3%	0%	60%	8H	0%	0%	NO	47.1%
48	HEE	HIGH	MARKET	REF	REF	3%	41%	30%	8H	11%	0%	NO	48.8%
49	HEE	HIGH	MARKET	REF	REF	3%	30%	20%	8H &12H	0%	10%	**NO**	50.3%
50	HEE	HIGH	MARKET	REF	REF	3%	10%	30%	8H	30%	0%	NO	50.4%
51	HEE	HIGH	MARKET	REF	REF	3%	10%	20%	8H &12H	10%	10%	**NO**	51.4%
52	HEE	HIGH	MARKET	REF	REF	3%	41%	30%	8H	10%	0%	NO	53.5%
53	HEE	HIGH	MARKET	REF	REF	3%	10%	0%	N/A	30%	23%	NO	54.0%
54	HEE	HIGH	MARKET	REF	REF	3%	30%	30%	8H	27%	0%	NO	54.4%
55	HEE	HIGH	MARKET	REF	REF	3%	30%	60%	8H	0%	0%	NO	55.5%
56	HEE	HIGH	MARKET	REF	REF	3%	0%	20%	8H &12H	30%	10%	**NO**	57.1%
57	HEE	HIGH	MARKET	REF	REF	3%	0%	60%	8H &12H	0%	0%	**YES**	57.2%
58	HEE	HIGH	MARKET	REF	REF	3%	41%	60%	8H	0%	0%	NO	57.5%
59	HEE	HIGH	MARKET	REF	REF	3%	0%	50%	8H	30%	0%	NO	57.1%
60	HEE	HIGH	MARKET	REF	REF	3%	35%	0%	8H	20%	23%	YES	59.9%
61	HEE	HIGH	MARKET	REF	REF	3%	30%	40%	8H	30%	0%	NO	60.0%
62	HEE	HIGH	MARKET	REF	REF	3%	15%	60%	8H	15%	0%	NO	60.3%
63	HEE	HIGH	MARKET	REF	REF	3%	15%	60%*	8H	15%	0%	NO	60.5%
64	HEE	HIGH	MARKET	REF	REF	3%	10%	38%	8H	30%	0%	NO	60.8%
65	HEE	HIGH	MARKET	REF	REF	3%	0%	60%	8H	0%	11%	NO	61.0%
66	HEE	HIGH	MARKET	REF	REF	3%	10%	50%	8H	30%	0%	**NO**	61.1%
67	HEE	HIGH	MARKET	REF	REF	3%	10%	20%	8H &12H	30%	11%	**YES**	70.6%
68	HEE	HIGH	MARKET	REF	REF	3%	10%	20%	8H &12H	30%	11%	YES	61.2%

Continued

(Continuation of Table D.1)

No	Scenario	Temperature	Fuel Price	GDP	Household Growth	Discount Rate	Renewable Shares (% of Peak Load)					TL Augment	% of RES Supply
							PV	CSP (% &TES)		WIND	NUC		
69	HEE	HIGH	MARKET	REF	REF	3%	30%	60%	8H	11%	0%	NO	61.2%
70	HEE	HIGH	MARKET	REF	REF	3%	10%	60%	8H	20%	0%	NO	61.4%
71	HEE	HIGH	MARKET	REF	REF	3%	10%	30%	8H	30%	11%	**YES**	61.9%
72	HEE	HIGH	MARKET	REF	REF	3%	0%	60%	8H	30%	0%	NO	62.2%
73	HEE	HIGH	MARKET	REF	REF	3%	41%	60%	8H	11%	0%	NO	62.6%
74	HEE	HIGH	MARKET	REF	REF	3%	30%	60%	8H	14%	0%	NO	62.8%
75	HEE	HIGH	MARKET	REF	REF	3%	60%	20%	8H	30%	11%	NO	63.7%
76	HEE	HIGH	MARKET	REF	REF	3%	60%	20%	8H	30%	11%	YES	64.0%
77	HEE	HIGH	MARKET	REF	REF	3%	10%	60%	8H	30%	0%	NO	64.7%
78	HEE	HIGH	MARKET	REF	REF	3%	30%	50%	8H	30%	0%	NO	64.8%
79	HEE	HIGH	MARKET	REF	REF	3%	10%	60%	8H	30%	0%	NO	64.8%
80	HEE	HIGH	MARKET	REF	REF	3%	30%	30%	8H	30%	11%	NO	65.4%
81	HEE	HIGH	MARKET	REF	REF	3%	30%	20%	8H	30%	11%	**YES**	65.6%
82	HEE	HIGH	MARKET	REF	REF	3%	17%	60%	8H	30%	0%	NO	66.0%
83	HEE	HIGH	MARKET	REF	REF	3%	20%	60%	8H	30%	0%	NO	66.5%
84	HEE	HIGH	MARKET	REF	REF	3%	40%	30%	8H	30%	11%	NO	67.7%
85	HEE	HIGH	MARKET	REF	REF	3%	30%	40%	8H	30%	11%	**NO**	69.1%
86	HEE	HIGH	MARKET	REF	REF	3%	10%	30%	8H	30%	23%	NO	69.4%
87	HEE	HIGH	MARKET	REF	REF	3%	10%	38%	8H	30%	23%	NO	69.4%
88	HEE	HIGH	MARKET	REF	REF	3%	10%	38%	8H	30%	23%	YES	69.4%
89	HEE	HIGH	MARKET	REF	REF	3%	10%	50%	8H	30%	11%	NO	69.8%
90	HEE	HIGH	MARKET	REF	REF	3%	10%	60%	8H &12H	30%	0%	NO	70.1%
91	HEE	HIGH	MARKET	REF	REF	3%	40%	40%	8H	30%	11%	**NO**	70.6%
92	HEE	HIGH	MARKET	REF	REF	3%	10%	40%	8H &12H	30%	11%	**YES**	70.6%
93	HEE	HIGH	MARKET	REF	REF	3%	10%	38%	8H	30%	23%	YES	70.9%
94	HEE	HIGH	MARKET	REF	REF	3%	0%	60%	8H	30%	11%	**NO**	71.0%
95	HEE	HIGH	MARKET	REF	REF	3%	10%	41%	8H	30%	23%	NO	71.4%
96	HEE	HIGH	MARKET	REF	REF	3%	0%	60%	8H	30%	11%	YES	71.8%
97	HEE	HIGH	MARKET	REF	REF	3%	30%	50%	8H	30%	11%	**NO**	72.1%
98	HEE	HIGH	MARKET	REF	REF	3%	30%	50%	8H	30%	11%	YES	72.2%
99	HEE	HIGH	MARKET	REF	REF	3%	10%	60%	8H	30%	11%	**NO**	72.4%
100	HEE	HIGH	MARKET	REF	REF	3%	10%	60%	8H	30%	11%	YES	73.1%
101	HEE	HIGH	MARKET	REF	REF	3%	10%	60%	8H	30%	11%	YES	73.3%
102	HEE	HIGH	MARKET	REF	REF	3%	10%	50%	8H &12H	30%	11%	**YES**	73.4%

Continued

(Continuation of Table D.1)

No	Scenario	Temperature	Fuel Price	GDP	Household Growth	Discount Rate	Renewable Shares (% of Peak Load)					TL Augment	% of RES Supply
							PV	CSP (% &TES)		WIND	NUC		
103	HEE	HIGH	MARKET	REF	REF	3%	10%	50%	8H &12H	30%	11%	**YES**	73.9%
104	HEE	HIGH	MARKET	REF	REF	3%	10%	50%	8H &12H	30%	11%	**YES**	74.3%
105	HEE	HIGH	MARKET	REF	REF	3%	10%	55%	8H &12H	30%	11%	**YES**	74.5%
106	HEE	HIGH	MARKET	REF	REF	3%	30%	50%	8H &12H	30%	11%	**NO**	74.9%
107	HEE	HIGH	MARKET	REF	REF	3%	10%	55%	8H &12H	30%	11%	**NO**	75.2%
108	HEE	HIGH	MARKET	REF	REF	3%	30%	50%	8H &12H	30%	11%	**YES**	75.3%
109	HEE	HIGH	MARKET	REF	REF	3%	10%	55%	8H &12H	30%	11%	**YES**	75.7%
110	HEE	LOW	MARKET	REF	REF	3%	10%	50%	8H &12H	30%	11%	**YES**	74.3%
111	HEE	HIGH	CURRENT	REF	REF	3%	10%	50%	8H &12H	30%	11%	**YES**	74.3%
112	HEE	HIGH	MARKET	REF	REF	5%	10%	50%	8H &12H	30%	11%	**YES**	74.3%
113	HEE	HIGH	MARKET	REF	REF	7%	10%	50%	8H &12H	30%	11%	**YES**	74.3%
114	HEE	HIGH	MARKET	REF	REF	10%	10%	50%	8H &12H	30%	11%	**YES**	74.3%
115	LEE	HIGH	MARKET	REF	REF	3%	10%	50%	8H &12H	30%	11%	**YES**	73.9%
116	HEE	HIGH	EIA REF	REF	REF	3%	10%	50%	8H &12H	30%	11%	YES	0.743
117	HEE	HIGH	EIA HIGH	REF	REF	3%	10%	50%	8H &12H	30%	11%	YES	0.743
118	HEE	HIGH	EIA LOW	REF	REF	3%	10%	50%	8H &12H	30%	11%	YES	0.743
119	HEE	HIGH	MARKET	REF	REF	3%	10%	50%	8H &12H	30%	11%	NO	73.7%
120	HEE (High)	HIGH	MARKET	REF	REF	3%	10%	50%	8H &12H	30%	11%	YES	74.3%
121	HEE (Low)	HIGH	MARKET	REF	REF	3%	10%	50%	8H &12H	30%	11%	YES	74.3%
122	HEE (High)	HIGH	MARKET	REF	REF	3%	34%	0%	SM-2 12H	25%	8%	YES	45.2%
123	HEE (ref)	HIGH	MARKET	REF	REF	3%	36%	5%	SM-2 12H	26%	3%	YES	44.6%
124	HEE (low)	HIGH	MARKET	REF	REF	3%	33%	14%	SM-2 12H	27%	0%	YES	47.1%
125	HEE (high)	HIGH	MARKET	REF	REF	3%	34%	0%	SM-2 12H	32%	8%	YES	49.2%
126	HEE (Ref)	HIGH	MARKET	REF	REF	3%	36%	0%	SM-2 12H	34%	6%	YES	48.8%
127	HEE (low)	HIGH	MARKET	REF	REF	3%	35%	10%	SM-2 12H	34%	0%	YES	49.7%

Appendix E

ACADEMIC END-USER LICENSE AGREEMENT FOR ENERGY EXEMPLAR SOFTWARE PRODUCT

Academic End-User License Agreement
for Energy Exemplar Software Products

Use of the software "PLEXOS" Models, "PLEXOS CONNECT", "PLEXOS Integrated Energy Models", PLEXOS Solver and/or any PLEXOS derivatives (hereinafter "Software") is subject to the terms of this End-User License Agreement (hereafter, the "Agreement").

"PLEXOS" Models, "PLEXOS CONNECT", "PLEXOS Integrated Energy Models", PLEXOS Solver are copyrighted by Drayton Analytics Pty Ltd and Energy Exemplar Pty Ltd, ("the Author").

The Software is licensed, not sold, to Nabeel H. Alabbas, Center for Energy and Environmental Policy, University of Delaware. Address: 278 Graham Hall, Newark, Delaware, USA (hereafter "Licensee") by Energy Exemplar LLC, 3013 Douglas Blvd Suite120 Roseville, CA 95661 (hereafter "Licensor") for and on behalf of the Author, for Ph. D. Research: Identifying Pathways Toward Sustainable Electricity supply and Demand Using Integrated Resource Strategic Planning Model for Saudi Arabia and only under the terms of this Agreement. The Author retains ownership of all intellectual property rights in and in relation to the Software itself, and any enhancements, modifications, updates, upgrades, new releases or versions of the Software, and reserves any rights not expressly granted to Licensee.

1. Grant and Term of License

a) Licensor grants Licensee the non-exclusive, non-transferable right for consideration of one Australian dollar, the receipt of which is acknowledged by the Licensor to:

   i) use one copy of the Software, whether supplied as a stand-alone or a server license, on a single computer at a time for each license issued by Licensor for the Software under this Agreement. The Software is in "Authorised Use" on a computer when either:

      - the computer has a current Software license key issued by Licensor; or
      - the computer obtains a license automatically from a license server with a key issued by Licensor.

   ii) make copies of the Software in machine-readable form solely for backup purposes.

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b) Licensor will issue the license key in accordance with clause 1(a) upon execution of this Agreement.

c) The Term shall be taken to have commenced from the date that the Software is first in "Authorised use", that is, the date the license is activated by the Licensor, and shall continue for a term of 6 months (the "Term") unless terminated pursuant to clause 6 of this Agreement, provided that the Licensor may at its discretion, renew the license for further Term or Terms after the expiration of any Term.

d) In the event that Licensee does not satisfy the following conditions, Licensor may in its absolute discretion, cancel the Software license key and terminate this Agreement :-

i) perform all of its obligations under this Agreement during the Term;

ii) maintain accurate and up-to-date records of the number and location of all copies of the Software;

iii) properly supervise and control the use of the Software and use its best endeavours to ensure Authorised Use in accordance with the terms of this Agreement;

iv) agrees with any new conditions required by the Author and Licensor, and has paid to Licensor any fees payable for the further term;

v) must, at the 3 month stage of the Term:
   a. provide information on progress of academic research projects / courses being taught, for approval to continue, for the Licensee recognises that a PLEXOS license is not automatically extended after 3 months and is only done so at the strict discretion of the Licensor.

vi) must, prior to the expiration of the Term or any renewal Term:
   (A) if the Licensee is an Academic Institution :
   a. teach a minimum of one course per year using PLEXOS, and
   b. complete and submit to Licensor a brief report, summary or papers at the end of the license period stating the following information:
      i. the name and level of the course(s) on which Licensee has used PLEXOS; the approximate number of students who attended, and any feedback from the students;
      ii. details of academic research projects in which PLEXOS was used, including copies of publications which refer to PLEXOS; either provide reference to at least one publication for each license granted (one being an internationally recognised publication) or annual regional database update, and

iii. any other information, reports, links etc which shows how Licensee has used PLEXOS.

(B) if the license is granted to an individual:

a. provide any information, reports, papers, links etc which shows how PLEXOS is being used, and at the completion of the work, show successful usage by providing a copy of the thesis or article published.

e) A solver must accompany every PLEXOS license. Energy Exemplar will activate, free of charge as part of a PLEXOS license, Mosek (LP Only), EELPS, SCIP and GLPK. The Licensee will therefore only have access to Linear Programming functionality when selecting one of these solvers during their simulations, for which support from Energy Exemplar is free of charge. Energy Exemplar also supports MOSEK (MIP), Xpress, CPLEX and Gurobi, all of which have Mixed Integer Programming (MIP) capabilities. If the Licensee chooses to model with MIP, it is the responsibility of the Licensee to obtain their own license for these solvers and provide Energy Exemplar with the evidence. The Licensee shall be liable to pay Energy Exemplar for solver support fees for MOSEK (MIP), Xpress, CPLEX and Gurobi.

2. Restrictions

a) Licensee may not:

i) Use the Software in any way except:-

- by an individual employed by (or, with respect to academic institutions, enrolled in a full-time course of study at) an accredited academic institution organised and operated exclusively for the purpose of teaching,
- at the location of the academic institution, and
- The use of a PLEXOS academic license for commercial purposes, including for paid research projects, is strictly forbidden. If the Licensee is found to be in breach of this condition, the Licensor shall take immediate legal action for the recovery of owed license fees, which shall be equal to the fee for an annual PLEXOS research license pro-rated for the term of the Licensee's use.

ii) Reverse engineer, decompile, disassemble or modify the Software or any part thereof.

iii) Rent or lease the Software.

iv) Without written consent of Licensor, provide or otherwise make the Software available in any form to any person other than the authorised user nominated in this Agreement.

3. Acknowledgment and Grant of Right to Use Information

a) In all publications and reports which use results generated with the Software, Licensee must refer to the Licensor and the Software by name and provide the website link:-

www.energyexemplar.com

b) The Licensee grants the Licensor permission to use any information provided by the Licensee to the Licensor pursuant to this Agreement for marketing and the development of the Software.

4. Warranties

a) Licensor warrants that:

i) Licensor has full power and authority to issue this license;

ii) Licensor has not previously entered into an agreement involving the Software that conflicts with any portion of this Agreement;

iii) the Software and its documentation do not infringe any copyright, violate any property right or privacy rights.

b) Licensor will, for the full term of this Agreement, defend, indemnify, and hold Licensee harmless against all claims, demands, suits, losses, costs, damages, and expenses that Licensee may sustain or incur as a result of any breach of a warranty in clause 4(a).

c) These warranties and indemnities in this clause 4 will survive in the event that this Agreement is terminated.

5. Support

5.1 Provision of technical support

a) Licensor will provide support in the use of the Software, using such means and under such conditions as the Licensor may from time to time notify to the Licensee, such conditions including that:

i) Licensee has executed this Agreement; and

ii) Licensee has paid to the Licensor any solver support fees applicable; and

iii) Support is conducted via the Licensor's website, which may include user support forums.

b) Licensor does not guarantee that all issues can be addressed, or that issues can be addressed within a time period that Licensee might require. If Licensee requires a level of technical support or responsiveness that is guaranteed, Licensee may contract with Licensor to provide such a service subject to fees agreed mutually.

5.2 The support provided by Licensor is subject to the following conditions:

a) The support set out in clause 5.1 does not include:

i) solver support for MOSEK (MIP), Xpress, CPLEX and Gurobi, unless paid for by the Licensee.

ii) correction of errors or defects caused by operation of the Software in a manner other than that currently specified by the Author;

iii) correction of errors or defects caused by Licensee's modification, revision, variation, translation or alteration of the Software not authorised by the Author;

iv) correction of errors caused in whole or in part by the use of computer programs other than the Software;

v) correction of errors caused by the failure of Licensee to provide suitably qualified and adequately trained operating and programming staff for the operation of the Software;

vi) training of operating or programming staff;

vii) development of market databases for use with PLEXOS;

viii) rectification of operator errors;

ix) rectification of errors caused by Licensee's incorrect use of the Software;

x) rectification of errors caused by an equipment fault;

xi) equipment maintenance;

xii) diagnosis or rectification of faults not associated with the Software;

xiii) furnishing or maintenance of accessories, attachments, supplies, consumables or associated items, whether or not manufactured or distributed by Licensor;

xiv) correction of errors arising directly or indirectly out of Licensee's failure to comply with this Agreement or any other agreement with Licensor; or

xv) correction of errors or defects which are subject of a warranty under another agreement.

b) If Licensee makes a request to Licensor in writing for any of the support services in clause 5.2(a), Licensor may provide or arrange for the provision of these services for a fee agreed with Licensee or at Licensor's or the service provider's standard rates on a time and materials basis.

5.3 Product Updates

a) The Author may, from time to time, improve, extend, or update the Software product. Licensee is entitled to be notified of such updates by Licensor, and Licensor will make those updates available to Licensee via the Internet.

5.4 Documentation

a) Licensee will have access to online materials for the Software via www.energyexemplar.com. These materials may be updated without notice to Licensee from time to time.

b) No printed documentation is supplied with the Software.

5.5 Extension of Software Functionality

a) Licensee may request that certain functionality be added to the Software, or that certain existing functionality be modified or enhanced. All such requests must be made via the support area in the Licensor's website. Upon receipt of a request, Licensor will refer the request to the Author, who will review the request and inform Licensor of:

i) the feasibility of the proposal; and

ii) the likely time required to implement the proposed functionality.

b) Where the proposed functionality would be available to all licensed users, the Author may choose to develop the functionality at no charge to Licensee.

c) If either:

i) The Author determines that the proposed functionality is not feasible; or

ii) The Author otherwise decides not to develop the functionality; or

iii) Licensee does not wish the proposed functionality be made available to all licensed users of the Software;

then, the Author may choose to develop the functionality at a cost to Licensee on a time and materials basis, and otherwise on terms agreed between the Authors and Licensee.

6. Termination

a) This License is effective for the Term unless it is terminated in accordance with clauses 1(d) and 6 of this Agreement.

b) This Agreement will terminate immediately without notice from Licensor if Licensee fails to comply with any provision of this Agreement, or if Licensee becomes, threatens or resolves to become or is in jeopardy of becoming subject to any form of insolvency administration.

c) Upon termination:

i) Licensee must destroy any copy of the Software and related documentation and all copies thereof in their possession; and

ii) Licensor may retain any monies paid; and

iii) Licensor and the Author may pursue any additional or alternative remedies provided by law.

7. Release and Limitation of Liability

a) While reasonable efforts have been made by the Author and Licensor to ensure the Software operates substantially as described, neither the Author nor Licensor can guarantee proper operation in every possible configuration. For this reason, the

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b) With the exception of the Licensor's or Author's liability obligations regarding intellectual property infringement or personal injury or death, in no event will the Licensor or the Author be liable to the Licensee for any damages (including, without limitation, economic loss, loss of profits, business interruption, loss of contracts or information or any other consequential or foreseeable loss or damage) arising directly or indirectly out of the use of the Software, or out of any goods or services supplied pursuant to this Agreement.

c) All statutory or implied conditions and warranties are excluded to the extent permitted by law.

d) To the extent permitted by law, the liability of Licensor for any breach of this Agreement, or for any breach of a condition or warranty which cannot legally be excluded, shall be limited, at the option of Licensor, to one or more of the following:

   i) if the breach relates to goods, the replacement of the goods, or the supply of equivalent goods, by Licensor, or at Licensor's option, payment of the cost of replacing the goods or of acquiring equivalent goods; and

   ii) if the breach relates to services, the supplying of the services again by Licensor, or at Licensor's option, paying the cost of having the services supplied again.

8. Patents, Trademarks, Copyright and Intellectual Property Rights

a) Licensee acknowledges that any and all of the trademarks, trade names, copyrights, patents, and other intellectual property rights used or embodied in or in connection with the Software shall be and remain the sole property of the Author or such party as may be identified therein or thereon "the Owner". Licensee shall not during or at any time after the termination of this Agreement (whether in whole or with respect to support only) in any way question or dispute the ownership by the Owner of any such rights.

b) In the event that new inventions, designs, processes or copyright relating specifically to the Software evolve as a result of this Agreement, Licensee acknowledges the same shall be the property of the Author unless otherwise agreed in writing;

c) Licensee shall defend, indemnify and hold licensor harmless from and against any and all liability, loss, expense (including reasonable attorneys' fees), or claims for injury or damages arising out of the performance of this Agreement but only in proportion to and to the extent such liability, loss, expense, attorneys' fees, or claims for injury or damages are caused by or results from the gross negligent or intentional acts or omissions of Licensee, its officers, agents or employees.

9. Confidential Information

a) Any information, data, drawings, specifications, documentations, software listings, source or object code of the Software (Confidential Information) which the Licensor and/or the Author may have imparted to the Licensee relating to the Software or support thereof is proprietary and confidential and shall be used by the Licensee solely in accordance with the provisions of this Agreement. The Licensee shall hold the Confidential Information in confidence with at least the same degree of care it uses to protect its own Confidential Information. The obligations of confidentiality under clause 10 a) do not apply to Confidential Information that, i) is disclosed to Licensee by a third party entitled to do so, ii) was already lawfully in the Licensee's possession when it was given to Licensee and was not otherwise acquired from the Licensor or Author directly or indirectly, iii) is generally available to the public or subsequently becomes so available other than by reason of a breach of this License Agreement, or iv) is necessary to comply with any court order. The obligations of confidentiality terminate five (5) years after the date of termination of this License Agreement.

b) Licensee shall not itself or through any subsidiary, agent, or third party modify, vary, enhance, copy, sell, lease, license, sub-license or otherwise deal with the Software or any part or variations, modifications, copies, releases, versions, or enhancements thereof or any supporting software or have any software or other program written or developed for it based on any confidential information supplied to it by Licensor and/or the Author.

10. Assignment

a) This Agreement is personal to Licensee and Licensee must not assign or otherwise deal with this Agreement except with the prior written consent of Licensor. Licensor is not required to give consent or justify the withholding of consent, and may give consent subject to any reasonable conditions.

b) Licensor and the Author (or either of them) may transfer all or any part of its rights, interests, obligations or liabilities under this Agreement by assignment or novation. Licensee consents at any time this assignment or novation and waives any requirement for Licensor or the Author to provide prior notice to Licensee of such assignment or novation.

11. Taxes

a) In the event that stamp duty or any other taxes are payable under this Agreement, Licensee shall be liable to pay all duties and taxes payable in connection to this Agreement.

12. Force Majeure

a) Licensor shall be under no liability to Licensee in respect of anything which, apart from this provision, may constitute breach of this Agreement arising by reason of force majeure, namely circumstances beyond the control of Licensor, which shall include but not be limited to acts of God, perils of the sea, air, fire, flood and drought, explosion, sabotage, accident, embargo, riot, civil commotion, including acts of local government and parliamentary authority; breakdown of equipment and labour disputes.

13. General Provisions

a) This Agreement constitutes the entire agreement between the parties and supersedes all prior representations, agreements, statements and understandings, whether verbal or in writing.

b) Any express statement of a right of Licensor and/or the Author under this Agreement is without prejudice to any other right of Licensor and/or the Author expressly stated in this Agreement or existing in law.

c) Each covenant, condition and provision of this Agreement that is capable of having effect after the end of this Agreement continues in force although this Agreement has ended or has otherwise been fully performed.

d) Failure or neglect by Licensor to enforce any of the provisions hereof shall not be construed nor deemed to be a waiver of Licensor's rights hereunder nor in any way effect the validity of any part of this Agreement nor prejudice Licensor's right to take subsequent action.

e) If anything in this Agreement is unenforceable, illegal or void then it is severed and the rest of this Agreement remains in force.

The parties acknowledge and agree that this Agreement was negotiated in California and is to be governed by and construed in accordance with the laws of the State of California, and each party agrees to submit to the non-exclusive jurisdiction of any California court or federal court sitting in the State of California.

Name: Steven Broad

Signed:

Date: 1 Sept 2016

For: Energy Exemplar LLC

Licensee (User) Name: <Nabeel Alabbas>

Signed: < >

Date: <9/1/2016>

Authorised University Representative or Supervisor's Name: < Lado Kurdgelashvili>

Signed: < L. Kurdgelashvili >

Date: <9/1/2016>

For: <Center for Energy and Environmental Policy, University of Delaware>

Appendix A : Solvers Licenses

MOSEK, CPLEX and Xpress-MP are protected by copyright laws and international copyright treaties, as well as other intellectual property laws and treaties.

By using the Software, Licensee agrees to be bound by the respective terms of the solver's license agreements, which can be found at the following websites;

For MOSEK: www.mosek.com

For CPLEX: www.ilog.com

For Xpress-MP: By using an embedded version of Xpress-MP, Licensee agrees that this Agreement applies mutatis mutandis XpressMP

Appendix F

COPYRIGHT TRANSFER AGREEMENT AND PERMISSION TO REPUBLISH FOR IAEE CONFERENCE PROCEEDINGS

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The following articles first appeared in the proceedings of the 34th USAEE/IAEE Conference:

Identifying pathways toward sustainable electricity supply and demand using integrated resource strategic planning model for Saudi Arabia

Weather-based long-term electricity demand forecasting model for saudi arabia: a hybrid approach using end-use and econometric methods for comprehensive demand analysis