# A mixed-complementarity problem approach for solving multi-sector, multi-region electricity systems in the presence of government interventions

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**Jury* :**

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Dedicated to my parents, Steve and Yugene, my sister Lisa, and Sunny.

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# Acronyms.

| | |
|---|---|
| ADWE | Abu Dhabi Water and Electricity Authority |
| Bcf | Billion cubic feet |
| CCGT | Combined cycle gas turbine |
| $CO_2$ | Carbon dioxide |
| CSP | Concentrated Solar Power |
| DEWA | Dubai Electricity and Water Authority |
| ECRA | Electricity Cogeneration Regulatory Authority |
| FEWA | Federal Electricity and Water Authority |
| GCC | Gulf Cooperation Council |
| GCCIA | Gulf Cooperation Council Interconnection Authority |
| GT | Gas turbine |
| GW | Gigawatts |
| KAHRAAMA | Qatar General Electricity & Water Corporation |
| KAPSARC | King Abdullah Petroleum Studies and Research Centre |
| KEM | KAPSARC Energy Model |
| LP | Linear program |
| MCP | Mixed complementarity problem |
| MIGD | Million Imperial Gallons per Day |
| MMBtu | Million British Thermal Units |
| MSF | Multi-stage flash |
| MW | Megawatts |
| NDC | Nationally Determined Contribution |
| OPWP | Oman Power and Water Procurement Company |
| PV | Photovoltaics |
| RO | Reverse osmosis |
| SEC | Saudi Electric Company |
| SEWA | Sharjah Electricity and Water Authority |
| ST | Steam turbine |
| TBtu | Trillion British thermal units |
| TWh | Terawatt-hours |
| U.A.E. | United Arab Emirates |

# Abstract

The aim of this dissertation was to quantify the economic impact of connecting electricity systems in the presence of interacting, and sometimes competing, policy objectives. The GCC region was chosen as a case study because of several appealing properties. Consisting of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, the GCC is a region integral to the global energy system, where substantial oil and gas resources are produced and exported to world markets. The region is also a substantial energy consumer, due in part to industrial policies that position themselves as leading exporters of refined and chemical products, but also because of the government interventions in prices and quantities in the transformation and end-use sectors. These distortions provide economic incentives to consumers to increase the *quantity* of energy and the *types* of energy products consumed.

This dissertation made several contributions. First, this dissertation directly incorporated the role of interventions in the study of energy system interconnectivity. Interventions include control on prices and quantities of inputs to energy transformation processes, including the electricity and water desalination sectors. These interventions were studied in the context of individual energy systems where inter-sectoral price and quantity controls distort the competitive equilibrium, affecting investment and operation decisions. The framework was extended to a regional energy system under autarky and cooperation to quantify the mismatch in gains among the member states with and without interventions. An additional contribution was investigating the temporal nature of these interventions and reform strategies in relation to economic costs and gains to the member states, and towards global ambitions like reducing $CO_2$ emissions from electricity production. Finally, the importance of sequencing policy actions like subsidy reforms, electricity exchange, and carbon pricing was quantified, which demonstrated how policies can be additive or have competing objectives.

The mixed-complementarity problem (MCP) approach was utilized in this dissertation. Typically, an electricity sector is studied using an optimization framework; however, a linear program only represents the specific case of perfect competition. The MCP approach enabled price and quantity interventions of agents to appear as market clearing conditions in an equilibrium problem. The MCP formulated in this dissertation was designed specifically for a multi-sector energy system in one country, then extended to multiple interconnected countries. A recursive dynamic solution algorithm was employed to approximate lack of perfect foresight of agents in the model.

The first set of results demonstrated the MCP formulation and its viability to studying price and quantity interventions in Saudi Arabia. Substantial economic gains were observed under a range of subsidy reform scenarios through 2030. The economic agents responded to rationalized fuel prices by investing in more efficient transformation processes and increasing oil exports. A static analysis of the six GCC countries quantified the economic losses from heterogeneous intervention schemes in each country and how they impede electricity exchange. The multi-country, multi-period analysis (through 2030) examined how subsidy reform, electricity exchange, and carbon pricing policies interact. Subsidy removal delivered the largest economic gains. Carbon pricing provided marginal gains if revenues were recycled. Counterintuitively, the average marginal contribution electricity exchange to was negative, reflecting the embedded loss from exporting subsidized electricity to other countries. Thus, it was shown how sequencing subsidy reforms before implementing electricity exchange or carbon pricing is a prerequisite for producing a net economic gain.

# Chapter 0. General Introduction.

## 1. Motivation

Regional power system integration is claimed to offer the potential to contribute toward reliable and cost-effective energy services that support economic development aspirations at the country and regional level (The World Bank, 2013). From a technical perspective, an integrated electricity system could leverage the comparative advantages of the regional players in terms of capital stocks, resource bases, and disparities in marginal production costs to improve reliability, reduce reserve margins, and avoid redundant capital investments that might be made in autarky (i.e., when one is self-sufficient and plans in isolation). If more efficient generation units are used, or renewable technologies satisfy new demand in a regional market, there could be reduced fuel consumption and subsequently $CO_2$ emissions.

From a non-technical perspective, policies have different social aims. Success of a policy from the initial point of view can differ depending on the aim. A policy might prioritize economic or social welfare gains at the cost of technical efficiency. Thus, it is crucial for policy development to consider both technical and non-technical costs and gains. Policy design is critical to establishing the rules and incentives for agents (producers and consumers) to ensure a policy succeeds in its intentions while minimizing unintended consequences.

There are many economic considerations and regulatory policies that affect regional power system integration. Price and quantity controls are a common form of intervention in energy systems in low, middle-, and high-income economies. Price controls can be in the form of subsidized fuel inputs for power producers, guaranteed purchase contracts, preferential financing for project development, and so forth. This thesis focuses on the technical feasibility of electricity exchange in the context of market interventions in the form of price and quantity controls on fuel inputs.

These policy mechanisms and subsequent impacts are relevant in many countries across the world, not only in the Arabian Peninsula, as studied in this body of work. Governments intervene in energy systems in pursuit of social objectives. These objectives can be designed to foster a nascent industry, such as aluminum, cement, or steel production, that are economically and energetically expensive. In some cases, these objectives are to provide affordable electricity services to citizens. In many cases, these objectives are overlapping and even working at cross-purposes.

In some cases, low-cost electricity production encourages over consumption, while low-cost fuel inputs incentivize inefficient production. In the case of Saudi Arabia, domestic oil consumption is incentivized by the low administered price of fuel inputs to the power sector. The trajectory and magnitude of this incentive structure is described in detail by Lahn and Stevens in *Burning Oil to Keep Cool* (Lahn and Stevens, 2011). In many ways, that paper is instigator of this body of work. Other studies by researchers at the Oxford Institute for Energy Studies provide additional insight on Saudi Arabia's neighbor Kuwait (Fattouh and El-Katiri, 2013; Mezher et al., 2011; Poudineh et al., 2020).

Ultimately, someone must pay for policies, and the electricity sector is no different. Interventions such as price and quantity controls have an economic cost associated with them. The decline in global oil price indices in 2014 through the time of writing have put additional stress on some country's fiscal balances. The countries of the GCC studied in this dissertation are acutely affected by the downturn in prices, which has prompted subsidy reform measures to varying degrees.

The analyses performed here are intended to inform those decision makers and provide insight in to the intended and unintended consequences of interventions and exchange that can occur in pursuit of economic social, and environmental goals. Interventions in the electricity system may be inconsistent with environmental policies and goals. As demonstrated in Chapter 4, there are substantial consequences of interventions and exchange on $CO_2$ emissions, which can run counter to stated climate goals. Furthermore, the analytical framework developed under this research project is intended to be applicable to other regional energy systems where economic distortions are a substantial component of policy interventions. These areas can include Southeast Asia, Northeast Asia, and the greater Middle East-North Africa region.

### A brief review of studies on integrated power systems

There is a substantial literature around electricity system integration, ranging from technical feasibility studies to market design, and market power. A representative sample of relevant studies are summarized here.

Gnansounou and Dong (2004) analyzed strategies for an inter-regional electricity market in East China (Shandong and Shanghai) (Gnansounou and Dong, 2004). At the time of publication, China was in the process of unbundling the generation and transmission system and contemplating a competitive energy market. They considered three scenarios for Shandong and Shanghai: a system in autarky; limiting exchanges to imports and exports with the objective of minimizing operation costs; and full coordination between the two agents (perfect competition) to minimize operation and investment costs. They report results using a least-cost optimization planning model and find that electricity exchange is profitable for both regions if agents can coordinate operation and investment decisions (third scenario).

More recently, Li et al (2016) and Guo (2016) performed simulations of the Chinese electricity system (Guo et al., 2016; Li et al., 2016). Li et al (2016) used a cluster integer unit commitment model to quantify the impact of expanding inter-regional transmission capacity on system costs, performance, and $CO_2$ emissions. They found that grid expansion enables coal-fired generation to meet demand, lowering system marginal production costs but increasing $CO_2$ emissions. This study illustrates that $CO_2$ emissions do not necessarily improve from inter-regional electricity exchange.

Pudjianto et al (2014) investigated the value of grid scale energy storage in Great Britain. The context for their analysis is the continued deployment of variable renewable sources to meet climate objectives. National and international transmission networks were considered given the distributed nature of generation (and storage) sources and demand. The authors represented the electricity system as a mixed-integer linear program that enables them to model both investment and dispatch decisions (Pudjianto et al., 2014). For Europe, Leuthold et al (2005) and Neuhoff (2013) examine the role of inter-regional electricity exchange on renewable integration using cost-minimization optimizations of the electricity system (Leuthold et al., 2005; Neuhoff et al., 2013).

## 2. Geographical importance: GCC as a case study

### 2.1. The Gulf Cooperation Council

The Gulf Cooperation Council (GCC) region is an interesting and timely case study. The GCC economies are energy-intensive and face a challenging and uncertain future in an increasingly carbon constrained world. Specifically, decarbonizing electricity production in the GCC could have substantial ramifications on international oil and gas markets. In the region, subsidies for industrial fuel inputs have incentivized inefficient investments for electricity production, while subsidized tariffs have led to high per capita domestic consumption. In a low oil price regime, subsidies have become an increasing burden on national finances, prompting economic diversification programs. Finally, power and water production are tightly linked in the GCC. Given the arid climate and scarce renewable water resources, large amounts of energy are used to desalinate seawater. Likewise, substantial electricity is produced during thermal seawater desalination.

## 2.2. The GCC Interconnector

Countries in the GCC have installed a network of high-voltage transmission lines, known as the GCC Interconnector, which links the member states of Saudi Arabia, Bahrain, Kuwait, Oman, Qatar and the United Arab Emirates, shown in Figure 1. The Interconnector has been envisioned as a platform to facilitate coordination in electricity generation among the GCC countries that would support the ongoing economic reform initiatives. Completed in 2011, the Interconnector has enabled the in-kind exchange of electricity among member states to maintain system reliability (Gulf Cooperation Council Interconnection Authority, 2017). While the Interconnector has successfully provided reliability services to GCC countries, it has not yet realized its full potential as a platform to fully integrate the individual electricity systems.


*Figure 1. Map of GCC members and dedicated transmission for the GCC Interconnector (shown by the thick black lines). The dashed lines represent existing transmission capacity utilized by the Interconnector.*

Exchanging electricity through the Interconnector is not straight forward because of the diversity in interventions by the GCC member states.

Under the right circumstances, the GCC countries could benefit from more coordinated electricity production as the countries have non-coincident peaks in electricity demand. However, the link has not provided the full benefits of integrating the individual grids of the member countries because of the structure of the electricity and water sectors in each country.

Low administered prices on fuels used for electricity generation, which vary by country, are a key barrier to regional movements of electricity because it is not likely that a country wants to incur the costs of exporting the value of its subsidies.

Without reforming these prices or designing a market mechanism to account for the full cost of electricity production, any electricity sold across borders means the exporting country subsidizes consumers in the importing countries. These subsidies cannot be recouped because a large portion of the subsidies are provided before the point of delivery. Fuel subsidies are virtually impossible to trace and recapture because system wide effects on investment and operations are not measured in standard accounting systems. Thus, the current structures of domestic markets are a barrier to cross-border exchange.

## 2.3. Relevant studies of the GCC energy situation

In the GCC region, substantial literature exists for the role of energy subsidies and economic impacts, but not power system integration. Lahn & Stevens (2011) at Chatham House explored the role of continuing domestic oil consumption in Saudi Arabia. They extrapolated domestic energy consumption and concluded that Saudi Arabia could become an oil importer by 2038 (Lahn and Stevens, 2011). This study led to a quantitative analysis of subsidy reforms in Saudi Arabia by researchers at the King Abdullah Petroleum Studies and Research Center (KAPSARC) in Riyadh, Saudi Arabia. There, Matar et al (2015) found that subsidy reforms could lead to more efficient investments in the Saudi Arabian power sector (Matar et al., 2015). Bassam Fattouh of the Oxford Institute for Energy Studies explored energy subsidy reforms separately in Kuwait and Saudi Arabia (Fattouh and El-Katiri, 2013). Boersma & Griffiths (2016) summarized ongoing fuel subsidy and consumer tariff reforms in the U.A.E. (Boersma and Griffiths, 2016).

The GCC Interconnector Authority, the independent system operator, commissioned a study on potential savings from electricity trade, but did not consider the underlying economic distortions of energy production in the GCC (GCCIA 2017).

The member countries of the Association of Southeast Asian Nations (ASEAN) are pursuing regional economic integration, of which an integrated electricity system is a component (Zamora, 2015). The ASEAN Power Grid (APG) is a close analog to the motivations and potential of an integrated GCC electricity system, in terms of aggregate installed capacity and goals for integration. Ahmed et al (2017) performed a simulation of the APG to evaluate optimal cross-border power flow through interconnections to assess feasibility of alternative transmission technology (Ahmed et al., 2017). Unlike the GCC Interconnector, the APG is not fully constructed. The authors constructed a least-cost optimization model of 15 nodes in the APG and found that implementing high-voltage direct current transmission could be more beneficial than the planned construction of alternating current lines (Ahmed et al., 2017).

In Table 1, the selected studies are evaluated using the following criteria: (A) whether it used formal quantitative methods; (B) if the study looked at impacts beyond the power sector (e.g., seawater desalination or climate change); (C) if multiple sectors were assessed in an integrated manner; and (D) if economic distortions (e.g., subsidies) were considered.

*Table 1. Summary of themes for selected studies.*

| Studies | (A) Quantitative Analysis of Integration | (B) Impacts Beyond Power Sector | (C) Integrated Energy System Assessment | (D) Role of economic distortions |
|---|---|---|---|---|
| **Newbery et al** | X | | | |
| **Böckers et al** | X | | | |
| **Mansur et al** | X | | | |
| **Ahmed et al** | X | | | |
| **Pudjianto et al** | X | | | |
| **Guo et al** | X | X | | |
| **Lahn & Stevens** | | | | X |
| **Fattouh** | | X | | X |
| **Matar et al** | | X | X | X |
| **Boersma & Griffiths** | | X | | X |
| **GCCIA** | X | | | |
| **Wogan PhD** | X | X | X | X |

This dissertation links domains A-D by filling the gap by performing a quantitative and holistic analysis of power system integration in the GCC region by incorporating the interaction of multiple energy-intensive sectors and the underlying economic distortions.

## 3. Scope and objectives

This thesis makes the contributions to the several separate but related bodies of literature: economic distortions, subsidies, and electricity exchange. This work establishes a methodology for incorporating distortionary policy interventions in energy systems models using the MCP formulation. The MCP framework is extended to include interaction among energy systems experiencing different types and levels of distortionary policies.

The methodology is then demonstrated by quantifying the divergence from competitive equilibrium due to subsidizing energy inputs in the GCC member states, which is a useful metric to judge potential gains from policy reform. Second, the costs that energy subsidies impose on regional energy system exchange is quantified, along with testing alternative policies to increase welfare gain to agents participating in exchanges. Finally, the environmental impact of subsidy reform and electricity exchange on $CO_2$ emissions from fuel combustion is quantified.

More specifically, three interrelated research questions are explored:

1. How would integration affect the development of national and regional electricity systems in the short- and medium-term?
2. How do government interventions in fuel prices and quantities affect electricity exchange?
3. What economic, efficiency, and environmental costs and gains do these interventions impose, and do they enhance or hinder electricity exchange?

Each research question is investigated in sequential exercises, each culminating in a peer-reviewed article.

## 4. Organization of the dissertation

The organization of the dissertation is as follows.

### 4.1. Chapter 1. Empirical and methodological background.

In this chapter, the methodological background is established, and a framework developed to analyze the research questions. The chapter begins with a review of interventions in power systems – types of interventions, the rationale behind them, and some unintended complications – to set the context for this body of work. The rest of this chapter describes the mixed-complementarity problem (MCP) modeling approach and mathematical formulation.

### 4.2. Chapter 2. Energy system planning in the presence of policy interventions: analysis of an energy system in autarky.

This chapter focuses on the largest energy producer and consumer in the GCC, Saudi Arabia. The MCP formulation is developed for Saudi Arabia to capture the price and quantity interventions. The analysis is performed on a multi-period basis using a recursive dynamic approach. The chapter analyses different approaches to removing administered fuel prices and quantities. The results are substantial on their own, and inform the development of the larger, interconnected, GCC variant of the model. $CO_2$ emissions are not the focus of this analysis and instead are investigated in Chapter 4.

### 4.3. Chapter 3: Energy system planning in the presence of policy interventions (part II): a static analysis of the costs and gains of policy options for coordinating electricity generation in the Gulf Cooperation Council.

This chapter extends the analysis framework from Chapter 2 by including the remaining five GCC members. In this chapter, decisions made by each country in isolation from the others (the status quo) are quantitatively assessed to establish a baseline that represents the existing situation. Then the ability for countries to coordinate production of electricity via cross-border exchanges is added. This analysis is performed as a static analysis to isolate the impact of trade and interventions on planning decisions and economic impacts. This chapter explores how subsidies act as a barrier to integration and quantify the impact of trade while retaining subsidies and devise a scheme that could provide benefits of integration while preserving some of the social benefits that subsidies provide. A sensitivity analysis is performed to show how gains depend on scale of the Interconnector capacity.

### 4.4. Chapter 4: Regional energy and decarbonization coordination in the GCC: a multi-period analysis of economic interventions and electricity exchange on power sector $CO_2$ emissions.

In the final analysis chapter, the longer-term potential gains from integration are analyzed using the multi-period formulation. This exercise captures the effects of ongoing investments in technologies and how operational decisions adapt over time. The methodology developed in Chapter 2 and 3 are combined to investigate the impact of administered price reforms, electricity exchange, and costs associated with one environmental externality ($CO_2$). Several sensitivities are performed to capture the uncertainty around oil, natural gas, and coal prices; renewable technology cost declines; Interconnector capacity; and magnitude of $CO_2$ emission penalties.

## 5. Summary of the main findings

### 5.1. Key takeaways

Several themes emerge from the analyses and are summarized below.

- **Combining administered fuel price reform, electricity exchange, and a penalty on $CO_2$ emissions delivers substantial changes to the investment and operational decisions in the GCC electricity system through 2030.** The marginal impact of an individual measure is not always great, or even positive. Additionally, not all gains are equally distributed among GCC members and not all gains are positive. It is likely that each member state must enjoy positive gains for a regional electricity system to succeed. Distributional impacts should also be considered.
- **Administered fuel price reform provides greater economic gains than electricity exchange or a $CO_2$ penalty, on an absolute and marginal basis.** With such a policy, the incentive structure is substantially reworked so that a competitive equilibrium drives decision-making, leading to economically efficient outcomes.
- **Sequencing of policies matters.** Fuel price subsidy reform policy delivers the largest average marginal increase in economic gain to the GCC, as does carbon pricing if revenues are recycled. Electricity exchange always contributes negatively includes because the outflow of subsidies from one country to another. The
- **Policies can counteract each other.** The average marginal increase in economic gain is less than the aggregate sum of individual policies. The loss from competing policy objectives ranges between 5.5 percent to over 10 percent of potential economic gains, with and without recycling carbon penalty revenues, respectively.
- **System-wide accounting is necessary to capture the full picture of economic gains and losses.** For example, a price on $CO_2$ viewed in isolation decreases the net economic gain; however, recycling revenues from $CO_2$ penalties adds positive cash flow that can be used to offset increases in prices or satisfy other objectives.
- **Potential electricity exchange in the GCC Common Market could lead to increased emissions and work counter to some GCC country's goals for decarbonization**. This outcome could occur regardless of ongoing energy price reform initiatives in some GCC countries as existing carbon-intensive generation like coal-fired power plants satisfy domestic and regional GCC electricity demand.

Summaries of the key findings from the individual analyses are presented below.

## 5.2. Chapter 2

When considering only one country, Saudi Arabia, and the fixed transfer prices among sectors, it is shown that a continuation of existing policies would not produce the economic signals that are necessary to encourage investment in alternative power generation technologies nor an efficient portfolio of equipment. In other words, domestic oil consumption would continue in the power and water desalination sectors. Immediately deregulating fuel prices results in a rapid move to a more efficient energy system where nuclear and renewable technologies become cost-effective. Primary consumption of oil and natural gas can be reduced by up two million barrels of oil equivalent per day in 2032 (for a cumulative savings of between 6.3 and 9.6 billion barrels of oil equivalent through the planning horizon), relative to a continuation of existing policies. The energy system sees a net economic gain up to half a trillion 2014 USD from increased oil exports, even when accounting for investments in nuclear and renewables. Less sudden or disruptive policies that gradually increase fuel prices or introduce investment credits help to facilitate the integration of alternative technologies into the Saudi energy system and achieve efficiencies close to those resulting from immediate deregulation. Potential economic gains under the gradual deregulation of fuel prices yields a smooth transition path for technologies without much of a reduction in the economic gains observed with the Immediate Deregulation scenario.

Higher fuel prices lead to investment in more efficient plants. Similarly, lowering capital costs, while maintaining administered prices, is also shown to improve the equipment mix. The introduction of investment credits that lower capital costs demonstrates how the system could achieve most of the economic gains of Immediate Deregulation while maintaining fuel prices at levels well below marginal values.

Although a continuation (in real terms) of current pricing policies would not result in the introduction of nuclear and renewable plants, the efficiency of electricity generation would improve over time due to investment in combined-cycle plants.

$CO_2$ emissions were not considered in this analysis because the focus was on isolating the role of administered prices and quotas. The role of $CO_2$ emissions will be investigated in depth in Chapter 4.

## 5.3. Chapter 3

The key finding is that domestic fuel subsidies are the key economic barrier to regional electricity exchanges from which all the member countries benefit. In the absence of subsidy removal across the region, Saudi Arabia would export $12.2 billion (in real 2015 U.S. dollars) in subsidies-by-wire annually as other GCC countries purchase low-priced electricity generated with subsidized fuels.

The bulk of the annual economic benefit results from removing fuel subsidies: $42.6 billion. From a consumer perspective, the foregone subsidies could be returned as an equivalent income transfer, while achieving the benefits of trade. The economic gain increases by $1.1 billion annually when coupling subsidy removal with electricity exchange. Over 5 percent (33 TWh) of GCC electricity production would be exchanged at market prices. The U.A.E., Kuwait, and Bahrain are the largest net exporters, while Saudi Arabia becomes the largest net importer of electricity (28.7 TWh) – equivalent to 8 percent of its demand.

Substantial investment would accompany these exchanges. Over 50 percent of existing capacity would be replaced by more efficient combined-cycle gas turbines and utility-scale PV at a cost of $7.3 billion.

A significant aspect of the capacity shift is the replacement of electricity/water cogeneration plants with water production switching to reverse osmosis. The thermal cogeneration plants make the electricity systems less flexible because of the need to produce water. Retiring thermal cogeneration plants and replacing them with combined-cycle plants and reverse osmosis plants increases the flexibility of the national grids and allows them to take advantage of the interconnection. Indeed, this is happening in the GCC.

The important lesson from increasing the use of the Interconnector before tackling deregulation is that in moving from current highly regulated systems to a more market-based approach on a piece-meal basis can increase costs without the proper sequencing of policy changes. The Interconnector can provide substantial economic benefits; however, the conditions must be right for the benefits to be realized.

The static analysis performed in this chapter does not capture the stock and flow dynamics of $CO_2$ emissions. Chapter 4 combines the approach developed in the previous chapter with the electricity exchange developed in this chapter to represent the dynamic aspects of $CO_2$ emissions in the context of price reforms and electricity exchange.

## 5.4. Chapter 4

The findings suggest that potential electricity exchange in the GCC Common Market could lead to increased emissions and work counter to some GCC country's goals for decarbonization, regardless of ongoing energy price reform initiatives in some GCC countries. Regional energy and climate cooperation in the GCC are technically and economically possible under the auspices of Article VI of the Paris Agreement as demonstrated by this analysis. GCC countries can consider this mechanism for future NDC development and national planning activities.

Combining administered fuel price reform, enabling electricity exchange, and imposing a $CO_2$ emissions penalty reduces the most $CO_2$ emissions while delivering substantial economic gain to all GCC countries. However, this policy package is only marginally more effective at reducing emissions than removing controls on fuel prices and quantities, even in the absence of electricity exchange and a carbon price. Electricity exchange offers marginal emissions reductions when coupled with deregulation and higher emissions when retaining interventions, due to an expansion of coal-fired capacity. Electricity exchange offers marginal emissions reductions when coupled with deregulation and higher emissions when retaining interventions, due to an expansion of coal-fired capacity.

An analysis of average marginal contributions from each policy shows that a non-trivial loss in economic gain would result from combining the three policies. The fuel price subsidy reform policy delivers the largest average marginal increase in economic gain to the GCC. Carbon pricing can also contribute positively if revenues are recycling. Counterintuitively, the marginal impact of electricity exchange is negative with and without recycling carbon revenues. The expectation is that electricity exchange would bring gains through cooperation, shared resources, and competitive advantages. However, taken in the context of the fuel price subsidies, the average marginal contribution of electricity exchange is negative because of the losses due to exchange without subsidy reform. Thus, the losses from electricity exchange without subsidy reform are substantial. This finding underlines the importance of sequencing electricity exchange after reforming domestic price and quantity interventions.

# Chapter 1. Empirical and methodological background and approach.

## 1. Introduction

This chapter contains a discussion of the methodological approach. It begins with an overview of different types of models used to analyze energy systems, including energy exchanges. Following this overview is a brief discussion of optimization, specifically linear programs, *vis à vis* energy systems analysis, which leads to the selection of the mixed-complementarity problem (MCP) formulation. A mathematical derivation of a generalized MCP for an energy system is presented. The KEM-GCC model was developed using this mathematical formulation and was used for the analyses in Chapters 2, 3, and 4. In the last section of this chapter, a graphical representation of the GCC energy system is displayed.

## 2. Overview of modeling approaches

The overview of modeling approaches begins with a broad focus. There is a rich literature on estimating gains from energy system planning and integration in both developed and developing economies. There are two common methods for computing gains from policies, including market integration (Newbery et al. 2016; Böckers et al. 2013). One method is to estimate relationships based on empirical evidence of a system before and after a set of policies. The second method is to simulate the mechanics of a system for a range of scenarios.

### 2.1. Estimation approaches

Estimation is useful when there are heterogeneous agents and multitudes of factors that influence decisions by many uncoordinated agents. In energy systems, demand at the sectoral level often falls in this category. Energy consumers can have varying levels of incomes, budget constraints, preferences for goods and services, willingness to pay, and elasticities to price. It is therefore difficult to represent each type of agent's decision-making process. However, by gathering data for a statistically representative sample one can estimate production and consumption functions for an aggregate population. Thus, the outcomes of agents' decisions are modeled, but without much insight into the mechanics of the decisions by individual agents.

Three recent studies illustrate the estimation approach to investigating change in welfare from integrating electricity systems. Böckers et al (2013) analyzed the benefits of market integration in Europe and efficiency gains from more efficient capacity utilization and competition. They collected load data from 21 European countries (encompassing six regional transmission groups) and analyzed electricity prices at peak hours. Through an autoregressive model, they found that gains increased when peak demands were not correlated because idle generation capacity can be utilized. While perfect competition was not expected or observed, integration did result in welfare gains.

Newbery et al (2016) estimated potential benefits of coupling interconnectors to increase the efficiency of short-term trading and balancing services across borders. In a study of the PJM Interconnection in the U.S., the authors examined gains from decentralized trading vs centralized auction markets through a regression analysis (Mansur et al., 2012). Their analysis showed that an organized market design improved market efficiency by facilitating price formation and information exchange, notably with respect to congestion externalities. Thus, the market was able to support greater trade beyond the bilateral trade arrangements that existed prior to an organized market. This finding is relevant to the GCC because bilateral trades have historically been the bulk of all electricity exchanges.

## 2.2. Engineering analysis

If there are a small number of agents, then the individual decision processes can be modeled. This is usually done for engineering processes where the individual steps are known. Typically, one constructs a model with profit-maximizing or cost-minimizing agents subject to some physical constraints (Murphy et al., 2016). The agents then make decisions on what processes to use.

Many energy processes are modelled this way. Power system capacity planning models are typically constructed as cost-minimizing agents that must meet an exogenous power demand by making decisions about operating different transformation processes by converting fuel to electricity, and whether to invest in new technologies or utilize existing ones. One of the first commercial applications of linear programming model was for optimizing refinery processes (Murphy et al., 2016). Here, processes are well understood, and the refinery operator can be assumed to have a profit-maximizing or cost-minimizing objective (Manne, 1958).

Such a bottom-up approach accounts for the processes and mechanics of a system, including investment decisions. Typically, investments in technologies are made over a time horizon using an NPV approach using useful lifetime, discount rate, capital, O&M costs, and salvage value. Agents are assumed to perform net present value calculations for all technologies to make an investment decision. In a dynamic optimization problem, the decision space is expanded from what technology to invest in to when the investment should be made.

Auction methods are used in energy systems in practice and in simulations. Some energy markets use auctions to determine which generator will supply electricity or maintain a desired level of capacity. The auctions serve as a tool for price discovery. Simulations of auctions are typically performed when evaluating different market designs.

There are drawbacks to the engineering approach. Simulations are based on hypothetical behaviors that can sharply depart from real ones, whereas econometrics avoids this shortcoming. The net present value approach to investment decisions commonly employed in engineering analyses may be sharply biased if irreversibility and uncertainty is disregarded (Dixit and Pindyck, 1994). While engineering analyses explicitly represent many costs associated with processes and investments, hidden costs are often not considered or difficult to model. For example, an analysis may suggest an investment in energy efficiency measures but may neglect the non-financial switching costs (e.g., disruption in the household from renovations, time finding a contractor, etc.), which can be significant.

### *Common engineering-style models*

There are two broad classifications: energy system and power system models (Foley et al., 2010; Pfenninger et al., 2014). These occupy opposite ends of a spectrum; however, the boundary can be fluid. An energy system model includes multiple sectors and is used to assess the potential evolution of a national, regional, or global energy system on medium- to long-term timescales.

Commonly used energy system models are TIMES/MARKAL, MESSAGE, and OSeMOSYS (Howells et al., 2011; Loulou and Labriet, 2008; Schrattenholzer, 1981). A power system model represents the production, transmission, and distribution of electricity with high resolution and usually on short timescales (less than an hour) and can include market design and competitive games

(Cournot or Bertrand competition). These models are well-suited to representing the variable nature of renewable technologies. A software tool called PLEXOS is a commonly used power system model (Energy Exemplar, n.d.). However, these commonly used software packages are unable to answer the questions posed in this dissertation for reasons discussed in the next section.

The selection of broad approach (estimation versus engineering) and then a method within that class depends on several factors. The first factor is the appropriateness of the approach to answer the research question(s). A second factor is data availability. For the research questions in this dissertation, an engineering approach was chosen because it is suitable for investigating the investment and operating decisions by agents (GCC countries), and also required to represent the types of economic distortions of interest. Furthermore, empirical evidence from the in-kind exchanges does not exist in the public domain, making an econometric analysis infeasible. This dissertation makes contributions to the second class of models, in which a small number of agents' decisions are modeled.

## 3. The MPEC family of models

The precise modeling approach undertaken in this analysis belons to a group of models called mathematical program subject to equilibrium constraints (MPEC). As its name suggests, MPECs are used to optimize an overarching objective in a top-level game subject to a set of equilibrium constraints in the lower level game (Gabriel et al., 2010). Figure 2 illustrates the MPEC family of mathematical models that will be discussed further and their relationship to each other.

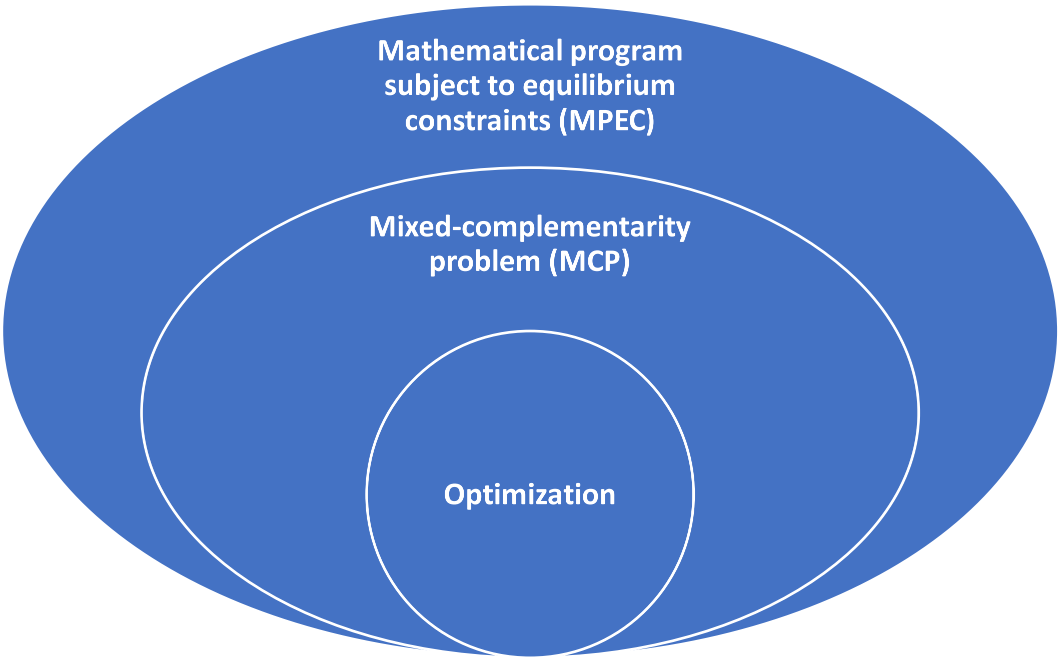



*Figure 2. Relationship of modeling approaches.*

The specifics of MPECs are beyond the scope of this dissertation. However, it is instructive to note that the MPEC family includes both MCPs and optimization models. Figure 2 is adapted from a graphical representation of equilibrium models in Murphy et al., (2016).

### 3.1. Optimization

Optimization problems are more familiar to many economists and researchers in this field. Optimization problems are typically employed as a set of linear equations (a linear program) where the objective is to maximize or minimize the profit or cost, respectively, to meet a given demand subject to a set of technical constraints. A brief formulation of a linear program is shown in Equation 6 through Equation 10 later in this chapter.

Linear programs are quite convenient and powerful depending on the type of problem and questions of interest but only under a certain set of criteria, including but not limited to having an integrable demand curve and having marginal cost equal marginal value (Dantzig, 1951). Thus, linear programs are applicable when the conditions for perfect competition are met. This rule means that linear programs do not accurately portray situations when there are few agents (agents exercise market power) or there are pricing rules and distortions that move the system away from a perfectly competitive equilibrium. The supply and demand curves presented in Murphy et al (2016) illustrate the market equilibrium under these types of imperfect competitive situations (Murphy et al., 2016).

Looking specifically at pricing rules, linear programs can be used but the solution of the full problem is rather cumbersome. In a multi-sector model of an energy system, each sector can be represented by its own linear program. Subsidies, caps, and other constraints can be implemented independently of the other sectors. To solve the entire system, an iterative approach (Gauss-Seidel) can be used to pass the price and quantity information among sectors (Murphy et al., 2016). Simply combining all sectors in one linear program would treat the combined system as a case of perfect competition. Thus, the defining characteristics of quotas or price interventions at the sector level are lost. In fact, this is how many well-known energy systems models operate, including those used by the U.S. Energy Information Administration. The National Energy Management System (NEMS) model is a collection of sectoral models that converge on an equilibrium through an iterative Gauss-Seidel process (U.S. Energy Information Administration, 2020).

### 3.2. MCP

The mixed-complementarity problem (MCP) approach overcomes the limitations of optimization (linear programming) models because the equilibrium conditions are explicitly written, and can be written in a way such that the equilibrium exists outside of the case of perfect competition (Ruiz et al., 2014). For example, MCPs have been used extensively to evaluate market power (Egging and Gabriel, 2006; Gabriel and Smeers, 2006; Gabriel et al., 2013; Greenberg and Murphy, 1985).

Operationally, because an MCP is an equilibrium problem, it can be solved in one step (rather than iterating using a Gauss-Seidel method) without losing the properties that make the problem interesting (e.g., price or quantity controls, market power).

In the following section, the MCP formulation is developed visually for several cases to arrive at the complementarity conditions. The visual representation then leads to the mathematical definition of the market clearing conditions, where the complementarity conditions are again apparent. Finally, a general example of two sectors with price controls is developed to illustrate why an MCP formulation is necessary.

## 4. MCP formulation of a market equilibrium

### 4.1. Visual representation of the complementarity condition

The familiar supply and inverted demand curve is utilized to illustrate four equilibrium outcomes (Figure 3).

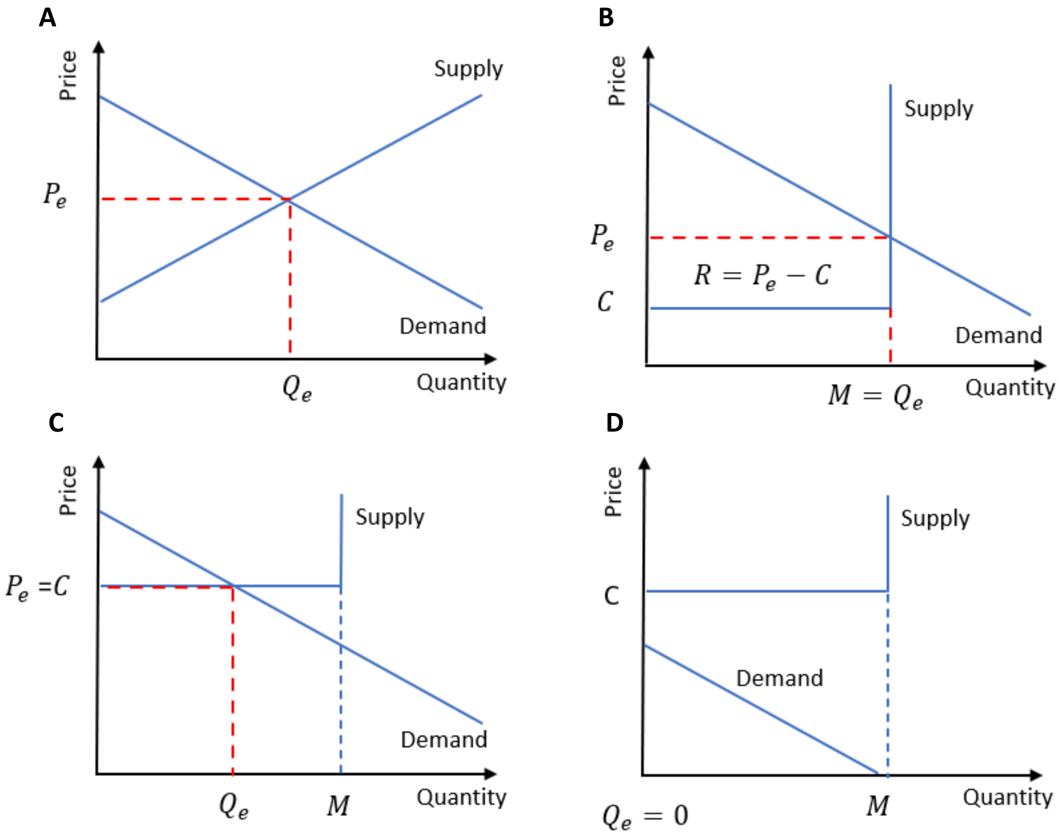



*Figure 3. Equilibrium conditions when a) supply and demand intersect at the equilibrium; b) demand is above production; c) demand intersects production costs; d) production cost is above demand.*

### *Perfect competition (a)*

The well-known equilibrium when the conditions for perfect competition are satisfied is shown in Figure 3a. The market clears where the supply and demand curves intersect, at price $P_e$ and quantity $Q_e$. The marginal cost of producing a good is the marginal value to the consumer, which is the price paid by the consumer. As will be illustrated below, reality can be more complex. At the equilibrium, a good may not be produced or the price may include an economic rent. Perfect competition does not include these. A real-world example is associated gas production (gas is produced as a byproduct of oil production). Some producers argue that the marginal cost of extraction is zero. The market price for gas can be set by other higher cost producers. Therefore, an economic rent exists for the low-cost producer.

### *Demand is above production cost (b)*

In Figure 3b, the upward-sloping supply curve is replaced with a single supply step. This represents a limit on production capacity, denoted by $M$. Additional supply steps could be included to represent supply curves for different producers. The demand curve is above the production cost, $C$, for any quantity, at or below production capacity. The market clears at a price equal to the marginal value for consumers $P_e$ and a quantity equal to the production capacity $M$. The scarcity rent is calculated by the difference between the clearing price and producer cost.

*Demand intersects production cost (c)*

When the supply curve intersects the demand curve, the production cost sets the clearing price, $P_e$ (Figure 3c). At this price, the quantity produced, $Q_e$, is short of the production capacity, $M$. Thus, there is no scarcity and economic rent equals 0.

This set of options reveals the complementarity condition: either the unused capacity or the margin is zero. Both conditions cannot be satisfied at the same time. This is equivalent to the complementarity condition in optimization.

*Production cost is above demand (d)*

If the production cost is greater than the demand curve, the producer will not produce. This condition means that no price clears, $Q_e$, is 0, and the capacity constraint is not reached.

### 4.2. Mathematical representation of the complementarity condition

The four cases are summarized in Table 2.

*Table 2. Summary of equilibrium cases.*

| | Case | Quantity produced | Margin beyond cost |
|---|---|---|---|
| **a** | Supply and demand curves intersect at equilibrium | $Q_e$ | $R = 0$ |
| **b** | Production cost below demand curve | $Q_e = M$ | $R = P_e - C \geq 0$ |
| **c** | Production cost intersects demand curve | $0 \leq Q_e \leq M$ | $R = P_e - C = 0$ |
| **d** | Production cost above demand curve | $Q_e = 0$ | $R = 0 \geq P_e - C$ |

Letting $P_e = mv(Q)$, cases b, c, and d can be written as:

*Equation 1. Production cost below demand curve (b).*

$$mv(Q) - C - R = 0 \qquad Q = M \qquad R > 0$$

*Equation 2. Production cost intersects demand curve (c).*

$$mv(Q) - C = 0 \qquad 0 \leq Q \leq M \qquad R = 0$$

*Equation 3. Production cost above demand curve (d).*

$$mv(Q) - C < 0 \qquad Q = 0 \qquad R = 0$$

Using the complementarity symbol $\perp$ Equation 1, Equation 2, and Equation 3 become:

*Equation 4. Complementarity relationship for economic rent.*

$$0 \leq M - Q \perp R \geq 0$$

*Equation 5. Complementarity relationship for costs.*

$$0 \leq C + R - mv(Q) \perp Q \geq 0$$

where Equation 4 shows that there is an economic rent *iff* the production limit is reached, and Equation 5 shows that a good is not produced *iff* the marginal cost exceeds the marginal value.

## 4.3. Generalized formulation for a two-sector economy

The complementarity relationship is now illustrated for a simple two-sector economy.

### *Optimization problem formulation*

Consider two sectors: a fuel sector and a power sector. The Fuel sector can be represented as a profit maximizing agent, and the Power sector can be represented as a cost minimizing agent. The Fuel sector's objective is to produce a quantity of fuel, $f$, for consumption by the power sector at least cost. The power sector demands $F$. The cost of fuel production is $C$, and the production capacity is $S$. The Lagrange multiplier on the supply constraint is $\mu$ and the Lagrange multiplier on the supply-demand balance is $\pi$.

*Equation 6. Fuel sector's objective function.*

$$\max_{f} F * p - f * C$$

*Equation 7. Fuel supply constraint.*

$$0 \leq f \leq S \qquad \perp \mu \geq 0$$

*Equation 8. Fuel supply and demand constraint.*

$$f \geq F \qquad \perp \pi \geq 0$$

The Power sector's objective is to meet electricity demand at least cost, which requires consuming fuel produced by the Fuel sector at a price p. The Power sector produces electricity $e$, to meet exogenous demand, $D$. Fuel consumption, $F$, is determined by some efficiency coefficient, $H$. The Lagrange multiplier on the demand balance is $\alpha$.

*Equation 9. Power sector's objective function.*

$$\min_{e} F * p$$

*Equation 10. Power supply and demand constraint.*

$$D - e \leq 0 \qquad \perp \alpha \geq 0$$

*Equation 11. Fuel demand constraint.*

$$F = e * H$$

The equilibrium for the combined system is found by combining the objective functions into Equation 12 and concatenating the constraints. Note that in the combined objective function the revenue to the Fuel sector is negated by the costs incurred by the Power sector. The price information is no longer explicitly represented in the objective function.

*Equation 12. Combined objective function.*

$$\min_{e,f} f * C - F * p + F * p$$

For a problem that meets the criteria for optimization (e.g., perfect competition), this would be stopping point. The linear program can now be solved by a variety of widely available algorithms such as Simplex or Branch and Bound (Padberg, 1999).

### *Equilibrium problem formulation*

The MCP is formed by constructing the Karush-Kuhn-Tucker (KKT) conditions. The KKT conditions expose the explicit optimality conditions that define the equilibrium (Ruiz et al., 2014).

Constructing the KKT conditions is accomplished by forming the *Lagrangian* of the combined problem Equation 7, Equation 8, Equation 10, Equation 11, and Equation 12. Figure 4 illustrates the primal and dual problems.

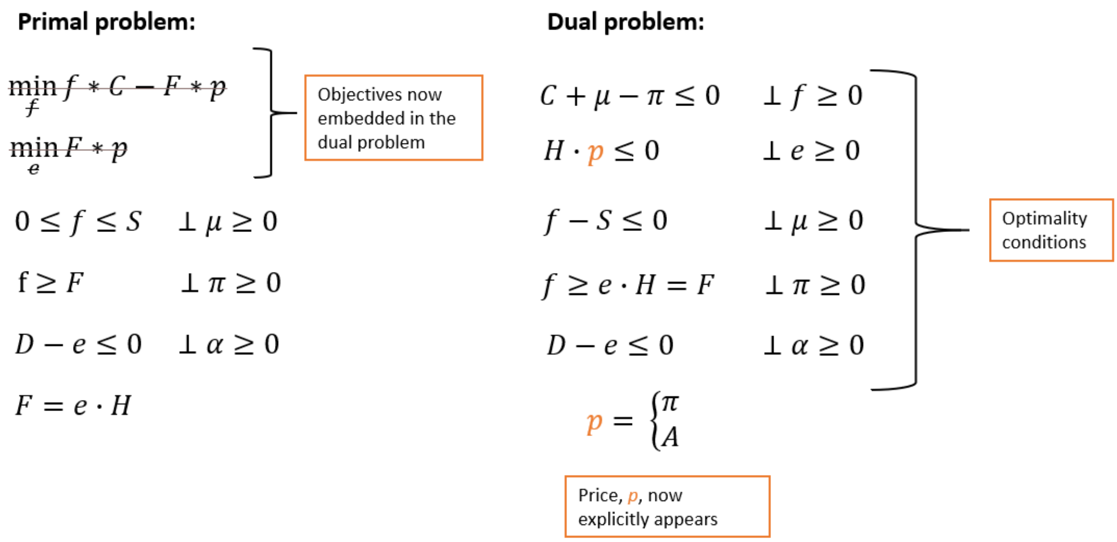



*Figure 4. Primal and dual problems for a two-sector economy.*

Together, the primal and dual constraints form the optimality conditions, as noted above. Note that price information is retained in $p$. The price $p$ can be manipulated to be some arbitrary value, $A$. For example, $A$ can be set government-administered prices for fuels, where the price is administered below the price at perfect competition, $p \leq \pi$. Thus, perfect competition arises when $p = \pi$ and optimization problems exist within the broader class of equilibrium problems.

The MCP formulation presented above is easily extended to multiple regions in the same way that multiple sectors are represented. The formulation presented in Chapter 4 illustrates the multi-regional implementation of the MCP.

## 5. Graphical representation of the GCC energy system

Six energy-intensive sectors are identified for this dissertation: power production; seawater desalination; upstream fuel supply; refining, petrochemicals, and cement. The sectors and linkages are illustrated in Figure 5. These sectors can be considered holistically to represent the interdependent nature of the energy system and illuminate trade-offs that are not obvious *a priori*.

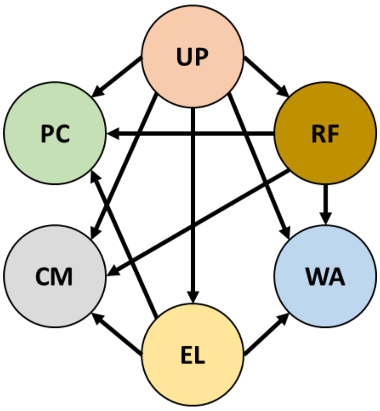



*Figure 5. A representation of the energy-intensive sectors and cross-sectional flows in an individual energy system.*

The energy systems in the GCC countries are represented the following way: the upstream fuel sector (UP) supplies oil and natural gas to power (EL) and water (WA) sectors for direct combustion to produce electricity and desalinated water. Oil and gas flow downstream to the refining (RF), petrochemicals (PC), and cement (CM) sectors to make products, which can be sold domestically or to international markets. The fuel sector also exports oil and natural gas to international markets.

The black arrows connect the sectors are transfers of both goods and prices. As shown in the MCP derivation above, the power sector may purchase fuel from the upstream sector at an administered price. Both sectors (agents) satisfy demand at this transaction price even if it means operating at a loss. It is this concept of the administered fuel price that is explored in Chapters 2, 3, and 4; however, only Chapter 2 considers all six sectors. The multi-sector representation is reduced to the upstream, electricity, and water desalination sectors for the six countries of the GCC, shown below in Figure 6. The reduction was made to keep the data collection and calibration process feasible while enabling a focused analysis on the electricity sector.

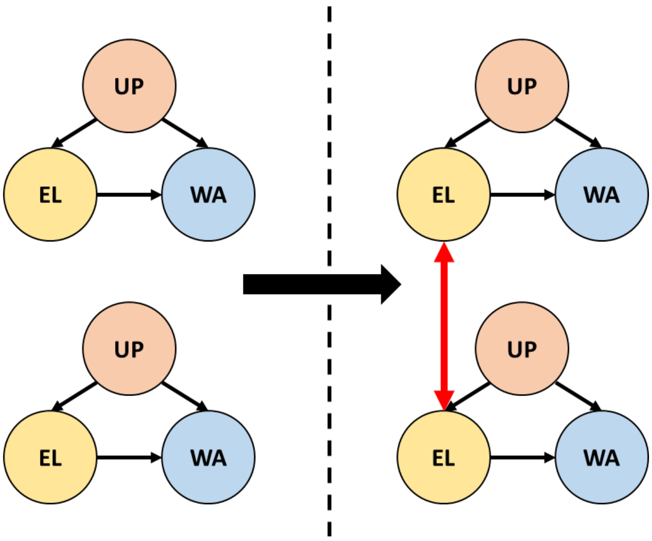



*Figure 6. A multi-regional system in autarky on the left and after integration on the right.*

In autarky, shown on the left side of Figure 6, each country utilizes its own resources to produce electricity, desalinated seawater, and refined products with its own subsidy regime. The processes for refined products are not modeled; they are assumed to be available for purchase from the upstream sector. The countries make investment and operation decisions to maximize their welfare (through resource exports and meeting demand for energy services) independently of the other countries. After integration, the right side of Figure 6, the countries can satisfy domestic electricity demand through self-production or through exchange, denoted by the red arrow.

# Chapter 2. Analysis of an energy system in autarky.

## Abstract

In Saudi Arabia, industrial fuel prices are administered below international prices and firms make decisions based on low energy prices, increasing domestic energy demand. This analysis explores alternative policies designed to induce a transition to a more efficient energy system by immediately deregulating industrial fuel prices, gradually deregulating fuel prices, and introducing investment credits or feed-in tariffs. It uses a dynamic multi-sector, mixed-complementarity model. Continuing existing policies results in a power system still fueled completely by hydrocarbons.

The alternative policies result in a transition to a more efficient energy system where nuclear and renewable technologies become cost-effective and produce 70% of the electricity in 2032. Introducing the alternative policies can reduce the consumption of oil and natural gas by up to 2 million barrels of oil equivalent per day in 2032, with cumulative savings between 6.3 and 9.6 billion barrels of oil equivalent. The energy system sees a net economic gain up to half a trillion 2014 USD from increased oil exports, even with investments in nuclear and renewables. The results are robust to alternative assumptions regarding the value of oil saved and the growth in end-use energy demand.

## 1. Introduction

Oil consumption in Saudi Arabia has grown at an annual rate of 5% since the year 2000 raising concerns over the ability for the Kingdom to maintain future exports (British Petroleum, 2014). For instance, Lahn and Stevens extrapolate future energy consumption and state that Saudi Arabia could become a net importer of oil in a little more than 20 years (Lahn and Stevens, 2011).

Constrained natural gas supply and low administered fuel prices offered to industry result in substantial quantities of oil consumed in electricity generation and industrial production. Low fuel prices have hindered the deployment of more efficient power generation and industrial technologies. Matar et al. show the potential economic gains that could have been realized in 2011 by deregulating the transfer prices of fuels among industrial sectors, or by introducing government credits to encourage investment in more efficient power generation capacity (Matar et al., 2015). They demonstrate that as much as 860 thousand barrels per day of crude oil could have been saved in 2011 through changes in electricity, water, and industrial production, leaving end-consumer prices of transportation fuels and electricity unchanged. Matar et al. also provide a background on Saudi energy consumption and the literature on energy subsidies and fuel price reform. This multi-period analysis extends those results by examining the consequences of alternative pricing policies on the energy system.

Few studies have investigated future energy consumption in Saudi Arabia. Mansouri et al. examined a move towards a future electricity generation mix in the Kingdom focused on solar photovoltaic (PV) and carbon capture and storage (CCS) (Mansouri et al., 2013). Applying a life cycle assessment approach, they studied multiple scenarios where different combinations of CCS and PV deployment levels are imposed. Others, like Al-Saleh and Taleb, have conducted survey methods to gauge the prospects for renewable technologies in the future Saudi power mix (Al-Saleh, 2009; Taleb, 2009).

The analysis presented in this paper uses a multi-sector model to characterize the investment and operational decisions under various regulatory policies where transfer prices of fuels between sectors are not necessarily marginal costs or marginal values. The impact of fuel pricing policies on the energy system in inducing investment in more efficient power generation technologies is presented. The policy scenarios analyzed include deregulating transfer prices of fuels and introducing investment credits or equivalent feed-in tariffs. All policies maintain the current end-user prices for electricity and transportation fuels in real terms; this implies a slight shift in policy since the actual prices are fixed in nominal terms. The effects of various policies on the evolution of the power generation mix and fuel consumption through 2032 are analyzed using a multi-period version of the KAPSARC Energy Model (KEM). The economic gains attained from alternative policies are compared with the gains from a continuation of existing policies.

KEM incorporates the "baseline scenario" macroeconomic assumptions in Oxford Economics' global economic and industry models. The study explores the following cases:

- Continuing existing pricing policies;
- immediate deregulation of fuel prices to industrial sectors;
- phased deregulation of fuel prices to industry; and
- combining incentives and small fuel price increases that capture many of the benefits of deregulation.

The next section provides a background on fuel pricing policies in the Kingdom. Section 3 details KEM, additional model features incorporated for this analysis, and data inputs. Section 4 describes the policy scenarios analyzed, followed by a discussion of the model results in section 5.

## 2. The role of industrial fuel prices

In Saudi Arabia, administered prices of fuels lower costs in sectors that in turn sell their products at administered prices in order to support development objectives (by promoting economic diversification, or by providing electricity and water at low prices to the public). This, however, creates both a lack of economic coordination among sectors and inefficient choices within sectors. The equipment mix and fuel consumption rates in the large energy-consuming sectors reflect the low administered prices charged for fuels. Table 3 contains the transfer prices charged to the power, water desalination, and petrochemicals sectors.

*Table 3. Transfer prices for fuels paid by the power, water, and petrochemicals sectors.*

| Fuel | Price |
|---|---|
| Methane and ethane | 0.75 USD/MMBtu |
| Arab light | 4.24 USD/bbl |
| Arab heavy | 2.67 USD/bbl |
| Diesel | 0.65 USD/MMBtu |
| Heavy fuel oil 360cst | 0.36 USD/MMBtu |

Currently, Saudi power generation capacity is composed almost entirely of conventional thermal plants fueled by crude oil, refined oil products, and natural gas. The Joint Oil Data Initiative (JODI) states that direct use of crude oil approached 900 thousand barrels per day in July 2014, or about 9 percent of the country's total production, the vast majority of which was used for power generation (JODI, 20f14).

## 3. Overview of KEM

KEM is a partial equilibrium model representing the upstream, power, water, refining, petrochemicals and cement sectors in Saudi Arabia. The model is formulated as a mixed-complementarity problem (MCP) that captures the administered fuel prices that permeate the Saudi energy economy. A standard optimization approach cannot be used because administered prices are different from marginal costs. Prior to modeling of administered prices in MCPs, the only approach to finding a regulated equilibrium was treating an optimization model as an embedded sub-model and iterating with a complex set of calculations (Greenberg and Murphy, 1985). As explained in Murphy et al. (2016), an MCP formulation can directly represent important aspects of regulations and price controls (Murphy et al., 2016). Matar et al. explains how this is done (Matar et al., 2014). The power and water sectors meet exogenous demand for electricity and water at their least cost, given the prices and equipment costs they see. The remaining sectors are export-oriented and meet domestic demand while maximizing profits from exports. The sectors covered and the flows of energy are shown in Figure 7.

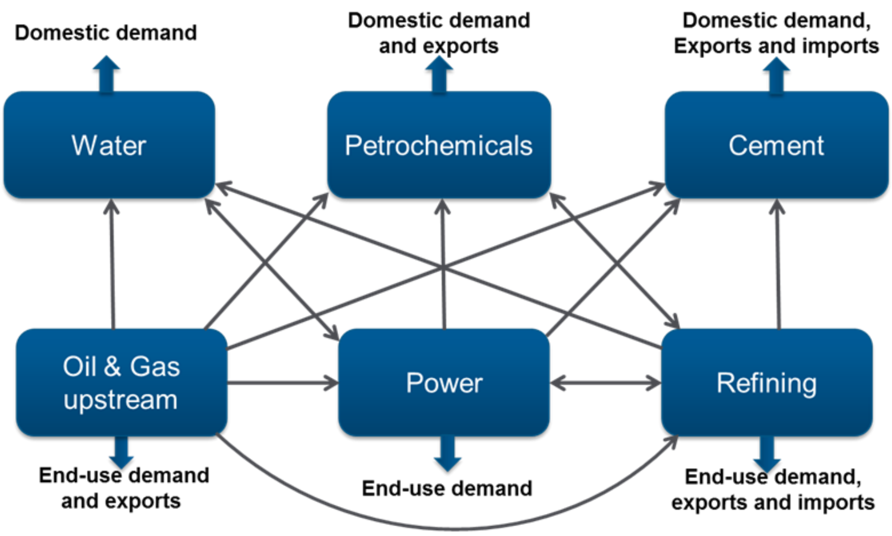



*Figure 7. The sectors represented in KEM and the major flows among sectors.*

The version of KEM used here is an extension of the model described in Matar et al. (2015) (Matar et al., 2015). The central difference is that this version is a multi-period model that represents the impact of alternative energy policies over time, while the previous version is a single-period static model that examines the long-run consequences of policies without examining transition issues.

A technique called recursive dynamics is used to find the equilibrium for all years through the forecast horizon of 2032 (described in Appendix 2A). This method is a compromise between assuming full information, with capacity added optimally through the model's horizon, and the myopia of the single-period model.

As detailed by Matar et al. (2014, 2015), the model is calibrated to data for the year 2011, but also includes partial data for 2012 through 2014 (Matar et al., 2015, 2014). The years 2012 to 2014 are treated as part of the forecast period because of the incomplete data. The planning for power generation expansion begins in 2015 and includes plants already under construction, which are listed in Appendix 2B. The data includes aggregate capacities for power, water, other industrial process technologies, and reported demands.

The Oxford Economics Global Economic (GEM) and Global Industry (GIM) models generate a set of consistent macroeconomic assumptions that we use in defining our scenarios. Projected demands beyond the calibration year are calculated using the GEM and GIM outlooks. Appendix 2C gives an overview of the assumptions common to all policy scenarios. Appendix 2D details the assumptions made for technology costs.

For specific details about how different sectors are represented in the model, see Matar et al. (2014, 2015) (Matar et al., 2015, 2014). Additional developments and technologies introduced in the multi-period version of the model used in this paper are described in Appendix 2E. All price results are expressed in real 2014 dollars.

## 4. Policy scenarios analyzed

Policy choices analyzed in this paper focus on fuel-pricing policies, feed-in tariffs, and levels of investment credits. In all scenarios, existing electricity prices to all sectors are maintained, including the price of electricity transferred between the power and desalination sectors. Residential electricity prices and gasoline prices are unchanged in all scenarios. Higher residential and transportation efficiency standards have been enforced since 2013 or will be implemented in the near term. These standards will have long-term effects on the shape of the load curves and the magnitude of the peak loads and will also affect future demand for transportation fuels. This analysis does not consider the implications of those efficiency policies on end-user demand.

In all scenarios:

- The contractual agreements on methane and ethane prices of $0.75 per MMBtu in the petrochemicals sector for existing plants are retained.
- In every sector of the model, the volume of future purchases of heavy fuel oil (HFO) and diesel at administered prices are capped at the levels observed in 2011. The use of heavy fuel oil in steam turbines with desulfurization units is exempt from this restriction. The international price of oil follows the trajectory in Figure 16.

The following subsections describe the scenarios.

### 4.1 Current policy baseline

The current administered transfer prices of fuels are constant in real terms until 2032. Natural gas supply is below demand at current prices. Therefore, quotas for gas supplied to gas-consuming sectors through the forecast horizon are extrapolated by maintaining the same sectoral allocation percentages observed in 2011. This scenario highlights issues with existing policies. Fuel allocations can lead to excess supply in some consuming sectors over time because the demands for the sectors' outputs do not grow at the same rate and the technology stock changes over time. This analysis assumes that any natural gas that is not consumed is re-allocated to the electricity sector.

In all scenarios, the years up to 2015 are treated as a Current Policy scenario without the sectors able to anticipate alternative policies beginning in 2015.

### 4.2 Immediate deregulation

In this scenario prices for fuels are marginal costs or marginal values while prices of electricity and water are held constant. The equilibrium has the lowest economic cost of the scenarios presented here and serves as a benchmark for economic efficiency. This scenario uses world prices for crude oil and oil products and endogenously determined domestic market-clearing prices for natural gas starting in 2015.

## 4.3 Gradual deregulation

Beginning in 2015, transfer prices of fuels are raised gradually to world prices for oil and prices that clear the domestic market for natural gas over an eight-year period. The incremental costs over immediate deregulation can be compared with non-modeled costs of an immediate price shock from deregulation.

## 4.4 Implicit fuel contracts

In the Implicit Fuel Contracts scenario, sectors continue to receive allocations of natural gas and petroleum products at low prices, despite no formal long-term contracts as in petrochemicals. The model sets the initial allocations of fuels in each sector and region at the existing consumption levels at current administered prices. The allocations are gradually reduced to zero over eight years, at which time all fuel prices are deregulated. Incremental fuel purchases beyond the allocated amounts are at market-clearing prices. Because incremental supply is available at market prices, no allocation mechanism is necessary. The formulation of this scenario in KEM is detailed in Appendix 2F.

## 4.5 Investment credits

The goal of the Investment Credit scenario is to improve economic efficiency without either decreasing profits or increasing losses for the firms from raising fuel prices. Investment credits for new capacity reduce investment costs and bring the relative costs of fuel and capacity in this scenario closer to their relative costs under deregulation. This leads to some of the efficiencies in the deregulation case without forcing losses on the sectors that cannot raise their prices in response to increasing fuel costs.

Starting in 2015, administered prices of crude oil and natural gas are raised to $30/bbl and $1.50/MMBtu, respectively, and are kept constant in real dollars, matching the prices in an investment credit scenario by (Matar et al., 2015). The fuel can flow to where it is the most valuable, without enforcing sectoral quotas. A simple formula for deriving the prices of refined products is applied, setting the administered prices of diesel and HFO to the administered crude oil price multiplied by the ratio of their world market prices to the world price of oil. The investment credit for non-carbon power generation technologies is 50% of capital costs. Capacity expansion has a technology-specific lead time. For the new technologies with capital costs that decrease over time, the capital cost to which the credit is applied is the cost in the year the decision is made.

This formulation differs from that in Matar et al. (2015) which involved solving a mathematical program subject to equilibrium constraints, or MPEC, to determine the set of investment credits that maximize economic benefit. Adding the time dimension and a larger set of eligible technologies in this analysis explodes the computational difficulty of using the solution method in the single-period model. The current scenario design was chosen for this reason.

Although the same credit is applied to all eligible technologies, the model can be run with any combination of technology-specific credits at a range of levels to determine if other values are of interest.

### 4.6 Feed-in tariffs

As an alternative to investment credits, the government can, instead, provide feed-in tariffs to achieve the same renewable and nuclear capacity additions observed in the Investment Credit Scenario. A feed-in tariff consists of guaranteeing a price for a given quantity of electricity produced using selected new technologies so that equipment producers can lower costs by working down the experience curve, eventually competing with current technologies. Rather than run the model separately for this scenario, the feed-in tariff for the new technology that is implied in the Investment Credit scenario is calculated. Thus, the estimates do not take into account who pays the feed-in tariff, which could alter the cash flows of the utilities.

The difference between investment credits and feed-in tariffs is that an investment credit lowers the equipment cost to make the technology economic and is one payment. A feed-in tariff is a guarantee of an ongoing income stream, which implies an ongoing subsidy.

## 5. Results and discussion

The sum of annual net economic gains, discounted at the real rate of 5%, is used to evaluate the effectiveness of the scenarios. The net economic gain for the Saudi energy economy (aggregating the government and the model's sectors) is defined as the difference between incremental export revenues and incremental costs incurred annually compared with the Current Policy scenario; the cost component uses the annualized investment costs for each of the years the equipment is used over the planning horizon. The economic gains between 2015 and 2032 for the analyzed scenarios are shown in Table 4.

*Table 4. Discounted sum of annual economic gains between 2015 and 2032.*

| Scenario | Total net economic gain (billions of 2014 USD) |
|---|---|
| Current Policy | - |
| Investment Credits/Feed-in Tariffs | 430 |
| Implicit Fuel Contracts | 462 |
| Gradual Deregulation | 476 |
| Immediate Deregulation | 505 |

The Immediate Deregulation scenario produces the highest gain and serves as a benchmark for economic efficiency. The high economic gains seen in the alternative scenarios arise in part from displacing the use of oil in power generation due to the introduction of non-fossil fuel generation technologies. Gradual deregulation and implicit fuel contracts lead relatively quickly to decisions made based on marginal costs, which is why they outperform the Investment Credits case, where the relative prices of fuels versus capacities don't exactly match the relative prices under Immediate Deregulation.

Figure 8 presents the projected net cash flows for the Saudi energy economy compared with those observed in the Current Policy scenario.

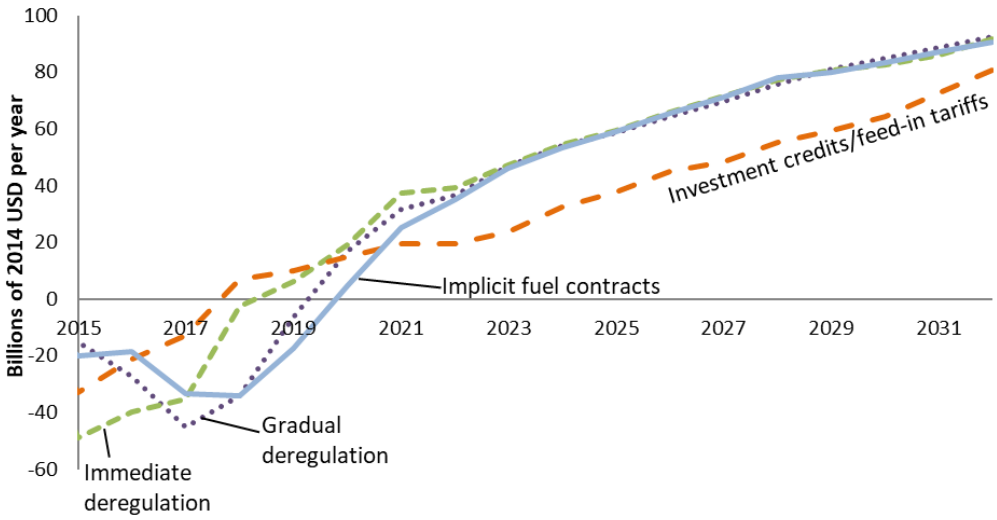



*Figure 8. Annual net cash flows for the Saudi energy economy compared with the Current Policy scenario.*

The net cash flows are calculated in the same way as the economic gain, except that the full investment and financial costs are used and are distributed over the construction period of the plants. Immediate Deregulation starts out with a large increase in cash outflows because the shock of the price jumps makes a large portion of the existing equipment uneconomic even when new equipment requires paying capital costs. The replacement of existing equipment happens more slowly with gradual deregulation and implicit fuel contracts. Nevertheless, these three cases eventually have the same cash flows. The large investment in renewable and nuclear technologies in the alternative scenarios allows for higher oil exports, which generate the cash flow gains. The sum of the annual oil revenues over the planning horizon greatly exceeds the cash outflows required for investment in the early years.

Figure 9 shows the same cash flow profile for the power sector. The utilities have lower cash flow in all scenarios.

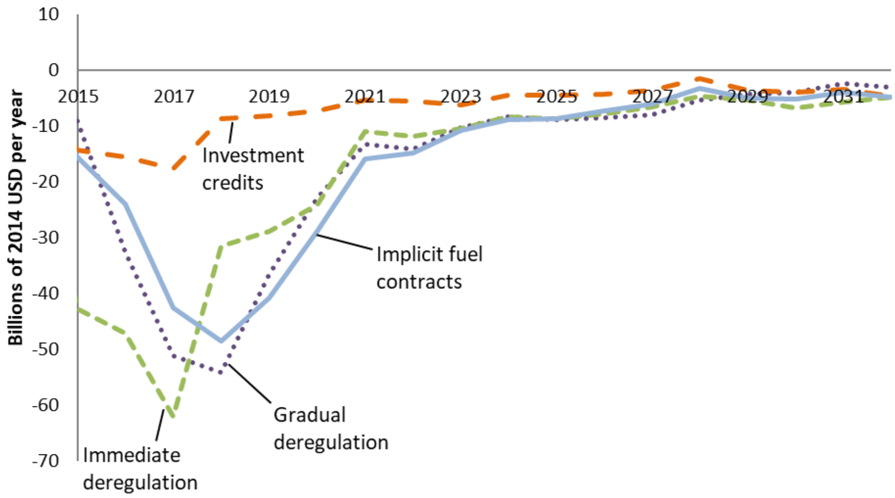



*Figure 9. Annual net cash flows for the power sector relative to Current Policy scenario.*

As expected, the combination of high fuel prices and investment in alternative technologies yields large negative flows in the early years that dissipate over time, once the equipment mix stabilizes. The large outflows early on probably require government support, because consumer prices do not change. The graph highlights a major benefit of investment credits in incentivizing the adoption of renewable and nuclear technologies. As the government would bear half of the investment cost, this would significantly lower the costs shouldered by the power sector.

## 5.1 The implications of fuel pricing policies on future energy consumption

Figure 10 and Figure 11 present the historical profiles and model projections for total domestic primary oil and natural gas consumption in millions of barrels of oil equivalent per day. In the three scenarios leading to deregulation, the country can go for 15 years with consumption below current levels. Eventually, a stabilized equipment mix combined with population and GDP growth lead to higher consumption.

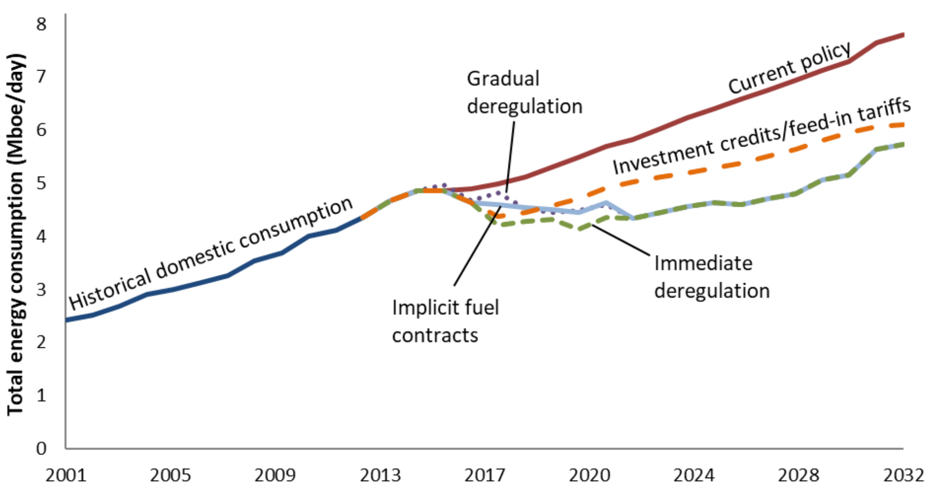



*Figure 10. Total domestic primary crude oil, natural gas, and gas condensate consumption.*

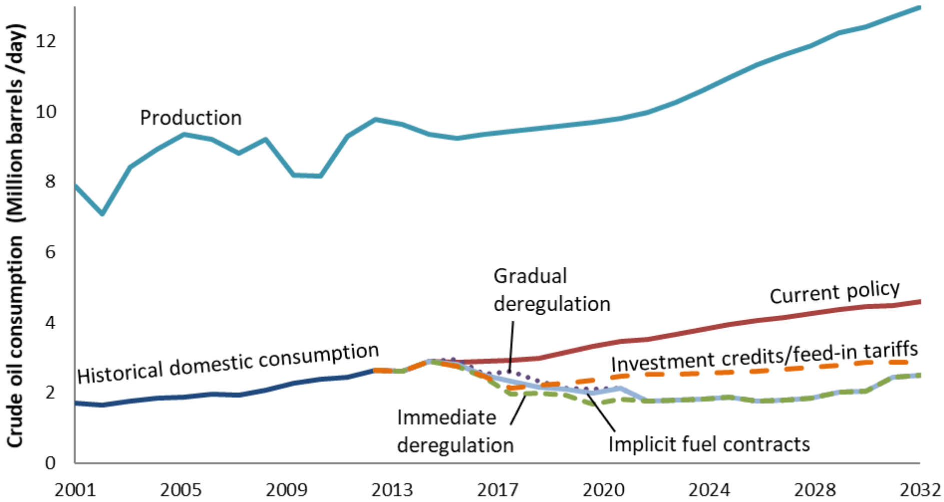



*Figure 11. Domestic crude oil consumption and production.*

Saudi Arabia exports significant quantities of refined products. The above figures are only for crude oil and include all the oil used domestically, even the amounts used for exported petroleum products. With crude oil and gas condensate exports removed, as shown in Figure 12, domestic petroleum liquids demand does not return to current levels over the planning horizon. Furthermore, Saudi Arabia can maintain its exports without major increases in production.

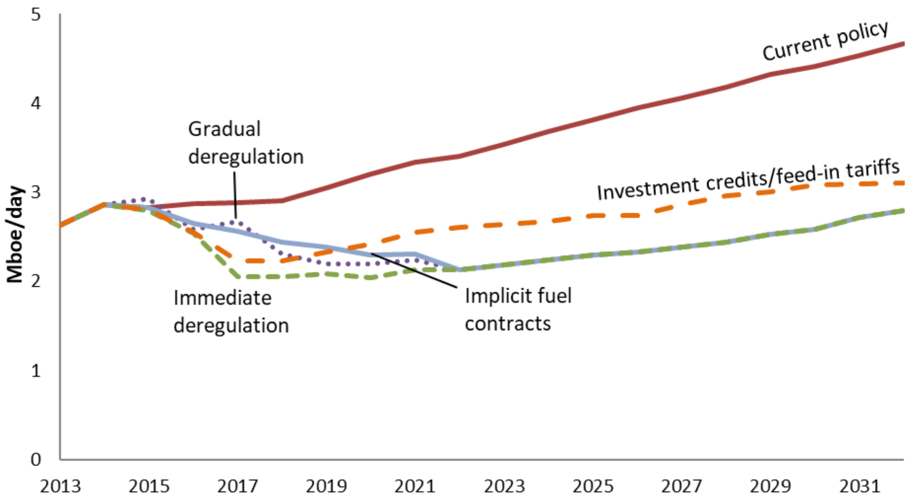


*Figure 12. Consumption of crude oil and gas condensate excluding the energy embodied included in net exports of refined products.*

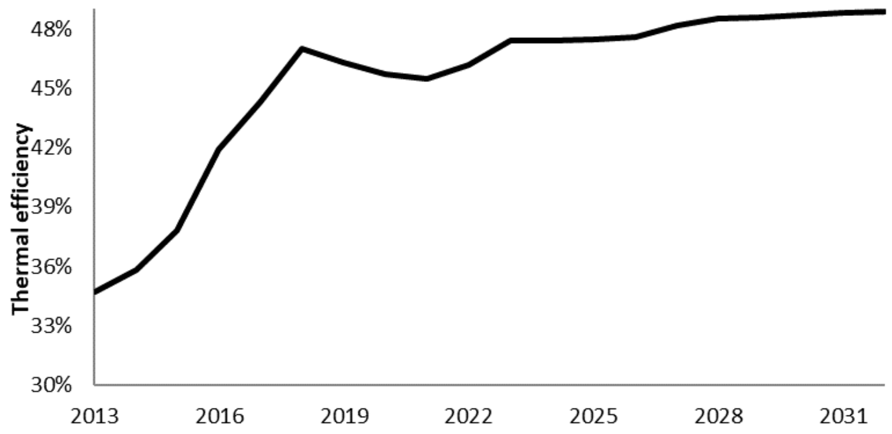
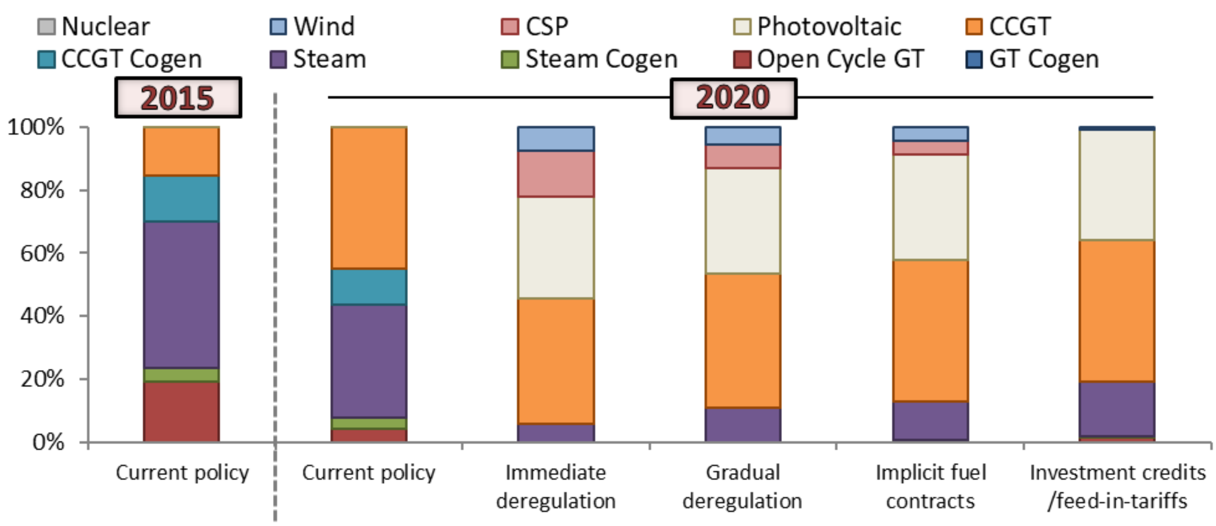



*Figure 13. Average thermal efficiency of generated electricity by the power sector in the Current Policy scenario.*

Even when continuing current policies, the efficiency of generation improves over time and compensates for a portion of demand growth, shown in Figure 13. The improvement comes from converting existing single-cycle gas turbines to combined-cycle plants or building new combined-cycle plants, not from assuming improvements in plant efficiencies.

## 5.2 The technology mix for electricity generation

A continuation of current fuel pricing and allocation policies discourages investment in renewable and nuclear capacity. Figure 14 shows the shares of electricity generation by technology between 2015 and 2032. The optimal technology mix is similar across scenarios in 2015, due to construction lead-times.



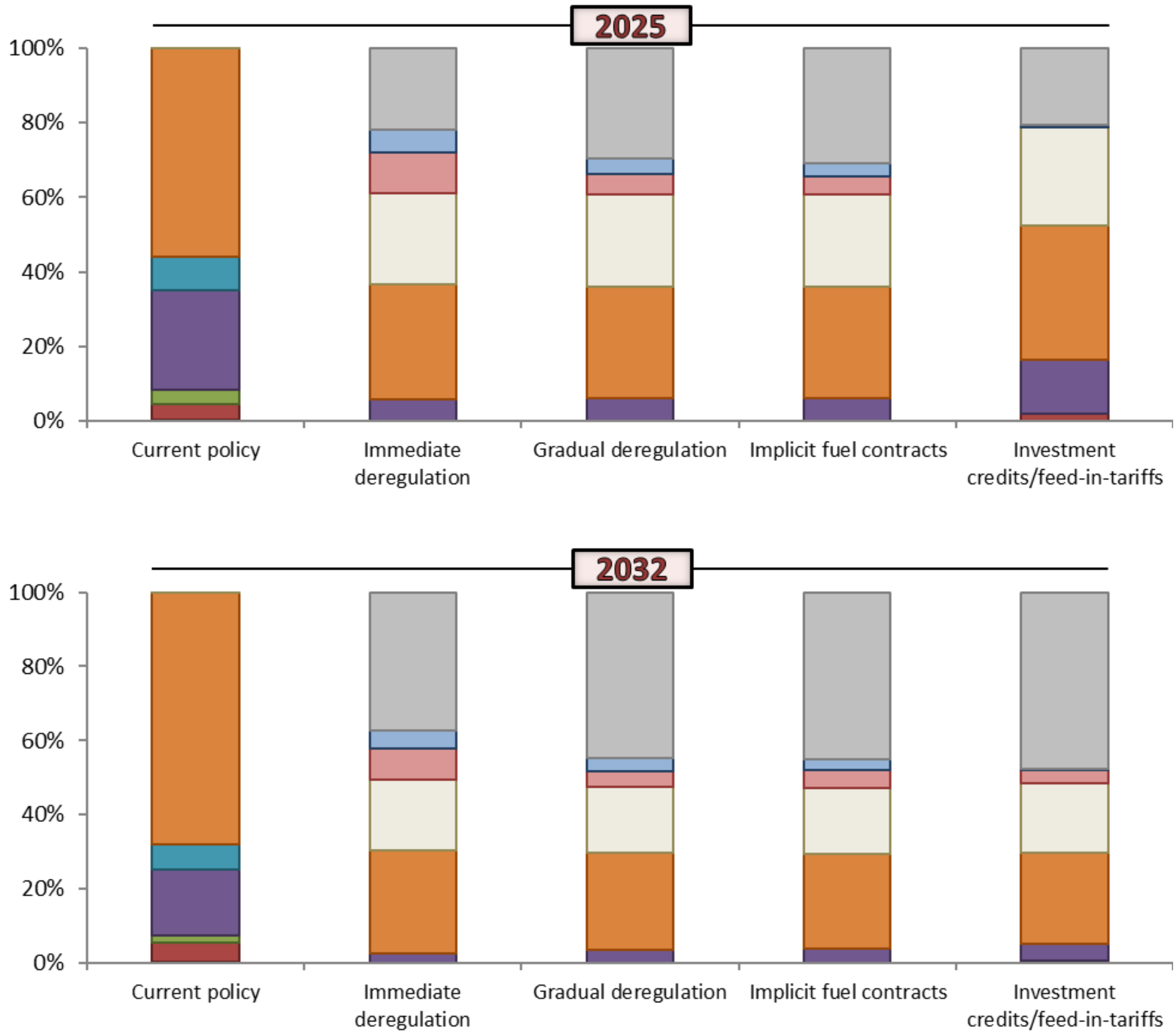



*Figure 14. Technology shares in total electricity generation (TWh) 2015-2032.*

Our analysis shows that the immediate deregulation of prices results in a surge in alternative technologies. Given the lack of experience with these technologies in the Kingdom, this rapid introduction is unlikely. However, this case can be considered a measure of what is economic. An additional case explores what happens with the successive elimination of nuclear and CSP capacity. The Gradual Deregulation and Implicit-Fuel Contracts scenarios produce a less rapid investment surge, illustrating the value of policies that provide for a measured adjustment. The Investment Credit and Feed-in Tariff scenarios create the appropriate cost and income trade-offs for solar and nuclear plants to emerge. These two scenarios show steadier additions of alternative capacity over time, while producing more than 85% of the economic gains realized in the Immediate Deregulation scenario.

A substantial amount of investment in new power infrastructure is required to meet projected demand growth with much less replacing decommissioned plants. In the Current Policy scenario, where more than 57 GW of conventional thermal plants are added by 2032, $103 billion would be spent to expand the generation capacity from 2013 levels. The Implicit Fuel Contracts Scenario leads to the construction of 131 GW of additional capacity, of which 110 GW are nuclear and renewables. Achieving the associated technology mix requires $392 billion in capital investment - including $356 billion for nuclear and renewables.

In all alternative scenarios, nuclear technology progressively dominates the generation mix by 2032. As shown in Figure 14, nuclear capacity does not contribute to electricity production until a decade after the base year because of the seven-year lead time for nuclear plants. In the intervening years, the model makes adjustments that have shorter lead times such as converting existing gas turbines to combined cycle units (or simply building new ones) and developing renewable resources.

However, nuclear poses challenges in Saudi Arabia beyond cost-effectiveness. To analyze this issue, an immediate-deregulation scenario preventing nuclear construction was examined. Here the nuclear base load capacity is mostly filled by a combination of PV and CSP plants, where CSP with the addition of energy storage complements solar PV in providing baseload electricity. The total net economic gain is then 500.1 billion of 2014 USD. Note that nuclear has proven to be politically feasible in the neighboring United Arab Emirates while the high level of CSP may not be realistic since that technology has yet to prove its commercial viability. When nuclear and CSP are both excluded as potential technologies, deregulating fuel prices results in investment in significant PV and wind capacity: 120 GW and 81 GW at a cost of $224 billion and $121 billion, respectively.

In the Investment Credit scenario, 123 GW of new capacity is brought online. The associated capital investment is $384 billion. By 2032, the power sector sees 52 GW of PV, 5 GW of concentrating solar power (CSP), 2 GW of wind, and 46 GW of nuclear power installed. The larger amounts of added capacity in the alternative scenarios reflect the lower capacity factors for intermittent renewable plants and the increased need for thermal capacity to back up the renewable generators when they cannot generate power due to cloud cover or low wind conditions.

The operating decisions made by the model provide insight into the value of adding CSP with thermal storage to the power generation mix. For example, the Immediate Deregulation scenario results in 11.5 GW of installed CSP capacity by the year 2032, which suggests a complementary relationship with photovoltaic plants. When PV plants operate during the day, CSP plants operate below capacity and store solar heat for later use. The stored heat is then dispatched to satisfy the early evening electricity demand and some of the nighttime load. This way, solar energy can be exploited throughout much of the day.

Due to limitations in ramping plants with thermal storage as described in Appendix 2A, all the scenarios presented here assume CSP capacity does not contribute to the reserve margin requirement. A new scenario was developed to test the potential added economic value to CSP with those restrictions removed. When running the Immediate Deregulation scenario if CSP with thermal storage can fully contribute to the planning reserve, the added value resulted in an installed capacity of 13.3 GW – or around two more GW versus when ramping limitations are enforced.

Table 5 shows the feed-in tariffs that would be necessary as a substitute for investment credits to achieve the national renewable and nuclear capacity observed in the Investment Credit scenario.

*Table 5. The range of feed-in tariffs applied to renewable and nuclear capacity to achieve the technology mix in the Investment Credits scenario in 2014 US dollars.*

| Online years | Feed-in tariff by technology (cents/kWh) | | | |
|---|---|---|---|---|
| | PV | CSP | Wind | Nuclear |
| 2017-2022 | 6.5 to 6.0 | | | |
| 2018-2019 | | | 7.9 | |
| 2026-2032 | | 8.1 to 7.6 | | |
| 2022-2032 | | | | 5.9 |

The values are shown as a range corresponding to the years the plants come online (and would be applied throughout the operating life of the plant). The decrease over time is due to declines in capital and fixed operating costs over time. A key practical difference is that investment credits are applied at the point of initial investment, whereas the feed-in tariffs are calculated at the time the capacity comes online.

## 5.3 Exploring the investment credit and fuel price trade-offs

The mix of technologies remain the same when all prices are scaled by the same amount. Existing equipment choices are skewed towards ones with low capital costs because the administered fuel prices are so low. Raising fuel prices and lowering capital costs through investment credits brings the relative prices of equipment and fuels closer to the relative prices of deregulated fuels, leading to a more efficient equipment mix.

As shown in Figure 9, investment credits reduce the large initial capital outlays significantly, bringing the relative costs of fuel and capacity in this scenario closer to their relative costs under deregulation.

Two variants are now considered. The first retains the current administered fuel prices but introduces the 50% credit for all alternative technologies. The second raises the fuel prices as in the Investment Credits scenario but eliminates the investment credits. Not raising prices leaves alternative technologies uneconomic, given the low fuel prices and no economic gain. Raising fuel prices to the levels in the Investment Credits scenario generated a discounted sum of annual economic gains of $72 billion in 2014 dollars, showing that combining credits with higher prices produces a far greater gain. These results highlight the importance of including both measures to achieve the fuel-to-capital cost ratios that are necessary to encourage the adoption of alternative technologies.

## 5.4 Fuel consumption for electricity generation

In Saudi Arabia, electricity is mostly generated using crude oil and refined petroleum products and fossil fuels continue to power new capacity under existing policies. Figure 15 presents the amounts of fuels projected for electricity generation and cogeneration in the years 2015 and 2032. The consumption of crude oil declines significantly or disappears in the alternative scenarios. Oil-fired generation is replaced with natural gas and non-fossil technologies, except in the Investment Credits scenario. Despite an unchanged gas allocation, replacing turbines with combined-cycle plants frees up the gas needed to expand gas-fired generation. According to the results, all forms of oil would be removed from the power system by the year 2022.

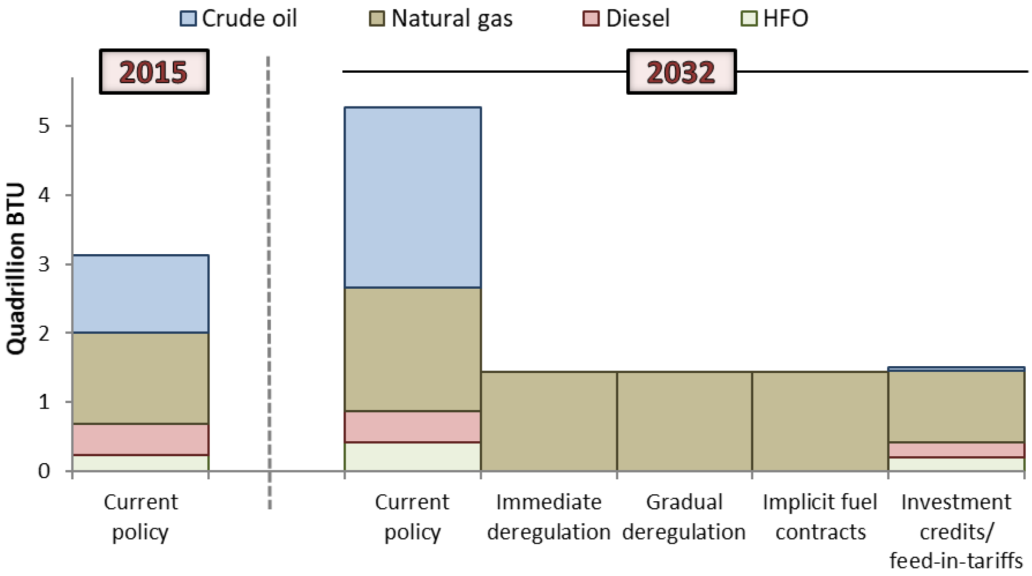



*Figure 15. Fuel consumption for electricity generation.*

These reductions in primary consumption of crude oil result in savings of nearly two million barrels of oil equivalent per day in 2032 relative to a continuation of existing administered fuel prices, with a cumulative savings between 6.3 and 9.6 billion barrels of oil equivalent through 2032. Crude oil savings in the first six years are along the same order of magnitude as the estimated 860 thousand barrels per day savings found in the 2011 counterfactual by Matar et al. (2015). These annual savings significantly increase in the subsequent years. The multi-period nature of this analysis illustrates that planning decisions result in an accumulation of energy savings throughout the planning horizon.

## 5.5 Valuing natural gas in the Saudi economy

As natural gas is assumed to be neither exported nor imported, this raises the question of assessing its implied domestic market price. This price is determined by the model as the value, for the Saudi energy economy, of adding 1 MMBtu of natural gas supply. Figure 16 shows the projected marginal value of natural gas in the Immediate Deregulation scenario and compares it to the exogenously assumed industrial oil price projection.

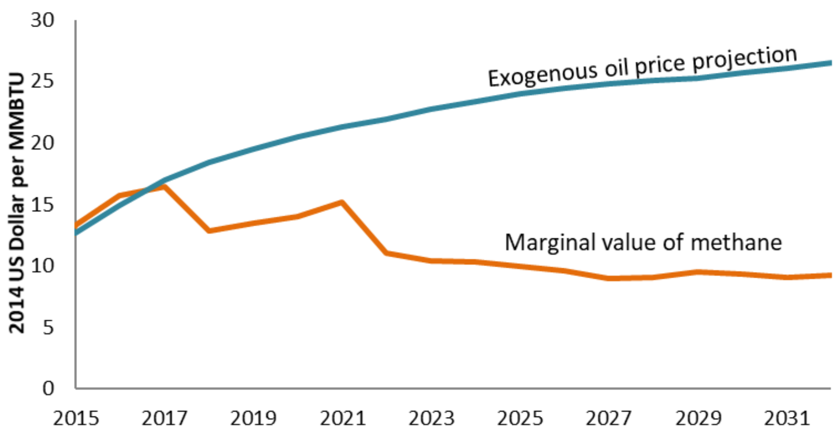


*Figure 16. The calculated marginal value of methane in the Immediate Deregulation scenario.*

The two prices are essentially correlated until crude oil is no longer used for power generation in 2018. The gas price declines because the capital stock becomes more efficient. HFO is used for power generation until 2022, due to the introduction of a steam plant with a desulfurization unit that is planned to come online in 2017. In this analysis the marginal value of gas stabilizes at around $9 per MMBtu in the long-run.

## 5.6 Sensitivity to world prices and macroeconomic assumptions

Saudi Arabia is a major oil exporter with spare production capacity and large reserves and it often values a barrel of oil saved from domestic consumption at a price that is lower than the international market price. To illustrate the sensitivity of our results, the Current Policy and Immediate Deregulation scenarios were run when valuing the oil saved at half the projected oil price. Deregulating fuel prices then results in reducing consumption of oil and natural gas by 1.9 million barrels of oil equivalent per day in 2032, with a cumulative saving of 9.4 billion barrels. When both the value of oil saved and projected growth in end-use energy demand are halved, cumulative savings fall to 8.5 billion barrels of oil equivalent. Figure 17 shows the total energy consumption through 2032 for these additional scenarios.

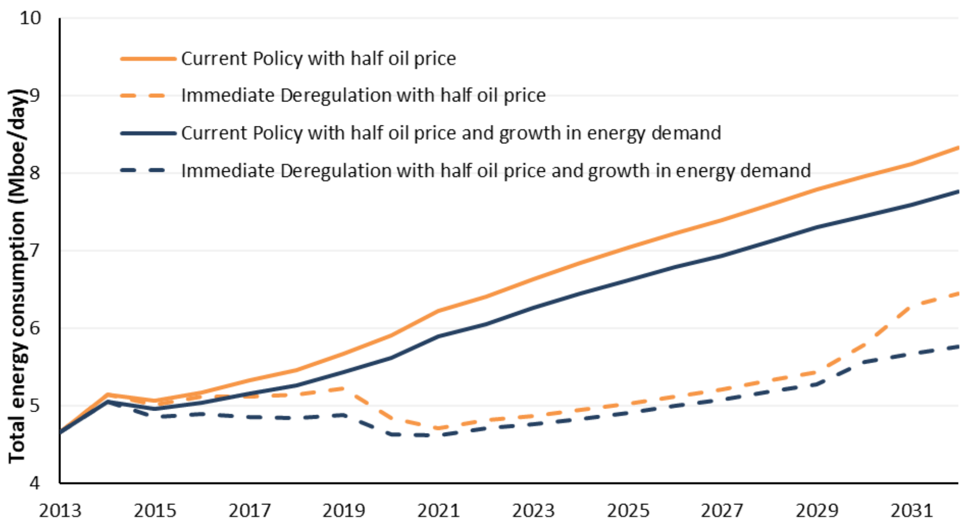



*Figure 17. Total energy consumption when halving oil price and growth in projected end-use energy demand.*

The relative costs of fuel and equipment still induce investments in nuclear, PV, and CSP when fuel prices are deregulated. The decisions made in the early years of the planning horizon yield insight into how alternative assumptions influence the energy system's transition. Considering only a reduced value of oil saved results in significant savings in total energy consumption in 2020, the first year nuclear plants come online. The model invests in nuclear plants in the early years in anticipation of growing energy demand, rather than investing more in lower-cost combined cycle plants (which would generate cost savings in the short-term). When the model also anticipates slower growth in energy demand, the least-cost decision is to invest quickly in more combined cycle units and build fewer nuclear plants later. Overall, these findings illustrate the robustness of our results.

## 6. Conclusions and policy implications

A continuation of existing policies would not produce the economic signals that are necessary to encourage investment in alternative power generation technologies nor an efficient portfolio of equipment. Immediately deregulating fuel prices results in a rapid move to a more efficient energy system where nuclear and renewable technologies become cost-effective. Primary consumption of oil and natural gas can be reduced by up two million barrels of oil equivalent per day in 2032 (for a cumulative savings of between 6.3 and 9.6 billion barrels of oil equivalent through the planning horizon), relative to a continuation of existing policies. The energy system sees a net economic gain up to half a trillion 2014 USD from increased oil exports, even when accounting for investments in nuclear and renewables. Less sudden or disruptive policies that gradually increase fuel prices or introduce investment credits help to facilitate the integration of alternative technologies into the Saudi energy system and achieve efficiencies close to those resulting from immediate deregulation. Potential economic gains under the gradual deregulation of fuel prices yields a smooth transition path for technologies without much of a reduction in the economic gains observed with the Immediate Deregulation scenario.

In this analysis, higher fuel prices lead to investment in more efficient plants. Similarly, lowering capital costs, while maintaining administered prices, is also shown to improve the equipment mix. The introduction of investment credits that lower capital costs demonstrates how the system could achieve most of the economic gains of Immediate Deregulation while maintaining fuel prices at levels well below marginal values. Although a continuation (in real terms) of current pricing policies would not result in the introduction of nuclear and renewable plants, the efficiency of electricity generation would improve over time due to investment in combined-cycle plants.

Notably, $CO_2$ emissions were not considered in this analysis because the focus was on isolating the role of administered prices and quotas. The role of $CO_2$ emissions will be investigated in depth in Chapter 4.

# Chapter 3. The costs and gains of policy options for coordinating electricity generation in the Gulf Cooperation Council.


## Abstract

This chapter investigates the economic impacts of policies for coordinating electricity production in the Gulf Cooperation Council (GCC) through electricity trade. The GCC countries have installed a network of high-voltage transmission lines that links Saudi Arabia, Bahrain, Kuwait, Oman, Qatar, and the United Arab Emirates. The Interconnector has successfully provided reliability services but has not yet realized its full potential as a platform to fully integrate the individual electricity systems.

A static analysis of 2015 was performed using a partial equilibrium model with detailed power generation and water production sectors for each country. The economic losses and gains are calculated for each country and in aggregate before and after coordination through electricity trade. First, the potential gains from coordination subject to the existing national policies for fuel subsidies were assessed. Next, coordination when fuel inputs are not subsidized were considered. Finally, a scenario was devised that aims to retain the benefits of coordination without removing fuel subsidies. The results indicate that subsidy removal is necessary for each country to gain from electricity trade. Removing fuel subsidies provides the bulk of economic gains: $42.6 billion. Utilizing the Interconnector further increases annual gains by $1.1 billion.


## 1. Introduction

Countries in the Gulf Cooperation Council (GCC) have installed a network of high-voltage transmission lines, known as the GCC interconnector, which links the member states of Saudi Arabia, Bahrain, Kuwait, Oman, Qatar, and the United Arab Emirates (U.A.E.). The Interconnector was conceived as a tool to "provide the safety and security of the GCC's electrical grids and to avoid power outages by 100 percent" and as a platform to facilitate coordination among countries that would support the ongoing reform initiatives (Gulf Cooperation Council Interconnection Authority, 2017).

The Gulf Cooperation Council Interconnection Authority (GCCIA) is the independent system operator and plans to transition the system to a fully operational market, based on the Nord Pool model (Elshurafa et al., 2017). The Authority aims to save an average of $1.3 billion a year over 25 years through reducing costs from building and operating new power plants and reducing redundant reserve margins (Gulf Cooperation Council Interconnection Authority, 2017). The Interconnector was completed in 2011 and has maintained system reliability through enabling in-kind exchange of electricity among member states. The solid black lines in Figure 18 represent the dedicated Interconnector lines. In the U.A.E. and Oman, a dedicated Interconnector line was not constructed because the existing national grids have already been connected, indicated by the dashed lines.


*Figure 18. Map of GCC members and the GCC Interconnector (shown by the thick black lines). Source: Google Maps, KAPSARC.*

Under the right circumstances, the GCC countries could benefit from more coordinated electricity production as the countries have non-coincident peaks in electricity demand. However, the link has not provided the full benefits of integrating the individual grids of the member countries because of the structure of the electricity and water sectors in each country. Low administered prices on fuels used for electricity generation, which vary by country, are a key barrier to regional movements of electricity because it is not likely that a country wants to incur the costs of exporting the value of its subsidies. Without reforming these prices or designing a market mechanism to account for the full cost of electricity production, any electricity sold across borders means the exporting country subsidizes consumers in the importing countries. These subsidies cannot be recouped because a large portion of the subsidies are provided before the point of delivery. Fuel subsidies are virtually impossible to trace and recapture because system wide effects on investment and operations are not measured in standard accounting systems. Thus, the current structures of domestic markets are a barrier to cross-border exchange.

Currently, with the reduction in government revenues from hydrocarbon exports, all GCC member nations are in the process of reforming their power sectors. Saudi Arabia is exploring the creation of an electricity market such as those in the United States and Europe. That is, they are moving to pricing that more closely reflects cost of production. As an intermediate step, on January 1, 2016, Saudi Arabia raised the price of natural gas by 77 percent and crude oil by 50 percent for power and water producers (Wogan, 2017). The government of Saudi Arabia has announced future price increases as part of the ongoing reforms in Vision 2030 (Kingdom of Saudi Arabia Vision 2030, 2016).

Given the interest in domestic restructuring and ongoing demand growth, the potential savings from a greater use of the Interconnector to lower costs and improve the efficiency of electricity generation and transmission in the region are investigated. This is done by constructing a set of scenarios that examine a range of fuel-subsidy and electricity-exchange policies.

# 2. The GCC Power and Water System

## 2.1 Background

This section provides an overview of the GCC power and water system. Relevant energy related statistics for 2015 (except where noted below) are presented in Table 6. A more detailed discussion at the country-level is provided in Wogan, et al (Wogan, 2017).

Energy is the foundation of the modern GCC economies. In 2015, energy products represented over 65 percent of total exports in four of the six GCC countries (Massachusetts Institute of Technology, 2016a, 2016b, 2016c, 2016d). In the remaining two (U.A.E. and Bahrain), energy products are over one-third of all exports (OPEC (Organization of the Petroleum Exporting Countries), 2017). Fossil fuel resources are also inputs to domestic industries, including power and water production. In 2015, nearly 7 quadrillion British thermal units (QBtu) were consumed by the power and water sectors in the GCC.

Aggregate GCC electricity production was over 604 TWh in 2015, with over half coming from the U.A.E. and Saudi Arabia. On the consumption side, both Qatar and Kuwait reported the highest consumption at 14.6 and 15.4 MWh per capita (Kuwait MEW (Kuwait Ministry of Electricity and Water), 2016a; QEWC (Qatar Electricity and Water Company), 2016). On the low end, Oman and Saudi Arabia reported 7.6 and 9.3 MWh per capita, respectively. Saudi Arabia had the highest peak demand at 62.3 GW with Bahrain having the lowest peak at 3.4 GW (data for Bahrain only available for 2016) (Electricity & Water Authority Kingdom of Bahrain, 2016). Consumption for the U.A.E is an aggregation of the four independent systems (United Arab Emirates Ministry of Energy & Industry, 2016).

The following subsections discuss power generation technologies, fuels, subsidies, water desalination, and the Interconnector.

*Table 6. Key energy statistics.*

| | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. | Total |
|---|---|---|---|---|---|---|---|
| **Population (million)** | 1.4 | 4.2 | 4.2 | 2.4 | 31.0 | 9.6 | 52.8 |
| **Energy exports (percent)** | 41 | 85 | 65 | 85 | 69 | 36 | - |
| | | | | | | | |
| **Installed power capacity (GW)** | 4.0 | 18.3 | 7.4 | 8.6 | 79.2 | 28.3 | 145.8 |
| **Peak load (GW)** | 3.4 | 12.8 | 6.1 | 7.27 | 62.3 | 22.6 | - |
| **Electricity Production (TWh)** | 15.4 | 68.3 | 31.3 | 38.9 | 323.0 | 127.4 | 604.3 |
| **Consumption (MWh per capita)** | 12.1 | 15.4 | 7.6 | 14.6 | 9.3 | 13.2 | - |
| | | | | | | | |
| **Installed desalination capacity (million $m^3$)** | 0.50 | 2.04 | 0.95 | 1.53 | 7.16 | 4.73 | 16.9 |
| | | | | | | | |
| **Fuel consumption (QBtu)** | 0.2 | 0.7 | 0.3 | 0.4 | 3.8 | 1.5 | 6.9 |

### *2.1.1 Technology capacities*

Over 145 GW of power generating capacity is installed across all six countries, roughly equivalent to the installed capacity of the Association of Southeast Asian Nations (ASEAN) (International Energy Agency, 2015). Around 40 GW of open-cycle gas turbines (OCGTs) and 28 GW of single cycle steam turbines supply almost half of all power (Figure 19). More efficient combined-cycle gas turbines (CCGTs) are only 14 percent of capacity (20 GW). Combined power and water plants supply the largest proportion of power in the GCC at over 56 GW of capacity. These plants are referred to as "cogeneration" or "thermal desalination" in this study.

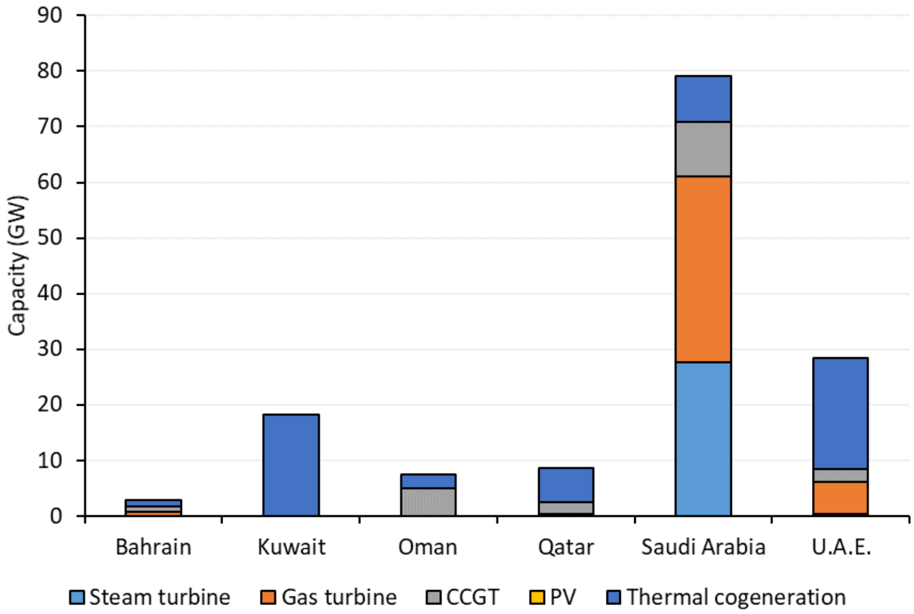



*Figure 19. Power capacity by technology type.*

Fuel costs are maintained at low levels, or priced competitively below global market levels, which provides an economic incentive for utilities to invest in inefficient single-cycle turbines and cogeneration plants. Despite an abundance of solar radiation in the region, at the end of 2015 only 76 MW of photovoltaics (PV) were installed (included but not visible in Figure 19), representing 0.05 percent of all installed capacity. PV capacity has increased since 2015 due to renewable policies and decline in costs.

### *2.1.2 Fuels*

The power and water systems of the GCC states consumed 6.8 QBtu of fossil fuels (annual), with natural gas accounting for 4.6 QBtu annually. Figure 20 presents the consumption of fossil fuel by type for the year 2015.

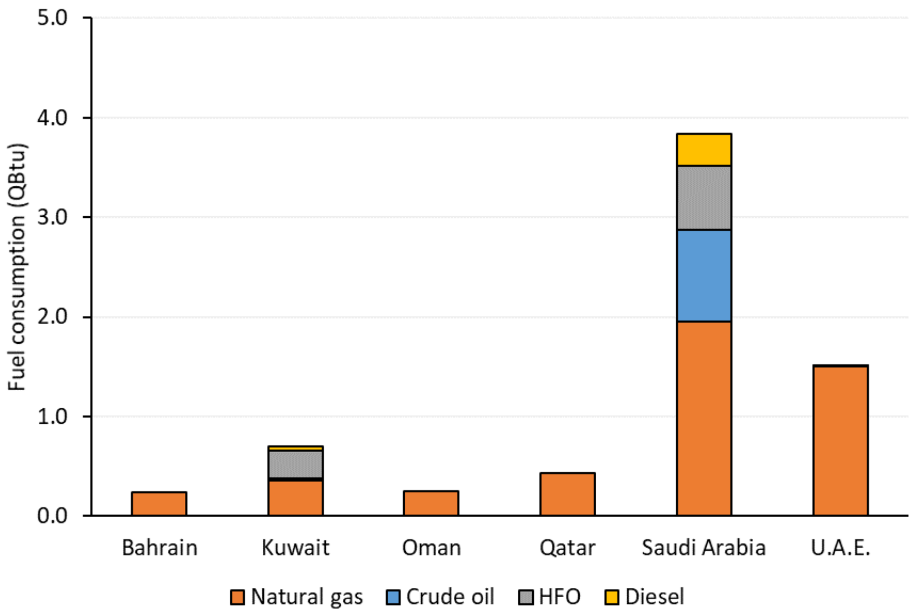



*Figure 20. Estimated fuel mix for power and water sectors by GCC member state.*

As noted above, water and power production in Saudi Arabia, the largest fuel consumer, account for roughly 4 percent of its crude oil production (SEC (Saudi Electricity Company), 2015). Kuwait consumes a combination of natural gas and HFO, and smaller volumes of crude oil and diesel (Kuwait MEW (Kuwait Ministry of Electricity and Water), 2016a). In Bahrain, Oman and Qatar, natural gas is the primary fuel (KAHRAMAA (Qatar General Electricity & Water Corporation), 2014; Kingdom of Bahrain NOGA (Kingdom of Bahrain National Oil and Gas Authority), 2015; OPWP (Oman Power and Water Procurement Company), 2015). Natural gas is the primary fuel for power and water production in the U.A.E. (DEWA (Dubai Electricity and Water Authority), 2014; SEWA (Sharjah Electricity & Water Authority), 2012; UAE FEWA (United Arab Emirates Federal Electricity & Water Authority), 2015; UAE Ministry of Energy, 2015).

### 2.1.3 Fuel Subsidies

A key feature of the GCC energy system is the prevalence of subsidized fuel prices. Domestic utilities purchase most fuels at highly subsidized prices and pass on the savings in the form of affordable energy services to citizens and industries. Subsidies are defined as prices administered by the government below export (market) value. The low price of fuels not only has induced investment in inefficient steam and open cycle turbines but also remains a key impediment to sending electricity between countries. The following fuel prices are used throughout this study for scenarios with administered fuel prices (Table 7) (Wogan, 2017).

*Table 7. Administered fuel prices observed 2015.*

| | Natural gas ($/MMBtu) | Crude oil ($/bbl) | HFO ($/MM bbl) | Diesel ($/MM bbl) |
|---|---|---|---|---|
| **Bahrain** | 2.75 | 55.00 | - | - |
| **Kuwait** | 3.53 | 42.10 | 44.43 | 62.73 |
| **Oman** | 2.00 | 55.00 | - | - |
| **Qatar** | 1.50 | 55.00 | - | - |
| **Saudi Arabia** | 0.75 | 4.24 | 2.08 | 3.60 |
| **U.A.E.** | 2.85 | 55.00 | - | - |

Natural gas prices for Oman and Qatar are estimated. For the U.A.E. $2.85 was reported by (Sgouridis et al., 2016). It is assumed Bahrain, Oman, Qatar and the U.A.E. pay an international price for crude oil, assumed here to be $55 per bbl.

#### *2.1.4 Linkage with water sector*

A key feature of the electricity sector in all the countries is the tight linkage between the electricity system and the water sector, given the arid climate and severe water scarcity (Napoli et al., 2018). The water utilities both consume electricity – in reverse osmosis (RO) plants, which use membranes to separate desalinated water from saltwater – and generate electricity with the multi-stage-flash technology, which generates electricity in a first stage and then uses the remaining heat to distill seawater (thermal cogeneration).

Water has the property that it can be stored inexpensively while electricity cannot. Cogeneration links electricity and water production together while water storage means the demand patterns are different (Mezher et al., 2011). Cogeneration plants can adjust the ratio of power to water production to better match the asynchronous demands. In winter, operation occurs at low power-to-water ratios and the plants send steam to the desalination units. Seawater desalination plant capacities are presented in Figure 21. Thermal distillation refers to plants that produce only potable water (no electricity) by boiling seawater.

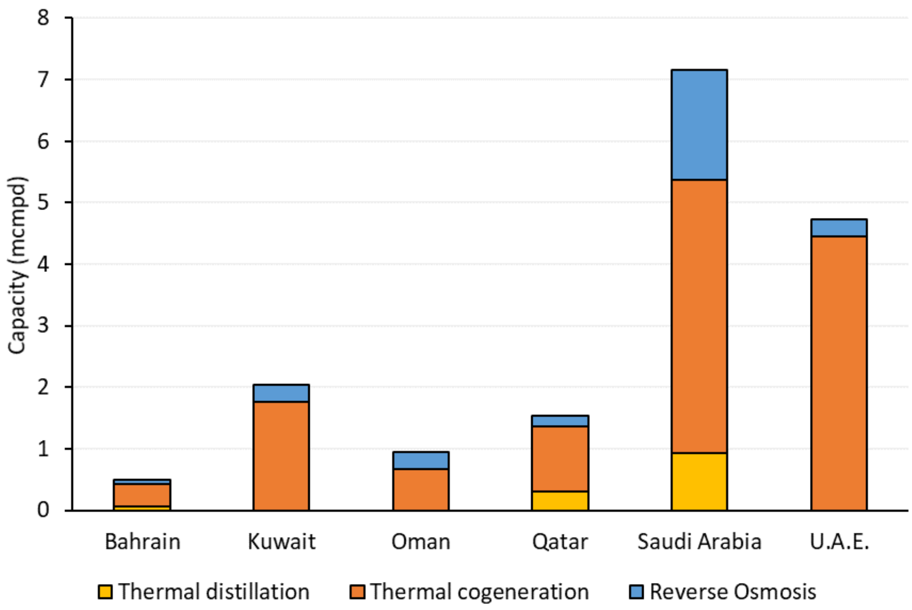



*Figure 21. Water production by technology in million m3 per day.*

Aggregate GCC capacity for water production is nearly 17 million m3 per day, 42 percent of that capacity is in Saudi Arabia alone (ECRA (Electricity & Cogeneration Regulatory Authority), 2015). Nearly two-thirds of GCC water production is produced in conjunction with power. Many of these plants operate as base-load units that produce water and electricity in fixed proportions. Saudi Arabia currently has some cogeneration plants that can control the ratio of power and water produced. More efficient RO plants are less than one-fifth of desalination capacity, with most found in Saudi Arabia. As RO facilities consume electricity instead of producing it, more power generation capacity is needed to meet electricity demand.

### *2.1.5 GCC Interconnector*

The Interconnector consists of a main corridor with feed lines to the individual country systems (Figure 22). Capacities of the linkages are 1200 MW for Kuwait, Qatar, and Saudi Arabia, and 600 MW for Bahrain. The Interconnector backbone does not physically run through the U.A.E. to connect Oman to the system. Instead, the U.A.E. National Grid acts as a bridge to Oman's national grid (Gulf Cooperation Council Interconnection Authority, 2017).

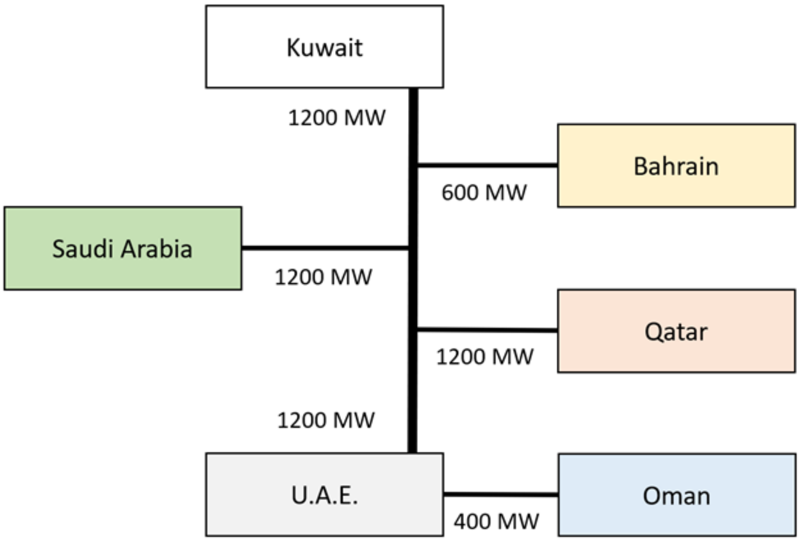



*Figure 22. The GCC Interconnector and capacities.*

There are multiple connection points in Saudi Arabia, but they are modeled as one connection point in the Eastern province.

### 2.2 Existing Estimates of Benefits

The GCCIA reported that it "aims to save more than $33 billion" over the next 25 years through avoided capacity investments, reduced O&M costs and operational reserves. This estimate is equivalent to $1.3 billion average annual savings and is the upper range of estimates publicly available. In a 2015 presentation, the GCCIA CEO reported "$23.6 billion [could be saved through] reduction of fuel and O&M costs for the period 2014 and 2038", which is an average of $940 million annually (Al-Ibrahim, 2015). The presentations do not report on the methodology used, particularly assumptions about fuel subsidies and electricity prices.

In 2016, the GCCIA launched the Power Trade Pilot Program and saw the highest level of energy exchange in its eight-year history. GCCIA waived an estimated $6.6 million in grid utilization fees to spur trade activities. According to the Authority, total exchanges utilizing the Interconnector topped 1.3 TWh at an estimated value of $160 million. According to the GCCIA, this value was calculated using tariffs agreed upon by the member states. In total, GCCIA estimates the Interconnector provided approximately $404 million in value to the member states through avoided capacity investments, fuel and O&M savings, and a reduction in spinning reserve requirements (Gulf Cooperation Council Interconnection Authority, 2017)

## 3. Methodology

The KAPSARC Energy Model for GCC (KEM-GCC) was developed to explore the potential benefits and costs of using the Interconnector for economic exchanges of electricity. KEM-GCC is open source and available to download from GitHub at https://github.com/wogandavid/KEMGCC. The following subsections describe the model formulation, scope, data requirements, and calibration.

### 3.1 Model formulation

KEM-GCC is a partial equilibrium model of three industrial sectors: fuel supply (oil and gas upstream); power production; and water desalination. Each sector is a cost-minimizing (or profit maximizing) agent. The Karush-Kuhn-Tucker (KKT) conditions are derived for each sector and form one integrated mixed-complementarity problem (MCP). The model is formulated as an MCP because the transfer prices for fuels, electricity, and water among sectors are regulated at levels below marginal cost. With this formulation it is possible to model existing fuel pricing policies and perform experiments where prices are formed at the competitive equilibrium. For example, the optimality conditions for fuel costs are equal to the administered price if the inequality is binding. This methodology was previously applied to study the energy-intensive sectors of Saudi Arabia and the role of subsidy reforms described in Chapter 2 and (Matar et al., 2017). A mathematical treatment of using MCP for energy systems modeling is available in Chapter 1 and (Murphy et al., 2016).

### *3.1.1 Fuel supply sector*

The fuel supply sector provides fuel inputs to the power and water sectors. Four fuels are available: crude oil, natural gas, diesel, and HFO. The fuel supply sector can produce fuel from domestic reserves or import and export to the global market. Natural gas is traded intra-regionally via the Dolphin pipeline.

### *3.1.2 Power sector*

The power sector minimizes operating and capital costs to meet exogenous electricity demand. The following technologies are available for operation and deployment in the model: steam turbines, OCGTs, CCGTs, PV, concentrated solar power (CSP), nuclear, and onshore wind. Open cycle gas turbines can be converted to CCGTs. Exogenous electricity demand was discretized into eight hourly loads for two types of days and three seasons for a total of 48 load segments per country. Country specific load curves are presented in Appendix 3B. This segmentation is sufficient to capture the diurnal variation in electricity demand and renewable resource availability while balancing model size and solution time. The power sector can purchase and sell electricity from the water sector.

### *3.1.3 Water sector*

The water sector minimizes operating and capital costs to meet exogenous water demand. Demand is specified along the same 48 load segments as the power sector. Both thermal desalination units in the form of MSF and RO are available technologies.

### *3.1.4 Geographic representation*

KEM-GCC has been updated to include the five remaining GCC countries and the Interconnector link (Figure 22). To capture the geographic dispersion of electricity and water demand, the six GCC states were disaggregated into 12 regions. Bahrain, Kuwait, and Qatar are each represented as individual regions due to their small size. For simplicity, Oman is also considered as a single region even though it has three electricity systems: the Main Interconnected System, which includes Muscat; the Dhofar Power System, which includes Salalah; and the Rural Areas System. Saudi Arabia is divided into four regions (east, west, south, and central) that correspond to the service area definitions of the Saudi Electricity Company (SEC). The U.A.E. is represented as four regions: Abu Dhabi, Dubai, Sharjah, and the Federal Electricity and Water Authority (FEWA), which encompasses the remaining emirates.

### *3.1.5 Power transmission*

Electricity transmission within and between regions is represented using a transshipment formulation. Constructing KEM-GCC as a transmission model could more accurately represent the physics and operation of transmission and is a possible avenue for further research.

## 3.2 Input data

Electricity and water demand are exogenous and based on reports by the respective national authorities for Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (ECRA (Electricity & Cogeneration Regulatory Authority), 2015; Kuwait MEW (Kuwait Ministry of Electricity and Water), 2016a, 2016b; OPWP (Oman Power and Water Procurement Company), 2015; Qatar Ministry of Development Planning and Statistics, 2014; UAE FEWA (United Arab Emirates Federal Electricity & Water Authority), 2015). Hourly power demand data for Bahrain was not obtained. As a workaround, demand was scaled for the eastern region of Saudi Arabia by Bahrain's peak demand. This assumption is reasonable given the geographic proximity, similar climate, and smaller peak load (3.4 GW) for Bahrain.

Technology costs from the U.S. Energy Information Administration (EIA) are used for thermal technologies and International Energy Agency (IEA) costs are used for renewable technologies (presented in Appendix 3A) (U.S. Energy Information Administration, 2017). It is acknowledged that renewable technology costs have fallen since 2015 – especially for solar PV – but given that the scope of this analysis is to present counterfactuals for 2015, published data from IEA is used. A sensitivity analysis is included using a lower capital cost for PV in Appendix 3D, where the benefits of the Interconnector with these costs are estimated.

### *3.2.1 Calibration*

The model was calibrated to closely reproduce fuel consumption and technology utilization reported in 2015 by using administered prices (Table 7). The model was run with a one-year myopic horizon and enforced the technology lead-time requirements. In this configuration, the only technology that can be "built" is a conversion of OCGTs to CCGTs because this activity has no lead-time. The myopic horizon means that the model considers a single year in the discounting the costs of activities instead of over a long-run static equilibrium.

## 3.3 Scenarios

First, a baseline was established using the current policies of each country. The economic surplus was compared with current policies versus complete fuel price deregulation. Economic surplus is defined as the gain in revenue from additional fuel exports and the savings from reduced fuel consumption and avoided capacity investments. Surplus includes a measure of consumer benefits. However, in this case it is presumed that the prices of electricity are fixed and consumer surplus is constant. Deregulation provides an estimate of the largest possible economic surplus. Since complete deregulation is unlikely, alternative regulations and estimate surplus measures were examined, providing the trade-offs between economic efficiency and the degree of government control. As of the time of publication, Saudi Arabia and Qatar have ceased diplomatic relations. For this reason, electricity exchange with Qatar was not included except as a sensitivity analysis.

A description of the six scenarios follows:

1. No Coordination: the baseline scenario where the Interconnector is not used and all current pricing and rationing policies in the GCC countries are retained.

2. Subsidy Exports: investigating the magnitude of fuel subsidies that would be exported. All current pricing and rationing policies in the GCC countries are implemented and electricity can flow through the Interconnector.
3. Fuel Price Deregulation: examining the efficiency gains by setting all fuel prices to marginal costs (or world market prices). Electricity does not flow through the Interconnector.
4. Deregulated Exchange: estimating the gains by setting all prices to marginal costs (or world market prices) and letting electricity flow through the Interconnector.
5. Renewable Exports: devised a scenario that prevents exports of subsidies-by-wire by using current fuel prices and allowing only renewable energy to flow through the Interconnector.
6. Hybrid Pricing: an increase in the quantity of energy that can be exchanged by introducing different prices for domestic consumption and exports. The current prices for domestic consumption are kept while fuel used to produce electricity sent through the Interconnector is charged at marginal cost. The electricity a country sends to the interconnector does not exceed the electricity it generates using unsubsidized fuels. In all countries domestic demand is met through domestic generation or imports.

In all scenarios, Interconnector capacity and energy and water demand were kept at 2015 levels. The baseline and all alternative scenarios reflect a long-run equilibrium where new, more efficient capacity can replace existing capacity (there are no lead times for technology deployment). Nuclear and coal plants were not considered as alternatives because none were deployed in 2015. Specific subsidies are not included for renewable technologies in the model, although in practice, governments have provided policy support, such as preferential financing, which have improved the economics of renewable technologies (Elshurafa, 2017).

The annualized capital cost of newly built capacity is used in calculating the estimated benefits or costs of a policy. The value of fuel savings and added consumption is measured using opportunity costs. For fuels that are imported or exported, the cost is the border price while the cost for fuels not imported or exported is the shadow price (determined endogenously). Table 7 contains the administered prices for fuels by country. A price of $55 per bbl for international oil was assumed. LNG can be imported for $9 per MMBtu and exported at a netback price of $7 per MMBtu.

# 4. Results and discussion

## 4.1 No Coordination: establishing a baseline

In this scenario the utilities do not send electricity through the interconnector.

Modest capacity expansion occurs in this scenario and closely follows the calibration results, showing that the utilities based their capacity decisions on the subsidized fuel prices. Thus, the model provides a reasonable baseline for evaluating policy alternatives. Saudi Arabia converts 3.4 GW of open cycle gas turbines (OCGTs) to combined cycle gas turbines (CCGTs). Unlike in the calibration, Kuwait deploys 2 GW of new thermal desalination capacity. Because fuel prices are kept low, renewables are not cost-competitive and no capacity is added. Electricity production, particularly in Saudi Arabia and the U.A.E., utilizes steam and OCGTs with substantial thermal desalination (Figure 23).

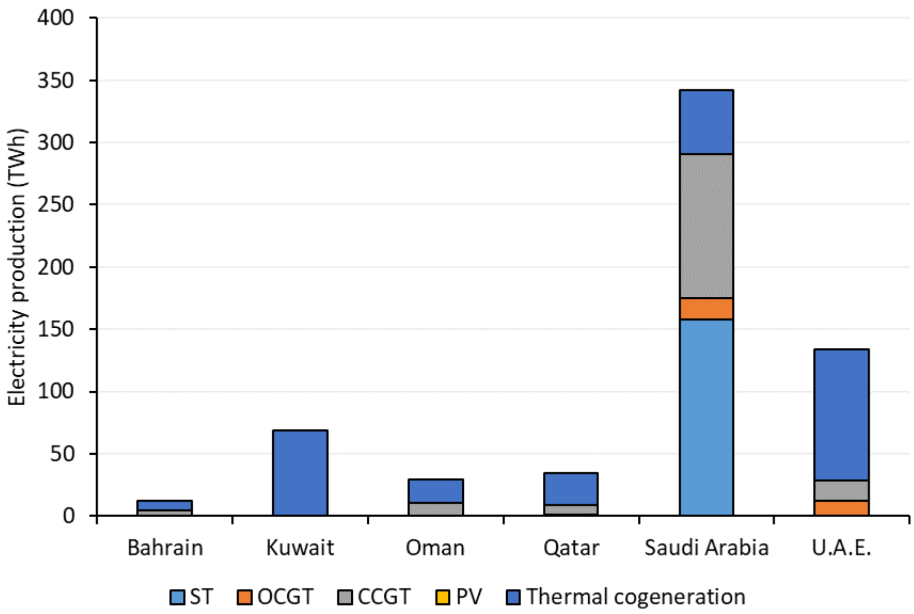



*Figure 23. Electricity production by technology in No Coordination.*

The counterfactual scenarios are assessed against this scenario.

## 4.2 Subsidy exports: the consequences of using the connector without price reform

In the absence of full energy price reform, electricity exports would transfer subsidies from one country to another through exported power generated using subsidized fuels. This is a key barrier to market-based electricity trade in the GCC. To estimate the magnitude of subsidy transfers by wire, the No Coordination scenario was modified by allowing electricity flows between countries with electricity produced at administered fuel prices.

According to the analysis, over 30 TWh of electricity would cross borders (Table 8). In this scenario Saudi Arabia is the largest net exporter of electricity (25.5 TWh), a consequence of having the lowest fuel prices in the GCC. Kuwait is the largest recipient of Saudi Arabian electricity (11.7 TWh), decreasing its consumption of HFO by 40 percent. The U.A.E. cuts LNG imports by 50 percent by importing electricity.

*Table 8. Cross-border electricity flows with subsidy leakage.*

| To / From | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. | *Gross exports* |
|---|---|---|---|---|---|---|---|
| **Bahrain** | | | | - | 0.1 | | 0.1 |
| **Kuwait** | | | | - | | | - |
| **Oman** | | | | - | | 2.8 | 2.8 |
| **Qatar** | - | - | - | - | - | - | - |
| **Saudi Arabia** | 5.8 | 11.7 | | - | | 8.8 | 26.0 |
| **U.A.E.** | | | 1.1 | - | 0.4 | | 1.5 |
| ***Gross imports*** | 5.8 | 11.7 | 1.1 | - | 0.5 | 11.4 | 30.4 |
| ***Net Exports*** | -5.7 | -11.7 | 1.7 | - | 25.5 | -9.8 | |

The outflow of fuel subsidies can be reflected two ways. If the incremental fuel consumed because of Interconnector use were left underground, the value would be the fuel costs incurred by that consumption. The estimate of this outflow of subsidies from Saudi Arabia to be $2.2 billion. This amount is equivalent to the estimate of what is spent on Saudi Arabia's fuel consumption in the No Coordination case. If the incremental fuel were to be exported, the value would be the opportunity cost of foregone exports – an additional $10 billion.

The loss in economic surplus for Saudi Arabia is $4.5 billion. Consequently, restricting the Interconnector to just emergencies makes economic sense with current fuel pricing. For trading to be economic, alternative scenarios for fuel pricing were explored. Fuel-price deregulation with trading offers the largest gain in economic surplus. To understand the value of economic trading separately from fuel-price deregulation, the economic gains with fuel-price deregulation but no trading must first be estimated.

## 4.3 Fuel price deregulation without trading

For this scenario, fuel prices are no longer administered and instead reach values determined by supply and demand. The system, representing all GCC countries, gains $42.6 billion in economic surplus from efficiencies induced by higher fuel prices.

Higher fuel prices drive the deployment of 66 GW of CCGTs and 7.8 mcmpd per day of RO desalination (Table 9). Saudi Arabia sees the largest economic benefit at $32 billion.

*Table 9. Capacity additions in Fuel Price Deregulation for power plants (GW) and RO plants (mcmpd).*

| | OCGT conversion | CCGT new build | PV | *Total Power* | *RO* |
|---|---|---|---|---|---|
| **Bahrain** | | 0.1 | | 0.1 | 0.1 |
| **Kuwait** | | 7.5 | | 7.5 | 0.8 |
| **Oman** | | 4.0 | | 4.0 | 0.2 |
| **Qatar** | 0.1 | 3.1 | | 3.2 | 0.7 |
| **Saudi Arabia** | 3.4 | 40.9 | 12.0 | 56.3 | 3.6 |
| **U.A.E.** | 0.1 | 10.5 | | 10.6 | 2.3 |
| ***Total*** | 3.5 | 66.1 | 12.0 | 81.7 | 7.8 |

CCGTs supply 82 percent of electricity production (Figure 24). Steam turbines and open-cycle gas turbines are used during peak load segments. Close to 50 percent of the existing capacity is replaced by CCGTs. This result reveals the magnitude of inefficiency in the existing electricity system, where substantial steam and open-cycle turbine capacity become too costly to operate (due to their higher heat rates and higher fuel costs).

In Saudi Arabia, with prices increased to global levels, HFO and diesel are no longer consumed for water desalination. At the same time, substantial RO capacity comes online. The water sector continues to produce electricity to run the RO units by consuming methane and a small volume of crude oil. PV becomes the marginal investment as CCGT operation is limited by the methane supply. The other countries do not invest in PV as there are sufficient methane resources to supply CCGTs. This result is sensitive to the solar PV costs in 2015. Appendix 3C shows that the recent cost declines would induce substantially more PV investment (68 GW) and less combined-cycle investment (58 GW).

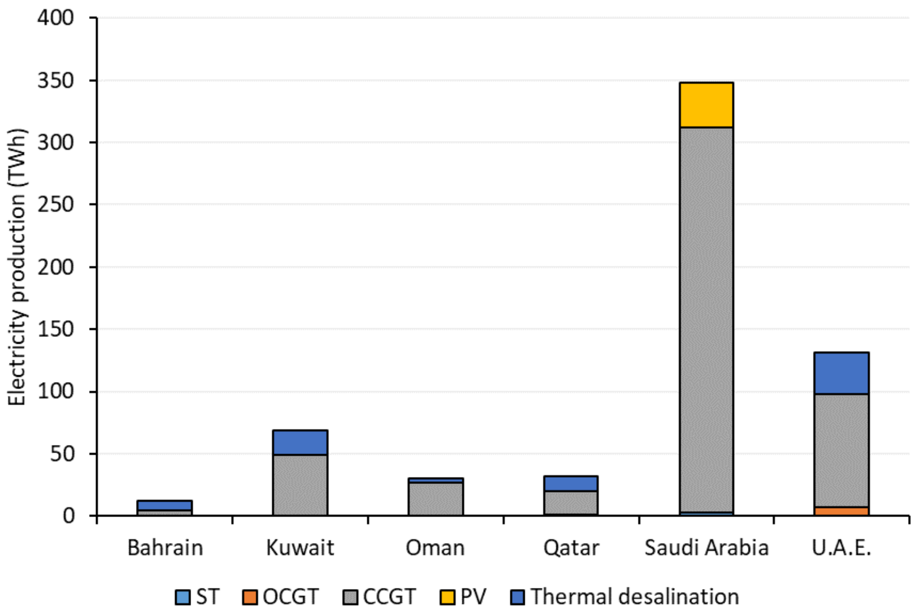



*Figure 24. Electricity production by technology in Fuel Price Deregulation (TWh).*

The power system becomes more flexible with the introduction of RO capacity, which decouples power and water production. This change allows power production to ramp up without an increase in water production. RO capacity can increase or decrease output to meet water demand without requiring changes in cogenerated power.

Electricity production becomes more efficient. Total GCC fuel consumption decreases by 29 percent, driven by the deployment of CCGTs and the substitution of natural gas for oil and oil products. For Oman, Qatar and Saudi Arabia, fuel savings translate directly to an increase in exports (Table 10).

*Table 10. Change in natural gas and crude oil in Fuel Price Deregulation relative to No Coordination.*

| | Natural gas (bcf) | | | Crude oil (MM bbl) | |
|---|---|---|---|---|---|
| | **Consumption** | **Imports** | **Exports** | **Consumption** | **Exports** |
| **Bahrain** | | | | | |
| **Kuwait** | 66.2 | 66.2 | | | |
| **Oman** | -62.3 | | 62.3 | | |
| **Qatar** | -79.8 | | 79.8 | | |
| **Saudi Arabia** | 111.7 | | | -88.5 | 88.5 |
| **U.A.E.** | -201.9 | -213.1 | | | |
| **Total** | -166.0 | -146.9 | 142.1 | -88.5 | 88.5 |
| **Change** | -5% | -36% | 2% | -40% | 4% |

Kuwait offsets HFO consumption by increasing LNG imports. In the U.A.E., fuel savings eliminate the need for LNG imports. Saudi Arabia consumes 37 percent less energy while producing the same quantity of electricity.

## 4.4 Deregulated Exchange: estimating the potential for using the Interconnector with fuels priced at market

Coupling electricity exchange with fuel subsidy removals adds an incremental benefit of $830 million annually for an economic gain of $43.5 billion over the baseline. This scenario can be interpreted as the technically and economically optimal market outcome. The five independent energy systems effectively become one integrated system that meets demand in each region at least cost by coordinating investment decisions and electricity transmission through pricing signals.

It is observed that slightly more electricity could be exchanged when treating the GCC as a single integrated system of five members, leaving out Qatar, with deregulated fuel prices relative to the Subsidy Export scenario (Table 11). The flows reversed with Saudi Arabia becoming a net importer of electricity (28.7 TWh) while Kuwait becomes a net exporter.

*Table 11. Cross-border electricity transmission in TWh in Deregulated Exchange. Totals may not match due to rounding.*

| To / From | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. | *Gross exports* |
|---|---|---|---|---|---|---|---|
| **Bahrain** | | | | | 5.8 | | 5.8 |
| **Kuwait** | | | | | 11.5 | | 11.5 |
| **Oman** | | | | | | 3.5 | 3.5 |
| **Qatar** | | | | | | | |
| **Saudi Arabia** | | 0.2 | | | | 0.1 | 0.2 |
| **U.A.E.** | | | 0.1 | | 11.6 | | 11.6 |
| ***Gross imports*** | | 0.2 | 0.1 | | 28.9 | 3.6 | 32.7 |
| ***Net exports*** | 5.8 | 11.3 | 3.4 | | -28.7 | 8.1 | |

Desalination via RO plants increases electricity demand in Saudi Arabia. This demand is met by CCGTs and 12 GW of newly deployed PV combined with electricity imports (Table 12 and Figure 25). As seen in the Fuel Price Deregulation scenario, the deployment of CCGTs and subsequent electricity production creates a more flexible power system by decoupling power and water production. The capacity additions in Qatar are the result of deregulation without electricity exchange.

*Table 12. Capacity additions in Deregulated Exchange for power plants (GW) and RO plants (bcm). Totals may not match due to rounding.*

| | OCGT conversion | CCGT new build | *PV* | *Total (GW)* | *RO (bcm)* |
|---|---|---|---|---|---|
| **Bahrain** | | 0.8 | | 0.8 | 0.2 |
| **Kuwait** | | 8.5 | | 8.5 | 0.8 |
| **Oman** | | 4.3 | | 4.3 | 0.2 |
| **Qatar** | 0.1 | 3.1 | | 3.2 | 0.7 |
| **Saudi Arabia** | 3.4 | 37.5 | 13.8 | 54.6 | 3.6 |
| **U.A.E.** | 0.1 | 11.7 | | 11.8 | 2.3 |
| ***Total*** | 3.5 | 65.9 | 13.8 | 83.2 | 7.9 |

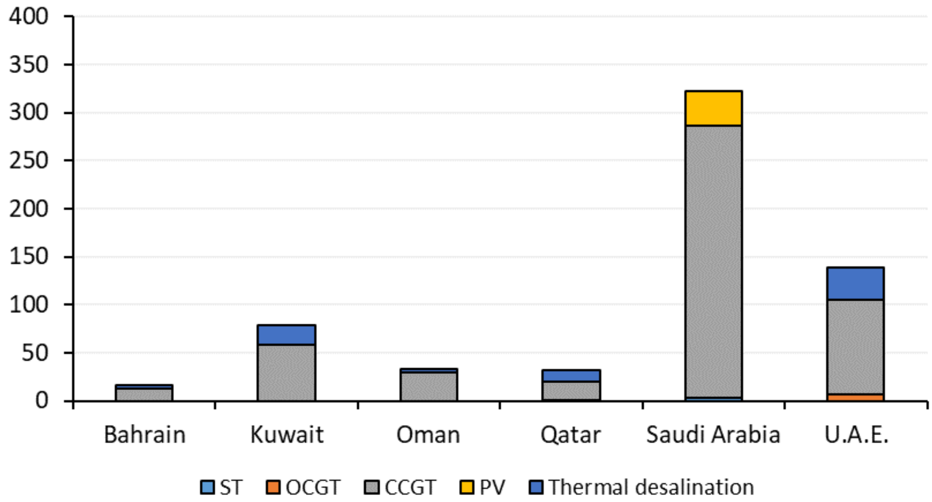



*Figure 25. Electricity production by technology in Deregulated Exchange (TWh).*

Electricity exports from Kuwait to Saudi Arabia are fueled by increased natural gas consumption. Kuwait increases its LNG imports by 130 bcf relative to No Coordination (and 64 bcf over Fuel Price Deregulation) (Table 13). Qatar LNG exports increase because of more efficient power generation.

*Table 13. Change in natural gas and crude oil use between the No Coordination and Deregulated Exchange scenarios.*

| | Natural gas (bcf) | | | Crude oil (MM bbl) | |
|---|---|---|---|---|---|
| | **Consumption** | **Imports** | **Exports** | **Consumption** | **Exports** |
| **Bahrain** | 32.5 | | | | |
| **Kuwait** | 130.2 | 130.2 | | -0.1 | 0.1 |
| **Oman** | -42.6 | | 43.0 | | |
| **Qatar** | -79.8 | | 80.6 | | |
| **Saudi Arabia** | 110.1 | | | -124.6 | 124.6 |
| **U.A.E.** | -160.6 | -160.6 | | | |
| **Total** | -10.3 | -30.4 | 123.7 | -124.7 | 124.7 |
| **Change** | -1% | -7% | 2% | -56% | 3% |

For Saudi Arabia, importing electricity offsets crude oil consumption, which frees 340 thousand bpd for export. From a GCC system perspective, revenue from exporting more crude outweighs the opportunity costs of consuming gas.

### 4.4.1 Deregulated exchange including Qatar

By including Qatar, total cross-border transmission increases to over 44 TWh – an increase of 34 percent from having a deregulated market without Qatar. Saudi Arabia is a net importer of electricity (41 TWh) while Kuwait, Qatar and the U.A.E. become net exporters. Qatar sends 11.6 TWh of gas-by-wire to Saudi Arabia (Table 14).

*Table 14. Cross-border electricity transmission in TWh when deregulating fuel prices and allowing exchange among all GCC countries. Totals may not match due to rounding.*

| From \ To | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. | *Gross exports* |
|---|---|---|---|---|---|---|---|
| **Bahrain** | | | | | 5.8 | | 5.8 |
| **Kuwait** | | | | | 11.5 | | 11.5 |
| **Oman** | | | | | | 3.5 | 3.5 |
| **Qatar** | | | | | 11.6 | | 11.6 |
| **Saudi Arabia** | | 0.2 | | | | 0.1 | 0.3 |
| **U.A.E.** | | | | | 11.6 | | 11.6 |
| ***Gross imports*** | | 0.2 | | | 40.5 | 3.5 | 44.3 |
| ***Net exports*** | 5.8 | 11.3 | 3.4 | 11.6 | -40.5 | 8.1 | |

Saudi Arabia exports an additional 370 thousand bpd when Qatar participates in the GCC exchange (Table 15).

*Table 15. Change in natural gas and crude oil use when Qatar participates in electricity exchange.*

| | Natural gas (bcf) | | | Crude oil (MM bbl) | |
|---|---|---|---|---|---|
| | **Consumption** | **Imports** | **Exports** | **Consumption** | **Exports** |
| **Bahrain** | 32.5 | | | | |
| **Kuwait** | 130.2 | 130.2 | | -0.1 | 0.1 |
| **Oman** | -42.6 | | 42.6 | | |
| **Qatar** | -15.0 | | -15.0 | | |
| **Saudi Arabia** | 109.0 | | | -137.0 | 137.0 |
| **U.A.E.** | -160.6 | -160.6 | | | |
| **Total** | -53.4 | -30.4 | 27.6 | -137.1 | 137.1 |
| **Change** | -2% | -10% | 2% | -62% | 3% |

Economic gain increases by an additional $240 million with Qatar included, for total economic gain of $1.1 billion relative to No Coordination. This value is close to the estimate reported by the GCCIA of around $1.3 billion in annual savings from electricity trade (Gulf Cooperation Council Interconnection Authority, 2017).

These results suggest that including Qatar in electricity exchanges would deliver net economic gains for all countries.

### *4.4.2 Expanding the Interconnector*

Based on this modeling, only 5 percent of total GCC electricity demand would be exchanged with the current Interconnector capacity in Deregulated Exchange. This quantity increases to 180 TWh when capacity expansion is allowed (assuming deregulated fuel prices and incorporating Qatar). The deregulated gas price paid by Qatari generators is greater than the netback price of $7 per MMBtu. Saudi Arabia becomes the largest importer of gas-by-wire from Qatar (113 TWh), which requires an additional 10.5 GW of line capacity between Qatar and Saudi Arabia, or nearly ten times the existing capacity. Within Saudi Arabia, the domestic grid would expand by 75 GW between the East and West regions to accommodate the influx of electricity imports.

Electricity imports substitute for Saudi Arabian electricity production using HFO, diesel and crude oil. As a result, oil exports increase by 610 thousand bpd. While the link between the U.A.E. and Oman is not a dedicated GCCIA line, an additional 1.9 GW of capacity could be added. Adding Interconnector capacity and allowing the export of Qatari gas-by-wire enables an economic gain of $44.6 billion to the GCC (accounting for investment in Interconnector and domestic transmission capacity).

## 4.5 Enable GCC transmission at deregulated prices while retaining the administered prices for domestic sales

The GCC countries might want to maintain low domestic energy prices while exporting electricity to each other. Electricity exports already occur to maintain reliability (Gulf Cooperation Council Interconnection Authority, 2017). Two options are now explored. The first permits exporting electricity produced just from renewable sources. For the second, there is an introduction of a two-tiered fuel price regime where electricity is produced for domestic consumption at administered prices and electricity for export is produced at market prices. Exported electricity is then priced at marginal cost. This hybrid approach is a compromise between retaining the rent transfers from state to citizenry in the form of low-cost energy services and finding higher value uses for fuel resources through electricity exports.

The quantity of cross-border transmission is limited to the quantity of electricity produced from renewable sources and/or fuels at market value. This prevents subsidized electricity from being exported. It is impossible to track or manage individual electrons, but this mechanism is sufficient to distinguish production at different fuel prices and by renewables.

### *4.5.1 Renewable electricity exports*

Saudi Arabia has discussed exporting electricity from its announced utility-scale renewable projects (Abbas and Habriri, 2017). This scenario considers the export of renewable electricity while retaining administered prices for domestic consumers. The analysis finds that Saudi Arabia exports 4.2 TWh of renewable energy to Kuwait. Saudi Arabia invests in 1.5 GW of large-scale PV, but subsidized fuel prices dampen the economic prospects of additional renewable energy deployment. Investment costs contribute to a system-wide economic loss of $70 million. The impact on fuel consumption and imports is marginal because fuel prices are still administered.

### *4.5.2 Hybrid pricing*

Saudi Arabia again is the only net exporter of electricity with 11.7 TWh of exports (out of 11.8 TWh total). Kuwait is the largest recipient (11.7 TWh). The hybrid pricing scheme reduces total electricity exports by over one-third compared to the Subsidy Leakage scenario (Table 16).

*Table 16. Cross-border electricity flows with hybrid pricing.*

| To / From | Bahrain | Kuwait | Qatar | Oman | Saudi Arabia | U.A.E. | *Gross exports* |
|---|---|---|---|---|---|---|---|
| **Bahrain** | | | | | | | |
| **Kuwait** | | | | | | | |
| **Oman** | | | | | | | |
| **Qatar** | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Saudi Arabia** | 0.1 | 11.7 | | | | | 11.8 |
| **U.A.E.** | | | | | | | |
| ***Gross imports*** | 0.1 | 11.7 | | | | 0.1 | 11.8 |
| ***Net exports*** | | -11.7 | | | 11.8 | -0.1 | |

Renewable capacity is not deployed given the low price of domestic electricity. No significant decoupling of the power and water sectors occurs because thermal desalination plants are still economic when consuming subsidized fuels.

This scenario reveals that even with two pricing tiers, subsidies are exported indirectly as electricity. In Saudi Arabia, both gas and crude oil consumption increase. Marginally priced natural gas is consumed for electricity export in CCGTs. CCGT capacity and gas supply becomes fully utilized. Crude oil consumption increases to meet domestic electricity demand and is used on the margin in less-efficient steam and OCGTs (Table 17). Since gas is more heavily subsidized than oil and Saudi Arabia rations gas, the country incurs an economic loss on exports of gas-generated electricity because of the losses from increased oil consumption in inefficient plants and decreased oil exports.

Electricity imports substituted the consumption of HFO and diesel in Kuwait. LNG imports also increase.

*Table 17. Change in natural gas and crude oil use between Hybrid Pricing and No Coordination.*

| | Natural gas (bcf) | | | Crude oil (MM bbl) | |
|---|---|---|---|---|---|
| | **Consumption** | **Imports** | **Exports** | **Consumption** | **Exports** |
| **Bahrain** | 1.3 | | | | |
| **Kuwait** | 74.3 | 74.3 | | -0.1 | 0.1 |
| **Oman** | -0.2 | | | | |
| **Qatar** | | | | | |
| **Saudi Arabia** | 103.7 | | | 1.5 | -1.5 |
| **U.A.E.** | 0.1 | 0.1 | | | |
| **Total** | 178.2 | 74.1 | | 1.4 | -1.4 |
| **Change** | 5% | 18% | | 1% | |

Economic surplus increases by $80 million relative to No Coordination for a gain of $150 million than the renewable-only exchanges. This scenario shows how hard it is to wall off subsidized markets and allow deregulated transactions.

## 4.6 Total system costs

As seen in the results above, there are countries that gain economically from the export or import of electricity. The costs and gains for each country in each scenario are computed. The net gain is calculated as the revenue from fuel exports net of capital investment less fuel imports and operation and maintenance costs. Capital costs are discounted over the lifetime of the equipment. The revenue and effects of exporting and importing electricity are included in the calculation. The net effect is observed at a country level and net out at a regional system level.

The incremental gains of each scenario relative to the No Coordination Scenario are presented in Table 18.

*Table 18. Incremental gains relative to No Coordination scenario (in billion 2015 U.S. dollars).*

| | Subsidy Export | Fuel Price Deregulation | Deregulated Exchange | Renewable Exports | Hybrid Pricing |
|---|---|---|---|---|---|
| **Bahrain** | 0.1 | 0.5 | 0.6 | | |
| **Kuwait** | 0.5 | 1.4 | 1.5 | 0.2 | 0.4 |
| **Oman** | -0.1 | 1.5 | 1.5 | | |
| **Qatar** | | 2.2 | 2.2 | | |
| **Saudi Arabia** | -4.5 | 32.0 | 32.6 | -0.2 | -0.3 |
| **U.A.E.** | 1.0 | 5.0 | 5.1 | | |
| **Total System** | **-3.1** | **42.6** | **43.5** | **< -0.1** | **< 0.1** |

The bulk of the gains ($42.6 billion) are the result of subsidy removal, which induces investment in and operation of more efficient technologies. The incremental gain of adding electricity exchange on top of fuel price deregulation is $830 million for a total of $43.5 billion in annual economic surplus. Saudi Arabia realizes the largest gain because it substitutes expensive electricity production from crude oil (in terms of opportunity cost) with electricity imports and more efficient utilization of natural gas. Although the U.A.E. also exports electricity, the newly deployed CCGTs provide efficiency gains that both lower its production costs and contribute to higher export revenues. Including Qatar increases the economic gain by an additional $240 million for a total annual gain of $1.1 billion.

For comparison, the estimated total economic gain of $43.5 billion is much larger than the value published by the GCCIA, which expects an estimated annual average savings of $1.3 billion over the next 25 years. One explanation is that the GCCIA estimates do not fully capture the gains from subsidy removal, which are substantial, as shown by this analysis, which considers the structural shifts induced by fuel subsidy removal, and specifically incudes the opportunity cost of fuels. A detailed analysis of the GCCIA methodology would be needed to put the results in a comparable basis.

The incremental change is positive, which suggests the value of a policy package consisting of fuel price deregulation in conjunction with coordination. An important result is that each country sees a gain. This means there are no winners and losers. In the language of cooperative game theory, the game has a core because all countries have an incentive to participate. Given that the results are for single year static counterfactuals, larger gains are possible over a multi-year horizon.

## 5. Conclusions

The analysis finds that domestic fuel subsidies are the key economic barrier to regional electricity exchanges from which all the member countries benefit. In the absence of subsidy removal across the region, Saudi Arabia would export $12.2 billion (in real 2015 U.S. dollars) in subsidies-by-wire annually as other GCC countries purchase low-priced electricity generated with subsidized fuels.

The bulk of the annual economic benefit results from removing fuel subsidies: $42.6 billion. From a consumer perspective, the foregone subsidies could be returned as an equivalent income transfer, while achieving the benefits of trade. The economic gain increases by $1.1 billion annually when coupling subsidy removal with electricity exchange. Over 5 percent (33 TWh) of GCC electricity production would be exchanged at market prices. The U.A.E., Kuwait, and Bahrain are the largest net exporters, while Saudi Arabia becomes the largest net importer of electricity (28.7 TWh) – equivalent to 8 percent of its demand.

Substantial investment would accompany these exchanges. Over 50 percent of existing capacity would be replaced by more efficient combined-cycle gas turbines and utility-scale PV at a cost of $7.3 billion. As discussed in Appendix 3C, lower PV capital costs would drive up to 68 GW of investment in the GCC and increase aggregate economic gain to $46 billion while reducing the benefits of exchanges to $800 million.

A significant aspect of the capacity shift is the replacement of electricity/water cogeneration plants with water production switching to reverse osmosis. The thermal cogeneration plants make the electricity systems less flexible because of the need to produce water. Retiring thermal cogeneration plants and replacing them with combined-cycle plants and reverse osmosis plants increases the flexibility of the national grids and allows them to take advantage of the interconnection. Indeed, this is happening in the GCC.

The important lesson from increasing the use of the Interconnector before tackling deregulation is that in moving from current highly regulated systems to a more market-based approach on a piece-meal basis can increase costs without the proper sequencing of policy changes. The Interconnector can provide substantial economic benefits; however, the conditions must be right for the benefits to be realized.

Like Chapter 2, this chapter did not consider $CO_2$ emissions. The static analysis performed in this chapter does not capture the stock and flow dynamics of $CO_2$ emissions. Chapter 4 combines the approach developed in the previous chapter with the electricity exchange developed in this chapter to represent the dynamic aspects of $CO_2$ emissions in the context of price reforms and electricity exchange.

The next phase of the analysis explores the potential for electricity exchange over multiple years (Chapter 4). This provides insight into evolution of the GCC power system by considering technology lead times and growth in energy and water demand. Chapter 4 incorporates the decline in PV costs and ongoing and planned renewables and nuclear projects in the GCC with an emphasis on the impact of $CO_2$ externalities.

# Chapter 4. A multi-period analysis of economic interventions and electricity exchange on power sector $CO_2$ emissions.


## Abstract

The Gulf Cooperation Council (GCC) economies are energy-intensive and face a challenging and uncertain future in an increasingly carbon constrained world. The power and water sectors are particularly carbon intensive. GCC countries have strategies to decarbonize through national development plans and nationally determined contributions (NDCs) through the Paris Agreement process. This study investigates policy packages specific to the GCC countries with respect to decarbonizing the power and water sectors and quantifies benefits that regional coordination could bring to achieve decarbonization aspirations through 2030. To do so, this study builds on the analyses of administered price reform in Saudi Arabia (Chapter 2) and electricity exchange in the context of administered prices (Chapter 3). Unlike those two chapters, Chapter 4 explicitly investigates $CO_2$ emissions as part of a combined policy package. Three policy measures are considered, individually and in combination: removing fuel price and quota controls (deregulation); a time-varying carbon price; and increased electricity exchange utilizing the GCC Interconnector. The time-varying carbon price starts at \$5 per tonne of $CO_2$ in 2019 and increases by \$5 per tonne to reach \$60 per tonne in 2030.

Simulation results show that combining the three policy measures together reduces the most $CO_2$ emissions while delivering substantial economic gain to all GCC countries. However, this policy package is only marginally more effective at reducing emissions than removing controls on fuel prices and quantities, even in the absence of electricity exchange and a carbon price. Electricity exchange offers marginal emissions reductions when coupled with deregulation and higher emissions when retaining interventions, due to an expansion of coal-fired capacity. The findings suggest that electricity exchange in the GCC Common Market could lead to increased emissions and work counter to some GCC country's goals for decarbonization, regardless of ongoing energy price reform initiatives in some GCC countries. Regional energy and climate cooperation in the GCC are technically and economically possible under the auspices of Article VI of the Paris Agreement as demonstrated by this analysis. GCC countries can consider this mechanism for future NDC development and national planning activities. The largest economic gain results from a policy package of electricity exchange coupled with removing fuel price and quantity controls.

The model is a partial-equilibrium model covering the upstream, power, and water desalination sectors for each of the six GCC countries and formulated as a mixed-complementarity problem. This formulation enables analysis of quotas and fixed transfer prices between sectors, representative of government interventions in these sectors. The model is solved recursively in annual time steps between 2015 and 2030. The methodology and findings are relevant for other countries and regions of the world where government intervention in the power sector results in economic inefficiencies.


## 1. Introduction

The Gulf Cooperation Council (GCC) economies face a challenging and uncertain future in an increasingly carbon constrained world. Concerns about climate change are prompting energy exporting countries to reexamine their role in the future global economy. The GCC economies are energy- and carbon-intensive for two reasons. Their comparative advantage in world markets are energy-intensive industries, including oil production and refining and bulk petrochemicals. They share the hydrocarbon wealth with their citizens through providing energy at subsidized prices. At the same time, they There is real concern about the peak in demand for commodities like oil. These concerns are amplified when considering the potential for a peak in demand for carbon-intensive commodities. Thus, the approach to the UN-sponsored climate negotiations by the GCC economies is one of economic diversification with climate co-benefits. It is here that domestic reforms could have substantial ramifications on international oil and gas markets. Specifically, incentivizing more efficient technologies for electricity and water production in the GCC could provide economic gains for the domestic national accounts while reducing the carbon-intensity of economic activity. Reductions in domestic oil and gas consumption expand their export capacity.

Subsidies for industrial fuel inputs have incentivized inefficient investments for electricity production, while subsidized tariffs have led to high per capita domestic consumption. In a low oil price regime, subsidies have become an increasing burden on national finances, prompting economic diversification programs.

In recent years, the GCC countries have invested in a network of high-voltage transmission lines, known as the GCC Interconnector (heretofore referenced as the Interconnector), which links the member states of Saudi Arabia, Bahrain, Kuwait, Oman, Qatar and the United Arab Emirates (shown in Figure 26 as thick black lines). The Interconnector is envisioned as a platform to facilitate coordination in electricity generation among the GCC countries that would support the ongoing economic reform initiatives. Completed in 2011, the Interconnector has enabled the in-kind exchange of electricity among member states to maintain system reliability (Gulf Cooperation Council Interconnection Authority, 2017). While the Interconnector has successfully provided reliability services to GCC countries, it has not yet realized its full potential as a platform to fully integrate the individual electricity systems.

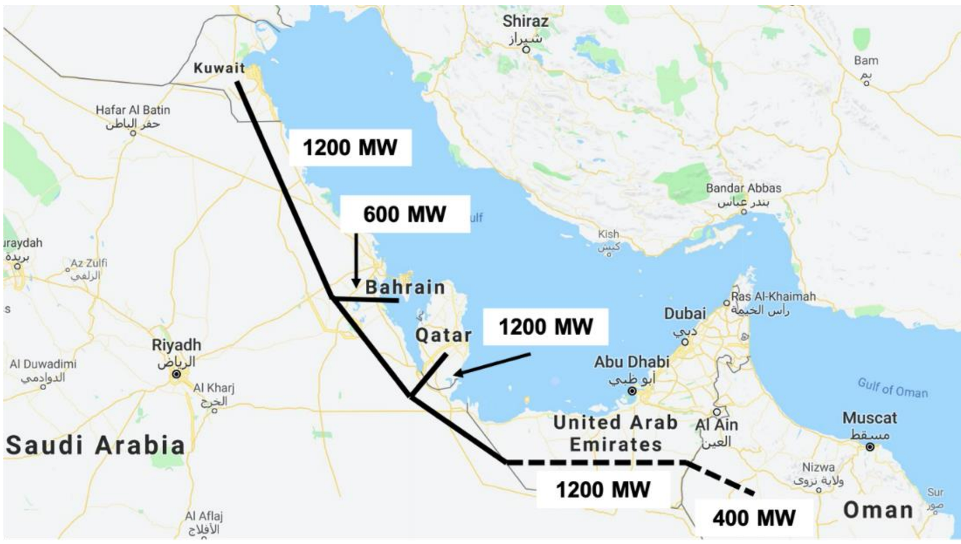



*Figure 26. GCC Interconnector.*

Under the right circumstances, the GCC countries could benefit from more coordinated electricity production as the countries have non-coincident peaks in electricity demand.

However, the link has not provided the full benefits of integrating the individual grids of the member countries because of the structure of the electricity and water sectors in each country.

Low administered prices on fuels used for electricity generation, which vary by country, are a key barrier to regional movements of electricity because it is not likely that a country wants to incur the costs of exporting the value of its subsidies. Without reforming these prices or designing a market mechanism to account for the full cost of electricity production, any electricity sold across borders means the exporting country subsidizes consumers in the importing countries. These subsidies cannot be recouped because a large portion of the subsidies are provided before the point of delivery. Fuel subsidies are virtually impossible to trace and recapture because system wide effects on investment and operations are not measured in standard accounting systems. Thus, the current structures of domestic markets are a barrier to cross-border exchange.

In this context, this study examines the economic, technical efficiency, and environmental gains that could be obtained by removing economic barriers to electricity production in the GCC. This study considers the role that electricity exchange can play in aiding or hampering the gains, and in turn, how these actions could contribute to the decarbonization ambitions in the GCC and counterbalance some of the costs of other $CO_2$ mitigation policies.

This paper begins with a review of relevant economic reforms that relate to the power and water sector and discusses decarbonization targets and goals at the country level. In Section 3, the analysis methodology is presented with a discussion on the model formulation and the nine core scenarios. In Section 4, the data sources and assumptions are presented. Section 5 contains the discussion of the analysis in terms of investments of technologies, fuel consumption, and economic gains. A suite of sensitivity analyses is presented at the end of this section. Finally, the key findings and policy recommendations are summarized in the Conclusion. Additional detail on the assumptions are presented in the Appendices.

## 1.1. Ongoing policy reforms and decarbonization efforts

Currently, with the reduction in government revenues from hydrocarbon exports, all GCC member nations are in the process of diversifying their economies. These reforms affect the power and water desalination sectors because they are major domestic consumers of oil and gas resources. Furthermore, these sectors are also large contributors to carbon dioxide ($CO_2$) emissions. This section reviews the key policy initiatives for economic reform and decarbonization in each of the GCC countries. The policies are shown in Table 19 and are described in more detail below. Three key indicators are provided to put the policies in context. Energy intensity (EI) is a measure of the amount of energy consumed per unit of economic activity in mega-Joules (MJ) per 2011 USD (The World Bank, 2020a). Carbon intensity (CI) is the amount of $CO_2$ emissions per unit of activity, expressed in kg per PPP of GDP (The World Bank, 2020b). Absolute $CO_2$ emissions in 2014 are expressed in million tonnes (The World Bank, 2020c).

*Table 19. Summary table of relevant power and water sector planning and decarbonization policies*

| Country | Relevant Documents | Measures | Key Indicators |
|---|---|---|---|
| Bahrain | National Renewable Energy Action Plan<br>Economic Vision 2030<br>Nationally Determined Contribution | Renewable energy target of 5% (2025) and 10% (2035)<br>$CO_2$ reduction by 0.392 million tonnes per year | EI = 9.8<br>CI = 0.51<br>Emissions = 31 |
| Kuwait | Nationally Determined Contribution<br>Kuwait Statistical Year Book, 2018 | 15% generation from renewables by 2030 | EI = 5.0<br>CI = 0.34<br>Emissions = 95 |
| Oman | Nationally Determined Contribution | Increased share of renewable energy<br>Adopt low-carbon and high-efficiency technologies | EI = 6.3<br>CI = 0.36<br>Emissions = 61 |
| Qatar | Nationally Determined Contribution | No specific measures | EI = 6.4<br>CI = 0.36<br>Emissions = 108 |
| Saudi Arabia | Nationally Determined Contribution | 130 million tonnes per annum reduction by 2030 (contingent on oil exports) | EI = 5.8<br>CI = 0.37<br>Emissions = 601 |
| U.A.E. | Nationally Determined Contribution<br>National Climate Change Plan<br>UAE Vision 2021<br>UAE National Energy Strategy 2050<br>Dubai Clean Energy Strategy 2050 | 27% clean energy mix by 2021;<br>50% clean power generation by 2050;<br>Abu Dhabi: 7% renewable energy by 2020;<br>Dubai: 7% (2020), 25% (2030), 75% 2050 | EI = 5.3<br>CI = 0.35<br>Emissions = 211 |

### *Bahrain*

Bahrain consolidated its renewable energy and efficiency activities under the Sustainable Energy Unit in 2014. The National Renewable Energy Action Plan contains the Kingdom's energy, efficiency, and climate initiatives. Bahrain set renewable energy capacity target shares of 5% by 2025 and 10% by 2035 (Sustainable Energy Unit Kingdom of Bahrain, 2017). The drivers for Bahrain are noted as energy self-sufficiency. The kingdom's power and water sectors rely solely on natural gas. Renewable energy is thus an effort to reduce dependence on imported gas. Bahrain's INDC frames its actions as economic diversification activities with climate co-benefits (Kingdom of Bahrain, 2015). Only the renewable energy targets are considered in this analysis.

### *Kuwait*

Kuwait relies heavily on oil, oil products, and to a lesser extent, natural gas for its power and water production. Total energy related activities produce 95% of the country's GHGs (State of Kuwait, 2015). No specific $CO_2$ reduction targets are mentioned in the INDC, except that Kuwait will work towards a lower carbon economy relative to a business-as-usual scenario between 2020 and 2030. Among mitigation activities, Kuwait's INDC and latest statistical publication notes renewable energy as one aspect of a broader plan. Kuwait plans to produce 15% of total electricity from renewable energy in 2030, estimated to be between 4,500 - 5,000 megawatts

(MW) (Kuwait MEW (Kuwait Ministry of Electricity and Water), 2018a). As in other GCC countries, concerns about rising demand and reliance on domestic resources is driving plans to diversify domestic power mixes.

### *Oman*

The country plans to add both coal-fired generation and renewable capacity through 2030. According to a presentation by the Oman Power and Water Procurement Company, created in 2005 when Oman unbundled the electricity sector, Oman has a renewable production target of 10% by 2025 and expects that contribution of renewables might reach as high as 20% by 2030, although it has not set such a target. At the same time, Oman plans to add 3.0 gigawatts (GW) of coal-fired capacity by 2030 – about 40 percent of existing generation capacity (OPWP (Oman Power and Water Procurement Company), 2019). According to Oman's INDC, the country will slow emissions growth by 2% between 2020 and 2030, a reduction around 1.8 thousand tonnes from estimated to be around 9.0 thousand tonnes.

### *Qatar*

The State of Qatar positions its climate change actions as "economic diversification with mitigation" through energy efficiency and clean energy and renewables, which includes natural gas (State of Qatar Ministry of Environment, 2015). The submission notes interest in renewable energy but cites lack of access to technology. No specific $CO_2$ reduction targets or pathways are mentioned.

### *Saudi Arabia*

Saudi Arabia is reforming its electricity sector in order to meet rising power demand, reduce its expenditure on energy subsidies and diversify its economy in support of the objectives of Vision 2030 and the National Transformation Program (The Kingdom of Saudi Arabia, 2015). The Kingdom's objective is to move away from an energy economy based on regulated fuel prices to a system with fuel prices more closely aligned with international prices, through a series of fuel price reforms.

Saudi Arabia introduced its first set of fuel price increases at the end of 2015 (see Table 23). With prices still well below international benchmarks, Saudi Arabia's 2018 budget set targets for the gradual alignment of domestic fuel prices with international prices by 2025, including petrol and diesel. Petrol and diesel prices are adjusted quarterly to align with global oil price benchmarks. In January 2018, all electricity tariffs except for industry and government were raised (Faeq, 2019). Prices have not increased since then (Wogan, 2020a).

Saudi Arabia is planning to eliminate the consumption of crude oil in the power sector by investing in natural gas and renewable capacity (primarily onshore utility-scale PV and wind)(SEC (Saudi Electricity Company), 2018).

Saudi Arabia's NDC is based on a dynamic baseline representing a combination of two scenarios:

- Scenario 1: Robust oil export revenues in support of an increasingly diversified economy.
- Scenario 2: Domestic utilization of oil and gas in support of accelerated domestic industrialization.

The primary difference in the scenarios is whether oil is allocated for export (Scenario 1) or domestic consumption (Scenario 2). Scenario 1 is designed so that oil revenues (from export) are used to fund economic growth and diversification. These activities would have a co-benefit of avoiding up to 130 million tonnes of $CO_2e$ annually by 2030 compared to a business-as-usual scenario. The baseline assessment period is 2021-2030, to be extended over time to 2050. However, the business-as-usual scenario has not been defined, at least in public documents. Scenario 2 can be interpreted as a fall back scenario, in which case the NDC would need to be rewritten to accommodate the increased emissions from continued energy-intensive economic activities (Wogan et al., 2019a).

### *U.A.E.*

The United Arab Emirates released a national strategy to diversify and decarbonize its power generation mix (United Arab Emirates Ministry of Energy & Industry, 2019). The strategy calls for a switch from nearly all electricity produced from natural gas to a capacity mix of 44% renewable energy, 38% natural gas, 12% clean coal, and 6% nuclear by 2050. The strategy is rooted in reducing government expenditures on energy and energy services in the face of projected growth in electricity demand, while contributing to government's objective to become self-sufficient in natural gas supply (Dey, 2018).

The U.A.E. has formalized its climate change goals and policies under the National Climate Change Plan (hereafter referred to as the "Climate Plan"), which underpins the country's NDC. At a high level, the Climate Plan contains objectives to mitigate GHG emissions, increase resilience through adaptation, and to diversify the economy to non-oil sectors (Ministry of Climate Change and Environment, 2017). Of note, the U.A.E. has a short-term goal for 27% clean energy mix by 2021 and a long-term target for 50% clean power generation by 2050 (United Arab Emirates, 2020). At the emirate level, Abu Dhabi is targeting 7% renewable energy by 2020. Dubai has the same target for 2020, increasing to 25% by 2030, and 75% by 2050 (United Arab Emirates, 2019).

## 1.2. GCC Interconnector

The Interconnector is positioned as a platform for a common GCC electricity market called the Gulf Common Market, set to launch in 2020 (United Arab Emirates Ministry of Energy & Industry, 2019). It is managed by a Gulf Cooperation Council Interconnector Authority (GCCIA), a joint-stock company subscribed by the six GCC states (Gulf Cooperation Council Interconnection Authority, 2020a). Prior to 2016, the Interconnector was used for both unscheduled and scheduled exchanges. Electricity exchanges from 2010 through 2019 are charted in Figure 27. Unscheduled exchanges represent emergency situations where electricity is needed from another country to maintain system reliability. Most of the exchanges were scheduled, meaning that electricity was sent from one country to another in one part of the year, and an equivalent amount was returned later in the year.

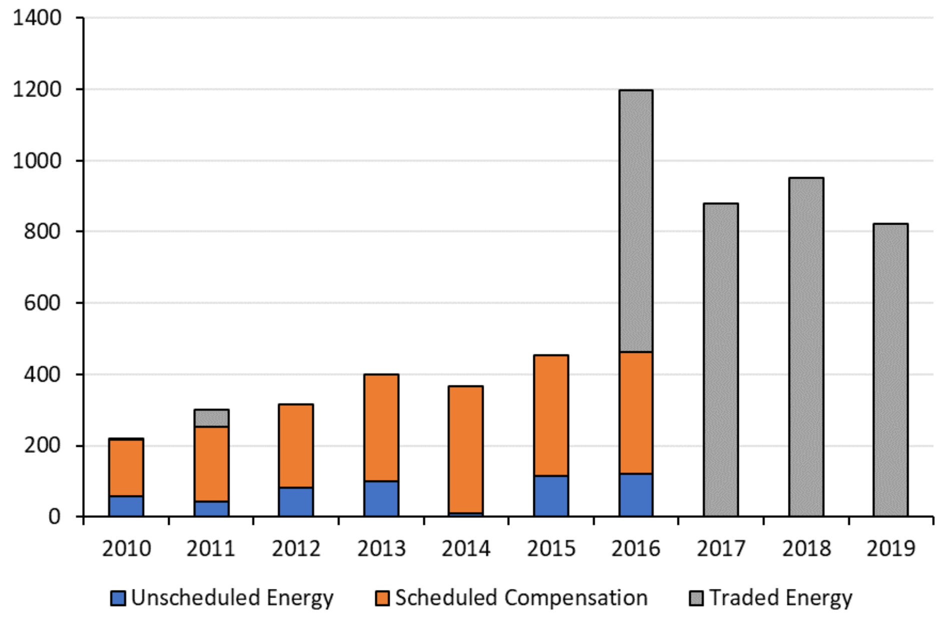



*Figure 27. Reported electricity exchange on the GCC Interconnector in GWh.*

In 2016, the GCCIA launched the Power Trade Pilot Program and saw the highest level of energy exchange in its eight-year history (Gulf Cooperation Council Interconnection Authority, 2020b). GCCIA waived an estimated $6.6 million in grid utilization fees to spur trade activities. According to the Authority, total exchanges utilizing the Interconnector approached 1.2 TWh at an estimated value of $160 million. According to the GCCIA, this value was calculated using tariffs agreed upon by the member states. In total, GCCIA estimates the Interconnector provided approximately $404 million in value to the member states through avoided capacity investments, fuel and O&M savings, and a reduction in spinning reserve requirements.

## 1.3. Literature review

In the GCC region, substantial literature exists for the role of energy subsidies and economic impacts. Lahn & Stevens (2011) at Chatham House explored the role of continuing domestic oil consumption in Saudi Arabia. They extrapolated domestic energy consumption and concluded that Saudi Arabia could become an oil importer by 2038 (Lahn and Stevens, 2011). This study led to a quantitative analysis of subsidy reforms in Saudi Arabia by KAPSARC that found that subsidy reforms could lead to more efficient investments in the Saudi Arabian power sector (Matar et al., 2015). Bassam Fattouh of the Oxford Institute for Energy Studies explored energy subsidy reforms separately in Kuwait and Saudi Arabia. Boersma & Griffiths (2016) summarized ongoing fuel subsidy and consumer tariff reforms in the U.A.E. (Boersma and Griffiths, 2016; Fattouh and El-Katiri, 2013). Recently, Shehabi (2020) investigates economic diversification in Kuwait and finds that "constraints and distortions [in the country] impair structural change" and relaxing these can enable economic efficiency – a key finding supported in this analysis (Shehabi, 2020).

There are fewer investigations on gains from electricity exchange in the GCC region. The GCCIA commissioned a study on potential savings from electricity trade. The GCCIA reported that it "aims to save more than $33 billion" over the next 25 years through avoided capacity investments, reduced O&M costs, and operational reserves. This estimate is equivalent to $1.3 billion average annual savings and is the upper range of estimates publicly available (Gulf

Cooperation Council Interconnection Authority, 2017). In a 2015 presentation, the GCCIA CEO reported "$23.6 billion [could be saved through] reduction of fuel and O&M costs for the period 2014 and 2038", which is an average of $940 million annually. The presentations do not report on the methodology used, particularly assumptions about fuel subsidies and electricity prices. More recently, the GCCIA website provides updated estimates: "the potential for power trading during 2015 was more than US$ 500 million and the more than US$ 25 billion (Net Present Value) for the 25-year horizon. In the year 2016, the power trading volume in GCC region has already registered 1,320,000 MWh with participation of five of the six member states in trading activity and concluding more than 15 contracts." (Gulf Cooperation Council Interconnection Authority, 2020b)

Previous research by the author shows that around $1 billion in economic gain could be realized by the GCC countries through coordination via electricity exchange when considering the underlying economic distortions of energy production in the GCC. This study extends that analysis by projecting investments and savings through 2030.

## 2. Methodology

This section describes the custom model developed for this analysis. A custom model rather than a conventional cost-minimizing linear program is required for the type of economic system present in the GCC countries. The derivation of a generalized MCP framework for an energy system is presented in Chapter 1. The rationale and formulation are described below.

### 2.1. KAPSARC Energy Model – GCC

KEM-GCC is a partial equilibrium model of three industrial sectors: fuel supply (oil and gas upstream); power production; and water desalination. Each sector is a cost-minimizing (or profit maximizing) agent. The fuel supply sector provides fuel inputs to the power and water sectors. Four fuels are available: crude oil, natural gas, diesel, and HFO. The fuel supply sector can produce fuel from domestic reserves or import and export to the global market.

The power sector minimizes operating and capital costs to meet exogenous electricity demand. The following technologies are available for operation and deployment in the model: steam turbines, open-cycle gas turbines (GT), combined-cycle gas turbines (CCGT), coal-fired plants, utility-scale photovoltaics (PV), concentrated solar power (CSP), nuclear, and onshore wind. Offshore wind is not being considered by any GCC country. Open cycle gas turbines can be converted to CCGTs. I discretize exogenous electricity demand into eight hourly loads for two types of days and three seasons for a total of 48 load segments per country. This segmentation is sufficient to capture the diurnal variation in electricity demand and renewable resource availability while balancing model size and solution time. The power sector can purchase and sell electricity from the water sector. The water sector minimizes operating and capital costs to meet exogenous water demand. Demand is specified along the same 48 load segments as the power sector. Both thermal desalination units in the form of multi-stage flash (MSF) and reverse osmosis (RO) are available.

The GCC is divided in to 12 sub-regions to facilitate the modeling of national and subnational policies and dynamics in the energy system. Bahrain, Kuwait, Oman, Qatar are modeled as single sub-regions. In Saudi Arabia, the definitions by the electricity regulator are used: eastern, western, central, and southern. In the U.A.E., the regulatory definitions are used: Abu Dhabi, Dubai, Sharjah (SEWA), and the Federal Electricity and Water Authority (FEWA), which covers the remaining less populated emirates.

The model is formulated as a mixed-complementarity problem (MCP) and not a linear program. The MCP formulation is necessary because the transfer prices for fuels, electricity, and water among sectors are regulated at levels below marginal cost. With this formulation it is possible to model existing fuel pricing policies and perform experiments where prices are formed at the competitive equilibrium. A mathematical treatment of using MCP for energy systems modeling is available in Murphy et al., 2016.

This methodology was originally developed to study the energy-intensive sectors of Saudi Arabia and the role of subsidy reforms (Matar et al., 2017). The methodology was extended to assess the role of subsidies in impeding the utilization of the GCC countries, but only for a single time period (Wogan et al., 2019b). For this analysis, the model was developed further to assess the dynamics of investment and operation decisions, as discussed in the next subsection.

The mathematical formulation is presented below. Technical constraints like those guaranteeing uptime or capturing ramp-up and ramp-down requirements are omitted for clarity. The sets and parameters in the equations are in Table 20, followed by the endogenous variables in Table 21.

*Table 20. Sets and parameters.*

| | |
|---|---|
| $z$ | Sector objective value |
| $t$ | Time step |
| $r, rr$ | Set of regions (to, from) |
| $c, cc$ | Set of countries (to, from) |
| $f$ | Set of fuels |
| $p$ | Set of technologies |
| $d_t$ | Discount coefficient |
| $C$ | Capital cost of a technology |
| $c$ | Annualized capital cost |
| $i$ | Sector discount rate |

*Table 21. Endogenous variables.*

| | |
|---|---|
| $Fuel\ Consumption_{p,f,t,r,c}$ | Fuel consumption |
| $Capacity\ Build_{p,t,r,c}$ | New capacity investments |
| $Electricity\ Production_{p,f,t,r,c}$ | Electricity production activity |
| $Electricity\ Exchange_{t,r,c,rr,cc}$ | Electricity exchange from $r$ to $rr$ |
| $Fuel\ Imports_{f,t,r,c}$ | Fuel imports |
| $Fuel\ Exports_{f,t,r,c}$ | Fuel exports |

*General formulation*

Each sector is first constructed as a linear program with an objective function that minimizes a sum of the capital, O&M, and fuel consumption costs. The objective function for the power sector is shown in Equation 13.

*Equation 13. Objective function.*

$$\min_{endogenous\ variables} z = \sum_{t} \{Total\ Capital\ Cost_t + Total\ O\&M\ Cost_t\} * d_t + \sum_{t,p,f,r,c} \{Administered\ Fuel\ Price_{f,t,r,c} * Fuel\ Consumption_{p,f,t,r,c}\} * d_t$$

where the discount coefficient $d_t$ is a function of operational life by technology, discount rate, current period, and the myopic horizon. The myopic horizon is discussed below.

The costs are accounted for in Equation 14 and Equation 15. Total capital cost is the amount of investment required in time step $t$ based on the discounted capital cost of a technology and the amount of capacity built by the model. The discounting is expressed in Equation 24. Capacity built by the model is a sum of both endogenous and exogenous build activities and is carried over to the next time period (Equation 16).

*Equation 14. Investment balance.*

$$Total\ Capital\ Cost_t = Capital\ Cost_{p,t,r,c} * Capacity\ Build_{p,t,r,c}$$

*Equation 15. O&M balance.*

$$Total\ O\&M_t = O\&M\ Cost_{p,r,c} * Electricity\ Production_{p,f,t,r,c}$$

*Equation 16. Capacity balance.*

$$Existing\ Capacity_{p,t,r,c} + Capacity\ Build_{p,t,r,c} + Exogenous\ Addition_{p,t+1,r,c} - Exogenous\ Retirement_{p,t+1,r,c} = Existing\ Capacity_{p,t+1,r,c}$$

The inequalities in Equation 17 and Equation 18 link the amount of electricity produced by the model to meet the exogenous demand. $Electricity\ Production$ is the level of activity of a technology $p$ consuming a fuel $f$ in region $r$ in country $c$. Electricity can enter or leave the region through the $Electricity\ Exchange$ variable.

*Equation 17. Electricity supply.*

$$\sum_{p,f} Electricity\ Production_{p,f,t,r,c} \geq Electricity\ Supply_{t,r,c}$$

*Equation 18. Electricity demand.*

$$Electricity\ Supply_{t,rr,cc} + \sum_{r,c} Electricity\ Exchange_{t,r,c,rr,cc} - \sum_{r,c} Electricity\ Exchange_{t,r,c,rr,cc} \geq Electricity\ Demand_{t,rr,cc}$$

Fuel consumption in each region and country is computed using the $Heat\ Rate$ (i.e., technical efficiency) of each technology $p$ consuming fuel $f$. The marginal values of fuel consumption (Equation 19) and fuel demand (Equation 20) are orthogonal and enter the dual constraint (Equation 22).

*Equation 19. Fuel consumption.*

$$Fuel\ Consumption_{p,f,t,r,c} \geq Heat\ Rate_{p,f,r,c} * Electricity\ Production_{p,f,t,r,c} \perp \gamma_{p,f,t,r,c}$$

*Equation 20. Fuel demand.*

$$\sum_{r,c} Transported\ Fuel_{f,t,r,c,rr,cc} \geq Fuel\ Consumption_{p,f,t,r,c} \perp \lambda_{f,t,r,c}$$

*Equation 21. Fuel supply.*

$$Fuel\ Production_{f,t,r,c} + Fuel\ Imports_{f,t,r,c} - Fuel\ Exports_{f,t,r,c} - \sum_{rr,cc} Transported\ Fuel_{f,t,r,c,rr,cc} \geq 0$$

The MCP formulation arises by taking the partial first order derivative of each constraint with respect to each decision variable. The objective function (Equation 13) then "drops out" and is embedded in the dual constraints. In this way, the optimization problem is transformed to an equilibrium problem, where the primal constraints represent quantity balances, and the dual constraints represent the economic balances. This representation enables the analysis of quotas and administered prices by modifying the market clearing conditions. The dual equations are quite lengthy. Thus, only one dual equation is presented to provide a representation of the concept.

*Equation 22. Pricing rule.*

$$price_{f,t,r,c} = \begin{cases} \lambda_{f,t,r,c}, & Marginal\ pricing \\ Administered\ Fuel\ Price_{f,t,r,c}, & Administered\ pricing \end{cases}$$

*Equation 23. Dual constraint for fuel price.*

$$price_{f,t,r,c} * d_t - \gamma_{p,f,t,r,c} \geq 0 \perp Fuel\ Consumption_{p,f,t,r,c}$$

Equation 22 is the pricing rule. Administered prices are enforced by "intervening" in the equilibrium by removing the marginal value of fuel demand ($\lambda$) and replacing it in Equation 23 with the exogenous $Administered\ Fuel\ Price$ from Table 19. In this analysis, scenarios using administered fuel prices do not contain the marginal value $\lambda$, and the reverse for scenarios where fuel prices are deregulated. The marginal values of Equation 19 and Equation 20 are positive when those constraints are binding, representing a scarcity.

## 2.2. Multi-period (2015-2030)

The model formulation used in this analysis builds on the foundation utilized in the single-year static analysis of GCC electricity exchange (Wogan et al., 2019b). The model has been expanded to solve over a user-defined time horizon. In this analysis the time horizon is set between 2015 and 2030.

KEM-GCC is formulated as a recursive dynamic problem, where a solution is reached for a subset of time periods smaller than the total forecast horizon, as illustrated in Figure 28. The subset of time is the planning horizon. Once a solution is reached, the model carries the solution for the first year of the planning horizon forward to the next period. The solutions for the other years are discarded because they will be determined in future iterations. The model then steps forward and solves over the planning horizon. It proceeds recursively in this manner until the end of the forecast horizon.

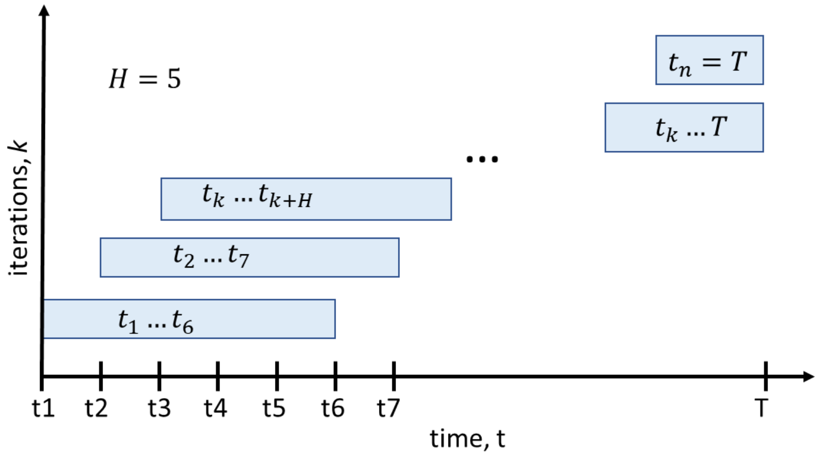



*Figure 28. The recursive dynamic algorithm for a planning horizon, p, of 5 periods.*

Mathematically, this can be written as the following: for a forecast horizon $T$, a planning horizon $H$ is selected such that $H < T$. The model begins in time $t_1$ and optimizes over the period $t_1 \dots t_{1+H}$. The solution to this problem is then used as the starting point for the next recursion. The solution for $t_2$ through $t_{1+H}$ are discarded. The optimization begins again for a period $t_2 \dots t_{2+H}$. As the planning horizon approaches the end of the horizon, the planning horizon decreases by a time step until the last solution is obtained over a period of one timestep in period $t_T$. The last period is solved as a static, single-period problem.

In this analysis, the base year is 2015 with a planning horizon ($H$) of five years. The total forecast horizon ($T$) is 2030. The first iteration solves an optimization problem for the years 2015 through 2020. Solutions for all five years are produced, but only the 2015 solution is retained and used as a starting point for the next recursion. The model then performs an optimization problem for the years 2016 through 2021, discarding the solution for 2017 through 2021 before proceeding.

At each time step the investment cost is the annualized cost occurring within the planning horizon. Each technology has a useful economic life associated with it (Matar et al., 2017). The cost of investing in year $t + k(k \in \{0, \dots H\})$ is the present value (in year $t + k$) of the annualized cost occurring between years $t + k$ and $t + H$.

The annualized capital cost is:

*Equation 24. Annualized capital cost.*

$$a = \frac{I}{\sum_{l=0}^{L-1} \frac{1}{(1+i)^l}}$$

Where $I$ is the capital cost of a technology, $L$ is the useful economic life, and $i$ is the discount rate. A discount rate of 6% was assumed for this analysis.

At time $t$ in KEM the capital investment $c$ in year $k$ beyond $t$ in the recursion is the present value of the annualized capital cost over the remaining years in the planning horizon.

*Equation 25. Cost in year k beyond t.*

$$c_{t,k} = a \sum_{j=0}^{H-k} \frac{1}{(1+i)^j}$$

The recursive dynamic approach approximates the bounded rationality that decision-makers face when planning and investing in technologies. While electricity and water demand are provided exogenously, the recursive dynamic approach means the model agents do not have full foresight of demand, thus the agent's decisions differ from a fully deterministic setting.

### 2.3. Combining the dynamic approach and multi-region model

The novel functionality of this model is along three axes: decisions among multiple sectors within one country (energy system), with the possibility of transfer prices or quota exogenously imposed by the decision-maker; interaction and possible coordination between multiple countries (Equation 21), each with their own energy system (as previously noted); and along a time dimension, where intertemporal decisions on investments, consumption, and exchange can vary.

## 3. Scenarios

Three policy levers were introduced: subsidy removal, carbon price, and exchange. Subsidy removal refers to removing any price or quota interventions by the respective government. For example, in Saudi Arabia, all fuel prices observed by the power and water sectors would be determined at the competitive equilibrium, rather than set by a policy maker. Fuel quotas are sector specific limits on fuel consumption set by a policymaker and introduced as an exogenous constraint. Some government representatives prefer the term administered for price controls, rather than subsidies, as it conveys that the government is imposing a price, one that is technically higher than the production cost, but lower than the market clearing price in a competitive equilibrium. This clearing price is obtained by inspecting the dual variables (*shadow prices*) of the fuel constraints. In these scenarios, the dual variables reflect the price controls; the alternative scenarios provide more interesting values.

A regional carbon price is introduced to provide the economic incentive to decarbonize the power and water sectors. The carbon price introduced in this analysis is time-varying, starting at \$5 per tonne of $CO_2$ in 2019 and increasing by \$5 per on each year to \$60 per tonne in 2030. This price schedule illustrates the impact on carbon emissions and country-level decisions.

The third policy lever is utilizing the Interconnector for electricity exchange. As noted earlier, a small amount of electricity is exchanged using the Interconnector. This scenario enables electricity exchange based on coordination among the six countries to deliver least-cost electricity production and consumption.

The scenario configurations are shown in Table 22 below.

*Table 22. Scenarios.*

| Scenario | Subsidy removal | Carbon price | Exchange |
|---|---|---|---|
| A | No | No | No |
| B | No | Yes | No |
| C | No | No | Yes |
| D | No | Yes | Yes |
| E | Yes | No | No |
| F | Yes | Yes | No |
| G | Yes | No | Yes |
| H | Yes | Yes | Yes |

In all scenarios, administered fuel prices (when applicable), future capacity expansions, technology cost projections, exogenous fuel prices, and electricity and water demand are the same, unless otherwise noted. In all permutations, the Interconnector capacity is kept fixed at the existing capacity levels shown in Figure 26. Each scenario is assessed according to technology investments, fuel consumption, electricity production and exchange, carbon emissions, and economic gains and losses.

Scenario **A** serves as a reference scenario because it is a continuation of active policies. However, policy development is dynamic, and it is expected that the current suite of policies will not remain in perpetuity, especially with the planned Gulf Common Market, expected to begin operations in 2020. As such, the scenarios provide direction and magnitude of policy packages.

## 4. Data and inputs

### 4.1. Projected electricity demand

Electricity and water demand are exogenous and based on reports by the respective national authorities for Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (ECRA (Electricity & Cogeneration Regulatory Authority), 2011). Historical demand from 2012 through 2017 and projections through 2030 are plotted in Figure 29.

Hourly power demand for Bahrain was not obtained. As a workaround, the demand was estimated by scaling demand for the eastern region of Saudi Arabia by Bahrain's peak demand. This assumption is reasonable given the geographic proximity, similar climate, and smaller peak load (3.4 GW) for Bahrain.

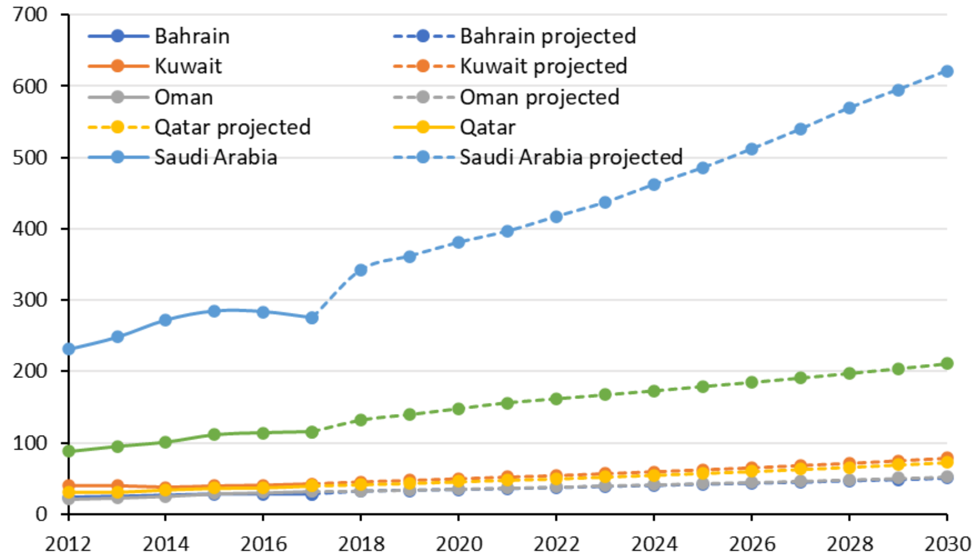



*Figure 29. Historical and projected electricity demand in TWh.*

Electricity demand is projected to double in Bahrain due to large industrial projects like aluminum smelting (Sustainable Energy Unit Kingdom of Bahrain, 2017). In Kuwait, demand is projected to increase by 5 percent annual through 2025. This analysis assumes the growth rate will continue to 2030 (Kuwait MEW (Kuwait Ministry of Electricity and Water), 2018a). In Oman, demand is assumed to continue growing at around 8 percent annually (OPWP (Oman Power and Water Procurement Company), 2018).  According to the KAHRAMMA, Qatar's electricity demand is projected to continue growing at around 7 percent annually (KAHRAMAA (Qatar General Electricity & Water Corporation), 2018). Electricity demand for Saudi Arabia is projected to continue growing at 7-8 percent according to the Long Term Plan by Electricity & Cogeneration Regulatory Authority of Saudi Arabia (ECRA (Electricity & Cogeneration Regulatory Authority), 2020). Growth in the U.AE. is projected to be slower than in the other GCC countries at around 3 percent annually (United Arab Emirates Ministry of Energy & Industry, 2019).

This analysis does not consider demand response. It is possible that firms and individuals may adjust their demand to price. Demand response was not considered in this analysis to keep the focus on the response of the electricity producing firms to price inputs. A subsequent study could consider the combination of response by electricity producing firms and electricity consuming agents.

The short- and long-term impacts of COVID-19 were not considered because the analysis was completed before the global pandemic began. Along with demand response discussed above, alternative demand projections would be suitable for a subsequent study.

### 4.2. Technology cost assumptions

Technology costs are a combination of costs from the Saudi Electricity Company, the U.S. Energy Information Administration (EIA), and expert input. Technology cost declines for renewable technologies are based on cost assumptions reported by the International Energy Agency (IEA) (Figure 30) (International Energy Agency, 2020; U.S. Energy Information Administration, 2020). Learning rates are not endogenously determined in the model based on the assumption that the GCC countries are not significantly contributing to the dynamics of learning rates.

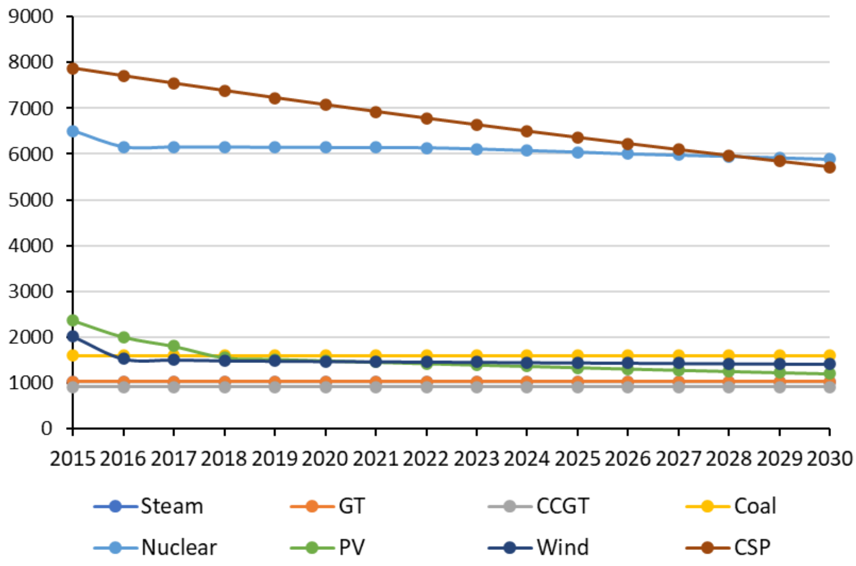



*Figure 30. Technology cost assumptions in 2019$/kW.*

Capital costs for solar photovoltaics are based on the levelized cost of electricity from the United Arab Emirates. Costs declined from 5.84 US cents/kWh in 2015 to 2.94 US cents/kWh in 2017 (United Arab Emirates Ministry of Energy & Industry, 2019).

## 4.3. Fuel prices

The model is calibrated to closely reproduce fuel consumption and technology utilization reported in 2015 through 2017 by respective country data sources, as discussed in the following sub-sections. Where applicable fuel prices are administered according to the prices in Table 23. Natural gas is expressed in units of U.S. dollars per million British Thermal Units (MMBtu), crude oil, HFO, and diesel in U.S. dollars per barrel (bbl).

*Table 23. Assumed regulated fuel prices in 2015.*

| Country | Natural gas ($/MMBtu) | Crude oil ($/bbl) | HFO ($/bbl) | Diesel ($/bbl) |
|---|---|---|---|---|
| Bahrain | 2.75 | 55.00 | - | - |
| Kuwait | 3.53 | 42.10 | 44.43 | 62.37 |
| Oman | 2.00 | 55.00 | - | - |
| Qatar | 1.50 | 55.00 | - | - |
| Saudi Arabia | 0.75 | 4.24 | 2.08 | 3.60 |
| U.A.E. | 2.85 | 55.00 | - | - |

As of this writing, administered fuel prices in Saudi Arabia have not changed from these levels (Wogan, 2020b). In Bahrain, natural gas prices were raised to $3.25/MMBtu and will rise to $4/MMBtu as planned by the government (Bahrain Mirror, 2018). Prices in the other countries are assumed to be constant.

Assumptions for world oil, natural gas, and coal prices are presented in Figure 31 in U.S. dollars per MMBtu equivalent. Prices through 2019 are historical (Macrotrends, 2020, n.d.; U.S. Energy Information Administration, 2019). These prices affect the model through the export revenues and cost of importing fuels from outside the GCC.

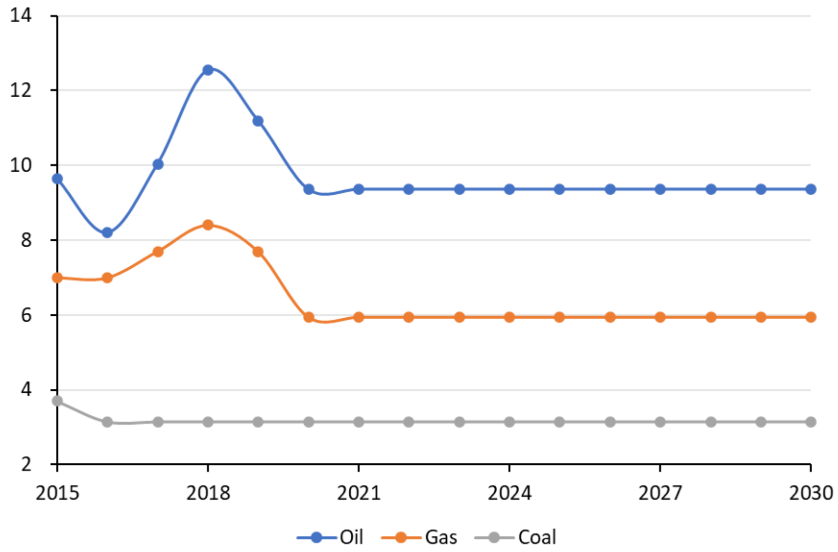



*Figure 31. Export price assumptions in $/MMBtu.*

A price forecast is not used because of the large uncertainty. Instead, the prices maintain the same level seen in 2019. The relative prices are more significant than the absolute level. The relative prices affect the investment and operation decisions by the model while the absolute level is primarily for computing the export revenue component of economic gain (Section 5v). A sensitivity analysis was performed for different fuel prices (see Section 5vi).

## 4.4. Planned technology capacity expansion and fuel production

Existing capacities and planned expansions are an exogenous input to the model. The model endogenously determines additional capacity investments but does not endogenously retire capacity, although the model can choose not to use the capacity. In other words, the investment decisions are irreversible. The country-specific capacity expansions are discussed in the following subsections. The technology capacities prescribed to the model are tabulated in Appendix 4A.

Any plans for increasing or decreasing fuel production, imports, or exports are also exogenously prescribed. The model does not endogenously invest in new fuel production capacity or retire capacity.

### *Bahrain*

Starting cumulative power generation capacity in 2015 was 3.9 GW, of which 1.6 GW was gas turbine, 1.3 GW was steam turbine, and the remaining 0.99 GW was dual fuel capable gas turbines. No capacity additions or retirements were reported through 2017. Water production capacity also remained steady at 0.68 million cubic meters per day (MM m3/day). No plant expansions were reported (Electricity & Water Authority Kingdom of Bahrain, 2018; Electricity and water Authority, 2017; Kingdom of Bahrain EWA (Kingdom of Bahrain Electricity and Water Authority), 2016).

### *Kuwait*

The Kuwait Ministry of Electricity and Water reports power and water statistics for Kuwait. Combined power and water plant capacity as of 2017 was about 18.6 GW and 2.8 MM m3/day (Kuwait MEW (Kuwait Ministry of Electricity and Water), 2018a, 2018b). Between 2018 and 2023 another 3.0 GW of CCGT capacity is expected to come online while 660 MW of steam turbine generation will be retired. Total capacity in 2023 will be 21.7 GW.

### *Oman*

Plant capacity expansions in Oman are sourced from the Oman Power and Water Procurement Company's 2017 Annual Report. Planned and executed power and water purchase agreements between 2016 and 2022 are 4.59 GW and 330.6 MIGD (1.25 MM m3/day). While several existing PPAs and WPAs will expire during this period, I assume that these plants are still operational and available to renew purchase agreements or participate in the spot market.

According to SP Global, Oman is expected to increase crude oil production from 970 thousand barrels per day (bpd) in 2019 to 1.1 million bpd in 2022. Gas production is expected to increase from 352 trillion Btu TBtu (1 billion cubic feet per day (bcf/day)) to 529 TBtu (1.5 bcf/day) in 2021 (Saadi, 2019).

### *Qatar*

Beginning in 2015, Qatar has a combined power and water capacity of 8.6 GW and 1.4 MM m3/day, respectively. A new project, the Umm Al Houl Project, is a major combined water and power facility with 2.5 GW and 0.59 MM m3/day of power and water capacity. Phase I of the project was finished in 2017 and Phase II finished in 2019 (POWER TECHNOLOGY, 2020).

Gas production is expected to add 1,531 TBtu (33 tonnes per annum) by 2024 and an additional 742 TBtu (16 tonnes per annum) by 2027 (Wang and Perkins, 2019)

### *Saudi Arabia*

Saudi Arabia started with 69 GW in 2015. According to annual reports by Saudi Electric Company, 12.4 GW of power capacity was added through 2017. The company plans to add 5.0 GW of power capacity through its own power plants and through IPPs. Through 2021, Saudi Arabia has planned to add 5.6 GW through capacity owned by Saudi Electric Company and additional 11.9 GW through IPPs (SEC (Saudi Electricity Company), 2019).

### *United Arab Emirates*

There was around 28.7 GW of installed power capacity across all four emirates in 2015. According to the United Arab Emirates Ministry of Energy & Industry, the country will add over 13.7 GW through 2023, including 5.4 GW of nuclear, 4.2 GW of ultra-supercritical coal, and 2.3 GW of solar (Report, 2016; United Arab Emirates Ministry of Energy & Industry, 2019). A 30 MIGD (0.11 MM m3/day) reverse osmosis plant commenced operation in Abu Dhabi in 2018.

## 5. Analysis and results

The modeling results are discussed in this section starting with **Scenario A**, which serves as a reference scenario. The impact of removing fuel price and quantity interventions is then discussed in Scenario **E**. **Scenario G**, which combines the reforms of **E** and adding electricity exchange as an option, is discussed next. Finally, the impact of introducing the time-varying carbon price is examined in **Scenario H**. Appendix 4A contains detailed figures of results for electricity supply through 2030 (Figure 46), electricity supply by country in 2030 (Figure 47), fuel consumption (Figure 48), $CO_2$ emissions (Figure 49), power plant capacity (Figure 50), and cumulative capital investments (Figure 51).

## 5.1. Reference

In **Scenario A**, the technology capacity expansion and activity trends starting in the first years of the projection period persist through 2030 (Figure 32). Cumulatively, CCGTs are the largest electricity producers (501 TWh) followed closely by thermal cogeneration (392 TWh) in 2030. Planned additions of coal come online and begin electricity production in 2021 and 2023 in Dubai and FEWA jurisdictions, respectively, while the 5.6 GW Barakah reactor in Abu Dhabi is fully operational starting in 2021. The Federal Electricity and Water Authority (FEWA) covers the smaller emirates, i.e., those other than Dubai, Abu Dhabi, and Sharjah. In Kuwait, the generation mix remains nearly all thermal cogeneration (combined power and water production). In Saudi Arabia, CCGTs are the largest investment at 38 GW, while over 8 GW of less efficient steam turbines were the second largest investment.

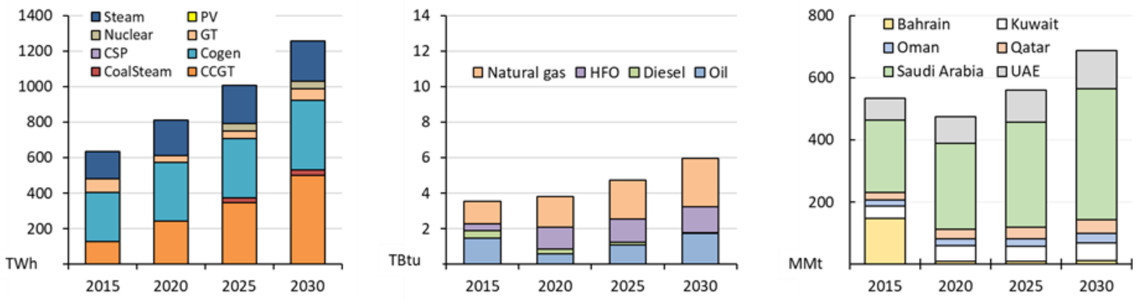



*Figure 32. Results for the Reference (Scenario A): electricity production (left), fuel consumption (center), and $CO_2$ emissions (right).*

Saudi Arabia is the largest electricity producer in the region, followed by the U.A.E. and Kuwait. In Saudi Arabia, steam turbines begin as the foundation of electricity supply, while production from additional CCGTs increases to over half of production by 2030. The magnitude of Saudi Arabia's production relative to the other GCC countries means that policies and decisions in Saudi Arabia have a substantial impact in the region. Electricity production grows rapidly in Saudi Arabia at a 4.8% compound annual growth rate. In the U.A.E., in the first 5 years of the simulation thermal cogeneration plants supply most of the electricity, but this quantity decreases as coal and nuclear capacity is introduced. In no country is there a substantial electricity production from renewables (PV, wind, or CSP).

Power and water-related $CO_2$ emissions in Scenario **A** would reach nearly 700 million tonnes per year by 2030, an increase of around 55% from 2015. Saudi Arabia and the U.A.E. produce the bulk of emissions, in line with their respective electricity demands. In both Kuwait and Saudi Arabia, crude oil and refined petroleum products are consumed, contributing to the growth in emissions. In the U.A.E., coal-fired generation reverses a brief decline in $CO_2$ emissions. Notably, **Scenario C** shows the highest $CO_2$ emissions of all modeled scenarios. In **Scenario C**, electricity exchange is allowed without price or quantity reforms.

The fuel price and quota constraints in **Scenario A** mean that fossil fuels and less efficient technologies are lower cost options through the simulation. Steam turbines, particularly in Saudi Arabia, are invested in and operated because up-front capital costs and variable fuel costs are lower than more efficient alternatives. The variable fuel costs for all fossil fuel consuming plants reflect the artificially low fuel prices relative to the true marginal price.

## 5.2. Fuel price controls and quota removal

In **Scenario E**, fuel price controls and quotas are removed, and the model allocates fuel consumption based on the marginal values at the competitive equilibrium (Figure 33). The marginal values reflect the short-run marginal costs, i.e., the additional cost of consuming an additional unit of fuel but are determined simultaneously in the context of available technology options. The relative costs of those investments (e.g., more expensive, and efficient CCGTs compared to steam turbines) affect the investment decisions, which ultimately affect whether a fuel is consumed.

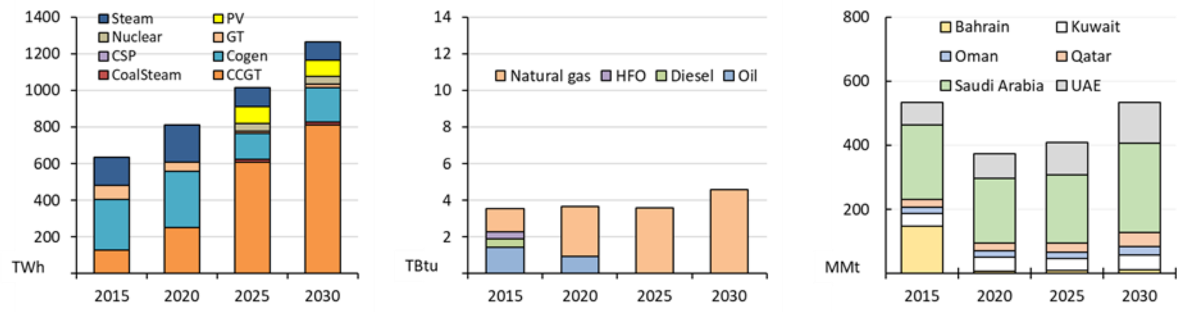



*Figure 33. Results when removing fuel price controls and quotas (Scenario E): electricity production (left), fuel consumption (center), and $CO_2$ emissions (right).*

Removing the fuel price controls and quotas lead to different results than **Scenario A**, as expected. In Saudi Arabia, cumulative technology additions nearly reach 90 GW (up from 51 GW in **Scenario A**). The additional capacity includes more CCGTs (a total of 56 GW) and over 20 GW of solar PV. The additional CCGT capacity is partly to provide spinning reserve for the PV systems. The higher prices for all fossil fuels make PV technology a lower-cost alternative. Diesel, HFO, and crude oil are too expensive to consume as fuel. In the case of crude oil, the increased value makes it more attractive as an export commodity than fuel input. While natural gas becomes more expensive, it is consumed extensively in Saudi Arabia starting in 2021 after a phase out of crude oil in 2019 and 2020.

In Kuwait, 8 GW of PV are deployed. Like Saudi Arabia, the increase in fuel prices substantially alters the relative costs of fuels and technologies in all countries. CCGT deployment, and thus natural gas consumption is modest, with coal eventually substituting for natural gas starting in 2023 in Kuwait. Without a carbon price, coal generation remains a cost-effective option for the U.A.E, where 4 GW is deployed. The shifting cost structure means the combined capital cost of coal technology and ongoing coal fuel costs are less expensive over time than continued reliance on natural gas consuming technologies.

It is worth noting is that a substantial quantity of water desalination switches to reverse osmosis (RO) processes in the U.A.E. RO technologies use membranes to remove salt and minerals from seawater – rather than evaporation – meaning less thermal cogeneration capacity is required.

Despite the deployment of 4 GW of coal capacity in **Scenario E**, $CO_2$ emissions decrease compared to **Scenario A** (Figure 36). There are several peaks and valleys in the emissions through 2030 due to the period between operation of gas-fired power plants and when coal plants come online. $CO_2$ emissions in 2024 are nearly equivalent to levels in 2015, but then begin to climb steadily due to coal-fired generation.

**Scenario E** shows the dual nature of a deregulation type policy pathway. Market forces resulted in more efficient allocation of fossil fuel resources technology compared to **Scenario A**, but not accounting for $CO_2$ as an externality is detrimental from a carbon emissions policy standpoint. Removing price and quantity interventions provide positive direction in system-wide economic efficiency, but these measures should be accompanied by other policies to account for $CO_2$ emissions or reliance on fossil fuels (such as coal).

## 5.3. Electricity exchange (Scenarios C, D, G, and H)

Electricity exchange is one way for GCC countries to coordinate on energy and climate policies. The outcome of energy consumption and subsequent $CO_2$ emissions in each country is dependent on the configuration of the policy package: i) whether price and quantity controls remain in effect; and ii) if a carbon price is implemented. As studied in the preceding analysis (Wogan, 2018), exchanging electricity without reforming price and quantity controls is in effect an export of domestic subsidized electricity production. As shown previously, even creating two tiers of electricity production – one subsidized for domestic consumption and one unsubsidized tier for export – would not realize the largest economic gains possible.

The option of a carbon prices adds another degree of freedom for GCC decision makers. **Scenarios C** (price and quantity controls, no carbon price) and **G** (no carbon price or controls) are the relevant scenarios for observing the marginal impact of electricity exchange. **Scenarios D** and **H** include a carbon price and are discussed in the subsequent sub-section. The results for Scenarios C, D, and H are shown in Figure 34 and Figure 35. Scenario G is not shown because the level of exchange is close to zero. The values of electricity exchange are in Table 40 through Table 43 in Appendix 4B.

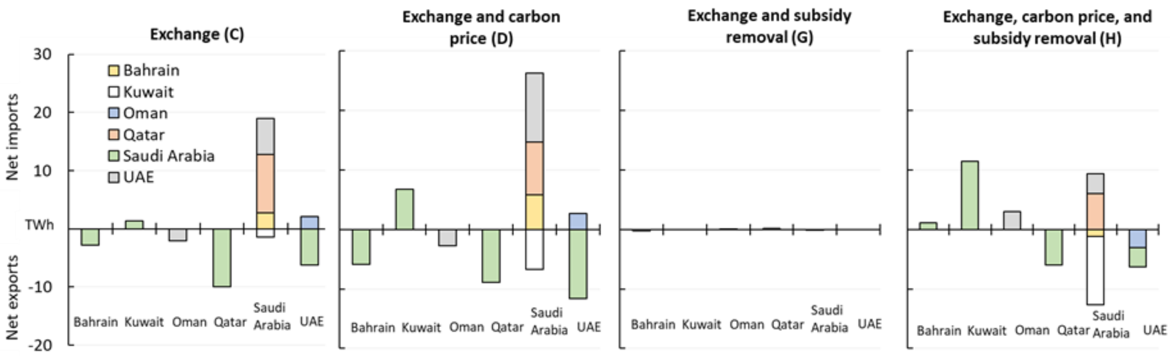



*Figure 34. Electricity exchange in 2030 for scenarios C, D, and H. Scenario G is not shown.*

Enabling exchange creates one large GCC electricity system, where generation assets are available for producing electricity to satisfy demand in any other country or sub-region. For this analysis, there is no additional fossil fuel trade beyond the existing natural gas transfers via the Dolphin pipeline or crude oil between Saudi Arabia and Bahrain. Retaining the price and quantity controls in this regional electricity system means a country with the lowest cost generation will supply electricity to others, assuming it has enough fuel resources.

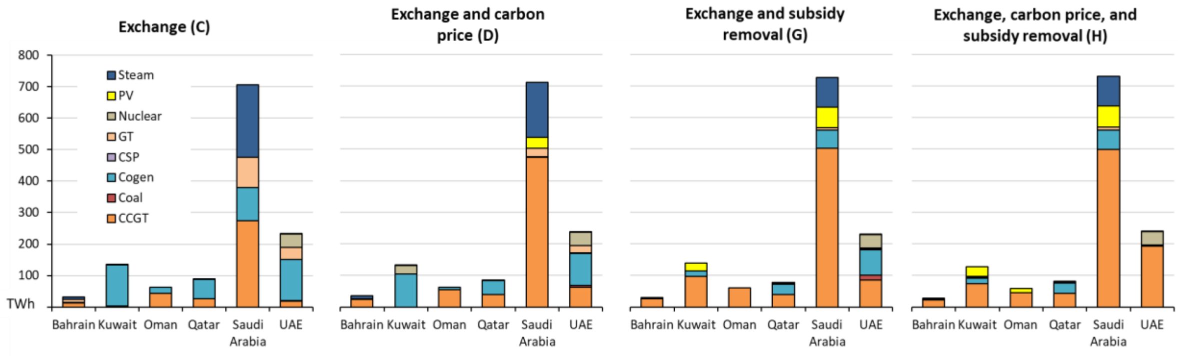



*Figure 35. Electricity generation with exchange in 2030.*

In this scenario, thermal cogeneration electricity production is largest and capacity additions are lowest among all scenarios. This result suggests that electricity trade with price and quantity controls allows existing capacity to be utilized more, avoiding the need for additional capacity investments, which would be more efficient (on an energy or $CO_2$ basis). CCGTs for electricity production and RO for water production are too costly in this scenario because it makes economic sense for existing capacity to consume fuels at below market value.

Moreover, diesel consumption increases in Kuwait and crude oil consumption increases substantially in Saudi Arabia, fueling thermal cogeneration units, and steam and gas turbines. Natural gas consumption does not increase because quotas in Saudi Arabia are still enforced. As a result of the fuel mix, $CO_2$ emissions are the highest in **Scenario C**, nearly 100 million tonnes higher than Scenario **A** in 2030.

The largest net electricity exchange occurs in **Scenario D**. The addition of a carbon price affects Saudi Arabia disproportionately due to its reliance on carbon-intensive fuels (crude oil, HFO, and diesel). At the equilibrium it is less costly for Saudi Arabia to import electricity from the U.A.E., Qatar, and Bahrain.

Removing fuel price and quantity controls in **Scenario G** reduced $CO_2$ emissions growth by up to 120 million tonnes relative to Scenario C in 2030 (Figure 36). The level of electricity exchange in Scenario G, whether on an absolute or net basis, is the lowest of all exchange scenarios. The only net exchange occurs between Saudi Arabia and Qatar (0.8 TWh). As discussed in the previous sub-section, the implicit price brought on by the competitive equilibrium forces different investment and operation decisions by each country. As seen in **Scenario E**, crude oil becomes more valuable as an export commodity for Saudi Arabia. See subsection vi for discussion of oil price sensitivity. Coal consumption again occurs in Kuwait and Oman. This observation implies that the price signal induced by the market equilibrium leads to a system that requires less reliance on electricity production from neighboring countries. This point is relevant for decision-makers in the GCC countries as they consider ongoing fuel price reforms and intentions to open the GCC Common Market. The existing Interconnector capacity might be sufficient and not used much beyond reliability transfers (which is what it is used for at the time of writing this article).

Electricity exchange is most balanced in **Scenario H**. Increasing fuel costs drives the change in electricity production relative to **Scenario C** (subsidized prices), either through a carbon price alone (**Scenario D**), subsidy removal (**Scenario G**), or the combination (**Scenario H**)The largest exchange occurs between Saudi Arabia and Kuwait.

## 5.4. Time-varying carbon price

A time-varying carbon price is introduced in **Scenario B** (no reform to fuel price and quantity controls, no electricity exchange), **D** (adding electricity exchange), **F** (no controls but also no exchange), and **H** (no fuel price or quantity controls coupled with electricity exchange). The carbon price starts at \$5 per tonne of $CO_2$ in 2019 and increases by \$5 per tonne to \$60 per tonne in 2030. In these scenarios, the carbon price increases the cost of consuming a fossil fuel, where the incremental cost incurred depends on the carbon content of the fuel. In **Scenario B**, $CO_2$ emissions are noticeably lower than **Scenario A**, as expected (Figure 36). The effect of the carbon price is not immediately observable by inspecting the fuel consumption because no substantial fuel switching occurs. Saudi Arabia and Kuwait continue to consume crude oil, diesel, HFO, and natural gas. Natural gas consumption in Saudi Arabia remains constrained by quota. However, the absolute level of fossil fuel consumption decreases, leading to the decrease in emissions.

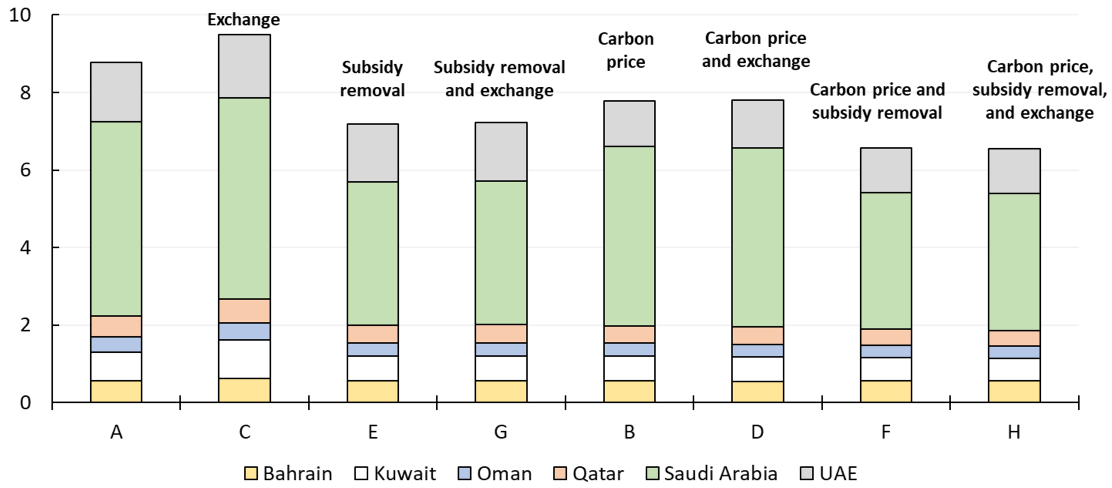



*Figure 36. Cumulative $CO_2$ emissions for all scenarios 2015 through 2030.*

Fossil fuel consumption decreases because of investment in more efficient technology and non-fossil capacity. In Saudi Arabia, an additional 20 GW of CCGT capacity is built, which is used to supply electricity for power sector demand and RO plants. As a result, electricity production from thermal cogeneration plants decreases. The carbon price changes the fuel cost differentials such that solar PV becomes cost-competitive in Saudi Arabia: nearly 12 GW are deployed. In Kuwait, the country builds over 4 GW of nuclear capacity.

**Scenario D** turns out to not be that different than Scenario B. The technology deployments are nearly identical as are the $CO_2$ emissions (Figure 36). A substantial amount of electricity exchange occurs. If reducing $CO_2$ emissions is the primary objective, then a carbon price can be sufficient. If increased utilization of the Interconnector is also desired then the results of **Scenario D** show that exchanges will occur, but with no meaningful reduction in $CO_2$ emissions. Thus, implementing a carbon price is one way to counter the growth in $CO_2$ emissions observed in **Scenario C** (as discussed in the previous sub-section).

**Scenario F** and **H** are quite similar, the only difference is electricity exchange is enabled in **Scenario H**. The key driver of change in both scenarios is the removal of price and quantity controls. Natural gas again becomes the most consumed fuel in all countries, especially Saudi

Arabia, while high-value refined products and crude oil are not consumed domestically and are instead exported. CCGT capacity is expanded and solar PV is built in all countries except Bahrain.

In terms of $CO_2$ emissions, **Scenarios F** and **H** produce the lowest absolute levels of emissions (Figure 36). $CO_2$ emissions in **Scenario H** are marginally lower than in **F**. This policy package is only marginally more effective at reducing emissions than coupling a carbon price with removing controls on fuel prices and quantities (**F**). As observed in **Scenario D**, electricity exchange will occur but is itself not a primary driver of $CO_2$ emissions reductions.

In **Scenario H**, Saudi Arabia is a net importer of electricity, allowing it to offset a small quantity of emissions. Coupling the three policy measures together can be most effective at reducing $CO_2$ emissions (Figure 36). Cumulative fuel consumption across all countries and all years is marginally lower than without exchange (**F**), as expected by the lower $CO_2$ emissions.

## 5.5. Economic considerations

The net gain is calculated as the revenue from fuel export revenues net of capital investment less fuel import expenses and operation and maintenance costs, cumulative over 2020 through 2030 (the model results are the same across all scenarios between 2015 and 2019). Capital costs are amortized at the assumed discount rate over the lifetime of the equipment. The revenue and effects of exporting and importing electricity are included in the calculation. The net effect is observed at a country level and net out at a regional system level. The net economic gains and losses are presented in Table 24.

*Table 24. Cumulative economic costs and gains in billion USD.*

| Scenario | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. | GCC |
|---|---|---|---|---|---|---|---|
| **A** | - | - | - | - | - | - | - |
| **B** | -0.0 | -2.2 | -0.8 | 1.2 | -16.4 | -16.0 | -34.1 |
| **C** | -23.1 | -124.5 | -36.6 | -43.2 | -350.6 | -167.2 | -745.4 |
| **D** | 0.8 | -9.8 | -1.4 | 2.3 | -15.3 | -14.3 | -37.8 |
| **E** | 9.3 | 20.7 | 21.1 | 30.4 | 680.0 | 84.3 | 845.8 |
| **F** | 9.3 | 21.8 | 21.4 | 30.3 | 680.8 | 81.0 | 844.6 |
| **G** | 9.3 | 20.4 | 21.1 | 30.4 | 680.6 | 84.2 | 846.0 |
| **H** | 9.8 | 16.8 | 19.7 | 31.8 | 690.5 | 85.7 | 854.1 |

There is a clear distinction in economic gain between scenarios where fuel price and quota controls are maintained (**Scenarios A-D**), and where they are removed (**Scenarios E-H**). Viewed through this lens, it is evident that the largest economic gains come from removing interventions on price and quantities. Comparison between **F** and **H** shows an incremental gain of $9.5 billion between 2020 and 2030. On an average annual basis, this value is close to the estimate in the preceding study and the GCCIA's own study (Gulf Cooperation Council Interconnection Authority, 2017).

This analysis goes beyond the GCCIA's estimates by illustrating the magnitude of potential losses (**Scenario C**). All countries experience a net loss compared with the status quo (**Scenario A**) because of the opportunity cost of oil and gas exports. A continuation of price controls means that inefficient technologies continue to produce electricity and consume fuel that could otherwise be exported at a much higher market price.

Comparisons between **A** and **B**, **C** and **D**, **E** and **F**, and **G** and **H** show the effects of carbon price. Notably, in scenario **D** a carbon price recovers nearly all the losses accrued in scenario **C** from subsidy leakage. The carbon price is also a potential source of revenue for governments. Table 25 includes carbon tax revenues in the net economic gain calculation.

*Table 25. Cumulative economic costs and gains in billion USD, including revenues from $CO_2$ tax.*

| Scenario | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. | GCC |
|---|---|---|---|---|---|---|---|
| **A** | - | - | - | - | - | - | - |
| **B** | 4.3 | 116.5 | 13.5 | 8.0 | 12.8 | 14.0 | 169.0 |
| **C** | -23.1 | -350.6 | -124.5 | -36.6 | -43.2 | -167.3 | -745.4 |
| **D** | 5.0 | 115.9 | 5.3 | 7.7 | 14.9 | 17.2 | 166.0 |
| **E** | 9.3 | 680.0 | 20.7 | 21.1 | 30.4 | 84.2 | 845.7 |
| **F** | 13.5 | 771.1 | 36.4 | 29.6 | 41.1 | 109.1 | 1000.8 |
| **G** | 9.3 | 680.6 | 20.4 | 21.1 | 30.3 | 84.2 | 846.0 |
| **H** | 14.0 | 781.2 | 30.5 | 27.3 | 42.8 | 114.4 | 1010.2 |

**Scenarios B** and **D** now show net economic gains when including carbon tax revenues, while **Scenarios F** and **H** increase net economic gains. Viewed through this lens, recycling carbon taxes increases the economic gains, rather than viewed as a loss. How these revenues are recycled in the individual economies is not considered, but this perspective is still valuable to policymakers in the GCC as they deliberate economic diversification and decarbonization ambitions. Carbon tax revenues could be counted as a revenue source for governments, distributed to public- or private- owned producers, or a combination.

Taken together, the scenarios illustrate the importance of sequencing reforms. Introducing cross-border electricity exchange before addressing domestic price and quantity controls would lead to substantial economic losses (**Scenario C**). Furthermore, introducing an economic measure like introducing a carbon price to increase $CO_2$ mitigation in the absence of domestic price and quantity reforms would also result in economic losses. The scenarios that perform best are those that first address the domestic price and quantity policies, then introduce cross-border exchange and/or a carbon price (**Scenarios E**, **F**, **G**, and **H**). Considering revenues from a carbon tax further increases the economic gains.

## 5.6. The marginal contribution of a policy option

Thus far, the marginal gains and losses have been presented relative to the baseline scenario in a cumulative fashion. However, as noted earlier, the sequencing of policies matters because some policies can counteract other policies. The Shapley value can be used to quantify the marginal contribution of a policy option (Murphy and Rosenthal, 2006; Shapley, 1953). This value is a useful metric for decisionmakers to understand the potential conflicts in policies and provide insight into the sequencing of policies. The Shapley value for the three policy types in this analysis (excluding revenues from carbon pricing) are presented in Table 26. The Shapley equation and calculations are provided in Appendix 4E.

*Table 26. Shapley values for the three policy instruments, excluding revenue from carbon pricing in billion USD.*

| Policy | Shapley value |
|---|---|
| Carbon price | -9.5 |
| Electricity exchange | -245.8 |
| Fuel price subsidy reform | 990.9 |
| Total Shapley value | 735.6 |
| Cumulative individual policy gains | 854.1 |
| Loss | 118.5 |

The fuel price subsidy reform policy delivers the largest average marginal increase in economic gain to the GCC (990.9 billion USD). The carbon price and electricity exchange policies negatively contribute to the economic gain. Taken together, the total economic gain to the GCC is 735.6 billion USD, which is lower than the economic gain presented in Table 24 because the carbon price and electricity exchange policies partially counteract the fuel price subsidy policy.

*Table 27. Shapley values for the three policy instruments while including revenues from carbon pricing, in billion USD.*

| Policy | Shapley value |
|---|---|
| Carbon price | 136.4 |
| Electricity exchange | -245.8 |
| Fuel price subsidy reform | 967.2 |
| Total Shapley value | 857.9 |
| Cumulative individual policy gains | 1010.3 |
| Loss | 152.4 |

The introduction of revenues from carbon pricing immediately reorients the gains from the individual policies, as shown in Table 27. As expected, the carbon price policy contributes positively to the economic gain (136.4 billion USD) because the policy is now a revenue generator, rather than an expense for the GCC countries. The average marginal contribution from subsidy reform decreases from 990.9 to 967.2 billion USD because the gains are now also coming from recycling carbon revenue. The loss from competing policy objectives increased to 152 billion USD, an increase from 119 billion USD without recycling carbon revenue.

The marginal impact of electricity exchange is negative with and without recycling carbon revenues (-245.8 billion USD). This result is counterintuitive. *A priori*, the expectation is that electricity exchange would bring gains through cooperation, shared resources, and competitive advantages. However, taken in the context of the fuel price subsidies, the average marginal contribution of electricity exchange is negative because of the losses due to exchange without subsidy reform. The calculation for this loss includes the outflow of subsidies from one country to another, represented as the opportunity cost of foregone export revenue (Wogan et al., 2019b). Thus, the losses from electricity exchange without subsidy reform are substantial. This finding underlines the importance of sequencing electricity exchange after reforming domestic price and quantity interventions.

This analysis only considered the marginal value of policies. A future analysis could consider the marginal value of sequencing policies and countries in a GCC coalition.

## 5.7. Sensitivity analyses

The following sensitivity analyses were performed:

- lower and higher carbon prices;
- lower technology costs for renewables;
- reduced oil price relative to natural gas; and
- a doubling of Interconnector capacity.

The assumptions are shown in Appendix 4D. Two carbon prices of USD 30 per tonne and USD 90 per tonne in 2030 were tested (Table 28). Relative to the main price of USD 60 per tonne in 2030, the lower price leads to around 100 million added tonnes cumulatively, while a higher price leads to a maximum decrease in scenarios **B** and **D** of over 400 million tonnes. Scenarios **F** and **H** are less sensitive, but still show emission decreases of less than 200 million tonnes. This sensitivity analysis supports the findings that domestic price and quantity policies are important because emission reductions in Scenarios **F** and **H** are already lower than **B** and **D**.

Economic gain for all main scenarios and sensitivity analyses are shown in Table 29 and Table 30, without $CO_2$ revenue recycling and with, respectively.

*Table 28. $CO_2$ emission sensitivity results relative to USD 60 per tonne of $CO_2$.*

| Scenario | 30 | 60 | 90 |
|---|---|---|---|
| B | 138 | 7,739 | -423 |
| D | 143 | 7,742 | -452 |
| F | 138 | 6,457 | -170 |
| H | 146 | 6,437 | -169 |

*Table 29. Cumulative net economic gain (excluding $CO_2$ revenues) relative to Scenario A for main and sensitivity scenarios.*

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| **Main** | - | -34.1 | -745.4 | -37.8 | 845.8 | 844.6 | 846.0 | 854.1 |
| **$CO_2$ USD 30** | | -37.8 | | -38.5 | | 843.6 | | 853.2 |
| **$CO_2$ USD 90** | | 73.2 | | 74.8 | | 841.3 | | 850.8 |
| **Low oil** | -2560.0 | -2588.4 | 2988.0 | -2591.8 | -2252.0 | -2250.8 | -2251.5 | -2244.3 |
| **Low RE cost** | - | -34.1 | -745.4 | -37.8 | 845.8 | 844.6 | 846.0 | 854.1 |
| **Interconnector 2x** | | | -751.4 | -46.4 | | | 843.0 | 859.3 |

*Table 30. Cumulative net economic gain (including $CO_2$ revenues) relative to Scenario A for main and sensitivity scenarios.*

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| **Main** | - | 169.0 | -745.4 | 166.0 | 845.7 | 1000.8 | 846.0 | 1010.2 |
| **$CO_2$ USD 30** | | 109.3 | | 108.8 | | 954.7 | | 964.1 |
| **$CO_2$ USD 90** | | 327.6 | | 327.1 | | 1044.0 | | 1053.1 |
| **Low oil** | -2560.0 | -2385.3 | -2988.0 | -2388.1 | -2252.0 | -2077.5 | -2251.5 | -2070.7 |
| **Low RE cost** | - | 169.0 | -745.4 | 166.0 | 845.7 | 1000.8 | 846.0 | 1010.2 |
| **Interconnector 2x** | | | -751.4 | 158.1 | | | 843.0 | 1015.8 |

A net economic loss relative to the main scenario occurs when adjusting the projected oil price to be less than natural gas. A lower oil price leads to lower revenue from oil exports, particularly for Saudi Arabia. The results are not sensitive to the assumed decrease in capital cost of PV, wind, and CSP technologies. While the capital costs decreased, the relative costs did not alter the investment decisions. Doubling the Interconnector capacity shows slight economic losses with and without revenue in the exchange scenarios **C**, **D**, and **G** because of increased capital investments. Scenario H shows a slight economic gain due to slightly lower capital investment.

## 6. Conclusion

A summary of the results is presented in Table 31. Overall, **Scenario G** shows largest economic gain, but at a trade-off between $CO_2$ emissions. A policy package consisting of subsidy removal, time-varying carbon price, and electricity exchange simultaneously achieves substantial $CO_2$ emissions reductions while delivering substantial economic gain.

*Table 31. Summary of findings. $CO_2$ emissions are cumulative in gigatonnes; economic gains are in billion USD.*

| Scenario | Subsidy removal | Carbon price | Exchange | $CO_2$ emissions | Relative Economic gain |
|---|---|---|---|---|---|
| A | No | No | No | 8.3 | - |
| B | No | Yes | No | 7.4 | -34.1 |
| C | No | No | Yes | 9.5 | -745.4 |
| D | No | Yes | Yes | 7.4 | -37.8 |
| E | Yes | No | No | 7.6 | 845.8 |
| F | Yes | Yes | No | 5.7 | 844.6 |
| G | Yes | No | Yes | 7.8 | 846.0 |
| H | Yes | Yes | Yes | 5.6 | 854.1 |

The findings suggest that potential electricity exchange in the GCC Common Market could lead to increased emissions and work against some GCC country's goals for decarbonization, regardless of ongoing energy price reform initiatives in some GCC countries. Regional energy and climate cooperation in the GCC are technically and economically possible under the auspices Article VI of the Paris Agreement as demonstrated by this analysis. GCC countries can consider this mechanism for future NDC development and national planning activities. The largest economic gain results from a policy package of electricity exchange coupled with removing fuel price and quantity controls.

The average marginal contribution of each policy illustrates the importance of how policies are sequenced. When viewed through this perspective, subsidy removal provides the bulk of the marginal increases in economic gain to the GCC countries. A carbon price also contributes a substantial gain if the revenues are recycled. Electricity exchange in an additive sense contributes a small gain but introduces a loss on the margin. Thus, electricity exchange should be sequenced after reform of domestic price and quantity interventions.

The model formulation is well-suited to this type of analysis. The MCP framework allows for solving all sectors simultaneously without relying on iterating between sectors, while explicitly representing the market interventions of interest. The methodology and findings are relevant for other countries and regions of the world where government intervention in the power sector results in economic inefficiencies, such as countries in south-east Asia that are in process of increasing electricity exchange.

# Chapter 5. Conclusions.

## 1. Motivation

The overall aim of this dissertation was to model and quantify the economic impact of connecting electricity systems in the presence of interconnected, and sometimes competing, policy objectives. Within this question were related questions about the specific configuration of the electricity systems in question. One of the key contributions of this work was directly incorporating the role of interventions in the larger study of interconnectivity. Issues around social and industrial policy objectives at the country level manifest themselves in the form of government interventions in terms of price and quantities of inputs to energy processes, including the electricity sector. Often, it was found that these policies work against other goals, such as climate change targets. Thus, it was necessary to first take a systems-wide approach of the energy and economic characteristics at the country level, and then proceed to the regional system. These interventions were studied in the context of individual energy systems where inter-sectoral price and quantity controls can distort the competitive equilibrium.

The GCC region was chosen as a case study because of several appealing properties. Consisting of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, it is a region integral to the global energy system, where substantial oil and gas resources are produced and exported to world markets. Moreover, the region is also a substantial energy consumer, due in part to industrial policies that position themselves as leading exporters of refined and chemical products, but also because of the government interventions in prices and quantities in the transformation and end-use sectors. These distortions provide economic incentives to consumers to increase the *quantity* of energy and the *types* of energy products consumed. In the transformation sector, this is apparent in the investment in relatively inefficient power plant technologies that in some cases rely on crude oil. While important, the impact of these interventions on end-use sectors was not studied.

The six countries of the GCC are also a bellwether for other developing economies, particularly in south-east Asia and Africa that have growing energy demand and where energy plays an important role in providing social services through subsidized energy prices. The methodology and findings in this dissertation can be rescaled and repurposed to these other important regions.

## 2. Methodology

To accomplish this analysis, the mixed-complementarity problem (MCP) approach was utilized. MCPs are a subset of a larger family of equilibrium problems. Typically, an electricity sector is studied using an optimization framework. This engineering-based approach lends itself well to representing known processes and constraints for producing electricity. However, the presence of price and quantity interventions makes the standard approach of linear programming in a multi-sector system infeasible. The MCP approach overcomes this limitation of optimization by treating the optimal decisions under price and/or quantity constraints among agents as an equilibrium problem where the interventions can directly be formulated as the market clearing conditions.

The MCP approach formulated in this dissertation was designed specifically for an energy system and was extended to study multiple interconnected systems. This formulation enabled the analysis of interconnected energy systems each with unique social and economic constraints.

Key fuel production and trade, electricity, and water desalination processes in each country were modeled. Interventions in the form of administered fuel prices or quantity restrictions on fuel inputs to these processes were included in the market clearing conditions of the MCP. Electricity exchange was then added, enabling each country to utilize the existing GCC Interconnector transmission capacity to satisfy its own demand or sell to another country.

## 3. Key Findings

The analysis began with a multi-period analysis of Saudi Arabia (Chapter 2). This analysis facilitated the development of the core MCP model. Additionally, focusing on one country as a starting point was more feasible from a model development, data collection, and calibration standpoint. The key finding from Chapter 2 was removing price and quantity interventions would substantially alter the investment and operation decisions in Saudi Arabia's energy system. The power and water sectors would be incentivized to invest in more efficient technology (including solar PV) and drastically reduce consumption of crude oil. This crude oil was then available for export, providing a net economic gain to the economy.

The remaining five countries of the GCC were added in Chapter 3. Electricity exchange utilizing the Interconnector became an option. Building on the findings from Chapter 2, Chapter 3 considered exchange with and without reforming the interventions in a static (single year) setting. It was demonstrated that electricity exchange among countries while retaining interventions would result in a large outflow of subsidized electricity from Saudi Arabia to its neighbors. A novel scenario was constructed where countries operated with a hybrid system of interventions. Electricity production for domestic consumption remained subsidized while exported electricity was priced at marginal cost. The gains from this arrangement were not substantial. The largest economic gains were found by removing the price and quantity interventions for all electricity production and allowing exchange.

The analysis culminated in Chapter 4 by investigating the interconnected GCC electricity system in a multi-period environment. The set of available policies was expanded from intervention reform and electricity exchange to include $CO_2$ emissions reductions. Permutations of these three policies were performed to illustrate the impacts on economic gains and $CO_2$ emissions reductions. On an aggregate basis, the combination of all three policies resulted in the largest economic gain (aggregated across the GCC countries and cumulatively over the projection period) and largest emissions reductions. However, the bulk of the gains along both dimensions is due to removing the interventions.

Further investigation was performed to isolate the contribution of each of the three policies to the overall economic gain. By looking at the average marginal contributions of the policies (Shapley values), three findings were identified. First, removing interventions was responsible for most of the economic gains. Second, recycling revenues from a carbon pricing policy adds to the gain, decreasing the average marginal contribution of intervention reform. Third, electricity exchange always contributed negatively to economic gain. This result was unexpected but is consistent with the accounting of the cross-subsidies among countries and the opportunity cost of foregone crude oil exports. The key finding from this exercise was that sequencing of policies is crucial to satisfying an array of objectives, some of which may run counter to each other. As demonstrated, electricity exchange and carbon pricing (assuming revenues are not recycled) can counteract gains from reforming interventions, reducing the overall economic gain.

## 4. Future work

The analysis of Shapley values in Chapter 4 introduced an interesting follow-up question: in addition to sequencing policies, how does sequencing countries affect the overall economic gain in the GCC? In other words, what set of GCC countries participating in electricity exchange result in overall economic gain? There may exist a subset of six GCC countries that deliver the largest economic gain, given the domestic configuration of resource endowments, technology stock, and interventions.

Additionally, the MCP formulation utilized throughout this dissertation proved to be a powerful tool. In its current state, the model exists in a form suitable for this analysis. There is an opportunity to generalize the MCP formulation of an energy system for wider use, particularly in the open-source energy modeling community, to enable studies of other regions that face similar questions about the technical and economic aspects of their electricity systems as they develop, either in autarky or in cooperation with their neighbors.

# Appendices

## Appendix 2A: The Dynamic Framework: A Recursive Approach

The standard approach in a multi-period model is to set a sufficiently long planning horizon, replicate much of the structure of the single-period model and optimize over the whole horizon. This approach has the virtue of matching the full-information assumption in most economic models. However, the model can be very large, and a deterministic representation of full information does not represent the real uncertainties in the future. It is possible to step back from full information by generating a probability distribution of outcomes in each period, including scenarios in the model for each possible outcome. The problem with this approach is that over time the scenarios branch from one period to the next, leading to a tree of possibilities and several variables and constraints that grows exponentially with the number of time periods. Exacerbating the problem with adding an uncertainty representation to the model is that probability distributions of parameters many years out are rarely known and probably unknowable, making the added value of a stochastic representation unclear in a model with a long planning horizon. Easing the problem is a standard behavior of the solution to a multi-period model with optimal capacity additions: after several periods the capacity additions stabilize into a clear pattern. In the case of electricity generation, after several periods all the types of generation equipment that are economic are added. Once this happens, adding periods to the planning horizon no longer changes the solution in the years of interest, and, more importantly, the marginal value of equipment is the cost of new equipment, preserving the value of existing equipment throughout its economic life. Thus, having a solution with this property, or having a solution close to this property makes it possible to keep the planning horizon relatively short. This property is reached early in the planning horizon because Saudi Arabia has a relatively rapidly growing economy.

Given the issues associated with choosing a planning horizon, KEM incorporates a form of bounded rationality known as recursive dynamics: capacity is added with a planning horizon less than that of the forecast period and the model is solved recursively, stepping forward through all of the years in the planning horizon. The planning horizon covers five years. As the model steps through the forecast years, the planning horizon shrinks and in the last year of the forecast, $T$, the horizon is a single period. In this study $T$= 2032.

Stated more formally, the model performs an optimization of capacity for the years $t$, $t+1$, ..., $t+H$ and optimizes operating decisions for year $t$. When in year $t+1$, the capacity decisions made in prior years for years $t+1$, $t+2$, ..., $t+H+1$ are replaced with an optimization over those years. This representation leads to the same capacity additions as a model with a capacity planning horizon that matches the horizon of the model when this type of capacity is added in the years beyond the planning horizon because the capacity added in any year retains its value throughout the horizon of the model.

In this framework, the cost of adding capacity available in year $t+k(k \in \{0, \dots H\})$ is the present value (in year $t+k$) of the economic depreciation/annualized cost occurring between years $t+k$ and $t+H$. Let

$i$ = interest rate

$L$ = useful life of the equipment

$I$ = investment cost measured at the time the facility first operates, including interest paid during construction.

*Equation 26. Annualized capital cost.*

$$a = \frac{I}{\sum_{l=0}^{L-1} \frac{1}{(1+i)^l}}$$

At time $t$ in KEM the cost of plant and equipment in the kth year beyond $t$ in the recursion is the present value of the annualized capital cost over the remaining years in the planning horizon.

*Equation 27. Cost in kth year beyond t.*

$$c_{t,k} = a \sum_{j=0}^{H-k} \frac{1}{(1+i)^j}$$

The agent optimization in each year t can therefore be viewed as a multi-period optimization done over $H$ years. The only capacity that is retained in year $t+1$ in the solution is the capacity added in year $t$. All out-year capacities are discarded as their only role in the model is to make the capacity additions in $t$ less myopic. The solution process then moves to finding the equilibrium for the year $t+1$ with the new sub-model covering years $t+1$ through $t+H+1$. Again, only the results for year $t+1$ are retained when solving the sub-model subsequent years.

The model distinguishes three different kinds of capacity, existing capacity as of 2013, capacity added from plants currently under construction, the total new builds of capacity prior to year $t$ beyond what is currently under construction. Projects already under construction or with firm commitments, as well as the scheduled decommissioning of existing capacity, are included in determining the amount of existing capacity in each forecast year. The capacity "built" in year $t$, when $t$ is the solution year of interest, is added to the last category when moving forward to year $t+1$

Consider a plant that requires l years to build. This plant can be added to the capacity mix available in year $t+k$ $(k \in \{0, \ldots T\})$ if the lead time is sufficient to build the plant, that is, $t+k \geq 2015+l$. The notion is that the decision to build this plant could have been made in or after 2015. The sub-model also allows equipment with low capital costs, such as turbines, to be built with zero lead times. This ensures the feasibility of the sub-model.

## Appendix 2B: Plants Already Under Construction

At the initial condition, power generation and water desalination capacities already installed by the end of 2012 are included as existing capacity. Plants that were scheduled to come online in 2013 and 2014 are assumed to have been completed. To be conservative, all planned power, refining, and water desalination projects are added as existing capacity at the end of their expected year of operation. Table 32 presents the capacities of power plants already under construction or for which the investment has been made as of 2014. Until 2014, the model can only decide to build gas turbines.

*Table 32. Power plants already under construction across Saudi Arabia as of 2014.*

| Project Name | Capacity (GW) | Technology | Expected year of operation |
|---|---|---|---|
| SEC PP12 | 2.00 | CC | 2015 |
| SEC PP10 | 2.20 GW of GT to be converted | Conversion to CC | 2015 |
| Rabigh 2 IPP | 2.10 | CC | 2017 |
| Shuqaiq Steam Power Plant | 2.64 | Steam with flue gas desulfurization | 2017 |
| Jeddah South Thermal Power Plant | 2.65 | Steam | 2017 |
| Qurayyah IPP | 3.93 | CC | 2017 |

Existing steam and gas turbine capacities that exceed their operating life are withdrawn from service according to the plan published by ECRA (ECRA (Electricity & Cogeneration Regulatory Authority), 2014).

## Appendix 2C: Assumptions Common to all Policy Scenarios

The projected growth rates of population are used to estimate the regional growth in municipal water demand. The projections published by ECRA are used to shift the 2011 regional load curves throughout time, with the peak electricity demand approaching 120 GW by 2032 (ECRA (Electricity & Cogeneration Regulatory Authority), 2010). The growth rates of end-use demand for petroleum products are shown in Figure 37.

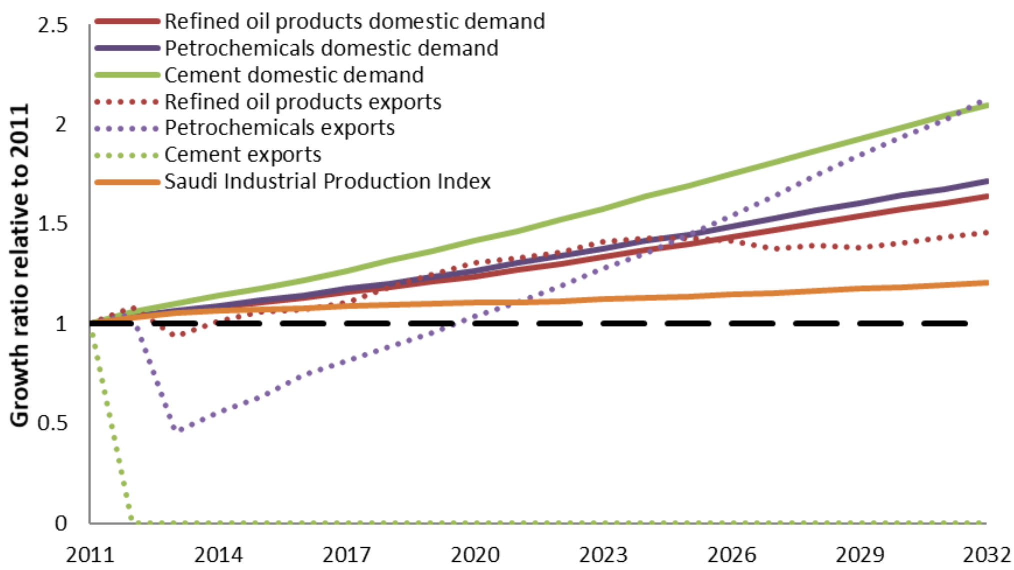



*Figure 37. Estimated national demand growth for sectors' outputs and exports growth relative to 2011.*

Public estimates are used for the future supply of oil and gas. Saudi crude oil production in 2032 is projected by Oxford Economics' GEM to be just short of 13 million barrels per day. The production shares of Arabian crude grades are assumed to remain constant over time.

Projected crude-oil prices in real USD (2014) per barrel are calculated by taking the nominal oil price projections of GEM and deflating the series using the Saudi imports deflator. As Saudi Arabia is a major oil exporter with spare capacity, it may value a barrel of oil saved from domestic consumption at a price that is lower than the international market price. As shown by Matar et al. (2015), the value attributed to the oil saved significantly influences the magnitude of the economic gain realized by alternative policies. In the main scenarios, the value crude oil saved is valued at its international price. A sensitivity analysis is performed in Section 5.6. In addition, export prices for refined oil products and petrochemicals are estimated by assuming that the margin between their prices and that of crude oil remains constant over time, based on the prices observed in 2011 (SAMA, 2014).

Estimated domestic demand and export growth relative to 2011 are shown in Figure 37. First, projections of the Central Department of Statistics and Information (CDSI) for the total population of Saudi Arabia are incorporated. Second, Oxford Economics' GIM is used to estimate projected gross outputs for the petrochemicals, refining, and cement sectors. Additionally, projected real GDP and estimates for income elasticities are used to compute the portion of the gross outputs aimed at meeting domestic demand; an elasticity of unity is applied for cement demand, a value of 0.65 is used for petrochemicals demand, and the value of 0.58, reported by Al-Yousef (2013), is applied for the demand of refined oil products (Al-Yousef, 2013). The difference between projected gross output and domestic demand is used to cap annual exports in the model. In the case of petrochemical exports, actual export data published by the CDSI for 2012 are used. GIM projections are applied thereafter. As an extension of current policy, the 2012 ban on cement exports is extended through the planning horizon. The consumption of oil and gas by industrial sectors not captured in the model is increased by the projected growth of Oxford Economics' Saudi Industrial Production Index.

Saudi natural gas production is projected by the EIA (2013) to increase by an average 1.73 percent per year between 2011 and 2032 (U.S. Energy Information Administration, 2013). The split between ethane and methane in natural gas production is assumed to remain constant. It is also assumed that natural gas produced in Saudi Arabia will continue to be used only for domestic consumption. Table 33 below displays the supply estimates for natural gas and the projected world price of Arabian Light crude.

*Table 33. Projected Saudi Arabian natural gas supply to industrial sectors and the price of crude oil to 2032.*

| | 2015 | 2020 | 2025 | 2030 | 2032 |
|---|---|---|---|---|---|
| **Arabian Light crude price (2014 $/bbl)** | 68.8 | 111.7 | 130.9 | 139.9 | 144.4 |
| **Methane and ethane supply (QBtu)** | 3.17 | 3.5 | 3.9 | 4.50 | 4.7 |

Note that a 10% reserve margin on electrical generating capacity is enforced in every region to ensure grid reliability.

## Appendix 2D: Cost Assumptions

The estimated costs for power generation technologies in 2014 and their construction lead times are summarized in Table 34. All costs are given in 2014 USD, with the adjustments made using the Saudi import price index for capital costs and the Saudi consumer price index for operating costs. Because the model uses inflation-adjusted real USD, the capital and variable operation and maintenance costs of conventional thermal and nuclear technologies are kept constant between 2011 and 2032. The capital and fixed O&M costs of PV and onshore wind turbines decrease over time and are estimated from the cost curves used by IEA (International Energy Agency, 2013). Degradation of PV capacity over time due to thermal stresses is also considered. Jordan and Kurtz (2012) reported a degradation rate of 1% per year for crystalline silicon in desert climates (Jordan and Kurtz, 2012). For Concentrated Solar Power (CSP), the expected percent reduction in the cost reported by IEA (2013) is applied to the 2011 value cited by IRENA (IRENA, 2012). The evolution of capital and fixed O&M costs for the renewable technologies is shown in Figure 38.

*Table 34. Real costs for power generation technologies in 2014 and their lead times (sources: KAPSARC analysis.*

| Power Technology | Capital cost (2014 thousand $/kW) | Fixed O&M cost (2014 $/kW/year) | Non-fuel variable O&M cost (2014 $/MWh) | Lead time (years) |
|---|---|---|---|---|
| Gas turbine | 1.61 | 12.31 | 4.40 | -* |
| Combined cycle | 1.89 | 13.63 | 3.63 | 3 |
| Conversion of single-cycle gas turbine to combined cycle | 0.26 | - | - | 1 |
| Steam | 2.30 | 12.31 | 1.80 | 2 |
| Steam with $SO_2$ Scrubber | 2.79 | 18.35 | 4.87 | 2 |
| Nuclear | 4.88 | 109.88 | 2.35 | 7 |
| PV | 2.42 | 30.27 | 0 | 2 |
| CSP (with thermal storage) | 7.03 | 70.29 | 3.09 | 3 |
| Wind (onshore) | 1.56 | 24.57 | 0 | 3 |

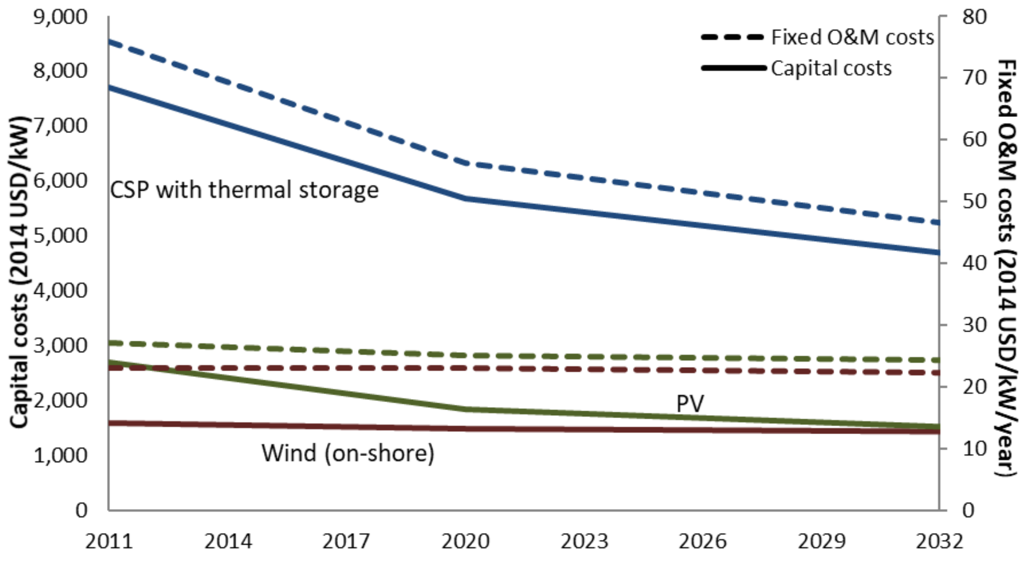



*Figure 38. Profiles of capital and fixed O&M costs over time for renewable technologies.*

The costs incurred from installing an $SO_2$ scrubber are added to the costs of a steam plant without flue-gas desulfurization; capital and operation costs of a scrubber are reported by the

United States Environmental Protection Agency (EPA) (U.S. Environmental Protection Agency, 2013). Additionally, EPA estimates a 1.33% heat rate increase due to the higher in-plant consumption of electricity to operate a scrubbing unit.

Technologies represented in the desalination, petrochemical, refining, and cement sub-models are well-established and, therefore, constant real investment costs are used over the projection horizon.

## Appendix 2E: Model Development

Compared to Matar et al. (2015), additional power generation technologies now represented in KEM are CSP with thermal storage, wind turbines, and steam plants with flue gas desulfurization. Temporal information is required for the use of thermal storage in a CSP plant (rather than a load duration curve representation. A load curve is used to represent the levels of demand at different times of the day, with weekdays distinguished from weekends. Three seasons are also represented: winter and summer, with the fall and spring seasons combined into a single season, which means there are six load curves per region. Figure 39 to Figure 41 show the average hourly weekday loads corresponding to each season and region for 2011. As illustrated by Figure 39 for the southern region, the load curves are discretized into eight load segments, with the discretization selectively performed to provide finer resolution around the afternoon and early evening periods. The chronological representation of demand also allows the specification of administered electricity tariffs for industrial sectors that vary seasonally and by time-of-day.

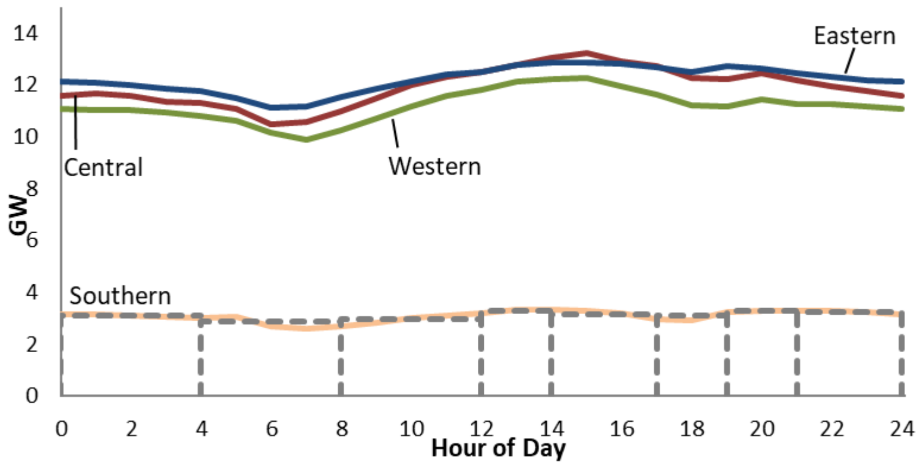



*Figure 39. Weekday hourly loads in the summer.*

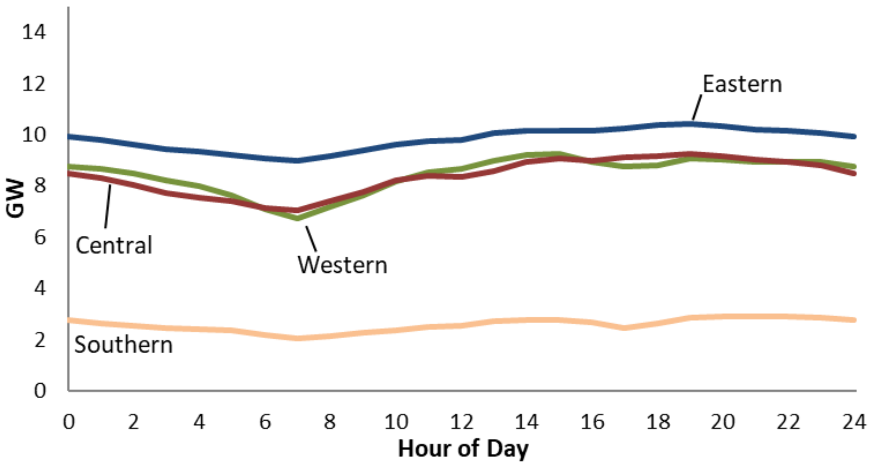



*Figure 40. Weekday hourly loads in the spring and fall.*

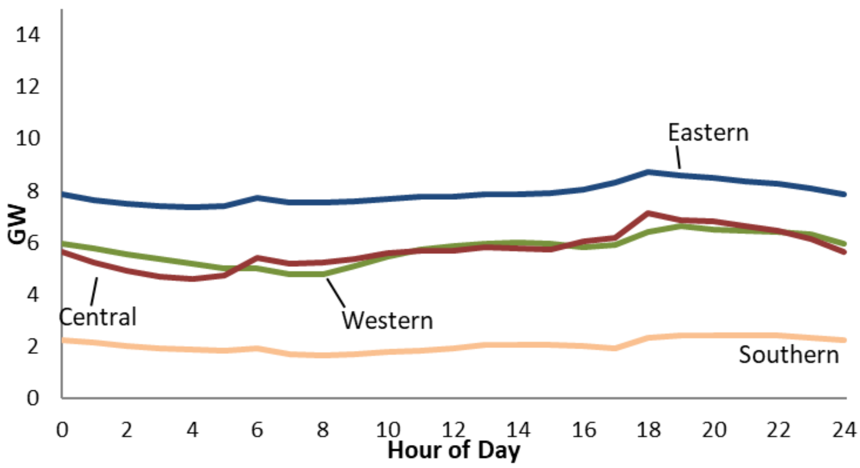


*Figure 41. Weekday hourly loads in the winter.*

The representation of CSP in the current version of KEM is limited to parabolic trough technology with molten salt thermal energy storage. The storage mechanism can store enough heat to operate the plant at full capacity for up to eight hours. Figure 42 illustrates the approach taken to model the operating decisions of a CSP plant. Heat transferred out of the solar field may either be used to provide instantaneous heat to the steam generator or be stored for use when it is needed (Kearney, 2010). Using the direct normal irradiation (DNI) measurements made by the National Renewable Energy Laboratory (NREL) and King Abdulaziz City for Science and Technology (KACST), the amount of solar irradiation directly incident on the aperture plane of the collectors is first calculated to determine the rate of energy transfer from the solar field (NREL (National Renewable Energy Laboratory) and KACST (King Abdullah City for Science and Technology), 2013). Single-axis tracking is done by arranging the collectors along the north-south axis and varying their tilt angle from east to west throughout the day.

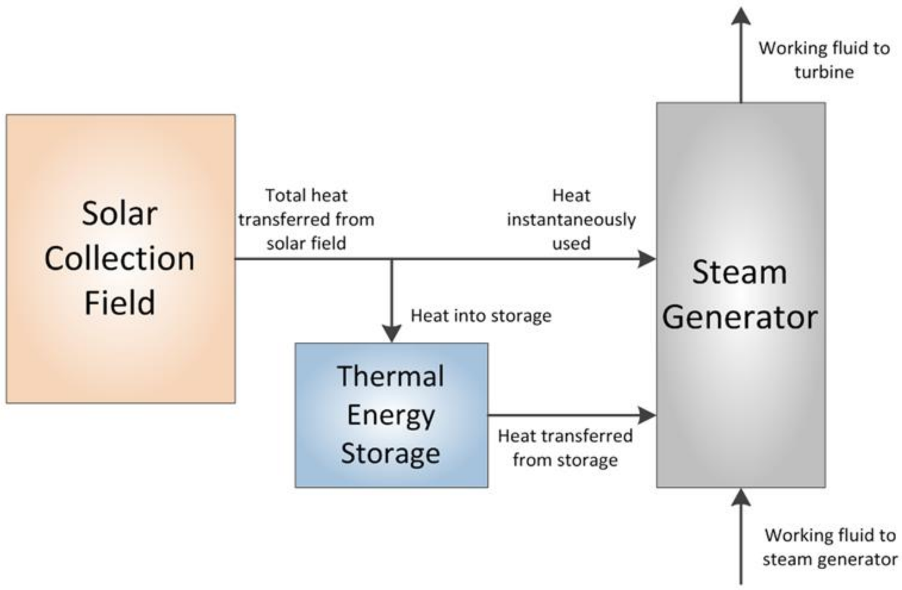



*Figure 42. Heat flows in a CSP plant with thermal storage.*

Because of irreversibilities such as friction effects, the model assumes a 35% loss in heat between the point of reception and either the storage device or the steam generator (Rovira et al., 2013). An energy balance is performed on the storage mechanism that, once heat is stored, considers cycling losses and hourly heat dissipation. Madaeni et al. estimate a cycling loss of 1.5%, and Sioshansi and Denholm document a 0.031% hourly loss of stored heat for a molten salt system (Madaeni et al., 2012; Sioshansi and Denholm, 2010). We incorporate a Rankine cycle thermal efficiency for a typical CSP plant to calculate the amount of electricity generated from the heat input. Like Sioshansi and Denholm, this analysis assumes that CSP plants do not contribute to the planning reserve margin due to limitations in ramping and start-up. The major performance characteristics of CSP in the model are summarized in Table 35.

*Table 35. Major performance characteristics of CSP in KEM.*

| | |
|---|---|
| **Net thermal efficiency of Rankine cycle** | 38% |
| **Aperture area per unit of generation capacity*** | 10 $km^2/GW_e$ |
| **Heat transfer loss from solar field** | 35% |
| **Hourly heat dissipation in storage device** | 0.031% |
| **Heat loss due to cycling** | 1.5% |
| **Thermal storage limit** | Energy equivalent to 8 hours of full operation |

Another power generation technology added to KEM is onshore wind turbines. The rate of energy transfer with wind is proportional to its speed cubed. Wind turbines are designed to operate only if the wind speeds are between some cut-in and cut-off speeds, and their power output plateaus once their rated wind speed is observed. For a typical turbine, the analysis implements a cut-in speed of 3 meters per second, a cut-off speed of 25 meters per second, and a rated speed of 13 meters per second (Al-Abbadi, 2005).

Hourly wind speed data for Saudi Arabia could not be obtained. Instead, monthly Weibull distribution curves of hourly data presented by Rehman et al. are used to estimate profiles of the hourly wind speeds using the season- and region-specific Weibull shape and scale parameters (Rehman et al., 1994; Rehman and Ahmed, 2004). The shapes of the daily profiles are then calibrated to the distributions' mean values and the average diurnal speed variations graphically presented by Al-Abbadi.

For each region, the power output of the turbine in every load segment is normalized by the maximum annual output, and the decisions to operate any existing capacity or install additional units are made based on the impact the output would have on the load curve. Due to the intermittent nature of wind speeds, the additional costs of operating spinning reserves are also captured when operating wind turbine capacity.

Steam plants with flue gas desulfurization exhibit slightly different operating characteristics compared with those without. While the use of HFO is bounded by values observed in 2011, this restriction is lifted for plants with desulfurization units. In addition, the increased self-consumption of electricity due to the operation of a desulfurization unit results in lower thermal efficiency for the plant.

## Appendix 2F: The Implicit Fuel Contracts Scenario

This section details the mathematical implementation of the Implicit Fuel Contracts Scenario. Let

| | |
|---|---|
| *R* | indexes the regions |
| *F* | indexes the fuels |
| *S* | indexes the sectors |
| *i* | indexes the operating activities that consume fuels |
| $QA_{sfr}$ | the quantity of fuels allocated at the lower price |
| $DS_{sfr}$ | the discount from marginal cost of fuel for the lower-priced step |
| $OP_{sifr}$ | the operate activities that consume fuel $f$ |
| $x_{sfr}$ | the amount of fuel consumed at the lower price |
| $\alpha_{sifr}$ | the fuel consumption per unit of operation of $OP_{sifr}$ |

| | |
|---|---|
| $P_{sfr}^{m}$ | the marginal cost of gas, the dual on the fuel material balance |
| $\mu_{sfr}$ | the dual on the allocation constraint |
| $\nu_{sfr}$ | the dual on the fuel consumption limit |
| $P_{sfr}^{adm}$ | the administered price on the first supply step |

Note that the time index is left off to simplify the notation.

*Equation 28. Fuel f consumed in sector s in region r.*

$$\sum_i \alpha_{sifr}\, OP_{sifr} \quad (P_{sfr}^{m})$$

Two constraints are added. The first limits the amount of lower-cost fuel to the allocation and the second limits the amount of lower-cost fuel to the amount of fuel consumed. The equations become:

*Equation 29. Allocation of lower-cost fuel.*

$$x_{sfr} \le QA_{sfr} \quad (\mu_{sfr})$$

*Equation 30. Limits on the amount of lower-cost fuel consumption.*

$$x_{sfr} \le \sum_i \alpha_{sifr}\, OP_{sifr}\, .\ (\nu_{sfr})$$

The standard LP dual is written in Equation 31.

*Equation 31. Dual of the linear program.*

$$-P_{sfr}^{m} + \mu_{sfr} + \nu_{sfr} \ge 0$$

When $x_{sfr} \ge 0$,

*Equation 32. Initial complementarity condition.*

$$-P_{sfr}^{m} + \mu_{sfr} + \nu_{sfr} = 0$$

With the price cap on supply, $P_{sfr}^{adm}$ is set as the price of fuel *f*. In the MCP, the LP dual equation can be written in Equation 33.

*Equation 33. Fuel price.*

$$P_{sfr}^{m} \le P_{sfr}^{adm} + \mu_{sfr} + \nu_{sfr}$$

Here the duals in Equation 27 and Equation 28 add to the value of the rent on the allocated fuel. The complementarity condition becomes,

*Equation 34. Complementarity condition with rent of allocated fuels.*

$$P_{sfr}^{m} \le P_{sfr}^{adm} + \mu_{sfr} + \nu_{sfr} \perp x_{sfr}$$

If $P_{sfr}^{m} < P_{sfr}^{adm}$, then supply is available below the administered price. If this is allowed, unallocated gas is taken first. If this happens, this is a meaningful result. Note: once the model has a demand response, the rents on the allocated fuels must be passed on to consumers through average-cost pricing.

## Appendix 3A: Technology costs

*Table 36. Technology costs used in KEM-GCC.*

| Technology | Capital cost ($/GW) | Variable O&M ($/GWh) | Fixed O&M ($/GW) |
|---|---|---|---|
| **Steam turbine** | 1026 | 3420 | 17.2 |
| **OCGT** | 1026 | 4430 | 17.2 |
| **CCGT (new build)** | 911 | 3420 | 10.7 |
| **CCGT (converted)** | 180 | 3420 | 10.7 |
| **Nuclear** | 5288 | 2250 | 98.1 |
| **PV** | 2360 | - | 24 |
| **CSP** | 5250 | - | 210 |
| **Wind** | 2020 | - | 50 |

## Appendix 3B: Load curve data

Exogenous electricity demand is represented as 48 load segments per country. Hourly data for Saudi Arabia was collected then discretized into eight hourly loads for two types of days (weekday and weekend) and three seasons (summer, winter, and a combined spring-fall). The daily load segments begin at midnight for a duration of four hours. As the day progresses, shorter durations per segment are used to capture the fluctuation in the demand profile.

*Table 37. Periods and duration of daily load segments.*

| Load segment | Period | Hours |
|---|---|---|
| **L1** | 00:00 – 04:00 | 4 |
| **L2** | 04:00 – 08:00 | 4 |
| **L3** | 08:00 – 12:00 | 4 |
| **L4** | 12:00 – 14:00 | 2 |
| **L5** | 14:00 – 17:00 | 3 |
| **L6** | 17:00 – 19:00 | 2 |
| **L7** | 19:00 – 21:00 | 2 |
| **L8** | 21:00 – 24:00 | 3 |

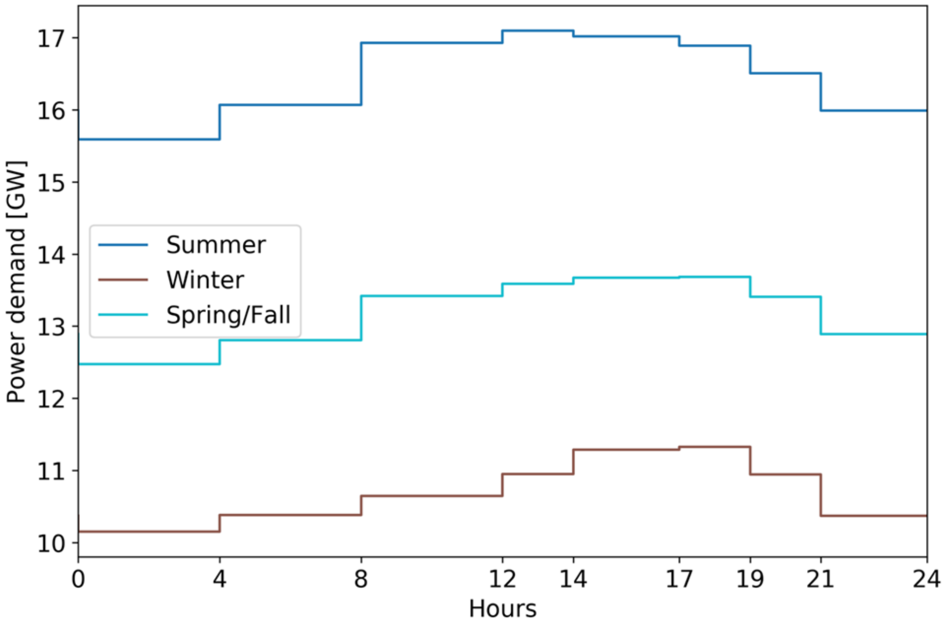



*Figure 43. Load segments for the eastern region of Saudi Arabia in 2015. Unique load segments are used for the remaining 11 regions in the model.*

## Appendix 3C: Solar and wind resource profiles

Solar insolation and wind speed data were collected for Saudi Arabia, Qatar, and the UAE from the National Renewable Energy Laboratory (NREL) database (NREL (National Renewable Energy Laboratory), 2018a). Data were not obtained for Bahrain, Kuwait, or Oman. It is assumed these countries take the same values as Abu Dhabi. Data were adjusted for time zone differences. The hourly data were discretized into load segments corresponding to the eight discrete segments and three representative seasons (as discussed in Appendix B). Heatmaps of solar and wind resources for Saudi Arabia illustrate the temporal and geographic variation (Figure 44 and Figure 45).

The south and central regions of Saudi Arabia have the highest incidence of solar irradiance (DNI). The level of solar irradiance varies across seasons and regions, from a low of 49 watts per m2 (W/m2) in winter in the Eastern region to 760 W/m2 in summer in the Central region. Across regions, solar irradiance is consistently highest in L4 (Figure 44).

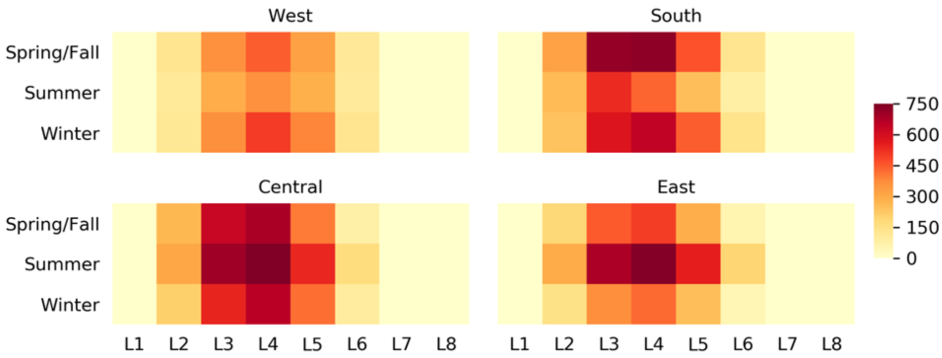



*Figure 44. Direct normal irradiance for Saudi Arabia in W/m2.*

KEM assumes utility-scale fixed panels for the PV technology. The hourly operation of solar is proportional to direct normal irradiance (DNI). Degradation effects and efficiency losses are included. This corresponds to an equivalent capacity factor of 24 percent, which is at the upper range of assumptions for single-axis utility scale PV reported by NREL (NREL (National Renewable Energy Laboratory), 2018b).

Wind is available during all hourly segments across the GCC. In non-coastal regions (e.g., Central Saudi Arabia), wind speeds peak in the evening hours and decrease during daylight hours. Wind speed in coastal areas (e.g., East Saudi Arabia) peaks during daylight hours.

Wind speed in Saudi Arabia varies significantly over regions and seasons. Across all regions and seasons, average wind speeds are highest in load segment L5. The highest wind speed of 8 meters per second (m/s) is found during this three-hour period in the eastern region in the Spring/Fall season (Figure 45).

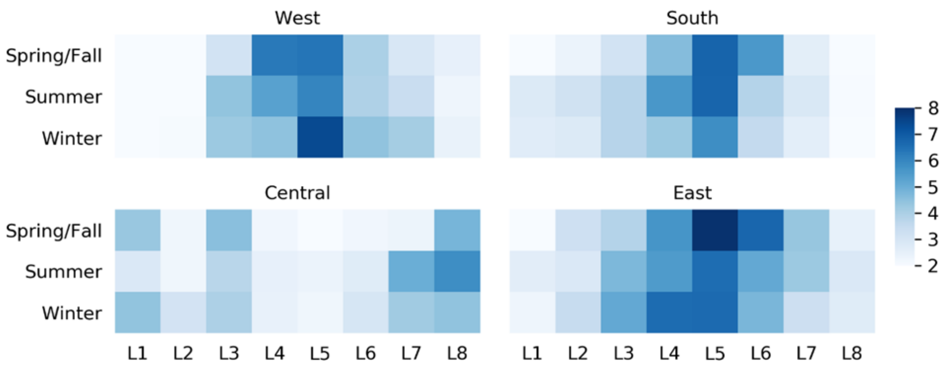



*Figure 45. Wind speeds for Saudi Arabia in m/s.*

Power generated by wind is proportional to the wind velocity raised to the third power. Wind technology is assumed to be onshore wind. This corresponds to an equivalent capacity factor of 20 percent for wind in Saudi Arabia.

## Appendix 3D: Sensitivity to lower cost PV

Solar PV capital costs have declined since 2015 leading to investments in the technology by both state-owned utilities and private investors. The two deregulation scenarios (Section 4.3 and 4.4) were rerun using PV capital costs at half the EIA 2016 costs and examine the impact on electricity exchange.

As expected, it is found that solar PV investment increases as it becomes cost-competitive with other technologies with and without electricity exchange. Capacity investment in the exchange scenario is shown in Table 38. In Saudi Arabia, PV capacity is built instead of CCGTs. PV deployments approach 68 GW.

*Table 38. Capacity investments made when solar PV costs are reduced by half. Totals may not match due to rounding.*

| | OCGT conversion | CCGT new build | PV | Total (GW) |
|---|---|---|---|---|
| **Bahrain** | | 0.8 | | 0.8 |
| **Kuwait** | | 7.4 | 3.9 | 11.8 |
| **Oman** | | 3.5 | | 3.5 |
| **Qatar** | 0.1 | 2.7 | 2.1 | 4.9 |
| **Saudi Arabia** | 3.4 | 32.3 | 59.4 | 95.7 |
| **U.A.E.** | 0.1 | 11.6 | 2.2 | 13.9 |
| ***Total*** | 3.5 | 58.4 | 67.6 | 130.6 |

Cross-border electricity exchange is affected (Table 39). Saudi Arabia imports 4.6 TWh less electricity because it produces more electricity for itself from PV. Exports from Kuwait decrease by 2.5 TWh. Total electricity exchange is similar at 32.8 TWh, due to constraints in the Interconnector capacity.

*Table 39. Cross-border electricity flows in Deregulated Exchange when PV capital costs are reduced by half.*

| To / From | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. | *Gross exports* |
|---|---|---|---|---|---|---|---|
| **Bahrain** | | | | | 5.5 | | 5.5 |
| **Kuwait** | | | | | 9.0 | | 9.0 |
| **Oman** | | | | | | 2.3 | 2.3 |
| **Qatar** | | | | | | | |
| **Saudi Arabia** | 0.3 | 2.6 | | | | 1.8 | 4.6 |
| **U.A.E.** | | | 1.5 | | 9.8 | | 11.4 |
| ***Gross imports*** | 0.3 | 2.6 | 1.5 | | 24.3 | 4.2 | 32.8 |
| ***Net exports*** | 5.3 | 6.4 | 0.8 | | 19.7 | 7.2 | |

The aggregate economic gain with reduced PV costs increases by up to \$2.3 billion (to \$45.7 billion), which illustrates the substantial gains from low-cost non-fossil generation sources for both domestic consumption and exchange. However, the marginal increase of exchange (with low PV costs) decreases to \$790 million (\$40 million less than in Section 4.4). The primary reason the Interconnector provides less economic gain is because the build out of PV provides a domestic energy source without fuel costs, even in the absence of exchange, thus reducing the marginal benefit of exchange.

These results illustrate the importance of the recent cost declines in solar PV relative to fossil technologies. These cost declines will be incorporated in the next stage of this work when we will explore the investments in technologies and subsidy removals over a medium-term horizon.

## Appendix 4A: Detailed results

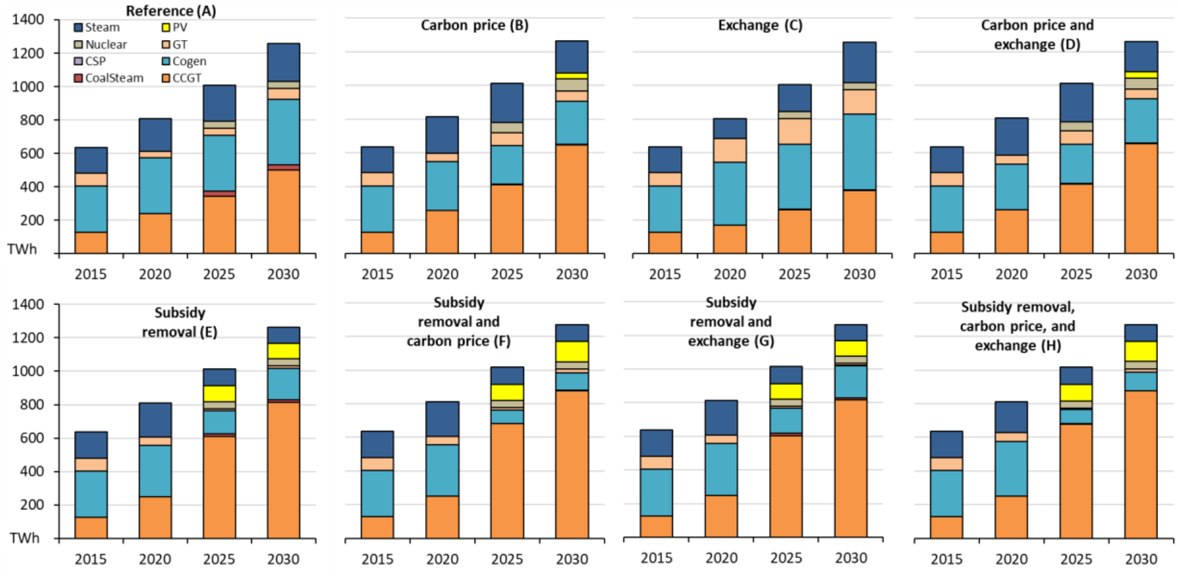



*Figure 46. Electricity supply through 2030 by scenario in TWh (vertical axis) through 2030.*

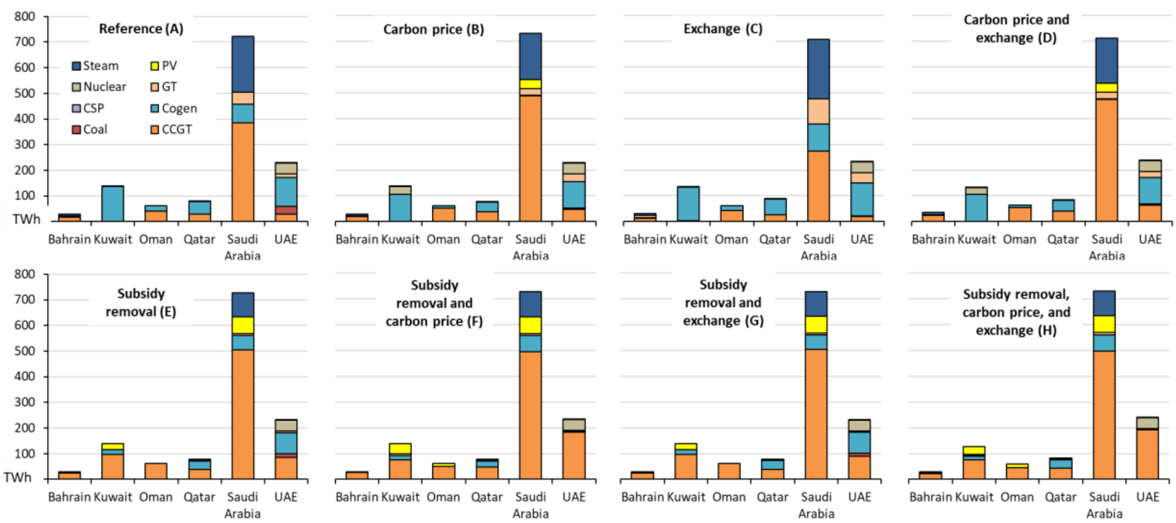


*Figure 47. Electricity supply in TWh in 2030 by country.*

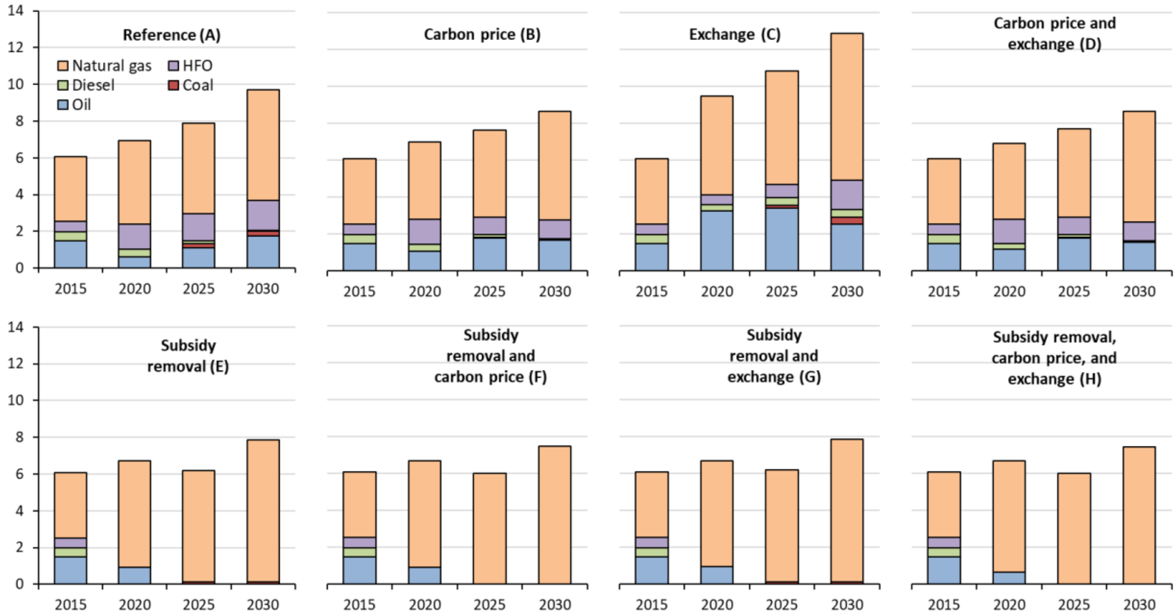



*Figure 48. Fuel consumption in TBtu through 2030.*

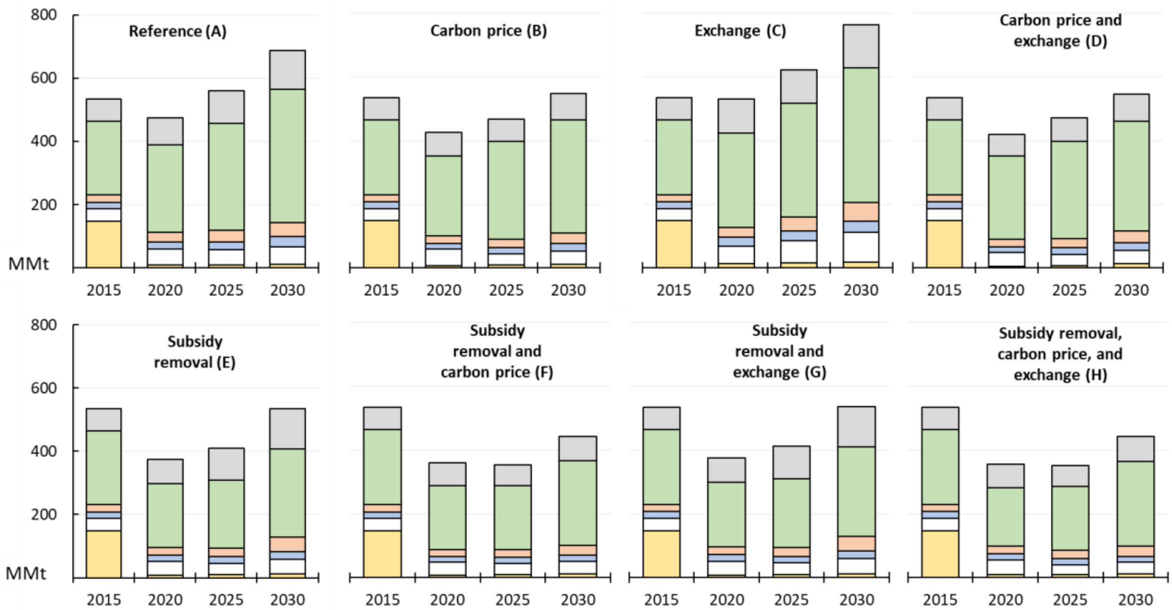


*Figure 49. $CO_2$ emissions from the power and water sectors by scenario in million tonnes (vertical axis) over the projection period (horizontal axis).*

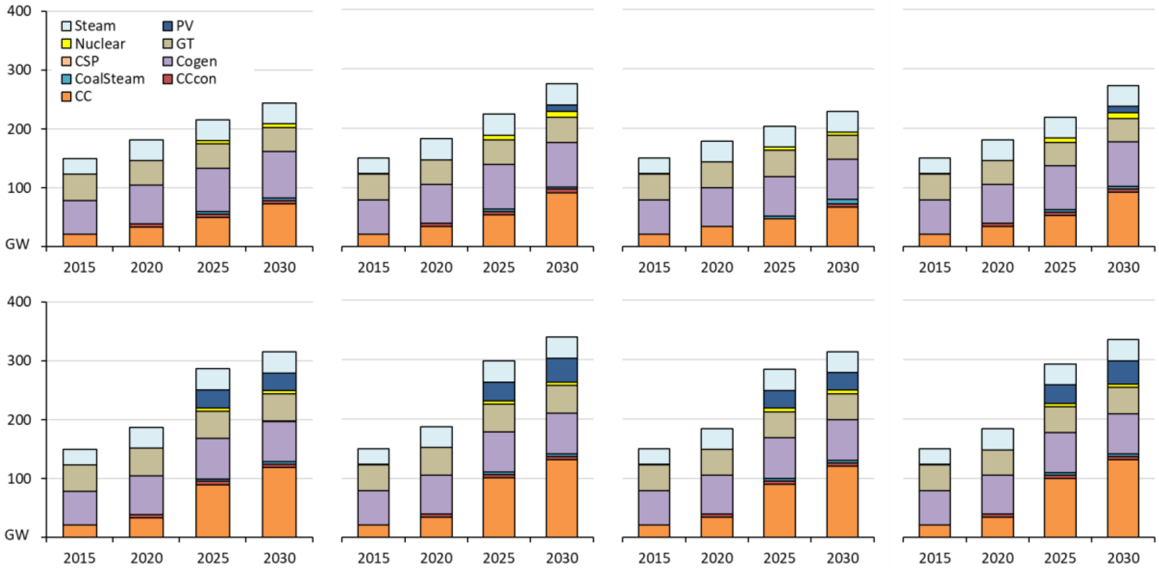



*Figure 50. Power plant capacity in GW (vertical axis) through 2030.*

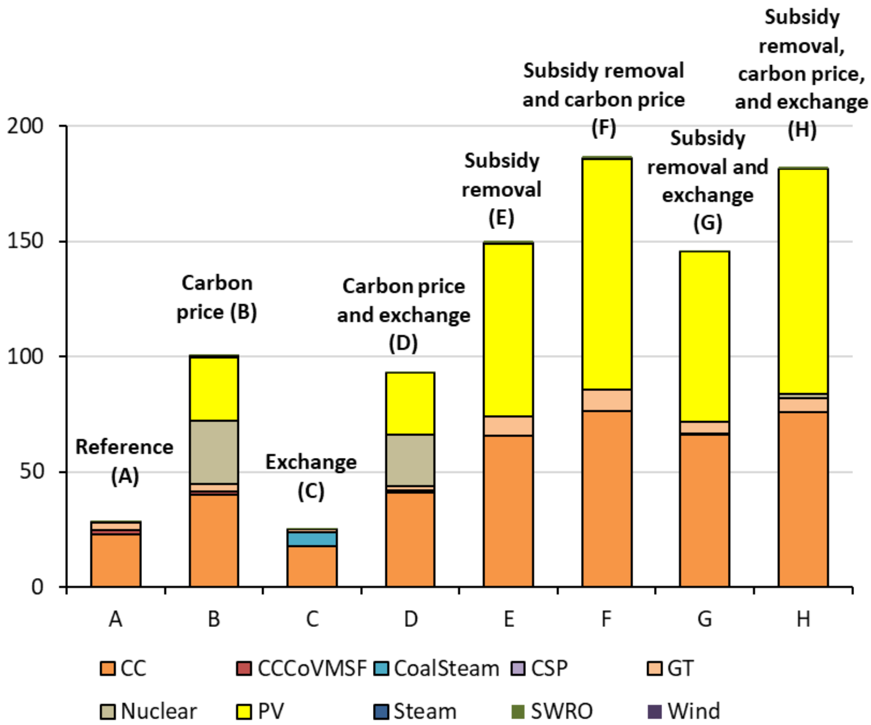



*Figure 51. Cumulative investments in billion USD (vertical axis) by scenario (horizontal axis).*

## Appendix 4B: Electricity exchange tables

*Table 40. Electricity exchange in TWh in Scenario C in 2030.*

| From \ To | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. |
|---|---|---|---|---|---|---|
| **Bahrain** | | | | | | |
| **Kuwait** | | | | | 1.4 | |
| **Oman** | | | | | | |
| **Qatar** | | | | | | |
| **Saudi Arabia** | 5.4 | | | 11.2 | | 6.9 |
| **U.A.E.** | | | 2.8 | | | |

*Table 41. Electricity exchange in TWh in Scenario D in 2030.*

| From \ To | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. |
|---|---|---|---|---|---|---|
| **Bahrain** | | | | | | |
| **Kuwait** | | | | | 6.7 | |
| **Oman** | | | | | | |
| **Qatar** | | | | | | |
| **Saudi Arabia** | | | | 8.9 | | 11.6 |
| **U.A.E.** | | | 2.7 | | | |

*Table 42. Electricity exchange in TWh in Scenario G in 2030.*

| From \ To | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. |
|---|---|---|---|---|---|---|
| **Bahrain** | | | | | | |
| **Kuwait** | | | | | | |
| **Oman** | | | | | | |
| **Qatar** | | | | | | |
| **Saudi Arabia** | | | | 0.8 | | |
| **U.A.E.** | | | | | | |

*Table 43. Electricity exchange in TWh in Scenario H in 2030.*

| From \ To | Bahrain | Kuwait | Oman | Qatar | Saudi Arabia | U.A.E. |
|---|---|---|---|---|---|---|
| **Bahrain** | | | | | 0.2 | |
| **Kuwait** | | | | | 8.8 | |
| **Oman** | | | | | | 2.4 |
| **Qatar** | | | | | | |
| **Saudi Arabia** | | | | 5.6 | | 0.6 |
| **U.A.E.** | | | | | | |

## Appendix 4C: Capacity addition assumptions

*Table 44. Bahrain.*

| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|
| **Steam** | 1.3 | | | | | | | | |
| **GT** | 1.6 | | | | | | | | |
| **CC** | 1.9 | | | | | | | | |
| **PV** | | | | | | | | | |
| **CSP** | | | | | | | | | |
| **Nuclear** | | | | | | | | | |
| **Wind** | | | | | | | | | |
| **Steam Co.** | 0.2 | | | | | | | | |
| **GT Co.** | 0.1 | | | | | | | | |
| **CCGT Co.** | | | | | | | | | |

*Table 45. Kuwait.*

| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|
| **Steam** | | | | | | | | | |
| **GT** | | | | | | | | | |
| **CC** | | | | | | | | | |
| **PV** | 0.0 | | | | | | | | |
| **CSP** | | | | | | | | | |
| **Nuclear** | | | | | | | | | |
| **Wind** | | | | | | | | | |
| **Steam Co.** | 9.0 | | | | | | | | |
| **GT Co.** | 7.0 | | | | | | | | |
| **CCGT Co.** | 2.3 | | | | | 0.3 | | 1.8 | |

*Table 46. Oman.*

| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|
| **Steam** | | | | | | | | | |
| **GT** | | | | | | | | | |
| **CC** | 5.0 | 0.1 | | | 3.3 | | 0.5 | 0.7 | |
| **PV** | | | | | | | | | |
| **CSP** | | | | | | | | | |
| **Nuclear** | | | | | | | | | |
| **Wind** | | | | | | | | | |
| **Steam Co.** | | | | | | | | | |
| **GT Co.** | | | | | | | | | |
| **CCGT Co.** | 2.5 | | | | | | | | |

*Table 47. Qatar.*

| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|
| **Steam** | | | | | | | | | |
| **GT** | 1.3 | | | | | | | | |
| **CC** | 2.0 | | | | | | | | |
| **PV** | | | | | | | | | |
| **CSP** | | | | | | | | | |
| **Nuclear** | | | | | | | | | |
| **Wind** | | | | | | | | | |
| **Steam Co.** | | | | | | | | | |
| **GT Co.** | 1.7 | | | | | | | | |
| **CCGT Co.** | 4.5 | | 0.8 | 0.8 | | | | | |

*Table 48. Saudi Arabia.*

| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|
| **Steam** | 25.3 | 4.4 | 3.6 | 0.4 | | | | | |
| **GT** | 35.9 | 0.4 | 0.1 | 0.8 | | | | | |
| **CC** | 10.0 | 3.9 | | 2.1 | 1.5 | 7.0 | 5.4 | | |
| **PV** | | | | | 0.3 | | | | |
| **CSP** | | | | | | 0.2 | | | |
| **Nuclear** | | | | | | | | | |
| **Wind** | | | 0.0 | | | | | | |
| **Steam Co.** | 5.2 | | | 0.8 | | | | | |
| **GT Co.** | 0.2 | | | | | | | | |
| **CCGT Co.** | 0.7 | 2.7 | 2.7 | 0.8 | | | | | |

*Table 49. U.A.E.*

| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|
| **Steam** | | | | | | | | | |
| **GT** | 5.7 | | | | | | | | |
| **CC** | 2.4 | 0.3 | | 1.2 | | | | | |
| **PV** | 0.0 | | 0.2 | 0.2 | | 1.8 | | 0.2 | |
| **CSP** | 0.1 | | | | | | | | |
| **Nuclear** | | | | | | 5.6 | | | |
| **Coal** | | | | | | | 1.8 | | 2.4 |
| **Wind** | | | | | | | | | |
| **Steam Co.** | 2.2 | | | | | | | | |
| **GT Co.** | | | | | | | | | |
| **CCGT Co.** | 18.3 | | | | | | | | |

## Appendix 4D. Assumptions in sensitivity analyses

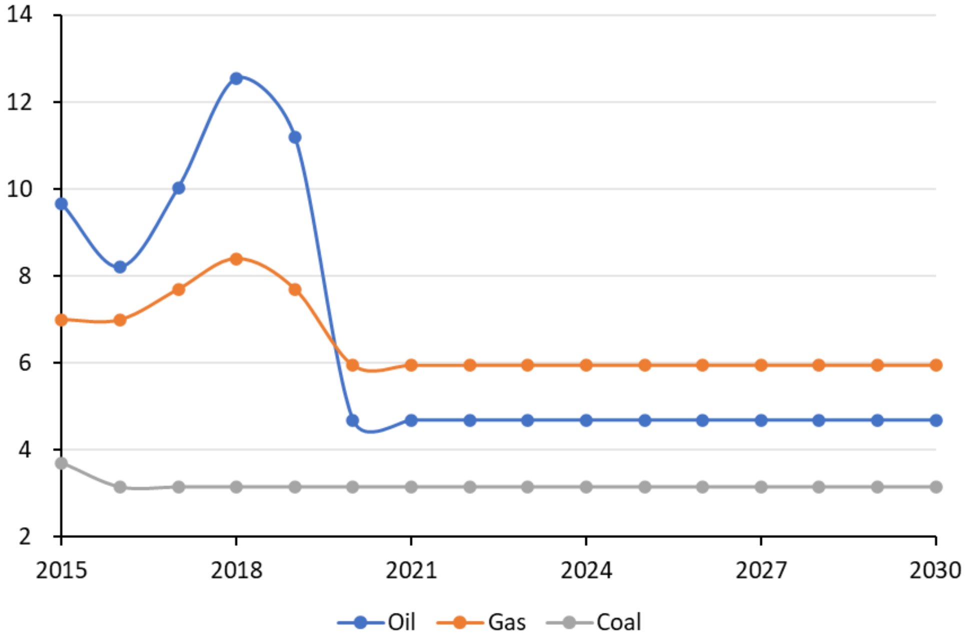



*Figure 52. Assumption for oil price sensitivity analysis.*

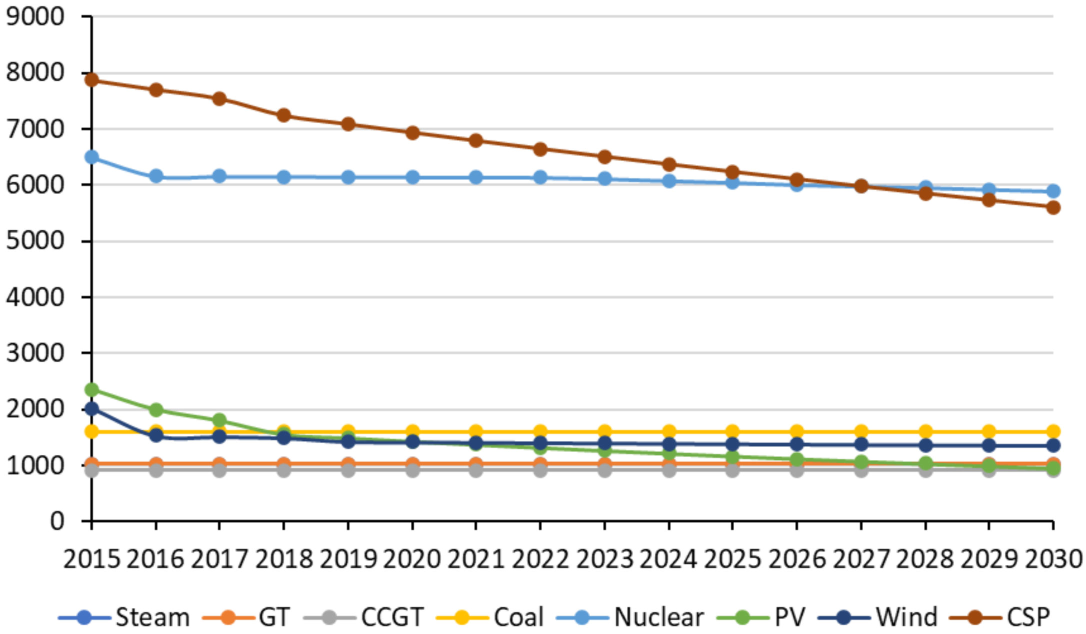



*Figure 53. Assumption for technology sensitivity analysis.*

## Appendix 4E. Calculating Shapley values

The Shapley value represents the average marginal contribution of a policy to a set of policies (Murphy and Rosenthal, 2006). It is a useful metric that provides insight beyond the additive benefits of expected returns from a set of policies. Policies can be thought of as agents joining a coalition (set of policies). The Shapley value is calculated using Equation 35.

*Equation 35. The Shapley formula.*

$$\varphi_i(v) = \sum_{S \subseteq N-\{i\}} \frac{|S|!\,(N-|S|-1)!}{N!}[v(S \cup \{i\}) - v(S)]$$

The term $\frac{|S|!(N-|S|-1)}{N!}$ represents the share contribution of each policy to the marginal value, where N is the total set of policies. The term $[v(S \cup \{i\}) - v(S)]$ represents the marginal value of introducing policy $i$ in to the subset of policies, $S$. The term $|S|$ is the cardinal of set $S$. In this analysis, there are three policies: carbon price, electricity exchange, and fuel price subsidy removal. These are noted as C, E, and R, respectively for the following calculations. The components of the Shapley equation are tabulated in Table 50 through Table 52. The Shapley parameters when recycling carbon revenue are shown in Table 53 through Table 55. The Shapley values are the marginal economic contribution of that policy in billion USD.

*Table 50. Parameters of the Shapley equation for the carbon price policy, without recycling carbon revenues (billion USD).*

| $S$ | $v(S \cup \{C\}) - v(S)$ | $\|S\|$ | $\frac{\|S\|!\,(N-\|S\|-1)!}{N!}$ | Shapley Value |
|---|---|---|---|---|
| {} | -34.1 | 0 | 1/3 | -11.4 |
| E | -3.7 | 1 | 1/6 | -0.6 |
| R | -1.2 | 1 | 1/6 | -0.2 |
| ER | 8.1 | 2 | 1/3 | -2.7 |
| | | | | **-9.5** |

*Table 51. Parameters of the Shapley equation for the electricity exchange policy, without recycling carbon revenues (billion USD).*

| $S$ | $v(S \cup \{E\}) - v(S)$ | $\|S\|$ | $\frac{\|S\|!\,(N-\|S\|-1)!}{N!}$ | Shapley Value |
|---|---|---|---|---|
| {} | -745.4 | 0 | 1/3 | -248.5 |
| C | -3.7 | 1 | 1/6 | -0.6 |
| R | 0.3 | 1 | 1/6 | 0.0 |
| CR | 9.6 | 2 | 1/3 | 3.2 |
| | | | | **-245.8** |

*Table 52. Parameters of the Shapley equation for the subsidy reform policy, without recycling carbon revenues (billion USD).*

| $S$ | $v(S \cup \{R\}) - v(S)$ | $\lvert S\rvert$ | $\frac{\lvert S\rvert!\,(N - \lvert S\rvert - 1)!}{N!}$ | **Shapley Value** |
|---|---|---|---|---|
| {} | 845.8 | 0 | 1/3 | 281.9 |
| C | 878.7 | 1 | 1/6 | 146.4 |
| E | 1591.4 | 1 | 1/6 | 265.2 |
| CE | 891.9 | 2 | 1/3 | 297.3 |
| | | | | **990.9** |

*Table 53. Parameters of the Shapley equation for the carbon price policy while recycling carbon revenues (billion USD).*

| $S$ | $v(S \cup \{C\}) - v(S)$ | $\lvert S\rvert$ | $\frac{\lvert S\rvert!\,(N - \lvert S\rvert - 1)!}{N!}$ | **Shapley Value** |
|---|---|---|---|---|
| {} | 169.1 | 0 | 1/3 | 56.4 |
| E | -3.1 | 1 | 1/6 | -0.5 |
| R | 155.0 | 1 | 1/6 | 25.8 |
| ER | 164.3 | 2 | 1/3 | 54.8 |
| | | | | **136.4** |

*Table 54. Parameters of the Shapley equation for the electricity exchange policy while recycling carbon revenues (billion USD).*

| $S$ | $v(S \cup \{E\}) - v(S)$ | $\lvert S\rvert$ | $\frac{\lvert S\rvert!\,(N - \lvert S\rvert - 1)!}{N!}$ | **Shapley Value** |
|---|---|---|---|---|
| {} | -745.3 | 0 | 1/3 | -248.4 |
| C | -3.1 | 1 | 1/6 | -0.5 |
| R | 0.3 | 1 | 1/6 | 0.0 |
| CR | 9.5 | 2 | 1/3 | 3.2 |
| | | | | **-245.8** |

*Table 55. Parameters of the Shapley equation for the subsidy reform policy while recycling carbon revenues (billion USD).*

| $S$ | $v(S \cup \{R\}) - v(S)$ | $\|S\|$ | $\frac{\|S\|!\,(N - \|S\| - 1)!}{N!}$ | **Shapley Value** |
|---|---|---|---|---|
| {} | 845.8 | 0 | 1/3 | 281.9 |
| C | 831.7 | 1 | 1/6 | 138.6 |
| E | 1591.4 | 1 | 1/6 | 265.2 |
| CE | 844.3 | 2 | 1/3 | 281.4 |
| | | | | **967.2** |

# References

Abbas, F.J., Habriri, N., 2017. Saudi Arabia to become 'major exporter' of renewable energy. Arab News.

Ahmed, T., Mekhilef, S., Shah, R., Mithulananthan, N., 2017. Investigation into transmission options for cross-border power trading in ASEAN power grid. Energy Policy 108, 91–101. https://doi.org/10.1016/J.ENPOL.2017.05.020

Al-Abbadi, N., 2005. Wind energy resource assessment for five locations in Saudi Arabia. Renew. Energy 30, 1489–1499.

Al-Ibrahim, A., 2015. GCC Interconnection: Opportunities and Challenges Working towards an Electricity Trade Price.

Al-Saleh, Y., 2009. Renewable energy scenarios for major oil-producing nations: The case of Saudi Arabia. Futures 41, 650–662.

Al-Yousef, N., 2013. Demand for Oil Products in OPEC Countries: A Panel Cointegration Analysis. Int. J. Energy Econ. Policy 3, 168–177.

Bahrain Mirror, 2018. Bahrain Raises Natural Gas Price to $3.25 per Million Thermal Units [WWW Document]. URL http://www.bahrainmirror.com/en/news/45628.html

Böckers, V., Haucap, J., Heimeshoff, U., 2013. Cost of Non-Europe in the Single Market for Energy ANNEX IV Benefits of an integrated European electricity market: the role of competition. https://doi.org/10.2861/19914

Boersma, T., Griffiths, S., 2016. Reforming Energy Subsidies: Initial Lessons from the United Arab Emirates.

British Petroleum, 2014. Statistical Review of World Energy 2014.

Dantzig, G.B., 1951. Maximization of a Linear Function of Variables Subject to Linear Inequalities, Activity Analysis of Production and Allocation. Wiley, New York.

DEWA (Dubai Electricity and Water Authority), 2014. DEWA Sustainability Report 2014.

Dey, P., 2018. UAE to become self-sufficient gas producer by 2030: Al-Mazrouei [WWW Document]. Argaam Invest. Co. URL https://www.argaam.com/en/article/articledetail/id/580350

Dixit, R.K., Pindyck, R.S., 1994. Investment under Uncertainty. Princeton University Press.

ECRA (Electricity & Cogeneration Regulatory Authority), 2020. The Long Term Plan [WWW Document]. URL https://ecra.gov.sa/en-us/AboutECRA/ECRACommeties/Pages/THE-LONG-TERM-PLAN-FOR-POWER-GENERATION,-WATER-PRODUCTION-AND-FUEL-REQUIREMENTS.aspx

ECRA (Electricity & Cogeneration Regulatory Authority), 2015. Annual Statistical Booklet for Electricity and Seawater Desalination Industries.

ECRA (Electricity & Cogeneration Regulatory Authority), 2014. Annual Statistical Booklet for Electricity and Seawater Desalination Industries 2013.

ECRA (Electricity & Cogeneration Regulatory Authority), 2011. Bringing Demand-Side Management To the Kingdom of Saudi Arabia. Brattle Gr.

https://doi.org/10.1021/jo0624041

ECRA (Electricity & Cogeneration Regulatory Authority), 2010. Revised Generation Planning Report: Electricity Generation and Transmission Plan.

Egging, R.G., Gabriel, S.A., 2006. Examining market power in the European natural gas market. Energy Policy 34, 2762–2778. https://doi.org/https://doi.org/10.1016/j.enpol.2005.04.018

Electricity & Water Authority Kingdom of Bahrain, 2018. EWA Statistics 2018.

Electricity & Water Authority Kingdom of Bahrain, 2016. EWA Statistics.

Electricity and water Authority, 2017. Electricity and water authority statistics 2017- Kingdom of Bahrain.

Elshurafa, A., Mansouri, N., Matar, W., Pierru, A., Pradhan, S., Wogan, D., 2017. Transitioning to Liberalized Energy Markets.

Elshurafa, A.M., 2017. Reporting LCOE for Solar PV : Apples to Apples Comparisons 1–20.

Energy Exemplar, n.d. PLEXOS [WWW Document].

Faeq, F., 2019. Higher Saudi fuel prices are a small price to pay for reform [WWW Document]. Arab News. URL https://www.arabnews.com/node/1527706

Fattouh, B., El-Katiri, L., 2013. Energy subsidies in the Middle East and North Africa. Energy Strateg. Rev. 2, 108–115. https://doi.org/10.1016/j.esr.2012.11.004

Foley, A.M., Gallachóir, B.P.Ó., Hur, J., Baldick, R., Mckeogh, E.J., 2010. A strategic review of electricity systems models. Energy 35, 4522–4530. https://doi.org/10.1016/j.energy.2010.03.057

Gabriel, S., Smeers, Y., 2006. Complementarity Problems in Restructured Natural Gas Markets BT - Recent Advances in Optimization, in: Seeger, A. (Ed.), . Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 343–373.

Gabriel, S.A., Conejo, A.J., J, D.F., Hobbs, B.F., Ruiz, C., 2013. Complementarity Modeling in Energy Markets, 1st ed. Springer-Verlag New York, New York.

Gabriel, S.A., Shim, Y., Conejo, A.J., de la Torre, S., García-Bertrand, R., 2010. A Benders decomposition method for discretely-constrained mathematical programs with equilibrium constraints. J. Oper. Res. Soc. 61, 1404–1419. https://doi.org/10.1057/jors.2009.84

Gnansounou, E., Dong, J., 2004. Opportunity for inter-regional integration of electricity markets: the case of Shandong and Shanghai in East China. Energy Policy 32, 1737–1751. https://doi.org/10.1016/S0301-4215(03)00164-2

Greenberg, H.J., Murphy, F., 1985. Computing Regulated Market Equilibria with Mathematical Programming. Oper. Res. 33, 935–955.

Gulf Cooperation Council Interconnection Authority, 2020a. Company Profile [WWW Document]. URL http://www.gccia.com.sa/P/company_profile/11

Gulf Cooperation Council Interconnection Authority, 2020b. Energy Trading [WWW Document]. URL http://www.gccia.com.sa/P/energy_trading/79

Gulf Cooperation Council Interconnection Authority, 2017. Annual Report 2016. Gulf Cooperation Council Interconnection Authority, Saudi Arabia, Dammam.

Guo, Z., Ma, L., Liu, P., Jones, I., Li, Z., 2016. A multi-regional modelling and optimization approach to China ' s power generation and transmission planning. Energy 116, 1348–1359. https://doi.org/10.1016/j.energy.2016.06.035

Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., Decarolis, J., Bazillian, M., Roehrl, A., 2011. OSeMOSYS : The Open Source Energy Modeling System An introduction to its ethos , structure and development. Energy Policy 39, 5850–5870. https://doi.org/10.1016/j.enpol.2011.06.033

International Energy Agency, 2020. Techno-economic inputs [WWW Document]. URL https://www.iea.org/reports/world-energy-model/techno-economic-inputs

International Energy Agency, 2015. Development Prospects of the ASEAN Power Sector.

International Energy Agency, 2013. World Energy Outlook 2013.

IRENA, 2012. Concentrating Solar Power: Volume 1: Power Sector. Renewable Energy Technologies: Cost Analysis Series.

JODI, 2014. JODI Database.

Jordan, D., Kurtz, S., 2012. Photovoltaic Degradation Rates – An Analytical Review.

KAHRAMAA (Qatar General Electricity & Water Corporation), 2018. Annual Report Year 2018. https://doi.org/10.16309/j.cnki.issn.1007-1776.2003.03.004

KAHRAMAA (Qatar General Electricity & Water Corporation), 2014. Statistics Report.

Kearney, D., 2010. Utility-Scale Parabolic Trough Solar Systems: Performance Acceptance Test Guidelines.

Kingdom of Bahrain, 2015. Intended Nationally Determined Contribution [WWW Document]. URL https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Bahrain First/INDC_Kingdom_of_Bahrain.pdf

Kingdom of Bahrain EWA (Kingdom of Bahrain Electricity and Water Authority), 2016. Statistics 2016 [WWW Document]. Mon. Availab. Peak Load Rep.

Kingdom of Bahrain NOGA (Kingdom of Bahrain National Oil and Gas Authority), 2015. Annual Report 2015.

Kingdom of Saudi Arabia Vision 2030, 2016. National Transformation Program 2020.

Kuwait MEW (Kuwait Ministry of Electricity and Water), 2018a. 2017 Electricity Statistical Year Book.

Kuwait MEW (Kuwait Ministry of Electricity and Water), 2018b. Water Statistical Year Book 2018.

Kuwait MEW (Kuwait Ministry of Electricity and Water), 2016a. Statistical Year Book - Water.

Kuwait MEW (Kuwait Ministry of Electricity and Water), 2016b. Statistical Year Book - Electrical Energy.

Lahn, G., Stevens, P., 2011. Burning Oil to Keep Cool The Hidden Energy Crisis in Saudi Arabia.

Leuthold, F., Dietrich, K., Hennemeier, U., Hetzel, S., Jeske, T., Rumiantseva, I., Rummel, H., Sommer, S., Sternberg, C., Vith, C., Advisors, A., Von Hirschhausen, C., Holz, F., Dresden, F.P., 2005. Trends in German and European Electricity Working Papers WP-GE-08 Nodal Pricing in the German Electricity Sector – A Welfare Economics Analysis, with Particular Reference to Implementing Offshore Wind Capacities Nodal Pricing in the German Electricity Sec.

Li, Y., Lukszo, Z., Weijnen, M., 2016. The impact of inter-regional transmission grid expansion on China's power sector decarbonization. Appl. Energy 183, 853–873. https://doi.org/10.1016/J.APENERGY.2016.09.006

Loulou, R., Labriet, M., 2008. ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. Comput. Manag. Sci. 5, 7–40. https://doi.org/10.1007/s10287-007-0046-z

Macrotrends, 2020. Brent Crude Oil Prices - 10 Year Daily Chart [WWW Document]. URL https://www.macrotrends.net/2480/brent-crude-oil-prices-10-year-daily-chart

Macrotrends, n.d. Natural Gas Prices - Historical Chart [WWW Document]. URL https://www.macrotrends.net/2478/natural-gas-prices-historical-chart

Madaeni, S.H., Sioshansi, R., Denholm, P., 2012. How Thermal Energy Storage Enhances the Economic Viability of Concentrating Solar Power, in: Proceedings of the IEEE 100. pp. 335–347.

Manne, A.S., 1958. A Linear Programming Model of the U. S. Petroleum Refining Industry. Econometrica 26, 67–106. https://doi.org/10.2307/1907384

Mansouri, N.Y., Crookes, R.J., Korakiantis, T., 2013. A projection of energy consumption and carbon dioxide emissions in the electricity sector for Saudi Arabia: The case for carbon capture and storage and solar photovoltaics. Energy Policy 63, 681–695.

Mansur, E.T., White, M.W., Borenstein, S., Hogan, W., Kwoka, J., Riordan, M., Wolak, F., 2012. Market Organization and E¢ ciency in Electricity Markets.

Massachusetts Institute of Technology, 2016a. Kuwait [WWW Document]. Obs. Econ. Complex.

Massachusetts Institute of Technology, 2016b. Oman [WWW Document]. Obs. Econ. Complex.

Massachusetts Institute of Technology, 2016c. Qatar [WWW Document]. Obs. Econ. Complex.

Massachusetts Institute of Technology, 2016d. Saudi Arabia [WWW Document]. Obs. Econ. Complex.

Matar, W., Murphy, F., Pierru, A., Rioux, B., 2015. Lowering Saudi Arabia's fuel consumption and energy system costs without increasing end consumer prices. Energy Econ. 49, 558–569. https://doi.org/10.1016/j.eneco.2015.03.019

Matar, W., Murphy, F., Pierru, A., Rioux, B., Wogan, D., 2017. Efficient industrial energy use: The first step in transitioning Saudi Arabia's energy mix. Energy Policy 105, 80–92. https://doi.org/10.1016/j.enpol.2017.02.029

Matar, W., Pierru, A., Rioux, B., 2014. Modeling the Saudi Energy Economy and Its Administered Components: The KAPSARC Energy Model. USAEE Work. Pap.

Mezher, T., Fath, H., Abbas, Z., Khaled, A., 2011. Techno-economic assessment and environmental impacts of desalination technologies. Desalination 266, 263–273.

https://doi.org/10.1016/j.desal.2010.08.035

Ministry of Climate Change and Environment, 2017. National Climate Change Plan of the United Arab Emirates 2017-2050, Ministry of Climate Change and Environment.

Murphy, F., Pierru, A., Smeers, Y., 2016. A tutorial on building policy models as mixed-complementarity problems. Interfaces (Providence). https://doi.org/10.1287/inte.2016.0842

Murphy, F.H., Rosenthal, E.C., 2006. Allocating the added value of energy policies. Energy J. 27, 143–156. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol27-No2-8

Napoli, C., Wogan, D., Wise, B., Yaseem, L., 2018. Policy Options for Reducing Water for Agriculture in Saudi Arabia, in: Biswas, A.K., Tortajada, C., Rohner, P. (Eds.), Assessing Global Water Megatrends. Springer Nature, Singapore, pp. 211–230. https://doi.org/https://doi.org/10.1007/978-981-10-6695-5

Neuhoff, K., Barquin, J., Bialek, J.W., Boyd, R., Dent, C.J., Echavarren, F., Grau, T., Hirschhausen, C. Von, Hobbs, B.F., Kunz, F., Nabe, C., Papaefthymiou, G., Weber, C., Weigt, H., 2013. Renewable electric energy integration : Quantifying the value of design of markets for international transmission capacity ☆. Energy Econ. 40, 760–772. https://doi.org/10.1016/j.eneco.2013.09.004

Newbery, D., Strbac, G., Viehoff, I., 2016. The benefits of integrating European electricity markets. Energy Policy 94, 253–263. https://doi.org/10.1016/J.ENPOL.2016.03.047

NREL (National Renewable Energy Laboratory), 2018a. PVWatts Calculator.

NREL (National Renewable Energy Laboratory), 2018b. 2018 Annual Technology Baseline. Golden.

NREL (National Renewable Energy Laboratory), KACST (King Abdullah City for Science and Technology), 2013. NASA Remote Sensing Validation Data: Saudi Arabia.

OPEC (Organization of the Petroleum Exporting Countries), 2017. OPEC Annual Statistical Bulletin.

OPWP (Oman Power and Water Procurement Company), 2019. Renewable Energy Development Plan.

OPWP (Oman Power and Water Procurement Company), 2018. Annual Report 2017.

OPWP (Oman Power and Water Procurement Company), 2015. Annual Report.

Padberg, M., 1999. Linear Optimization and Extensions, in: Padberg, M. (Ed.), Simplex Algorithms. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 49–86. https://doi.org/10.1007/978-3-662-12273-0_5

Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty- fi rst century energy challenges. Renew. Sustain. Energy Rev. 33, 74–86. https://doi.org/10.1016/j.rser.2014.02.003

Poudineh, R., Sen, A., Fattouh, B., 2020. An integrated approach to electricity sector reforms in the resource rich economies of the MENA. Energy Policy 138, 111236. https://doi.org/10.1016/j.enpol.2019.111236

POWER TECHNOLOGY, 2020. Umm Al Houl Combined-Cycle Power Plant [WWW Document]. URL https://www.power-technology.com/projects/umm-al-houl-combined-cycle-power-plant/

Pudjianto, D., Aunedi, M., Djapic, P., Strbac, G., 2014. Whole-Systems Assessment of the Value of Energy Storage in Low-Carbon Electricity Systems. IEEE Trans. Smart Grid 5, 1098–1109. https://doi.org/10.1109/TSG.2013.2282039

Qatar Ministry of Development Planning and Statistics, 2014. Electricity and Water Statistics.

QEWC (Qatar Electricity and Water Company), 2016. Statistic Report 2015.

Rehman, S., Ahmed, A., 2004. Assessment of wind energy potential for coastal locations of the Kingdom of Saudi Arabia. Energy 29, 1105–1115.

Rehman, S., Halawani, T.O., Husain, T., 1994. Weibull Parameters for Wind Speed Distribution in Saudi Arabia. Sol. Energy 29, 473–479.

Report, S., 2016. Annual Statistical Report 2016.

Rovira, A., Montes, M.J., Varela, F., Gil, M., 2013. Comparison of Heat Transfer Fluid and Direct System Generation technologies for Integrated Solar Combined Cycles. Appl. Therm. Eng. 52, 264–274.

Ruiz, C., Conejo, A.J., Fuller, J.D., Gabriel, S.A., Hobbs, B.F., 2014. A tutorial review of complementarity models for decision-making in energy markets. EURO J. Decis. Process. 2, 91–120. https://doi.org/10.1007/s40070-013-0019-0

Saadi, D., 2019. Oman oil output to reach 1.1 mil b/d by 2022: S&P Global Ratings [WWW Document]. URL https://www.spglobal.com/platts/en/market-insights/latest-news/oil/102119-oman-oil-output-to-reach-11-mil-b-d-by-2022-sampp-global-ratings

SAMA, 2014. Saudi Arabian Monetary Agency: Annual Statistics.

Schrattenholzer, L., 1981. The energy supply model message.

SEC (Saudi Electricity Company), 2019. Annual Report 2018. Riyadh.

SEC (Saudi Electricity Company), 2018. 2017 Annual Report Annual Report.

SEC (Saudi Electricity Company), 2015. Annual Report. Riyadh.

SEWA (Sharjah Electricity & Water Authority), 2012. Statistics [WWW Document].

Sgouridis, S., Abdullah, A., Griffiths, S., Saygin, D., Wagner, N., Gielen, D., Reinisch, H., McQueen, D., 2016. RE-mapping the UAE's energy transition: An economy-wide assessment of renewable energy options and their policy implications. Renew. Sustain. Energy Rev. 55, 1166–1180. https://doi.org/10.1016/j.rser.2015.05.039

Shapley, L.S., 1953. A Value for N-person Games, in: Kuhn, H.W., Tucker, A.W. (Eds.), Contributions to the Theory of Games II, Annals of Mathematical Studies 28. Princeton University Press.

Shehabi, M., 2020. Diversification effects of energy subsidy reform in oil exporters: Illustrations from Kuwait. Energy Policy 138, 110966. https://doi.org/10.1016/j.enpol.2019.110966

Sioshansi, R., Denholm, P., 2010. The Value of Concentrating Solar Power and Thermal Energy

Storage.

State of Kuwait, 2015. Intended Nationally Determined Contributions [WWW Document]. URL https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Kuwait First/Kuwait First NDC_English.pdf

State of Qatar Ministry of Environment, 2015. Intended Nationally Determined Contributions Report.

Sustainable Energy Unit Kingdom of Bahrain, 2017. The Kingdom of Bahrain National Renewable Action Plan.

Taleb, H.M., 2009. Barriers hindering the utilisation of geothermal resources in Saudi Arabia. Energy Sustain. Dev. 183–188.

The Kingdom of Saudi Arabia, 2015. The Intended Nationally Determined Contribution of the Kingdom of Saudi Arabia under the UNFCCC 1–7.

The World Bank, 2020a. Energy intensity level of primary energy.

The World Bank, 2020b. CO2 emissions (kg per PPP $ of GDP) - Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates [WWW Document]. URL https://data.worldbank.org/indicator/EN.ATM.CO2E.PP.GD?end=2014&locations=BH-KW-OM-QA-SA-AE&start=2014&view=bar

The World Bank, 2020c. CO2 emissions (kt) - Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates [WWW Document]. URL https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?end=2014&locations=BH-KW-OM-QA-SA-AE&start=2014&view=bar

The World Bank, 2013. Middle East and North Africa Integration of Electricity Networks in the Arab World Regional Market Structure and Design.

U.S. Energy Information Administration, 2020. ASSUMPTIONS TO AEO2020 [WWW Document]. URL https://www.eia.gov/outlooks/aeo/assumptions/

U.S. Energy Information Administration, 2019. Coal explained: Coal prices and outlook [WWW Document].

U.S. Energy Information Administration, 2017. Assumptions to the Annual Energy Outlook 2016.

U.S. Energy Information Administration, 2013. International Energy Outlook 2013.

U.S. Environmental Protection Agency, 2013. Documentation for EPA Base Case v.5.13 Using the Integrated Planning Model.

UAE FEWA (United Arab Emirates Federal Electricity & Water Authority), 2015. Electricity Statistics.

UAE Ministry of Energy, 2015. Statistical Data for Electricity and Water 2013-2014.

United Arab Emirates, 2020. UAE Energy Strategy 2050 [WWW Document]. URL https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/federal-governments-strategies-and-plans/uae-energy-strategy-2050#:~:text=The strategy aims to increase,AED 700 billion by 2050.

United Arab Emirates, 2019. Dubai Clean Energy Strategy [WWW Document]. URL https://u.ae/en/about-the-uae/strategies-initiatives-and-awards/local-governments-strategies-and-plans/dubai-clean-energy-strategy

United Arab Emirates Ministry of Energy & Industry, 2019. UAE State of Energy Report 2019.

United Arab Emirates Ministry of Energy & Industry, 2016. Annual Statistical Report 2016.

Wang, H., Perkins, R., 2019. Qatar boosts LNG expansion plans with new "mega trains" [WWW Document]. URL Qatar boosts LNG expansion plans with new "mega trains"

Wogan, D., 2020a. Email communication with Walid Matar, Research Fellow, KAPSARC.

Wogan, D., 2020b. Interview.

Wogan, D., 2017. GCC Energy System Overview - 2017.

Wogan, D., Carey, E., Cooke, D., 2019a. Policy Pathways to Meet Saudi Arabia's Contributions to the Paris Agreement. https://doi.org/10.30573/KS--2018-DP49

Wogan, D., Murphy, F., Pierru, A., 2019b. The costs and gains of policy options for coordinating electricity generation in the Gulf Cooperation Council. Energy Policy 127, 452–463. https://doi.org/10.1016/j.enpol.2018.11.046

Zamora, C.G., 2015. ASEAN PLAN OF ACTION FOR ENERGY COOPERATION (APAEC) 2016-2025.