Power Shifts: A Techno-Economic Analysis of Multinational Electricity Market Development in the Middle East

by

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B.Sc. Mechanical Engineering, Massachusetts Institute of Technology (2014)

Submitted to the Institute for Data, Systems, and Society
in partial fulfillment of the requirements for the degree of

Master of Science in Technology and Policy

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Abstract

Electricity demand has been rising rapidly in the six Gulf Cooperation Council (GCC) countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates). As a result, the diversification and sustainable transition of their electricity sectors has been a priority. As part of these efforts, the GCC countries interconnected their electricity grids in 2011, with the aim of sharing reserve capacity, thus enhancing system reliability.

The GCC has sought to further utilize this interconnection by developing a regional market in order to exchange power real-time across borders and reap the economic efficiencies of regional trade. However, the utilization rate of the interconnector remains low (around 8%) due to fuel subsidies, different stages of national electricity market development, and the lack of clear trading rules.

This thesis analyzed how the interconnector could be better utilized. A network constrained multi-period economic dispatch with optimal DC power flow and uniform loss representation model was developed in order to assess the economic benefits of cross-border trade within the GCC. It covered fifteen years of planned capacity expansions, from 2016 to 2030, resulting in a model that incorporates 428 power plants across the six GCC countries and a high-level network representation with 26 nodes and 68 high-voltage transmission lines.

Analysis specifically focused on how operational costs (fuel and variable operation & maintenance costs) and electricity prices could be reduced by trading power across borders on current and planned GCC infrastructure. Based on the data available, our model revealed that about USD $1 Billion could be saved in annual operational costs (about 2% when using international fuel prices) from this regional electricity trade.

The model also revealed the overwhelming impact of fuel subsidies, calculating that the GCC would spend more on fuel subsidies for electricity production annually (around USD $60 Billion) than the complete yearly operational costs of the six countries combined without. Removal of subsidies would significantly affect the volume and direction of exports across the network, flipping some countries from net importers to exporters, as well as impacting the utilization rate of transmission lines.

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Omnia cum tempore.

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Acronyms

ADWEC Abu Dhabi Water and Electricity Company.

BOO Build-Own-Operate.

CPV Concentrating Photo-voltaic.

CSP Concentrated Solar Power.

DCPF Direct Current Power Flow.

ECRA Saudi Arabian Electricity and Co-Generation Regulatory Authority.

EIA United States Energy Information Agency.

FACTS Flexible Alternating Current Transmission Systems.

GCC Gulf Cooperation Council.

GCCI Gulf Cooperation Council Interconnection.

GCCIA Gulf Cooperation Council Interconnection Authority.

GSEE Global Solar Energy Estimator.

HV High-Voltage.

HVDC High Voltage Direct Current.

IEA International Energy Agency.

IPP Independent Power Producer.

IRENA International Renewable Energy Agency.

IWPP Integrated Water and Power Project.

KAPSARC King Abdullah Petroleum Studies and Research Center.

KSA Kingdom of Saudi Arabia.

LNG Liquefied Natural Gas.

LP Linear Program.

MENA Middle East & North Africa.

MER Mercado Eléctrico Regional.

MILP Mixed-Integer Linear Program.

NPV Net Present Value.

NREL National Renewable Energy Laboratory.

NSE Non-Served Energy.

O&M Operation and Maintenance.

OPF Optimal Power Flow.

PV Photo-voltaic.

SEC Saudi Electric Company.

SIEPAC Sistema de Interconexión Eléctrica de los Países de América Central.

TMY Typical Meteorological Year.

TOU Time-Of-Use.

UAE United Arab Emirates.

Chapter 1

Introduction

In the past twenty years, there has been a push toward the creation of "supranational" or "regional electricity markets", markets of a higher hierarchical level of organization encompassing several national, state, or local systems. Historically these interconnections served to enhance system reliability, rather than cost dispatching efficiency, meaning power was only traded, often in bilateral or multilateral agreements, when the systems needed back-up energy to ensure system integrity. In recent years this perspective has evolved, and the question is asked of how much these regional grids, and the subsequent development of real-time power exchanges across borders, can have an economic benefit for the interconnected parties.

In establishing these regional grids, particularly at a multinational level, there is a balancing act to play between four sometimes opposing forces: (a) guaranteeing national security in terms of power supply, (b) decreasing total capital costs of the power system by reducing cross-border redundant capacity, (c) driving economic efficiency by trading the lowest marginal generation across borders, (d) ensuring system stability and resiliency.

Since power security is a national priority, this often sets a lower bound on the capital costs as countries want to retain the capacity to satisfy their critical national demand. National power security can also be compromised if cross-border trading impacts grid stability. This entails cross-border connections are often DC interconnections, which shield from frequency instabilities and diminish long-range losses, albeit at a greater infrastructure cost. Yet these cross-border interconnections can also enable economic efficiency (and thus lower electricity costs) via real-time trading and dispatch of the lowest marginal cost power across borders.

While it is generally agreed upon that such cross-border power trading will have economic benefits region-wide, the implementation of a market poses several institutional and regulatory challenges. Indeed, cross-border trading of electricity often entails that prices will rise in regions with low generation cost as they sell their electricity. Thus, one of the greatest challenges in designing and implementing a regional market is to change the "national mentality" of all actors into a "regional mentality", where maximization of global social welfare of the region becomes a shared objective. Historically, countries have been very reluctant to trade electricity across borders: global exports of electricity are around 3% of total production; this is quite low for the energy sector as other energy-related commodities average at 64% for oil and 31% for gas and 16% for coal. [1] This is due to the characteristics of electricity that make it an unusual commodity, as well as the challenges in developing functional cross-border markets.

Effective implementation of these multinational electricity markets requires extensive infrastructure planning, sound market design, and a robust regulatory framework. These structural, institutional, and regulatory requirements needed for successful regional market functioning are generally known and understood *in theory* - the real challenge is determining the correct pathway toward their development, particularly when stakeholders have competing interests.

In determining the path forward, several questions remain: How much are countries willing to rely on each-other to meet their national demand, and by how much can interconnections reduce the need for new capacity investments? Given existing electricity infrastructure, how much can operational costs and electricity prices be reduced by designing a market that will dispatch the lowest-marginal-cost electricity across borders? What policy steps need to be taken to achieve these goals?

1.1 Motivation

There is a body of literature devoted to regional electric power systems planning and market design, including developing and analyzing long-term strategic plans. Many of these studies employ the use of large optimization models, which, due to the significant advances in optimization algorithms and computational processing power, have allowed for increased complexity in the systems modeled. Such analyses have served to inform energy policy, infrastructure planning, and long-term term national strategies.

Yet, for all the mathematical tools available, policy-makers decisions are often shaped by political strategy rather than pure techno-economic rationality. As with any policy process, individual actors are constantly trying to influence policy for their own benefit or to align with their values, advocating for choices that may not lead to a higher social welfare in the aggregate. For example, a producer may have a strong private incentive to object to a new market design if it will result in a more competitive marketplace with lower prices; a buyer that relies upon a constrained network path for delivery will likely oppose increasing competition for this scarce resource. When these actors happen to be different sovereign nations, a complex game of energy geopolitics can follow. Unlike oil or gas, the unique characteristics of electricity lead to a set of heightened risks that countries are hesitant to take.

As a recent *Economist* article noted, "to outsource a significant proportion of your electricity generation to a neighbor is to invest huge trust in that neighbor's political stability and good faith."[2] The lack of such trust was, indeed, one reason Desertec[1] failed. If trust can be established, the technology exists to harness and transmit power across borders for shared economic benefit. The real question, is thus: *whether the political will exists.*

Consequently, this thesis was motivated by a desire to explore the dynamics of regional coordination in power systems and understand how different market rules, long-term de-

[1] Proposed project to interconnect the North African and European electricity grids to export solar power

velopment plans, and domestic policies shift the relative benefits amongst the connected countries, thereby impacting the geopolitical will to engage in such an undertaking.

1.2 Objectives

Within these broader research motivations, this thesis focuses on the specific case of the Gulf Cooperation Council (GCC) countries, which are dealing with how to transition their energy sector into a more sustainable one. As part of these efforts, the Gulf Cooperation Council Interconnection (GCCI) was built in order to link the power grids of the six countries, namely Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE). The connector, however, has only been used for reserve capacity, and thus only used at 8% of its full potential. [3] The objective is thus to identify how the interconnector could be better utilized, focussing specifically on evaluating the benefits of trading electricity across existing and planned electricity infrastructure of the GCC.

1.3 Key Questions

The central question of this thesis is: **What is the economic impact of cross-border electricity trade amongst the GCC countries and how could a regional market be developed?** In answering this question, the following topics will also be explored:

- Which countries benefit the most from regional trade?
- How is the electricity price in different member states impacted by regional trade?
- How do market distortions such as fuel subsidies impact the volume and value of trades?
- Given these distortions, could "in-kind" trading based on time-of-use blocks serve as an intermediary step?
- What are the best practices from other regions in the world that can be applied to the GCC regional market?
- What institutions and regulatory frameworks are needed to facilitate cross-border trade?
- What are the potential geopolitical consequences of regional trade?

1.4 Intended Audience

In the majority of strategic studies in the electricity sector, the metrics of interest are the system-wide aggregate costs and benefits, as optimizing these are generally the primary objectives of power systems. While this thesis will certainly explore system-wide benefits, we have tried to go one step further in analyzing and comparing the relative "power shifts" between countries. This thesis attempts to provide insights into why certain public policies or regulatory changes face stronger geopolitical resistance than others. The intended audience for this thesis extends beyond the policy-makers themselves to the politicians who play a key role in negotiating and adopting these policies. The former, whose goals tend to lie in maximizing social welfare, will still benefit from the modeling and assessment of policy options presented in this work. The latter, whom above all are interested in how policies benefit their constituents, will benefit from the analysis of how the different policies shift the balance of "winners and losers".

1.5 Thesis Structure

This thesis divides the background and literature review into two parts: Chapter 2 provides an overview of electric power system fundamentals, electricity markets, and the challenges of regional integration. Chapter 3 provides an overview of the economic and resource landscape of the Gulf Cooperation Council countries as well as broader trends in the Middle East impacting the power sector. Chapter 3 also reviews the development of and challenges facing the existing GCC electricity interconnection. The next two chapters are devoted to the quantitative methods and data. Chapter 4 presents our modeling methodology beginning with a brief literature review of modeling methodologies, a discussion of the model developed for this thesis, followed by its mathematical formulation. Chapter 5 lays out the different case studies, including analysis of the inputs and parameters influencing the different scenarios modeled. The results, including analysis and policy implications are discussed in Chapter 6. The thesis concludes with a discussion of the geopolitical implications, policy recommendations, and suggestions for further work in Chapter 7.

Chapter 2

Electric Power Systems and Regional Electricity Markets

In order to analyze the impact of a GCC regional electricity interconnection and the pathways to developing a functioning market, a brief discussion of electric power systems and electricity markets is necessary. The first question is why develop a regional electricity market? The answer lies in part with the more fundamental question of why develop a "liberalized" electricity market in the first place, rather than having electric power systems be centrally-planned? In order to answer this second question, it is important to understand the technical and economic dimensions of electric power. Thus this section will briefly review the answers to these questions, presenting the key points of academic literature on the topic.

2.1 Electric Power Systems Overview

While the work of this thesis focuses on the economic aspects of multinational electricity grids, due to the unique properties of electricity, the economics are impacted by the physical constraints, notably those of generation technologies and transmission lines. Consequently a brief discussion of electric power system fundamentals, mostly focused on generation and transmission, is useful.

Electric power systems encompass the generation, transmission, and distribution of electricity, represented in Figure 2-1. Generation is the most "upstream" of the system, consisting of various types of power plants and generation technologies. Transmission are the "highways" of the electric power world, responsible for transporting power at high-voltage large distances. Distribution are the local roads, bringing power to end consumer once it has been stepped down to lower voltages.

Electricity is a unique good in that supply must in theory always exactly match demand, as there exist very limited possibilities for storage. A thorough review of power system economics can by found in [4], however some key principles are laid out below.

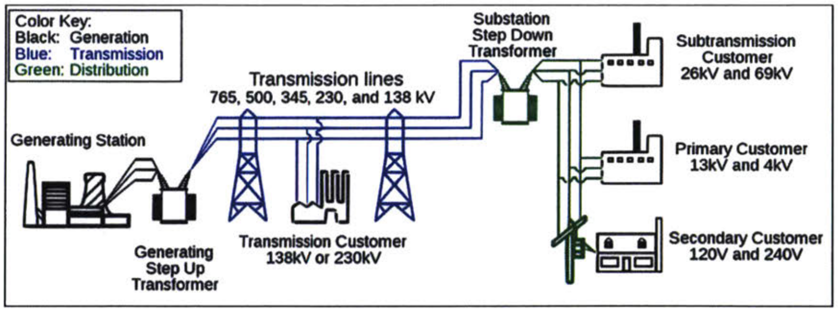


Figure 2-1: Electric Power System [5]

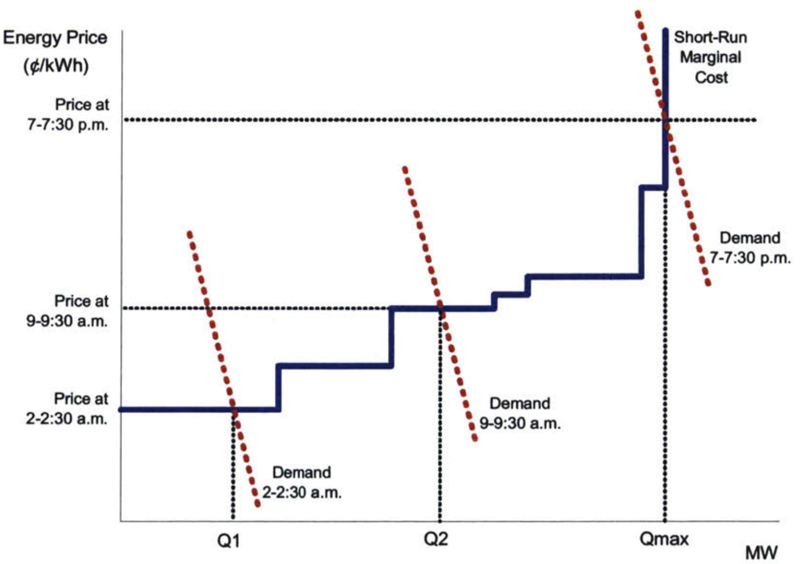


Figure 2-2: Electricity Spot Price: Short-Run Marginal Costs [6]

Generators supply power to meet demand. Consistent with the principles of economics, the generator with the lowest variable cost is dispatched first, followed by the next highest generator, and so on, as shown in Figure 2-2. The first-dispatched generators, the ones that always run to meet the minimum demand are known as "baseload generators"; those that run only a few times in the year to meet the system peaks are known as "peaking generators." Generators that fall in between are known as "load following". However, different generation technologies have different technical characteristics that can influence when they are dispatched, thus influencing the cost of supplying power. Many baseload technologies, such as coal and nuclear have low marginal costs, but also tend to be ill-suited to varying their power output. A nuclear power plant, can take several days to start up and shut down, thus no national power system would be designed with 100% baseload technologies. The technologies used as load following and peaking plants, in essence technologies that have the ability to ramp up and down quickly, tend to be internal combustion generators (diesel fuel or oil) and gas turbines.

The optimal generation mix is determined by the load shape, the fixed and variable costs of the generators, as well as the operational flexibility of the different types of power plants.

The part of the world this thesis focuses on, the Middle East, is atypical in its generation mix: nearly the entirety of the generation mix are technologies with high marginal costs. In fact, certain countries, such as Saudi Arabia, have majority oil, crude, and diesel based generation mixes with inefficient internal combustion units. Other countries like Qatar, have entirely gas-based generation mixes.

In addition to the unique characteristics of the generators, the cost of electricity is also impacted by the transmission network, specifically the physical constraints that limit the flow of power to a specific node and the existence losses on the lines that reduce the final power delivered. Contrary to many other types of grid infrastructures, such as gas pipelines, electrical energy cannot be directed at will through a particular pass.

Rather, energy flows are distributed across the lines according to their impedances, the injections and withdrawals of power at the different nodes and the specific grid topology. Larger systems with more lines and longer distances may reduce the grids ability to maintain system operation, causing instability that may affect the balance between generation and demand. [7] This may reduce line transmission capacity to less than its natural thermal limit, further complicating the expansion and interconnection of systems.

Figure 2-3 provides a simple example of this. If 100MW of power are to be distributed from Bus 1 to Bus 2, via two lines that have different characteristics impacting their admittance (L_1 having 3 times the admittance of L_2) the flow of energy will be distributed as shown: 75 MW across line L_1 and 25 MW across line L_2.

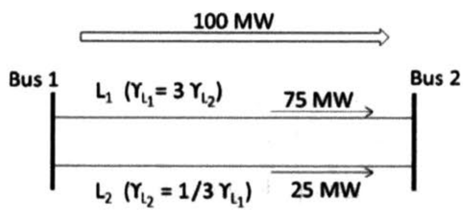


Figure 2-3: A simple example of Kirchhoff's Second Law: the distribution of energy flow across the two parallel lines with different admittance values [8]

The losses across the line can be categorized as fixed, ohmic (resistive), and non-technical losses. The first losses are essentially fixed magnetization losses in transformers, and thus are independent of the power flowing across the grid. The second type of losses, ohmic (resistive) losses, are proportional to the square of the power flow in the lines. The third type of loss result from theft on the line. [9]

These two technical characteristics have important implications for the integration of two power systems, particularly that the flows anywhere in the system can be greatly impacted by the loss or addition of a new line or generator. Furthermore, the flows and the use of electric lines do not depend on trades between actors, but rather on the energy injected and withdrawn at each node and the topology of the network. The second point has important implications for determining whom to charge (and how much) for the use of the transmission grid.

2.1.1 Electricity Price Formulation

The combination of different generation costs as well as the flows constrained by transmission lines result in different prices across the network. This concept, known as locational marginal prices (LMPs) was first analyzed in detail by the MIT professor Fred Schweppe and his collaborators in the early 1980s [10] using the term "spot prices". Locational Marginal Prices (LMPs) are the marginal cost of supplying, at least cost, the next increment of electric demand at a specific location (node) on the electric power network, taking into account both supply (generation/import) bids and demand (load/export) offer and the physical aspects of the transmission system including transmission and other operational constraints. The LMP or nodal price at a particular system node is defined as the "systemś short-term marginal operating cost of meeting an increment in demand at that particular node as economically as possible and within the constraints imposed by the system." [11]

2.1.2 Power System Operation

In addition to ensuring that real-time electricity demand is met in real time, power system operators must ensure system security. In real-time operation this means that for every generator supplying electricity there are systems in place to provide back up generation should there be an unexpected failure in the system. This is known as operating reserve. In essence, it is extra generating capacity available to the system operator within a short interval of time to meet demand in case a generator goes down or there is another disruption to the supply. Operating reserve is made up of the spinning reserve and non-spinning reserve.

The spinning reserve comes from increasing the power output of generators that are already supplying power. It is known as spinning reserve as in many generating systems this is done by increasing the torque applied to the turbineś rotor (which is already spinning).

Non-spinning reserve is also known as supplemental or capacity reserve. In general it refers to the extra generating capacity that is not currently connected to the system but can be brought on-line after a short delay (what this delay is varies by power systems). In isolated systems, non-spinning reserves are generally generators that can be started-up in a short period of time (such as a diesel generator). However, in interconnected power systems, such as the one studied in this thesis, includes the power available by importing from other systems, which could be spinning or not.

2.1.3 From Regulated Systems to Markets

The combination of the aforementioned technical and economic characteristics of electricity, combined with economies of scale, resulted in natural monopolies in the power sector. Governments allowed these monopolies to exist, subject to regulatory oversight. Thus in many power systems around the world, a single vertically-integrated electric utility company, often state-owned, held the role of managing and operating national electric power systems.

As a "central planner", these utilities were involved in the long-term planning of new generation and transmission infrastructure, medium-term planning of generator commitment, and short-term economic-dispatch of committed generators. In addition, these utilities were also responsible for system security by ensuring sufficient back-up capacity was available in the event of a failure.

However, several problems began to emerge. There was often little incentive to keep these utilities from becoming inefficient or over-investing, since prices to end consumers were fixed by regulatory authorities at an amount that would cover operational and investment costs. Different regulatory schemes were set up to correct this, to varying degrees of success. A review of different regulatory schemes as well as the various issues and challenges can be found in [12].

Following the creation of markets in other industries with natural monopolies (notably the telecommunications sector), governments decided to allow the invisible hand of market forces drive the optimal price and quantity of electricity to be produced. The hope was that competition would reduce prices, drive innovation, and improve service.

The creation of an electricity market or "liberalization" of electricity markets was first done in Chile in 1982 and England and Wales in 1990; the trend has followed around the world since. A review of the history of market liberalization can be found here: [12]. In recent years, the need for an influx of capital in strained government coffers has been another driving motive to privatize the power sector through liberalized markets. This last point has become an additional motivator for the creation of electricity markets in the Middle East region, since the 2014 oil price drops have significantly decreased government revenues.

From an economic theory perspective, markets consist of letting market forces drive optimal allocation of goods. In theory perfect central-planning and perfect markets yield the same results, however both tend to fail to reach that optimum. In the case of central planning, lack of incentives and information gaps can yield to a sub-optimum result. On the markets side, market failures such a market power, information asymmetries, barriers to entry and externalities could lead to a sub-optimal allocation of goods. Given the unique features of electricity, there exist plenty of opportunities for market failures. Thus the establishment of a suitable market structure (who are the players, what portion of the market are they allowed to operate in) and clear market rules (how do they transact) are crucial.

In electricity, due to the existence of natural monopolies in certain areas of the value chain, the market must be structured in a way to separate actors operating in competitive versus non-competitive areas. This, in essence, requires splitting up operation, management, (and often) ownership of various assets and associated functions. Generation is deregulated, meaning private firms are able to bid their capacity into a market. Transmission, a natural monopoly, remains regulated. Transmission owners must allow all generation companies equal access to their lines, in exchange for a fee. The question, how to determine cost allocation for transmission lines is a difficult one, and an important consideration for multinational power systems. It is discussed further in Section 6.2

2.1.4 Market Operation

With assets and functions separated into different actors, markets must be established for coordinating the match of bids across actors. (These systems of markets tend to vary by country, and coordinating between them is one of the reasons regional markets are difficult to implement, as discussed in Section 2.2.)

Any entity known as the System Operator (sometimes in conjunction with a Market Operator) is responsible for running the wholesale markets and operating the system. The electricity wholesale market consists of all the commercial transactions of buying and selling of energy as well as other services (back-up) related to the supply of electricity. These are generally organized in a series of successive markets (shown in Figure 2-4) where first market actors (supply and demand) trade energy, and then, in the periods closer to real-time, the System Operator acquires the "ancillary services" products related to the supply of electricity. The trading timetable covers a number of timescales: months or years before a trade is to be implemented, day-ahead markets to real-time when the transaction takes place. After the trades, settlement of accounts occurs, including payment of transmission costs. [7]

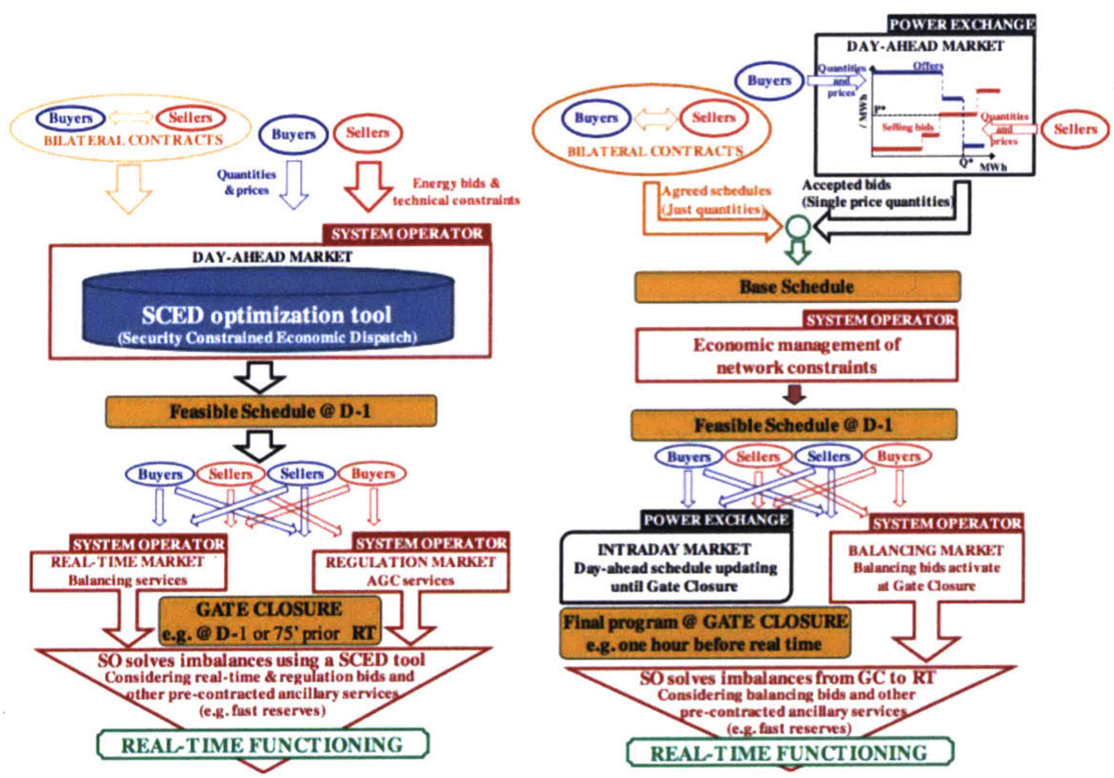


Figure 2-4: The US and European Electricity Market Sequence [7]

The first transactions that occur are long-term markets. These can take the form of futures contracts on prices or bilateral contracts between two parties. The majority of the exchanges on the GCCI exchange have been of this type. This is followed by day-ahead markets where the system operator will match bids from suppliers and demands to generate a feasible schedule. Based on this schedule, the system operator will also acquire ancillary services from the market to ensure that the reserve margins are met. There may be some intra-day balancing markets where buyers and sellers can trade as well. Finally in real-time, the operator will dispatch the system according to the bids, and then resolve any imbalances or transmission congestion using the ancillary services contracted. However, in the event those are insufficient, in most countries the System Operator also had the right to take control and call for other reserves.

2.2 Regional Markets

A regional electricity market is one that interconnects multiple independent national or state power systems. It has the effect of allowing suppliers and buyers from outside each region to participate in the market through a centralized bidding process and coordinated use of the shared regional transmission network.

There has been a trend toward the development of regional electricity markets around the world driven primarily by the opportunities to improve system reliability, lower the overall costs of electricity supply, and reduce new capacity investment costs. [13] Regional markets can help provide reserve capacity for other country's systems, by serving as "back-up", not only for primary, but also secondary and tertiary reserves depending on the level integration. Thus, new capacity investments can be reduced as regions can rely on each other for reserve capacity, especially if the countries' load peaks are not aligned. As discussed in Chapter 3, this was the original driver for the development of the GCCI. Regional markets also help improve market efficiency by allowing for the utilization of lower and more efficient generators, as well increasing competition by allowing for more competitors to participate. Regional markets can also reduce investment costs by capturing economies of scale in new generation assets by allowing multiple countries to co-invest in a share plant. The latter is less the driving case in the GCC region, but more applicable to smaller developing countries such as in Central America. Regional markets enhance security of supply by enabling the diversification of primary energy resources.

The main challenge to functioning regional markets is reaching the "single system paradigm", in essence reaching a harmonization of market rules, coordinated system planning and investment, and joint institutions to allow the market to operate as if it were one system. In reality, this is quite difficult as few nations are willing to cede control of their power systems, given that electricity is seen as a strategic asset of national security importance. [8] [14] For example, even if clear market rules are established, a country could fear that a neighboring nation my renege on its contractual obligations to supply power, potentially leaving that state in a critical short-supply situation. Finally, another challenge with regional markets is the issue common to all trade: prices of the mostly exporting areas will go up with exports, thereby hurting consumers.

Last but not least, if a regional market is to be successful, it must ensure that all participants are on a level playing field - that is operating with the same set of rules. The lack of regulatory harmonization among the systems involved is often one of the greatest challenges. A specific example of this are network charges. Different countries often have different structures for their network charges. Some charge these only to generators, others only to consumers. Determining who pays which charges when trades flow across border adds a further barrier to integration.

2.2.1 Stages in Regional Market Integration

Regional markets must effectively integrate the national markets. This generally happens in a a series of stages.

The first stage is when the national systems are physically interconnected. Once the interconnection is in place, generation companies or system operators can engage in bilateral trade deals between systems. Generally these contracts are pre-agreed upon rather than real-time transactions. This helps improve the reliability of supply, particularly in providing reserve capacity. There is generally a minimum level of technical coordination as well as some harmonization of security and reliability criteria. This is the current phase of the GCC interconnector, discussed further in Chapter 3.

The second stage is when operation of the individual national systems is coordinated. The goal is for national systems to reduce their production costs by applying common technical and economic rules. A wholesale energy market is created where generation companies and suppliers can buy and sell power regionally. Basic regulatory provisions are created to provide fair market conditions.

The final stage of regional market integration is when operation is fully integrated between the national markets. There is some debate as to whether a supra-national system operator is required (this debate is discussed further in Ch 7). All agents can participate in the market and most importantly transmission network expansion is jointly planned at regional-wide level.

Chapter 3

Middle East Power Sector

The development of a multinational electricity market amongst the GCC countries is strongly influenced by the changing energy and economic landscape of the region. This chapter provides an overview of the GCC countries' resources, power system development, and recent economic trends. It concludes with a brief summary of some of the prior studies conducted on the development of a regional market.

3.1 Regional Overview

The Gulf Cooperation Council region are some of the world's largest hydrocarbon producing countries. The six member countries, Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates (UAE), hold almost a third of proven crude-oil reserves, and approximately a fifth of global gas reserves. [15]. Fossil fuel extraction and exports have been key drivers of economic growth, which in turn has brought widespread prosperity and development to the region.

Economic growth has led to a rise in living standards and industrial activity; consequently, fossil fuels have been increasingly used to meet these rising domestic energy needs. As a result, local governments have looked toward diversifying their local energy supply. A key component of this is transforming the electricity sector into a more sustainable one.

As shown in Figures 3-1 and Figures 3-2, the six GCC members have very different resource splits: three are very well endowed with oil and gas (Saudi Arabia, Kuwait, and UAE), one is well endowed with gas (Qatar), one has moderate oil and gas resources (Oman), and only one has relatively poor endowments of hydrocarbons (Bahrain). As a result, all GCC countries are heavily dependent on gas for power generation, with Saudi Arabia[1] and Kuwait also heavily dependent on oil. This can be clearly seen in the electricity consumption by fuel source for which the 2015 numbers are shown in Table 3.1.

[1] In many GCC countries the majority of the natural gas is associated gas, which is produced along with oil. Efforts in Saudi Arabia to expand onshore non-associated gas production have experienced difficulties in finding and extracting natural gas because of its high sulfur content (making the gas more expensive as it must undergo an additional process to remove the impurities) and low domestic natural gas prices. As a result, investing in natural gas projects has been financially unattractive.

Countries	Crude Oil* Proved Reserves (Billion Barrels)	Share of proven world reserves (%)	Production of Crude Oil (Thousand Barrels per Day)	Share of global production (%)	R/P ratio (years)	Share of exports out of production (%) **
Bahrain	0.1	0%	49.5	0%	7.0	0%
Kuwait	104.0	6%	2618.6	3%	109.0	69%
Oman	5.0	0%	943.5	1%	14.0	77%
Qatar	25.2			2%	1540.4	2%
Saudi Arabia	268.4	16%	9735.3	13%	75.0	78%
United Arab Emirates	97.8	6%	2820.0	4%	95.0	87%
GCC Total	**500.5**	**30%**	**17707.3**	**23%**	**57.5**	**65%**
World	1655.6	100%	77832.8	100%	58.0	58%

Figure 3-1: GCC Crude Oil Reserves [15]

Countries	Proved Reserves of Natural Gas (tcf)	Share of proven world reserves (%)	Dry Natural Gas Production (Billion Cubic Feet)	Share of global production (%)	R/P ratio (years)	Share of exports out of production (%)
	2014	2014	2013	2013	2014	2013
Bahrain	3	0%	554	1%	6	0%
Kuwait	64	1%	576	1%	110	0%
Oman	18	0%	1,127	1%	27	36%
Qatar	885	13%	5,598	5%	159	79%
Saudi Arabia	291	4%	3,526	3%	82	0%
United Arab Emirates	215	3%	1,928	2%	112	14%
GCC Total	**1,476**	**21%**	**15,323**	**11%**	**83**	**21%**
World	6,973	100%	121,283	100%	56	32%

Figure 3-2: GCC Natural Gas Reserves [15]

Many of the GCC countries have developed plans to address this dependency on fossil fuels, in part by diversifying their generation mix. The current (2016) and future generation capacities (2030) are shown in Figure 3-3, and discussed in further detail in Chapter 5.

Table 3.1: GCC 2015 Final Electricity Consumption (GWh) [17][2]

	Bahrain	Kuwait	Qatar	Saudi Arabia	UAE	Oman
Oil	9	43183	0	149531	1582	863
Gas	17238	24735	41499	188804	125488	31895
Solar PV	0	0	0	1	53	0
Solar Thermal	0	0	0	0	243	0
Other	0	0	0	0	0	0
Imports	205	0	0	0	42	0
Exports	-213	0	0	0	0	0
Total	17247	67918	41499	338336	127408	32758

[2]With correction for Bahrain using Bahrain Electricity & Water Authority Statistical Yearbook[16]

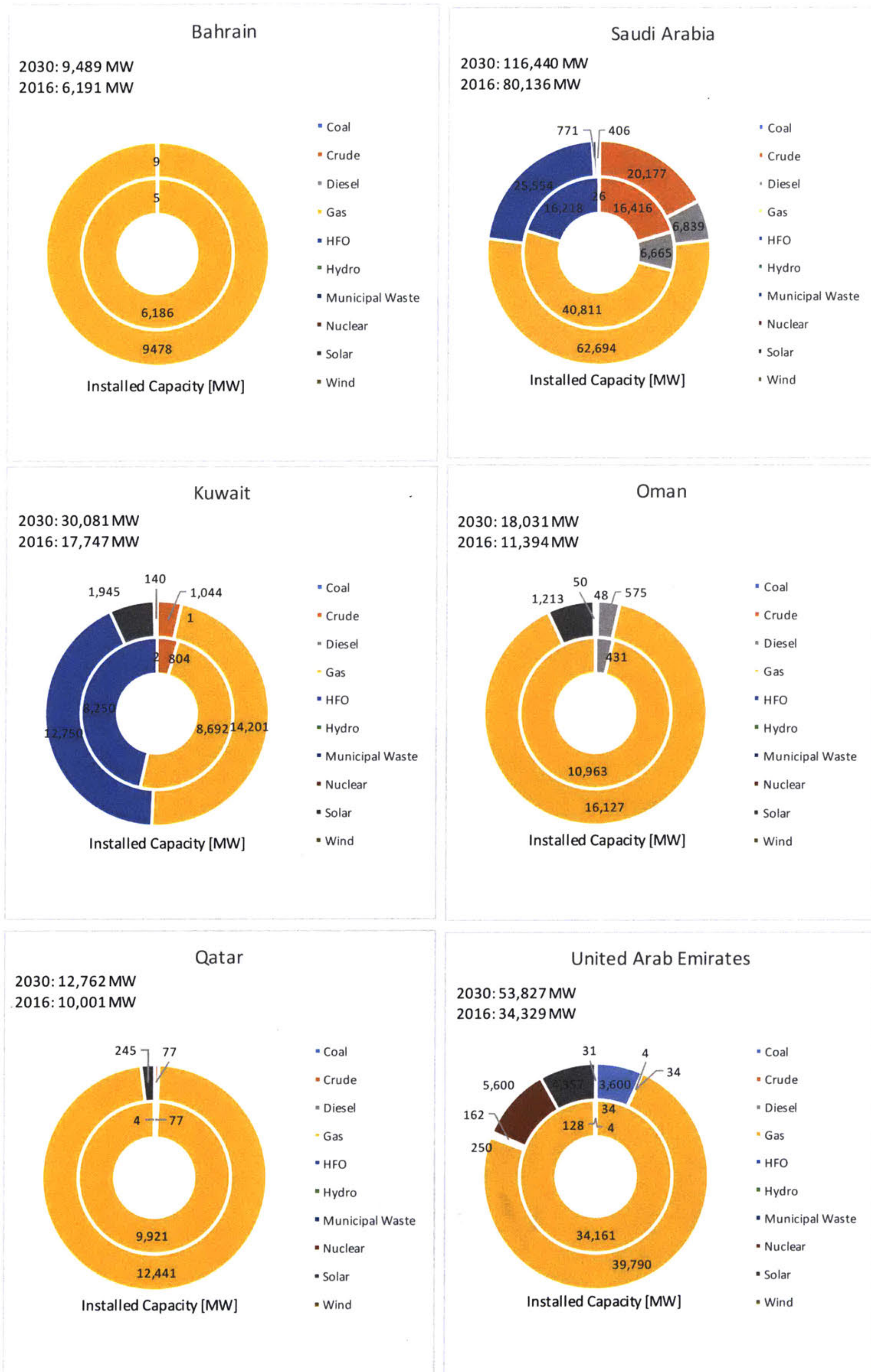


Figure 3-3: 2016 and Projected 2030 Installed Generation Capacity. Data Source: [18]

3.1.1 Demand

These energy transition plans all have the same objective: ensuring future demand can be met. While the actual demand volume differs amongst the GCC countries, due to population size and level of industrial development, energy consumption is substantial on a per-capita basis. A 2015 World Bank report [19] revealed that Kuwait, Bahrain, the UAE and Oman have energy consumption per-capita levels far above those of most other industrialized countries including the US, India, Russia, China and Japan. Qatar is the world's highest. [19] Furthermore domestic electricity demand has been growing in all of the GCC countries, driven by industrialization, population growth, water desalination, and rising standards of living. Figure 3-4 shows the rapid growth in electricity demand over the past 10 years, broken down by sector in Figure 7-2.

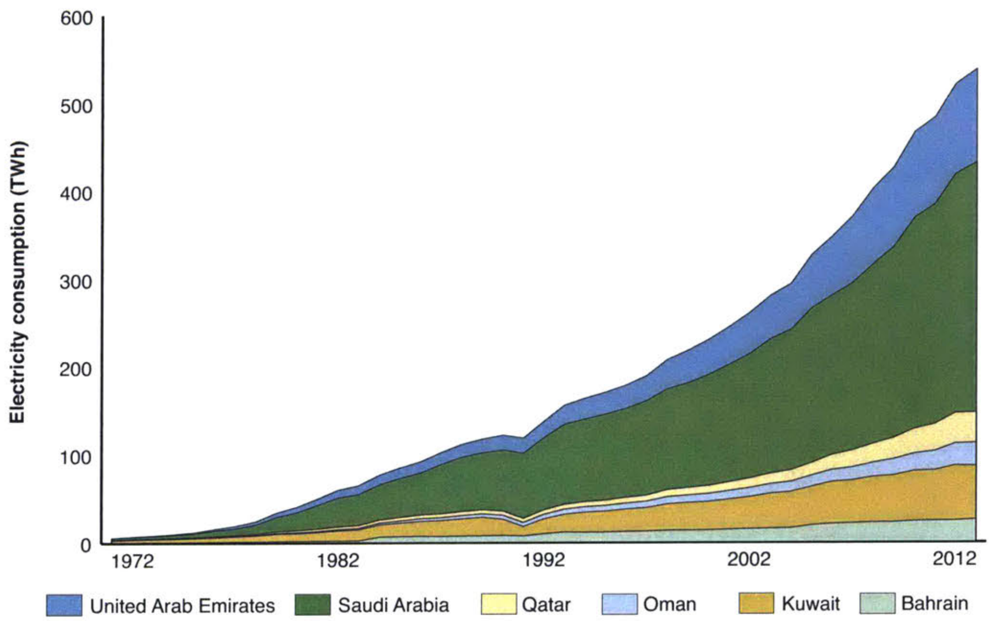


Figure 3-4: Past GCC Electricity Demand Growth [20]

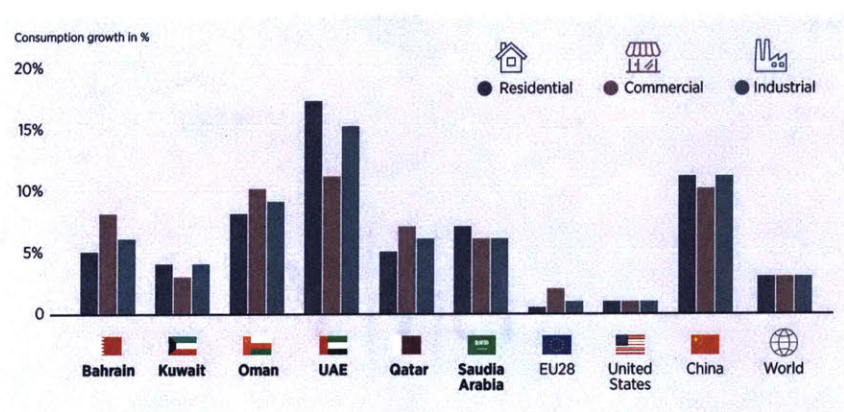


Figure 3-5: GCC Annual electricity consumption growth by user group, 2003-2013 (%) [21]

Demand is projected to continue at a rapid rate, as shown in Figure 5-4. For the next five years, growth is projected to be an average of 6.8% per year in the GCC region, slowing to 3.9% per year from 2026-2030. A further break-down and analysis of the individual countries' electricity demand profiles is conducted in Chapter 5.

Table 1 Renewable energy capacity by country in 2030

		Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates
Capacity (GW)	2030	0.7	10.9	2.4	1.8	29.3	33.3

Table 2 Demand projections by year and by country

		Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates
Growth Rate (used for projections of demand)	2016-2020	6.0%	7.0%	9.0%	6.0%	6.5%	6.5%
	2021-2025	4.0%	6.0%	7.0%	4.0%	4.5%	5.0%
	2026-2030	3.0%	4.5%	6.0%	3.0%	3.0%	4.0%

Figure 3-6: GCC Electricity Demand Growth Projections Until 2030 [21]

3.1.2 Sustainable Transition Plans

As a result of this rapid growth, many of the GCC countries have established sustainable energy transition plans, aimed at curbing demand growth via energy efficiency measures and diversifying their electricity mix. Figure 3-7 provides a summary of regional sustainable transition plans.

In addition to transforming their domestic energy systems, the GCC countries have made an effort to improve regional integration of energy infrastructure. This has led to the development of regional gas pipelines and integration of electricity networks. The first milestone in this regional integration was the completion of the Dolphin Natural Gas pipeline, which exports natural gas from Qatar. In 2007 gas began to flow to the UAE and in 2008 to Oman. Bahrain is building a Liquefied Natural Gas (LNG) terminal and there are plans to further connect the Gulf Countries. [22]. The more recent development following the integration of natural gas infrastructure was the integration of electricity networks.

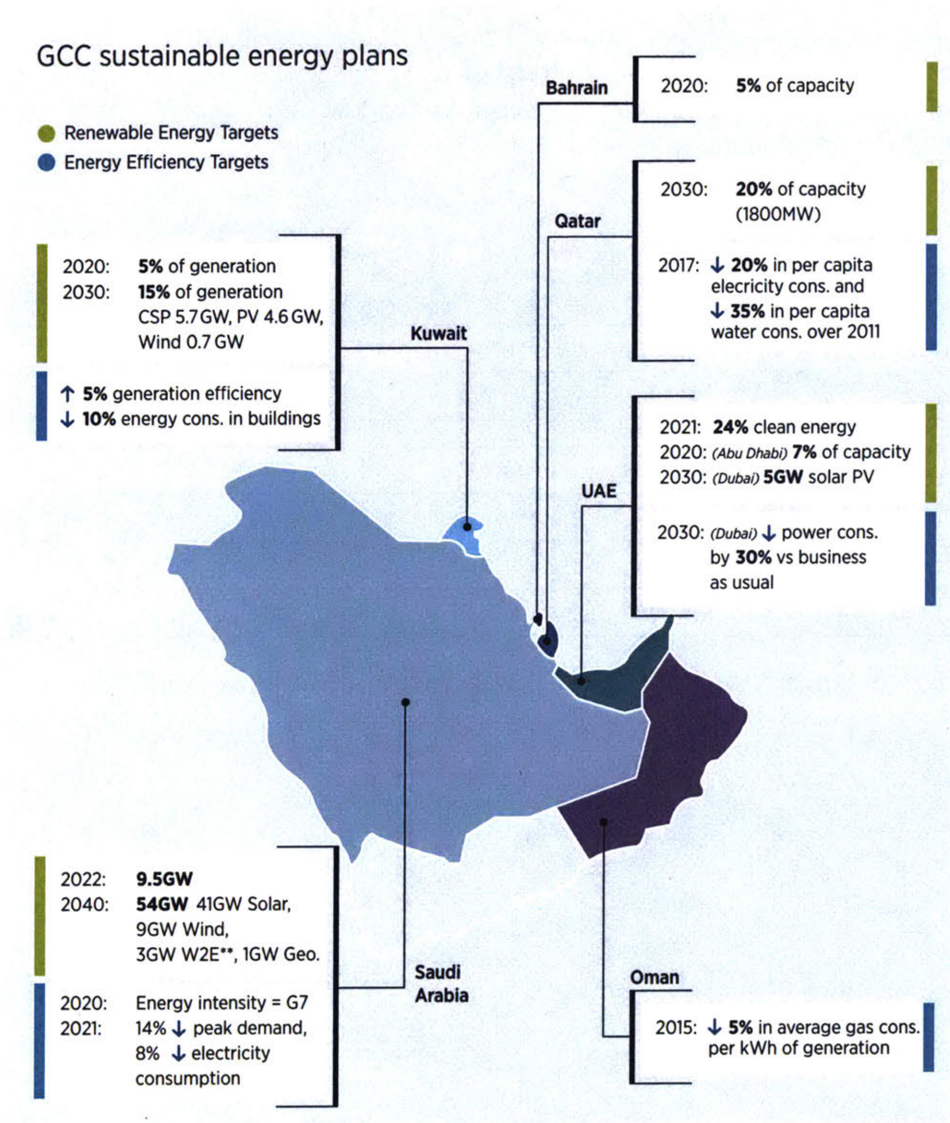


Figure 3-7: GCC Sustainable Energy Plans [15]

3.2 Electricity Interconnection

In parallel to the aforementioned measures taken to addressing the rapidly growing demand for energy, the GCC countries have sought to strengthen the security of their power networks. This led to the development of the GCC Interconnection Authority, which was envisioned primarily to allow participating countries to share reserve capacity in order to minimize overall investment in new generation assets at peak demand periods. It could further be used to exchange power in the event of emergencies.

The project was set in motion in 2001 with the establishment of a joint stock company, the Gulf Cooperation Council Interconnection Authority (GCCIA), which would manage the construction and later operation of the interconnector. Each of the six GCC countries contributed to the initial capital investment, with the share split was determined by the 1990 present value of the anticipated capacity expansion savings for each country. [23] [24] This calculation resulted in an initial share capital of $US 1,407,000,000, divided amongst the countries as shown in Figure 3.2. Construction of the final phase of the interconnector was completed in 2011, resulting in the network shown in Figure 3-8.

Table 3.2: GCCIA Initial Share Split [23]

Stakeholder	No. of Shares	Nominal Value	Percent
UAE	216,678	$ 216,678,000	15.40%
Bahrain	12,663	$ 12,663,000	9.00%
KSA	444,612	$ 444,612,000	31.60%
Oman	78,792	$ 78,792,000	5.60%
Qatar	124,619	$ 124,619,000	11.70%
Kuwait	375,669	$375,669,000	26.70%

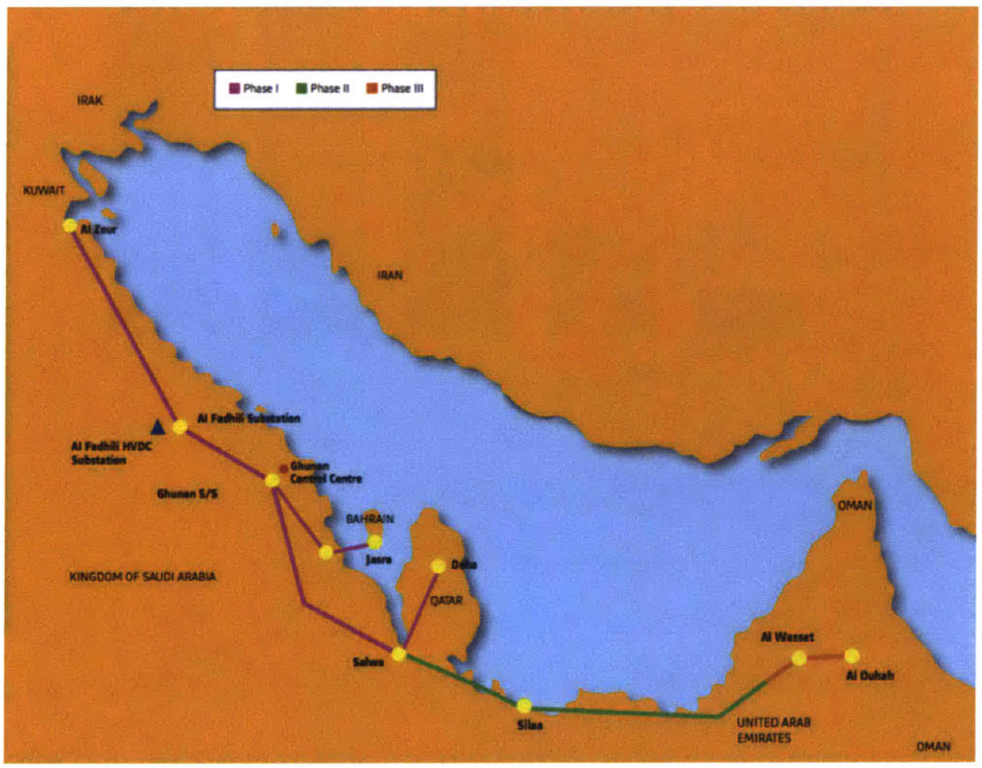


Figure 3-8: GCC Interconnector Map

3.2.1 Current Use

Since being put into operation, the Interconnection has been minimally used (a recent GCC report estimated the utilization rate at 8%) [25] This is consistent with its original purpose: reserve capacity sharing and emergency back-up. It was only later that the idea that the interconnection could be used for real-time power exchanges was considered. This becomes evident when reviewing the total volume of energy traded on the exchange over the past five years. As shown in Figure 3-9, with the exception of a few trades in 2011, all power exchanges have be in "unscheduled" exchanges, meaning reserves exchanges.

As of now there is a limited real-time market. The reasons for this are as follows: First, the domestic energy markets are in various stages of development causing a mismatch of market rules and regulations. Section 3.3 discusses these further. Second, fuel subsidies, discussed further in Section 3.3.1, cause price distortions as well as are a barrier to trade in countries a reluctant to "export subsidies". Finally, clear rules for power exchanges, particularly around transmission allocation and cost allocation have yet to be developed, creating regulatory uncertainty.

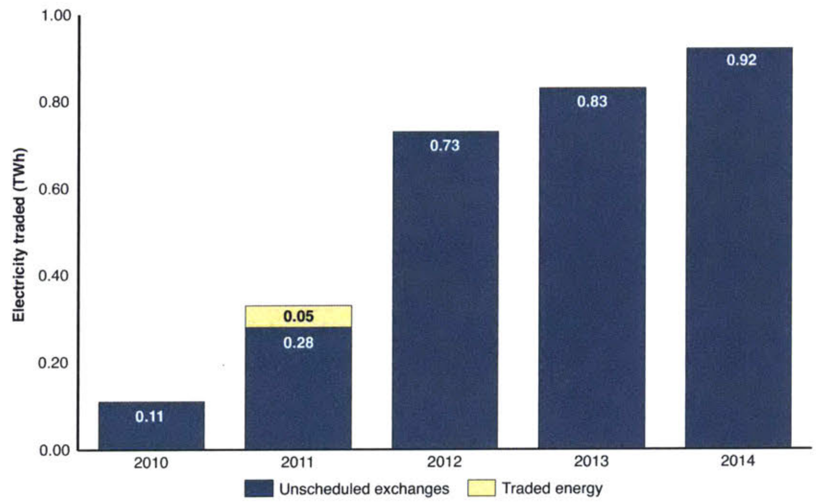


Figure 3-9: Power exchanges in over the GCCI. Unscheduled exchanges refer to reserve exchanges. [25][26]

3.2.2 GCCI Rules and Regulations

One of the barriers to a functioning regional market is the lack of clearly defined rules. This section provides an overview of the existing legal framework and rules in place.

The GCCIA is still in early stages, particularly in the area of establishing rules for unscheduled (spot market) power exchanges, as these exchanges were not part of the original purpose of the interconnector. The framework consists of a General Agreement, Power Exchange & Trading Agreement, and Interconnector Transmission Code as seen in Figure 3-10.

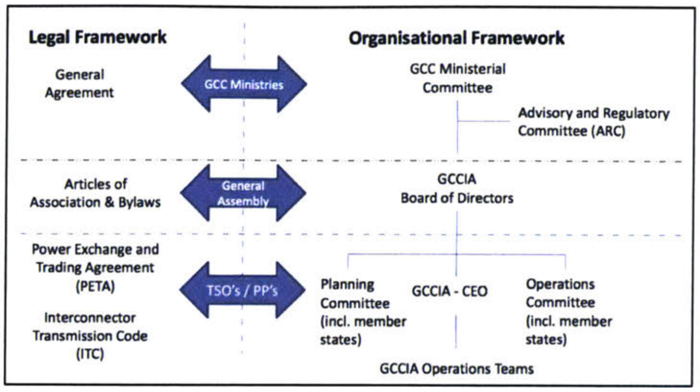


Figure 3-10: GCCIA Legal Framework [25]

The **General Agreement** lays out the fundamental agreement between member states with respect to the Interconnection, by setting out the rules and regulations to be applied on the Member States with respect to the interconnector. This agreement is a high-level "treaty" of sorts, agreeing to a multi-lateral aspect of the GCCIA. It does not appear to establish the GCCIA as an authority with "supra-national" powers.

The **Power Exchange Trading Agreement** (PETA) is the legal framework for trade signed by the participating entities, primarily the transmission owners and operators in member countries. This agreement outlines the obligations of all participating entities, including an obligation to maintain a minimum standing reserve margin of capacity relative to system peak demand and operating reserves, and arrangements by which members may use reserves from other countries to satisfy those obligations. This would need to be expanded to include the legal obligations of trades made in real-time.

The **Interconnector Transmission Code** is the "technical code" for the interconnector, which contains the specifics for how the interconnector is to be operated, including Operating Reserve allocation. This Code would need to be expanded with more specific market rules needed for power trading.

In the interconnected GCC system, the spinning reserve is shared amongst generators. The technical code stipulates that the reserve margins must correspond to the largest single credible incident, increased by a margin of 10%. The GCCIA has defined a "credible incident" as the failure of the largest unit installed within each system (although countries are free to choose a more restricting rule, such as in the case of Kuwait which set it as two simultaneous plant outages). The code further specifies that the reserve allocated to each unit shall not exceed 5% of its size. The sharing of the spinning reserves between the member states is determined by their share of total generation capacity in the synchronous system. [27] [28] Specifically, if the systems of the individual countries were entirely separate, the minimum total spinning reserve requirements would have to be 5138 MW, as shown in Table 3.3 [26]. However, because of the interconnector, each country can be used to provide reserves for each other. In accordance with the GCCIA transmission code, the minimum spinning reserve requirement would be 1028 MW (which is the size of the largest unit in the UAE). It would be allocated based on each countries percentage of total system capacity. It is important to note that because Saudi Arabia is not on the same synchronous AC system (it is connected via a back-to-back High Voltage Direct Current (HVDC) station since it runs at 60Hz), it is not included in the spinning reserve requirement, since the failure of a power plant on the Saudi side would have no impact on the 50Hz side (and vice-versa).

Table 3.3: Spinning Reserve Requirements For each Country with and without the Interconnection. [26]

Country	Isolated (MW)	Connected (MW)
Bahrain	759	82
KSA	730	N/A
Kuwait	957	236
Oman	819	151
Qatar	845	133
UAE	1028	455
Total	**5138**	**1028**

The Interconnector Regulations and Rules are not publicly available, but GCCIA reports do not indicate that further specifics about market rules have been written. This is quite problematic as each country has different market structures and rules.

3.3 Domestic Energy Markets

The different stages of domestic market development coupled with the lack of harmonization of rules is a further limiting factors for the establishment of a functioning regional market. This section provides a brief overview of the current domestic market status of each country.

Saudi Arabia

Saudi Arabia's electric supply is dominated by the Saudi Electric Company (SEC), which is a vertically integrated monopoly. SEC is a joint-stock company with shares traded publicly in Saudi capital markets, however about 80% of the company is owned by the government (74% directly and 6% through Saudi Aramco). In 2001, the Electricity and Co-Generation Regulatory Authority was created with the mission to "ensure the adequacy, reliability, quality and cost efficiency of the power supply" [29]. Oversight of the electricity industry fell under the Ministry of Water and Electricity (MOWE). Together these two entities share the joint responsibility for transitioning the power sector to a competitive market. Although there is no competitive electricity market at this time, there are plans to un-bundle the SEC into one transmission system, one distribution company and four generation companies. The market will initially be structured as a single-buyer market structure. [30].

Kuwait

Kuwait's power sector is dominated by a vertically integrated utility owned and operated by the Ministry of Electricity and Water. There is no independent regulator and Kuwait has only recently approved its first independent power producer.

Bahrain

Power generation in Bahrain follows the Build-Own-Operate (BOO) model. There are several private companies and the Electricity and Water Authority (EWA) acts as the single buyer of power from the BOO plants. The EWA also acts as the regulatory authority for the power sector, as there is no independent regulatory agency. The Ministry of Electricity and Water is responsible for electricity production and distribution in Bahrain.

Qatar

Qatar has already begun the restructuring and privatization of its electricity sector. All power generation in Qatar is now done by the private sector and Integrated Water and Power Project (IWPP)s. The Qatar General Electricity and Water Corporation buys power from the IWPPs and plans for new generating capacity. The Ministry of Energy and Industry issues licenses for power generation and transmission as well as monitors and ensures that licensees comply with standards and laws. As of now there is no independent regulator and, given the small-scale of the power system, the country is implementing a single-buyer market model. [31]

United Arab Emirates

The UAE's power sector is organized differently in each of the seven emirates, with four different service providers. However, the UAE Ministry of Energy is studying a common federal framework. [31] The Emirate of Abu Dhabi's power sector reforms are around the most advanced in the GCC. There is an independent regulatory agency, the Abu Dhabi Regulation and Supervision Bureau, which regulates all companies undertaking activities associated with electricity production, transmission and distribution. Abu Dhabi is the only emirate to have implemented a privatization program in the electricity sector and to have unbundled transmission from generation. [32]

Oman

Oman was the first GCC country to introduce the Independent Power Producer (IPP) and IWPP models, and has successfully privatized many of its power plants. The state-owned Oman Electricity Transmission Company is responsible for the transmission network, while the state-owned Oman Power and Water Procurement Company acts as the single buyer, purchasing all electricity from generators and selling it on to the distribution companies and large consumers. There are three state-owned distribution and supply companies of which the Electricity Holding Company owns 99.99% and the Ministry of Finance owns the remaining 0.01%. [31] The Authority for Electricity Regulation (AER) is the independent regulator.

3.3.1 Subsidies

Subsidies are a major issue in the GCC countries, causing significant distortions in the market. Subsidies exist both on the supply-side (as fuel subsidies) and on the demand-side (as subsidized electricity tariffs). This is further complicated as there is no commonly agreed definition of what constitutes a subsidy. The IMF [33] estimates that 2015 pre-tax Middle East & North Africa (MENA) subsidies (which they defined as the difference between consumer prices and the costs of supply) amounted to US$154 billion in 2015.

In the case of regional trade, fuel subsidies cause the greatest distortion as they effect the costs of power generation. The IMF estimated that petroleum, natural gas and coal account for the largest share of post-tax subsidies in the MENA region (around 89%), whereas electricity subsidies accounted for 11%.[33] The economic impact of fuel subsidies on GCC cross-border power trade is analyzed in Chapter 6.

Fuel Subsidies

The biggest distortion in GCC electricity markets are caused by fuel subsidies. While the governments of various countries have justified these on the basis that they provide protection for vulnerable consumers and improve the competitiveness of energy intensive industries, they cause distortions in the functioning of the markets. [34][35] The drop in hydrocarbon prices starting fall of 2014 has driven many Gulf States to attempt to ease out these subsidies with varying degrees of success. Few countries make public the amount by which they subsidies fuel prices (especially for power generation and industrial use). Estimated amount for natural gas subsidies in 2015 are shown in Figure 3-11.

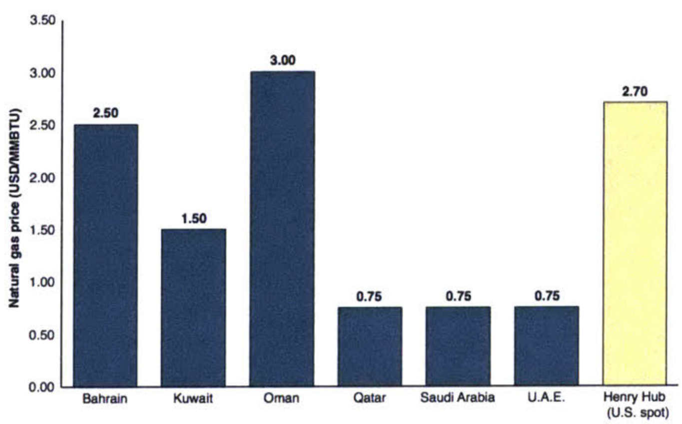


Figure 3-11: Natural Gas Subsidies in GCC Countries [20]

Electricity Subsidies

In addition to fuel subsidies, electricity tariffs are also subsidized, driven by both economic and socio-political reasons, resulting in domestic energy prices lower than international standards. While this thesis only looks at wholesale electricity prices, and thus does not incorporate tariff subsidies, these are still important to note, as such subsidies can also influence demand - particularly in encouraging over-consumption. A summary of electricity demand-per-capita and consumer electricity tariffs subsidization is presented in Figure 3-12 below.

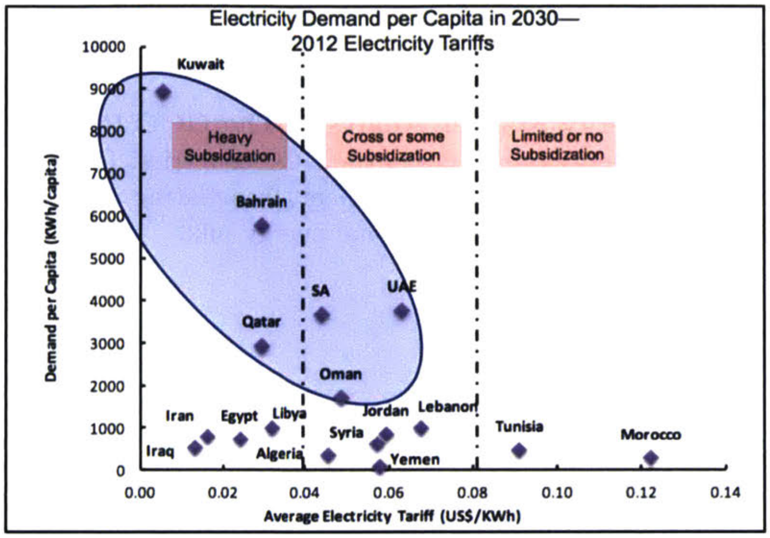


Figure 3-12: Projected 2030 Electricity Demand per capita with 2012 Electricity Tariffs [19]

3.4 Prior Studies

The desire to develop a regional market is not new, and several studies have been conducted on this. However most of the reports focus on qualitative analysis of the benefits of market development. None of the published studies appear to have employed power system modeling techniques discussed in Chapter 4. The following section briefly reviews the findings of major studies. These studies were used to benchmark the results of this thesis as well as to estimate missing input data.

GCCIA: Market Study Report (2004)
[24] This report is likley the most comprehensive report conducted thus far on the development of a regional electricity market in the GCC. The report remains mostly qualitative, providing descriptions of regional trends in the GCC as well as an in-depth overview of the theory of regional market design. It also includes some review of regional market development in other parts of the world and provides some high-level policy recommendations for the GCC countries.

IRENA: 2030 Pan-Arab Renewable Energy Strategy (2014)[36]
This report is focused on a high-level renewable strategy for the MENA region. It identifies key economic drivers and trends in the region, but does not delve into the details of regional market development.

GCCIA: Developing Power Trade Through the GCC Interconnector (2014)[37]
This conference presentation from 3rd Power Trade Forum in Abu Dhabi, is one of the few publicly available publications that contains some financial estimates about the value

of the Interconnection. This presentation is used to validate the results presented in this thesis.

GCCIA: Annual Report (2015)[25]
This annual report estimates the total economic value of the power exchanges across the interconnection during 2015 to be about $390 million. The majority of this value was estimated from savings made from avoiding new investment in capacity and spinning reserves.

IRENA: Renewable Energy Market Analysis: The GCC Region (2016) [15]
This report examines the energy economies of the GCC countries. It discusses the opportunities and barriers for renewable energy deployment, formulating recommendations for the greater integration of renewable into the regional energy mix.

Chapter 4

Methodology and Formulation

As discussed in Chapter 2, operating the electricity grid requires a complex hierarchy of decision-making. The longest-term decisions are to determine generation and transmission expansion plans in order to meet future projected demand. In the medium term, decisions about which generators to commit (bring on-line) are necessary. Finally in the short term, decisions about how to dispatch on-line generators in order to meet demand in the most economic manner are needed.

4.1 Literature Review

In regulated power systems, a central-planner or utility is responsible for this hierarchy of decisions. In de-regulated markets, these decisions are made by private firms, seeking to maximize their profit. Models can be used to study both.

4.1.1 Market Models

Given that this thesis studies the development of a regional electricity market, one approach could be to use a market model to study market dynamics. There exists a variety of models based on game theory, which explore actors' behavior, assuming that decisions should take competitors reactions into consideration. [38] The models can be grouped into three main categories (1) single firm optimization models (2) Cournot Equilibrium models (3) Simulation models. The first two are based on formalizing the conditions for reaching the Nash equilibrium conditions - the point when no actor in the market can improve its own position. In other words, they attempt to mimic the market's price clearing process in different ways. The third is based on a set of sequential rules that represent the dynamics of each firm's strategic behavior.

However, these models are quite difficult to implement as they require knowledge of individual actor's preferences in order to derive a mathematical formulation that represents their strategic response to a competitor's move. Furthermore, these models make it extremely difficult to include a detailed representation of the system being evaluated, such as the network. Consequently, for this thesis the "deterministic" models which take a central planner perspective were more appropriate.

As the economic theory demonstrates, decisions made under perfect centralized planning and those made under perfect competition, yield the same results (under some restrictive conditions, and ignoring the different human behaviors and the political and social factors that might result in significant differences between the two regulatory approaches). However, this theoretical equivalence allows to approximate the outcome of competitive markets in a powerful and simple way: we can use traditional cost-minimization power system models to simulate the results of a perfect regional electricity market. Therefore, this thesis makes the aforementioned assumptions when modeling the different scenarios.

4.1.2 Power Systems Models

Power systems models are crucial in electricity planning and market design as they can help predict, simulate or reproduce the various aspects of real electric power system conditions at will. Ideally, these models would cover all the details relating to system operation over time. However this is quite difficult and, in general, a single model cannot represent in full detail the complexity of both operation and investment decisions for both networks and energy resources. This limitation is sometimes referred to as the "short blanket" problem[1]. [39] Instead, different models covering different time horizons, geographical scope, and operational details are developed, aiming to find the balance between computational tractability and preserving the key system characteristics of interest. These models take a central-planning approach, focusing on minimizing costs in order to satisfy demand.

Models that focus specifically on the operational aspects of the grid can be split up by time horizon. Certain models will deal with the long-term planning aspects, such as which generators and lines should be built. Other models will serve to determine how much power each plant should produce, on a shorter, minute by minute horizon. This classification of operational decision-making models is represented in Figure 4-1 below.

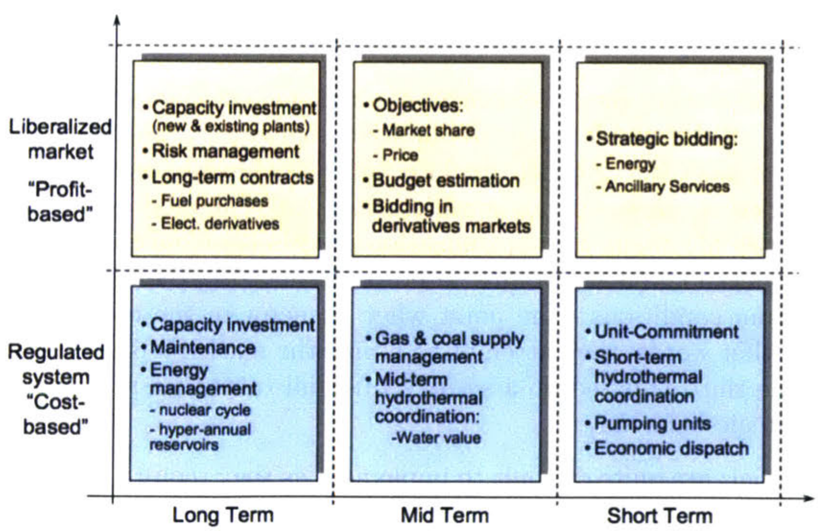


Figure 4-1: Decision Support Models for Power Systems [40]

[1] If you pull a short blanket up to cover your head, you cannot also cover your feet and vice versa[39]

The first set of models are those utilized for long-term for capacity expansion planning and often do not account for operational constraints or inter-temporal details. A common model employs the use of screening curves and a load duration curve to highlight the economic trade-offs between the fixed costs and variable costs of a generation technology. Such models generally do not reveal the actual dispatch of the generators as they do not take into account load profiles. [41] The introduction of intermittent sources further complicates expansion planning as they tend to increase the cycling of other generation assets, which must ramp up and ramp down in response to changes to sun or wind conditions.

The second set of models are those used in the short-to-medium term planning, and tend to account for temporal constraints as well as more technical details. One such type of model is the Unit Commitment Model, which attempts to determine which generators should be on or off during a certain time period (and in the case of storage capacity how much to store or discharge). These models can be formulated as Mixed-Integer Linear Programming models, using binary variables for various decisions, such as whether a generator is switched on or off. (This matters in the short-to-medium term as most generators have long start-up and shut-down times as well as minimum power outputs and ramping limitations - accurately representing these constraints is crucial)

Finally the very short-term models include economic dispatch and optimal power flow. The former attempts to dispatch the generators that are already on-line in order to meet demand while minimizing costs. Optimal Power Flow (OPF) takes this further by modeling how power should flow along the transmission network. Depending on the level of detail modeled, OPF methods can become extremely complex.

4.1.3 Network Representation

For this thesis, accounting for the network is key if we want to assess power exchange across regions.

Models that account for the network in full detail pose the most difficulty, both in terms of data requirements as well as the significant complexity added. This is because a full AC representation would result in a non-linear model, as the impedances determining division of flows between the lines are a function for the flows themselves. Solving a non-linear model is computationally heavy in the scope of Economic Dispatch with OPF models, as these are equations need to be solved iteratively if using the traditional Newton-Raphson method. Thus several simplifications must be made in order to linearize the model. The literature presents several methods to do so, each accounting for various levels of detail in the technical depiction of the grid. The two aspects of the grid that generally need to be captured are the (1) power flows and (2) losses along the lines.

The simplest and easiest model is the"copper plate" model, which in essence disregards the network completely. All generators and demand nodes are modeled as if in a single location and there are consequently no losses.

The second, relatively simple type of network model is known as the "transportation model". This model only takes into account Kirchhoff's First (Junction) Law, which reduces both the computational requirements of the optimization as well as the data required. Losses can be modeled as fixed losses, or based on a linear approximation.

The third, more detailed network model is a "Linearized Direct Current Power Flow (DCPF)". A DCPF is good simplification to use when capturing the physical constraints of the lines is necessary. [42] The simplification attempts to accurately portray two key aspects of the network: (1) the power flows and (2) the line losses. The first refers to adding constraints to the model such that the power flows follow the laws of physics, namely Kirchoff's Second Law, as discussed in Chapter 2. The second refers to accurately modeling the line losses, which result from ohmic (resistive), fixed, and non-technical losses. The most detailed method is to use a piecewise linear approximation of the quadratic losses.

For this thesis, the model developed is capable of either Transportation or DCPF network representations.

4.1.4 DC Power Flow

The most commonly used method for modeling power flows is a simplified DC approximation of AC power flow. [43] This linearization rests on three assumptions:

1. Line resistances are negligible compared to line reactances.
2. The voltage profile is flat.
3. Voltage angle differences between neighboring nodes are small.

The first DC power flow assumption allows us to model the systems as a lossless transmission line. The higher the voltage level of the considered grid, the more valid this assumption is. Purchala[44] tested the correctness of this assumption on a 30-node test network and concluded that for R/X ratios below 0.50, the average error is always smaller than 5% and falls below 2% average error for R/X ratios below 0.20. In the GCCI system modeled, the average R/X ratio is .0822, which further justifies this assumption.

The second DC power flow simplification assumes a flat voltage profile. It is however almost impossible to avoid voltage differences in an electricity grid. For small standard deviations in voltages (less than 0.01 p.u.), the average error made by this assumption is limited to 5%. [43] However, realistic examples of voltage differences in actual power systems show that this assumption is the most critical one and is the largest source of DC power flow errors. [43]

The third DC power flow assumption is that voltage angle differences between neighboring nodes are small. In general, this assumption is more correct if the grid is weakly loaded. Prior reports had shown that the GCCI grid was only used at 8% of its capacity [26], so this assumption holds.

Furthermore, given that the questions this thesis explores are more transactions across lines rather than technical characteristics such as system stability, these assumptions are acceptable.

In addition to accurately representing power flow, there is the issue of transmission line losses, which result from ohmic (resistive), fixed, and non-technical losses. Ohmic losses are quadratic and would need to be approximated via piece-wise linearization. [45]. However, some investigations have shown that this offers little or no performance benefit over a simple constant-loss approximation, but adversely affects computation [46]. Thus, for the sake of simplicity, this model approximates ohmic losses as a fixed percentage of power flow along a line. Non-technical losses refer to energy stolen from the system, and do not apply in this case.

4.2 Model Framework

Given that the central question of this thesis is to assess the economic impact of cross-border trades in the GCC, it was important to capture the short-term inter-temporal details since this could significantly affect the direction, volume, and value of power exchanges between countries. As such the model developed could be described as a "network constrained multi-period economic dispatch with optimal DC power flow and uniform loss representation". The model was then run with different generation and network scenarios to evaluate future expansion plans. A description of the model and mathematical formulation are presented below.

4.3 Mathematical Formulation

The following is the mathematical notation for the model.

4.3.1 Notation

Table 4.1: Indices and Sets

Notation	Description
$t \in T$	t denotes an hour and T is the set of hours in data series
$y \in Y$	y denotes a year and Y is the set of years in data series
$i \in I$	i denotes a node and I is the set of nodes in data series
$z \in Z$	z denotes a zone (country) and Z is the set of zones (countries) in data series
$l \in L$	l denotes a line and L is the set of lines in data series
$g \in G$	g denotes a generator and G is the set of generators in data series
$f \in F$	f denotes a fuel type and F is the set of all fuels in data series
$G_f^{fuel} \subset G$	G_f^{fuel} is the subset of generators using fuel type f
$G_i^{loc} \subset G$	G_i^{loc} is the subset of generators located at node i
$G_z^{zone} \subset G$	G_z^{zone} is the subset of generators located in zone z
$G_y^{year} \subset G$	G_y^{year} is the subset of generators in existence at year y
$L_y^{year} \subset L$	L_y^{year} is the subset of lines in existence at year y

Table 4.2: Parameters

Notation	Description
D_{ity}	Electricity demand at node i at time t during year y (MWh)
K^{nse}_{zy}	Price of non-served energy in zone z during year y (\$/MWh)
K^{fuel}_{fzy}	Price of fuel f in zone z during year y. (\$/MJ)
Υ_{zy}	Reserve margin requirement in zone z during year y (MWh)
Ξ_g	Heat rate of generator g (MMBTU/MWh)
Δ^G_{gy}	Generator build status: 1 if generator g in existence at year y, 0 otherwise
Δ^L_{ly}	Line build status: 1 if line l in existence at year y, 0 otherwise
$P^{\max}_g, P^{\min}_g$	Max and min output of generator g (MW)
Γ^{solar}_{it}	Capacity factor for solar in location i at time t during year y (%)
X_l	Reactance of line l (p.u.)
Λ_l	Capacity of line l (MW)
Θ_l	Max angle difference for line l (radians)
R	Max portion of reserve margin allowed to be met by generator g (%)
Ω	Loss rate along line l (%)
$s(l)$	Send bus of line l
$r(l)$	Receive bus of line l
Ψ_{fity}	Fuel type f limitations at node i at time t during year y (MMBTU)

Table 4.3: Decision Variables

Notation	Description
ρ_{gty}	Output of generator g at time t in year y (MW)
m_{gty}	Reserve margin of generator g at time t in year y (MW)
ϕ_{lty}	Flow in line l from start bus $s(l)$ to end bus $r(l)$ at time t in year y (MW)
ζ_{lty}	Losses on line l at time t in year y (MW)
$\theta_{s(l),ty}$	Voltage angle at start bus of line l at time t in year y (radians)
$\theta_{r(l),ty}$	Voltage angle at end bus of line l at time t in year y (radians)
nse_{ty}	Unmet load at time t in year y (MW)
u_{gty}	Commitment status of generator g at time t in year y (1 or 0)

4.3.2 Objective Function

$$\min \left\{ \overbrace{\sum_{f\in F}\sum_{g\in G}\sum_{t\in T}\sum_{y\in Y}(\rho_{gty}\Xi_g K^{fuel}_{fzy})}^{\text{Operational Costs}} + \overbrace{\sum_{i\in I}\sum_{t\in T}\sum_{y\in Y}(nse_{it}K^{nse}_{zy})}^{\text{NSE Costs}} \right\} \tag{4.1}$$

4.3.3 Constraints

$$P_g^{\min}\Delta_{gy}^G u_{gt} \leq \rho_{gty} + m_{gty} \leq P_g^{\max}\Delta_{gy}^G u_{gt} \qquad \forall g\ ,\forall t \tag{4.2}$$

$$\sum_{g\in G_i}\rho_{gty} - \sum_{l:s(l)=i}\phi_{lty} + \sum_{l:r(l)=i}\phi_{lty} + nse_{ity} = D_{ity} + \sum_{l:r(l)=i}\frac{\zeta_{lty}}{2} - \sum_{l:s(l)=i}\frac{\zeta_{lty}}{2} \quad \forall i\ ,\forall t\ ,\forall y \tag{4.3}$$

$$\phi_{lty} = \frac{\theta_{s(l),ty} - \theta_{r(l),ty}}{X_l} \qquad \forall l\ ,\forall t\ ,\forall y \tag{4.4}$$

$$-F_l^{\max}\Delta_{ly}^L \leq \phi_{lty} \leq F_l^{\max}\Delta_{ly}^L \qquad \forall l\ ,\forall t\ ,\forall y \tag{4.5}$$

$$-\Theta_l \leq \theta_{s(l),ty} \leq \Theta_l \qquad \forall l\ ,\forall t\ ,\forall y \tag{4.6}$$

$$-\Theta_l \leq \theta_{r(l),ty} \leq \Theta_l \qquad \forall l\ ,\forall t\ ,\forall y \tag{4.7}$$

$$\theta_{s(1),ty} = 0 \qquad \forall t\ ,\forall y \tag{4.8}$$

$$0 \leq nse_{ity} \leq D_{ity} \qquad \forall i\ ,\forall t\ ,\forall y \tag{4.9}$$

$$0 \leq m_{gty} \qquad \forall g\ ,\forall t\ ,\forall y \tag{4.10}$$

$$m_{gty} \leq R(\Upsilon_{zy}) \qquad \forall g\ ,\forall t\ ,\forall y, \forall z \tag{4.11}$$

$$\sum_{g\in G_z^{zone}} m_{gty} \geq \Upsilon_{zy} \qquad \forall g\ ,\forall t\ ,\forall y, \forall z \tag{4.12}$$

$$\zeta_{lty} = \Omega(\phi_{lty}) \qquad \forall l\ ,\forall t\ ,\forall y \tag{4.13}$$

$$0 \leq \rho_{gty} \leq \Gamma_{it}^{res} P_{gy}^{\max} \qquad \forall g \in G_{f=(\text{solar,wind})}^{\text{fuel}}\ ,\forall t\ ,\forall y \tag{4.14}$$

$$\forall i,\ \forall f \neq solar\ , \sum_{g\in(G_i^{\text{loc}}\cup G_f^{\text{fuel}})}\frac{\rho_{gty}}{\Xi_g} \leq \Psi_{fity} \qquad \forall t\ ,\forall y \tag{4.15}$$

4.3.4 Pre-computed Constants

$$\forall y,\ P^{\max}_{gy} = 0 \qquad \forall g \notin G^{year}_{y} \tag{4.16}$$

$$K^{fuel}_{fzy} = 0 \qquad \forall f = solar\ , \forall z\ , \forall y \tag{4.17}$$

$$P^{\max}_{g \notin G^{\text{year}}_{y}, y} = 0 \qquad \forall y \tag{4.18}$$

4.4 Model Description

The model in essence is a minimization of system operational costs and energy-not-served subject to the constraints of the system (Eq. 4.1). The expression $\rho_{gty}\Xi_g K^{fuel}_{fzy}$ describes the operational costs of a generator g, given by the power output of a generator multiplied by its heat rate and the price of the fuel in that location. $nse_{it}K^{nse}_{zy}$ is simply the amount of unmet demand (Non-Served Energy (NSE)) multiplied by the cost of energy not served.

Equation 4.2 forces the sum of the output of the generator, ρ_g, and the reserve margin of the generator, m_g, to be less than the maximum output (capacity) $P^{\max}_g$ of the generator. Δ^G_{gy} is a parameter that establishes whether the generator has been built. If it hasn't Δ^G_{gy} takes a value of zero, constraining the output to be zero. u_{gt} is a binary variable that determine the commitment status of the generator at time t (whether it is on or off). If it is off, $u_{gt} = 0$, once again constraining power output of the generator.

Equation 4.3 is the balance of power constraint (Kirchoff's First Law). ϕ_{lty} are the flows along line l. In order to ensure flows along a line are not double counted, the model uses the indices $s(l)$ and $r(l)$ to refer to the sending and receiving buses of line l. Half the transmission losses along a line are accounted for at each node.

Equation 4.4 is the voltage angle constraints, or Kirchoff's second law. $\theta_{s(l)}$ and $\theta_{r(l)}$ are the voltage angles at the sending and receiving busses of line l. Equation 4.5 ensures the flow along the line does not exceed the limits $F^{\max}_l$. The parameter Δ^L_{ly} takes on a value of 0 if the the line has not been built, constraining the flows to 0. The next set of equations (Eqs. 4.6, 4.7, and 4.8) set the voltage angle limits as well as the reference node.

Because the original purpose of the GCCI was for reserve capacity sharing, reserve margins were incorporated into the model (Eq. 4.11 and Eq. 4.12). In the GCC case, the technical code (described in Section 3.2.2) specifies that no single generator can supply more than 5% of the reserve margin.

Equation 4.13 fixes the losses along line l. In the GCC case, these were set to a fixed rate $\Omega = 0.10$, based on a review of statistical reports on the GCC region, discussed further in Section 5.2.7. Better technical data on the line could allow for a better approximation.

Equation 4.14 limits the maximum output of intermittent generation sources (solar and wind) using an hourly profile. For example Γ^{res}_{it} takes on a value of 0 for all times t during the night for solar generation sources.

Fuel constraints between regions, namely of natural gas, have been an issue in recent years, particularly in Saudi Arabia, where most of the gas is sourced in the Eastern Provinces. Equation 4.15 sets the fuel constraints for each region.

4.5 Model Implementation

The model was implemented using JuMP[47], a domain-specific modeling language for mathematical optimization embedded in the Julia Language[48], a high-level, high-performance dynamic programming language for numerical computing. The solver used was the Gurobi Solver[49] developed by Gurobi Optimization Inc.

4.5.1 Model Features

The model architecture was specially designed to take advantage of many of the speed-increasing features of JuMP and Gurobi, as well as implement best practices from the software industry to further improve model resolution time.

JuMP set notation: Utilizing the high-level comprehensions of the Julia Language allows for tighter problem formulation.

Tight Linear Program (LP) relaxation of Mixed-Integer Linear Program (MILP): Utilizing JuMP's "fix" function[2], which allows for computing dual variables and conducting sensitivity analysis.

Caching files for "hot-starting": The model caches ever single successful model result, allowing the solver to re-start from the last solution to reduce running times for successive solves.

Hashing: The model also compares the hashes of the inputs. If it determines it is identical to a previous input, it simply outputs the results rather than original input.

Unit Tests: In order to ensure the model was running as anticipated, a series of unit test were written. These are part of a software testing method by which individual units of source code along with associated control data are tested to ensure the program is running appropriately. This enabled to check that the model outputs were those anticipated, especially as it grew in complexity.

4.5.2 Source Code

The source code of the model is included in Appendix B.

[2] `https://jump.readthedocs.io/en/latest/refvariable.html`

Chapter 5

Modeling Cases, Inputs, and Parameters

The modeling cases were set up to answer the central question of this thesis: what is the economic impact of cross-border electricity trade amongst the GCC countries?

In addition, these cases were used to answer the following secondary questions:

- Which countries benefit the most from cross-border trade?
- How are electricity prices in different member states impacted by regional trade?
- What is the impact of market distortions, namely fuel subsidies, on the direction, volume, and value of trades?
- What can the model tell us about required generation and transmission investments?

5.1 Modeling Scenarios

In order to conduct the analyses, cases were set up as the combination of two fuel scenarios and two network configurations: International and Subsidized Fuel Prices, With and Without Cross-Border Trading. Each scenario was first run for 2016 historical data (for which we could compare the model results with known historical outcomes to validate the model) and then for 2030, using demand projections in conjunction with announced capacity expansion plans. (See Table 5.1).

5.2 Model Inputs

In order to model the electric power systems of the six GCC countries as well as the GCC Interconnector, data on the different components described in Chapter 2 was needed.

The following section describes and analyses some of these data inputs. The 2016 run was used to validate model results with known historical outcomes. Certain approximations or

Table 5.1: Eight Modeling Scenarios

Scenario #	Year	Trading	Fuel Prices
1	2016	No	International
2	2030	No	International
3	2016	No	Subsidized
4	2030	No	Subsidized
5	2016	Yes	International
6	2030	Yes	International
7	2016	Yes	Subsidized
8	2030	Yes	Subsidized

reasonable estimates were made for missing data, including manipulating data from different years to try and establish the base 2016 scenario.

The model encompasses the following features of the GCC electric power system:

- 6 Countries
- 428 Power Plants
  - 10 Fuel Types
  - 11 Generation Technologies
- 26 Nodes
- 68 HV Transmission Lines
- Full-year hourly demand (8760h)
- Hourly data for Typical Meteorological Year (TMY) solar irradiation and wind speed
- 15 years of expansion plans and demand growth

The full list of data sources is made available in Appendix A.1.

5.2.1 Demand

The objective of the study was to explore the evolution of trades with time. As such, it was important to use hourly demand modeled at a regional level.

Only the two largest countries, the Kingdom of Saudi Arabia (KSA) and the UAE were split up into smaller regions (shown in Figure 5-10). Saudi Arabia was split into eight operating regions. In order to approximate regional demand, the aggregated demand was split between the regional nodes based on relative population size with some adjustments based on GCCIA and feedback from meetings with KSA stakeholders. The UAE was split up into four regions. Data from the Abu Dhabi Water and Electricity Company (ADWEC) statistical report [50] contained peak and minimum loads by region. The average of these two was used to scale the the country-level hourly data into the four sub-regions.

Historical 2016 hourly demand for each country was provided by the GCCIA. The yearly load profile for each of the countries is shown in Figure 5-1. The system peak (108,579.69

MW) occurred on Tuesday August 23rd, 2016 and the system minimum (39,434.71 MW) occurred on Friday January 15, 2016. The normalized (divided by minimum load) daily load profiles for the countries on these dates are shown in Figures 5-2 and 5-3.

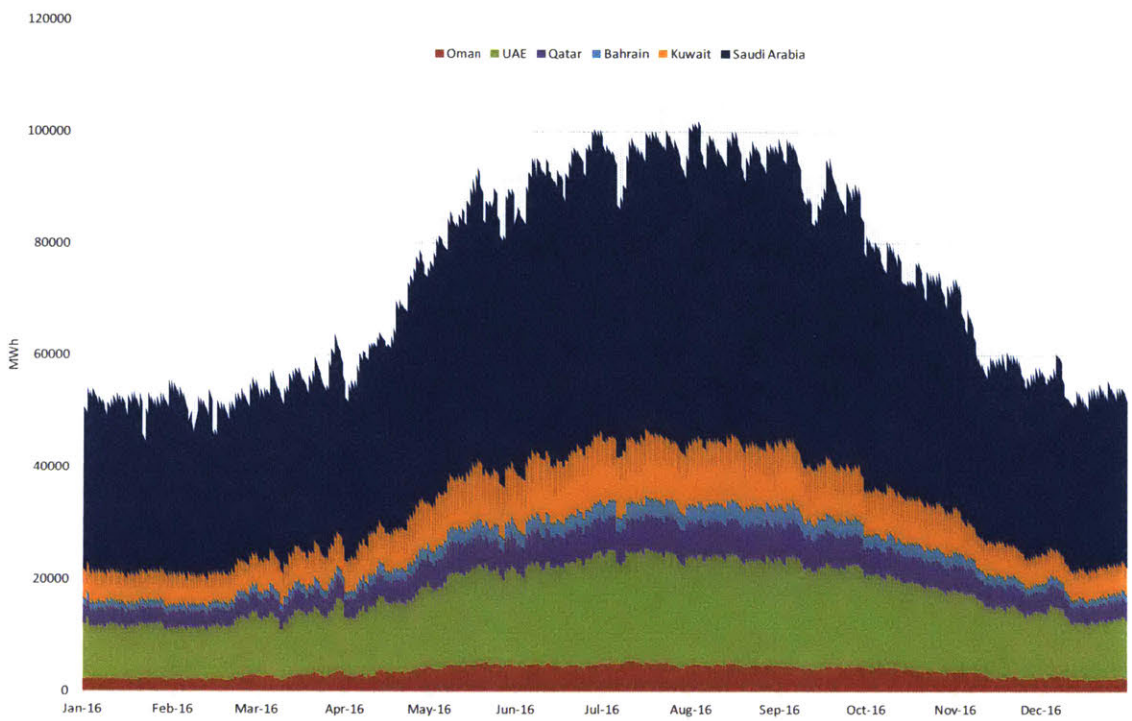


Figure 5-1: GCC 2016 Electricity Demand

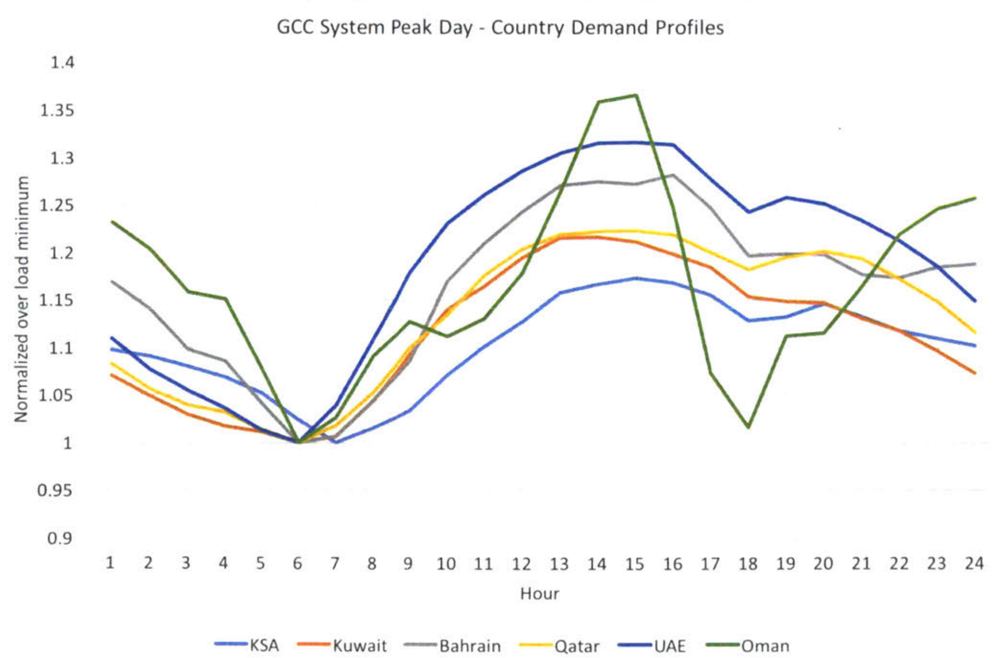


Figure 5-2: System Peak (Aug. 23rd) Normalized Load Profiles

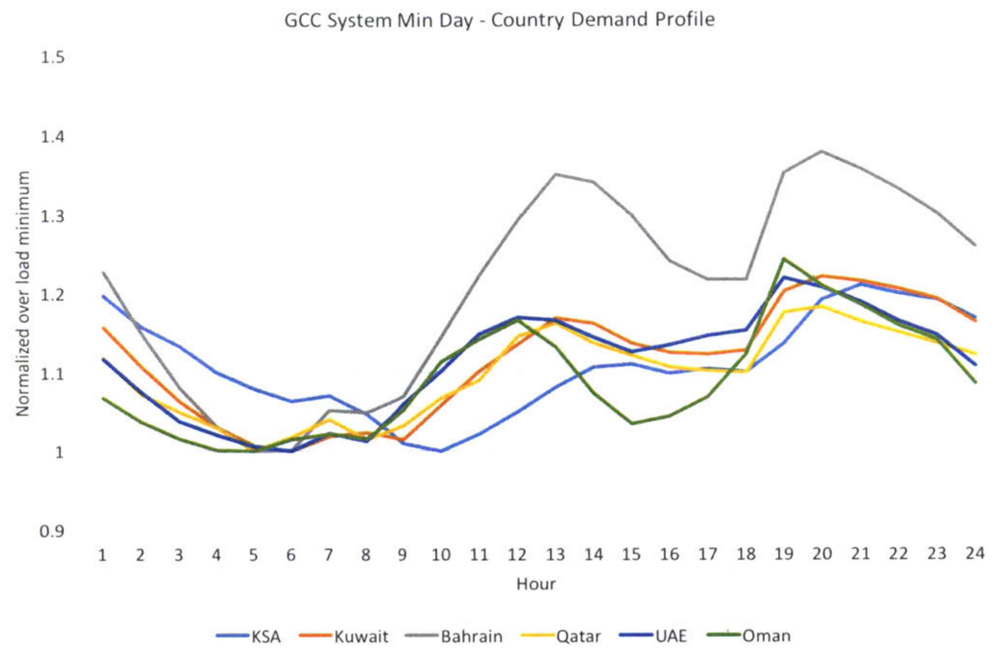


Figure 5-3: System Min (Jan 15th) Normalized Load Profiles

Forecasts: 2017-2030

Future GCC electricity demand was forecast using the following growth rates determined by International Renewable Energy Agency (IRENA)[21], shown in Figure 5-4. All 8760 hours of demand were increased by the growth rate. More advanced forecasting techniques involving a breakdown into load profiles by sector and relative scaling of those profiles according to the sector growth rates, would be more accurate, however detailed load profiles by sector were unavailable. Several of these forecasting techniques are discussed in Future Work section in Chapter 7.

		Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates
Table 1 Renewable energy capacity by country in 2030							
Capacity (GW)	2030	0.7	10.9	2.4	1.8	29.3	33.3
Table 2 Demand projections by year and by country							
Growth Rate (used for projections of demand)	2016-2020	6.0%	7.0%	9.0%	6.0%	6.5%	6.5%
	2021-2025	4.0%	6.0%	7.0%	4.0%	4.5%	5.0%
	2026-2030	3.0%	4.5%	6.0%	3.0%	3.0%	4.0%

Figure 5-4: GCC Electricity Demand Projections [21]

From the demand data received from the GCCIA, the 2016 total system demand was 637.491 GWh. Using the projected growth rates (shown in Figure 5-4), the estimated 2030 total system demand would be 1,337.96 GWh.

Table 5.2: Heat Rates by Technology. [51]

Generation Type	Fuel	H/R [MMBTU/MWh]
Steam Generator	Oil	10.197
Gas Turbine	Oil	13.55
Internal Combustion	Oil	10.379
Combined Cycle	Oil	9.676
Steam Generator	Gas	10.372
Gas Turbine	Gas	11.302
Diesel Generator	Gas	9.322
Combined Cycle	Gas	7.655
Steam Generator	Nuclear	10.458

5.2.2 Generation

A total of 428 different power plants were included in the model. Data for both current and future plans was obtained from the 2016 GlobalData database. [18]. These were cross-checked and improved with published national expansion plans and recent press articles to ensure accuracy. The GPS coordinates of the power plants were used to group them into the regional zones.

In order to properly model system dispatch, and thus obtain locational marginal pricing for each of the zones, it was important to accurately capture plant technical characteristics such a ramp rates and minimum output as well as cost information. Power plant heat rates were estimated using International Energy Agency (IEA) data, [51], as shown in Table 5.2. Generator ramp rates and minimum output were estimated using [52], [53], [54]. These numbers are available in Appendix A.2.

Fixed and variable Operation and Maintenance (O&M) costs were estimated using IEA and National Renewable Energy Laboratory (NREL) data. [55] [56] For plants under construction or planned, future costs were estimated using NREL's 2009 projections [56]. Detailed costs are shown in the Appendix A.2

5.2.3 Fuel Prices

One of the key issues in the GCC region is the presence of fuel subsidies. Two scenarios were run, one with international fuel prices compiled by the United States Energy Information Agency (EIA) and the other using subsidized prices from Saudi Arabian Electricity and Co-Generation Regulatory Authority (ECRA) were used. The International Prices correspond to the European Hub, obtained from [57], shown in Table 5.3. The subsidized fuel prices were obtained from a 2016 King Abdullah Petroleum Studies and Research Center (KAPSARC) report [20], shown in Table 5.4.

Table 5.3: International Fuel Prices [57]

Fuel #	**Price ($/MMBTU)**
HFO	15.43
Gas	9.04
Diesel	21.67
Crude	19.26

Table 5.4: Subsidized Fuel Prices by Country ($/MMBTU) [20]

Fuel	**KSA**	**QAT**	**OMA**	**UAE**	**KUW**	**BAH**
HFO	0.43	0.43	0.43	0.43	0.43	0.43
Gas	0.75	0.75	3.00	0.75	1.50	2.50
Diesel	0.67	0.67	0.67	0.67	0.67	0.67
Crude	0.73	0.73	0.73	0.73	0.73	0.73

5.2.4 Renewable Sources

Given the intermittency of renewable sources, it was necessary to estimate locational hourly capacity factor for the different technologies. Hourly irradiation was only available for Riyadh, KSA and Abu Dhabi, UAE. For each node in the model, the data from the closest weather station was used. Hourly wind data was obtained from NASA's MERRA-2 database. [58] Although there are no wind farms currently in the GCC region, there are plans for 628 MW of wind generation to be added by 2030 - primarily in the windy North Western region of Saudi Arabia.

Solar

Three solar power technologies exist in the GCC region: Photovoltaic, Concentrating Photovoltaic, and Concentrating Solar Thermal. The majority of solar generation is of the first type, as well as most of the future planned solar generation capacity.

The solar panel output for Photo-voltaic (PV) technologies was determined by the Global Solar Energy Estimator (GSEE) model developed in [59]. It was assumed the panels were fix-tilt, with the angle set to the latitude of the location, as recommended by [60], who conducted a study specific to Madinah, Saudi Arabia.

The PV panel efficiencies were assumed to be 17%, which was the 2016 average commercial module efficiency according to a report by the Fraunhofer Institute [61]. In addition to standard Solar PV, several countries have built Concentrating Photo-voltaic (CPV) plants. For the sake of modeling ease, these were assumed to have the same capacity factors as the standard solar PV, especially as less than 3 MW are installed across all countries, and there are no future plans to continue the technology.

While there exist four variants of Concentrated Solar Power (CSP) technology: Parabolic Trough (PT), Fresnel Reflector (FR), Solar Tower (ST) and Solar Dish (SD), most projects planned in the GCC are the Parabolic Trough (PT) technology. Thus for the modeling this was assumed to be the predominant technology. A survey of CSP technologies published by IRENA-IEA-ETSAP [62] reveals efficiencies of CSP to be around 14-16%, thus 15% was used as average output. Furthermore no thermal storage was assumed, as many of the CSP technologies were coupled with combined cycled gas turbines for backup power, and these turbines were included in the thermal technologies generator list.

5.2.5 Country Marginal Cost Curve

The combination of the O&M costs, fuel prices, and heat rates allows us to generate the marginal costs curves for each country. These are crucial as they help determine the order of generation dispatch, ultimately determining electricity prices and trades.

Figure 5-5, represents the marginal cost curve for the 2016 installed capacity with International fuel prices as generated by the model. The marginal cost for the peaking technology is $325/MWh.

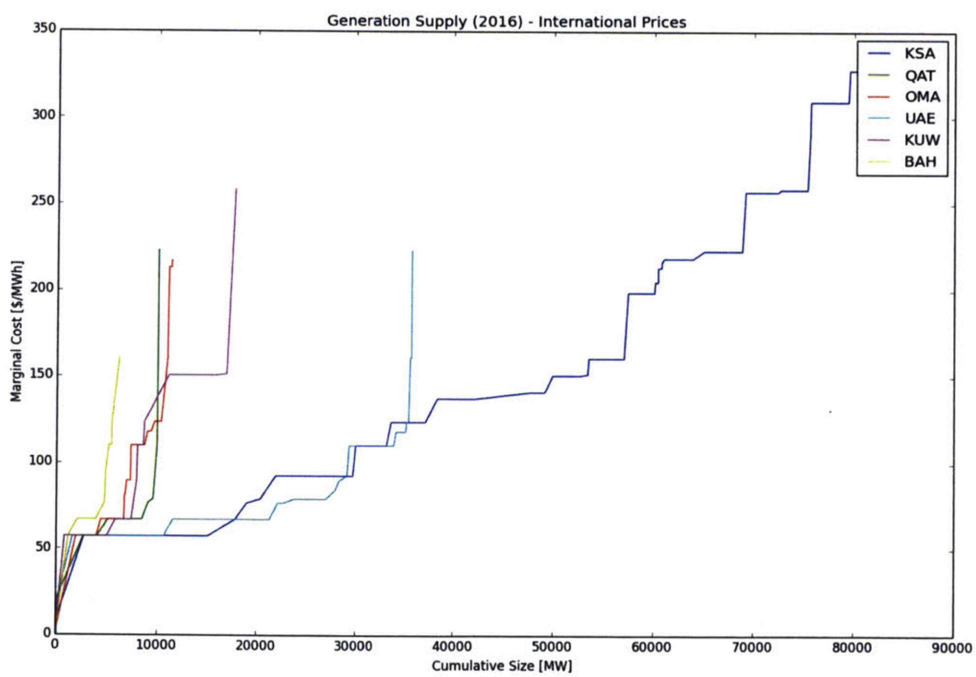


Figure 5-5: Incremental Cost Curve from Model Data

It is rare for utility companies to release variable costs of their power plants, however a 2016 GCCIA report[26] contained a single incremental cost curve with international prices (shown in Figure 5-6). A comparison of Figures 5-5 and 5-6 shows that the modeled variable costs are reasonable, thereby validating the computations performed to generate reasonable inputs for the model.

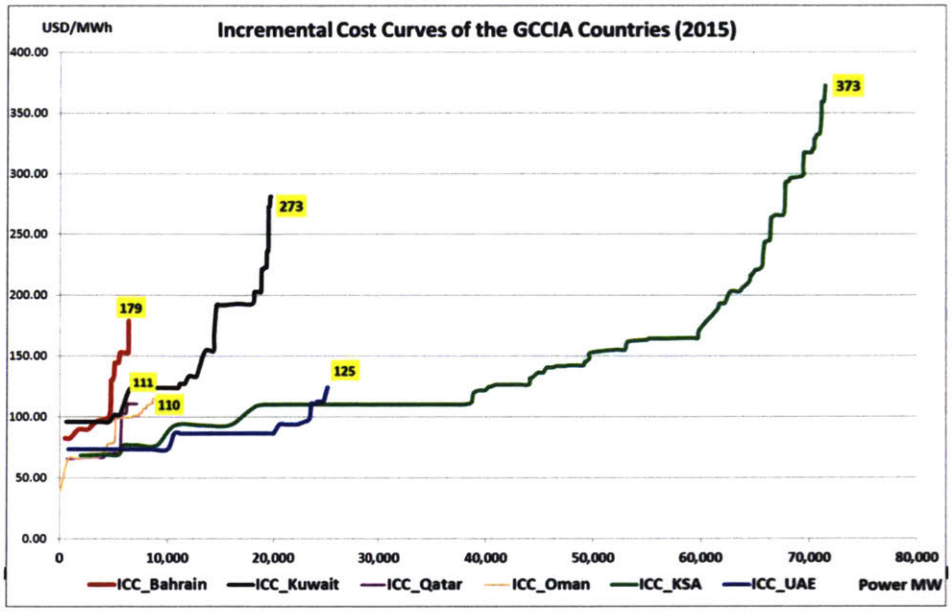


Figure 5-6: Incremental Cost Curve from GCCIA Report

The effects of fuel subsidies as well as new generation capacity expansion can be seen in the following curves, which represent the marginal cost curves for the remaining scenarios in years 2016 and 2030.

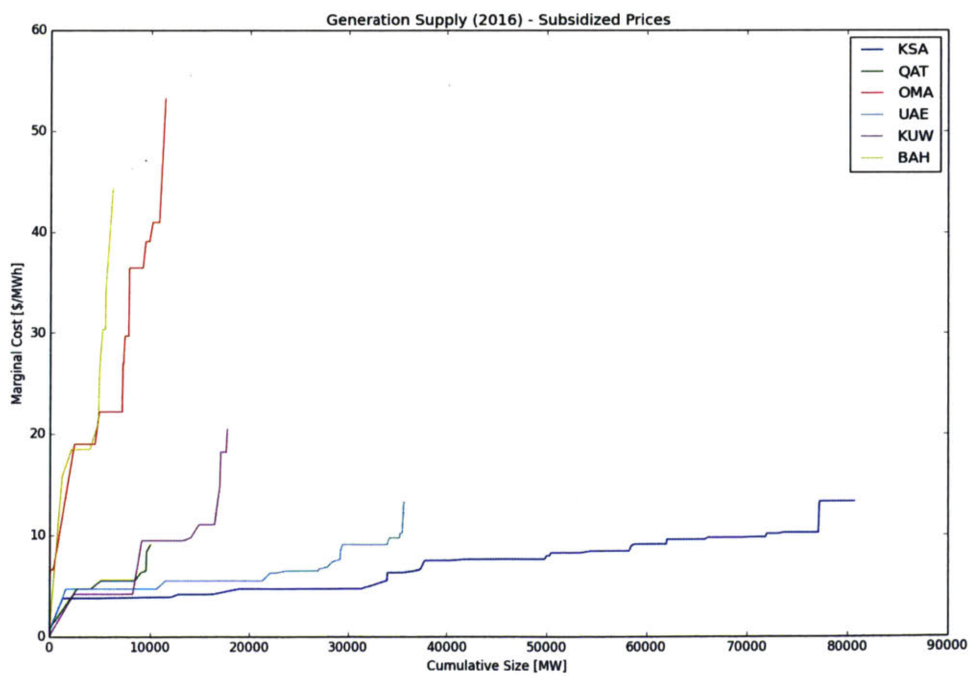


Figure 5-7: Incremental Cost Curve (2016 Subsidized Prices) from Model Data

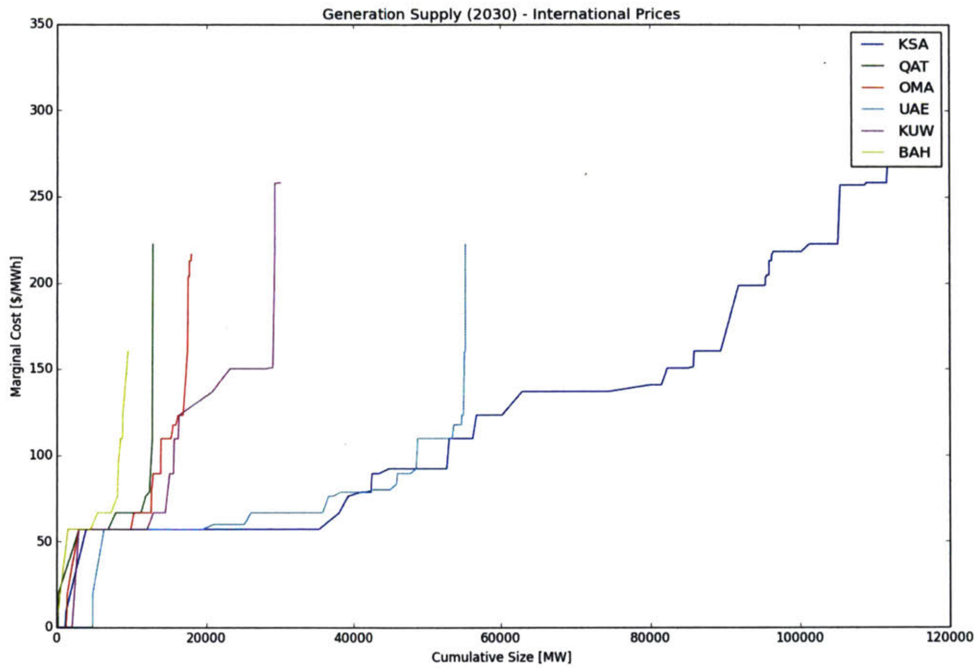


Figure 5-8: Incremental Cost Curve (2030 International Prices) from Model Data

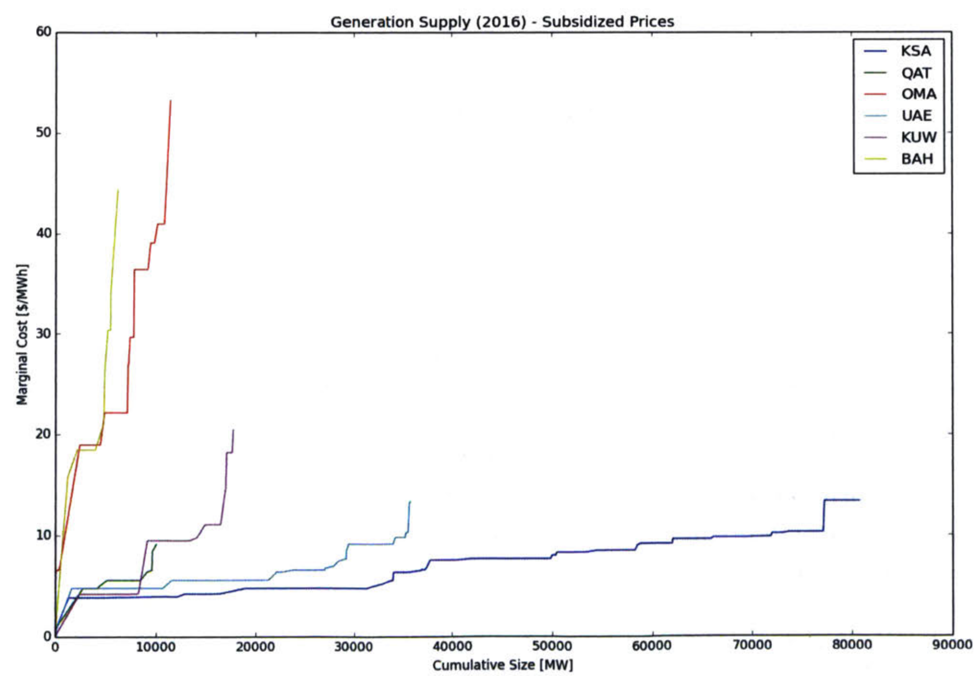


Figure 5-9: Incremental Cost Curve (2030 Subsidized Prices) from Model Data

5.2.6 Network

The model network, containing the GCCI as well as the UAE and KSA grids, was represented as shown in Figure 5-10. The data was partially complete with regards to the reactance and resistance of the lines, so these were estimated based on comparisons to similar lines. As described in Chapter 2, these parameters impact the distribution of power flows due to Kircchoff's laws. The internal network was not included for most countries, due to lack of nodal demand data, as well as detailed network information. When estimating unknown line information, efforts were made to respect the regional transfer capacities and technical parameters based on the cross-referencing examination various utility and ministry reports. Finally, network expansions plans based on national infrastructure planning reports [50] [29] were included. The detailed country network maps can be found in Appendix A.3.

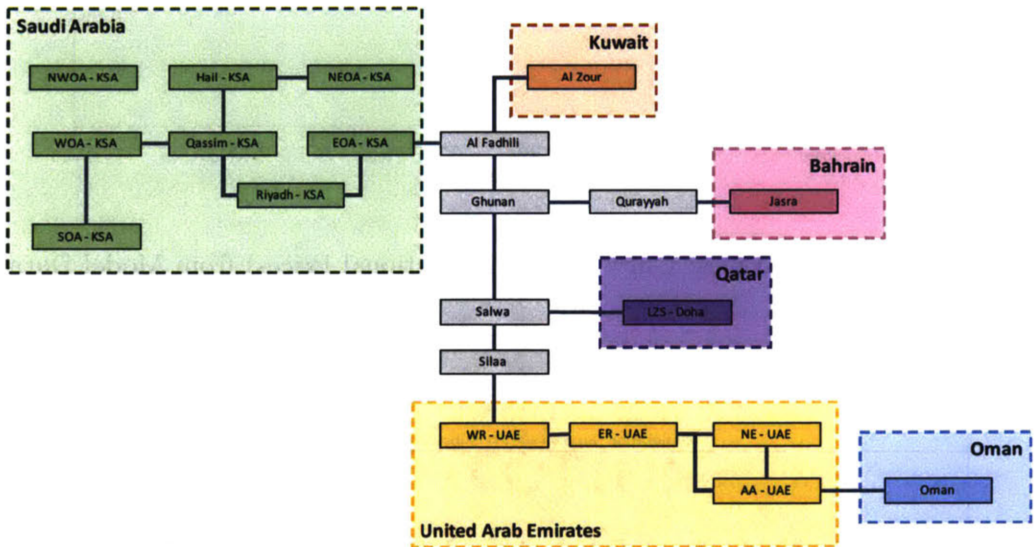


Figure 5-10: Model Network Diagram (2016)

As mentioned in Chapter 4, the model has the option to either use a DC approximation or transportation model representation. The former requires detailed information regarding technical characteristics of the lines, namely reactances and resistances, which are not publicly available. While some partial data was provided, attempting to determine these reactances and resistances from limited data proved difficult as these parameters are a function of line material, length, voltage, and design. Incorrect assumptions can affect the topology of the entire network, adversely constraining power flows. [63]. The model was run with various line parameters in the DCPF model and found in all instances to have the flows and trade across regions severely limited by the second law constraints, in manners that were inconsistent with known flows in the system - even when the voltage angle constraint was relaxed. For example, the maximum line utilization along a corridor where there was non-served energy at one of the nodes was 19% even if there was extra generation capacity at the other end due. This is indicative of erroneous technical line specifications since in reality a system would not be designed in such a way. Determining what the topology of the network should be was beyond the scope of this research. In fact, there is a entire realm of research in power systems devoted to "topology control", the understanding of how the small changes in physical characteristics of the lines in the network can impact the power flows across the entire system. Furthermore, there exists technologies such as Flexible Alternating Current Transmission Systems (FACTS) which can be used to increase the power transfer capabilities on transmission lines. [64]

Consequently, for the results and discussion that follows, the second network representation option of the model (which models the line flows are a "transportation network model", discussed in Section 4.1.3) was used, with losses as a percentage of flow through the line. This can be said to be a relaxation of the actual optimization problem, and thus all results that follow in essence set the "upper bound" or best-case scenario for optimal operation of the GCC power system.

5.2.7 Losses

In the model, the transmission losses were fixed at 10.00% of the power flowing through the line. Calculations based on the 2015 GCC annual report[65] showed that losses comprised about 13.87% of the volume traded across the interconnector in 2015. However it appears losses have been steadily decreasing, given losses were approximately 19.4% in 2009 and 15.0% in 2012 (shown in Figure 5-11). Furthermore a broader review of the MENA region claimed that the rate of electric power transmission and distribution losses in 2016 was 12.1%. [31]. Both these numbers are quite high for High-Voltage (HV) transmission losses, which tend to be lower than distribution losses. For reference the US and EU average is about 6% (including distribution). [66] The 2014 ECRA report[29], which only discussed the internal Saudi network, revealed average losses to be 7-10%, depending on line voltage.

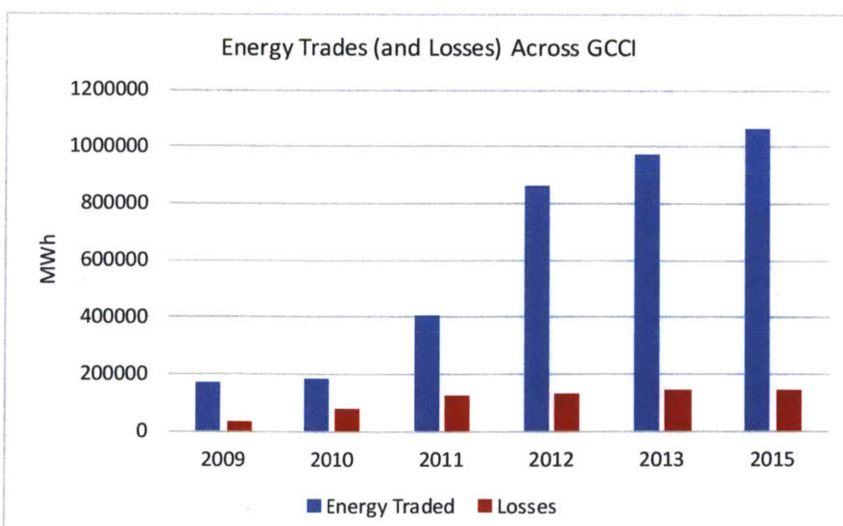


Figure 5-11: Energy Traded (with Losses) Across GCCI [65]

5.2.8 In-Kind Trading

Due to significant fuel subsidies, shown in Figure 5.4, trades valued at the marginal costs of production are extremely distorted. The GCCIA proposed the idea where instead of monetary transactions, electricity was accounted for "in-kind", that is to say by volume (MWh) of certain Time-Of-Use (TOU) periods exchange. The objective of this study was to identify which countries export and import during certain TOU blocks, to determine the feasibility of potential "in-kind trades". Figure 5-12 shows the average load profile for the GCCIA with the TOU blocks that were established for the analysis.

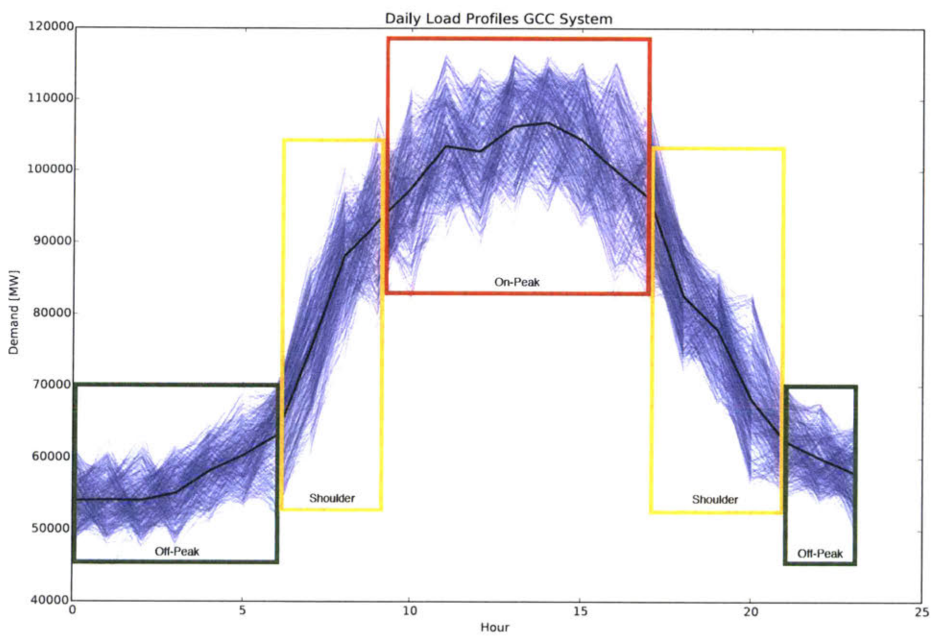


Figure 5-12: Typical Load Profile with TOU Blocks

Chapter 6

Results and Analysis

This chapter presents the quantitative results from the modeling cases presented in Chapter 5. It is important to note that the numerical results, findings, and conclusions are only as good as the data that was available to run the model. Furthermore, the overarching goal of this analysis is to be "prescriptive", rather than "predictive". In other words, these results aim to highlight how decisions affect outcome of regional trade in order to inform policy decisions rather than to accurately predict future prices and trade volumes.

Unless otherwise noted, all prices are in US Dollars.

6.1 Modeling Results

For the reasons discussed in Section 5.2.6, for the remainder of this thesis, the results using the "transportation network model" are presented. This is in essence a "relaxation" of the DCPF mode, thus setting a best-case scenario or "upper bound" for optimal system performance as network and losses will further constrain system.

6.1.1 Economic Impact

The total operational costs for the eight scenarios are shown in Table 6.1. In the baseline model for the year 2016, without price subsidies, the total operational cost of supplying electricity to all GCC countries without a regional grid was approximately USD $58.12 Billion. With cross-border trade this was reduced to down to USD $57.44 Billion.

This means that power trading across the grid could bring an anticipated savings of approximately USD $1 Billion per year (with un-subsidized prices) to the entire GCC region. The 2016 Net Present Value (NPV) of these savings across the next 15 years is around USD $5 Billion, using the 2.5 % discount rate of the Saudi Government (the largest shareholder). This is about twice the NPV $2.6 Billion (1990 USD$1.4 Billion) anticipated savings estimated in 1990 when the project was proposed, and these savings are purely from operational reductions.

Given that total GCC electricity consumption in 2016 was 637.491 TWh, the total operational costs of USD $58.12 Billion amounts to an average electricity price of USD

$91.2/MWh. Projected total GCC electricity demand in 2030 is 1,337.96 TWh with a total operational cost of USD $112.12 Billion. However with the influx of cheaper technologies the average electricity price would decrease to USD $83.85/MWh.

The results also underscore the significant impact of fuel subsidies, which artificially reduce operational costs by more than 80%. As discussed in more depth in Section 6.1.4, in the two 2016 Trading/Non-Trading scenarios with subsidized prices, the six governments combined would spend more than USD $63 Billion on fuel subsidies, more than the operational costs of the system without such subsidies!

Table 6.1: Total Operational Costs by Scenario (USD$ Billion)

Scenario	**International Fuel Prices**	**Subsidized Fuel Prices**[1]
No Trading (2016)	58.12	4.11
Trading (2016)	57.44	3.98
No Trading (2030)	113.78	9.52
Trading (2030)	112.12	8.88

6.1.2 Cross-Border Trade Volumes

The net import and export balances between countries are shown in Table 6.2. For all figures and tables, negative numbers denote net imports. These trades reveal how sensitive the balance of imports and exports are to subsidies. For example, in 2016 depending on subsidies both the UAE and Kuwait would switch from net importers (international prices) to net exporters (subsidized prices). Figures 6-1 and 6-2 show the import and export volumes on the 2016 system peak and system minimum days (August 23rd and January 15th) with the international fuel prices.

Table 6.2: Net Exports by Country (TWh)

Year	**Fuel Price**	**KSA**	**QAT**	**OMA**	**UAE**	**KUW**	**BAH**
2016	International	-8.12	4.87	2.85	-1.06	-1.49	2.95
2016	Subsidized	-4.23	5.31	-3.50	5.82	1.85	-5.25
2030	International	-10.3	5.41	1.75	-2.20	0.12	5.25
2030	Subsidized	-0.23	6.23	-2.08	-1.10	1.64	-4.46

[1]It is important to note that these are somewhat "artificial" operational costs, as country governments are significantly subsidizing the fuel used for electricity production.

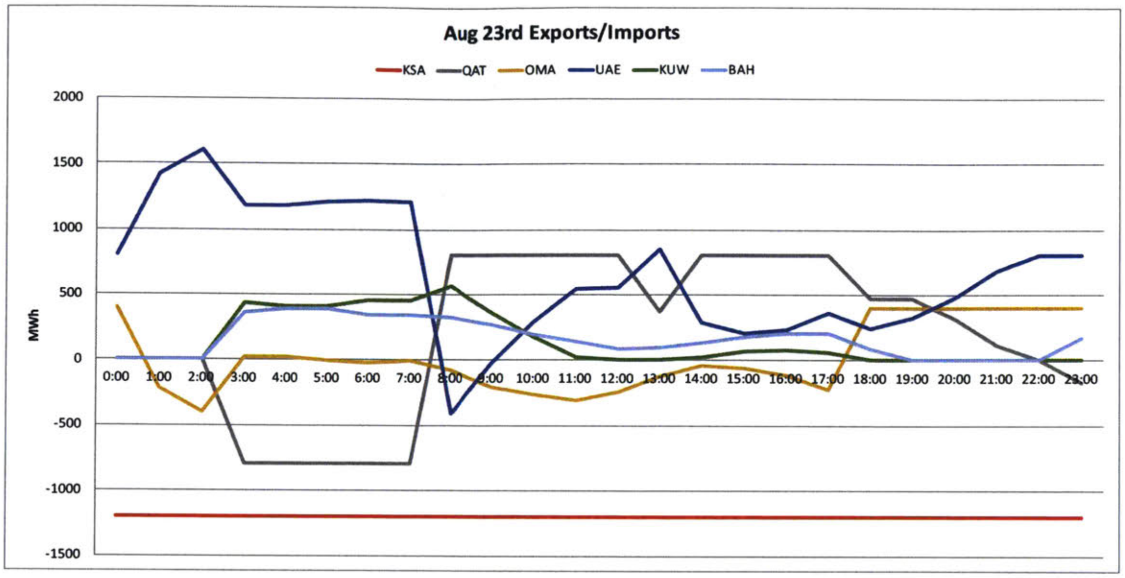


Figure 6-1: Import/Exports on System Peak Day. Negative value ares imports

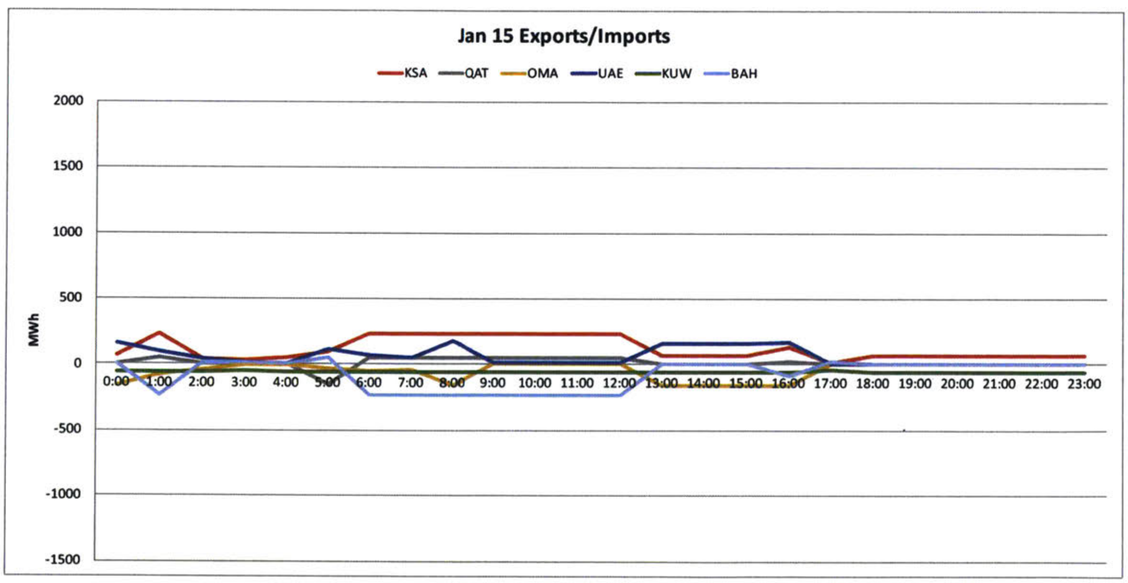


Figure 6-2: Import/Exports on System Minimum Day. Negative values are imports

6.1.3 Impact on Elecricity Prices

As expected, the countries that are net exporters see a slight increase in prices whereas the countries that are net importers see a slight decrease in average electricity prices. The price differences are shown in Table 6.3. What is evident is that trading would allow certain countries to benefit from more efficient and cheaper generation technologies in other regions.

Figures 6-3 and 6-4 show the impact of trades on system peak and system minimum days on nodal prices (corresponding to the trades shown in Figures 6-1 and 6-2). For reference, the network diagram showing the nodes and interconnections was shown in Chapter 5, Figure 5-10. AA_UAE refers to the Al Ain region of the UAE, which is the node where Oman and the UAE are interconnected. WR_UAE refers to the western region of the UAE, which is where the UAE connects with the GCC Interconnector. EOA_KSA refers to the Eastern Operating Area of Saudi Arabia, which is where the Saudi network interconnects with the GCCI. The most significant impact can be seen in the Eastern Operating Area of Saudi Arabia. On the system peak day, in the 2016 International Fuel Prices scenario, Saudi Arabia would see electricity prices reach around \$210/MWh. However with trades, the KSA has the ability to import cheap electricity from other countries, flattening out that price curve to a peak of only \$157/MWh.

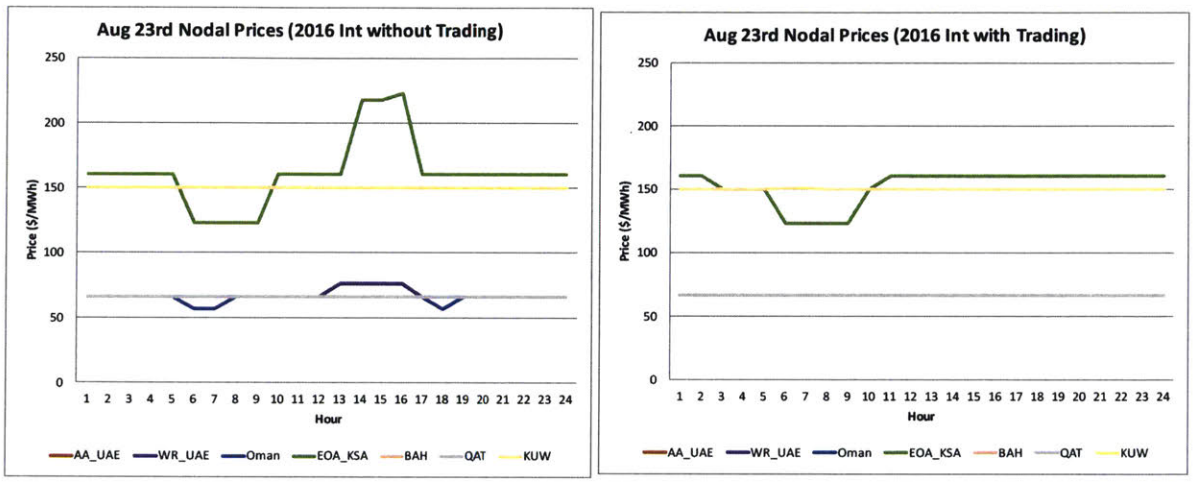


Figure 6-3: System Peak Day Nodal Prices: Trading vs. No-Trade (2016 Intl. Prices)

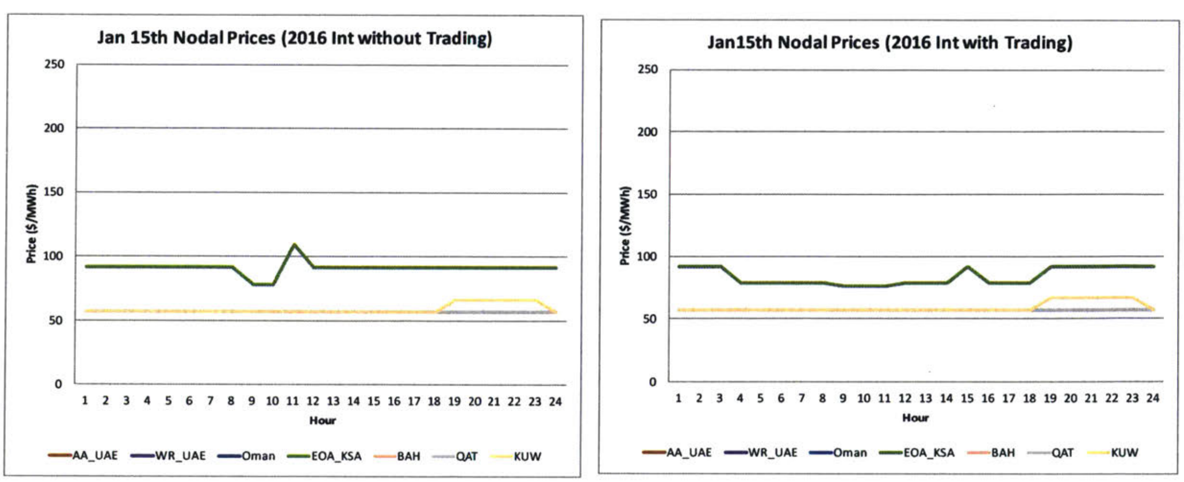


Figure 6-4: System Minimum Day Nodal Prices: Trading vs. No-Trade (2016 Intl. Prices)

Table 6.3: Trading vs. No-Trade Price Differences ($/MWh) (2016 - International Prices)

Country	No Trade	Trade	Price Difference (%)
UAE	65.45	65.18	-0.41
KSA	141.70	139.38	-1.6
Kuwait	104.03	99.41	-4.44
Oman	61.00	61.67	1.09
Bahrain	65.38	65.25	-0.20
Qatar	62.75	64.75	3.19

6.1.4 Impact of Fuel Subsidies

As discussed previously, fuel subsidies distort the market, impacting the volume and direction of trades between countries. Domestically, fuel subsidies impact the amount generated by each fuel type (and thus fuel consumption and cost). Figures 6-6 to 6-10 show the different production mixes for each scenario.

Bahrain, shown in Figure 6-7, is an interesting case. The model reveals that subsidies can flip the country from being a net Importer to a Net Exporter of electricity, thereby changing its annual electricity production from natural gas by 8.1 TWh, which is 48% of its annual production without trading.

The model also reveals that if the UAE were to maintain its current fuel subsidies, the Barakah Nuclear Power Plant, the first nuclear power plant in the GCC region, would be uncompetitive in 2030 as shown in Figure 6-6.

A comparison of the fuel consumption of countries with and without trading in the subsidized fuel scenarios multiplied by the amount subsidized by each government allows us to estimate how much a government would spend on subsidies. As expected, the countries that import as a result of cross-border trading with subsidized prices benefit from cross-border trading, as they are effectively importing other governments' subsidies. The clear "winners" in this scenario are Saudi Arabia, Oman, and Bahrain, who are importing subsidized electricity from Kuwait, the UAE, and Qatar.

Table 6.4: Government Spending on Fuel Subsidies (2016 - Subsidized Fuel Prices Scenario)

Scenario	KSA	QAT	OMA	UAE	KUW	BAH
No Trading ($ M)	42,192	2,215	1,826	7,082	9,378	748
Trading ($ M)	41,841	2,523	1,688	7,435	9,981	509
Difference ($ M)	-351	308	-137	353	603	-239
Difference (%)	-0.83	13.91	-7.52	4.99	6.42	-31.96

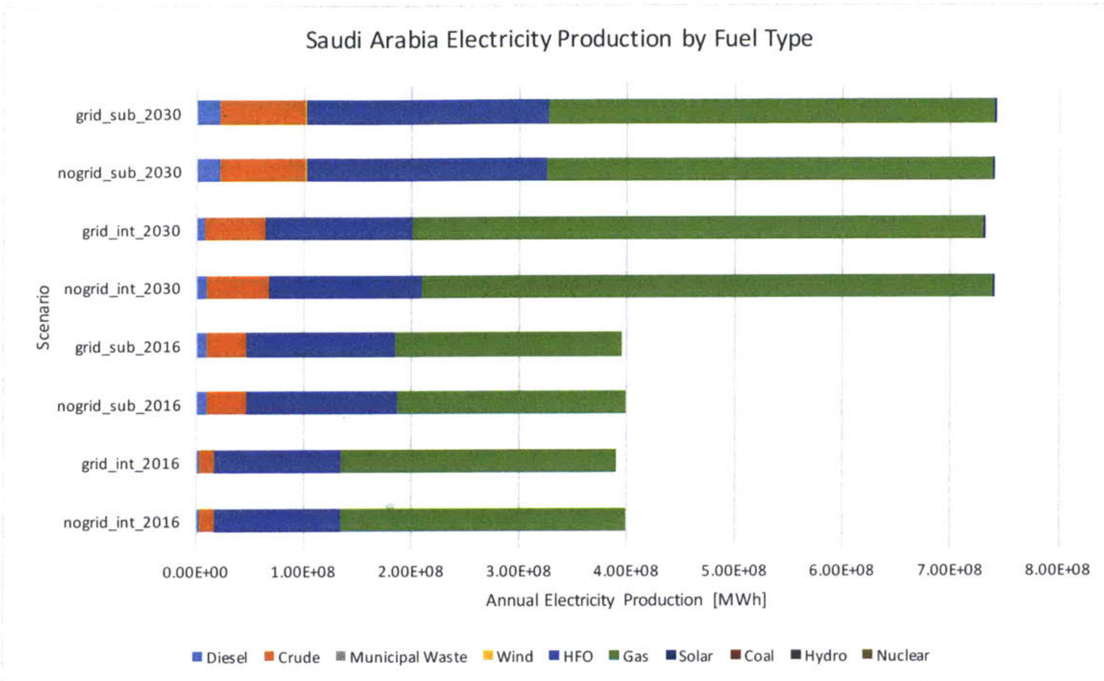


Figure 6-5: KSA Electricity Production by Fuel Type

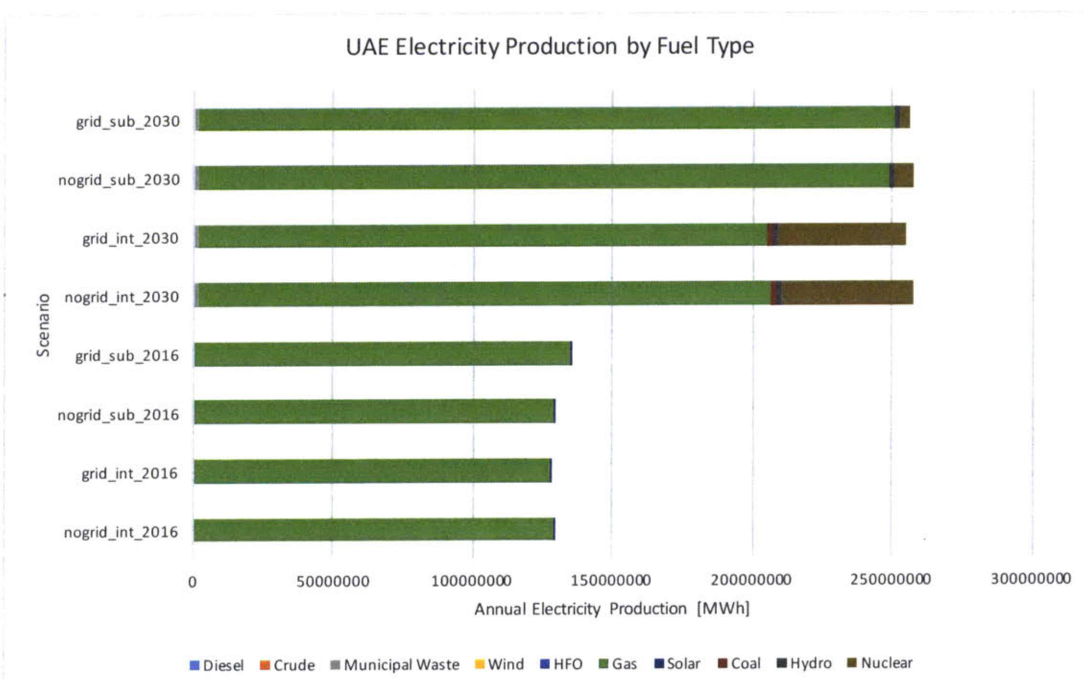


Figure 6-6: UAE Electricity Production by Fuel Type

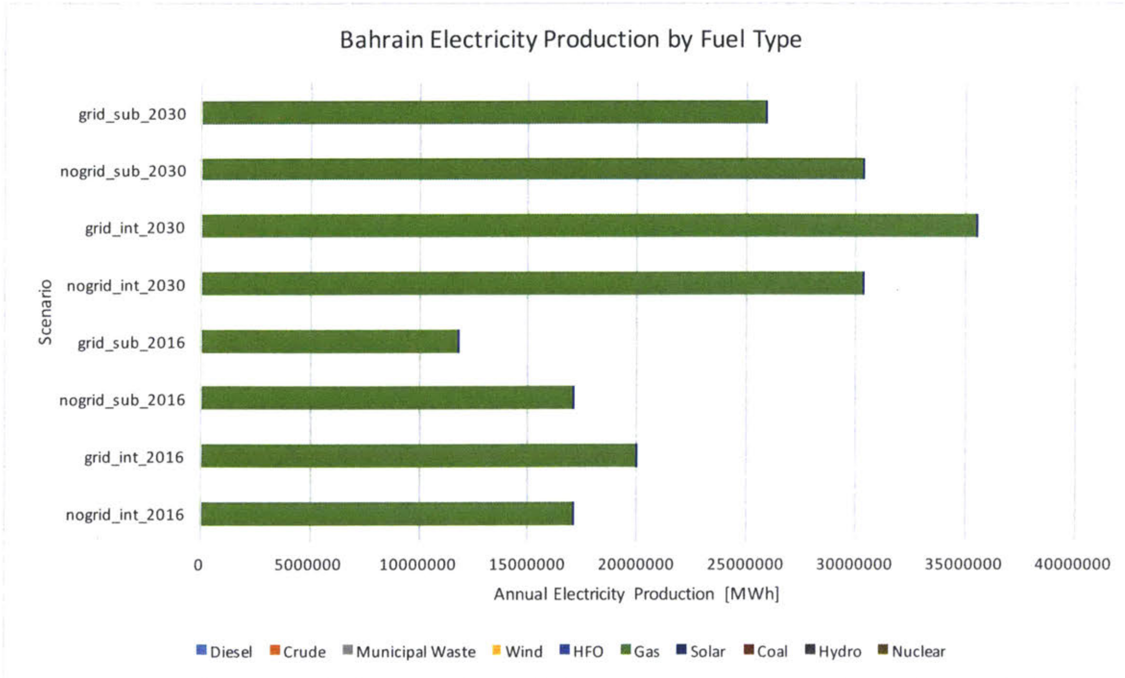


Figure 6-7: Bahrain Electricity Production by Fuel Type

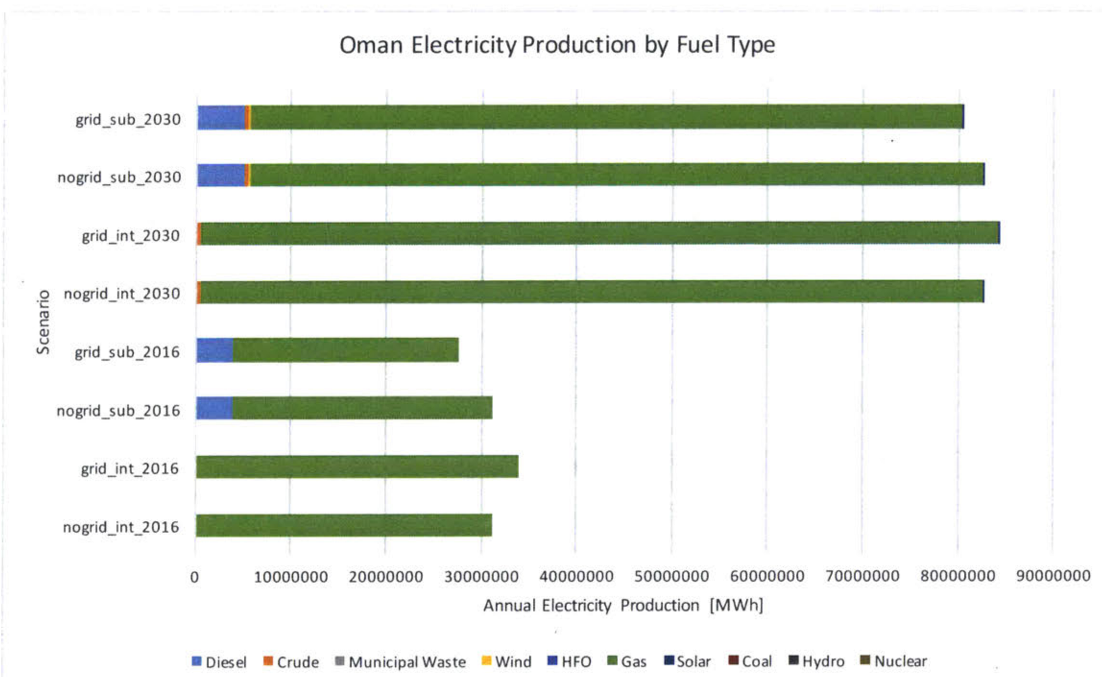


Figure 6-8: Oman Electricity Production by Fuel Type

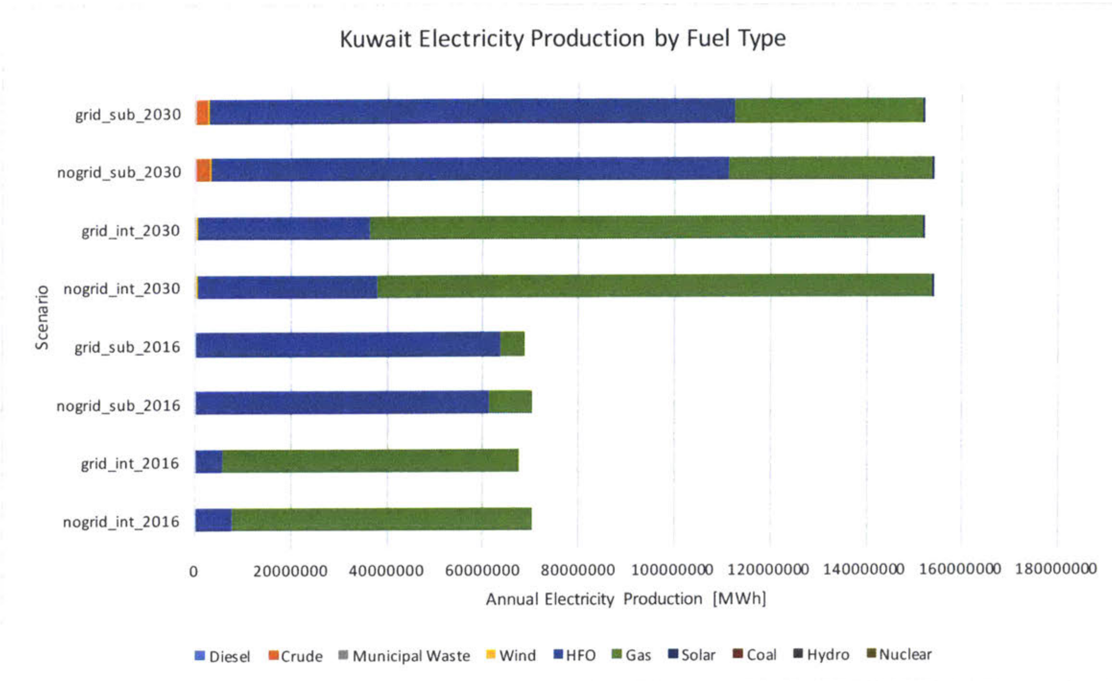


Figure 6-9: Kuwait Electricity Production by Fuel Type

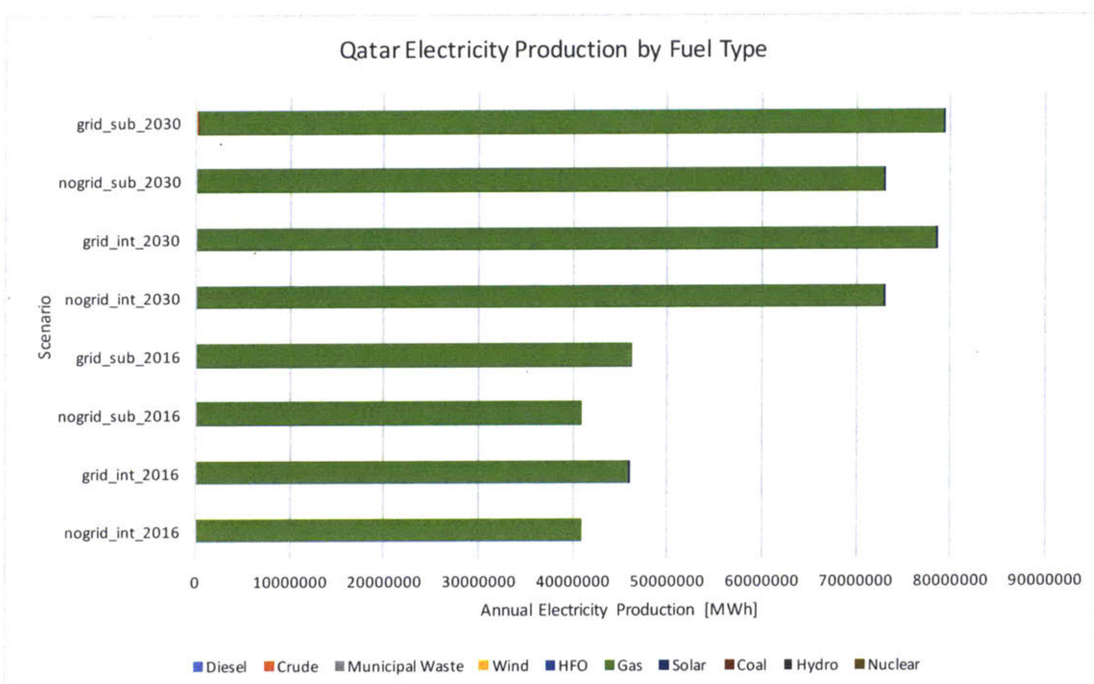


Figure 6-10: Qatar Electricity Production by Fuel Type

6.1.5 Transmission Congestion

For the two 2016 trading scenarios, the model revealed certain corridors[2], which might not be congested if trading is done with fuel price subsidies, may become congested once those subsidies are removed. Other corridors remain congested with either subsidized or international fuel prices, but the flows simply flip direction, such as is the case of the interconnector between Oman and the Al Ain Region in the UAE. Some of these congested corridors are domestic networks and are already being addressed by domestic infrastructure plans. Figure 6-11 shows the top twenty congested corridors in both the 2016 and 2030 cases. The corridors and nodes correspond to those depicted in the network map shown in Chapter 5, Figure 5-10. The bars represent the percent utilization of each of the lines. For example, the Qurayyah to Jasra corridor, which is the line where the Bahrain network connects with the GCCI network, is used at 100% in the 2016 Subsidized Fuel Price scenario. (As was discussed in Section 6.1.4, in the subsidized fuel price scenario Bahrain is constantly importing the cheaper power from other countries). When the subsidies are removed, Bahrain switches to an occasional exporter, hence the line utilizaton rate of about 63% in the 2016 International Fuel Prices Scenario.

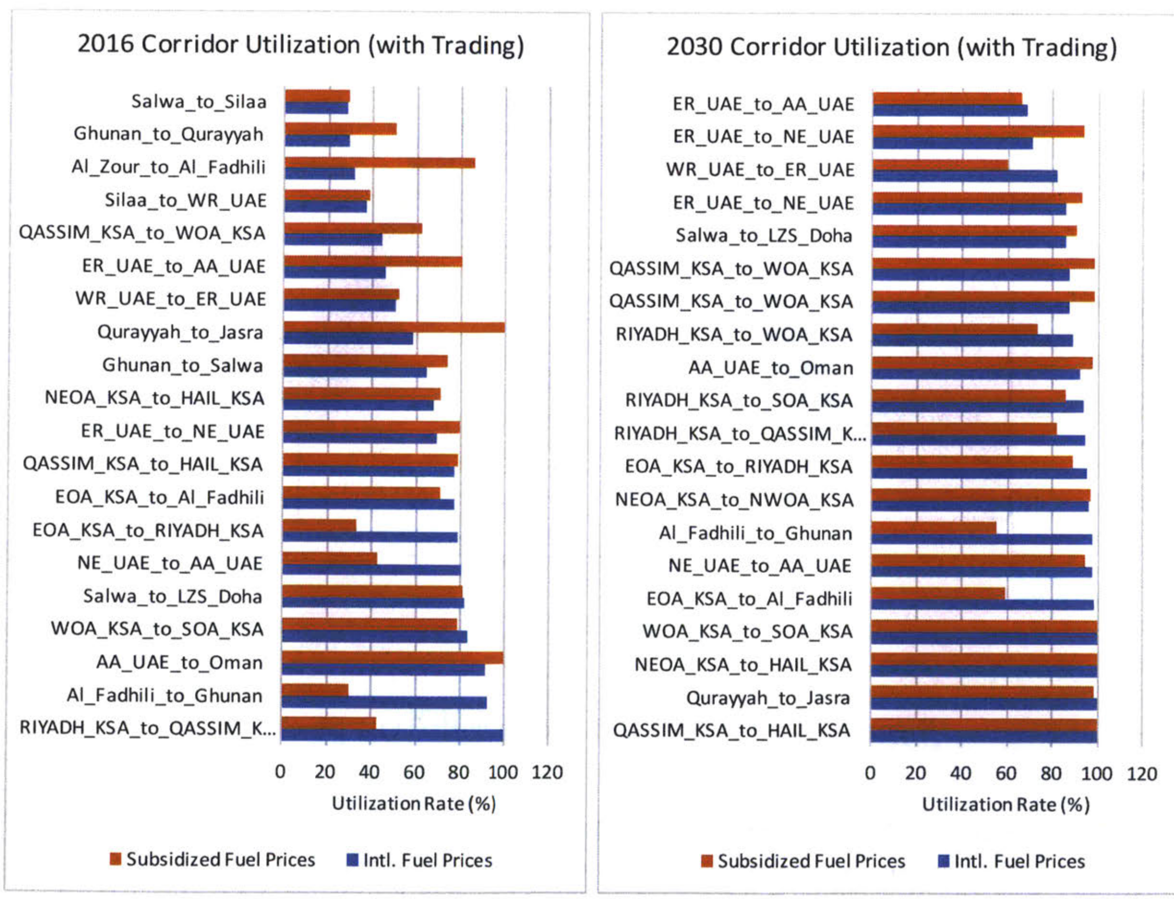


Figure 6-11: Top 20 Congested Corridors 2016 and 2030 with Trading

[2] the sum of all the lines between the two regions

6.1.6 "In-Kind" Trading

Given the distortions due to subsidies, one proposal put forward by the GCCIA was based on idea of the interconnector serving as a"battery bank", with countries being debited or credited for exchanges during specific times of use. In others words, trades would be done in-kind by TOU as discussed in Chapter 5, Section 5.2.8.

In order to analyze this potential trading method, the hours of the day were split into TOU blocks, and then the yearly net balance of energy traded during those blocks was totaled. The TOUs were defined as follows (shown in Figure 6-12).

- **On-Peak** 09:00 - 17:00
- **Shoulder** 06:00 - 09:00 & 17:00 - 21:00
- **Off-Peak** 21:00 - 06:00

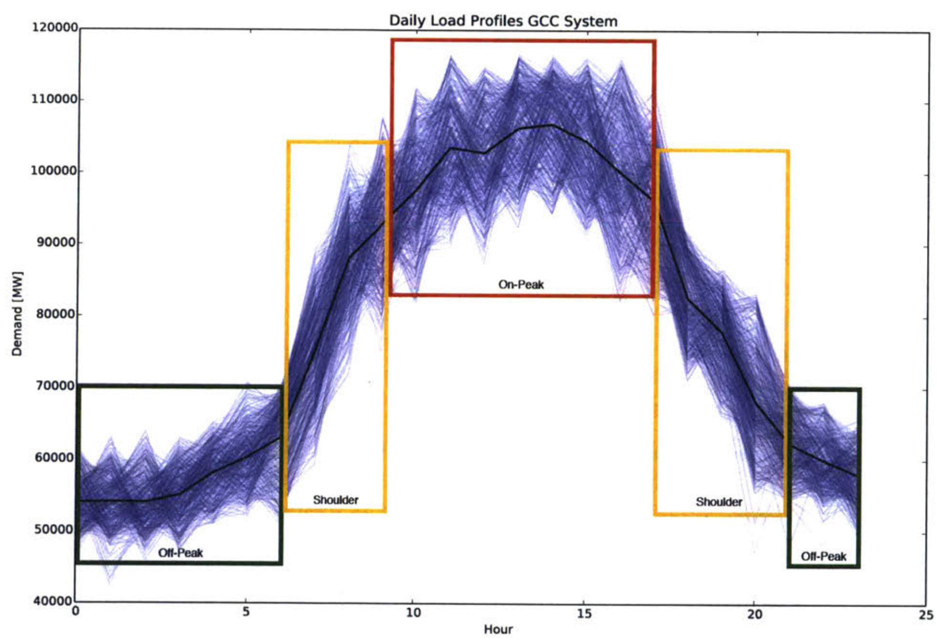


Figure 6-12: Typical Load Profile with TOU Blocks

The analyses were conducted using 2016 Subsidized Fuel Prices, since the motivation for the "in-kind" trading is to serve as an intermediate step for real-time trading with subsidies. As Figure 6-13 demonstrates, few countries have "net zero" balances[3] by the end of the year. This would require determining some formula for calculating a cost for each TOU

[3]A net-zero balance in TOU "in-kind" trading would mean that a country exported as much energy during that TOU block as it imported during that same TOU block over a fixed time period (i.e one year)

block, in order to settle the balances. Furthermore, the balances are dependent on the time period over which they are computed. For example a simple division of the year into two 6-month "summer" and "winter" periods (Figures 6-14 and 6-15) reveals that certain countries balances are greatly affected by shifts in their relative seasonal demand profiles. In the case of Saudi Arabia, a positive balance (meaning more exports) occurs over the summer. A closer examination of the marginal costs curves computed in Chapter 5, specifically Figure 5.2.5, reveals that Saudi peaking power plants (especially with subsidies) are less expensive than those of the other GCC countries. One could foresee that defining these TOU blocks and accounting periods could become a very political exercise as each country aims to make it such that the balances work in their favor.

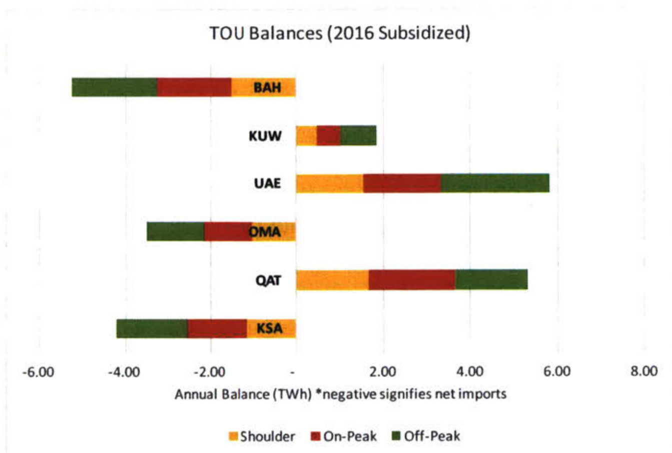


Figure 6-13: TOU Balances

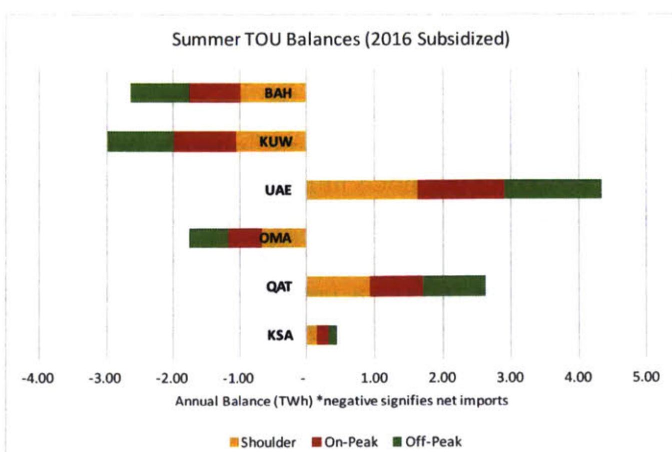


Figure 6-14: Summer TOU Balances

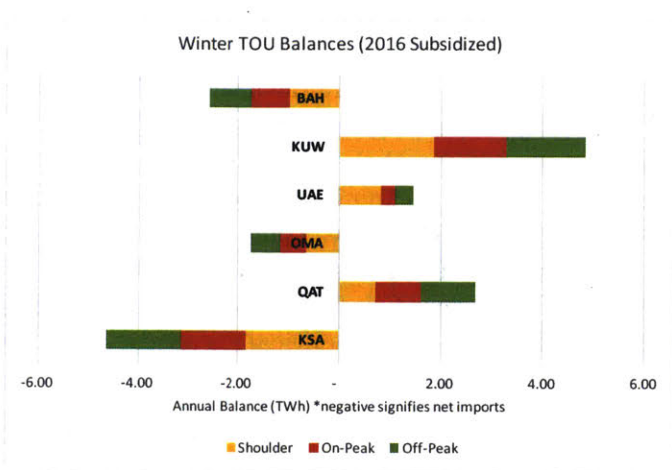


Figure 6-15: Winter TOU Balances

6.1.7 Winners and Losers

The above analyses bring us to the key final question: which countries benefit from the connector? The answer clearly is not a simple one as it depends on which scenario and from which stake-holder's perspective the problem is viewed.

We first look at which governments are currently benefiting (or would benefit) from cross-border trade with the current subsidies and generation mixes. As noted in Section 6.1.4, the countries who meet demand via imports not only see a reduction in prices, but the governments themselves spend less on fuel subsidies as less fuel is consumed. This comes at the trade-off that generators in importing countries are making less income as they are selling less electricity overwall. Furthermore, consumers in exporting countries may see higher prices (while generators make more income). In the 2016 Subsidized Fuel Price scenario, the "winners" are the governments of Saudi Arabia, Oman, and Bahrain, who are able to reduce the amount spent in fuel subsidies by around \$ 720 M between the three of them. However this is contingent on other countries retaining higher fuel subsidies. In fact Saudi Arabia recently announced [67] that it will be further cutting back on fuel subsidies, which could affect the economics.

To answer the question of "who benefits" when trades are conducted without fuel subsidies, one metric for this is to compare the operational costs of each country before and after trades and subtract/add the value of their exports/imports (which where estimated using the hourly nodal price as the exporting node multiplied by the volume of energy exchanged during that hour). The results of these calculations are shown in Table 6.5. The model calculated the total value of trades across the electricity interconnector at USD \$2.3 Billion. As can be seen, every country does receive a net benefit from trading across the Interconnector. While the total operational cost increases in the countries that are exporting, the value of their exports exceeds the production costs (assuming the volume of the trade is sold at the marginal generator cost). The final proportion split of benefits is shown in Table 6.5; these are the country trade benefits divided by the total trade benefits for the combined six GCC countries. The original share split of the initial GCCI investment (done in year 2001, discussed in Chapter 3.2) is shown below for comparison. As can be seen, Kuwait and Saudi Arabia benefit the most from regional trades. However of the nearly USD $700 Million reduction in operational costs, only $53 Million are converted to trade benefits, the rest are lost due to transmission losses.

Table 6.5: Operational Cost Reductions from Trade, 2016 Int. Prices. (In $ Millions)

($ Millions)	**KSA**	**QAT**	**OMA**	**UAE**	**KUW**	**BAH**
Op. Costs (No-Trade)	39,957.85	2,415.44	1,799.22	7,722.21	5,090.61	1,034.09
Op. Costs (Trading)	39,073.00	2,725.43	1,971.18	7,643.64	4,806.87	1,228.49
Difference	884.85	-309.99	-171.96	78.57	283.74	-194.40
Value of Exports	0.07	345.89	185.53	103.10	58.14	198.24
Value of Imports	870.70	26.75	11.19	181.02	316.36	2.82
Net Operational Benefit	**14.92**	**9.15**	**2.38**	**0.64**	**25.52**	**1.02**

Table 6.6: Country Share of Benefits from Interconnector

Scenario	**KSA**	**QAT**	**OMA**	**UAE**	**KUW**	**BAH**
Trade Benefits (%)	27.82	17.06	4.44	1.19	47.59	1.90
2001 Initial Share (%)	31.60	11.70	5.60	15.40	26.70	9.00

6.2 Policy Implications

The results presented above, in combination with the challenges of developing multinational electricity markets (discussed in Chapter 2), have multiple policy implications. In short, policies must address the following key questions:

- What are the next steps for further developing a market in the GCC countries?
- How should transmission capacity and costs be allocated?
- How should future investments be planned and those costs recouped?
- How should the regional system be operated?
- How should market distortions be dealt with?

Chapter 2 discussed the different stages of regional market integration. In the GCCI case, the market is in the proccess of transitioning into the second stage (some system operation coordination). The next step would be to further the development of domestic energy markets, since as discussed in Chapter 3, the GCC countries have liberalized their markets to varying degrees. In developing the market, clear harmonization of rules is necessary.

The GCCIA was considering using TOU trading as an intermediate step for enabling cross-border trade while subsidies are still in place. Our analysis shows that this TOU "in-kind" trading system would not be very effective as few countries balance to zero and the determination of "blocks" could be quite arbitrary and political.

As shown in the analyses above, the most critical issue are fuel subsidies (which diminish the electricity production costs by more than 80%). Countries should place the removal of subsidies at the top of their priority list. A first step toward this could be to reduce all subsidies to the lowest common denominator in the GCC. In addition to enabling countries to gain the benefits of a regional electricity market, this gives an additional justification to governments for easing out subsidies. A possible rule could be to require that GCC countries exchange electric power based on true costs, leaving subsidies as an internal matter.

6.2.1 Allocation of Transmission Capacity and Costs

One of the key issues in regional markets is how the transmission capacity should be allocated and furthermore how the transmission costs should be paid. This would require all the System Operators to coordinate the computation of available interconnection capacity via the use of a common network model. For the GCC region, the best option would be the use of a common nodal pricing model at the operational level, as this model implicitly takes care of determining available capacity. [11] This model was chosen for the Central American market, discussed further below in Section 6.2.3

The second related issue is how to allocate the transmission grid costs. The fundamental principle of transmission grid cost allocation is "beneficiaries pay". The transmission tariffs should not depend on the "commercial transactions taking place but on the location of the agents in the network and volume and timing of their power injections and withdrawals. Economic benefits, or perhaps, as a proxy, a flow-based network utilization method should be used to allocate regional transmission costs." [8] Thus, the region-wide charges should be computed based on how much each agent is expected to benefit from the line. Ideally, the charges would encompass the entire regional transmission system, computed as if there were only one transmission system in place, consistent with the "single system paradigm".

However this is difficult to translate into specific policies and regulations as there is no single scheme for cost allocation that is both technically and economically sound and easy to implement. Aligned with the work of [8], three recommendations are proposed. First, network users should not have to pay piece-wise for each transmission network accessed. Instead, a single regional transmission charge will grant users access to the entire regional network. (So a generator in Kuwait selling power to Oman should pay the same transmission charges as if it were selling power to a customer in Saudi Arabia). Second, the transmission charges should be allocated with a utilization-based method, implemented through a system of national charges. Third, regional transmission charges only apply to lines identified as part of the regional network. The latter is particularly key for the case of Oman and UAE, since the interconnection was built under the GCCIA yet utilizes the UAE grid. As of now the lines are considered part of the GCCI project, yet not considered "regional lines" for transmission cost allocation. [26]

6.2.2 Future Capacity Planning

The expansion of the transmission network should be planned at regional level. Ideally, the GCCIA should be responsible for evaluating the economic and social value of all potential future investments made by the national countries or the market agents. The process would need to strike a balance between respecting the sovereignty of member countries and maximizing efficiency from a regional perspective, and thus would need to be conducted in partnership with the relevant national authorities (outlined in Section 3.3). Certain parts of the world have had success with coalitions of users or merchant investors playing a role in developing new transmission lines (particularly in regions where authority is decentralized, planning processes are slow, or public authorities cannot raise funds). However, given the nature of the GCCIA, and the authority already vested in the institution, these latter two capacity planning methods are not recommended.

6.2.3 Market Operation

There exist three main methods that have been implemented in regional markets across the world for regional market operation. The first, and most integrated, has been a common trading platform, which has been the case in the EU. The second has been the bilateral coordination between independently dispatched local systems, which has been the trend between the regional markets spanning local state systems in the Eastern United States. The third has been to create a higher level regional market that manages the surpluses and deficits of the local markets, as was the case of the Central American regional market. For the case of the GCC, it would appear that this third option might be the best, given the political and technical aspects of the GCCI discussed previously.

One of the issues with market operation using the EU model is transmission congestion resolution. In this market, after bids are submitted at a regional level, the transmissions system operators compute the regional dispatch using a simpler transmission model. In real-time, if there are congestion issues, the system operators in each country can then re-dispatch according to the rules in that country, since it is assumed that each country has the capacity to internalize its on transmission congestion constraints. This raises the question of whether there should be a regional coordinator, and, in the context of multinational grids, does it have the authority to re-dispatch systems internal to countries?

Cadwalader and Hogan [68] demonstrate that coordination of congestion relief across a very large grid may not require a grand coordinator, *as long as each individual region with its own system operator is large enough to internalize the primary effects of its own transmission constraints.* This assumption is valid for many of current systems that were designed for self-sufficiency. They may not longer be valid in future, more integrated systems.

"The conjecture, therefore, is that a regional aggregation should be better when the interconnections are weaker in a particular sense. Not weaker in the sense that the connecting lines have only limited capacity, but weaker in the sense that the looped impacts across the boundaries are reduced relative to the looped impacts within the region. In the limit, obviously the best form of interconnection would be radial, where there would be no looped effects and no distant impacts on constraints and prices. The precise definition of weak loops is not clear, even in the simple example, but the goal is to have relatively little impact on the distant prices once a reasonable estimate of the prices is available." [68]

In its current configuration, the GCC could consider, in the long-term, operating its market in the manner of the Eastern US or European Union since it is quite radial and weakly interconnected. However, the issue of congestion relief is one that will need to be further explored, particularly if plans to further integrate the GCC Interconnection with other electricity grids in the MENA region are to be seriously considered. In the immediate future, the best option (which would also assuage some of the aforementioned issues of transmission capacity and cost allocation) would be a supra-national entity that serves as the regional coordinator as is the case with the Central American Regional Market.

Case Study: Central American Regional Market

The policies outlined above can perhaps be better understood by way of example. While there exist several "super-grids" with functioning regional markets in the world, the regional system that perhaps best resembles the GCCI is the Sistema de Interconexión Eléctrica de los Países de América Central (SIEPAC), the Central American Electrical Interconnection System. SIEPAC is the interconnection of six Central American countries: Panama, Costa Rica, Nicaragua, Honduras, El Salvador, and Guatemala. [69] Trades across this interconnection are coordinated via a regional market known as the Mercado Eléctrico Regional (MER) or Regional Electricity Market. The MER is likely the best model for the GCC countries to adopt in the short-term. It functions by having a system where a regional market overlays rather than replaces existing local markets. What this means is that every day, the six participating countries clear their own day-ahead internal markets. They then submit their offers to buy and sell at each one of the transmission nodes to the regional market. The regional market operator then runs a region-wide optimal load flow for the next day, which determines the optimal dispatch of generation and the nodal prices. The advantage of this system is that each country is able to maintain its autonomy while trading efficiently with the other countries in the region.

Similar to the case of the GCC countries, the SIEPAC project required the development at the regional level of the capacity to design, implement, operate and regulate the regional market and to design, build and operate the transmission line. [70]. The Marco Treaty, signed in 1996 between the countries, facilitated the creation of three permanent international organizations as legal entities, which serve as the core regional market organizations:

- The Regional Commission on Electrical Interconnection (Comisión Regional de Interconexión Eléctrica, CRIE), which serves as the regional regulator.
- The Ente Operador Regional (EOR), which is the regional system operator and regional market administrator.
- La Empresa Propietaria de la Red (EPR), which serves as the regional transmission line company.

In the MER, transmission charges are set by CRIE. The MER Transmission Code provides for recovery of transmission through three price components:

- A variable-cost component met through the nodal price residual and revenues from transmission right auctions
- A transmission toll based on actual flows on the lines.
- A complementary charge levied on all participants to capture any remaining unrecovered cost.

Further details about the design and functioning of the MER can be found in [70], and should serve as a guideline to the GCCIA in developing the regional market.

Chapter 7

Conclusion, Geopolitical Implications, and Future Work

7.1 Conclusion

This thesis analyzed the economic value the Gulf Cooperation Council could extract from trading on existing and planned cross-border electricity infrastructure, namely the Gulf Cooperation Council Interconnection linking the grids of six GCC Countries. Eight cases were run, for the years 2016 and 2030 looking at the impacts of cross-border trades with and without fuel subsidies. In the scenario with international fuel prices, which represents the "best case" optimal situation, the model demonstrated that approximately USD $1 Billion per year in total operational costs (fuel and O&M) could be saved with cross-border trades, representing 2% of total annual GCC operational costs. The model further showed that in this scenario, every country would see a net reduction in operations costs, with Kuwait and Saudi Arabia seeing the greatest portion of this. As expected electricity prices were found to increase slightly in countries that exported and decrease in countries that imported. Kuwait saw prices decrease the most by 4% and Qatar saw prices increase the most by 3%. The total value of trades across the interconnector amounted to approximately USD $2.3 Billion.

In order to reap these benefits from trading electricity across the existing or planned infrastructure, the GCCIA should implement the following three steps, discussed in detail in Chapter 6.

- Furthering the development of domestic electricity markets.
- Harmonizing market rules and grid access tariffs.
- Creating a "supra-national" system coordinator similar to that in the Central American Market.

In implementing these steps, particular attention should be devoted to transmission capacity and cost allocation.

However, the overwhelming impact on the value and direction of trades was the presence of fuel subsidies. We estimated the six governments combined spent approximately USD

$63.5 Billion (with or without trading) in subsidizing fuel for electricity production in 2016, artificially bringing operational costs down by more than 80%. This amounts to more than the operational costs of the system without subsidies, which our model calculates at USD $ 58.12 Billion with trading in 2016.

Assessing a GCCIA proposal for using a Time of Use scheme for"in-kind" electricity trading as an intermediate work-around to subsidies, our model revealed that such a system would be unlikely to work as few countries were "net zero" in any of the TOU blocks. Furthermore, defining the TOU periods would likely be highly disputed. Removal of fuel subsidies, would flip several countries (Oman, Bahrain, the UAE, and Kuwait) from being net importers to net exporters (and vice versa).

Thus, the highest priority should be to ease out subsidies.

Consequently, we propose the following measures to deal with the subsidies:

- **Removing fuel subsidies:** Some GCC countries have already taken steps toward this. However, this is a politically difficult decision as electricity prices will rise with fuel subsidy reductions.
- **Least-denominator fuel subsidy reductions:** As an intermediate step, the benefits of an integrated electricity market can still be reaped if subsidies are homogeneous across the region. It might be more politically feasible to harmonize subsidies to the lowest common denominator across the GCC (that is to the level of the country that subsidizes the least).
- **True-cost trading, blind to internal subsidies policy:** The most adequate (and politically acceptable) approach in the short-term would be to trade electricity based on the true-cost of production rather than the subsidized prices.

7.2 Geopolitical Risks

While the economic benefits of a fully integrated multinational market are clear, there are some significant geopolitical risks that must be considered. Within the broader context of cross-border energy trading, if a country becomes dependent on energy trade to meet domestic demand it become vulnerable to the use of an "energy weapon", where exporting countries utilize this trade dependency as a point of geopolitical leverage. Such instances have occurred in the oil and natural gas global trade. The most salient examples were the Russia-Ukraine Gas Disputes in 2008-2009 and recently 2014, where Russia cut off gas supplies to Ukraine resulting in shortages in Eastern Europe and hardship for many ordinary citizens in mid-winter.

Unlike international trade of hydrocarbons via pipelines (which have storage capabilities), a cut to electricity supply would have much more severe effects to a national economy. For example, in 2015 the Turkish power grid was hacked, resulting in an outage of 40 of Turkey's 81 provinces. The outage wreaked havoc on the country, stalling elevators, blacking out traffic lights and traffic management systems, rendering tens of thousands of credit card machines and ATMs useless, interrupting some cell phone and land-line telecommunications service, disrupting mass transit and rail travel, and closing thousands of public buildings, restaurants and markets. Estimates of the economic cost of such a power cut-off run in the several billions of dollars, [71] thus countries are wary to open their grid and trust foreign counter-parties.

This risk becomes even more salient in light of the recent 2017 Qatar Diplomatic Crisis, where several Arab countries, including Saudi Arabia, the UAE, and Bahrain cut diplomatic ties with Qatar in a dispute over regional security. The severing of relations included withdrawing ambassadors and imposing trade and travel bans. There were concerns that Qatar in retaliation would cut off its gas exports to the UAE (via the Dolphin Pipeline), which serves to meet about 30% of the UAE's energy needs.[72]

The best policy option to minimize this risk would be to limit the amount of integration regional networks. This does not imply that regional trade across existing regional connections should be limited, nor should development of regional markets be hindered. (Quite the opposite, it should be encouraged, as the results of this thesis demonstrate.) Rather, this simply indicates that there is likely a natural limit to the level of integration in order to protect national security. This further aligns with the discussion points regarding market operation presented in Chapter 6. Academic literature points to the existence of a natural limit for where regional grids can be integrated while still able to function autonomously without a central dispatcher running the entire system as one. The GCC grid is quite radial and therefore these risks are mitigated, however this "theoretical limit" carries important implications for further regional integration and market design as many of the GCC countries have expressed ambitions to create a pan-Arab electricity grid, shown in Figure 7-1 [19].

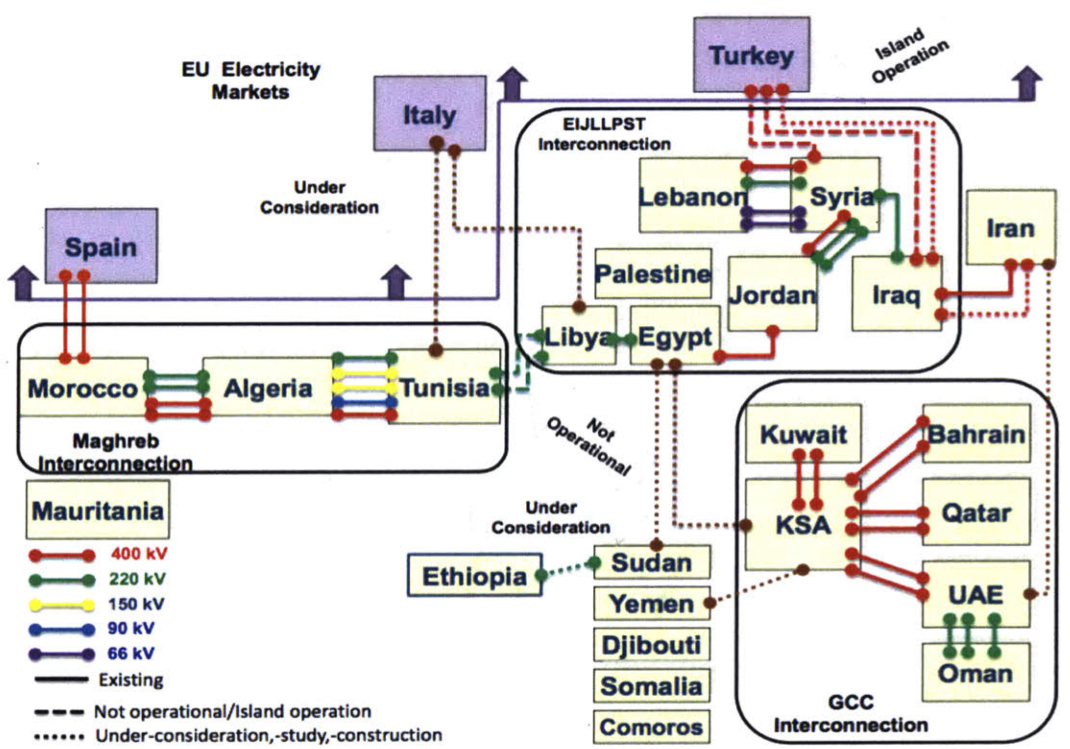


Figure 7-1: Potential Pan-Arab Electricity Grid [19]

7.3 Future Work

While the model in this thesis captures many of the key technical details influencing power flows across interconnected networks, there exist many options to improve the model results and expand the capabilities. These can be divided into three categories: (1) improving model accuracy (2) improving model implementation and (3) expanding model capabilities.

7.3.1 Improving Current Model Accuracy

Improving Model Accuracy consists of improving representation of technical details.

First and foremost, the model would greatly benefit from better data sets. As discussed in Chapter 5 many simplifications were made to the model, primarily due to data limitations, which ultimately limited the accuracy of the results. Future work should entail working closely with national system operators to better fine-tune the model inputs and assumptions.

The internal networks of countries were modeled by constraining transfer capacities between regions rather than modeling the detailed internal transmission and distribution networks. While such approximations have been acceptable in the past, with the growth in distributed generation and intermittent sources, the power flows across lines are more likely to vary across points in time. Capturing internal network constraints would certainly improve accuracy of location marginal prices and better identify potential transmission constraints.

The ohmic losses on transmission lines are quadratic and would need to be approximated via piece-wise linearization. [45]. If the physical properties of the transmission lines are known, line losses could be better approximated, thereby improving the DC approximation for power-flow. [73]

Given the limited data availability, only two full yearly (8760h) solar irradiation datasets were available. The distance between a node and either of these two sites was used to determine which irradiation profile should be used. However, variation in renewable resources across geographies is one of the drivers for regional integration; more accurate representation of these resources would better capture the trade potential.

National hourly demand was disaggregated using the techniques discussed in Chapter 5. An important improvement to the model would be to obtain better nodal demand data. Furthermore, a simple linear scaling of the hourly demand curves by the yearly growth rate was used to forecast future demand. In order to improve the model, more advanced forecasting techniques, which better account for growth rates by individual sector (such as those shown in Figure 7-2) and how they affect different seasonal and hourly peaks could be used.

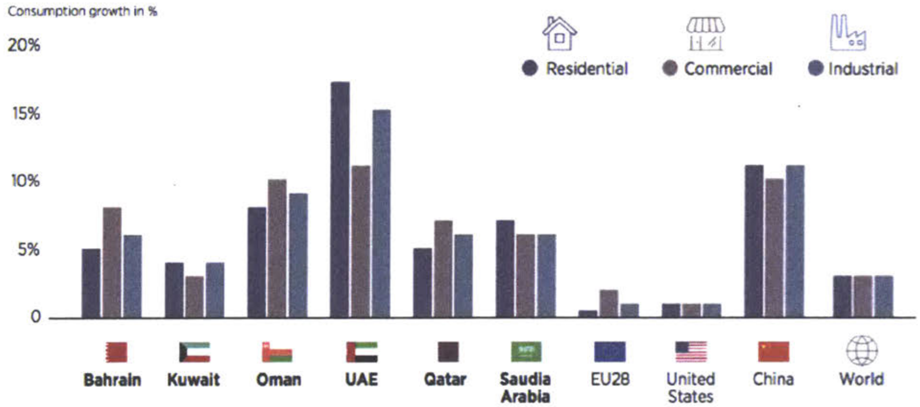


Figure 7-2: GCC Annual Electricity Consumption Growth by Sector, 2003-13 (%) [21]

7.3.2 Improving Model Implementation and Analysis

Improvements to the model implementation and analysis consist of overcoming computational limitations in order to provide more in depth analysis through additional model runs.

As with most computational models, sensitivity analyses to any of the parameters could be performed. In this particular thesis, the solve time of the GCC network was fairly long; each scenario, when run on an Intel Core i7 2.6 GHz Quadcore machine, had a solve time of about 30 minutes for each year. In this study eight scenarios were modeled, each with a full year, resulting in a four hour run-time. Additional scenarios could take several hours, if not days depending on the time horizon of interest. Full sensitivity analysis would require either improved computing hardware or significant run-time. A possible option could be to use representative periods to shorten model run-time, although determining such periods to accurately capture system dynamics can be an arbitrary and lengthy process.

Given the model is deterministic, it assumes perfect knowledge of future conditions. Since in reality those conditions are not known, the model could be adjusted into a stochastic one where probability distributions for unknown parameters are given. As with conducting sensitivity analysis, stochastic parameters would significantly increase model resolution time, as more scenarios would need to be run.

However, one of the advantages of using Julia and JuMP for model implementation is that many of the tools used for improving the run-time of general computing functions can be applied to this model. Several features could be added to the model to improve usability, especially if the model were to be reused to run different scenarios. One such feature could be to add a function to "stringify" the inputs, that is convert them to a string, and then using the Damerau-Levenshtein distance [74] to find the closest cached result. The closest cached result could then be used to"warm-start" the Gurobi Solver.

7.3.3 Expanding Model Capabilities

In this model, we only evaluated future announced expansion plans (new generators and new transmission lines). However, the model could be expanded into a two-stage optimization problem, which would first propose different transmission and generator options and then determine the optimal dispatch of the selected configuration. The model could then return the expansion configuration that results in the lowest total cost of investment and dispatch. Such a model would significantly increase model complexity and resolution time. However, if implemented correctly with appropriate solvers, the model could take advantage of several advanced optimization techniques.

Appendix A

Appendix: Tables and Figures

A.1 Data Sources

Table A.1: Data Input Sources

Data	Description	Source	Year
Generators	Full Set of Current and Future Powerplants in GCC Countries	GlobalData[18]	2016
Demand - 2016	8760 hours of demand for each GCC interconnection node	GCCIA	2016
GCC Network	Transmission topology and line parameters for GCC interconnection	GCCIA	2016
Generator Technical Parameters	Heat rates, ramp rates, and estimated costs	US EIA [55]	2016
International Fuel Prices	Market price for fuel input at major international hub	US EIA [55]	2016
KSA Fuel Prices	Subsidized fuel prices for generators	ECRA [20]	2016
Solar Capacity Factors	Average hourly historical Solar Irradiation Data for GPS location	NREL [56]	TMY

A.2 Generation Costs

Generation cost parameters used for the model.

Year	Capital Cost ($/kW)	Variable O&M ($/MWh)	Fixed O&M ($/kW-Yr)	Heat Rate (Btu/kWh)	Construction Schedule (Months)	POR (%)	FOR (%)	Min. Load (%)	Spin Ramp Rate (%/min)	Quick Start Ramp Rate (%/min)
2008	1250	–	–	–	–	–	–	–	–	–
2010	1230	3.67	6.31	6,705	41	6.00	4.00	50	5.00	2.50
2015	1230	3.67	6.31	6,705	41	6.00	4.00	50	5.00	2.50
2020	1230	3.67	6.31	6,705	41	6.00	4.00	50	5.00	2.50
2025	1230	3.67	6.31	6,705	41	6.00	4.00	50	5.00	2.50
2030	1230	3.67	6.31	6,705	41	6.00	4.00	50	5.00	2.50
2035	1230	3.67	6.31	6,705	41	6.00	4.00	50	5.00	2.50
2040	1230	3.67	6.31	6,705	41	6.00	4.00	50	5.00	2.50
2045	1230	3.67	6.31	6,705	41	6.00	4.00	50	5.00	2.50
2050	1230	3.67	6.31	6,705	41	6.00	4.00	50	5.00	2.50

Figure A-1: CCGT Generation Costs [56]

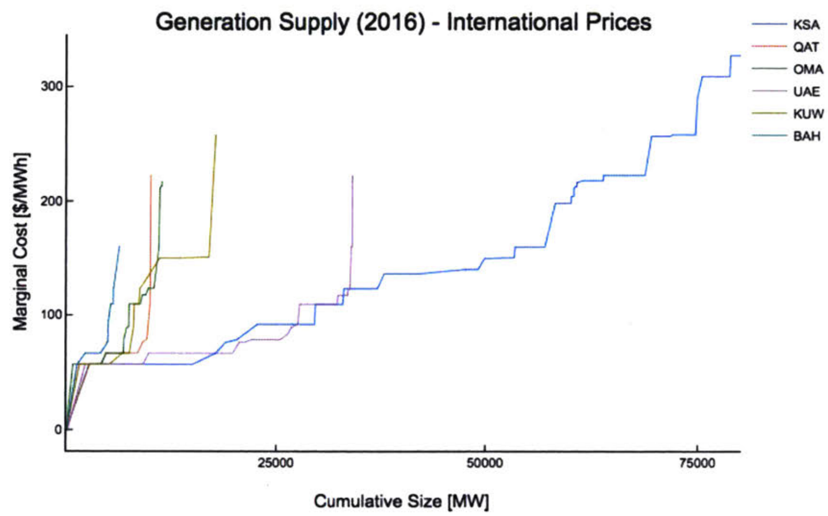
Year	Capital Cost ($/kW)	Variable O&M ($/MWh)	Fixed O&M ($/kW-yr)	Heat Rate (Btu/kWh)	Construction Schedule (Months)	POR (%)	FOR (%)	Min. Load (%)	Spin Ramp Rate (%/min)	Quick Start Ramp Rate (%/min)
2008	671	–	–	–	–	–	–	–	–	–
2010	651	29.9	5.26	10,390	30	5.00	3.00	50	8.33	22.20
2015	651	29.9	5.26	10,390	30	5.00	3.00	50	8.33	22.20
2020	651	29.9	5.26	10,390	30	5.00	3.00	50	8.33	22.20
2025	651	29.9	5.26	10,390	30	5.00	3.00	50	8.33	22.20
2030	651	29.9	5.26	10,390	30	5.00	3.00	50	8.33	22.20
2035	651	29.9	5.26	10,390	30	5.00	3.00	50	8.33	22.20
2040	651	29.9	5.26	10,390	30	5.00	3.00	50	8.33	22.20
2045	651	29.9	5.26	10,390	30	5.00	3.00	50	8.33	22.20
2050	651	29.9	5.26	10,390	30	5.00	3.00	50	8.33	22.20

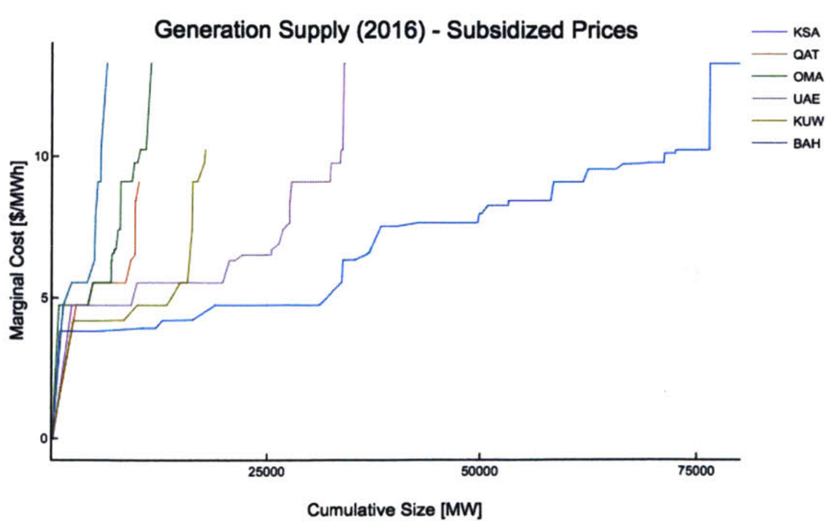
Figure A-2: Gas Turbine Generation Costs [56]

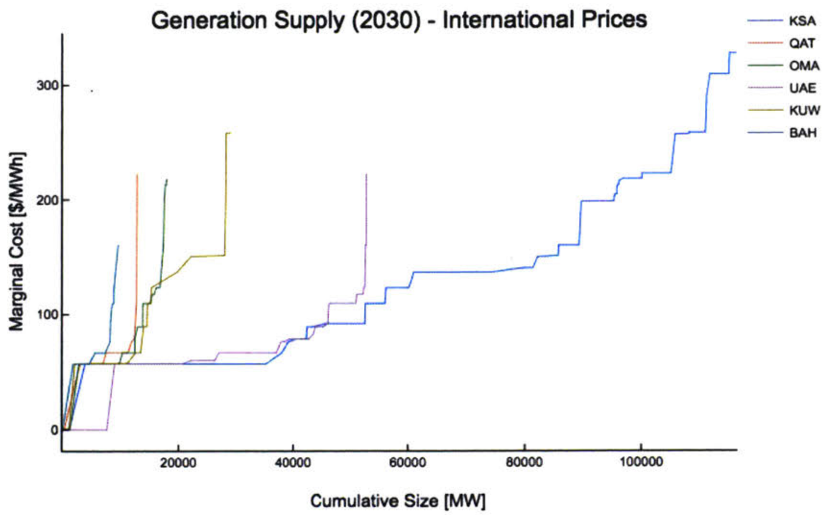
Year	Capital Cost ($/kW)	Fixed O&M[a] ($/kW-yr)	Heat Rate (Btu/kWh)	Construction Schedule (Months)	POR[b] (%)	FOR[c] (%)	Min. Load (%)	Spin Ramp Rate (%/min)	Quick Start Ramp Rate (%/min)
2008	6,230	–	–	–	–	–	–	5.00	5.00
2010	6,100	127	9,720	60	6.00	4.00	50	5.00	5.00
2015	6,100	127	9,720	60	6.00	4.00	50	5.00	5.00
2020	6,100	127	9,720	60	6.00	4.00	50	5.00	5.00
2025	6,100	127	9,720	60	6.00	4.00	50	5.00	5.00
2030	6,100	127	9,720	60	6.00	4.00	50	5.00	5.00
2035	6,100	127	9,720	60	6.00	4.00	50	5.00	5.00
2040	6,100	127	9,720	60	6.00	4.00	50	5.00	5.00
2045	6,100	127	9,720	60	6.00	4.00	50	5.00	5.00
2050	6,100	127	9,720	60	6.00	4.00	50	5.00	5.00

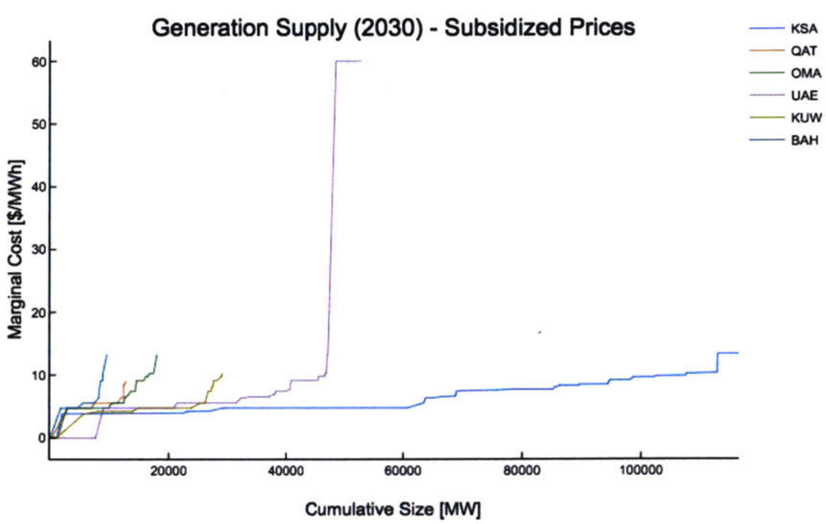
Figure A-3: Nuclear Generation Costs [56]

A.2.1 Marginal Cost Curves









A.3 Network Maps

The GCC network based on data provided by the GCCIA dating from 2016, and is represented in Figure A-4.

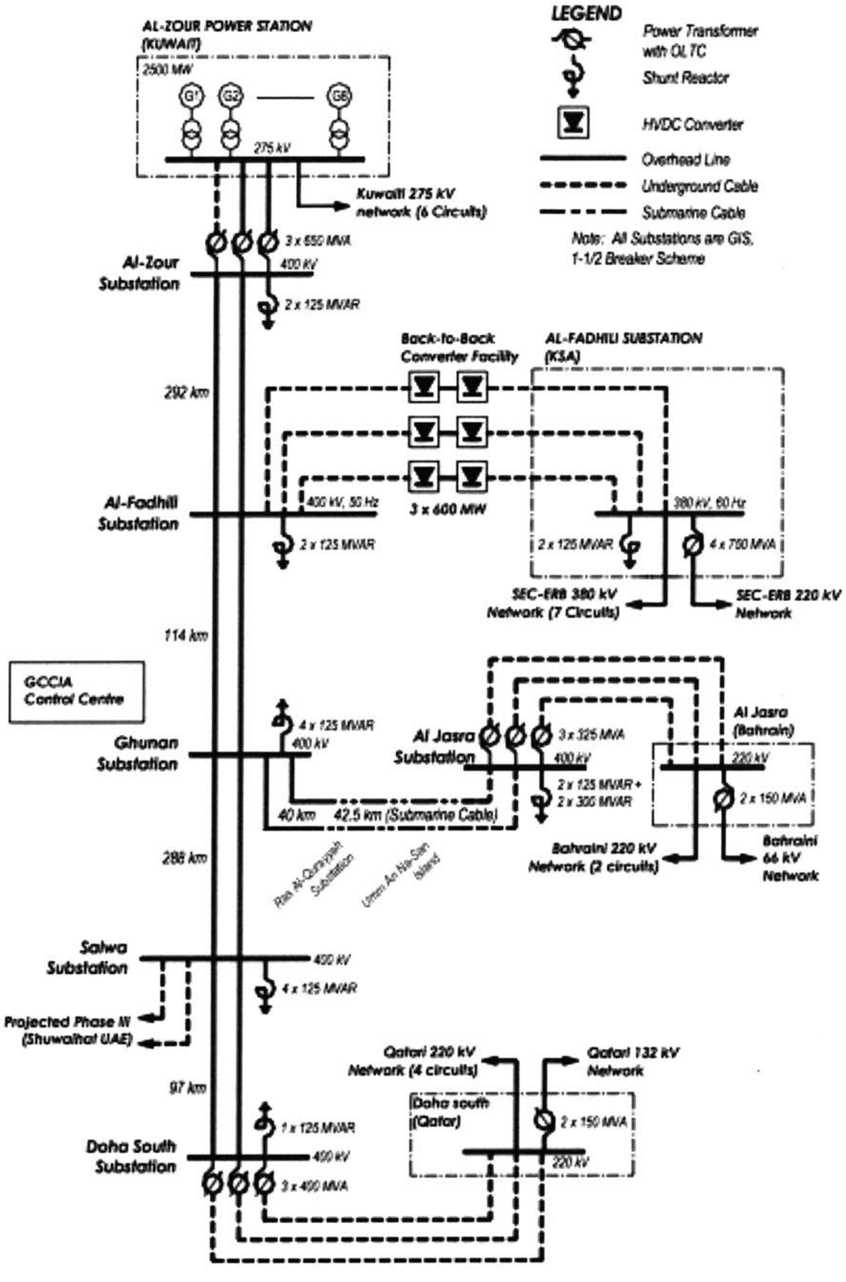


Figure A-4: GCC Network Map.

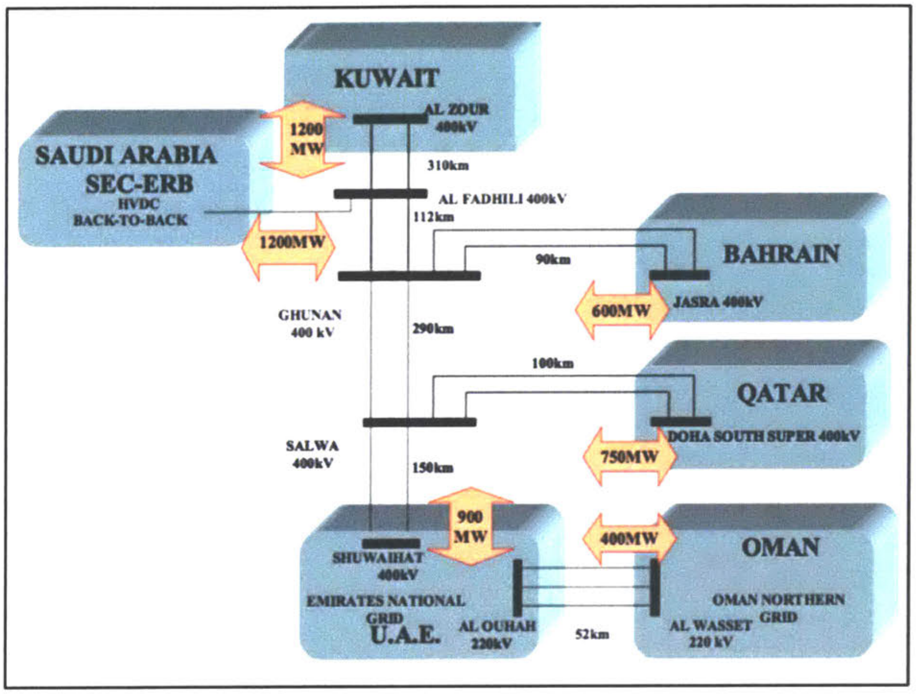


Figure A-5: GCCI Schematic

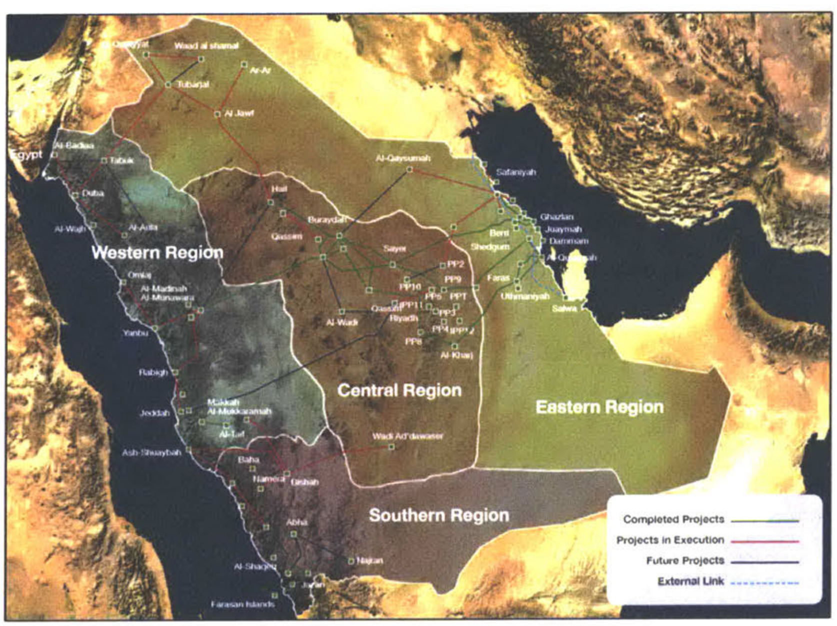


Figure A-6: KSA Transmission Map.

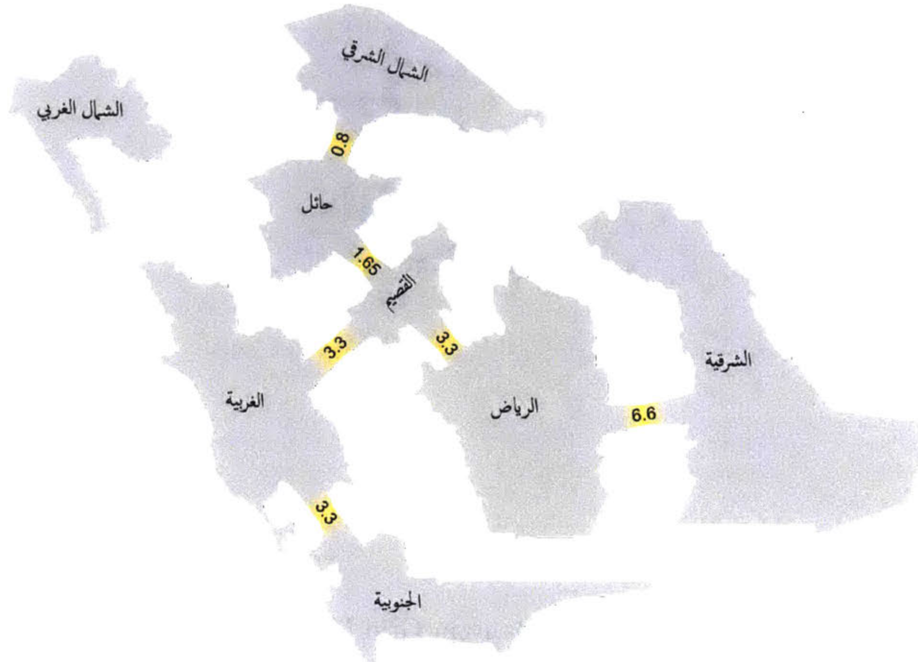


Figure A-7: KSA Transmission Map (2016)

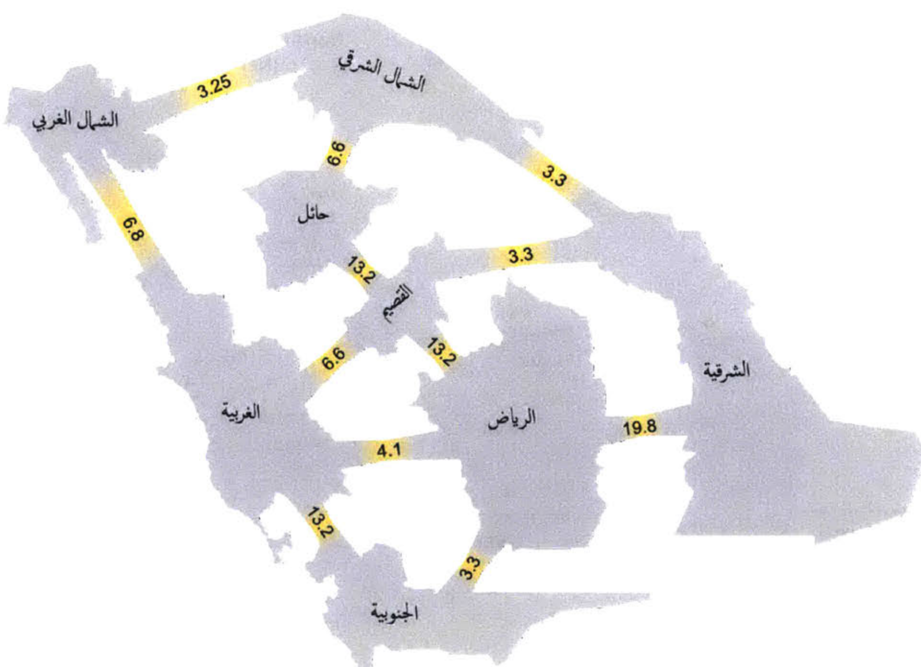


Figure A-8: KSA Transmission Map (2025)

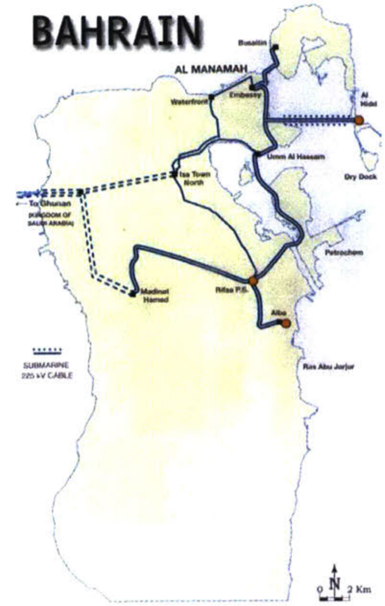


Figure A-9: Bahrain Grid Map [75].

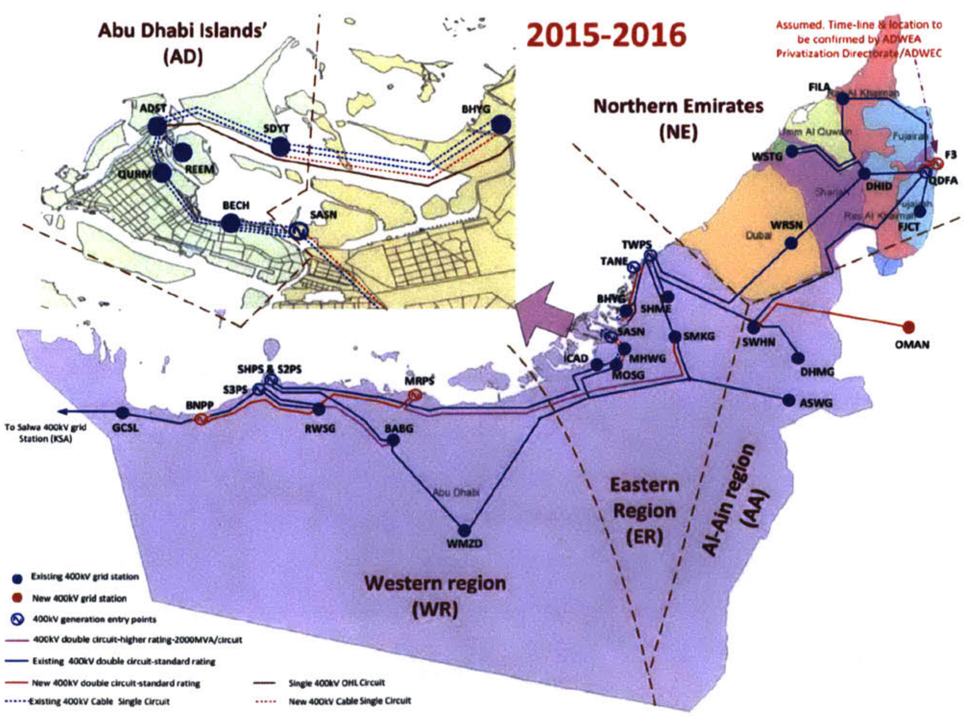


Figure A-10: UAE 2016 Grid Map [32].

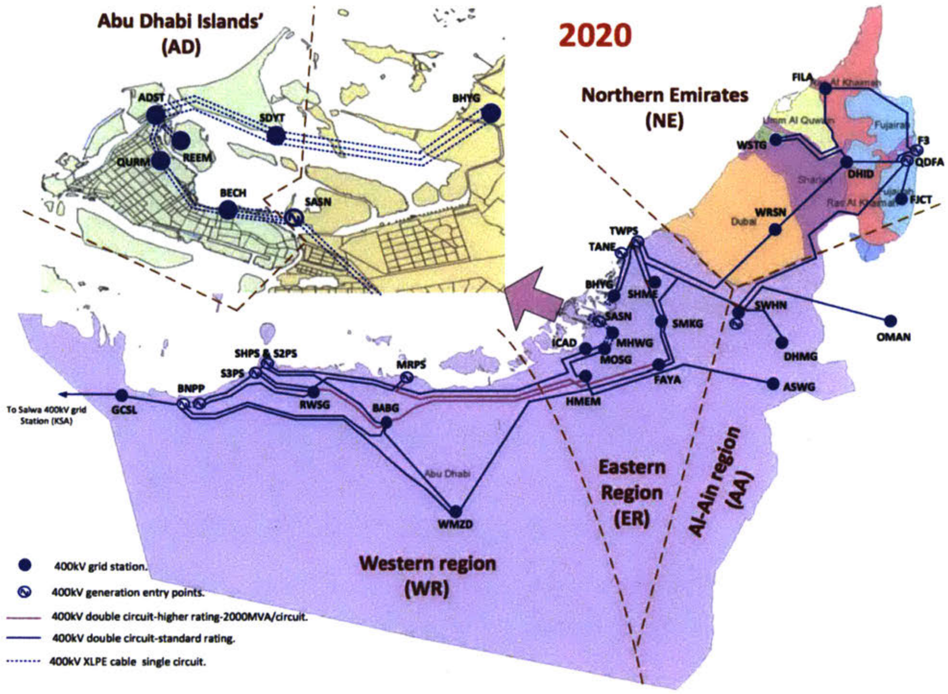


Figure A-11: UAE 2020 Grid Map [32].

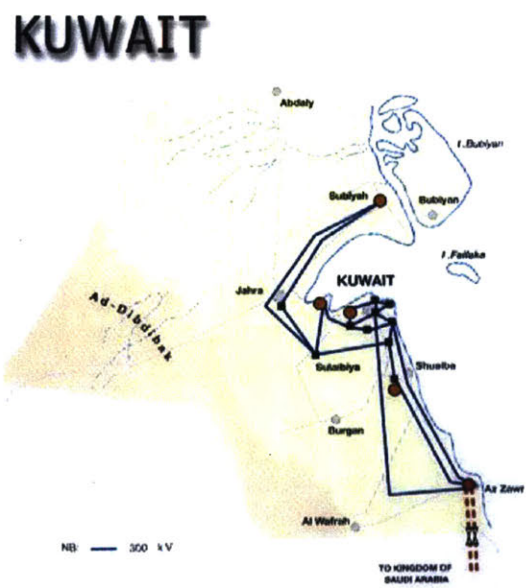


Figure A-12: Kuwait Grid Map. [75]

Appendix B

Appendix: Model Source Code

```julia
####
#   Author: Alix de Monts
#    ademonts@mit.edu
#    ademonts@alum.mit.edu
#
#   This work is licensed under a Creative Commons Attribution-NonCommercial
#   4.0 International License. https://creativecommons.org/licenses/by-nc/4.0/
#
#   In other words, feel free to re-use this code, but please cite this thesis.
#
####

using JuMP           # Used for mathematical programming
using Gurobi         # Solver for JuMP [Academic License Required]
using DataFrames     # Used for Data Frames
using MathProgBase   # High-level package used to modify MP variables
using JLD            # To save variables.


## For loading and saving data.

include("load_data.jl")
data = get_loaded_data()
save_name = hash(data)
save("$inpath""Cache/data_inputs/""$save_name"".jld", "data", data)


## Setting Model Parameters

function set_model_params(;fuel_scenario="international", gcc=true, year=2016,
                        nse_price=1000, time_interval=(1,168),
                        dcpf=false, kvl=false, loss_rate=0.12)

  params = Dict("fuel_scenario" => fuel_scenario, "gcc" => gcc,
           "nse_price" => nse_price, "year" => year, "dcpf" => dcpf,
           "kvl" => kvl, "loss_rate" => loss_rate,
           "time_interval" => collect(time_interval))
  save_name = hash(params)
  save("$inpath""Cache/param_inputs/""$save_name"".jld", "params", params)
  return params
end



## Run Model Function. If inputs are passed, used those, otherwise reloads
   data.

function run_model(params=nothing, data=nothing)

  if params == nothing
    params = set_model_params()
  end
  if data == nothing
    data = get_loaded_data()
  end
  model_inputs = Dict("data" => data, "params" => params)
```

```julia
## For saving inputs

save_name = hash(model_inputs)
save("$inpath""Cache/model_inputs/""$save_name"".jld", "model_inputs",
  model_inputs)



### Setting Parameters

#international vs subsidized fuel prices
fuel_scenario = model_inputs["params"]["fuel_scenario"]

# year model is run
yr = model_inputs["params"]["year"]

# price of non served energy
nse_price = model_inputs["params"]["nse_price"]

# whether trades are allowed across gcc
gcc = model_inputs["params"]["gcc"]

# whether the model uses DC approximation (vs transportation model)
dcpf = model_inputs["params"]["dcpf"]

# whether model uses kirchoff's volt law (vs fixed) line losses
kvl = model_inputs["params"]["kvl"]

#loss rate (for fixed line losses)
loss_rt = model_inputs["params"]["loss_rate"]

#time interval for model (1,8670) is a full year.
tr = range(model_inputs["params"]["time_interval"][1],
      model_inputs["params"]["time_interval"][2])

d_gens = model_inputs["data"]["generators"]
d_fuel = model_inputs["data"]["fuel_prices"]
d_buses = model_inputs["data"]["buses"]
d_lines = model_inputs["data"]["lines"]

# Trick to for when running model in the scenario without the GCC
# connection is to pretend lines aren't built yet!

if !gcc
    for k in collect(keys(d_lines))
        if d_lines[k]["network"] == "GCC"
            d_lines[k]["yr_built"] = 3000
        end
    end
end

### Defining Constants

const L = [k for k in collect(keys(d_lines)) if d_lines[k]["yr_built"] < yr]
const N = collect(keys(d_buses))
```

```julia
const G = [k for k in collect(keys(d_gens)) if d_gens[k]["yr_built"] < yr]
const T = collect(1:size(d_buses[N[1]]["demand"][yr],1))
const F = collect(keys(d_fuel[fuel_scenario]))
const P = unique([d_gens[p]["technology"] for p in G])
const angle_limit = 0.5*pi

### Definining Model
m = Model(solver=GurobiSolver())


### Variables
@variable(m, p[g in G,t=tr] >=0) # output gen g at time t
@variable(m, u[g in [k for k in G if (d_gens[k]["fuel"] in
      vcat(F,"Nuclear"))], t=tr], Bin) # commitment of gen g at time t
@variable(m, ϕ[l in L,t=tr]) #flow in line l at time t
@variable(m, θ[n in N,t=tr]) #voltage angle at bus b
@variable(m, ξ[l in L,t=tr]) #losses occuring along line l
@variable(m, nse[n in N,t=tr] >=0) #non-served energy at time t

### Helper Expressions (either for tracking values or to simplify code)

#fuel costs
@expression(m, fuelcosts[g in G], (d_gens[g]["fuel"] in F) ?
          d_fuel[fuel_scenario][d_gens[g]["fuel"]] :
          d_gens[g]["fuel"] == "Nuclear" ? 60.0 : 0.0)

#operational costs
@expression(m, op_costs, sum(p[g,t]*d_gens[g]["heat_rate"]*fuelcosts[g]
          for g in G, t=tr))

#costs of energy-not-served
@expression(m, nse_costs, sum(nse[n,t]*nse_price for n in N, t=tr))


### Objective Function
@objective(m,Min, op_costs + nse_costs)


### Constraints
@constraint(m, gen_max[g in G, t=tr], p[g,t] <= d_gens[g]["pmax"])
@constraint(m, gen_max_u[g in [k for k in G if (d_gens[k]["fuel"]
          in vcat(F,"Nuclear"))], t=tr],
          p[g,t] <= (d_gens[g]["pmax"])*u[g,t])
@constraint(m, gen_min_u[g in [k for k in G if (d_gens[k]["fuel"]
          in vcat(F,"Nuclear"))], t=tr],
          p[g,t] >= (d_gens[g]["pmin"])*u[g,t])

@expression(m, n_gen[n in N,t=tr], sum(p[g,t] for g in
          [k for k in G if d_gens[k]["bus"] == n]))
@expression(m, n_line_s[n in N,t=tr], sum(ϕ[l,t] for l in
          [k for k in L if d_lines[k]["start"] == n]))
@expression(m, n_line_r[n in N,t=tr], sum(ϕ[l,t] for l in
          [k for k in L if d_lines[k]["end"] == n]))

# Half of losses at send. Half of losses at receive.
@expression(m, n_loss_s[n in N,t=tr], sum(0.5*ξ[l,t] for l in
```

```julia
        [k for k in L if d_lines[k]["start"] == n]))
@expression(m, n_loss_r[n in N,t=tr], sum(0.5*ξ[l,t] for l in
        [k for k in L if d_lines[k]["end"] == n]))

#lines that start a n with positive flows are exporting
@expression(m, l_bal[n in N, t=tr], d_buses[n]["demand"][yr][t] - n_gen[n,t]
        + n_line_s[n,t] - n_line_r[n,t] - nse[n,t] + n_loss_r[n,t])

@expression(m, l_demand[n in N, t=tr], d_buses[n]["demand"][yr][t])

# Balance Constraint
@constraint(m, balance[n in N,t=tr], n_gen[n,t] - n_line_s[n,t] +
        n_line_r[n,t] + nse[n,t] -
        n_loss_r[n,t] == d_buses[n]["demand"][yr][t])

#Voltage Law (Kirchhoffs second law)
@constraint(m, voltagelaw[l in L, t=tr], ϕ[l,t] == (θ[d_lines[l]["start"],t]
        - θ[d_lines[l]["end"],t])/d_lines[l]["X"])

# Losses along the line.
@constraint(m, line_losses_l[l in L,t=tr], ξ[l,t] == loss_rt*ϕ[l,t])

# Line Limits
@constraint(m, upper_line_limit[l in L,t=tr], ϕ[l,t] <= d_lines[l]["MVA"])
@constraint(m, lower_line_limit[l in L,t=tr], ϕ[l,t] >= -d_lines[l]["MVA"])


# Angle Limits
@constraint(m, lower_angle_limit_s[l in L,t=tr],
        θ[d_lines[l]["start"],t] >= -angle_limit)
@constraint(m, upper_angle_limit_s[l in L,t=tr],
        θ[d_lines[l]["start"],t] <= angle_limit)
@constraint(m, lower_angle_limit_r[l in L,t=tr],
        θ[d_lines[l]["end"],t] >= -angle_limit)
@constraint(m, upper_angle_limit_r[l in L,t=tr],
        θ[d_lines[l]["end"],t] <= angle_limit)

# Setting the reference node.
@constraint(m, reference_node[t=tr], θ[d_lines[L[1]]["start"],t] == 0)

# NSE limits
@constraint(m, nse_limits[n in N,t=tr],
        nse[n,t] <= d_buses[n]["demand"][yr][t])

# Solar Irradiation limits
@constraint(m, solar_limits[g in [k for k in G if
        d_gens[k]["fuel"] == "Solar"], t=tr],
        p[g,t] <= d_gens[g]["pmax"]*d_buses[d_gens[g]["bus"]]["solar"][t])

# Wind limits
@constraint(m, wind_limits[g in [k for k in G if
        d_gens[k]["fuel"] == "Wind"], t=tr],
        p[g,t] <= d_gens[g]["pmax"]*d_buses[d_gens[g]["bus"]]["wind"][t])


# Solving the model
```

```julia
solve(m)

# Saving all the results
total_cost = getobjectivevalue(m)

g_results = Dict{Int64,Any}()
g_opcost = Dict{Int64,Any}()
g_fuelcost = Dict{Int64,Any}()
g_fuelcons = Dict{Int64,Any}()
for g in G
  g_results[g] = getvalue(p[g,:])
  g_fuelcost[g] = getvalue(p[g,:]) .* d_gens[g]["heat_rate"]
              .* getvalue(fuelcosts[g])
  g_fuelcons[g] = getvalue(p[g,:]) .* d_gens[g]["heat_rate"]
  g_opcost[g] = d_gens[g]["heat_rate"] .* getvalue(fuelcosts[g])
end

l_losses = Dict{Int64,Any}()
l_results = Dict{Int64,Any}()
for l in L
  l_results[l] = getvalue(ϕ[l, :])
  l_losses[l] = getvalue(ξ[l, :])
end

u_results = Dict{Int64,Any}()
for gt in [k for k in G if (d_gens[k]["fuel"] in vcat(F,"Nuclear"))]
  u_results[gt] = getvalue(u[gt,:])
end

n_l_r_results = Dict{String,Any}()
n_l_s_results = Dict{String,Any}()
n_results = Dict{String,Any}()
n_balance = Dict{String,Any}()
n_demand = Dict{String,Any}()
n_losses = Dict{String,Any}()
for n in N
  n_results[n] = getvalue(nse[n,:])
  n_l_r_results[n] = getvalue(n_line_r[n,:])
  n_l_s_results[n] = getvalue(n_line_s[n,:])
  n_balance[n] = getvalue(l_bal[n,:])
  n_demand[n] = getvalue(l_demand[n,:])
  n_losses[n] = getvalue(n_loss_r[n,:])
end

# Running the model a second time having fixed the commitment Binary
    variables
# in order to turn problem into LP (to obtain dual values)
for gt in [k for k in G if (d_gens[k]["fuel"] in vcat(F,"Nuclear"))]
  for t in tr
    JuMP.fix(u[gt,t],getvalue(u[gt,t]))
  end
end

solve(m)

n_prices = Dict{String,Any}()
```

```julia
  for n in N
    n_prices[n] = getdual(balance[n,:])
  end



  # Saving all the results to a Dictionary
  results = Dict("total_cost" => total_cost, "gen_output" => g_results,
                 "gen_fuelcost" => g_fuelcost, "gen_fuelcons" => g_fuelcons,
                 "gen_opcost" => g_opcost, "lines" => l_results,
                 "lines_s" => n_l_s_results, "lines_r" => n_l_r_results,
                 "nse" => n_results, "gen_commitment" => u_results,
                 "n_balance" => n_balance, "n_demand" => n_demand,
                 "nodal_prices" => n_prices, "nodal_losses" => n_losses,
                  "line_losses" => l_losses)

  model_inputs["results"] = results
  return model_inputs
end
```

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