DISSERTATION

AN ECONOMETRIC FRAMEWORK FOR ELECTRICITY INFRASTRUCTURE MODERNIZATION IN SAUDI ARABIA

Submitted by

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ABSTRACT

AN ECONOMETRIC FRAMEWORK FOR ELECTRICITY INFRASTRUCTURE MODERNIZATION IN SAUDI ARABIA

The electricity infrastructure in Saudi Arabia is facing several challenges represented by demand growth, high peak demand, high level of government subsidies, and system losses. This dissertation aims at addressing these challenges and proposing a multi-dimensional framework to modernize the electricity infrastructure in Saudi Arabia. The framework proposes four different scenarios—identified by two dimensions—for the future electric grid. The first and second dimensions are characterized by electricity market deregulation and Smart Grid technologies (SGTs) penetration, respectively. The framework analysis estimates global welfare (GW) and economic feasibility of the two dimensions.

The first dimension quantifies the impact of deregulating the electricity market in Saudi Arabia. A non-linear programming (NLP) algorithm optimizes consumers surplus, producers surplus, and GW. The model indicates that deregulating the electricity market in Saudi Arabia will improve market efficiency.

The second dimension proposes that allowing the penetration of SGTs in the Saudi electricity infrastructure is expected to mitigate the technical challenges faced by the grid. The dissertation examines the priorities of technologies for penetration by considering some key performance indicators (KPIs) identified by the Saudi National Transformation Program, and Saudi Vision 2030. A multi-criteria decision making (MCDM) algorithm—using the fuzzy Analytic Hierarchy Process (AHP)—evaluates the prioritization of SGTs to the Saudi grid. The algorithm demonstrates the use of triangular fuzzy numbers to model uncertainty in planning decisions. The results show that advanced metering infrastructure (AMI) technologies are the top priority for modernizing the Saudi electricity infrastructure; this is followed by advanced assets management (AAM) technologies, advanced transmission operations (ATO) technologies, and advanced distribution operations (ADO) technologies.

SGTs prioritization is followed by a detailed cost benefit analysis (CBA) conducted for each technology. The framework analysis aims at computing the economic feasibility of SGTs and estimating their outcomes and impacts in monetary values. The framework maps Smart Grid assets to their functions and benefits to estimate the feasibility of each Smart Grid technology and infrastructure. Discounted cash flow (DCF) and net present value (NPV) models, benefit/cost ratio, and minimum total cost are included in the analysis. The results show that AAM technologies are the most profitable technologies of Smart Grid to the Saudi electricity infrastructure, followed by ADO technologies, ATO technologies, and AMI technologies. Considering the weights resulting from the fuzzy AHP and the economic analysis models for each infrastructure, the overall ranking places AAM technologies as the top priority of SGTs to the Saudi electricity infrastructure, followed by AMI technologies, ADO technologies, and ATO technologies.

This dissertation has contributed to the existing body of knowledge in the following areas:

- Proposing an econometric framework for electricity infrastructure modernization. The framework takes into account technical, economic, environmental, societal, and policy factors.
- Building an NLP algorithm to optimize a counterfactual deregulation of a regulated electricity market. The algorithm comprises short run price elasticity of electricity demand (ε), level of technical efficiency improvement, and discount rate (r).
- Proposing an MCDM model using AHP and fuzzy set theory to prioritize SGTs to electricity infrastructures.
- Adapting a Smart Grid asset-function-benefit linkage model that maps SGTs to their respected benefits.
- Conducting a detailed CBA to estimate the economic feasibility of SGTs to the Saudi electricity infrastructure,

This work opens avenues for more analysis on electricity infrastructure modernization. Measuring risk impact and likelihood is one area for future research. In fact, risk assessment is an important factor in determining the economic feasibility of the modernization. Probabilistic economic analysis can be applied to assess the risk associated with the implantation of the previously mentioned dimensions. The parameters used

for the economic analysis, such as economic life of a project, and the discount rate, are usually deterministic. However, a probabilistic method can be applied to capture the uncertainty of the parameters. Another area for future research is the integration of both dimensions into one model in which GW resulted from market deregulation and SGTs insertion are summed.

ACKNOWLEDGMENTS

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DEDICATION

I dedicate this dissertation to my father, Abdulaziz Alaqeel, and to my mother, Norah Alaqeel.

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LIST OF SYMBOLS

ΔW	Change in global welfare
ε	Price elasticity of demand
η	Expected improvement in network efficiency after deregulation
λ_g	Shadow multiplier on government revenue
Π_g	Producers surplus under government operation
Π_p	Producers surplus under private operation
ϱ	Discount factor

LIST OF KEYWORDS

AAM	Advanced Assets Management
ADO	Advanced Distribution Operations
AHP	Analytic Hierarchy Process
AMI	Advanced Metering Infrastructure
AMR	Automated Meter Reading
Aramco	Saudi Arabian Oil Company
ATO	Advanced Transmission Operations
bcm	billion cubic meter
BSCFD	Billion Standard Cubic Feet per Day
Btu	British thermal unit
CAPEX	Capital expenditure
CBA	Cost Benefit Analysis
C_g	Average cost of producing Q_g
CGE	Computational General Equilibrium
CI	Consistency Index
CKM	Circular Kilometer
C_p	Average cost of producing Q_p
DCF	Discounted Cash Flow
DMS	Distribution Management System
DOE	Department of Energy
DG	Distributed Generation
DP	Dynamic Programming
DR	Demand Response
DSM	Demand Side Management

ECRA	Electricity and Co-generation Regulatory Authority
EDRP	Emergency Demand Response Program
EPRI	Electric Power Research Institute
ETP	European Technology Platform
FACTS	Flexible AC Transmission Systems
FCL	Fault Current Limiter
FTE	Full Time Equivalent
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
GP	Goal Programming
GW	Global Welfare
HAN	Home Area Network
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IP	Integer Programming
IPP	Independent Power Provider
IRR	Internal Rate of Return
IWPP	Independent Water and Power Producer
K.A.CARE	King Abdullah City for Atomic and Renewable Energy
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
LP	Linear Programming

MAIFI	Momentary Average Interruptions Frequency Index of durations under 5 minutes
MADM	Multi-Attribute Decision Making
MAUT	Multi-Attribute Utility Theory
MBTU	Million British Thermal Units
MCDM	Multi-Criteria Decision Making
MDMS	Meter Data Management System
MODM	Multi-Objective Decision Making
MOO	Multi-Objective Optimization
NETL	National Energy Technology Laboratory
NGSA	National Grid SA
NIST	National Institute of Standards and Technologies
NLP	Non-Linear Programming
NPV	Net Present Value
OECD	Organization for Economic Co-operation and Development
OMS	Outage Management System
OPEX	Operating Expense
O&M	Operations and Maintenance
P_g	Output price corresponding to Q_g
PHEV	Plug-in Hybrid Electric Vehicle
PME	Presidency of Meteorology and Environment
PMU	Phasor Measurement Unit
P_p	Output price corresponding to Q_p
PV	Photovoltaic
Q_g	Level of output under government operation
Q_p	Level of output under private operation
r	Discount rate

RE	Renewable Energy
ROA	Return on Assets
ROI	Return on Investment
RPS	Renewable Portfolio Standards
RI	Random Index
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCECOs	Saudi Consolidated Electrical Companies
SEC	Saudi Electricity Company
S_g	Consumers surplus under government operation
SGMM	Smart Grid Maturity Model
SGT	Smart Grid Technology
S_p	Consumers surplus under private operation
SWCC	Saline Water Conversion Corporation
TOU	Time-of-Use
T&D	Transmission and Distribution
UPFC	Unified Power Flow Controller
U.S.	The United States of America
WAMS	Wide Area Management System

CHAPTER 1

INTRODUCTION AND OVERVIEW

1.1 OBJECTIVE

The objective of this dissertation is to design a framework for the modernization of the electricity infrastructure in Saudi Arabia. The framework addresses the main challenges in the Saudi Arabian grid and proposes a model to transform the grid from its status quo to a modernized stage. Grid modernization implies improving electric grid operability, reliability, and security. Grid modernization is expected to enhance the ability of the power grid to adapt to emerging technologies and applications, like renewable energy (RE) sources, demand response (DR) programs, storage devices, and electric vehicles [1, 2].

The framework proposes that the modernization of the Saudi electricity infrastructure may progress in two dimensions. The first dimension is the deregulation of the electricity market. The second dimension is the insertion of SGTs into the Saudi Grid infrastructure. The first dimension refers to the unbundling of the generation sector of the electric power industry from the delivery sector [3]. The terms, *market deregulation*, *unbundling process*, and *restructuring plan*, are used interchangeably as they all imply electricity market reform. Grid modernization extends to improve the efficiency of electricity market mechanisms. Modernization calls for creating uniform marginal pricing with no structural bottlenecks in transmission networks. It aims to remove technical and structural barriers to cross-border retailers operations [4].

With regards to the second dimension, the Smart Grid is defined as the modernization of electric grid and electricity infrastructure by implementing digital information and control technologies and integrating distributed resources. According to the U.S. Department of Energy (DOE), Smart Grid is defined as the, "…*electric delivery network, from generation to the consumer integrated with the latest advances in digital and information technology to improve the electric system reliability, efficiency, security, and resiliency*" [5]. The Smart Grid European Technology Platform (ETP) defines Smart Grid as, "*An electricity network that can intelligently integrate the actions of* *all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies*" [6]. The Electric Power Research Institute (EPRI) defines Smart Grid as, "*A customer-centered, interactive, reliable, flexible, optimal, economical, economically responsive and, ultimately, a sustainable and environmentally responsible electrical power generation and distribution system*" [7]. The International Electrotechnical Commission (IEC) adopts a more technology focused definition for Smart Grid as, "…*the concept of modernizing the electric grid. The Smart Grid is integrating the electrical and information technologies in between any point of generation and any point of consumption*" [8]. The U.S. DOE established a federal Smart Grid task force under that identified objectives to establish an electricity infrastructure for the 21st century capable of providing ample, cheap, clean, efficient, and reliable electricity supply [9]. The ETP charted the "SmartGrids" program to set up a 2020 joint vision for the European electric network to enhance the flexibility, accessibility, reliability, and power quality of the electric network. It also aims at providing the most economic service and most efficient energy management to consumers [10, 11]. The National Energy Technology Laboratory (NETL) in the U.S. describes the characteristics of Smart Grid: the capability of self-healing, motivating and including consumers, resisting attack, providing power quality for the 21st century needs, accommodating generation and storage options, enabling markets, optimizing assets, and operating efficiently [12].

1.2 MOTIVATION

The Saudi electricity infrastructure is facing several challenges that result from the impressive growth of the national economy since the 1980s. Such challenges include the increased consumption of electricity, growth in peak demand, losses in the delivery network, and power quality issues. The motivation of this dissertation is to identify these challenges and propose a framework and a pathway to modernize the electricity infrastructure in Saudi Arabia. Below is a discussion on the challenges in more detail.

1.2.1 ENERGY CONSUMPTION

The country is a high consumer for oil. In fact, Saudi Arabia is the largest oil-consuming nation in the Middle East and, according to the British Petroleum Statistical Review of World Energy 2014, was the world's 12th largest consumer of total primary energy in 2013 at 9 quadrillion British thermal units (Btu). In

2013, Saudi Arabia produced about 13.1% of world production of oil and gas with about 12.1 million barrels a day [13]. Domestic consumption represented 2.9 million barrels per day of oil in 2013, almost double its consumption in 2000. The majority of petroleum consumed domestically is allocated for transportation fuels and direct power generation by burning [14]. Domestic energy consumption rose by 4.8% per year on average. If this level of consumption continues in the next decade, the level of export is expected to reduce significantly and the country will import oil [15].

Fig. 1.1 shows the increasing demand of electrical energy from 1990 to 2015 [16]. Average energy gross rate for the same period is 6.55% as shown in Fig. 1.2 [17]. This gross rate is considerably high if compared to the average gross rate in developed countries, which ranges between 1-2% [18]. This high gross rate implies a sharp growth in electrical energy demand, which requires expanding the installed capacity of the electric grid.

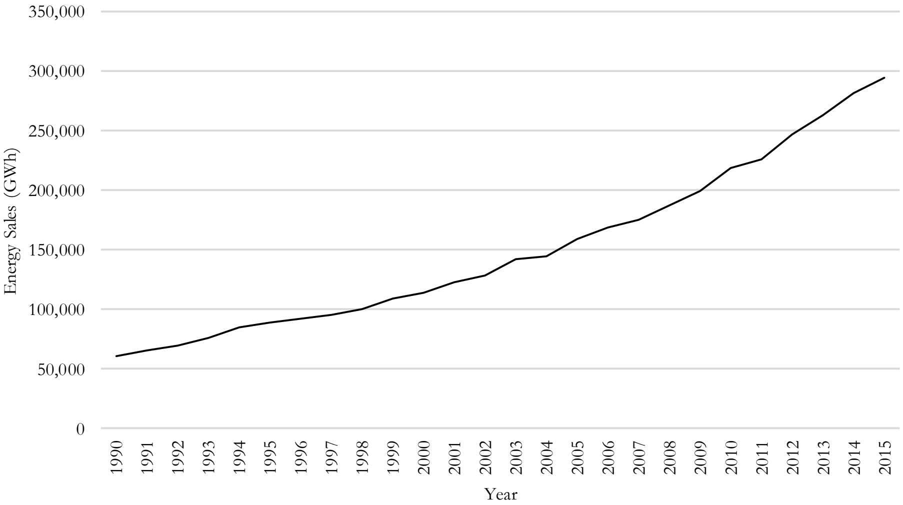

Fig. 1.1 Electrical Energy Demand in Saudi Arabia [16]

Fig. 1.2 Energy Sale Gross Rate [17]

The first challenge facing the electricity infrastructure in Saudi Arabia is the remarkable growth in energy consumption driven by population growth and improvement in standards of living. The growth is also driven by strong economic and industrial development. Harsh weather conditions and economic policies calling for diversifying energy-intensive industries, and highly subsidizing energy prices are yet major drivers for the growth [19]. As a result of the rapid increase in demand, the network is encountered with service interruptions, low generation capacity reserves, depletion of resources, high peak demand, and capital investment. Population growth has been a major driver for demand increase. Since 1960, the Saudi Arabian population increased by more than sevenfold to reach 30 million in 2015. In the same timeframe, the urbanization rate, which represents the share of people living in cities, rose from 31.25% to 83.13% [20]. This indicates population growth in cities is higher than that in non-urban areas, which forces cities to adapt to this growth in terms of services, life style, and available living residences [21]. Not only domestic population growth has been a reason for excessive consumption of energy, but also the increasing number of expatriates working in the country. It is estimated that there were about 9.2 million expatriated in 2013. The share of expatriates is about 30% of the population, ranking Saudi Arabia the 4th in the number of immigrants worldwide [19]. Population growth and the increase in expatriates and immigrants have led to increasing the number of service consumers. Fig. 1.3 shows the number of consumers from 1990 to 2015. Average gross rate of the number of consumers is 5.06% as show in Fig. 1.4 [17].

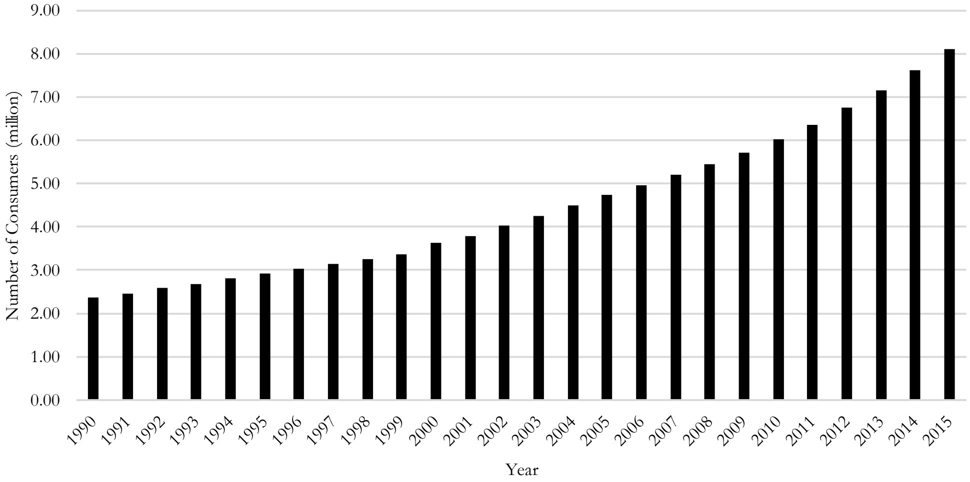

Fig. 1.3 Number of Consumers [17]

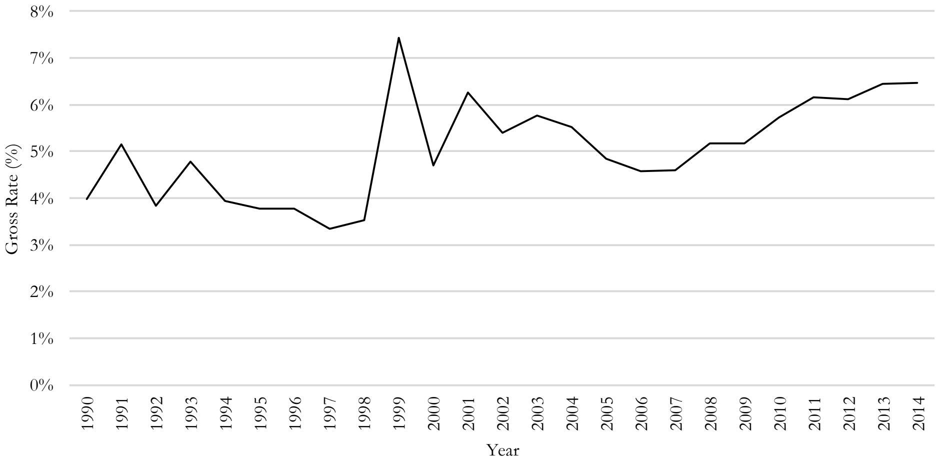

Fig. 1.4 Number of Customers Gross Rate [17]

As a result of the growth in energy consumption and the number of consumers, the length of transmission and distribution (T&D) networks have expanded vastly. Fig. 1.5 shows the gross rate for T&D networks lengths in the previous years.

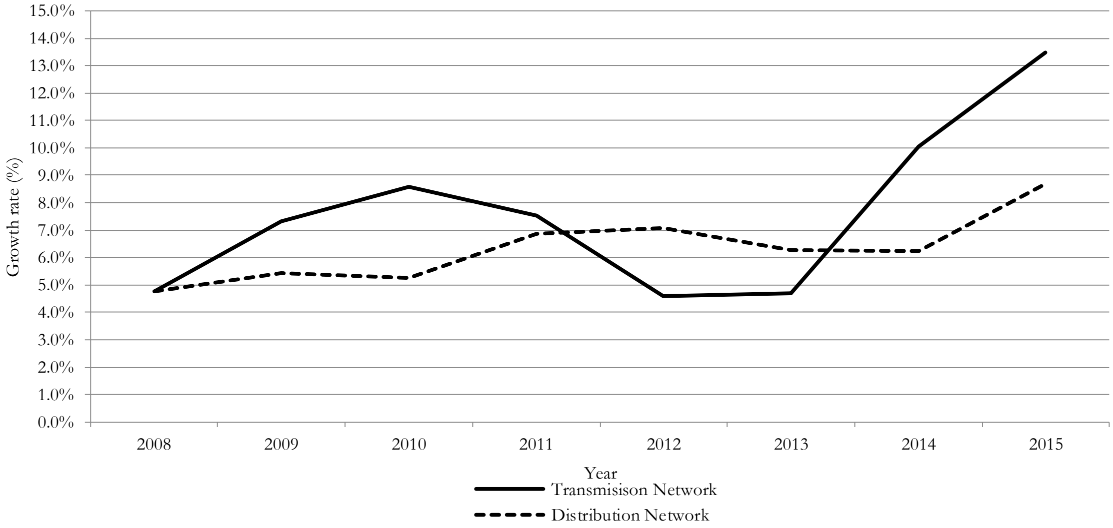

Fig. 1.5 T&D Networks Length Gross Rate [17]

Energy use per capita in Saudi Arabia is one of the highest in the world and well above the global average [22]. The primary energy consumption per capita was 6.8 tone of oil equivalent in 2009, which is four times higher than the world average [23]. In 2015, electricity consumption per capita in 2015 reached 9,346 kWh. Fig. 1.6 shows kWh/capita for the period of 1990 to 2015 [17].

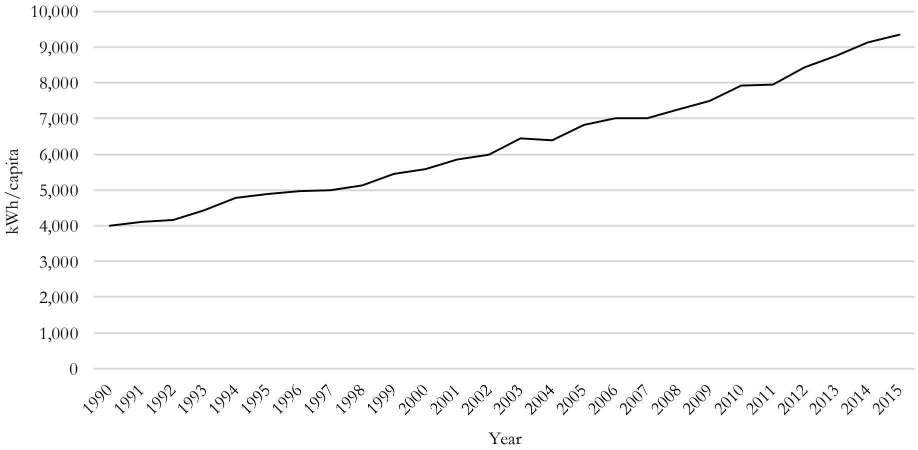

Fig. 1.6 Electricity Consumption per Capita [17]

Energy intensity is another indicator for the excessive consumption of energy in Saudi Arabia. Energy intensity measures the electricity required to generate a unit of output. Energy intensity, measured in electricity/Gross Domestic Product (GDP) ratio, in Saudi Arabia, showed a steady increase in the last decades which indicates a faster electricity consumption growth rate relative to the economic growth rate. In general, energy intensity in Gulf Cooperation Council (GCC) countries is one of the highest in the world including countries with similar or higher per capita income such as the member countries of the Organization for Economic Co-operation and Development (OECD). This may indicate the existence of waste and large losses in power sector [24, 25]. On average, final and primary energy intensities rose by 2.3% per year between 2000 and 2009 [23].

1.2.2 HIGH PEAK DEMAND

In Saudi Arabia, peak demand occurs on weekdays from 1 pm to 5 pm from June through September. Besides that, demand increases during the holy lunar month of Ramadan (month of fasting) and Dhul-Hijjah (month of pilgrimage) [26]. Typical demand curve falls in three intervals: peak period from 10 am to 6 pm, off-peak period from 6 pm to 12 midnight, and low-peak period from 12 midnight to 10 am [27]. In 2015, peak demand reached 62,260 MW. Peak demand has been growing at an average rate of 6.5% per year for the period from 1990 to 2015 as shown in Fig. 1.7. Fig. 1.8 shows the peak load gross rate [17]. Summer peak demand has increased by 93% between 2004 and 2014, from 28,000 to 56,000 MW. The demand is expected to increase by over 6% annually in the period between 2014 and 2020. This future demand will require power generation capacity to increase from 56,000 MW to 120,000 MW by 2032 [3].

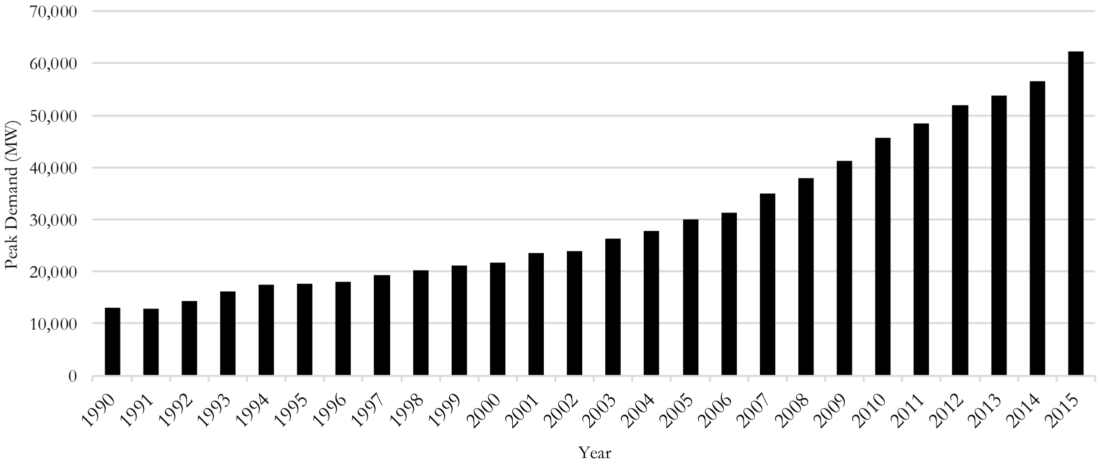

Fig. 1.7 Peak Demand from 1990 to 2015 [17]

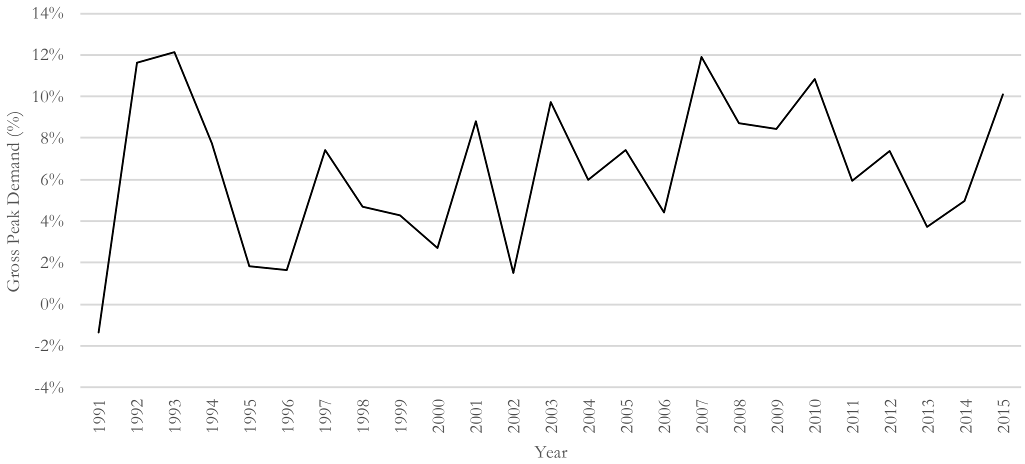

Fig. 1.8 Peak Demand Gross Rate [17]

Meeting peak demand is one of the main challenges facing the Saudi electricity infrastructure. Due to the severe-climate conditions, peak demand creates an unbalanced load structure that reaches its highest level for only a couple of hours per day and for a few days per year. In some events in summer seasons, peak demand increases to twice the average demand level [28]. High peak demand leads to consuming all generation capacity reserves, which could compromise system reliability. Meeting unexpected demand is expected to be challenging considering the low generation capacity reserve margin, and the variation in electricity consumption across the day due to high changes in temperature. Fig. 1.9 shows the difference between peak demand and installed capacity which indicates the problem of low generation capacity reserve margin [17].

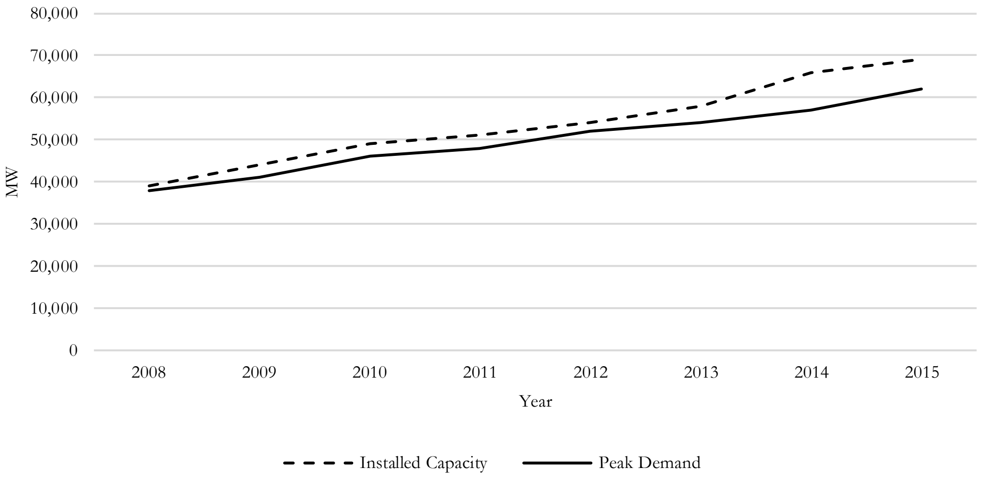

Fig. 1.9 Peak Demand and Installed Capacity [17]

Because of the harsh weather in Saudi Arabia, water production is highly dependent on desalination facilities. However, these facilities require large amounts of energy. Water consumption is experiencing a remarkable growth similar to the case with energy consumption. Total water production capacity increased from 2.0 million m^3 in 1993 to 5.7 million m^3 in 2013 [19, 29].

Increasing peak demand leads to service interruptions, resources depletion, and system stress. If the current trend of electricity consumption continues, domestic consumption of oil is expected to reach more than eight million barrels by 2030 [14]. According to a study undertaken to estimate the funding needs for the electricity services for the period 2010-2020, the economic investment required for electricity infrastructure modernization has been estimated at US $140 billion [27].

1.2.3 SYSTEM LOSSES

The grid network suffers considerable percentage of losses driven by power quality issues. Demand for air conditioning load in Saudi Arabia has grown significantly over the last years especially in summer seasons when air conditioning represents about 80% of the total system load. Such a growth has posed a serious issue in the network. Delay in voltage recovery following fault events has increased due to highly inductive loads, which is represented by air conditioning motors. This leads air conditioning motors to stall during voltage recovery periods after fault occurrence [30, 31]. The Saudi Electricity and Co-generation Regulatory Authority (ECRA) has identified air conditioning as one of the most significant underdeveloped areas in the demand side [16]. As a result of highly inductive load conditions, the grid system suffers events of incapability to provide the network with reactive power compensation. Such events lead to unacceptable voltage recovery after faults, and voltage collapse at peak load conditions.

Reference [30] presented a case study when a highly inductive load represented by air conditioning units had caused the motor to loss torque and voltage level to collapse. This led motor speed to decelerate. Thus, active and reactive currents are fed to the motor. The current causes a large voltage drop in the source impedance. As a result of these events, the network suffers network losses in energy delivered ranging between 8 and 9% each year [17].

One important factor contributing to the increase in air conditioning consumption is the climatic conditions that are similar to deserts climate. The desert climate is characterized by extreme heat during the day, and rapid drop in temperature at night. There is high variation in temperature and humidity because of elevation fluctuation and the subtropical high pressure. Moreover, temperature varies across the country [32]. Temperature in GCC, of which Saudi Arabia is part, is predicted to increase by 1.8 °C (3.24 °F) by 2040, 3.6 °C (6.48 °F) by 2070, and 4.0 °C (7.2 °F) by the end of the century. According to the Saudi Presidency of Meteorology and Environment (PME), the temperature in Saudi Arabia ranges between 44.0 to 47.0 °C (111.2 to 116.6 °F), and up to 50.0 °C (122 °F), during the summer season [33]. In 2040, Saudi Arabia is expected be the hottest region in GCC in the period between September to November [34]. Climate change can also affect the reliability and loadability of the distribution systems. A rise of 1.0°C (1.8 °F) in temperature increases peak demand by 4.6% [35].

Improving the efficiency of air conditioning would save up to 120,000 barrels of oil per day and around five billion cubic meter (bcm) of natural gas per year that are used for electricity generation otherwise. This level of improvement in efficiency could save about US $7.0 billion per year. Overcoming climate change impact and improving efficiency would allow the country to defer investments planned for grid expansion and modernization that may reach US $100 billion [36].

Another factor contributing to system losses is the building code currently practiced in the country. The current code is not sufficiently efficient at high temperatures as it wastes a relatively high level of the cooling air by dehumidifying indoor air which leads to a reduction in air conditioning efficiency when the outside temperature increases. Air conditioners used in Saudi Arabia are designed to perform at 35.0 °C (95 °F)according to international performance standards whereas the temperature, in Saudi Arabia, ranges between 44.0 and 47.0 °C (111.2 to 116.6 °F), as mentioned earlier [37].

As a result of these factors, the grid system suffers a considerable level of system losses. Some losses result from heat losses in the resistance of the electrical conductors at voltage transformation. Other losses are made up of energy delivery for consumption but not paid for as a consequences of several drivers like theft, non-registered consumers, and inaccurate billing and metering [38]. Fig. 1.10 shows the Saudi electrical system losses over the last years. Fig. 1.11 shows the energy not supplied over the last five years as a percentage of energy produced [17].

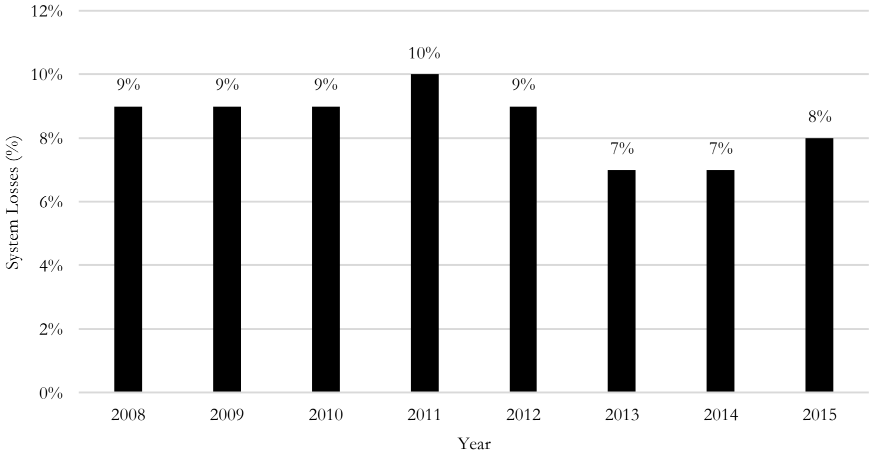

Fig. 1.10 System Losses [17]

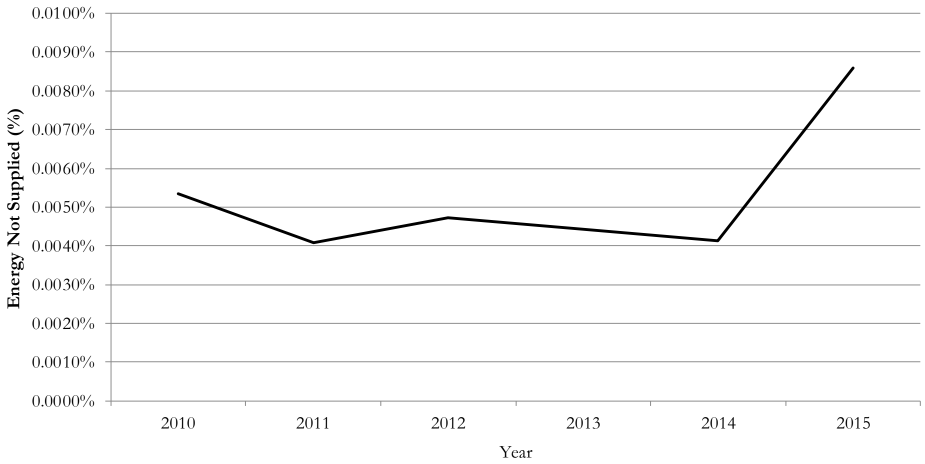

Fig. 1.11 Percentage of Energy Not Supplied [17]

1.2.4 OIL DEPENDENCY

Electricity production in Saudi Arabia depends only on fossil fuels. As mentioned earlier, domestic consumption represented 2.9 million barrels per day of oil in 2013, or the third of the country's production of oil. Such high level of fossil fuel consumption is driven by large oil reserves and relatively cheap cost for domestic oil extraction. High government subsidies are also other drivers for high level of domestic consumption. In fact, Saudi Electricity Company (SEC) is granted provision of oil for electricity generation in which the marginal cost of the barrel of oil provided is less than or equal to the actual marginal cost of US $5.0 per barrel [25, 39].

Such a scenario impacts the national security of the country. One reason is that fossil fuels are depleted resources. Another reason is that output generated is not commensurate with energy used. As mentioned earlier, energy intensity is relatively high compared to energy intensity levels in the industrialized countries, which implies systemic inefficiencies. Moreover, additional consumption of fossil fuel builds a significant opportunity cost against the potential sale of oil in the international market [38]. Fig. 1.12 shows the types of fuels used for electricity generation in Saudi Arabia. Fig. 1.13 breakdowns the installed capacity based off the types of generation units used for electricity production [17].

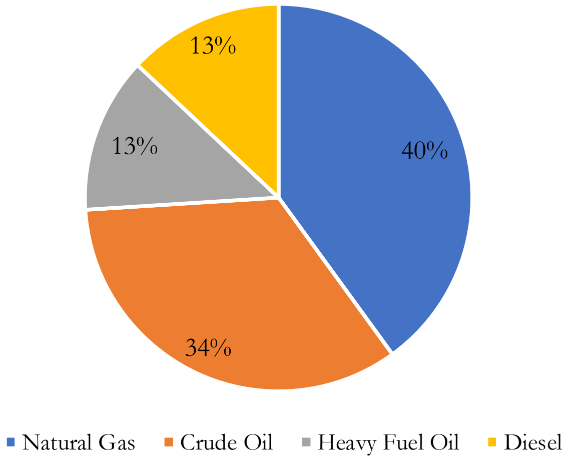

Fig. 1.12 Fuel Types Used for Electricity Generation [17]

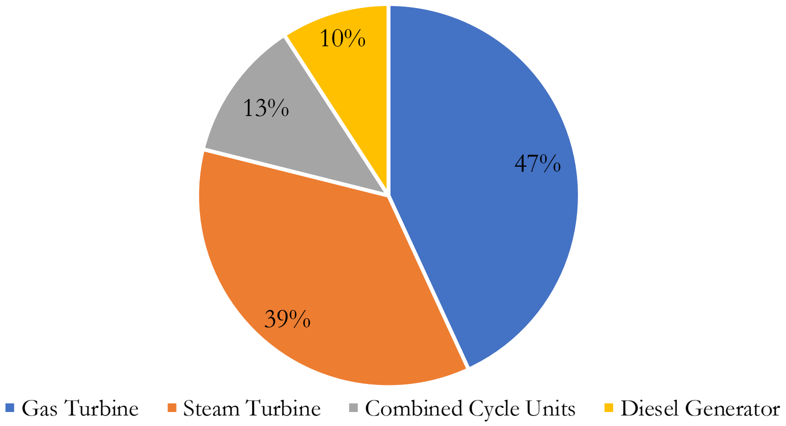

Fig. 1.13 Types of Generation Units [17]

RE production is absent so far. The country needs to diversify energy production and exploit its RE resources. Saudi Arabia has the potential to exploit RE resources specially concentrated solar, solar photovoltaics (PV), wind, geothermal, and waste-to-energy for electricity generation [25, 40].

1.2.5 AGING EQUIPMENT

Equipment aging is yet another challenge facing the Saudi electric grid. The economic life of several generation units has reached its end. For example, in 2010, about 8,390 MW generation units have come to the end of their economic life. The retiring units have to be replaced by new ones in order to maintain system efficiency, meet increasing demand, and reduce losses [41]. Fig. 1.14 shows the age of the generation units in the Saudi electric grid [17].

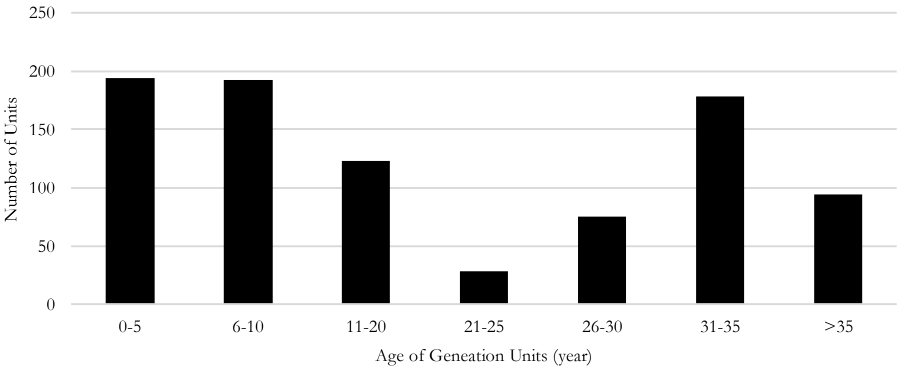

Fig. 1.14 Age of Generation Units [17]

As it is unpractical to phase out multiple generation units at the same time in order not to compromise system stability and create unbalance, ECRA has set a plan for replacing the aging equipment according to which no more than 2% of the installed capacity is allowed for replacement each year [41, 42].

1.2.6 SYSTEM RELIABILITY

The network is facing several outages and interruptions due to unplanned outages, overload, and generation failure. This subsection presents three reliability indices for the SEC grid obtained for the 2010-2015 period. The first one is System Average Interruption Duration Index (SAIDI), defined as the ratio of the total interrupted customer minutes and the number of customers. The second index is System Average Interruption Frequency Index (SAIFI), defined as the ratio between the total number of customer interruptions and the total number of customers served from the system. The third index is Momentary Average Interruptions Frequency Index of durations under 5 minutes (MAIFI) [43]. Fig. 1.15 shows the reliability indies of SEC network for the period of 2010-2015 [17]. All three reliability indices show network reliability is deteriorating over the last years.

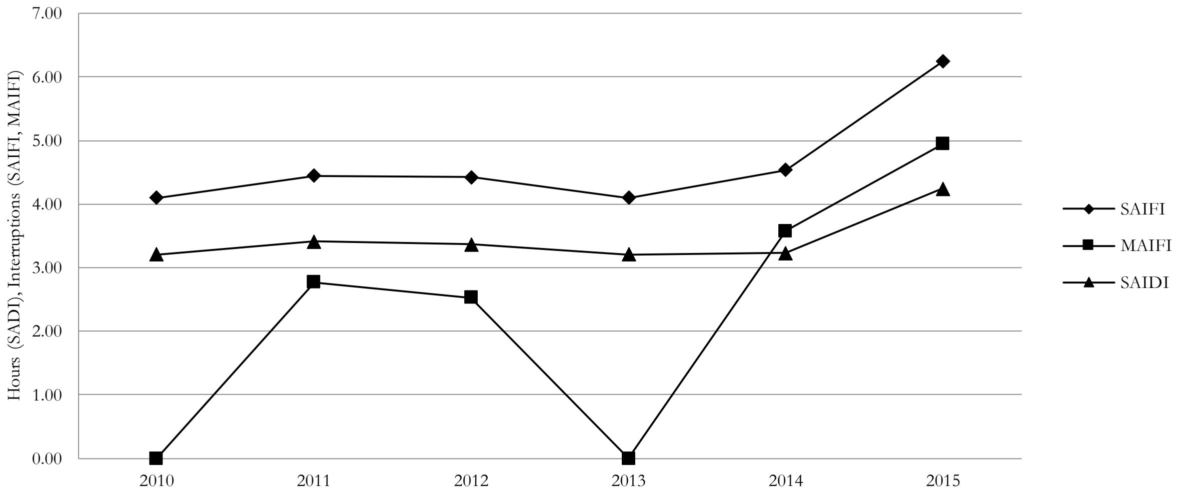

Fig. 1.15 Reliability Indices for SEC Network [17]

1.2.7 ELECTRICITY MARKET INEFFICIENCY

The electricity market in Saudi Arabia is vertically integrated. Such an organization has led to a fixed price structure. Vertically integrated utilities tend to overestimate the amount of generation capacity needed. Therefore, consumers pay for more than what they consume. Otherwise, government subsidizes a huge amount of energy to make electricity prices affordable to consumers [44]. Fig. 1.16 shows the distribution of average unit cost of energy in Saudi Arabia [17].

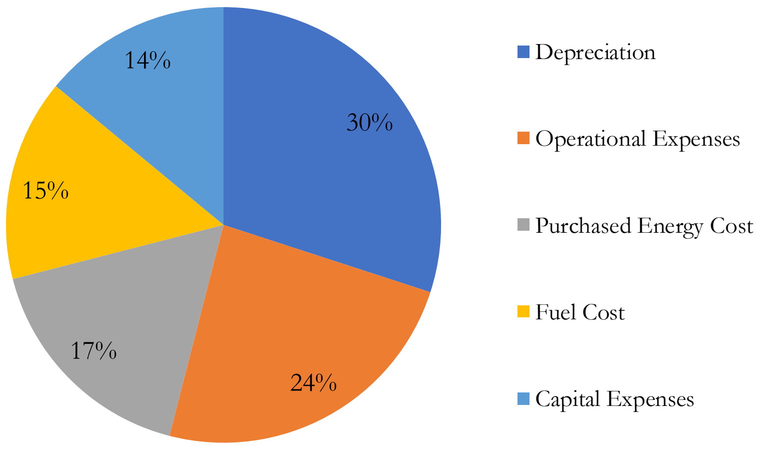

Fig. 1.16 Distribution of Average Energy Unit Cost [17]

As a result of such a structure, SEC, the operating company, aims first at satisfying the demand instead of optimizing the operations. SEC has no control over tariffs stipulation as it is set by government agencies. Government subsidies for electricity generation were US $40 billion in 2014 [16]. In other words, government subsidies account for 82% of the cost of electricity production, which makes the rate of electricity price in Saudi Arabia one of the lowest rates in the world. Saudi Arabia is ranked second worldwide in government subsidies provided for domestic energy prices [45]. Average cost of kWh paid by consumers is US $0.037, while it costs US $0.213 [28]. Fig. 1.17 shows the price of electricity unit sold, and cost of electricity unit before fuel and electricity subsidies [16]. Table 1-1 shows comparisons of fuel prices paid by the electricity producers in Saudi Arabia with international prices [16].

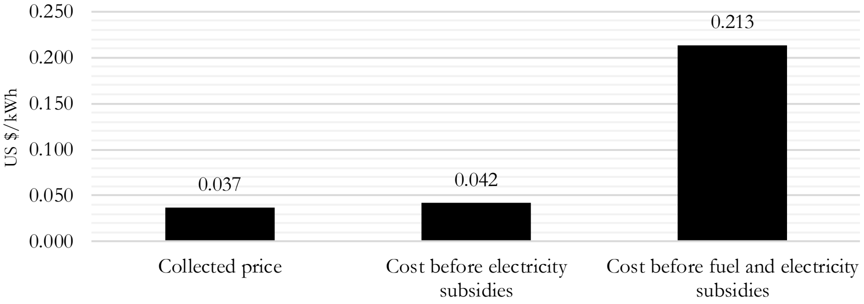

Fig. 1.17 Comparison of Electricity Unit Cost with/without Fuel and Electricity Subsidies [16]

Table 1-1. Comparisons of Fuel Prices Paid by Producers in Saudi Arabia with International Prices [16]

Fuel type	Price (US $/MBTU)	
	Paid by producers in Saudi Arabia	International
Heavy fuel oil	0.43	15.43
Gas	0.75	9.04
Diesel	0.67	21.67
Crude oil	0.73	19.26

Low market prices driven by high subsidies discourage consumers to conserve energy and engage in DR programs. Thus, ε (price elasticity of demand) is low. Price elasticity of demand links the price offered to the quantity sold. It is the ratio of the change in quantity consumed that results from a change in price, or vice versa. This relationship is an important tool to measure the change in electricity markets in terms of price and demand in the short-run and the long-run periods. In [46], 25 different studies of residential electricity demand are compared across electricity markets. In these studies, the short run elasticity varies in [0.03, 0.54], with the consensus measure around 0.2. In commercial sectors, elasticity for the short run varies in [0.17, 1.18] across multiple studies. In the industrial demand, there is an agreement on a consensus estimate of 1.3 even though it is difficult to place much confidence on this value since it is subject to aggregation and location biases [46]. Based off empirical studies, price elasticity of demand in the Saudi electricity market is found to be 0.04 which means that the demand for electricity is inelastic in the short run [24].

1.2.8 CARBON EMISSION

Saudi Arabia has experienced a sharp increase in energy consumption and carbon emissions in recent years as a result of its strong economic and industrial growth. Saudi Arabia is highly dependent on fossil fuels for energy generation. This scenario increases cumulative carbon dioxide level in the country [47]. Because of high energy consumptions, Saudi Arabia's share of carbon emissions worldwide in 2008 was at the 14th place, or a 1.54% share of worldwide emissions, with 118 million metric tons of carbon emissions [23]. Saudi Arabia is ranked the 21st among countries with the highest CO_2 emissions per capita in 2006, and the 16th by total CO_2 emission at 438.25 million metric tons of CO_2. The level of CO_2 intensity has risen by 2% per year since 2000 [23]. It is expected that this level will increase if the country stays highly dependent on fossil fuels for electricity generation [47].

1.2.9 FINANCIAL CHALLENGES

Electricity production is a high capital-intensive industry requiring relatively long timeframe for construction and operation. Installing sufficient power capacity to meet the increasing demand in the country is faced with financial challenges. As the gap between supply and demand is shrinking, as mentioned earlier, the country has to allocate proper financial investments to accelerate the development of the electricity infrastructure and meet the growing demand. Such investments are faced with challenges considering the plummeting and fluctuating prices of oil revenue since 2014 [24].

Based on expected demand growth, the country is required to boost supply capacity with 70,000 MW. As far as current investment plan, only 10,000 MW is already committed. Investments in T&D

networks, in terms of both upgrades and expansions of the electrical grids to support the system growth, are yet required to improve network reliability [38].

1.3 SCOPE

This dissertation proposes a framework that takes into consideration technical, societal, and economic aspects related to the modernization of the electricity infrastructure in Saudi Arabia. The approach offers a comparison between different scenarios. The application or the absence of the two dimensions determines these scenarios. Table 1-2 presents the four scenarios.

Table 1-2. Four Scenarios for the Proposed Approach [48]

	Regulated market	Deregulated market
No insertion of SGTs	(Current status) Regulated market No SGTs	(Scenario #2) Deregulated market No SGTs
Enabling the insertion of SGTs	(Scenario #1) Regulated market SGTs enabled	(Scenario #3) Deregulated market SGTs enables

This first-of-a-kind analysis serves as groundwork for econometric analysis exploiting the scenarios presented earlier. The econometric analysis helps identify the proper model for the future Saudi grid infrastructure that achieves targeted outcomes in terms of security of energy supply, energy conservation, reliability, stability, and grid modernization. The proposed econometric analysis provides a platform for the decision-making process towards specifying the future Saudi grid with respect to the two dimensions.

The proposed economic analysis requires decision-making tools to quantify the impacts of modernization, and prioritize the importance of SGTs. Decision making in electric power systems, faced with multiple quantitative and qualitative elements, is one of the most important issues in grid modernization. In such environments, decision makers deal with several scenarios that should be examined and investigated by multiple attributes. In literature, several methods and techniques are implemented for projects, technologies, or scenarios selections. Approaches tend to be either quantitative or qualitative, ranging from rigorous operations research methods to social-science-based interactive techniques. The process of determining optimal scenario among others need a consideration of objective and subjective criteria. When more than one scenario is involved, the volume of data and estimates needed to construct the basis for decision making increases. Computing the costs and benefits of each scenario increases analytic complexities. Models for selecting the optimal project, or alternatives were first emerged in the mid-1950's. The effort has been on building models that handle the analytic aspects of selecting optimal portfolios [49]. Most of decision-making models reside in several types: classical, portfolio, integrated, decision analysis, economic, mathematical, artificial intelligence, and MCDM models. Each type is discussed below in more detail.

Classical models are considered simple and easy to formulate. They assign a priority scale to each candidate alternative. The scale forms the basis for selecting the best alternative(s). Classical models consist of profiles, checklists, scoring models and economic indexes. Classical models act as filters to facilitate the structuring of decision processes. Although classical models are simple to formulate, their inherit simplicity precludes them from extensive subjectivity and qualitativeness. They also severe a limitation in terms of their ability to handle analytic complexities. Additionally, alternative selection is normally dynamic where alternative parameters and selection criteria values vary across time [49]. Therefore, classical models are not considered in this analysis.

Portfolio models were developed to overcome the deficiencies found in the classical models. In a portfolio model, alternatives selection and resource allocation are optimized. Linear and non-linear portfolio models are examples of portfolio models. The advantage of portfolio models is the ability of handling complex analytic problems [49]. In some portfolio analysis, a portfolio matrix is used where the contents and feasibility of each alternative are identified. Then, criteria are identified where each alternative is assigned with certain values [50]. However, these models, as well as the case with classical models, demand a large volume of quantitative input that is difficult to obtain. This makes portfolio models are of less importance for our analysis.

Integrated models are newer models emerged to overcome the deficiencies found in both classical and portfolio models. Integrated models combine two or more classical and portfolio models with behavioral decision processes. Some literature calls these models interactive models [51]. These models include Delphi, and the most important two types: the behavioral decision aid, and the decentralized hierarchical modeling.

The first one calls for reorienting the entire alternative selection process away from its focus on selecting an optimal alternative. As a result, achieving an optimal selection of alternatives becomes a byproduct of the consensus commitment to the plan. The behavioral decision aid promotes information sharing, and eliminates biases. An example of the behavioral decision aid is the Q-Sort-Interacting process. In the decentralized hierarchical modeling, candidate proposals are simulated through multiple iterations through different hierarchical organization decision levels until an overall consensus is reached. This is accomplished with the aid of an interactive mathematical model like the Mandakovic-Souder model [49].

Decision analysis models incorporate subjective and objective inputs from decision makers, experts, and data. These models have the advantage of the ability of assigning weight to alternative attributes (criteria). Examples of decision analysis models include multi-attribute utility theory (MAUT), decision trees, risk analysis, and the AHP. In the MAUT model, objective measurements are applied to decision making. For any decision problem, there exists a real valued function or utility defined by the set of feasible alternatives. Each alternative results in an outcome that may have a value on a number of different dimensions. MAUT seeks to measure each dimension value, then, aggregate these values through weighted linear average [52]. AHP is an MCDM model that organizes decision objectives, alternatives, and attributes into a hierarchical structure [53, 54].

Economic models include internal rate of return (IRR), NPV, return on investment (ROI), CBA, and option pricing theory [51]. Mathematical Programming models include integer programming (IP), linear programming (LP), NLP, goal programming (GP), and dynamic programming (DP) [51]. Artificial Intelligence models include expert systems and fuzzy sets [51].

MCDM is a branch of operations research. MCDM refers to making decisions considering multiple criteria. MCDM problems are classified into two classes: multi-objective decision making (MODM) and multi-attribute decision making (MADM) problems. MODM is also known as multi-objective optimization (MOO) [55]. A logical combination of several methods is not uncommonly used. MOO is used for problems involving more than one objective function. MOO is also referred to as multi-criteria or vector optimization problems. Most decision-making problems in engineering requires optimizing a number of conflicting objectives. If an improvement in one objective leads to deterioration in another, conflict exists. In such cases where there is competition between two or more objectives, there may exist no single, unique solution [56].

In this dissertation, a NLP algorithm is proposed to design an optimization model to improve the decision-making process of deregulating an electricity market. GW, which is defined as the sum of the net consumers surplus and the producers profits, is chosen as the criterion on which the decision of deregulating a market is based. CBA is employed in this work. CBA is an applied economic tool that considers benefits and costs associated with the application of a program, a project, or a setup. CBA serves as a tool to compare multiple alternative setups and to choose the one that maximizes benefits and reduces costs. CBA weights costs and benefits against economic values [57].

AHP is an MCDM tool used for this research. AHP is one of the most popular MCDM methods that can handle unstructured or semi-structured decisions with multi-criteria inputs. AHP is used in making decisions that involve ranking, selection, evaluation, optimization, and prediction. AHP can organize objectives, criteria, and alternatives into a hierarchal structure. AHP derives ratio scales from deductive and inductive inputs through multiple pairwise comparisons. Moreover, AHP is one of the few methods that is able to measure the consistency of the judgment of decision makers [53, 54].

Fuzzy AHP is another analytic tool used in this work. As mentioned earlier, decision makers' judgments involve uncertainty and imprecision. Fuzzy set theory is introduced to AHP to deal with the uncertainty and imprecision. These uncertainties are transformed into fuzzy sets and integrated into the AHP model. In the fuzzy set theory, an element has a degree of membership in a fuzzy set. The membership function represents the grade of membership of an element in a set. The membership values of an element vary in the interval [0, 1]. The membership function maps the variation in the value of linguistic variables into different linguistic classes [58, 59].

Economic analysis is also applied in this dissertation. A comprehensive CBA accompanied by computing benefit/cost ratio, DCF, NPV, and minimum total cost, is conducted to estimate costs and benefits of SGTs and the economic feasibility of electricity market deregulation.

1.4 SOFTWARE TOOLS

The NLP algorithm is built using Matlab® script. MS Excel® solver is used to solve the optimization problem described in Chapter 3. Fuzzy AHP algorithm described in Chapter 4 is built by coding the program in MS Excel® platform.

1.5 LITERATURE SEARCH

Literature search conducted for this dissertation covers a historic background of electricity generation and services in Saudi Arabia and how the electricity industry has emerged. The literature also presents and examines the challenges facing the Saudi electricity infrastructure [13-17, 20, 22-24, 33, 36, 37, 41, 42, 60, 61]. Solutions and approaches proposed to overcome the challenges are discussed in [13, 18, 22, 23, 25-30, 32, 34, 38, 45, 47, 62-69]. Saudi Vision 2030, the National Transformation Program, policies and regulatory aspects of the electric grid sector in Saudi Arabia are discussed in [19, 39, 40, 45, 47, 62, 63, 70-75]. This literature discusses, also, the Saudi electricity market aspects and market deregulation.

Definitions and aspects of grid modernization are discussed in [2, 4, 11, 12, 21, 35, 76-83]. Electricity markets mechanisms, economics, planning, and deregulation are discussed in [3, 44, 76, 84-101]. The Smart Grid, SGTs insertion, Smart Grid policy, planning, metrics, standards, and evaluations are discussed in [1, 2, 5-12, 46, 66, 81, 82, 102-137].

Economic analysis including CBA, benefits evaluations, and economic applications on power systems are discussed in [6, 54, 57, 99, 119, 132, 138-158]. Theories and concepts in economics and finance are presented in [159-162]. The definitions and applications of decision making, selection tools, MCDM, AHP, fuzzy set theory and fuzzy AHP are discussed in [45, 49-56, 58, 59, 163-176].

The rest of this section presents an overview of the Saudi electricity system in Saudi Arabia. It discusses the emergence of the electricity infrastructure from economic and technical perspectives. It also discusses the current status with respect to market structure.

1.5.1 BACKGROUND OVERVIEW ABOUT SAUDI ELECTRICITY SYSTEM IN SAUDI ARABIA

The origins of electricity generation in Saudi Arabia date back to 1907 when there were two generators providing the city of Madinah with lighting. One generator was fired with kerosene and the other one fired with coal. Then, small generators were scattered across the country to power the holy mosques, factories, and oil drilling companies. In 1950, government approval was issued for the establishment of two electricity companies, namely, the Saudi National Company for Electric Power in Jeddah, and the Al-Ahsa Electric Company. In the following years, small utility companies were established in major cities and towns across the country and run by private sectors, municipalities, and cooperative societies. In 1961, the first Department of Electrical Affairs was established under the Ministry of Commerce to issue permits and licenses for electricity industry. In that period, each electricity company charged different rates based off their resources and conditions. In the 1970s, major regulatory reforms in the electricity sector toke place by the establishment of the Ministry of Industry and Electricity. Later, the Ministry name was changed to the Ministry of Water and Electricity. In that period, a decision was taken to fix the electricity tariff at a uniform rate for all service providers. Then, all independent power providers (IPPs) were subsumed into four regional companies, or the so called Saudi Consolidated Electrical Companies (SCECOs). These consolidated companies encompassed IPPs serving Eastern, Central, Western, and Southern parts of the country. The northern region was still served by several IPPs [60].

Since then, the demand had grown vastly across the country as a result of an increase in population, economic growth, and low tariff structure supported by government subsidies. As a result, the government toke steps to restructure the electricity industry, improve service quality, reduce subsidies, and increase coverage across the country. In 1998, the government had decreed the merger of the four regional SCECOs into a single joint stock company known as SEC. In 2001, ECRA was established as an independent regulatory authority to oversee electricity and co-generation industry [41, 60]. In 2002, SEC was established to serve consumers with electricity across the country. In May 2016, a government decree was issued to replace the Ministry of Water and Electricity with the Ministry of Energy, Industry and Natural Resources. The newly created Ministry is responsible for policies concerning oil, gas, natural mineral, RE, and electricity [75].

SEC is dominating the electricity market by supplying 70% of total demand. SEC is a government-owned corporation whose shares are publicly traded in the Saudi Capital Market. About 81% of SEC ownership is owned by the government and Saudi Arabian Oil Company (Aramco) jointly. While SEC is responsible for the generation and distribution sectors, the transmission sector is run by the National Grid SA Company (NGSA), which is a limited liability corporation wholly owned by SEC. The Saline Water Conversion Corporation (SWCC) supplies a significant percentage of the electricity in the country. Table 1-3 shows a breakdown of the installed capacity for the main electricity producers in the country in 2015 [16].

Table 1-3. Breakdown of Electricity Providers [16]

Producing entity	Number of plants	Capacity (MW)	Generation percentage
SEC	47	57,138	70%
SWCC	7	6,222	7.6%
Hajar Electricity Co.	1	4,098	5.1%
Jubail Water and Electricity Co.	1	2,875	3.5%
Aramco	7	1,563	1.9%
Others	18	9,708	11.9%
Total	81	81,604	100%

Originally, the electricity market in Saudi Arabia is vertically integrated and operated by SEC as shown in Fig. 1.18. In 2012, a national restructuring plan has been set to unbundle the electricity industry sectors. The plan aims at creating a market for electricity trading. The first dimension of modernization approach presented in this dissertation aims to provide a framework for this effort [16].

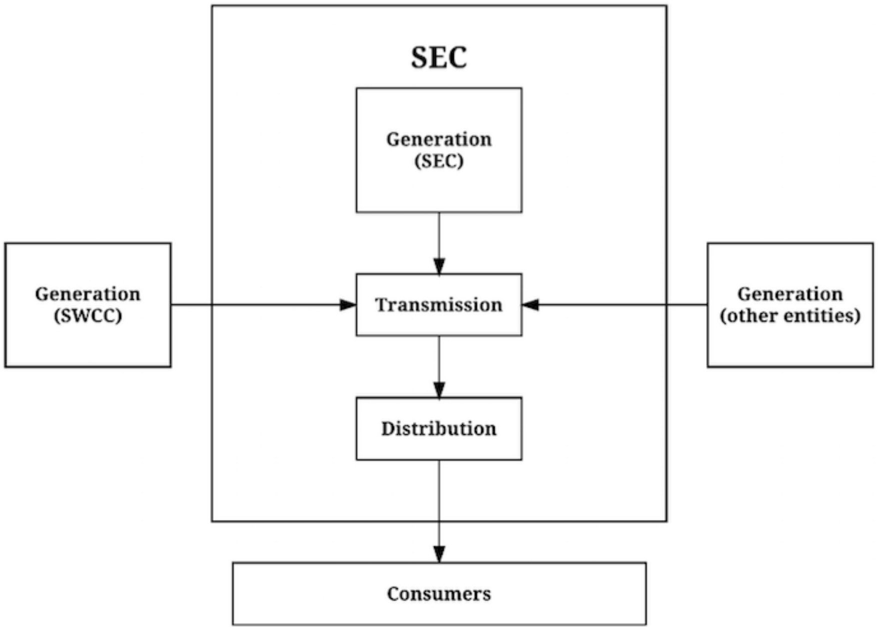

Fig. 1.18 Current Organizational Structure of the Saudi Electricity Market [16]

The plan is expected to follow three phases. The first phase started in 2012 by launching the NGSA Company to oversee and manage the transmission system. As mentioned earlier, NGSA is wholly owned by SEC. The first phase includes dividing the generation and distribution sectors pertaining to SEC into multiple companies. In this phase, the market will be transformed from vertically integrated to single buyer market. The principal buyer is expected to manage the sector's income, enter and oversee contracts with players in the market. Fig. 1.19 shows the organizational structure of the market after the first phase is completed [16].

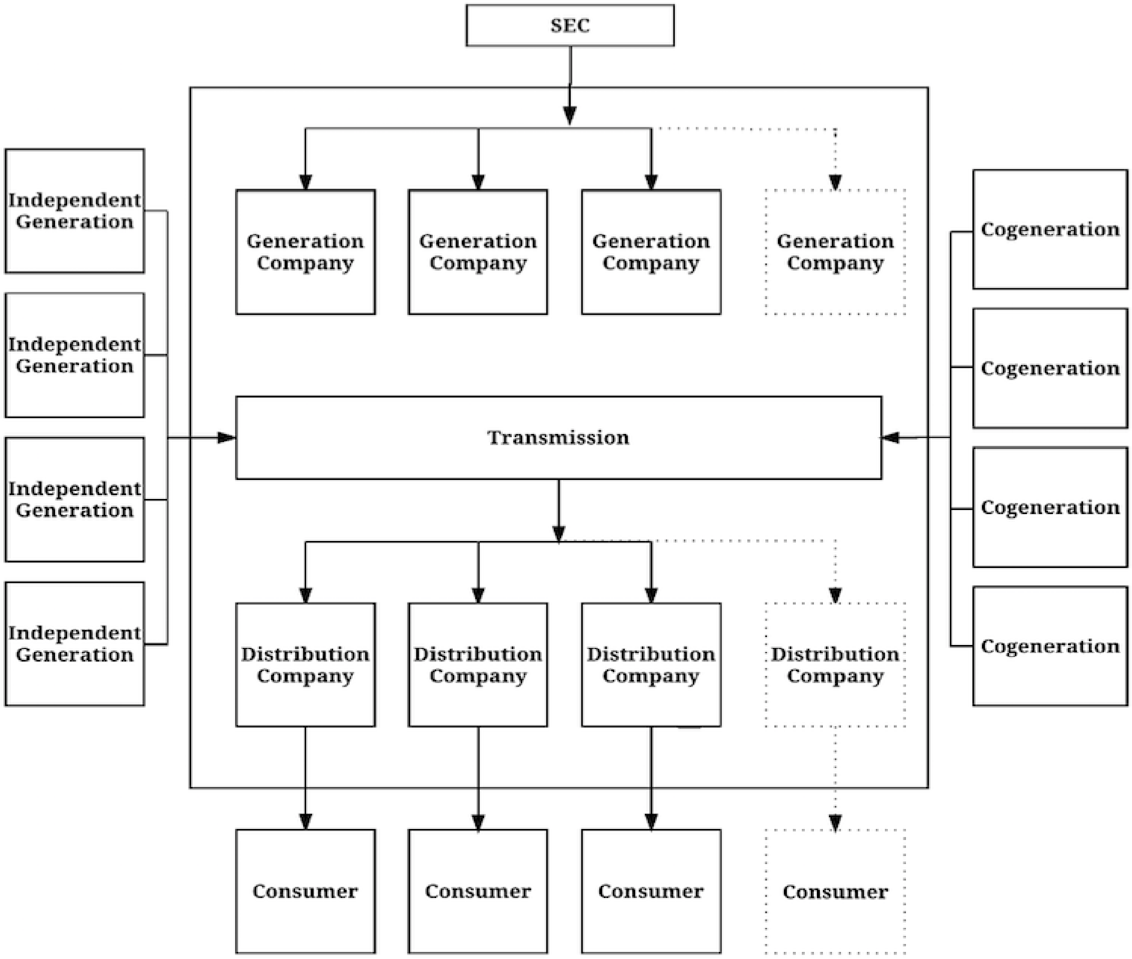

Fig. 1.19 Organizational Structure of the Market after the First Phase [16]

In a subsequent stage in the second phase, NGSA and the generation and distribution companies will be separated from SEC in which these entities compete through a wholesale competition structure. Separating NGSA from SEC will create an independent transmission operator that maintains open and unbiased policy of access to transmission capacity for use by all producers.

The third phase is the long-term stage in which the electricity market is expected to be fully deregulated. The ownership of the retailing sector will be separated from the holding company, SEC, as shown in Fig. 1.20 [16]. In light of the current progress, two entities have been established: the independent system operator, and the main buyer [16].

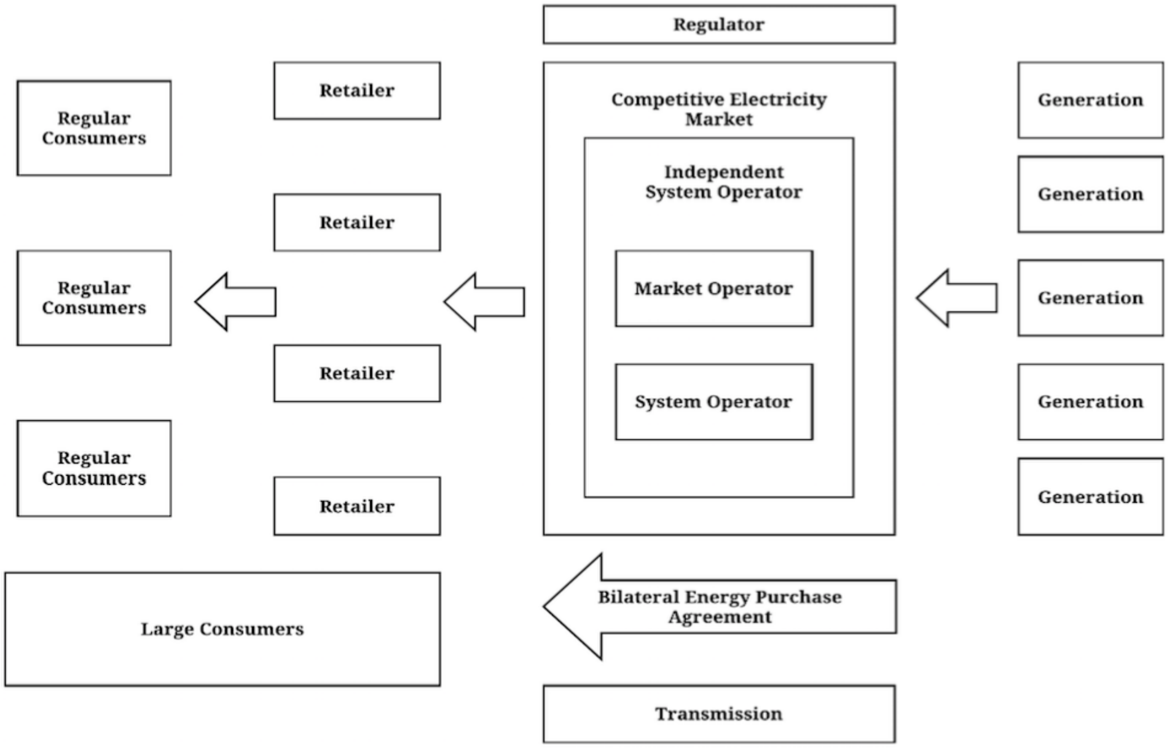

Fig. 1.20 Electricity Market Structure after Full Implementation of Restructuring Plan [16]

1.6 ORGANIZATION OF THE DISSERTATION

This dissertation is organized on the basis of the chronological development of the proposed framework of modernizing the Saudi electricity infrastructure and related publications. The references [48], [177], and [178], based on the research conducted for this dissertation, are published at different venues and the references [179], [180], and [31] are under review.

Chapter 1 provides an introduction to the research problem with an insight into the proposed dissertation. Chapter 2 describes the framework and is derived directly from [48], and the manuscript of [31] that is under review at the time of writing the dissertation. Chapter 3 introduces and analyzes the first dimension—electricity market deregulation and its impact on the modernization of the Saudi grid. It discusses the mechanism modeling of transforming the electricity market from regulated to deregulated status and estimating GW. This chapter is directly derived from [177]. Chapter 4 addresses the second dimension—

integrating SGTs to the existing grid—by proposing a MCDM framework using fuzzy AHP to prioritize the importance of SGTs for the Saudi electricity infrastructure. This chapter is directly derived from [178] and the manuscript of [179] that is under review at the time of writing the dissertation. Chapter 5 presents a comprehensive economic analysis to SGTs and prioritizes SGTs infrastructure based on their costs and benefits. This chapter is directly derived from the manuscript of [180] that is under review at the time of writing the dissertation. Chapter 6 address the policy, planning, and societal implications of the framework proposed. Chapter 7 proposes a subsequent future work.

CHAPTER 2

EXAMINING SOME PROSPECT SCENARIOS FOR THE ELECTRICITY GRID INFRASTRUCTURE MODERNIZATION IN SAUDI ARABIA[1]

2.1 INTRODUCTION

Electricity consumption in Saudi Arabia is rapidly growing due to the increase in population, expansion in national development projects, and heavily subsidized electricity prices. In order to meet the growing demand, the electric grid system is undergoing a national plan aiming to harness energy conservation, and improve the efficiency of electricity market. In this chapter, we suggest that grid modernization may progress in two dimensions: market deregulation, and SGTS penetration and implementation. Market deregulation refers to the decomposition of the components of electric power industry: generation, transmission, and distribution [3]. The terms: *market deregulation, unbundling process, and restructuring plan*, are used interchangeably as they all imply electricity market reform. Smart Grid is defined as the modernization of electric grid and electricity infrastructure by implementing digital information and control technologies and integrating distributed resources.

As part of the national plan, SEC has undertaken a restructuring program to unbundle its services. The plan started in 2012 with the launch of the NGSA to oversee and manage the transmission system. Four generation entities and one distribution entity will be launched during 2014. SEC will be the holding company of these entities and will set market standards, finance expansion projects, and administer the operations of high voltage levels (230 kV and above). The restructuring plan will take place in three stages. The first stage is the transition stage in which four generation entities, one transmission entity, and one distribution entity will be launched. All six entities will be fully owned by SEC. This stage will create a "single buyer" market. The second stage is the medium-term stage in which the ownership of the transmission entity and/or the

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[1] This chapter is extracted verbatim from "Examining some prospect scenarios for the electricity grid infrastructure modernization in Saudi Arabia," proceedings of *North American Power Symposium*, Pullman, WA, 2014.

generation entity will be separated from the holding company. This stage will create a principal buyer market with wholesale market competition. The third stage is the long-term stage in which the electricity market will be fully deregulated and retail market ownership is separated from the holding company [73, 181].

This chapter examines prospect scenarios for modernizing the electric grid system with regard to the two dimensions. The first dimension corresponds to market deregulation and the transition from being served by a sole government-owned entity to a deregulated market. The second dimension corresponds to the implementation of Smart Grid and the penetration of its technologies. The first scenario proposes a regulated market that enables the penetration of SGTs. The second scenario proposes a deregulated market, however, without penetration of SGTs. The third scenario proposes a deregulated market with the penetration of SGTs. Table 1-2 depicts the three scenarios along with the current status.

The chapter aims to offer a general overview about the proposed scenarios followed by insights in terms of benefits, cost, and risks associated with the implementation of each scenario. The examination of these scenarios sets the platform for further investigation anchored by econometric modeling and cost-benefit analysis in subsequent research.

2.2 A BRIEF OF HISTORY OF ELECTRICITY INFRASTRUCTURE IN SAUDI ARABIA

In 1961, the first authority that administered the electricity industry in Saudi Arabia was established under the Ministry of Commerce. In 1972, the Department of Electricity Services was established and separated from the Ministry of Commerce. In 1974, the Ministry of Commerce was divided into two agencies: the Commerce Agency and the Industry and Electricity Agency. In that year, the government started subsiding electricity services to all electricity service providers by setting below-the-actual-cost tariffs. In 1975, the Ministry of Industry and Electricity was formed followed by, in 1976, the establishment of the Electricity Corporation to coordinate electricity services in the country [60].

Since then, the electricity sector was operated by numerous IPPs, and cooperative societies before they were consolidated in 1981 into four major regional companies: Central, Eastern, Southern, and Western, or the so-called SCECOs. In 1998, the government decreed the merger of all four companies to form the SEC in 2000. The following year, ECRA was formed to regulate the power sector [41].

2.3 CURRENT STATUS

2.3.1 MARKET STRUCTURE

Electricity market in Saudi Arabia is vertically integrated. 74.3% of SEC, the national electricity provider, is owned by the government, and 6.9% by Saudi Aramco amounting to 81.2% of government ownership. Saudi Aramco is the state-owned oil and natural gas company. The rest of SEC (18.8%) is publicly owned [70].

2.3.2 OIL CONSUMPTION

Saudi Arabia is the largest consumer of petroleum in the Middle East, and the world's thirteenth largest consumer of total primary energy in 2009. More than 25% of domestic oil production, or about three million barrels per day, is consumed locally. The majority of petroleum consumed domestically is allocated for transportation fuels and direct power generation by burning. Carbon dioxide emissions totaled from fossil fuels consumption as of 2011 were 513.53 million Metric Tons [61].

2.3.3 POWER GENERATION

As of 2012, the total available installed capacity is 53,588 MW [181], and total installed capacity is 66,081 MW [182]. Gas turbines account for about 61.1% of the available installed capacity, steam turbines make up 32.4% of the capacity, combined cycle units yield 5.4% and diesel units yield 1% [181]. As of 2011, fuel types used in electricity generation include crude oil (37%), natural gas (37%), diesel (21%), and heavy fuel oil (5%) [182].

SEC owns 76.7% of the installed capacity, SWCC owns about 7.6%, and the rest of 24.8% is owned by different relatively small private companies. The retirement of some existing generating units (8,390 MW as of 2010) is another challenge facing the SEC in its efforts to meet the demand [41]. In 2007, SEC has allowed IPPs and independent water and power producers (IWPPs) to participate in power generation during peak times as through the “Program for Private Sector Participation in Electricity” project in which SEC purchases electricity from the privately owned generation plants and sells it to its consumers [26].

Saudi Arabia set the largest plan in the Middle East to expand its generation capacity from 55,000 MW to 120 by 2020 [61]. Part of this plan is to incorporate RE resources. In 2012, King Abdullah City for Atomic and Renewable Energy (K.A.CARE) announced that a capacity of 54,000 MW will be generated from RE resources by 2032. The projected plan includes generating 25,000 MW from concentrated solar power, 16,000 MW from solar PV, 9,000 MW from wind energy, 4,000 MW from waste-to-energy and geothermal energy [25].

2.3.4 DEMAND

Total electric energy consumed in 2012 was approximately 240.288 TWh [182]. Residential consumption accounts for 50% of total energy consumed [182]. Industrial consumption represents 17%, commercial 16%, government 13% and other 4% [182].

Peak demand occurs on weekdays from 1 pm to 5 pm from June through September. Besides that, demand increases during the holy lunar months of Ramadan (month of fasting) and Dhul-Hijjah (month of pilgrimage) [26]. Typical demand curve falls in three intervals: peak period from 10 am to 6 pm, off-peak period from 6 pm to 12 midnight, and low-peak period from 12 midnight to 10 am [27]. The current DR technique used is ‘forced reduction of load’ [27].

In order to control peak demand, SEC has launched awareness programs offering incentives to consumers to participate in peak load shifting or shaving. Few years ago, SEC Western Operating Area launched a voluntary program targeting industrial consumers in which they shift their load during peak periods for a compensation of bill reduction. The program was followed by a mandate by ECRA stating that time-of-use (TOU) tariff structure was to be applied on industrial consumers in which they pay a lower tariff; 26 Saudi halala/kWh during peak periods, and 15 halala/kWh during off-peak periods (1¢ US = 3.75 Saudi Halala) [26].

SEC reports that the number of customers served with electricity is increasing by 5.2% annually. Demand growth of electricity consumption increases by 8% every year, while it is only 1-2% in the developed countries. Energy consumption per capita increases by 6.5% annually [18]. Peak demand is growing at a rate of 7% per year leading to service interruptions, resources depletion, and system stress. If this trend of electricity consumption continues, it is predicted that domestic consumption of oil will reach eight million barrels by 2030 [61]. To meet the growing peak demand, the country is required to allocate about US $8 billion every year for expansion investments and grid modernization [27].

2.3.5 TRANSMISSION SYSTEM

Transmission system in Saudi Arabia is 96% interconnected. A full interconnection of the grid is projected in 2016 [61]. The length of the transmission network in 2012 is 51,881 km circular (increased by 77.9% after SEC was established 2000). The length of the distribution network in 2012 is 438,130 km circular (increased by 100% after 2000). Transmission-level voltages considered in the network are 380, 230, 132, 115, and 110 kV. As of 2012, the grid is comprised of 660 power transmission substations spread in the network. Peak load for the interconnected network (96% of the network) is 48,737 MW of which 2,500 MW are used for only 100 hours/year (two or three hours a day in summer) [72]. Peak load for the isolated network (4% of the network) is 3,202 MW [181].

The Saudi grid is interconnected to the rest of the five GCC members: Kuwait, Bahrain, Qatar, United Arab Emirates, and Oman. The GCC grid interconnection is comprised of a 400 kV double circuit overhead line linking Kuwait, Saudi Arabia, Qatar, Emirates, and Oman. Bahrain is interconnected to the link via a submarine cable. The 60 Hz power system of Saudi Arabia is interconnected to the other GCC countries, whose power systems are 50 Hz system, via three 600 MW back-to-back high voltage direct current (HVDC) converters [64]. Besides that, there is a plan to connect Saudi Arabia with Egypt by a 3,000 MW link. The link will reduce peak demand in both countries as the peak demand hours in Egypt vary from those in Saudi Arabia [61].

2.3.6 NETWORK

The number of customers served by SEC reached 6.7 million in 2012, a 91.1% growth after the company was established in 2000 [181]. The number of cities and/or communities served is 12,450, a 58.1%

growth after 2000 [181]. Relative distribution of the available capacity owned by SEC is: 32% for the Western region, 30% for the Eastern region, 29% for the Central region, and 9% for the Southern region.

It is estimated that about 80% of the total load is air-conditioning, (i.e., inductive load), which leads to the need to improve reactive power compensation [30]. ECRA has identified air conditioning as one of the most significant underdeveloped areas in the demand side [182]. Motor stalling and voltage collapse are common disturbances in the grid as well [30]. These factors, besides others, contribute to network losses that are about 9.95% as of 2011[182].

In 2011, SEC begun standardizing nominal household voltage level by switching from 127/220 V to 230/400 V in all new districts. In addition, the new standard mandates switching the voltage level of the existing homes to the new standard over the next ten years [182].

2.3.7 TARIFFS AND SUBSIDIES

SEC has no control over tariffs stipulation as it is set by government bodies. Tariffs applied to electricity services are differentiated by consumer sector; they vary from five to 26 halala/kWh for residential consumers, 12 to 26 halala/kWh for commercial consumers, and 26 halala/KWh for governmental consumers. For industrial consumers, the tariff is differentiated by season ranging from 12 to 26 halala/kWh [182].

Government subsidies for electricity generation were US $40 billion in 2012 [182]. As a result, the cost of producing one kWh declines from 80 halala to an average of 15 halala. In other words, government subsidies account for 81% of the cost electricity production [182], which makes the electricity price rates in the country one of the lowest rates in the world [28].

The current status of the growing consumption of electricity has raised many concerns with regard to network efficiency and the energy conservation policies set in-place. Investigating different scenarios of prospective grid infrastructure provides insights toward grid modernization. The subsequent sections discuss the examination of the two dimensions: deregulating the electricity market and enabling the penetration of SGTs, with respect to the current status and projected outcomes.

2.4 FIRST SCENARIO: VERTICALLY INTEGRATED MARKET WITH PENETRATION OF SGTs

The first scenario suggests a vertically integrated market structure with enablers for the penetration of SGTs. Given that, the market would continue being vertically integrated and controlled by the sole service provider, SEC.

2.4.1 BENEFITS

This scenario presents a stable transition to grid modernization as it falls within the purview of one main market player, SEC. By being a vertically integrated market structure, the implementation of this scenario may be attainable in terms of policy drafting, and Smart Grid realization. Regulatory aspects in this scenario would not highly deviate from the current ones, except for legislations regulating communication means between consumers and SEC, i.e. DR, and real-time monitoring.

Saudi Arabia with its traditional deep-rooted bundled electricity market structure would highly benefit from SGTs in reducing energy consumption, diversifying energy resources, and enhancing system stability and efficiency. ECRA has proposed a conservation plan that is backed by the implementation of demand side management (DSM). The plan will save 175 million oil barrels by 2021, and reduce both electricity consumption and peak demand by 8% and 14%, respectively [72]. The realization of a of Smart Grid-like modernization philosophy holds the potential for the optimal the use of transmission capacities and maintenance of the security of electricity supply. Proper penetration of SGTs would reduce network losses and power outages, control reactive power, and increase system reliability and stability. In addition, using advanced monitoring and control energy management systems can enhance the conservation and the efficiency of energy consumed by buildings.

DR is another application that is aimed at reducing electricity consumption, especially at peak hours of system use. In [27], a simulation of variable price structure and incentive-based methods for possible DR in the Riyadh region of the Saudi grid is performed. TOU rate and emergency demand response program

(EDRP) are simulated corresponding to the demand curve of Riyadh region. The simulation shows that the DR model alters the demand favorably for peak hours of electricity consumption.

Meeting peak demand is one of the main challenges facing the grid. Due to the severe-climate conditions and the increasing population, peak demand creates an unbalanced load structure that reaches its highest level for only a couple of hours per day and few days per year. In some events, peak demand increases to twice the average demand level [28]. SGTs would reduce peak demand and improve asset optimization [18].

RE resources possess high potential to provide Saudi Arabia with additional generation capacity to help meet the demand and reduce oil consumption. Moreover, the country is projected to export excess production of electricity from RE to the neighboring countries [18]. Although the potential of RE in Saudi Arabia is enormous, most of these resources are scattered in remote areas. Besides that, there is no policy set in-place to mandate the electric utility to produce a specific percentage of its installed capacity from RE resources such as the regulation of the renewable portfolio standards (RPS) in the U.S. [116]. Smart Grid enablers are viewed as crucial tools to facilitate such a plan. Implementing SGTs would boost RE integration to the grid as well as the integration of distributed generation units (DGs) that serve remote areas [18]. With the challenges brought by RE integration, the Smart Grid would reduce power intermittency, and improve power quality and reliability.

SEC has developed a plan to roll-out digital meters to all customers. More than 12,000 automated meter reading (AMR) units were installed for some key industrial or commercial consumers to set the stage for variable-tariff implementation. The plan will expand to install 40,000 meters for the future [181]. Automated meters increase the efficiency of meter readings, enable energy balance management in DGs, create dynamic electricity pricing structure, and enable the implementation of DSM.

2.4.2 COST

Implementing SGTs require a considerable amount of investment. Given the fact that the electricity market is regulated, investments allocated for SGTs might be questioned. Without feasible justification for such technologies, the implementation of Smart Grid would be unforeseeable. For example, how far would

SEC be willing to provide its customers with instantaneous monitoring and active control for their electricity consumption? The absence of market competition reduces the likelihood of the realization of these technologies.

Moreover, funding projects associated with SGTs would be a challenge. SEC has no control over tariff stipulation. Therefore, it might not be able to allocate the proper amount of investment for these projects.

2.4.3 RISKS

By being a market dominator, SEC might not acquire the motivation to undergo Smart Grid implementation projects, which might lead to underestimating plans for grid modernization, or at least to partially implementing SGTs. Partial implementation might lead to system instability and increase in electricity prices.

Within the bundled structure, even with SGTs being enabled, the overall market mechanism might not help SEC meet the increasing demand and improving system efficiency and stability. Although SGTs would facilitate RE integration, the cost of the kW produced by these resources is yet not comparable with the subsidized price of the domestically produced oil. In fact, SEC is granted provision of oil for electricity generation in which the marginal cost of the barrel of oil provided is less than or equal to the actual marginal cost of US $5 per barrel [25].

2.5 SECOND SCENARIO: DEREGULATING THE MARKET WITHOUT THE PENETRATION OF SGTs

This scenario presents a deregulated market, however, without the penetration of SGTs. The scenario depicts the idea of market reform without advancing the infrastructure with SGTs.

2.5.1 BENEFITS

Unbundled market structure would create a deregulated market where distribution companies and producers discover an equilibrium price and quantity of production. Deregulated structure improves market efficiency as every entity in the market would optimize its operations for the sake of profit maximization. By implementing this scenario, the market regulator would apply a balanced tariff setting structure in which the service providers can attain a reasonable profit. One of the main advantages of market deregulation is that a wholesale market for electricity will be structured, which would encourage RE producers as well as relatively small DGs to enter this market.

2.5.2 COST

Deregulating the market would create dynamic pricing mechanism leading to fluctuation in electricity prices in which the price is impacted by economic market conditions and market mechanisms. Improper exploitation of market power by one or more market players could arise leading to price manipulation. Another cost associated with this scenario is that incurred by system operators to maintain system stability.

2.5.3 RISKS

This scenario would create a market without a modernized grid. SGTs are crucial to improve grid stability and facilitate market deregulation. Improper deregulation may collapse the grid. An example of that is when the state of California unsuccessfully deregulated electricity market in 1998 leading to the energy crisis of 2000-2001 [93]. In a deregulated market, profit margin should be high enough for market players to compensate their costs and justify the risks associated with their investments. Enabling Smart Grid applications would assist these players to reduce their costs and optimize operations [93]. The absence of real-time monitoring, control, and communication would hurdle information transfer, load balancing, and DSM among market players and system operators. In a fully deregulated market structure, DGs like microturbines, solar cells, and wind turbines may be allowed to participate in the retail market. Therefore, meeting demand-supply balance would be a challenge requiring real-time monitoring and DSM. Partial deregulation of electricity market is yet another risk.

On the transmission system, SGTs such as phasor measurement units (PMUs) and wide area management system (WAMS), along with flexible AC transmission systems (FACTS), are major tools used to maintain the system stability and security of supply [93]. However, their ownership, location, deployment, and compensation for use needs to be handled equitably in a market scenario.

In general, this scenario presents a contradicting case in which market structure heads in one direction, while grid modernization heads in another direction. This scenario would create conflicts and complexity and may eventually compromise system reliability and stability. If the Saudi grid infrastructure is to follow this scenario, a smooth and continuous transition is required to maintain system reliability and stability.

2.6 THIRD SCENARIO: DEREGULATING THE MARKET AND ENABLING THE PENETRATION OF SGTs

This scenario presents a fully modernized structure in terms of market deregulation and grid advancement. It considers a deregulated market that enables the penetration of SGTs.

2.6.1 BENEFITS

As discussed in the previous scenario, a deregulated market structure would improve energy conservation, and reduce consumption. Transforming the market from being served by a government-owned entity to a deregulated market would increase market efficiency. In addition, enabling SGTs, as mentioned in the first scenario, holds the potential for enhancing information transfer, improving DSM, and increasing system reliability and stability.

Electric utility deregulation has been successful in some markets like PJM in the United States. Because of the proper deregulation along with the proper penetration of Smart Grid, the electric rates in Pennsylvania dropped from 15% above the U.S. average to 4.4% below the average [93].

DGs possess a high potential for the Saudi grid to meet the growing demand so long as enabling technologies for the Smart Grid are deployed concomitantly with the penetration of DGs. Microgrid is a concept evolved from the notion of integrating DGs so that the collection of DGs, end-user loads, and other assets can act as a single controllable unit in either the islanded or grid-paralleled mode [102, 103, 120], for performing special functions such as in disaster recovery or coordinated DR. Microgrids also possess the potential to supply electricity to loads in remote areas where the transmission network may not be readily available. The benefits of RE sources may also be highly exploited with the concept of microgrids. Microgrids can also provide different types of ancillary services to the grid like voltage support, frequency regulation, and harmonic cancellation [116]. For microgrids to be fully compatible with the wide-area grid, many enabling technologies (e.g., distributed control and protection systems, and advanced power electronics) must be deployed [116].

2.6.2 COST

Cost associated with the implementation of this scenario could be enormous. This cost includes the deployment of the infrastructure for SGTs, the cost incurred by various market entities due to the fluctuations in electricity prices, and the premiums (hedges against risks) handled by a system operator in order to maintain system stability. If such a scenario were to be implemented, there would be tremendous amount of efforts toward enacting regulatory frameworks and setting Smart Grid protocols and standards. The transition to this scenario should not take place at once but through multiple planned steps.

2.6.3 RISKS

Past practices undertaken by some electric grid markets, such as the state of California, show that deregulating electricity market without implementing advanced technologies capable of modernizing the grid to fit such a deregulated structure may cause crisis and may collapse the system [93]. Subsidies in oil price are yet another challenge that might turn down the opportunities for RE sources and DGs to enter the market. Other factors associated with market deregulations, like exploitation of market power by one or more players, partial deregulation, and improper deregulation, are potential risks when applying this scenario.

2.7 PATH FORWARD

Modernizing the grid infrastructure in Saudi Arabia with SGTs and/or market deregulation should be justified by the needs of the grid. Multiple sources in the literature have analyzed different practices performed in some regions with regard to Smart Grid implementation. The U.S. and Europe, for example, followed different approaches to develop and improve smart technologies in electric grid systems. The Smart Grid initiative in the U.S. is backed by national needs to secure energy provisions, meet demand, and reach energy independence. In Europe, on the other hand, there has been a need to improve the interconnected network that is comprised of 34 countries. The Smart Grid initiatives in Europe have been motivated by the environmental impacts of greenhouse gas (GHG) emissions caused by energy production [104].

Real-time monitoring, RE deployment, energy storage, and DR would help the Saudi grid meet the increasing demand. In the transmission system, PMUs and WAMS can enhance system communication and detection capability of service interruption [77].

Modernizing the Saudi grid requires initiatives and policies to propel the inclusion of SGTs and allow a deeper penetration [104]. These policies must be motivated by concepts of innovation, energy conservation, sustainability, market efficiency, and security of energy supply [104]. To grasp the benefits of SGTs, the Saudi grid must first acquire the enabling tools for successful implementation and deployment like DGs, energy storage systems, DSM, distribution automation and protection, and communication systems.

This chapter serves as groundwork for future econometric analysis exploiting the scenarios presented earlier. The econometric analysis helps identify the proper model for the future Saudi grid infrastructure that achieves targeted outcomes in terms of security of energy supply, energy conservation, reliability, stability, and grid modernization. The proposed econometric analysis will provide a platform for the decision-making process towards specifying the future Saudi grid with respect to the two dimensions: market deregulation and the penetration of SGTs.

2.8 CONCLUSION

The electric grid system in Saudi Arabia is undergoing a national plan to reduce the growing demand in electricity, improve energy conservation, diversify energy resources, and enhance grid reliability and stability. Different prospect scenarios for the Saudi grid are examined with respect to market deregulation and the penetration of SGTs. The chapter draws insights about proper future path towards grid modernization. The chapter shall serve future econometric modeling and cost-benefit analysis.

CHAPTER 3

EX ANTE COST-BENEFIT ANALYSIS FOR OPTIMAL DEREGULATION OF ELECTRICITY MARKETS[2]

3.1 INTRODUCTION

Several electricity markets around the world have undergone a deregulation plan to modernize the infrastructure of the grid. Deregulation in electricity markets is unbundling the generation sector from the delivery sectors of the electric power industry, and directly implies a reform action [3]. In several countries, electricity generation assets and markets are owned and operated by government entities; such an infrastructure is termed vertically integrated [94].

Government ownership of electricity markets has emerged from the notion that vertically integrated markets produce suboptimal supply-demand balance. This notion rests on some bounds: firstly, electric grid projects require large investments that only governments can afford; secondly, the cost of electricity production is characterized by economies of scale, creating a natural monopoly in the market; and, finally, it is perceived that the reliability of supply increases when the coordination of investment planning, stand-by capacity, operations, and maintenance is performed by one entity [94].

Advocates for the deregulation of electricity markets, however, believe that deregulation creates a competitive market, improves efficiency, and reduces cost. It also improves incentives by reallocating property rights from public to private sectors. It may also change the objective functions of operators faced with private sector initiatives. The presumed gain depends on the quality of regulatory framework set in place [85, 95].

Electricity market restructuring process is often accompanied with some adversities such as: (a) the shift of ownership from government to private sector may impacts technology, the economy, and the society;

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[2] This chapter is extracted verbatim from "Ex ante cost benefit analysis for optimal deregulation of electricity markets," proceedings of *IEEE Power and Energy Society General Meeting*, Boston, MA, 2016.

(b) new entities may emerge in the market and change the market's technical and financial characteristics; and, (c) the operational procedure might change as private ownership demands a more competitive practice. As a result of these changes, new regulatory policies, standards, and practices arise [85, 96].

In the U.S., the philosophy of deregulated markets started on the 1970s when the economist, Milton Friedman, advocated government interventions. This led to increasing consolidation among companies. Number of industries were deregulated including airlines, telecommunications, energy, and transportation. Before that, financial and banking systems encountered certain level of deregulation. The idea of deregulation was promoted by improving competitiveness of the market, which would result in economic growth, better service, and lower costs. Ultimately, the deregulation caused some companies to flourish and other to fade.

It is argued that deregulation of electricity markets would increase prices on consumers. Before deregulation, utilities, or electricity generators, set their prices by estimating the weighted average cost of production. Therefore, they receive their costs plus an allowed return on capital. After deregulation, electricity generators set the price based off the most expensive generator whose input is necessary to meet the demand, which is the marginal cost of production. It is argued that during regulation the price of electrical energy is relatively low during shortages, and relatively high during relative abundance.

From consumers' perceptive, electricity prices during deregulation may be lower than prices during regulation. The reason behind that is that during regulation, consumers are paid for capital cost of power plants during high-peak and off-peak periods, which means consumers pay for power plants that are idle during off-peak demand [101].

The chapter proposes an optimization model aimed at improving the decision-making process of deregulating an electricity market. GW, which is defined as the sum of the net consumers surplus and of the producers profits, is chosen as the criterion on which the decision of deregulating a market is based. The contribution of the chapter is embodied in employing electricity network efficiency as a parameter to model an *ex ante* setup. Non-ideal price elasticity of demand is also considered for the same purpose. We assume that the price elasticity of demand is constant. A formulation of the optimization problem serves as a ground for conducting a CBA. This analysis helps decide whether the deregulation is worthwhile or not.

The rest of the chapter is organized as follows: section 3.2 provides a literature review on measuring the impact of deregulating electricity markets; Section 3.3 introduces the concept of CBA; Section 3.4 discusses the proposed model; Section 3.5 discusses the formulation of the optimization model; Section 3.6 discusses the application of the model to the Saudi electricity market; Sections 3.7 and 3.8 present the results and a sensitivity analysis, respectively; and, Section 3.9 concludes.

3.2 IMPACT OF DEREGULATING ELECTRICITY MARKETS

Techniques used to measure the impact of the deregulation of electricity markets assume that deregulation will result in positive and negative impacts on either one or all facets, i.e., technical, economic, and societal. Reference [87] identifies two methods to analyze that impact. The first method assesses the impact from actual occurrences, or the so called *ex post*. The second method tries to predict the potential impact based on some historic trends. The latter method is called *ex ante*. Both methods require a wide range of variables at the initial stage of analysis. Reference [97] compares electricity prices and costs to assess the impact of market deregulation. However, this method faces a strong criticism; it does not address social benefits, i.e., surplus of producers, and consumers.

Some studies have examined the financial performance of deregulated market entities including net income and the performance of the share prices. This approach is discussed in [88, 98]. Other studies used return on assets (ROA) and a country's GDP as indices to track the changes [89]. However, these approaches do not consider GW. Profitability does not necessarily imply that an electricity market becomes better. Moreover, a country's GDP might increase or decrease because of several factors, none of which may relate to electricity market deregulation.

Some other studies have examined the productivity impact of deregulation using either labor productivity or total factor productivity [88, 91, 92, 159, 183]. This approach has also some shortcomings. In essence, it is hard to measure capital inputs accurately considering frequent changes in environmental regulations, technology, and services. It is also hard to untangle cause and effect. Therefore, this approach does not appropriately consider GW [84].

Other studies, like [90], measure the effect of deregulation on productive efficiency using frontier methodologies, suggesting that privatization either moves market entities closer to the efficiency frontier (efficiency change) or moves the frontier quickly (technical change). This approach distinguishes between technical changes and changes in efficiency as opposed to the previous approach. However, it still suffers the same drawbacks of the previous approach [84].

Finally, other studies apply CBA for market deregulation with valuable outcomes. CBA does not only consider real variable of interest, but also social cost and benefits. Several researchers adapt this approach in an *ex post* framework. Therefore, these studies leverage abundant data available after the deregulation. However, these studies are incapable of measuring CBA for market deregulation in *ex ante* basis.

3.3 CBA

This chapter presents an approach to create an *ex ante* model serving to examine the CBA for the deregulation of a vertically integrated electricity market. The proposed approach constructs a CBA model assuming that there would be no change in policy or market environment. It also assumes data related to such a market before deregulation is available. The proposed approach would eventually result in a counterfactual model of a deregulated electricity market.

CBA is an applied economic tool that considers benefits and costs associated with the application of a program, a project, or a setup. CBA serves as a tool to compare multiple alternative setups and to choose the one that maximizes GW. CBA weights costs and benefits against economic values [57].

CBA is considered to calculate the change in GW after market deregulation. GW, a metric used to determine the worthiness of market deregulation, quantifies the overall benefits obtained from the deregulation [44]. The metric is represented as an annual change in GW considering *r* (the discount rate) and a shadow multiplier as shown in (3.1) [99].

$$\Delta W = \sum_{t=0}^{\infty} \rho^{t} \left[\Delta S(t) + \lambda_{g} \Delta \Pi(t) \right] \tag{3.1}$$

The change in global welfare ($\varDelta W$) determines whether the market should undergo a deregulation or not. λ_g, is used to adjust the effect of money "worthiness" in GW calculations, and to adjust commodity prices in the cost-benefit calculation. Electricity prices under government operations may be regulated, subsidized, or price-capped. λ_g links the price to governmental intervention. $\varDelta S(t)$ and $\varDelta \Pi(t)$ represent the change for year (t) in consumers surplus and producers surplus (before tax), respectively. Equation (3.1) provides an estimate of how much a society would gain from market deregulation. Market deregulation is not considered unless $\varDelta W > 0$. Further, the equation is used to choose among multiple alternative prospect setups.

The value, ϱ, equals to $(1+r)^{-1}$, where r is the discount rate (i.e., the interest rate that determines the present value of future cash flow). A low interest rate indicates governments, through centralized banks, try to promote economic growth, and a high interest rate shows that governments try to reduce the amount of money in the economy in order to reduce inflation pressure. Discount rate indicates how risky and uncertain a proposed project or plan is. The greater the discount rate, the riskier and more uncertain the project would be and vice versa. Discount rate represents how much a society is willing to give up now, from its current consumption, in order to receive a given increase in future consumption [140].

Equation (3.1) is used to calculate $\varDelta W$ considering the present value of the sum of the changes in consumers surplus and producers surplus evaluated at λ_g. We assume that changes in wholesale prices are translated into equal changes in final consumer prices, since we are interested in measuring the impact of competition on performance. The assumption ignores any tariff structure or efficiency gains set in the distribution sector. We also assume tax revenue collected by government and tax exposed on private sectors are ignored.

Since the estimation of future variables is not always easy, some assumptions are necessarily considered. Reference [99] assumes that $\varDelta S(t)$ and $\varDelta \Pi(t)$ are constant over time and accrue in perpetuity. Therefore, equation (3.1) is simplified to

$$\varDelta W = \frac{1}{r}(\Delta S + \lambda_g \, \Delta \Pi) \tag{3.2}$$

In general, the theoretical approach for CBA is to calculate the present discounted sum for the consumption stream. However, this theoretical method is not easy to implement in practical applications because it requires a construction of a general equilibrium model that calculates an entire future stream of consumption for every policy [99]. Therefore, for practical applications, a partial equilibrium approach that identifies two different net benefits (consumers benefits and producers benefits) is adopted.

3.4 MODEL PARAMETERS

The two key values that determine costs and benefits associated with markets deregulation are Q_p and P_p. We can derive $\Delta\Pi$ collected at government and private operations such that;

$$\Delta\Pi = \Pi_p - \Pi_g \tag{3.3}$$

where;

$$\Pi_g = Q_g(P_g - C_g) \tag{3.4}$$

and

$$\Pi_p = Q_p(P_p - C_g) \tag{3.5}$$

In the previous two equations, producers surplus is calculated by multiplying the quantity sold by the difference between selling price and average cost of production. The values, P_g, C_g and Q_g pertain to the status quo; therefore, Π_g can be calculated before market deregulation. The change in consumers surplus, ΔS, is represented as $S_p - S_g$. Similar to Π_g, S_g can be calculated before market deregulation as it pertains to the status quo.

In order to calculate S_p, the demand curve is represented as a linear demand curve as shown in Fig. 3.1. S_p is simply the area under curve limited by P_p, or;

$$S_p = \frac{1}{2} Q_P \,(P_{co} - P_p) \tag{3.6}$$

where P_{co} is the choke off price at which the quantity sold, Q_p, is zero. The choke off price helps determine the intercept of the linear demand curve. The inverse demand function is represented as,

$$P = \frac{a}{b} - \frac{Q}{b} \tag{3.7}$$

where *a* is the intercept, and *b* is the slope.

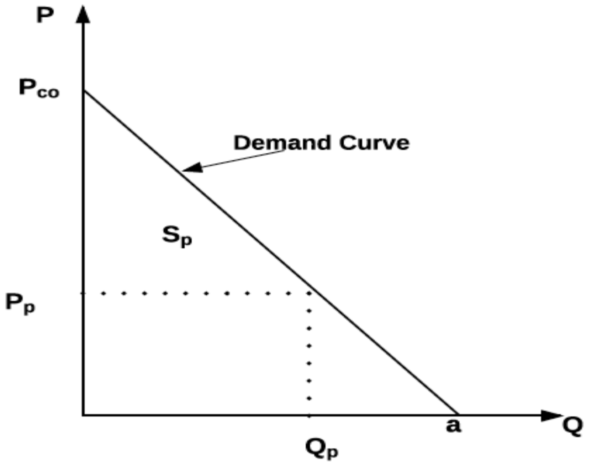

Fig. 3.1 Linearized Demand Curve of the Market after Deregulation

The price elastcity of demand, ε, links the price offered to the quantity sold. It is the ratio of the change in quantity consumed that results from a change in price, or vice versa. This relationship is a valuable tool to measure the change in electricity markets in terms of price and demand in the short-run and the long-run periods. For the purpose of this study, only the value of ε in the short run is considered because this study focuses on only the change in market behavior in terms of the price of electricity and the quantity sold right after market deregulation. In [46], 25 different studies of residential electricity demand are compared across deregulated electricity markets. In these studies, the short run ε varies in [0.03, 0.54], with the consensus measure around 0.2. In commercial sectors, ε for the short run varies in [0.17, 1.18] across multiple studies. In the industrial demand, there is an agreement on a consensus estimate of 1.3 even though it is difficult to place much confidence on this value since it is subject to aggregation and location biases [46].

In [160], the relationship between price elasticity of demand, demand curve, and choke off price is determined as

$$\varepsilon = \frac{\Delta Q}{\Delta P} . \frac{P}{Q} \tag{3.8}$$

According to the previous two equations, ε can be represented as

$$\varepsilon = -b\frac{P}{Q} \tag{3.9}$$

From the demand curve equation,

$$Q = a - bP \tag{3.10}$$

if the quantity sold is zero, the selling price is the value of P_{co}, which is

$$P_{co} = \frac{a}{b} \tag{3.11}$$

The term a is obtained as

$$Q(1 - \varepsilon) \tag{3.12}$$

After substituting the values of a and b into (3.11),

$$P_{co} = \frac{-(1 - \varepsilon)P}{\varepsilon} \tag{3.13}$$

According to the previous equation, the value, b, can be calculated as

$$b = \frac{-Q.\varepsilon}{P} \tag{3.14}$$

The value, P_g, will be replaced by C_g because, in regulated markets, P_g, does not accurately represent the real selling price in the demand curve in perfectly competitive market. Considering P_g leads to accounting for subsidies twice in the model; first when considering the subsidized P_g, and second through λ_g. Therefore, replacing P_g by C_g brings the model closer to reality. However, there is a limitation to this assumption. In a perfect market, the selling price equals the marginal cost of production. In our case, C_g is the average cost. For the sake of simplicity, and since obtaining the marginal cost of production in a regulated market is challenging, average cost may suffice in this analysis. In fact, in a regulated market, where normally a sole operator runs the market, the main aim of the operator is to satisfy demand, regardless of the cost of production since the selling price is either fixed or capped. This mechanism of pricing may justify our assumption of considering average cost instead of marginal cost. By finding the value of P_{co}, one can calculate S_p. Hence, we can substitute the values obtained for P_p, C_p, Q_p, and S_p in (3.2) to calculate the change in GW.

3.5 FORMULATING THE OPTIMIZATION MODEL

An optimization model is proposed to obtain the optimal values of the parameters mentioned in section 3.4. The optimization problem aims at maximizing ΔW. If ΔW yields a value greater than zero, the deregulation of the market may be feasible. If we consider a perfect market competition, a drop in GW from its optimal value must be zero. This drop, called deadweight loss, is defined as the result of the reduction in the amount traded caused by price distortion [44]. This value is used to determine the competitive perfectness of a market.

The objective function of the optimization problem is to maximize ΔW of the electricity market after deregulation. Equation (3.2) is considered as the objective function as shown in (3.15). The input values of the model are r, λ_g, and the parameters pertained to the market before deregulation. The value, r, is proposed based on the expected cash flow generated by the assets. λ_g is calculated as it pertains to the status quo to represent government subsidies.

From the objective function, the known parameters are S_g, Π_g, r, and λ_g. The unknown parameters are S_p, and Π_p. The latter is represented by three unknown parameters: P_p, C_p, and Q_p. Producers will be profit-seekers in the deregulated market, therefore, P_p is assumed to be bounded by P_{co} and C_p as shown in (3.16). Moreover, we assume that the deregulated market is more efficient than the regulated market. Therefore, C_p would be bounded by efficiency improvement limit as shown in (3.17). Efficiency improvement is assumed based on forecasted modernization in the electric grid after market deregulation. Such modernization is represented by the introduction of SGTs, which will be discussed in a subsequent research. For the purpose of the optimization model discussed in this chapter, efficiency improvement level is assumed. Equation (3.18) states a theoretical inequality constraint where Q_p should not exceed a, which is the quantity sold when the selling price is zero (See Fig. 3.1). Equation (3.19) states an equality constraint which is the demand curve equation. The objective function and constraints of the NLP algorithm are given by (3.15) and (3.16)-(3.19), respectively.

$$\mathrm{J}: max \left(\frac{1}{r} (\Delta S + \lambda_g \Delta \Pi) \right) \tag{3.15}$$

s.t.

$$C_p \leq P_p \leq P_{co} \tag{3.16}$$

$$(1-\eta) C_g \leq C_p \leq C_g \tag{3.17}$$

$$Q_p \leq a \tag{3.18}$$

$$Q_p = a - b. P_p \tag{3.19}$$

The value, η, refers to the electricity network efficiency from technical perspective. The value, S_p, is determined by the optimal values of P and Q, in which the market-clearing price is achieved. The model serves as a basis for the decision-making process of deregulated a regulated electricity market. The following section presents a case study applying the model on the vertically integrated Saudi market.

3.6 CASE STUDY

The electricity market in Saudi electricity market is encountering a restructuring plan to modernize the grid. In [48], the authors examined some prospect scenarios for modernization the electric grid with respect to two dimensions : the deregulation of the electricity market and the penetration of SGTs. The first dimension is discussed in this chapter. The second dimension will be discussed in subsequent research. The data presented in [48] are used to demonstrate the model. The values used are shown in Table 3-1.

Table 3-1. Parameters of the Status Quo Market

Parameters	Values
P_g (US$)	0.037
C_g (US$)	0.213
Q_g (TWh)	256.68
Π_g (US $ billion)	-45.175
S_g (US $ billion)	45.108
ε	0.2
λ_g	5.71

The proposed (assumed) values of r and η are 10% and 20%, respectively. The optimization problem is conducted in two setups. The first setup assumes that the initial values of the variables P_p, C_p, and Q_p are similar to the values of the status quo. The second setup assumes that the initial values of these variables are all zero.

3.7 RESULTS

3.7.1 INITIAL VALUES EQUAL THE STATUS QUO (SETUP 1)

We notice that producers would make profit as the selling price is higher than the cost of production after the government subsidies are cut (See Table 3-2). Quantity sold remains unchanged since we consider a short-run timeframe that does not allow consumers relatively much time to switch to another source of energy or adapt new conservation program. ΔW turns out positive, meaning the deregulation is recommended under the current conditions and assumptions.

3.7.2 INITIAL VALUES EQUAL ZERO (SETUP 2)

In this setup, we run the model considering the value zero for all three variables. As a result, the selling price increases, quantity sold decreases, change in producers surplus increases, and change in consumers surplus decreases (See Table 3-2). This setup is expected to take place in the long run as the initial values imply. It represents the counterfactual market if it starts from scratch as a deregulated market. Hence, producers would aim at supplying the minimum possible quantity that fulfills demand. Consumers are more willing to accept relatively higher prices. The P_p in setup 2 is almost three times the value of P_p in setup 1. Q_p is only 60% of that of setup 1. ΔW has shrunk 20.2% compared to setup 1. The results of both setups are shown in Table 3-2.

Observing how the model inputs affect ΔW, we find that it increases as ε and r decrease. This is expected since when ε increases, the lost demand from supply-demand mismatch increases, therefore, GW decreases. r represents how risky a setup is. As r increases, the forecast outcomes decrease. On the other hand, ΔW increases as λ_g and η increase. When government subsidies increase, there would be a greater room to optimize the market. Increasing η would also expand the limit to which C_p improves, which consequently increases ΔW.

The relatively large value of ΔW is justified by the assumptions made earlier. In reality, in a deregulated market environment, certain costs are imposed on some market players. Such costs include the fees of independent system operators, the cost of transmission capacity constraints, taxes, and market price fluctuations. All these costs are ignored in our model. Therefore, we would recommend the value of ΔW to be much larger than zero in order to accommodate for expected extra costs that would account for the deadweight loss and consequently reduce the value of ΔW.

Table 3-2. Optimization Results

Parameters	Values (Setup 1)	Values (Setup 2)
P_p (US$)	0.21	0.64
C_p (US$)	0.1706	0.171
Q_p (TWh)	256.68	154
P_{co} (US$)	1.28	1.28
a (TWh)	308	308
Π_p (US $ billion)	10.95	72.28
S_p (US $ billion)	136.89	49.28
$\Delta\Pi$ (US $ billion)	56.12	117.45
ΔS (US $ billion)	91.78	4.17
ΔW (US $ billion)	1,512.39	1,205.75

3.8 SENSITIVITY ANALYSIS

The sensitivity analysis shows the values of reduced gradients for the variables P_p, C_p, and Q_p in both setups equal zero (See Table 3-3). A reduced gradient value shows how the objective function would change if the variable value increases by 1. This means that the variable value may not be changed. The report also shows the values of the Lagrange multiplier which indicates how the objective function would change if the constraint increased by 1 (See Table 3-4). The Lagrange multiplier equals zero if a constraint is not binding. In our case, there are two binding constraints.

When looking at variables limits, we notice that the lower and upper limits equal the optimal limit for P_p and Q_p, which means these variables cannot be changed without affecting the optimal solution or violating constraints. C_p is driven to the lower limit. However, one might think this finding contradicts the finding obtained by the reduced gradient of C_p, which is zero. This is because C_p is included in one of the constraints. Therefore, the value of C_p does not only affect the variable value, but also the constraint. This finding shows that the value of η plays an important role in increasing ΔW.

Table 3-3. Sensitivity Analysis of Variables

Parameters	Original value	Final value	Reduced gradient	Lower limit	Upper limit
Setup 1					
P_p (US)	0.04	0.21	0	0.21	0.21
C_p (US)	0.213	0.171	0	0.171	0.213
Q_p (TWh)	256	256	0	256	256
Setup 2					
P_p (US)	0	0.64	0	0.64	0.64
C_p (US)	0	0.171	0	0.171	0.213
Q_p (TWh)	0	154	0	154	154

Table 3-4. Sensitivity Analysis of Constraints

Constraints	Constraint no.	Status	Slack	Lagrange multiplier
Setup 1				
$P_p \leq P_{co}$	1	Not binding	1.0666	0
$C_p \leq P_p$	1	Not binding	0.04266	0
$C_p \leq C_g$	2	Not binding	0.04266	0
$(1-\eta)C_g \leq C_p$	2	Binding	0	$1,466\ x\ 10^{9}$
$Q_p \leq a$	3	Not binding	$51.3\ x\ 10^{9}$	0
$Q_p = a\text{-}b.P_p$	4	Binding	0	6.09523
Setup 2				
$P_p \leq P_{co}$	1	Not binding	0.64	0
$C_p \leq P_p$	1	Not binding	0.5693	0
$C_p \leq C_g$	2	Not binding	0.04266	0
$(1-\eta)C_g \leq C_p$	2	binding	0	$880\ x\ 10^{9}$
$Q_p \leq a$	3	Not binding	$154\ x\ 10^{9}$	0
$Q_p = a\text{-}b.P_p$	4	Binding	0	3.6571

3.9 CONCLUSION

The chapter presents a non-linear programming model that optimizes the change in GW as a metric to evaluate the worthiness of deregulating electricity markets. The model is based on CBA. A case study of the Saudi electricity market is used for demonstration of the approach. The results show how ΔW is impacted by the initial values and the model parameters. Sensitivity analysis is performed to examine how the reduced gradients and the Lagrange multiplier are impacted by the variables and the constraints.

CHAPTER 4

A FUZZY ANALYTIC HIERARCHY PROCESS ALGORITHM TO PRIORITIZE SMART GRID TECHNOLOGIES FOR THE SAUDI ELECTRICITY INFRASTRUCTURE[3]

4.1 INTRODUCTION

The modernization of electricity grid infrastructure occurs in several stages of improvement and upgrades as evidenced in multiple electricity infrastructures across the world. In some grid systems, the focus has been on upgrading the infrastructure of assets and renewing the devices and machines, which are the backbone of the grid. In some other grid systems, the focus has been on improving the level and depth of inter-communication and control among grid sectors, namely generation, transmission, distribution, and consumers. In other electricity infrastructures, electricity markets were given much more attention by liberalizing the market and enabling two-way communication means between service providers and consumers.

Grid modernization is an essential goal towards an efficient, reliable, economic, and stable grid. Smart Grid plays an important role in grid modernization. Smart Grid, differing from the traditional grid, establishes an infrastructure that makes the grid capable of achieving certain goals such as increased observability and controllability of assets for enhanced performance and security. Smart Grid also holds the potential for reduced costs of operations, maintenance, and system planning. Ultimately, the grid will acquire the capabilities of self-correction, reconfiguration and restoration, and handling randomness of loads and uncertainty of renewable sourced generators, and real-time market participants [117].

This chapter addresses the penetration of SGTs for improving the performance of the electric grid. Many studies conducted to measure the benefit-to-cost ratio of technical aspects of the Smart Grid concluded

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[3] This chapter is extracted verbatim from "A fuzzy analytic hierarchy process algorithm to prioritize Smart Grid technologies for the Saudi electricity infrastructure," under review for publication with journal, May 2017.

that the ratio is about 4:1 to 6:1 [119]. However, the concern is *which technologies should be given the priority for implementation considering the current status and challenges facing an electricity infrastructure*.

From a planning perspective, designing policies that establish a pathway for transitional modernization for the electricity infrastructure is not straightforward. Decision making in electric power systems is faced with multiple quantitative and qualitative elements. In such environments, decision makers deal with several policies that should be examined and investigated using multiple attributes. This chapter proposes an MCDM framework using fuzzy AHP to prioritize the relative importance of candidate SGTs for electricity infrastructures. The framework is demonstrated on the Saudi Arabian electricity infrastructure through a case study presented in this chapter. One reason for choosing the Saudi electricity infrastructure is that the energy sector in the country is expected to encounter major reforms. The Saudi Council of Economic and Development Affairs has introduced the Saudi Vision 2030 [74]. It is an ambitious and comprehensive blueprint that expresses the country's long-term goals and expectations until the year 2030 for reinforcing and diversifying the capabilities of the country's economy. To achieve these aspirations, the Council has already launched many transformative programs that have paved the way for the Saudi Vision 2030. One of these programs is the National Transformation Program [74], introduced in April 2016, which is established to examine the role of the government agencies in implementing the policies required for delivering on national priorities. The National Transformation Program aims at establishing initiatives that have clear performance indicators to track the implementation of the Vision 2030. This program outlines the policies required for electricity infrastructure modernization, addresses challenges, and sets the targets to transform the grid from its status quo to a modernized version. In line with the implementation of the National Transformation Program, this chapter aims to provide policy makers with an econometric framework and analysis for a future transitional modernization of the Saudi electricity infrastructure.

Another reason for choosing the Saudi electricity infrastructure as a case study is that the infrastructure is facing several challenges in delivering reliable, continuous, and economic electricity to its consumers. Further details about these challenges are discussed in section 4.5 of this chapter. The chapter proposes a prioritized penetration of SGTs to enhance the reliability and stability of the electricity infrastructure, and mitigates the impact of the technical and economic challenges.

Initially, we introduced a framework to modernize the Saudi electricity grid. The framework proposes that grid modernization is to be achieved through two dimensions. The first dimension is to deregulate the electricity market. The second dimension is to allow the penetration of SGTs. A complete overview of the framework proposed by the authors can be found in [48]. The framework takes into consideration technical, societal, and economic aspects related to such a modernization effort. The approach offers a comparison between different scenarios by employing cost-benefit analysis and risk assessment. The framework introduces a tool to chart a roadmap for transitional modernization of the grid for policy makers. While the case study presented in this chapter is on the Saudi Arabian electricity grid, we believe the framework and analysis are generic enough for use by policy makers of other infrastructures, albeit with appropriately changed inputs.

The first dimension is modeled by building a NLP algorithm. The algorithm models the mechanism of deregulating the electricity market and estimating GW. The efficiency of the electric network is considered in an *ex ante* setup. The study shows that deregulating the market is expected to increase producers profits because the selling price is expected to be higher than the cost of production after the government subsidies are cut. Level of electricity output sold is expected to remain unchanged since we consider a short-run timeframe that does not allow consumers relatively much time to switch to another source of energy or adapt new conservation program. GW is expected to turn out positive, meaning that the deregulation is recommended under the certain conditions and assumptions. The complete work relating to the first dimension can be found in [177]. This chapter analyzes the second dimension. The rest of the chapter is organized as follows: Section 4.2 defines grid modernization. Section 4.3 discusses the implications of the term, Smart Grid. Section 4.4 provides a literature review about previous studies addressing electric grid modernization in Saudi Arabia. Section 4.5 provides an overview about the current status of the electricity infrastructure in Saudi Arabia. Sections 4.6 and 4.7 provide overviews of AHP, and fuzzy set theory and its use with AHP, respectively. Section 4.8 presents the problem framework, and discusses the application of the model through a case study for the Saudi electricity grid. Section 4.9 shows the analysis. Section 4.10 presents the results. And, Section 4.11 concludes and discusses the policy implications of the study findings.

4.2 GRID MODERNIZATION

The power grid infrastructure in many countries across the world suffers several challenges such as aggravated grid congestion driven by uncertainty in supply, especially after the introduction of RE sources [1]. Power transfer over interconnected regions can lead to propagating events of service interruptions. The increasing trend for grid interconnection creates a large footprint with a more complex system that gives rise to the importance of grid control and monitoring. From the physical and economic perspectives, power grid infrastructure suffers investment insufficiency and limitations of rights-of-way for expansion projects. These reasons are expected to potentially limit or prevent power grid infrastructures from meeting the increasing demand of energy. Aging infrastructure is yet another challenge facing power grids. The increasingly frequent regional bulk power system outages and fuel supply constraints are yet other challenges that lead to complex operating conditions. Grid modernization is expected to enhance the ability of power grids to adapt to emerging technologies and applications, like RE sources, DR programs, storage devices, and electric vehicles [1, 2].

Grid modernization implies improving electric grid operability, reliability, and security. It means different things to different grid systems. Reference [78] defines grid modernization as: increasing automation and seamlessly integrating data, models, protection, optimization and control of the power grid. In its report defining modern grid initiatives, the NETL in the U.S. describes the implementation steps required to transform the current grid to a smarter grid. The smarter grid is characterized by the capability of motivating and including consumers, providing power quality for the 21st century needs, enabling markets, resisting attack, accommodating generation and storage options, optimizing assets, self-healing and operating efficiently. These characteristics are expected to, ultimately, make the grid more agile and intelligent. Also, these are expected to establish the basis for a reliable, secure, economic, efficient, environmentally friendly, and safe grid infrastructure [12].

Technology integration is yet another important aspect of grid modernization that boosts grid reliability, self-sufficiency, awareness, and decreases carbon footprint. Advanced grid technologies are comprised of integrated communications along with sensing and measuring equipment and advanced components such as power electronics, energy storage, microelectronics, and superconducting devices. Advanced control methods are another facet of technology insertion that enable rapid diagnosis and appropriate response to events, support market pricing, and enhance asset management [79].

Grid modernization extends to improve the efficiency of electricity market mechanisms. Modernization calls for creating uniform marginal pricing with no structural bottlenecks in transmission networks. Moreover, grid modernization aims for removing technical and structural barriers to cross-border retailers operations [4]. From power substations standpoint, grid modernization implies autonomy, coordination, digitalization, flexibility, intelligence, resiliency, self-healing, and sustainability [163].

SGTs play an important role in electric grid modernization. Thus, the following section discusses the definitions and aspects of Smart Grid in more detail.

4.3 SMART GRID

According to the U.S. DOE, Smart Grid is defined as the, *"…electric delivery network, from generation to the consumer integrated with the latest advances in digital and information technology to improve the electric system reliability, efficiency, security, and resiliency*" [5]. The U.S. DOE established a federal Smart Grid task force under that identified objectives to establish an electricity infrastructure for the 21st century capable of providing ample, cheap, clean, efficient, and reliable electricity supply [9]. In addition to enhancing the reliability, efficiency, and security of the electric grid, the objectives of the Smart Grid are also expected to reduce of carbon emissions [80]. The Institute of Electrical and Electronics Engineers (IEEE), using the conceptual model of Smart Grid developed by the National Institute of Standards and Technologies (NIST), defines seven key domains, namely bulk generation, transmission, distribution, customers, operations, markets and service providers. Reference [5] conducted a survey study that examines the definition of Smart Grid undertaken by multiple government authorities, independent organizations, manufacturers, consultants, and utilities. While the definition of Smart Grid differs among these entities, there are common technologies encompassed in these definitions. These technologies are real-time communications, HVDC systems, FACTS, WAMS and PMUs infrastructures, improved protection technologies, advanced sensors, various automation and control software packages, and common communication methods among grid entities.

Smart Grid, differing from the traditional grid, establishes an infrastructure that makes the grid capable of achieving certain goals such as increased observability and controllability of assets for enhanced performance and security. Smart Grid also holds the potential for reduced costs of operations, maintenance, and system planning. Ultimately, the grid will acquire the capabilities of self-correction, reconfiguration and restoration, and handling randomness of loads and uncertainty of renewable sourced generators, and real-time market participants [117]. The following section highlights some findings from literature around SGTs insertion and grid modernization for the Saudi electricity infrastructure.

4.4 LITERATURE REVIEW

While literature research addressing SGTs insertion from technical and economic perspectives in Saudi Arabia are limited, several studies discuss the challenges facing the Saudi electric grid and the proposed solutions of introducing SGTs and addressing policy implications. References [18, 65] discuss the importance of SGTs in harnessing the benefits of untapped RE resources, and optimally integrating them into the grid. They also describe the attributes of a Smart Grid and how these attributes act as a driving force to modernize the electric grid. In [45], the authors propose an MCDM model using AHP to prioritize the importance of RE resources to the energy mix in Saudi Arabia. The assessment was carried out considering technical, economic, socio-political, and environmental criteria.

Reference [66] discusses the need for SGTs to the Saudi electricity infrastructure. Such technologies are the ones that deal with (1) the issues and solutions for RE integration, (2) optimization of load management and DR, (3) energy efficiency, and (4) power quality issues. It also suggests developing Smart Grid roadmap for SGTs penetration in Saudi Arabia. In [67], some applications of SGTs were demonstrated to mitigate the accelerating consumption of electrical energy, and improve energy efficiency. The study suggests that SGTs penetration draws substantial challenges in cyber security, two-way protection, financial funding, standards, and policies. Reference [38] identifies challenges facing the Saudi electric grid with SGTs implementation, and defines functional requirements for SGTs in Saudi Arabia. It also develops a deployment strategy, and advises in a gradual and timely rolling out of this strategy.

In [62], the author uses an engineering-based residential electricity demand model to analyze the outcomes of increasing the efficiency in the residential sector in Saudi Arabia. The study further addresses the issues with the current policies. In [68], a study was conducted in Saudi Arabia to measure the public's willingness to use solar energy as the main energy resource in their residences. The results show that high government subsidies and current policies are the main obstacles to public adaptation to green energy. Reforming the subsidies and crafting proper policies would enable SGTs and facilitate the introduction of green energy.

The following section discusses the challenges faced by the Saudi electricity infrastructure. It highlights the current status of the electricity grid in terms of demand, efficiency, reliability, and market structure.

4.5 CURRENT STATUS OF THE SAUDI ELECTRICITY INFRASTRUCTURE

The electricity infrastructure in Saudi Arabia is faced with several challenges result from the impressive growth of the national economy since the 1980s. The country is a high consumer for oil. Saudi Arabia is the largest oil-consuming nation in the Middle East and, was the world's 12th largest consumer of total primary energy in 2013 at 9 quadrillion Btu [13]. Domestic consumption represented 2.9 million barrels per day of oil in 2013, almost double its consumption in 2000. The majority of petroleum consumed domestically is allocated for transportation fuels and direct power generation by burning [14]. Domestic energy consumption rose by 4.8% per year on average. If this level of consumption continues in the next decade, the level of export is expected to reduce significantly and the country will import oil [15]. The primary energy consumption per capita was 6.8 tonne of oil equivalent in 2009, which is four times higher than the world average [22, 23]. In 2015, electricity consumption per capita in 2015 reached 9,346 kWh. Average electrical energy gross rate for the same period is 6.55% [17]. This gross rate is considerably high if compared to the average gross rate in developed countries, which ranges between 1-2% [18]. This high gross rate implies a sharp growth in electrical energy demand, which requires expanding the installed capacity of the electric grid. The growth in consumption is driven by population growth and improvement in standards of living. The growth is also driven by strong economic and industrial development. Harsh weather conditions and economic policies calling for diversifying energy-intensive industries, and highly subsidizing energy prices are yet major drivers for the growth [19].

As a result of rapid increase in demand, the network is encountered with service interruptions, low generation capacity reserves, depletion of resources, high peak demand, and capital investment. In some events in summer seasons, peak demand increases to twice the average demand level [17, 28]. Peak demand has been growing at an average rate of 6.5% per year for the period of 1990 to 2015 [17]. If the current trend of electricity consumption continues, domestic consumption of oil is expected reach more than eight million barrels by 2030 [14].

Electricity production in Saudi Arabia depends only on fossil fuels. Such a scenario impacts the national security of the country. One reason is that fossil fuels are depleted resources. Another reason is that output generated is not commensurate with energy used. Additional consumption of fossil fuel builds a significant opportunity cost against the potential sale of oil in the international market [25, 38, 39]. RE production is absent so far. The country needs to diversify energy production and exploit its RE resources. Saudi Arabia has the potential to exploit RE resources specially concentrated solar power, solar photovoltaic, wind energy, geothermal energy, and waste-to-energy for electricity generation [25, 40].

The sharp increase in energy consumption backed by fossil fuels has led cumulative carbon dioxide level to increase in recent years [47]. Saudi Arabia's share of carbon emissions worldwide in 2008 was at the 14th place, or a 1.54% share of worldwide emissions, with 118 million metric tons of carbon emissions [23]. Saudi Arabia is ranked the 21st among countries with the highest CO_2 emissions per capita in 2006, and the 16th by total CO_2 emission at 438.25 million metric tons of CO_2. The level of CO_2 intensity has risen by 2% per year since 2000 [23].

As mentioned earlier, high government subsidies placed for electrical energy prices are ones of the main drivers of the sharp increase in demand. The electricity market in Saudi Arabia is vertically integrated.

Such an organization has led to a fixed price structure [44]. Government subsidies for electricity generation were US $40 billion in 2014 [16]. In other words, government subsidies account for 82% of the cost of electricity production, which makes the rate of electricity prices in Saudi Arabia one of the lowest rates in the world. Saudi Arabia is ranked second worldwide in government subsidies provided for domestic energy prices [45]. Average cost of kWh paid by consumers is US $0.037, while it costs US $0.213 [28]. Low market prices driven by high subsidies discourage consumers to conserve energy and engage in DR programs. Thus, price elasticity of demand is low. Based off empirical studies, non-ideal price elasticity of demand in the Saudi electricity market is found to be 0.04 which means that the demand for electricity is inelastic in the short run [24].

Another challenge facing the Saudi electric grid is the considerable percentage of losses driven by power quality issues. Demand for air conditioning load has grown significantly over the last years especially in summer seasons when air conditioning represents about 80% of the total system load. Such a growth has posed a serious issue in the network. Delay in voltage recovery following fault events has increased due to highly inductive loads, which is represented by air conditioning motors. This leads air conditioning motors to stall during voltage recovery periods after fault occurrence [30]. As a result of these events, the network suffers network losses in energy delivered ranging between 8 and 9% each year [17, 38]. Aside from air conditioning load, the network is facing several outages and interruptions due to unplanned outages, overload, and generation failure. Fig. 4.1 shows three reliability indices for SEC, the main electricity provider in the country, network for the period of 2010-2015 [17, 43]. All three reliability indices show network reliability is deteriorating over the last years.

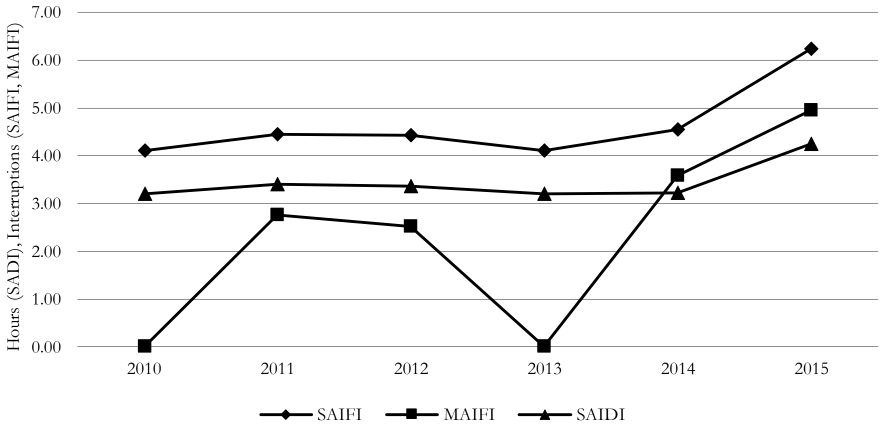

Fig. 4.1 Reliability Indices for SEC Network

Equipment aging is yet another challenge facing the Saudi electric grid. The economic life of several generation units has reached its end. The retiring units have to be replaced by new ones in order to maintain system efficiency, meet increasing demand, and reduce losses [41, 42]. The following section introduces AHP, one of the MCDM methods, which is applied along with fuzzy sets to prioritize the importance of SGTs to the Saudi electricity infrastructure.

Decision making in electric power systems, faced with multiple quantitative and qualitative elements, is a vital aspect in grid modernization. In such environments, decision makers deal with several scenarios that should be examined and investigated using multiple attributes. The following section introduces AHP, one of the MCDM methods, which is applied along with fuzzy sets to prioritize the importance of SGTs to the Saudi electricity infrastructure.

4.6 AHP

AHP is a popular MCDM method that can handle unstructured or semi-structured decisions with multi-criteria inputs. AHP is used in making decisions that involve ranking, selection, evaluation, optimization, and prediction. AHP can organize objectives, criteria, and alternatives into a hierarchal structure. AHP derives ratio scales from deductive and inductive inputs through multiple pairwise comparisons. Moreover, AHP is one of the few methods that can assess the consistency of the judgment of decision makers [53, 54, 172, 173].

The first step of AHP is to model the problem as a hierarchy, as shown in Fig. 4.2, containing the decision objective, attributes (i.e., criteria), and alternatives used to evaluate the alternatives.

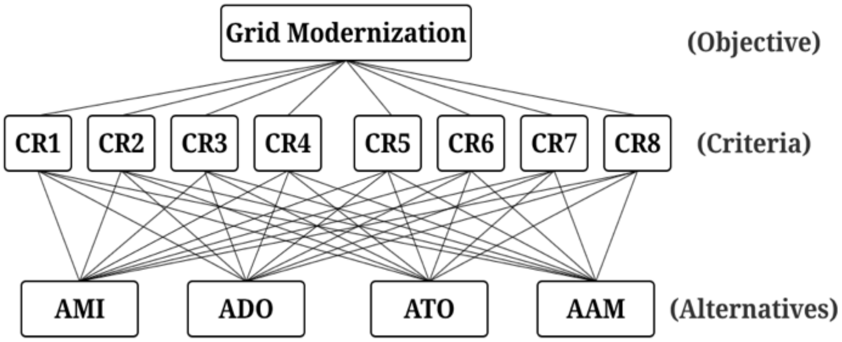

Fig. 4.2 Hierarchical Structure of the Problem

The second step is to construct a judgment matrix containing priority weights among the elements (i.e., criteria and alternatives) based on pairwise comparisons among the elements. The resulting judgment matrix is a reciprocal matrix of the following structure:

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & 1 & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \tag{4.1}$$

where, A is the judgment matrix of the criteria (or alternatives), and a_{ij} equals x_i/x_j. The values x_i and x_j are the weight values of elements i and j, respectively. i, and j=1, 2…n, where, n is the number of elements. The third step is to compute a weight vector, x, which represents the relative weights of the elements of the hierarchy such that,

$$Ax = \lambda_{max} x \tag{4.2}$$

where, λ_{max} is the largest eigenvalue of A. The vector, x, can be obtained by normalizing the principle eigenvector of A.

The next step is to assess judgment consistency. Small changes in the reciprocal matrix element might imply a small change in λ_{max}. The deviation of the element from n can be used as a measure of consistency as follows,

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4.3}$$

The matrix is to be consistent if CI=0, where CI is the consistency index. The value of CI can be compared with a random index (RI) in order to determine if there is any inconsistency in the matrix. RI generates random values between 0 and 1 that are used to determine if there is inconsistency in the judgment matrix. Reference [53] derived an equation that determines a fixed value of RI as follows:

$$RI = 1.98\,\frac{(n-2)}{n} \tag{4.4}$$

Determining the acceptance of inconsistency, if there is any, can be obtained by calculating consistency ratio, which is represented by the following equation:

$$Consistency\ Ratio = \frac{CI}{RI} \tag{4.5}$$

A comparison matrix is said to be consistent if consistency ratio is below 10% [53]. Otherwise, further analysis has to be taken to improve matrix consistency, which is out of the scope of this chapter. The interested reader is directed to the classical references on AHP, [53] and [54], for detailed descriptions.

Notwithstanding its usefulness, AHP is unable to sufficiently account for uncertainty and imprecision arising from subjectivity that is inherent to the decision makers' qualitative inputs. Moreover, AHP is mainly used in applications that are *crisp*, i.e., cases where the decisions are of the *yes-or-no* type rather than of the *more-or-less* type [175]. Human assessment of qualitative attributes is innately subjective and imprecise. The imprecision emerges from decision makers when considering the pairwise relative importance of elements

[164]. Reference [163] investigates the impact of framing and time pressure on human judgment performance in a complex multi-attribute judgment task. These limitations in AHP lead to the use of fuzzy logic method, or fuzzy AHP, that employs fuzzy set theory as an extension to the conventional AHP to capture the subjective requirements in the problem [165]. The following section presents the fuzzy set theory and fuzzy AHP.

4.7 FUZZY SET THEORY

As mentioned earlier, judgments of decision makers involve uncertainty and imprecision. Fuzzy set theory is introduced to AHP to deal with the uncertainty and imprecision. These uncertainties are transformed into fuzzy sets and integrated into the AHP model. Fuzzy set theory postulates that an element has a degree of membership in a fuzzy set, which is represented by a membership function. The membership values of an element vary in the interval [0, 1]. The variation in the linguistic variable values is mapped into different linguistic classes by the membership function [58, 59].

A membership function for any linguistic variable may be conceived by *apriori* knowledge of the linguistic variable, by developing functions with slopes, or by trial and error methods of experimentation [164, 166]. In this study, a triangular fuzzy set is adapted.

Fuzzy numbers are special fuzzy sets. Let us assume a special fuzzy set, $\widetilde{\mathrm{A}}$, such that

$$\tilde{\mathrm{A}} = \{(x, \mu_{\tilde{T}}(x)) | x \in X\} \tag{4.6}$$

where, X is a collection of objects denoted generically by x. The value of x ranges on the real line, $\mathbb{R}$: $-\infty < x < +\infty$. The membership function, $\mu_{\tilde{T}}$, maps X to the membership space from $\mathbb{R}$ to $\tilde{T}$, where $\tilde{T}$ is a triangular fuzzy number. $\tilde{T}$ is denoted as $\tilde{T}$=(l, m, u) where, l is the lower bound, m is the mean bound, and u is the upper bound of the membership function [167, 175]. The membership function of $\tilde{T}$ is as follows:

$$\mu_{\tilde{T}}(x) = \begin{cases} 0 & x < l \\ \dfrac{x-l}{m-l}, & l < x < m \\ \dfrac{u-x}{u-m}, & m < x < u \\ 0 & x > u \end{cases} \tag{4.7}$$

Then, the interval of confidence level, *a*-cut, is defined. The triangular fuzzy number can be represented as:

$$\forall\alpha \in [0,1]\ \tilde{T}_\alpha = [l^\alpha, u^\alpha] = [(m-l)\alpha + l, -(u-m)\alpha + u] \tag{4.8}$$

a-cut is a factor that incorporates the confidence of the decision makers over their preference or judgment. It is determined by experts based on experience and external factors impacting decision-making process [164, 168, 174].

In the conventional AHP, qualitative measurements are transformed into numeric scale to construct the comparison matrix. Table 4.1 shows the linguistic variables scale proposed by Saaty and used for conventional AHP [54]. Although the pairwise comparison in the conventional AHP is simple to apply, it inadequately represents subjective inputs with uncertainty and imprecision. Thus, a fuzzy ratio scale is used instead, as shown in Table 4.1, to incorporate fuzzy set theory idea to the conventional AHP scale [166]. Fig. 4.3 shows the membership function of triangular fuzzy numbers [164, 169].

Table 4-1. Numeric Scales for Conventional AHP and Fuzzy AHP

Conventional AHP scale	Definition	Fuzzy AHP scale	Membership function
1	Equal importance	$\tilde{1}$	(1, 1, 1)
2	Weakly more importance	$\tilde{2}$	(1, 2, 3)
3	Moderate importance	$\tilde{3}$	(2, 3, 4)
4	Moderate plus importance	$\tilde{4}$	(3, 4, 5)
5	Strong importance	$\tilde{5}$	(4, 5, 6)
6	Strong plus importance	$\tilde{6}$	(5, 6, 7)
7	Very strong importance	$\tilde{7}$	(6, 7, 8)
8	Very very strong importance	$\tilde{8}$	(7, 8, 9)
9	Extreme importance	$\tilde{9}$	(8, 9, 9)

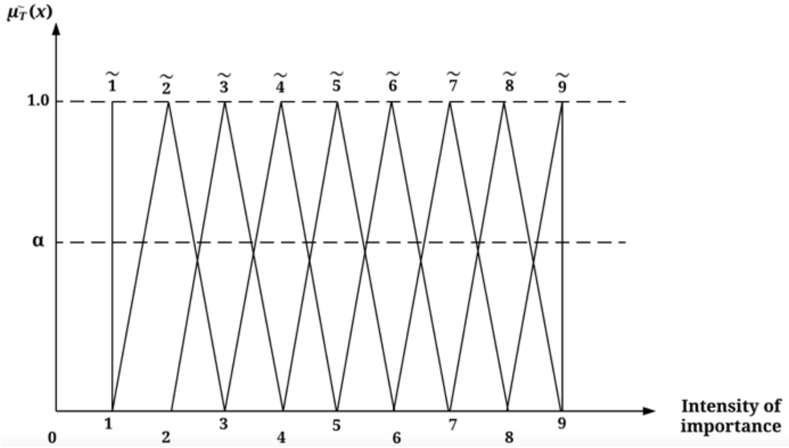

Fig. 4.3 Membership Function for Triangular Fuzzy Numbers

The procedure of fuzzy AHP approach starts with comparing elements, as explained in section 4.6 in the conventional AHP. Equation (4.1) is modified to contain fuzzy numbers as follows:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & 1 & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} \tag{4.9}$$

Then, the fuzzy eigenvalue is solved using the fuzzy version of equation (4.2):

$$\tilde{A}\tilde{x} = \lambda_{max}\tilde{x} \tag{4.10}$$

After that, *a*-cut is assigned with a value. The fuzzy numbers are then represented by their upper and lower limits using equation (4.8), for $0 < a < 1$, and all *i*, and *j*. For example, if the value of *a* is 0.5, and the fuzzy number is $\tilde{3}$, the operation of obtaining the upper and lower limits with respect to α is shown in Fig. 4.4.

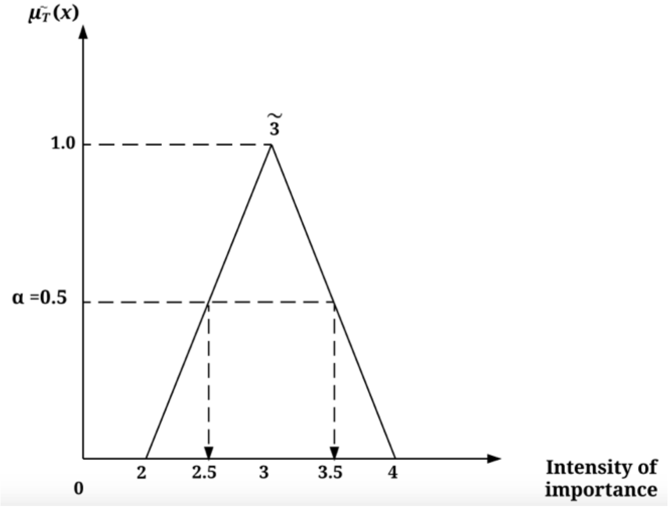

Fig. 4.4 α-cut Operation on Triangular Number

After that, the triangular fuzzy numbers are defuzzified. There are multiple ways to defuzzify fuzzy numbers. However, there is no systematic procedure for defuzzification [170, 171]. In this study, the geometric mean of the upper and lower limits of each $\tilde{T}$ is computed to defuzzify the numbers. The geometric mean is less affected by skewed data, which might be present in the triangular representation of fuzzy numbers. After defuzzification, the consistency ratio is calculated for each judgment matrix, as explained in section 4.6 with the conventional AHP. An application of the fuzzy AHP to determine the most important aspects of SGTs that lead to the modernization of the Saudi electricity infrastructure follows.

4.8 PROBLEM FRAMEWORK

The authors propose an econometric analysis that examines prospect scenarios for a modernized Saudi electricity infrastructure with regards to two dimensions. The first dimension is the deregulation of the electricity market. The second dimension is the penetration of SGTs. While the model framework of the econometric analysis is described in [48], the first dimension is described and analyzed in [177]. This chapter analyzes the second dimension. Allowing the penetration of SGTs and applications is, undoubtedly, an important driver for grid modernization. Thus, the aim of analyzing the second dimension is offering a framework that prioritizes candidate SGTs based on their importance considering the current characteristics and future targets of the Saudi electricity infrastructure. Moreover, the framework examines the implications on the policies designed for electricity infrastructure modernization.

To achieve such a goal, there is a need for computational tools having the capacity to frame decision-making process, to involve socio-economic factors, and to include objective and subjective inputs. Therefore, an MCDM method is implemented to carry out both deductive and inductive thinking and make numerical tradeoffs [118]. The authors believe that fuzzy AHP is an approach for addressing this problem. Fig. 4.2 shows the hierarchical structure of the problem.

The decision objective of this analysis is to modernize the Saudi electricity infrastructure by the allowing the penetration of SGTs. The criteria, which are the attributes used to evaluate the alternatives, are derived from the Saudi National Transformation Program [74]. Table 4.2 shows the criteria adapted from [74] and used for the analysis of this chapter. Table 4.2 also shows the KPIs used to measure each criterion.

Table 4-2. Problem Criteria and KPIs

	Criteria	KPIs
CR1	Increase fuel utilization efficiency	Efficient utilization of fuel in power generation
CR2	Enhance primary sources	Percentage of generation capacity reserve
CR3	Enhance supply security	Average number of outages for more than 5 minutes in the grid annually
CR4	Improve quality of electricity service	Average time of electricity outage
CR5	Increase service coverage	Percentage of population covered by electricity service
CR6	Privatization of electricity sector	Percentage of power plants through strategic partners
CR7	Reduce fuel consumption emissions	Percentage of reduction in CO_2 emission nationwide
CR8	Enable RE to contribute to national energy mix	Percentage of RE to total energy used

As mentioned earlier, the alternatives of the problem are the candidate SGTs. These technologies can be identified from technological, application, or infrastructural standpoints. The authors decide to identify candidate SGTs from the infrastructural perspective because it offers a broader view of the technologies. Moreover, this view allows infrastructure components to be clustered in groups of integrated technologies. This approach is adapted from the NETL model that defines four infrastructures for a modern Grid, where each infrastructure includes integrated technologies [12, 81, 82]. The description of the infrastructures (alternatives) and their technologies are shown in Table 4.3.

Table 4-3. Identification of the Alternatives, i.e., candidate SGTs

Infrastructure	Technologies
AMI	Smart meters
	Home area networks (HANs)
	Wide area communication infrastructure
	Meter data management system (MDMS)
ADO	Distribution automation
	Complex systems (microgrid, premium power parks)
	Distribution geographic information system (GIS)
	Outage management system (OMS)
	Distributed energy resources
	Advanced protection and control
	DMS
	Advanced grid components (high speed transfer switches, backup power supplies, Fault current limiter (FCL)
	Plug-in hybrid electric vehicle (PHEVs)
	Distributed storage devices
ATO	Substation automation
	WAMS
	Electricity markets
	Modeling, simulation, and visualization tools
	Advanced regional operational applications
	Advanced grid components (FACTS, HVDC, unified power flow controller (UPFC))
AAM	Asset health information
	T&D planning
	Condition-based maintenance
	System operating information
	Asset utilization operation optimization
	Engineering design and construction
	Modeling and simulation

The first alternative is AMI. This alternative targets the measurement and data collection systems like communications infrastructures, support systems and MDMS, and end-user meters. This alternative aims at enabling the measurement of detailed time-based usage of electricity flowing bi-directionally between the utilities and end-users. The second alternative is ADO, which refers to improving the reliability of distribution systems. It also enables self-healing functionality, and includes several various applications to support two-way power flow and microgrid operations. A microgrid is a collection of small generators, end-user loads, and other resources that can be controlled as a single unit in either the islanded or grid-connected mode. This self-sustaining concept of the electric grid is used in disaster recovery or coordinated DR. Microgrids also deliver electricity to loads in remote areas where access to the transmission network may be scarce. Microgrids also deliver ancillary services like voltage support, frequency regulation, and harmonic cancellation [103, 116]. The third alternative is ATO, which refers to integrating distribution systems with regional transmission organizations to boost system loadability and operability. Risk assessment system monitoring is provided by the technologies falling in ATO. The fourth alternative is AAM, which refers to the integration of grid technologies targeting existing and new assets. Such technologies provide intelligent applications for asset management, maintenance management, cost reduction, and asset utilization improvement. Moreover, AAM technologies provide applications for capacity planning performance, resource management , and engineering and facility design [82]. The next section presents the analysis.

4.9 ANALYSIS

Considering the criteria and alternatives identified in the previous section, a pairwise comparison process is followed to construct the judgment matrix for the criteria using objective data available in the National Transformational Program [74]. According to the program, the baseline, i.e., the status quo, and the 2020 targeted values for all KPIs are stated. These values are used to obtain the pairwise comparisons. For each criterion, its KPI targeted value is subtracted from its baseline value then divided by the targeted value in order to obtain a normalized value for each KPI. The resultant values imply how far each criterion is from the desired value (i.e., the targeted value in 2020). After that, each normalized value is divided by the others in order to obtain the pairwise comparisons. Table 4-4 shows the input data and the normalized values

Table 4-4. Input Data and Normalized Values for Criteria

Criteria (unit)	Baseline	2020 target	Normalized values
CR1 (%)	33	40	17.50%
CR2 (%)	10	12	16.67%
CR3 (Outage)	6.36	3	52.83%
CR4 (Minute)	262	120	54.20%
CR5 (%)	99	99.5	00.50%
CR6 (%)	27	100	73.00%
CR7 (BSCFD)	28	26	7.14%
CR8 (%)	0	4	100.00%

Since the input used to construct the pairwise comparison between criteria is objective, uncertainty or imprecision is not an issue. Thus, a conventional AHP approach is used. A scale of 1–100 is chosen for this comparison. This wide scale represents the absolute values of data, which reduces comparison inaccuracy. Thus, it is used instead of the conventional AHP scale shown in Table 4.1. The judgment matrix is, then, constructed as shown in Table 4-5. After that, local priority is calculated for each criterion after averaging the normalized values for each criterion as shown in Table 4-5. An example of obtaining pairwise comparisons is shown using CR1 and CR2. The normalized values for CR1 and CR2 are 17.5 and 16.667, respectively (from Table 4-4). The pairwise comparison for CR1 against CR2 is 17.5/16.667 or 1.05. This value implies that CR1 is 5% more important than CR2. This approach is considered reasonable as CR1 is 17.5% away from reaching the targeted values, whereas CR2 is only 16.667% from reaching its targeted value.

Table 4-5. Judgment Matrix and Local Priority for Criteria

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	Priority
CR1	1.00	1.05	0.33	0.32	34.82	0.24	2.45	0.17	0.054
CR2	0.95	1.00	0.31	0.30	33.16	0.22	2.33	0.16	0.052
CR3	3.01	3.17	1.00	0.97	105.1	0.72	7.39	0.52	0.164
CR4	3.09	3.25	1.02	1.00	107.8	0.74	7.58	0.54	0.168
CR5	0.02	0.03	0.01	0.00	1.00	0.00	0.07	0.00	0.002
CR6	4.17	4.38	1.38	1.34	145.2	1.00	10.22	0.73	0.227
CR7	0.40	0.42	0.13	0.13	14.21	0.09	1.00	0.07	0.022
CR8	5.71	6.00	1.89	1.84	199.0	1.37	14.00	1.00	0.311

After that, the judgment matrix for the alternatives is constructed. For this purpose, alternatives are examined against each criterion. This step is conducted by seeking subjective inputs. The subjective judgments are transformed into quantitative values by using a measurable index in order to construct pairwise comparisons between alternatives. In contrast to the judgment matrix of the criteria, the judgment matrix of the alternatives is constructed by applying fuzzy AHP for reducing uncertainty and imprecision. An experiment is designed to evaluate the importance of each alternative. In the experiment, each technology within an alternative is examined against each criterion by answering the following question: *Will this criterion be improved after the introduction of this technology?* The answer, a, is represented as follows:

$$a \in B;\ B(a) = \begin{cases} 1, & if\ the\ answer\ is\ yes \\ 0, & if\ the\ answer\ is\ no \end{cases} \tag{4.11}$$

where, B is a binary set. Considering the criterion KPI in answering helps in arriving at a relatively accurate decision. After that, the same procedure is applied to the next technology and then to the following alternative until each alternative should have a summed value of all values marked to each one of its technologies. The summed value is then divided by the number of technologies clustered within that alternative as depicted in Table 4.3. The resultant normalized number shows the criticality level of that alternative to the criterion.

Although answering the previously mentioned question requires subjective input by the participant or decision maker, the question is framed in such a way that the participant's judgment (subjectivity) is not dominant. This would increase judgment consistency and accuracy. In fact, examining whether a technology will improve a criterion or not can be performed with a moderate level of understanding of electric power system engineering. An example of that is when answering the question with regard to the first technology under AMI, "smart meter", and CR1, "increase the efficiency of fuel utilization". From a basic conceptual understanding of power system engineering, the answer to this question is 0. In this study, the authors provided their judgments gleaned from experience. The summed weight for each alternative with respect to each criterion is shown in Table 4-6. For example, the number of ADO technologies are ten. Only three of which have the potential to improve CR1, which are distributed energy resources, PHEVs, and distributed storage devices. This means only 3/10 of ADO technologies are important to CR1. Therefore, the value 0.3 is assigned in ADO-CR1 cell.

Table 4-6. Summed Weight for each Alternative

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8
AMI	0.000	0.750	0.500	0.750	0.000	0.500	0.000	0.750
ADO	0.300	0.500	0.900	0.900	0.400	0.100	0.200	0.300
ATO	0.000	0.429	0.857	0.857	0.571	0.429	0.143	0.714
AAM	0.857	0.571	1.000	1.000	0.429	0.143	0.857	0.143
Sum	1.157	2.250	3.257	3.507	1.400	1.171	1.200	1.907

From Table 4-6, the weights are normalized with respect to the summed values shown in the last row. The results are shown in Table 4-7. Then, from Table 4-7, the difference between each two alternatives with respect to each criterion is computed. For example, with respect to CR1, ADO and AAM have the values 0.259 and 0.741, respectively. This means AAM is greater than ADO by 0.482, which is shown in the ADO-AAM cells in Table 4-8. Applying this calculation between each two alternatives with respect to CR1 results in values shown in Table 4-8.

Table 4-7. Normalized Weight for each Alternative

	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8
AMI	0.000	0.333	0.154	0.214	0.000	0.427	0.000	0.393
ADO	0.259	0.222	0.276	0.257	0.286	0.085	0.167	0.157
ATO	0.000	0.190	0.263	0.244	0.408	0.366	0.119	0.375
AAM	0.741	0.254	0.307	0.285	0.306	0.122	0.714	0.075
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.000

Table 4-8. Reciprocal Difference of Alternatives Weights w.r.t. CR1

CR1	AMI	ADO	ATO	AAM
AMI	0.000	-0.259	0.000	-0.741
ADO	0.259	0.000	0.259	-0.481
ATO	0.000	-0.259	0.000	-0.741
AAM	0.741	0.481	0.741	0.000

After that, the difference between alternatives weights, from Table 4-8, is transformed into fuzzy set by using the fuzzy numeric scale shown in Table 4-9. The reciprocal difference of alternatives weights, from Table 4-8, is segmented into nine equal portions. Each portion corresponds to a fuzzy scale number (as shown in Table 4-9). As all positive weights, from Table 4-8, are transformed into fuzzy numbers, negative weights are simply transformed into the inverted fuzzy numbers of their reciprocal cells. Table 4-10 shows the fuzzified values of the subjective inputs.

Table 4-9. Transformation Scale of Subjective Inputs

Reciprocal difference of alternatives weights	Fuzzy scale	Membership function
0	$\tilde{1}$	(1, 1, 1)
0.010 - 0.134	$\tilde{2}$	(1, 2, 3)
0.135 - 0.258	$\tilde{3}$	(2, 3, 4)
0.259 - 0.381	$\tilde{4}$	(3, 4, 5)
0.382 - 0.505	$\tilde{5}$	(4, 5, 6)
0.506 - 0.629	$\tilde{6}$	(5, 6, 7)
0.630 - 0.753	$\tilde{7}$	(6, 7, 8)
0.754 - 0.876	$\tilde{8}$	(7, 8, 9)
0.877 - 1.00	$\tilde{9}$	(8, 9, 9)

Table 4-10. Fuzzified Numbers of Subjective Inputs w.r.t. CR1

CR1	AMI	ADO	ATO	AAM
AMI	$\tilde{1}$	$1/\tilde{4}$	$\tilde{1}$	$1/\tilde{7}$
ADO	$\tilde{4}$	$\tilde{1}$	$\tilde{4}$	$1/\tilde{5}$
ATO	$\tilde{1}$	$1/\tilde{4}$	$\tilde{1}$	$1/\tilde{7}$
AAM	$\tilde{7}$	$\tilde{5}$	$\tilde{7}$	$\tilde{1}$

The fuzzified numbers are then represented as triangular fuzzy numbers as shown in Table 4-11. After that, and from equation (4.8), the upper and lower limits of the triangular fuzzy numbers are computed with respect to *a*-cut as shown in Table 4-12. The value of *a*-cut reflects the confidence of the participants or decision makers in the subjective judgment they provided to the experiment. In this study, a value of 0.8 is assumed.

Table 4-11. Triangular Fuzzy Numbers for Judgment Matrix of Alternatives w.r.t. CR1

CR1	AMI	ADO	TO	AAM
AMI	(1, 1, 1)	$(1/5, 1/4, 1/3)$	(1, 1, 1)	$(1/8, 1/7, 1/6)$
ADO	(3, 4, 5)	(1, 1, 1)	(3, 4, 5)	$(1/6, 1/5, 1/4)$
ATO	(1, 1, 1)	$(1/5, 1/4, 1/3)$	(1, 1, 1)	$(1/8, 1/7, 1/6)$
AAM	(6, 7, 8)	(4, 5, 6)	(6, 7, 8)	(1, 1, 1)

Table 4-12. Upper and Lower Limits of Triangular Fuzzy Numbers

CR1	AMI	ADO	ATO	AAM
AMI	[1.00, 1.00]	[0.24, 0.26]	[1.00, 1.00]	[0.139, 0.147]
ADO	[3.80, 4,20]	[1.00, 1.00]	[3.80, 4,20]	[0.193, 0.210]
ATO	[1.00, 1.00]	[0.24, 0.26]	[1.00, 1.00]	[0.139, 0.147]
AAM	[6.80, 7.20]	[4.80, 5.20]	[6.80, 7.20]	[1.00, 1.00]

After that, the fuzzified numbers are defuzzified to obtain the crisp value. This is performed by computing the geometric mean of each fuzzified number. Table 4-13 shows the geometric mean value for each fuzzified number which represents the pairwise comparison weight between each two alternatives with respect to CR1.

Table 4-13. Judgment Matrix for Alternatives w.r.t. CR1

Geometric mean of triangular fuzzy numbers					Priorities	
CR1	AMI	ADO	ATO	AAM	Local	Global
AMI	1.00	0.253	1.00	0.143	0.07	0.004
ADO	3.99	1.00	3.99	0.21	0.23	0.012
ATO	1.00	0.253	1.00	0.143	0.07	0.004
AAM	6.99	4.99	6.99	1.00	0.63	0.034

Local and global priorities are also calculated for each alternative as shown in Table 4-13. Local priority is calculated according to the method explained earlier for the judgment matrix of the criteria in the conventional AHP. Global priority of an alternative is its local priority multiplied by the priority of the respective criterion shown in Table 4-5.

While the algorithm of the approach in this chapter is explained using analysis related to CR1, the same steps are applied to all alternatives with respect to the rest of the criteria. After applying the algorithm to all elements, the consistency ratio is calculated for the criteria matrix and all alternative-criterion matrices. Table 4-14 shows the values. As mentioned in section 4.6, a judgment matrix is considered consistent if consistency ratio is below 10.0%. Table 4-14 shows that the consistency ratio for all matrices are below 10.0%, indicating consistency in forming the judgment matrices.

Table 4-14. Consistency Ratios for all Judgment Matrices

Judgment matrix	λ_{max}	n	CR
Criteria	8	8	0.00%
Alternatives-CR1	4.285	4	9.60 %
Alternatives-CR2	4.1407	4	4.74 %
Alternatives-CR3	4.1407	4	4.74 %
Alternatives-CR4	4.2042	4	6.88 %
Alternatives-CR5	4.142	4	4.79 %
Alternatives-CR6	4.139	4	4.67 %
Alternatives-CR7	4.232	4	7.80 %
Alternatives-CR8	4.140	4	4.72 %

The last step is to compute the overall rank of the alternatives. Global priorities for each alternative are summed to give the weight of the respected alternative. The alternative with the greatest weight is the most important alternative, and so forth. Table 4-15 shows the weight calculations for each alternative, which shows the overall rank. The following section presents and discusses the results.

Table 4-15. Overall Rank of the Alternatives

Alternatives	Weight	Overall rank
AMI	0.3168	1
ADO	0.1810	4
ATO	0.2507	3
AAM	0.2515	2

4.10 RESULTS

In this study, the alternative, AMI, is the most important alternative followed by AAM, ATO, and ADO. It is noticed that the second and third alternatives in the rank are very close with regard to their weight value. Policy makers may consider AMI as the one with the highest priority with regards to the electricity infrastructure modernization program in Saudi Arabia considering the attributes (criteria) discussed earlier.

To examine the performance of fuzzy AHP approach, a comparison is conducted between fuzzy AHP and conventional AHP. For this purpose, the case study is repeatedly conducted by implementing only conventional AHP for both criteria and alternative analysis. The results show that AMI and ATO are in the first rank, followed by AAM, and ADO. The weight of alternative AMI decreased by 17.61%. The weight of alternative AAM decreased by 2.98%. The weight of alternative ATO increased by 3.70%. the weight of alternative ADO increased by 30.38%. the variation of alternatives weights in the two approaches shows that the inaccuracy and imprecision embedded in conventional AHP approach tends to overestimate the importance of ADO and ATO. This finding shows that fuzzy AHP provides policy makers with more realistic results because it addresses uncertainty and imprecision. Fig. 4.5 shows the weights obtained by applying fuzzy AHP and the conventional AHP in a radar chart.

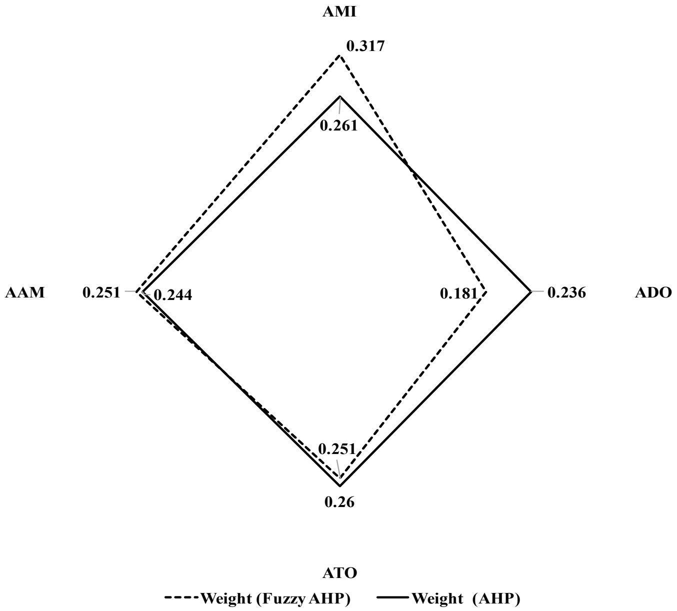

Fig. 4.5 Radar Chart for Alternatives Weights

Furthermore, the fuzzy AHP procedure is repeated considering *a*-cut as not a fixed value but assigned to a Likert scale to address participants' level of confidence over their judgment. This step aims at examining the impact of considering a fixed value of *a*-cut (as it is assumed in the chapter) on the precision of the results. Table 4-16 shows the weights and ranks of the alternatives of the fuzzy AHP approach after considering the value of *a*-cut as assigned to a Likert scale. The table also shows the weights and ranks of the alternatives resulted from conducting the conventional AHP approach. The original values resulted from fuzzy AHP approach (with a fixed value of *a*-cut) are also shown in Table 4-16 to facilitate the comparison among the three approaches. From Table 4-16, we notice that assigning *a*-cut to a Likert scale does not highly impact the weights of the alternatives. This suggests that considering a fixed value of *a*-cut may save time and effort while analyzing policy makers' preferences and judgments.

Table 4-16. Comparisons of the Weights and Ranks Resulting from Three Approaches

Alternatives	Conventional AHP		Fuzzy AHP (α-cut value: Likert scale)		Fuzzy AHP (α-cut value: fixed value)	
	Weight	Overall rank	Weight	Overall rank	Weight	Overall rank
AMI	0.261	1	0.303	1	0.3168	1
ADO	0.236	4	0.218	4	0.1810	4
ATO	0.260	2	0.234	3	0.2507	3
AAM	0.244	3	0.245	2	0.2515	2

4.11 CONCLUSION AND POLICY IMPLICATIONS

The chapter presents a framework for MCDM method to analyze and prioritize the importance of SGTs to the Saudi electricity infrastructure. A fuzzy AHP model is built to construct pairwise comparisons among attributes and alternatives. The results suggest that AMI technologies are the most important in order to achieve the 2020 targets stated in the National Transformation Program and the Saudi Vision 2030. The framework offers a tool to chart a roadmap for transitional modernization. The roadmap is intended to serve policy makers with prioritized progression of SGTs insertion to the electric grid.

The authors suggest that policies designed for electricity infrastructure modernization in Saudi Arabia should address the penetration of SGTs in a prioritized fashion. According to this study, AMI technologies are the most important SGTs for the Saudi electric grid considering the current status and the planned targets stated in the Saudi Vision 2030, followed by AAM technologies, ATO technologies, and ADO technologies. Modernizing the Saudi electricity infrastructure in a transitional progression is recommended considering the fact that electric grid modernization is a highly capital-intensive plan requiring a relatively long timeframe for construction and operation. According to [27], the investment required for electricity infrastructure modernization in Saudi Arabia has been estimated at US $140 billion. Based on expected demand growth, the country is required to boost supply capacity with 70,000 MW. As far as the current investment plan, only 10,000 MW is already committed [38]. Thus, modernizing the electric grid in Saudi Arabia is faced with financial challenges specially after the plummeting and fluctuating prices of oil revenue since 2014 [24].

In addition to the financial challenges, modernizing the electric grid should not come at the cost of compromising the grid reliability and stability. Introducing a new technology to an electricity infrastructure may impact the functionality and operability of the existing systems. Thus, a reasonable level of SGTs penetration is required to maintain system reliability and to adjust the existing system to the new changes. System engineers, operators, and planners are also required to adapt to the new technologies. Policy makers are recommended to consider a rollout penetration plan of SGTs by allowing only the technologies of the first choice, i.e., AMI. These technologies, then, will establish an infrastructure of integrated SGTs. Then, the second choice of infrastructure SGTs, i.e., AAM, follows, and so on.

Accordingly, and based off the discussion above, a transitional penetration of SGTs is required to establish a feasible plan for electricity infrastructure modernization. Policy makers in Saudi Arabia are recommended to consider the progressive modernization plan for the Saudi electricity infrastructure, which is expected to achieve a reliable transition that meets the Saudi Vision 2030 and the 2020 National Transformation Program.

CHAPTER 5

A COMPREHENSIVE COST-BENEFIT ECONOMIC ANALYSIS OF THE PENETRATION OF SMART GRID TECHNOLOGIES IN THE SAUDI ARABIAN ELECTRICITY INFRASTRUCTURE[4]

5.1 INTRODUCTION

The main objective of modernizing electricity infrastructures is to enhance the stability of the network, increase the reliability of supply, and to offer energy at reasonable and competitive prices to the consumers. Modernization calls for an economically feasible plan that transforms the electricity grid from its status quo to a smarter form by enabling the penetration of SGTs. Globally, electricity grid infrastructures are faced with several challenges including an increasing demand and worsening network congestions [1]. The Smart Grid is conceived to address these challenges and meet the needs of a sustainable, efficient, reliable, optimal, interactive, and economic electric system. This notion highlights the importance of developing a framework to evaluate SGTs. However, such a framework is faced with some challenges. Firstly, reliability, which is one of the most important benefits resulting from SGTs, has "public-goods" characteristics that are hardly translated into revenue. Secondly, the length of the obsolescence cycle of SGTs is yet unknown. Thirdly, some SGTs may be in the interest of some but not all parties in the electricity infrastructure [106]. Fourthly, SGTs incur high initial capital cost and, uncertainly, generate benefits across a long term. Fifthly, there is complexity in relating SGTs benefits to each technology and identifying the impact of each technology to each benefit. Some technologies provide multiple types of functions to result in multiple benefits. In other cases, multiple technologies provide one benefit. Lastly, considering the fact that active consumer participation is essential to capture the benefits of some of the SGTs, identifying the response of customers to participate in SGTs is uncertain, unclear and relevant to behavioral data specially at the early

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[4] This chapter is extracted verbatim from "A comprehensive cost-benefit economic analysis of the penetration of Smart Grid technologies in the Saudi Arabian electricity infrastructure," under review for publication with journal, May 2017.

stage of SGTs development [121, 122]. In additional to these challenges, other challenges related to SGTs integration to the grid are discussed in [107, 123].

Considering these challenges, there is a need for a thorough analysis to assess the outcomes of SGTs. In literature, some studies focus on the definition of SGTs benefits [124, 141, 142]. In [119], an economic framework is built to evaluate SGTs that achieves the U.S. DOE metrics and benefits. The framework maps Smart Grid assets to their functions, and maps benefits to functions and energy resources. Reference [125] introduces Smart Grid maturity model (SGMM), a business tool used by utilities to analyze current status of Smart Grid deployment and capability. It also proposes metrics to evaluate progress towards identified objectives. References [83, 126] consider a set of SGTs outcomes and estimate their benefits under different scenarios. Asset valuation is yet another tool used to calculate the profits realized after the utilization of certain assets [143, 144, 158, 176]. However, such a tool does not consider non-asset related valuations like system stability, supply reliability, and efficiency. Some studies offer a vision for smart power systems and identify technologies gaps [7, 105, 108-110]. Others, like [76, 111, 127], present a business case for network expansion by leveraging the potential of SGTs.

The original contribution of the work presented in this chapter is the development of an economic analysis framework that evaluates the benefits and costs of SGTs when inserted in an electricity infrastructure. The framework considers economic, reliability, environmental, and security benefits generated by the SGTs assessed in monetary values. The framework measures the outcomes and impacts of SGTs by computing the NPV, benefit/cost ratio, and minimum total cost. This study is demonstrated on the Saudi electricity infrastructure; however, the framework is generic enough for application to other electricity infrastructures. The framework is a comprehensive approach for economic analysis adapted from EPRI Smart Grid model, NETL modern grid initiative, and a study conducted by CESI and A.T. Kearney to estimate the impact of smart meters and smart equipment on the Saudi electric grid.

This work is part of a multi-dimensional economic framework developed to modernize electricity infrastructures. The first dimension addresses the deregulating of electricity markets. The second dimension addresses the prioritization and economic feasibility of SGTs. Interested readers can refer to [48, 177-179] for the abovementioned dimensions.

The rest of the chapter is organized as follows: section 5.2 discusses previous work conduced on applying CBA to SGTs. Section 5.3 discusses previous work conducted on the application of economic analysis of Smart Grid in the Saudi Arabian perspective. Section 5.4 presents the framework for economic analysis. Section 5.5 presents data and assumptions considered for the framework analysis. Section 5.6 shows the financial outcomes and costs associated with SGTs insertion. Section 5.7 discusses the results. Section 5.8 presents sensitivity analysis and implications. Section 5.9 concludes.

5.2 CBA FOR SGTs

The insertion of SGTs impacts all sectors of the electric power system, namely generation, transmission, and distribution. It also affects the two main players in electricity markets: producers and consumers. The level of impact varies based on the technology type inserted to the system and the level of penetration, which results in different values of costs and benefits for each player. One of the practical tools used to analyze projects or plans is the CBA, which is defined as an economic tool for identification, measurement, and comparison of costs and benefits of a scenario, project, investment, or program [57, 145]. Conducting CBA on a project or plan requires significant amounts of data, which are not always available. Instead, most econometric analyses focus on technology, application, or solutions evaluation. CBA seeks whether the benefits of a project, scenario, or policy, outweighs its costs. It analyzes costs and benefits from technical, economic, and societal perspectives. CBA surpasses other financial analyses that focus on only returns to investors.

Some studies propose frameworks for the insertion of SGTs. The authors in [104] discuss historical and technical events in the U.S. and Europe that aimed at modernizing the electric grid and ratifying Smart Grid policies. They also discuss enabling technologies that transform current electric structure. In [77], the authors present a comparison between the U.S. and Brazil in electricity infrastructure modernization trends and efforts. Reference [66] reviews initiatives taken by various electricity infrastructures planners across the world to benefit from implementing SGTs. Reference [112] presents an overview of the current Smart Grid policies and key regulatory trends in the European Union. It also presents risks and difficulties of implementation. Reference [128] reviews SGTs implementation in various electricity infrastructures, namely the U.S., Europe, China, and India, and their impact on power distribution efficiency and carbon footprint.

Other studies propose approaches to quantify costs and benefits of SGTs. Reference [146] provides an overview of some methodologies used in literature for assessing costs and benefits. Some literature focuses on computational general equilibrium (CGE) models and the level of investment allocated for SGTs [106, 122, 147, 148]. Other studies focus on the scalability, transferability, and replicability of Smart Grid projects [113, 114, 129, 130]. Reference [131] proposes a dynamic model for Smart Grid value composition where the model is built from the perspective of the theory of marginal opportunity cost and the concept of sustainable development. However, the model falls short of accounting for the social impact of SGTs. In [132], the U.S. DOE presents an analysis to estimate the benefits of energy conservation and carbon impact reduction obtained from SGTs. In [133], the authors introduce an approach to measure the smartness of electricity distribution grid by defining some metrics. Reference [149] conducts CBA for distribution management system (DMS) implementation on distribution networks as a Smart Grid solution. Reference [150] provides an AHP framework for Smart Grid pilot project evaluation. The framework adapts the *SMART* rule to build evaluation indicators. *SMART* rule evaluates whether a project is specific, measurable, achievable, relevant, and traceable. While the framework is credited for building a wide range of evaluation indicators, it considers only the present monetary values of costs and benefits. Moreover, the framework is project-based, not infrastructure-based as our work aims to be. In [134], the authors use the *iGrid* model to quantify the customer-side benefits of SGTs and estimate the benefits for the producers. In [151], the authors propose an approach to estimate costs and benefits associated with Smart Grid reliability investments for T&D planning by assessing reliability indices before and after SGTs deployment. However, this approach is focused on only the economic benefits generated by the reliability improvement. Some studies focus of conducting CBA for specific regional electric systems [138, 139, 152, 153]. Other studies suggest implementing agent-based simulation instead of equilibrium model. The agent-based simulation is, then, translated into benefit evaluation area [115, 122]. However, multi-agent approaches address SGTs needs from operational standpoint, while our work in this chapter is focused on comprehensively assessing costs and benefits from a system planning standpoint. Some other studies examine costs and benefits for utilities, albeit using a utility-centric approach [126, 135, 136, 154, 155].

Our work contributes to fill a gap in the existing literature by developing a generic and comprehensive framework to assess costs and benefits of SGTs insertion to an electricity infrastructure from the system planning perceptive. The analysis accounts for technical, economic, reliability, environmental, and security benefits. We demonstrate the effectiveness of our framework on the Saudi electricity infrastructure as it is poised to undergo a transformational modernization in the coming years. For completeness of the chapter, the following section discusses previous work on economic analysis of SGTs in the Saudi electric grid.

5.3 ECONOMIC ANALYSIS OF SMART GRID IN THE SAUDI ARABIAN PERSPECTIVE

As part of the Saudi Vision 2030 introduced in 2016 by the Saudi Council of Economy and Development Affairs, the Saudi Arabia is undergoing a plan to modernize the electricity infrastructure [74]. SGTs are crucial elements in any electric grid modernization program. Previous studies on electricity grid modernization in various locations around the world show that the benefit-to-cost ratio is about 4:1 to 6:1 [6, 79, 126, 137]. Our study aims to provide a generic and comprehensive framework for measuring the economic feasibility of SGTs in Saudi Arabia.

While research addressing the implementation of SGTs in Saudi Arabia from technical and economic perspective is limited, some studies discuss the opportunities and challenges of the insertion of SGTs to the Saudi electricity infrastructure. Reference [66] proposes critical areas for which SGTs are required in the Saudi electric grid. It also suggests using the SGMM to build a roadmap and investment model for SGTs insertion. Reference [38] estimates the costs and financial outcomes of smart meters and smart equipment to the Saudi electric grid. In [67], an application of some SGTs is demonstrated in the Saudi electric grid to study their outcomes after addressing the increasing level of consumption and improving energy efficiency. The study suggests that successful penetration of SGTs requires addressing challenges related to bi-directional protection, cyber security, financial funding, standards, and policies.

Other studies focus on the potential of RE sources in the Saudi electricity infrastructure. References [18, 65] discuss RE sources integration to the Saudi electric grid, and the importance of SGTs to enable such an integration. RE sources can help reduce oil consumption and diversify generation mix. In [45], an MCDM model using AHP is proposed to prioritize the importance of RE sources to the energy mix. Reference [62] applies an engineering-based residential electric demand model to analyze the outcomes of energy efficiency improvement. It also discusses the impact on policies and technologies beyond the scope of economic methods. In [68], a study conducted to examine the impact of installing solar energy for residential loads. The result calls for reducing government subsidies and updating current policies to facilitate the adoption of RE sources as well as SGTs. The following section presents the economic framework proposed in this chapter.

5.4 THE PROPOSED FRAMEWORK

This section introduces the framework and defines its scope, i.e. the boundaries within which the economic analysis is performed. The framework identifies SGTs, Smart Grid functions, and Smart Grid benefits and estimates the overall costs and benefits of the SGTs. Firstly, SGTs, or Smart Grid assets, are categorized into four main infrastructures adapted from the NETL model discussed in [12, 81, 82]. The four infrastructures and their technologies are listed in Table 5-1.

Secondly, Smart Grid functions are identified based on the electric grid sectors; hence, the functions are transmission, distribution, substation, and customer related. Transmission network functions include flow control and wide area monitoring and visualization. Distribution network functions include adaptive protection, automated feeder switching, automated islanding and reconnection, automated volt/var control, enhanced fault protection, and real-time load transfer. Substation-related functions include diagnosis and notification of equipment conditions, dynamic capability rating, and fault-current limiting capability. Customer-related functions include customer electricity use optimization and real-time load measurement and management. These functions are adapted from the EPRI Smart Grid model [156]. In the model, the functions are linked to some of Smart Grid assets.

Table 5-1. Smart Grid Infrastructures and Technologies (adapted from [12])

Infrastructure	Technologies	Infrastructure	Technologies
AMI	Smart meters	ATO	Substation automation
	HAN		WAMS
	Wide area communication infrastructure		Electricity markets
	MDMS		Modeling, simulation, and visualization tools
ADO	Distribution automation		Advanced regional operational applications
	Complex systems (microgrid, premium power parks)		Advanced grid components (FACTS, HVDC, UPFC)
	Distribution GIS	AAM	Asset health information
	OMS		T&D planning
	Distributed energy resources		Condition-based maintenance
	Advanced protection and control		System operating information
	DMS		Asset utilization operation optimization
	Advanced grid components (high speed transfer switches, backup power supplies, FCL)		Engineering design and construction
	PHEVs		Modeling and simulation
	Distributed storage devices		

Thirdly, Smart Grid benefits are classified into economic, reliability, environmental, and security benefits. The classification is adapted from the EPRI Smart Grid model [156]. Under each benefit category, a list of benefits is defined. The model links these benefits to the related functions performed by Smart Grid assets.

The contribution of our chapter is to create a comprehensive linkage between the Smart Grid assets and their benefits. The linkage maps all assets to their functions to the benefits. Table 5-2 shows the asset-benefit mapping. When linking benefits to assets, we consider only the direct benefits generated by the assets and the not indirect ones. While some assets generate investment and operations benefits, some others generate only investment or operations benefits. For example, engineering design and construction and T&D planning assets, under AAM, generate only investment

Table 5-2. Smart Grid Asset-Benefit Mapping

Smart Grid assets	Benefits																					
	Economic													Reliability						Environmental	Security	
	Improving assets utilization				T&D capital savings			T&D O&M savings			Theft reduction	Energy efficiency	Electricity cost savings	Power interruption				Power quality		Air emissions	Energy security	
	Optimizing generator operation	Deferring generation capacity investments	Reducing ancillary service cost	Reducing congestion cost	Deferring transmission capacity investments	Deferring distribution capacity investments	Reducing equipment failure	Reducing distribution equipment maintenance cost	Reducing distribution operations cost	Reducing meter reading cost	Reducing electricity theft	Reducing electricity losses	Reducing electricity cost	Reducing sustained outages	Reducing major outages	Reducing restoration cost	Reducing momentary outages	Reducing sags and swells	Reducing Co_2 emissions	Reducing SO_x, NO_x and PM10 emissions	Reducing oil usage	Reducing wide scale blackouts
AMI																						
Smart meters		X	X		X	X			X	X	X	X	X	X	X				X	X	X	
HANs		X			X	X						X	X						X	X		
Wide area communication infrastructure	X		X	X	X	X			X	X	X	X		X	X	X	X		X	X	X	X
MDMS		X		X	X	X	X	X				X	X	X		X	X	X			X	X
ADO																						
Distribution automation							X		X			X		X	X	X	X	X	X	X	X	X
Complex systems														X	X							
Distribution GIS				X	X	X	X															X
OMS				X	X	X	X							X		X	X	X				X
Distributed energy resources operations		X	X	X	X	X			X			X		X	X				X	X		
Advanced Protection and Control							X							X		X	X	X				X
DMS			X	X	X	X	X		X	X	X	X		X	X	X	X		X	X	X	X
Advanced grid components					X		X															
PHEVs	X	X	X	X	X	X								X					X	X	X	
Distributed storage devices	X	X	X	X	X	X						X	X	X			X	X	X	X		
ATO																						
Substation automation	X		X	X	X										X							X
WAMS	X		X	X	X										X							X
Electricity markets applications	X		X	X	X										X				X	X		X
Modeling, simulation and visualization tools	X		X	X	X										X							X
Advanced protection and control				X	X														X	X		
Advanced regional operational applications	X		X	X	X										X				X	X		X
Advanced grid components				X	X														X	X		
AAM																						
Asset health information				X	X	X	X	X						X		X					X	
T&D Planning	X	X	X	X	X	X						X	X						X	X		
Condition-based maintenance			X		X		X	X	X	X	X	X		X	X	X			X	X	X	
System operating information				X	X	X	X	X						X		X					X	
Asset utilization operation optimization	X	X	X	X	X	X	X			X	X	X	X	X	X		X		X	X	X	X
Engineering design and construction		X			X	X	X	X				X	X	X		X			X	X	X	
Modeling and simulation			X			X	X	X		X	X	X		X	X	X			X	X	X	

benefits, i.e., savings in investments allocated for grid modernization. The asset, modeling and simulations, under AAM also, generates only operations benefits, i.e., cost reduction in operations costs.

In this framework, the DCF model is applied to compute the present value of future cash flows resulting from SGTs for every year of the analyzed period. The DCF model is a basic valuation model for an asset that is expected to generate cash payment in the form cash earnings, interest and principal payment, or dividends. The mathematical representation of the DCF model is:

$$V_o = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_n}{(1+r)^n} \tag{5.1}$$

where, V_o is the present value of the anticipated cash flows from the asset, $CF_{1,2,\ldots,n}$ are the cash flows expected to be received up to n periods in the future, and r is the discount rate, which is the required rate of return per period [161].

After computing the DCF for every year, the NPV for each benefit is computed. The NPV of a capital budging project is the dollar amount of the change in the value of the firms because of undertaking the project. In our case, the NPV shows the dollar amount of the change in the value of the electricity infrastructure because of selecting one or more of SGTs. A positive NPV indicates that the value of the infrastructure will increase if the new SGT is inserted. Similarly, a negative NPV means the infrastructure's value will decrease if the new SGT is inserted. The formula for NPV is:

$$NPV = \frac{CF_1}{(1+r)^1} + \cdots + \frac{CF_n}{(1+r)^n} - Initial\ Investment \tag{5.2}$$

where, $CF_{1,2,\ldots,n}$ is the cash flow at the indicated times, r is the discount rate, and n is the life of the technology measured in number of years [161].

The discount rate, r, is the interest rate that determines the present value of future cash flow. A low interest rate indicates a promoting trend of development created by central banks. Conversely, a high interest rate shows inflationary, risker and uncertain trends [140]. Multiple studies adopt a discount rate of 5% to 5.5% in their evaluation of electricity economics in Saudi Arabia [42, 71]. In other studies, a discount rate of 7.5% is considered [38]. In our study, we apply a conservative approach, thus, a discount rate of 7.5% is adopted.

It is important to define the time horizon within which the benefits and costs of SGTs are analyzed. The time horizon varies per the nature of the investment, structure of the electricity infrastructure, and types of SGTs. Generally, time horizon for SGTs is between 20-30 years [155]. In our study, and according to some estimates related to the Saudi electricity infrastructure, we assume a conservative time horizon of 15 years [38].

The schedule of implementation is assumed to be seven years for ATO and ADO technologies. For AMI technologies, we assume a schedule of 12 years [38]. Technology maturity is defined for some applications. Some economic factors are defined such as carbon cost, and FTE. Electric grid characteristics, such as peak load, demand, and consumptions are defined. These boundaries are discussed in the subsequent section.

The following sections discuss the framework application on the Saudi electricity infrastructure as a case study. Although the case study presented in this chapter is on the Saudi electricity infrastructure, the framework and analysis are generic enough for use by policy makers of other infrastructures, albeit with appropriate changed inputs. In section 5.5, the data used and the assumptions made for this analysis are presented.

5.5 DATA AND ASSUMPTIONS

Data about the electricity grid in Saudi Arabia are taken from publicly available sources. According to [17], annual growth rate in T&D networks are 7.6% and 6.3%, respectively. Average technical losses in the grid network is 7%. Residential, industrial, governmental, commercial, and other consumptions sectors are 114.5, 51.8, 39.6, 47. 2, and 11.4 TWh, respectively. Other consumptions include the desalination, agriculture, and health sectors. Consumption growth rates for the sectors are 6.3%, 3.7%, 9.2%, 11.8%, and 1%, respectively. Peak demand in 2016 was 60,800 MW, of which the residential peak demand represents 57.4%, industrial peak demand represents 17%, governmental peak demand represents 12.7%, commercial peak demand represents 10.6%, and other peak demands account for 2%. The growth rate for peak demands in the aforementioned sectors are 5%, 8%, 3%, 7%, and 3%, respectively [17].

The current policy to introduce RE sources to the generation mix in Saudi Arabia aims at supplying 9,500 MW from RE sources to the energy generation mix as part of the Saudi Vision 2030 [74]. Annual installation of RE sources capacity in the next six years is planned to be 700, 1,200, 1,700, 1,800, 2,100, and 2,100 MW [69]. After that, we assume an annual addition of 1,600 MW to the generation mix. This assumption is made since there is no information about how future capacity of RE sources will be added to the grid. The assumed value of 1,600 MW is the average value of the six MW capacities for the first six years.

The levelized cost of electricity (LCOE) is used to compare the cost of electricity generated by different resources, which follows from the standard DCF model. LCOE corresponds to the cost of generating electricity including the cost of operations and fuel at domestic market prices. Levelized cost is the ratio of the total cost to the benefits [63, 162]. The LCOE in Saudi Arabia for electricity produced by fossil fuel resources is estimated to be 39 US $/MWh, and an average of 110 US $/MWh for electricity produced by RES. Considering expected technology maturity, LCOE produced from RE sources is excepted to decrease 7% yearly. On the other hand, LCOE produced from fossil fuel resources is expected to increase 8% yearly due to oil price increase and fluctuations and an increase in operations costs [63]. Domestic cost of oil barrel is US $5 [25]. Load factor for RE sources is assumed to be 0.2 [38].

Utilization factor for power plants is assumed to be 85%. The amount of fuel needed to produce one MWh of energy is estimated to be 7.94 million British thermal units (MBTU). Based on industry average, we make a conservative assumption for the price of an oil barrel of US $50 for the next 15 years. The MBTU per barrel of oil is 5.5, based on industry average. The price of CO_2 is estimated to be US $9.86 per tonne, growing at an annual rate of 16% till 2020, and then onwards at 5% [38]. The introduction of RE sources is expected to reduce emissions by 0.635 tonne of CO_2 per each MWh produced by RE sources, compared to the same capacity generated by fossil fuel sources otherwise [17, 38].

The penetration of SGTs to the T&D networks is expected to reduce operations cost by 8%. This reflects a saving of US $6,000, and US $2,000 for each circular kilometer (CKM) in T&D networks, respectively. The savings are realized in seven years, and after the introduction of ATO and ADO technologies. Moreover, it is estimated that US $400 million can be saved in T&D networks for each 1,000 MW saved from new generation capacity [17, 38].

SGTs are expected to improve the reduction of system losses by 10% by which SAIDI improves by 10% and, ultimately, energy consumption is saved by 0.7%. SAIDI is a reliability index defined as the ratio of the total interrupted customer minutes and the number of customers [43]. In 2015 in the Saudi electric grid, SAIDI was 254 minute/customer [17]. In addition to SAIDI improvement, SAIFI is expected to improve by 50%. SAIFI is a reliability index defined as the ratio of the total number of customer interruptions and the total number of customers served from the system [43]. In 2015, the SAIFI in the Saudi electric grid was 6.24 [17]. SAIFI is expected to take three years to reach the 50% improvement because of the time needed for technology maturity. Since this assumption does not state how technology maturity is expected to progress over the three year period, we assume an equal (linear) progression of technology maturity, therefore, a yield of 33.3% of total benefit is realized each year [17, 38].

DR programs are expected to be enabled after the introduction of SGTs. It is assumed that 5% reduction in the new generation capacity will be realized after peak shaving programs. Savings in new installed capacity are estimated to be US $1.06 billion for each 1,000 MW saved. In additional to new capacity savings, DR programs will generate savings in operations and maintenance (O&M) such that a reduction of US $4.5 will be realized for each one MWh saved [17, 38].

The average cost of meter reading per meter per year is assumed to equal US $0.8. Total number of meter reading employees required in Saudi Arabia is 3,200 and the average labor cost is US $1,333 per month. Average productivity is assumed to be 85 meters per day. Current annual number of manual meter connections and/or disconnections is 350,000. The number of manual connections and/or disconnections that can be solved by a Full Time Equivalent (FTE0 is 10 per day. Expected improvement in the reduction of non-technical losses is 40% after SGTs is introduced. Increasing billing accuracy is expected to yield US $21 million each year. Avoided replacement of traditional meters is expected to generate US $32 million savings each year [17, 38]. This concludes the section on data and assumption which will be used further. The following section discusses the outcomes and impacts of SGTs insertion and assigns monetary values to each outcome and impact.

5.6 ESTIMATING THE OUTCOMES AND COSTS

This section discusses the outcomes and costs of SGTs penetration to the Saudi electricity infrastructure. The outcomes and costs are represented in monetary values and analyzed based on their effect on the electric grid and the national economy. The report [38] discusses such impacts of considering direct and indirect financial outcomes. In our study, we adapt and integrate the outcomes mentioned in [38] to the rest of the framework. Financial outcomes are then translated into benefits. Then, the DCF model for annual outcomes is computed, followed by the computation of NPV for the total period.

The first outcome expected from introducing SGTs to the Saudi electricity infrastructure is reductions in operating costs. This outcome is realized after reducing and optimizing the resources required to operate and maintain the grid system. Manual network resources are replaced with automation solutions. The reduction in operation costs targets the T&D sector, which would improve system reliability. The second outcome is realized after improving the quality of service and minimizing technical losses. The third outcome is realized after increasing the continuity of service. SGTs are expected to improve system reliability by enhancing automated responses to outages and reducing outage duration, and hence, improving SAIFI.

The fourth outcome is realized after reducing meter reading costs because of SGTs. The fifth outcome is realized by reducing reading management cost and optimizing resources used in reading management. The sixth outcome is realized after reducing the restoration time associated with system faults and failures. Improving the restoration time is expected to reduce resources needed to resolve faults and failures. Ultimately, SAIDI will be improved by 10%. The seventh outcome is realized by reducing non-technical losses including theft and the non-invoiced energy delivered to end users. The eighth outcome is realized by improving the billing accuracy. Smart meters provide higher threshold for the minimum energy that can be metered than traditional meters which would increase accuracy. The ninth outcome is realized by the savings on the avoided replacement of traditional meters due to damage or shorter life duration.

The tenth outcome is realized after optimizing the energy generation resources mix and increasing RE sources capacity. SGTs enable DR programs for peak shaving, which are expected to reduce investments allocated for new installed capacity to meet the increasing peak demand. RE sources acquire the advantage of low operation costs compared to fossil fuel resources. The outcomes resulting from optimizing the energy mix are realized by reducing the cost of electricity production. The LCOE for annual load supplied by RE sources is less than that supplied by fossil fuel resources. The analysis shows that a positive DCF will be realized in the eighth year. The eleventh outcome is realized after increasing the fuel availability. High consumption of energy in Saudi Arabia is driven be the low cost of domestic fossil fuel. This outcome results from reducing the fuel consumption and selling fuel surplus in the international market. Reduction in fuel consumption occurs after the RE sources takes part in the energy mix. The twelfth outcome is realized after reducing the GHG emissions. Introducing SGTs is expected to reduce GHG, such as CO_2, after reducing fuel consumption from fossil fuel resources. Profit is realized from CO_2 certificates. The thirteenth outcome is realized after reducing the generation costs. SGTs help reduce CAPEX and operation costs of electricity generation. The fourteenth outcome is realized after reducing T&D capital costs. SGTs help reduce peak demand. Thus, cost savings in capital and operating expenditure in T&D networks will be realized. Table 5-3 shows NPV for each outcome over the analyzed period of 15 years and the associated total NPV.

Table 5-3. NPV of SGTs Financial Outcomes (adapted from [38])

SGTs outcomes	NPV (US $ billion)	SGTs outcomes	NPV (US $ billion)
1	1.84	8	0.12
2	1.10	9	0.18
3	0.06	10	2.06
4	0.45	11	5.21
5	0.001	12	1.08
6	0.005	13	1.70
7	1.41	14	0.62
Total NPV		15.87	

The costs of SGTs are divided into three categories: ATO costs, ADO costs, and AMI costs. The costs of AAM infrastructure applications are not estimated separately. However, they are included in ATO, ADO, and AMI cost estimations. The cost estimation is adapted from a study conducted by [38]. ATO costs include transmission network capital expenditure (CAPEX) and operating expenses (OPEX). OPEX includes the costs of O&M of capital equipment. CAPEX is divided into three expenditures. The first one is the installation costs of network equipment, automated systems, intelligent electronic devices (IEDs), and advanced grid components such as FACTS, HVDC, sensors, and PMUs. The second expenditure is the cost of enterprise back-office systems and equipment including GIS, OMS, and DMS. The third one is the cost of supporting IT/cyber security and communication infrastructure. This includes transmission line support, and fiber optics communication infrastructure.

ADO costs include distribution network CAPEX and OPEX. OPEX includes the cost of O&M of capital equipment. CAPEX includes the installation costs of network equipment for substation automation, distribution automation systems such as intelligent reclosers, relays, switches, sensors, capacitor banks, direct load and generator control, voltage and power flow control equipment. It also includes the cost of supporting IT and communication infrastructure among digitized devices in the distribution systems.

AMI costs include the CAPEX and OPEX of the procurement of equipment and systems of the three AMI layers: meter, intermediate, and application layers. AMI OPEX includes the cost of O&M. It also includes projects costs, communication/connectivity costs, consumed energy costs which are the cost of energy consumed by the measuring systems, and costs of services. AMI CAPEX includes the meter layer costs, which include modular meters, communication modules, new meters, and HAN. CAPEX also includes intermediate layer costs including the cost of concentrators and balancing meters, and the costs of modems and couplers. Lastly, CAPEX includes the application layer costs, which include the costs of development, testing and implementation of the AMI, integration and interfacing, computer equipment, and licensing. Total estimated costs for each category are shown in Table 5-4.

Table 5-4: Cost of SGTs

SGTs cost categories	Cost (US $ billion)
ATO costs	
CAPEX: equipment	(0.50)
CAPEX: enterprise back-office system	(0.01)
CAPEX: IT/cyber security	(0.05)
Total ATO CAPEX	(0.56)
OPEX	(0.03)
Total ATO	(0.59)
ADO costs	
CAPEX	(0.96)
OPEX	(0.12)
Total ADO	(1.08)
AMI costs	
CAPEX: meter layer	(0.99)
CAPEX: intermediate layer	(0.20)
CAPEX: application layer	(0.05)
Total CAPEX cost	(1.24)
OPEX	(0.45)
Total AMI cost	(1.69)
Total SGTs cost	(3.36)

After estimating the outcomes and costs, an egalitarian distribution is performed for each outcome value among the related benefits presented in Table 5-2. Likewise, an egalitarian distribution is performed for each cost value among the related assets shown in Table 5-1. The following section discusses the results of the analysis.

5.7 RESULTS

After performing the analysis described in the previous sections, the results indicate that the total benefits resulting from the insertion of SGTs in the Saudi grid are estimated as US $15.87 billion. The total costs of these SGTs are estimated as US $3.36 billion, thus resulting in a total profit of US $12.51 billion. This indicates SGTs are profitable to the Saudi electricity infrastructure subject to the assumptions in this study.

Moreover, this study performs three methods to evaluate the economic feasibility of SGTs. The first one is computing NPV for each technology. The results show that assets utilization optimization is the most profitable application of the SGTs to the Saudi electricity infrastructure. The second one is DMS, followed by engineering design and management, and condition-based maintenance operations. The rest of the results are shown in Table 5-5. Further discussion on these findings are presented in the subsequent section. The same analysis is performed considering NPVs for each Smart Grid infrastructure, namely AAM, ADO, AMI, and ATO. The results show that AAM technologies are ranked first, followed by ADO, AMI, and ATO. Table 5-6 shows the benefits, costs, and profits for each infrastructure.

The second method is computing benefit/cost ratio (B/C ratio) for each infrastructure. The results show that AAM is ranked first, followed by ADO, ATO, and AMI as shown in Table 5-6. The third method is computing the minimum total cost of each infrastructure. Minimum total cost is the investment cost and the O&M cost [157]. The results show ATO is the lowest infrastructure cost, followed by AAM, ADO, and AMI. The results are shown in Table 5-6. We, then, average the three ranking values for each infrastructure to obtain the overall ranking. The results show that AAM is the first, followed by ADO, ATO, and AMI, as shown in Table 5-6.

Aside from Smart Grid assets, the analysis shows total outcomes related to each benefit. The most profitable benefits are the reduction in domestic oil usage for electricity and deferring T&D capacity investments as shown in Table 5-7. Total benefits realized for each year are also computed. In addition, the benefits growth rate for each year is computed, i.e., difference in benefits values between two consecutive years. Table 5-8 shows benefits realized and benefits growth rate for each year of the analyzed period. The results show that high growth in benefits occurs in the second years because, firstly, SGTs will start generating benefits, and, secondly, there is yet a room for improvement in the infrastructure from which SGTs can leverage their benefits. Some other years encounter negative growth rate because some benefits have not been realized yet.

5.8 SENSITIVITY ANALYSIS AND IMPLICATIONS

After obtaining the results, sensitivity analysis is performed to examine the impact of the change in values of some parameters to the SGTs total benefits. To test the dependence on framework assumptions, we use 10% in the sensitivity analysis as advised by [100]. Table 5-9 shows the impact of 10% change in the initial values of some parameters on the total SGTs benefits. It shows that discount rate, followed by annual installation of RE sources and oil prices are the most sensitive parameters in the framework. The large impact of discount rate on total benefits implies that selecting a proper discount rate is crucial to arrive at an accurate estimation. Discount rates are set by central banks and determined by the economic cycle and economic conditions of a country.

The results also show that "assets utilization optimization" is the most profitable application, followed by DMS, engineering design and management, and condition-based maintenance operations as mentioned in section 5.7. This indicates an urgent need to optimize grid sectors and minimize losses by improving efficiency and enabling advanced and automated equipment. Low asset utilization is explained by high level of aging equipment and increasing level of losses in the Saudi electric grid. In [179], we identify equipment aging and system losses are of the main challenges facing the electric grid.

The findings of this work are intended to serve decision makers when planning for SGTs insertion to the electricity infrastructure. The findings imply the need to weight certain criteria when computing CBA of SGTs. The sensitivity analysis shows the criticality of oil prices on impacting the net benefits of SGTs. Considering the fluctuating oil prices in international markets, planners may take a conservative approach for cost-benefit estimation.

From the sensitivity analysis, we notice that the level of RE sources penetration to the generation mix plays an important role in increasing SGTs benefits. This shows that the deferred capacity from fossil fuel resources and supplied instead by RE sources have large financial benefits. This finding may propone to increase RE sources penetration.

Another implication derived from the results is the benefits of SGTs realized by reducing GHG emission. The electricity infrastructure in Saudi Arabia emits a considerable amount of CO_2 due to its high dependence on fossil fuel resources for electricity generation. This work may call for policies to reduce electricity generation emissions and increase RE sources penetration to the generation mix.

Table 5-5: Benefits, Costs, and Profits of each Technology

Smart Grid assets	Benefits (US $ billion)	Costs (US $ billion)	Profit (US $ billion)	Ranking
AMI				
Smart meters	1.209	(0.35)	0.863	6
HANs	0.463	(0.35)	0.117	22
Wide area communication infrastructure	1.109	(0.48)	0.626	10
MDMS	1.024	(0.35)	0.678	9
ADO				
Distribution automation	0.872	(0.12)	0.752	7
Complex systems	0.033	(0.12)	(0.087)	28
Distribution geographic Information system	0.166	(0.01)	0.151	20
OMS	0.306	(0.001)	0.304	16
Distributed energy resources operations	0.537	(0.12)	0.417	15
Advanced Protection and Control	0.169	(0.12)	0.049	23
DMS with PQ data	1.114	(0.12)	0.992	2
Advanced grid components for distribution	0.078	(0.12)	(0.042)	27
PHEVs	0.865	(0.12)	0.745	8
Distributed storage devices	0.655	(0.12)	0.535	13
ATO				
Substation automation	0.129	(0.12)	0.005	25
WAMS	0.129	(0.14)	(0.008)	26
Electricity markets applications	0.234	(0.001)	0.232	17
Modeling, simulation and visualization tools	0.129	(0.001)	0.128	21
Advanced protection and control	0.166	(0.013)	0.153	19
Advanced regional operational applications	0.234	(0.001)	0.232	17
Advanced grid components for transmission	0.166	(0.12)	0.042	24
AAM				
Asset health information	0.688	(0.07)	0.616	11
T&D Planning	0.507	(0.08)	0.428	14
Condition-based maintenance	1.021	(0.07)	0.950	4
System operating information	0.688	(0.07)	0.616	11
Asset utilization operation optimization	1.218	(0.08)	1.140	1
Engineering design and construction	1.014	(0.05)	0.965	3
Modeling and simulation	0.953	(0.04)	0.911	5

Table 5-6. SGTs Infrastructures Ranking

Infrastructure	Benefits (US $ billion)	Costs (US $ billion)	Profit (US $ billion)	Rank (NPV)	B/C ratio	Rank (B/C ratio)	Min. total cost (US $ billion)	Rank (min. total cost)	Average rank
AMI	3.805	(1.52)	2.28	3	2.50	4	(1.52)	4	3.66
ADO	4.795	(0.98)	3.82	2	4.91	2	(0.98)	3	2.33
ATO	1.186	(0.40)	0.78	4	2.95	3	(0.40)	1	2.66
AAM	6.089	(0.46)	5.63	1	13.17	1	(0.46)	2	1.33

Table 5-7. Financial Outcomes from each Benefit

Benefits			Outcomes (US $ billion)	Ranking
Economic	Improving asset utilization	Optimizing generator operation	0.207	17
		Deferring generation capacity investments	0.850	5
		Reducing ancillary service cost	0.491	10
		Reducing congestion cost	0.207	17
	T&D capital savings	Deferring transmission capacity investments	1.210	2
		Deferring distribution capacity investments	1.210	2
		Reducing equipment failure	0.364	14
	T&D O&M savings	Reducing distribution equipment maintenance cost	0.207	19
		Reducing distribution operations cost	0.559	8
		Reducing meter reading cost	0.429	11
	Theft reduction	Reducing electricity theft	0.384	12
	Energy efficiency	Reducing electricity losses	0.551	9
	Electricity cost savings	Reducing electricity cost	0.667	7
Reliability	Power interruption	Reducing sustained outages	0.368	13
		Reducing major outages	0.161	21
		Reducing restoration cost	0.166	20
	Power quality	Reducing momentary outages	0.319	15
		Reducing Sags and Swells	0.319	15
Environmental	Air emissions	Reducing Co_2 emissions	0.748	6
		Reducing SO_x NO_x and PM10 emissions	1.031	4
Security	Energy security	Reducing oil usage	5.421	1
		Reducing wide scale blackouts	0.007	22

Table 5-8. Benefits and Growth Rate for each Year

Year	Total DCF	Growth rate
1	0.494	-
2	0.676	36.8%
3	0.688	1.8%
4	0.687	-0.1%
5	0.704	2.4%
6	0.707	0.5%
7	0.795	12.5%
8	0.791	-0.6%
9	0.915	15.7%
10	1.041	13.8%
11	1.179	13.2%
12	1.320	11.9%
13	1.457	10.4%
14	1.600	9.8%
15	1.741	8.9%

Table 5-9. Sensitivity Analysis

Parameters	Change on parameters initial values	Change on total SGTs benefits
r (discount rate)	10%	-6.45%
Annual installation of RE sources	10%	5.27%
Oil price	10%	3.65%
Peak shaving by DR	10%	1.46%
Improvement in the reduction of non-technical losses	10%	0.89%
Improvement in the reduction of technical losses	10%	0.70%
Price of 1 tonne of CO_2	10%	0.68%

5.9 CONCLUSION

The chapter proposes an economic framework based on detailed cost-benefit analysis of the insertion of SGTs for electricity infrastructure modernization. The framework is built based on a comprehensive approach adapted from EPRI Smart Grid model, NETL modern grid initiative, and a study conducted by CESI and A.T. Kearney to estimate the impact of smart meters and smart equipment. The framework maps Smart Grid assets to their functions and benefits to estimate the feasibility of each Smart Grid technology and infrastructure. The framework is applied on the Saudi electricity infrastructure as a case study. The findings of this work show that AAM infrastructure technologies are the most profitable technologies of Smart Grid to the Saudi electricity infrastructure, followed by ADO technologies, ATO technologies, and AMI technologies.

CHAPTER 6

POLICY, PLANNING, AND SOCIETAL IMPLICATIONS

This chapter discusses the findings and implications obtained from Chapters 2, 3, 4, and 5. Initially, this research examines prospect scenarios for electricity infrastructure modernization in Saudi Arabia. The modernization is characterized by a multi-dimensional economic analysis. The first dimension addresses electricity market deregulation. The second dimension addresses the insertion of SGTs. The findings of the research conducted on the first dimension, in Chapter 3, show that a positive value of ΔW is expected after the deregulation of the Saudi electricity market. This implies that electricity market deregulation is recommended. The results also show that the selling price of energy increases five times the current price in the short run, and 17^{th} times the current prices in the long run. This increase in energy prices would increase producers surplus, and reduce consumers surplus. The quantity of electricity sold is expected to remain unchanged in the short run, and reduce by 40% in the long run. These results imply that electricity market deregulation would encourage investors to access the market since the producers surplus is expected to increase.

On the other hand, market deregulation is expected to decrease consumers surplus after the increase in electricity prices, which might create a negative social impact. Hence, consumers' acceptance to energy conservation and DR programs is expected to improve in order to help reduce the monthly electricity bill. This scenario is expected to help reduce total energy consumption and, therefore, reduce total peak demand.

The model proposed in Chapter 3 shows that ΔW increases as ε increases, and as r decreases. When ε increases, the lost demand from supply-demand mismatch increases, therefore, GW decreases. Moreover, r represents how risky a setup is. As r increases, the forecasted outcomes decrease. These findings show that low price elasticity of demand affects GW value, a notion leads us to recommend considering ε as an indicator for the level of market efficiency. Moreover, the value of ΔW increases as λ_g and η increase. When government subsidies increase, there would be a greater room to optimize the market. Increasing η would also expand the limit to which C_p improves, which consequently increases ΔW. This implies that government subsidies to electricity prices play a major role in limiting market efficiency.

With regards to the second dimension, the research, in Chapter 4, proposes a MCDM model using fuzzy AHP to prioritize SGTs to the Saudi electricity infrastructure. The prioritization considers technical, economic, societal, and environmental factors. The results show that AMI technologies are ranked first, then AAM technologies with 19.1% less importance weight than AMI technologies weight. ATO technologies come in the third rank with 22.7% less weight than AMI technologies weight. The fourth rank goes to ADO technologies with 28% less weight than AMI technologies weight. This implies the importance of AMI technologies over other technologies to meet the Saudi 2020 targets stated in the National Transformation Program and the Saudi Vision 2030. Additionally, the results offer a tool to chart a roadmap for transitional modernization. The roadmap is intended to serve policy makers with prioritized progression of SGTs insertion to the electric grid. The results suggest that policies designed for electricity infrastructure modernization in Saudi Arabia should address the penetration of SGTs in a prioritized fashion. Modernizing the Saudi electricity infrastructure in a transitional progression is recommended considering the fact that electric grid modernization is a highly capital-intensive plan requiring a relatively long timeframe for construction and operation.

In addition to the financial challenges, modernizing the electric grid should not come at the cost of compromising the grid reliability and stability. Introducing a new technology to an electricity infrastructure may impact the functionality and operability of the existing systems. Thus, a reasonable level of SGTs penetration is required to maintain system reliability and to adjust the existing system to the new changes. System engineers, operators, and planners are also required to adapt to the new technologies. Policy makers are recommended to consider a rollout penetration plan of SGTs by allowing only the technologies of the first choice, i.e., AMI. These technologies, then, will establish an infrastructure of integrated SGTs. Then, the second choice of infrastructure SGTs, i.e., AAM, follows, and so on.

Accordingly, and based off the discussion above, a transitional penetration of SGTs is required to establish a feasible plan for electricity infrastructure modernization. Policy makers in Saudi Arabia are recommended to consider the progressive modernization plan for the Saudi electricity infrastructure, which is expected to achieve a reliable transition that meets the Saudi Vision 2030 and the 2020 National Transformation Program.

In the second part of the analysis pertaining to the second dimension, in Chapter 5, a comprehensive economic CBA is conducted to assess the economic feasibility of SGTs to the Saudi electricity infrastructure. The economic analysis comprises three methods: NPV, benefit/cost ratio, and minimum total cost. The average ranking of SGTs infrastructures places AAM technologies at the first rank, followed by ADO technologies in the second rank with 43% less weight than AAM technologies weight. ATO technologies are placed at the third rank with 50% less weight than AAM technologies weight. AAM technologies are ranked fourth with 63.3% less weight than AAM technologies weight.

In order to draw a comparison between infrastructures' rankings resulted from fuzzy AHP analysis and the other ranking resulted from the economic analysis, Table 6-1 shows the weight of each infrastructure obtained from each analysis. The results show that AAM technologies are ranked first in the overall ranking. This finding is justified by the fact that the electricity infrastructure in Saudi Arabia is facing challenges represented in aging equipment, technical and non-technical losses, and high carbon emissions. Additionally, the characteristics of the Saudi electric grid and some other factors have a major impact on exacerbating these challenges. Such factors include the fact that 80% of total load in Saudi Arabia is air conditioning, which leads to frequent and cascading events of motor stalling. Other factors include the climatic conditions, and building codes currently in place. Drafting proper policies that encourage a conservative level of consumption and enabling DR program, along with the integration of AAM technologies, the high consumption of energy and peak demand will decrease considerably. AAM technologies can help improving assets utilization, enhancing condition-based maintenance, and advancing T&D design and planning.

AMI technologies are ranked second. Considering the current metering system in Saudi Arabia, the electric grid requires advanced metering system to reduce losses and costs associated with meter reading and management, enable other SGTs and bi-directional communication. ADO technologies and ATO technologies are ranked third and fourth, respectively. While T&D networks in Saudi Arabia are of less priority than AAM and AMI for electricity infrastructure modernization plan, they yet are important parts of it. Enabling ADO and ATO technologies has a huge impact on system reliably and stability. It also allows the integration of other infrastructures' technologies, i.e. AAM, and AMI. From the analysis presented in Chapter 5, some ADO and ATO technologies are of high benefit/cost ratio such as DMS, distribution automation, and PHEVs. Electricity market applications, and advanced regional operational applications are yet important applications that enable further phases of the modernization, i.e. electricity market deregulation, and market efficiency improvement.

Table 6-1. Overall Ranking of SGTs Infrastructures

Infrastructure	Fuzzy AHP weight	Economic analysis weight	Total weight	Overall ranking
AMI	1.000	0.367	1.367	2
ADO	0.720	0.570	1.290	3
ATO	0.773	0.500	1.273	4
AAM	0.809	1.000	1.809	1

From the economic analysis presented in Chapter 5, the financial outcomes resulting from each benefit, in Table 5-7, the most beneficial outcome is resulted from reducing oil usage. This finding is justified by the fact that relatively high percentage of domestic oil is consumed locally. This notion leads to increasing the level of energy consumption and building a significant opportunity cost against the potential sale of oil in the international market. SGTs are expected to enable RE sources and reduce technical and non-technical losses, which would reduce domestic oil consumption. Another benefit from SGT insertion is deferring investments allocated for T&D expansion. Considering the vast trend of energy consumption and the number of consumers in Saudi Arabia, as discussed in Chapter 1, SGTs can help optimize assets and enable other efficient means for energy generation, transmission, and distribution such as distributed energy resources, RE sources, and PHEVs. Another outcome expected from enabling SGTs is reducing CO_2, SO_X, NO_X, and PM10 emissions. High oil dependency for energy generation in Saudi Arabia is a major cause for the high level of these emissions. SGTs are expected to reduce air emissions and generate financial benefits.

Lastly, and from the discussion presented in this chapter, this research is intended to address the challenges facing the electricity infrastructure in Saudi Arabia. It also proposes a framework for modernization. The framework presents an econometric analysis for the modernization. The analysis accounts for technical, economic, societal, and environmental perspectives. The analysis targets scholars, researchers, policy makers, and planners interested in econometric analysis of electric grids, Saudi electricity grid, and electricity infrastructure modernization. It also proposes a roadmap for the modernization of electricity markets and enabling SGTs. The analysis shall serve as a tool for planners, policy and decision makers in drafting strategies and visions for modernizing electricity infrastructures and electric grids. Although the case study presented in this research is on the Saudi electricity infrastructure, the framework and analysis are generic enough for use by policy makers of other infrastructures, albeit with appropriately changed inputs.

CHAPTER 7

FUTURE WORK

The scope of the future work will continue assessing the impact of SGTs penetration in the Saudi electricity infrastructure. From the analysis applied on the second dimension in Chapters 4 and 5, the results obtained by the fuzzy AHP model that prioritized SGTs, and the economic analysis will be assessed to estimate consumers and producers surplus resulting from SGTs insertions. Then, the GW will be estimated. After that, the GW will be computed, compared to, and integrated with the GW resulting from deregulating the Saudi electricity market (i.e., the first dimension). The utility function will be applied to define demand utility, from which the cost of producing electricity, quantity of electricity sold, and the selling price of electricity are defined. Then, total GW is estimated, which is, Net Economic Benefit, of electricity infrastructure modernization.

Another approach to estimate GW for the second dimension is to relate costs and benefits of each SGT to the impacted side of the GW equation, i.e. consumers surplus, consumers costs, producers surplus, and /or producers costs. The costs and benefits of each SGT are obtained from the results presented in Chapter 5. A third approach is to examine the impact of SGTs insertion on the price elasticity of electricity demand.

The following step is to assess probable risks associated with the application of each scenario. With regards to the first dimension, risk assessment will be carried out to define technical and economic risks might result from deregulating the Saudi electricity market. Then, the expected impact of each risk will be quantified in monetary values. Moreover, this step includes developing a risk management plan that identifies risk impacts and likelihood of each risk. Uncertainty associated with the first dimension will be considered. Uncertainty is represented in the arising of new regulations formed in the market. Normally, the new regulations are faced with unforeseen problems such as supply shortage, conflict among market players, monopoly, and price increase. Financial problems are also potential risks to the market during and after deregulation. Price increase, volume risks, and high price volatility are examples of potential financial risks.

Trading electricity is unlike trading any other commodities because electricity is instantaneously perishable and cannot be stored on grid-scale storages. These characteristics of the electricity markets, where the supply-demand equilibrium must be maintained at all the time, might lead to compromise electricity infrastructure security. This step will address such problems and quantify their losses.

The subsequent step will be applying risk assessment on the penetration of SGTs in the Saudi electricity infrastructure. Like in the previous step, probable risks and expected losses will be defined and quantified in monetary values. Risk assessment will examine the impact and likelihood of each probable risk. Uncertainties associated with SGTs penetration will be defined. Such risks include system complexity, cyber security impacts, and impacts on system stability and reliability. Risks also include financial and societal aspects that may be realized after the application of one or more of the SGTs in the Saudi grid.

Probabilistic economic analysis will be applied to assess the risk associated with the implantation of the previously mentioned dimensions. The parameters used for the economic analysis, such as economic life of a project, and the discount rate, are usually deterministic. However, a probabilistic method can be applied to capture the uncertainty of the parameters.

The following step will be to combine the previously mentioned risk management plans and develop a risk management framework for electricity grid modernization in Saudi Arabia. The framework addresses probable risks, impacts, likelihood, and risk management plans. The framework will define a plan for electricity infrastructure transition from the status quo to a modernized status considering probable risks and mitigation plans.

A further step will be combining the first and second dimensions into one framework. An optimization algorithm will be proposed in which GW computed from the application of each scenario is integrated. The algorithm will optimize the parameters of each dimension. Such parameters include the characteristics of the Saudi electricity market like demand, selling price, quantity, interest rate, time frame of deregulation process. The parameters will also include SGTs insertion characteristics. The overall integrated framework will be geared toward optimizing the parameters considering costs, benefits, and risks associated with each dimension. After the algorithm is built, the optimization problem will help identify the best scenario, presented in Chapter 1, for the modernization of the Saudi electricity infrastructure.

REFERENCES

[1] K. Moslehi and R. Kumar, "Smart Grid - a reliability perspective," in *Innovative Smart Grid Technologies (ISGT)*, 2010, pp. 1-8.

[2] "Keeping the lights on in a new world," Electricity Advisory Committee, 2009.

[3] M. Shahidehpour, H. Yamin, and Z. Li, *Market Operations in Electric Power Systems: Forecasting, Scheduling, and Risk Management*: Wiley, 2003.

[4] S. Viljainen, M. Makkonen, S. Annala, and D. Kuleshov, "Vision for European electricity markets in 2030," Lappeenranta University of Technology, 9522650749, 2011.

[5] G. Reed, P. Philip, A. Barchowsky, C. Lippert, and A. Sparacino, "Sample survey of Smart Grid approaches and technology gap analysis," in *IEEE Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, 2010, pp. 1-10.

[6] M. Wakefield, "Methodological approach for estimating the benefits and costs of Smart Grid demonstration projects," Electric Power Research Institute (EPRI), Palo Alto, CA, USA, 1020342, Jan. 2010.

[7] M. Wakefield, "Smart Grid leadership report: Global Smart Grid implementation assessment," Electric Power Research Institute (EPRI), 1021417, Oct. 2010.

[8] "IEC Smart Grid standardization roadmap," SMB Smart Grid Strategic Group (SG3), Ed. 1.0 - 2009-12, 2010.

[9] "110th Congress of United States, Energy Independence and Security Act Title XIII-Smart Grid," Library of Congress, Washington DC, Congressional Research Service, Congress of United States, ADA475228, 2007.

[10] "European SmartGrids technology platform," European Commission, -Directorate-General for Research Sustainable Energy Systems, EUR 22040, 2006.

[11] "Towards smart power networks-Lessons learned from European research FP5 projects," European Commission, Directorate-General for Research Sustainable Energy Systems, EUR 21970, 2005.

[12] "A system view of the modern grid-The NETL modern grid initiative," The National Energy Technology Laboratory for the U.S. Department of Energy Office of Electricity Delivery and Energy Reliability, 2007.

[13] Y. Alyousef and P. Stevens, "The cost of domestic energy prices to Saudi Arabia," *Energy Policy,* vol. 39, no.11, pp. 6900-6905, 2011.

[14] EIA. (2014, Oct. 19). *Country overview: Saudi Arabia.* Available: http://goo.gl/hEH4X5

[15] G. Lahn and P. Stevens, "Burning oil to keep cool: The hidden energy crisis in Saudi Arabia," *Chatham House, London,* 2011.

[16] SEC, "SEC annual report (2015)," Saudi Electricity Company, Annual Report, 2016.

[17] "Annual statistical booklet for electricity and seawater desalination industries," Electricity & Cogeneration Regulatory Authority, 2016.

[18] F. R. Pazheri, N. H. Malik, A. A. Al-Arainy, E. A. Al-Ammar, A. Imthias, and O. K. Safoora, "Smart Grid can make Saudi Arabia megawatt exporter," in *Power and Energy Engineering Conference (APPEEC)*, 2011, pp. 1-4.

[19] M. Groissböck and M. J. Pickl, "An analysis of the power market in Saudi Arabia: Retrospective cost and environmental optimization," *Applied Energy,* vol. 165, pp. 548-558, 2016.

[20] (2016, Oct, 23). *World development indicators-Saudi Arabia population.* Available: https://goo.gl/myJRkW

[21] U. Al-mulali, H. G. Fereidouni, J. Y. M. Lee, and C. N. B. C. Sab, "Exploring the relationship between urbanization, energy consumption, and CO2 emission in MENA countries," *Renewable and Sustainable Energy Reviews,* vol. 23, pp. 107-112, 2013.

[22] A. S. Alshehry and M. Belloumi, "Energy consumption, carbon dioxide emissions and economic growth: The case of Saudi Arabia," *Renewable and Sustainable Energy Reviews,* vol. 41, pp. 237-247, 2015.

[23] K. Alkhathlan and M. Javid, "Energy consumption, carbon emissions and economic growth in Saudi Arabia: An aggregate and disaggregate analysis," *Energy Policy,* vol. 62, pp. 1525-1532, 2013.

[24] A. R. F. Al-Faris, "The demand for electricity in the GCC countries," *Energy Policy,* vol. 30, no.2, pp. 117-124, 2002.

[25] G. Lahn, P. Stevens, and F. Preston, "Saving oil and gas in the Gulf," Chatham House, Aug. 2013.

[26] R. R. Obaid, "Reducing peak electricity demand through 300MW wind farm north of Jeddah, Saudi Arabia," *nternational Journal of Engineering & Technology IJENT-IJENS,* vol. 11, no.2, pp. 134-140, April 2011.

[27] S. D. Maqbool, T. P. I. Ahamed, E. Al-Ammar, and N. H. Malik, "Demand response in Saudi Arabia," in *International Conference on Electric Power and Energy Conversion Systems*, 2011, pp. 1-6.

[28] A. Alshehri, A. Hussain, and Y. Mobarak, "Energy-conversion measures in the industries of Saudi Arabia and development of methodology for certification of energy personnel in the Kingdom," *Energy Policy,* vol. 64, pp. 203-208, Jan 2014.

[29] W. Matar, F. Murphy, A. Pierru, and B. Rioux, "Lowering Saudi Arabia's fuel consumption and energy system costs without increasing end consumer prices," *Energy Economics,* vol. 49, pp. 558-569, 2015.

[30] A. H. Al-Mubarak, S. M. Bamsak, B. Thorvaldsson, M. Halonen, and R. Grunbaum, "Preventing voltage collapse by large SVCs at power system faults," in *Power Systems Conference and Exposition*, 2009, pp. 1-9.

[31] T. Alaqeel, S. A. Almohaimeed, and S. Suryanarayanan, "A Review on the impact and mitigating solutions of air conditioning motor stalling on voltage recovery in the Saudi electric grid," in *North American Power Symposium (NAPS)*, Morgantown, WV, 2017 (Under review).

[32] F. Rahman, S. Rehman, and M. A. Abdul-Majeed, "Overview of energy storage systems for storing electricity from renewable energy sources in Saudi Arabia," *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 274-283, 2012.

[33] PME. (Apr, 1, 2016). *Climatic characteristic of summer* [Online]. Available: http://www.pme.gov.sa/en/cc.asp

[34] D. Kumetat, "Climate change in the Persian Gulf–regional security, sustainability strategies and research needs," in *Climate Change, Social Stress and Violent Conflict*, Hamburg, Germany, 2009, p. 20.

[35] S. Parkpoom and G. P. Harrison, "Analyzing the impact of climate change on future electricity demand in Thailand," *IEEE Transactions on Power Systems,* vol. 23, no.3, pp. 1441-1448, Aug 2008.

[36] S. Nachet and M.-C. Aoun, "The Saudi electricity sector: Pressing issues and challenges," ifri Centre Énergie, , 2015.

[37] "High EER at 46ºC Kingdom of Saudi Arabia air conditioner project," Proctor Engineering Group.

[38] "Smart metering and smart grids strategy for the Kingdom of Saudi Arabia," CESI and A.T. Kearney, B3006974, Jun. 2013.

[39] B. Fattouh and L. El-Katiri, "A brief political economy of energy subsidies in the Middle East and North Africa," Citeseer, OIES PAPER: MEP 11., 2015.

[40] A. Farnoosh, F. Lantz, and J. Percebois, "Electricity generation analyses in an oil-exporting country: Transition to non-fossil fuel based power units in Saudi Arabia," *Energy,* vol. 69, pp. 299-308, 2014.

[41] R. R. Obaid and A. H. Mufti, "Present state, challenges, and future of power generation in Saudi Arabia," in *IEEE Energy 2030 Conference*, 2008, pp. 1-6.

[42] "Updated generation planning for the Saudi electricity sector," Center of Engineering Research, KFUPM, Dec 2005.

[43] M. H. Bollen and I. Gu, *Signal Processing of Power Quality Disturbances*: Wiley, 2006.

[44] D. S. Kirschen and G. Strbac, *Fundamentals of Power System Economics*: Wiley, 2004.

[45] H. Al Garni, A. Kassem, A. Awasthi, D. Komljenovic, and K. Al-Haddad, "A multicriteria decision making approach for evaluating renewable power generation sources in Saudi Arabia," *Sustainable Energy Technologies and Assessments,* vol. 16, pp. 137-150, 2016.

[46] D. R. Bohi and R. f. t. Future, *Analyzing Demand Behavior: A Study of Energy Elasticities*: Published for Resources for the Future by the Johns Hopkins University Press, 1981.

[47] N. Y. Mansouri, R. J. Crookes, and T. Korakianitis, "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,* vol. 63, pp. 681-695, 2013.

[48] T. Alaqeel and S. Suryanarayanan, "Examining some prospect scenarios for the electricity grid infrastructure modernization in Saudi Arabia," in *North American Power Symposium (NAPS)*, Pullman, WA, 2014, pp. 1-6.

[49] T. F. Mandakovic and W. E. Souder, "Experiments with microcomputers to facilitate the use of project selection models," *Journal of Engineering and Technology Management,* vol. 7, no.1, pp. 1-16, 1990.

[50] M. Bohanec, V. Rajkovič, B. Semolić, and A. Pogačnik, "Knowledge-based portfolio analysis for project evaluation," *Information & Management,* vol. 28, no.5, pp. 293-302, 1995.

[51] A. D. Henriksen and A. J. Traynor, "A practical R&D project-selection scoring tool," *IEEE Transactions on Engineering Management,* vol. 46, no.2, pp. 158-170, 1999.

[52] J. Zietsman, L. R. Rilett, and S.-J. Kim, "Transportation corridor decision-making with multi-attribute utility theory," *International Journal of Management and decision making,* vol. 7, no.2-3, pp. 254-266, 2006.

[53] T. Saaty, *The Analytic Hierarchy Process*. New York: McGrew Hill, 1980.

[54] T. Saaty, *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*: RWS Publications, 2000.

[55] B. Lazzerini and F. Pistolesi, "A linear programming-driven MCDM approach for multi-objective economic dispatch in smart grids," in *SAI Intelligent Systems Conference (IntelliSys), 2015*, 2015, pp. 475-484.

[56] E. K. Chong and S. H. Zak, *An Introduction to Optimization* vol. 76: John Wiley & Sons, 2013.

[57] J. S. Wholey, H. P. Hatry, and K. E. Newcomer, *Handbook of Practical Program Evaluation*: Wiley, 2004.

[58] C. Negoita, *Expert Systems and Fuzzy Systems*. Menlo Park, CA: Benjamin-Cummings Pub. Co., 1985.

[59] H.-J. Zimmermann, "Fuzzy control," in *Fuzzy Set Theory—and Its Applications*, 3rd ed: Springer, 1996, pp. 203-240.

[60] "Historical perspective of electricity in Saudi Arabia," The Electricity and Co-generation Regulatory Authority, Riyadh, Saudi Arabia, , 2006.

[61] "Saudi Arabia report," U.S. Energy Information Administration, , 2013.

[62] W. Matar, "Beyond the end-consumer: How would improvements in residential energy efficiency affect the power sector in Saudi Arabia?," *Energy Efficiency,* vol. 9, no.3, pp. 771-790, 2016.

[63] A. Ahmad and M. Ramana, "Too costly to matter: Economics of nuclear power for Saudi Arabia," *Energy,* vol. 69, pp. 682-694, 2014.

[64] M. Al-Shaikh, N. Al-Shahrani, S. Mirza, F. Villella, F. Depierreux, and K. Karoui, "A modular model of the GCCIA HVDC back to back for operational and planning studies," in *GCC CIGRE*, Oman, 2012.

[65] H. A. Al-Saggaf, "Renewable energy and grid integration," in *2015 Saudi Arabia Smart Grid (SASG)*, 2015, pp. 1-8.

[66] F. R. Pazheri, H. Khan, and I. Ahamed, "Smart Grid implementation across the globe: A survey," in *IEEE PES Innovative Smart Grid Technologies*, India, 2011, pp. 1-5.

[67] S. H. Ghanam, B. S. Shahrani, A. S. Essa, M. M. Hamrani, F. A. Dubaikel, and A. T. Awami, "Saudi ARAMCO's efforts in Smart Grid," in *2011 IEEE PES Conference on Innovative Smart Grid Technologies - Middle East*, 2011, pp. 1-9.

[68] D. Düştegör, N. Sultana, N. Felemban, and D. Al-Qahtani, "Public acceptance of renewable energy and Smart-Grid in Saudi Arabia," in *2015 IEEE 8th GCC Conference & Exhibition*, 2015, pp. 1-6.

[69] A. Al-Yaquob, "Saudi Arabia solar industry: Country focus report," Saudi Arabia Solar Industry Sssociation, 2017.

[70] T. A. Al-Muhawesh and I. S. Qamber, "The prerequisite for competition in the restructured wholesale Saudi electricity market," *Energy Policy,* vol. 36, pp. 477-484, 2008.

[71] Y. Al-Saleh, P. Upham, and K. Malik, "Renewable energy scenarios for the Kingdom of Saudi Arabia," *Tyndall Centre for Climate Change Research Working Paper,* vol. 125, 2008.

[72] A. Al-Shehri, "Regulatory aspects for the promotion of renewable energies and energy conservation in Saudi Arabia," in *Fourth Saudi Solar Energy Forum, Riyadh, Saudi Arabia*, 2012.

[73] S. M. Aldekhayl, "Saudi electricity company," presented at the Power Generation, Orlando, FL, 2012.

[74] "National Transformation Program 2020-Kingdom of Saudi Arabian Vision 2030," Council of Economic and Development Affairs, 2016.

[75] (2016, Oct 28,). *Issuance of a statement from the royal court.* Available: https://goo.gl/i3aNuW

[76] M. O. Buygi, H. M. Shanechi, G. Balzer, M. Shahidehpour, and N. Pariz, "Network planning in unbundled power systems," *IEEE Transactions on Power Systems,* vol. 21, no.3, pp. 1379-1387, 2006.

[77] S. Suryanarayanan, P. F. Ribeiro, and M. G. Simoes, "Grid modernization efforts in the USA and Brazil - Some common lessons based on the Smart Grid Initiative," in *IEEE Power and Energy Society General Meeting*, 2010, pp. 1-5.

[78] A. P. S. Meliopoulos, G. J. Cokkinides, H. Renke, E. Polymeneas, and P. Myrda, "Grid modernization: Seamless integration of protection, optimization and control," in *47th International Conference on System Sciences (HICSS)*, Hawaii, 2014, pp. 2463-2474.

[79] S. W. Pullins, "The NETL modern grid initiative: What will the US modern grid cost?," in *IEEE Power Engineering Society General Meeting*, 2007, pp. 1-6.

[80] "2030: A national vision for electricity's second 100 years," United State Department of Energy, Office of Electric Transmission and Distribution, 2003.

[81] "Advanced metering infrastructure, NETL modern grid," Prepared for US Department of Energy Office of Electricity and Energy Reliability, 2008.

[82] Y. Du, M. Turner, Y. Liao, M. Sunkara, J. DeRouen, A. Greenwell*, et al.*, "Kentucky Smart Grid roadmap initiative," in *IEEE PES Innovative Smart Grid Technologies (ISGT)*, 2012, pp. 1-6.

[83] A. L'Abbate, G. Fulli, G. Migliavacca, and A. Purvins, "Application of innovative transmission technologies for the development of the future European power system," in *The Power Systems Computation Conference*, Stockholm, Sweden, 2011.

[84] D. M. Newbery and M. G. Pollitt, "The restructuring and privatisation of Britain's Cegb--Was it worth it?," *The Journal of Industrial Economics,* vol. 45, no.3, pp. 269-303, 1997.

[85] P. Domah and M. G. Pollitt, "The restructuring and privatisation of the electricity distribution and supply businesses in England and Wales: A social cost-benefit analysis," *Fiscal Studies,* vol. 22, no.1, pp. 107-146, 2005.

[86] E. S. Dehdashti, "Developing countries restructuring with benefits from competition (or not) [The business scene]," *IEEE Power and Energy Magazine,* vol. 2, no.5, pp. 16-23, 2004.

[87] M. G. Pollitt, "The impact of liberalization on the performance of the electricity supply industry: An international survey," *Journal of Energy Literature,* vol. 3/2, pp. 3-31, 1997.

[88] W. L. Megginson, R. C. Nash, and M. Randenborgh, "The financial and operating performance of newly privatized firms: An international empirical analysis," *The Journal of Finance,* vol. 49, no.2, pp. 403-452, Jun 1994.

[89] D. M. Newbery and M. G. Pollitt, "The restructuring and privatization of the U.K. electricity supply—Was it worth it?," *World Bank,* vol. 1, 09 1997.

[90] C. W. Price and T. Weyman-Jones, "Malmquist indices of productivity change in the UK gas industry before and after privatization," *Applied Economics,* vol. 28, no.1, pp. 29-39, Jan 1996.

[91] D. Parker and S. Martin, "The impact of Uk privatisation on labour and total factor productivity," *Scottish Journal of Political Economy,* vol. 42, no.2, pp. 201-220, May 1995.

[92] M. Bishop and D. Thompson, "Regulatory reform and productivity growth in the UK's public utilities," *Applied Economics,* vol. 24, no.11, pp. 1181-1190, 1992.

[93] N. K. Trehan and R. Saran, "Electric utility deregulation: Failure or success," in *IEEE Nuclear Science Symposium Conference Record*, 2004, pp. 4614-4617.

[94] A. Galal, *Welfare Consequences of Selling Public Enterprises: An Empirical Analysis*: World Bank, 1994.

[95] R. J. Green, "England and Wales: A competitive electricity market?," 1st ed: University of California Energy Institute POWER, 1998.

[96] S. Thomas, "The privatization of the electricity supply industry," in *The British Electricity Experiment: Privatization, the Record, the Issues, the Lessons*, J. Surrey, Ed., ed London: Earthscan Publications Ltd., 1996.

[97] G. K. Yarrow, *British Electricity Prices Since Privatization*: Regulatory Policy Institute for the Regulatory Policy Research Centre, 1992.

[98] M. Bishop, J. Kay, and J. A. Kay, *Does Privatization Work?: Lessons from the UK*: Centre for Business Strategy, London Business School, 1988.

[99] L. P. Jones, P. Tandon, and I. Vogelsang, *Selling Public Enterprises: A Cost-benefit Methodology*: MIT Press, 1990.

[100] "Projected costs of generating electricity," International Energy Agency and Nuclear Energy Agency, France, 662010031P, 2010.

[101] D. Bryfonski, *Deregulation*. Detroit: Greenhaven Press, 2011.

[102] C. Abbey, D. Cornforth, N. Hatziargyriou, K. Hirose, A. Kwasinski, E. Kyriakides*, et al.*, "Powering through the storm: Microgrids operation for more efficient disaster recovery," *IEEE Power and Energy Magazine,* vol. 12, no.3, pp. 67-76, 2014.

[103] M. Panwar, G. P. Duggan, R. T. Griffin, S. Suryanarayanan, D. Zimmerle, M. Pool*, et al.*, "Dispatch in microgrids: Lessons from the Fort Collins renewable and distributed systems integration demonstration project," *The Electricity Journal,* vol. 25, no.8, pp. 71-83, 2012.

[104] M. G. Simoes, R. Roche, E. Kyriakides, S. Suryanarayanan, B. Blunier, K. D. McBee*, et al.*, "A comparison of Smart Grid technologies and progresses in Europe and the U.S," *IEEE Transactions on Industry Applications,* vol. 48, no.4, pp. 1154-1162, Jul-Aug. 2012.

[105] T. Garrity, "Getting smart," *IEEE Power and Energy Magazine,* vol. 6, no.2, pp. 38-45, Mar-Apr 2008.

[106] L. De Castro and J. Dutra, "Paying for the Smart Grid," *Energy Economics,* vol. 40, pp. S74-S84, 2013.

[107] H. Farhangi, "A road map to integration: Perspectives on Smart Grid development," *IEEE Power and Energy Magazine,* vol. 12, no.3, pp. 52-66, 2014.

[108] P. Zhang, F. Li, and N. Bhatt, "Next-generation monitoring, analysis, and control for the future Smart control center," *IEEE Transactions on Smart Grid,* vol. 1, no.2, pp. 186-192, 2010.

[109] F. Li, W. Qiao, H. Sun, H. Wan, J. Wang, Y. Xia*, et al.*, "Smart transmission grid: Vision and framework," *IEEE transactions on Smart Grid,* vol. 1, no.2, pp. 168-177, Sep. 2010.

[110] S. M. Amin and B. F. Wollenberg, "Toward a Smart Grid: Power delivery for the 21st century," *IEEE Power and Energy Magazine,* vol. 3, no.5, pp. 34-41, 2005.

[111] Y. Zheng, Z. Hu, J. Wang, and Q. Wen, "IRSP (Integrated Resource Strategic Planning) with interconnected smart grids in integrating renewable energy and implementing DSM (Demand Side Management) in China," *Energy,* vol. 76, pp. 863-874, 2014.

[112] J. Crispim, J. Braz, R. Castro, and J. Esteves, "Smart Grids in the EU with smart regulation: Experiences from the UK, Italy and Portugal," *Utilities Policy,* vol. 31, pp. 85-93, 2014.

[113] Z. Ma, B. N. Jørgensen, and Z. Prljaca, "Global Smart Grid transferability: Insights from Europe, the US, and China," *Journal of Energy and Power Engineering,* no.9, pp. 1078-1092, 2015.

[114] D. Han and Z. Yan, "Evaluating the impact of Smart Grid technologies on generation expansion planning under uncertainties," *International Transactions on Electrical Energy Systems,* 2015.

[115] G. Basso, N. Gaud, F. Gechter, V. Hilaire, and F. Lauri, "A framework for qualifying and evaluating smart grids approaches: Focus on multi-agent technologies," *Smart Grid and Renewable Energy,* vol. 4, no.4, pp. 333-347, 2013.

[116] S. Suryanarayanan and J. Mitra, "Enabling technologies for the customer-driven microgrid," in *IEEE Power & Energy Society General Meeting*, 2009, pp. 1-3.

[117] J. Momoh, "Smart Grid design for efficient and flexible power networks operation and control," in *IEEE Power Systems Conference and Exposition (PSCE)*, 2009, pp. 1-8.

[118] J. Momoh, *Smart Grid: Fundamentals of Design and Analysis* vol. 63: John Wiley & Sons, 2012.

[119] S. J. Bossart and J. E. Bean, "Metrics and benefits analysis and challenges for Smart Grid field projects," in *Energytech*, 2011, pp. 1-5.

[120] "IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems," in *IEEE Std* vol. 1547ed: IEEE Standards Association, 2011.

[121] J. Jackson, "The utility Smart Grid business case: Problems, pitfalls and ten realworld recommendations," in *The 2nd Annual Evaluating the Business Case for Smart Grid Investments*, Orlando, US, 2011.

[122] F. Bouffard, "The challenge with building a business case for smart grids," in *IEEE Power and Energy Society General Meeting*, 2010, pp. 1-3.

[123] J. R. Roncero, "Integration is key to Smart Grid management," in *SmartGrids for Distribution (CIRED Seminar)*, 2008, pp. 1-4.

[124] "Building a Smart Grid business case," The National Energy Technology Laboratory, The Modern Grid Strategy, Aug. 2009.

[125] "Smart Grid maturity model," Carnegie Mellon University; Software Engineering Institute, CMU/SEI-2011-TR-025, Sep. 2011.

[126] S. Pullins and J. Westerman, "San Diego Smart Grid study," SAIC Smart Grid Team, Final Report, Oct. 2006.

[127] C. d. P. Rodríguez, A. C. Santos, D. Borge-Diez, and O. Monzón, "Smart Grid investment and technology roadmap for power system planning. Case study for a distribution system operator: EAECSA," in *IEEE International Energy Conference (ENERGYCON)*, 2014, pp. 1162-1169.

[128] S. Farooq and W. u. Zahoor, "Smart Grid-energizing towards a greener future," in *Power Generation System and Renewable Energy Technologies (PGSRET)*, 2015, pp. 1-5.

[129] K. May, L. Sigrist, P. Vingerhoets, A. Morch, P. Verboven, and L. Rouco, "Improving scalability and replicability of Smart Grid projects," in *23rd International Conference on Electricity Distribution (CIRED)*, Lyon, 2015.

[130] K. May, P. Vingerhoets, and L. Sigrist, "Barriers regarding scalability and replicability of smart grid projects," in *12th International Conference on the European Energy Market (EEM)*, 2015, pp. 1-5.

[131] "Smart Grid value analysis model based on sustainable development," in *China International Conference on Electricity Distribution (CICED)*, Shenzhen, 2014, pp. 830-832.

[132] R. G. Pratt, P. Balducci, C. Gerkensmeyer, S. Katipamula, M. C. Kintner-Meyer, T. F. Sanquist*, et al.*, *The Smart Grid: an Estimation of the Energy and CO2 Benefits*: Pacific Northwest National Laboratory, 2010.

[133] M. Arnold, H. Rui, and W. H. Wellssow, "An approach to Smart Grid metrics," in *2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies*, 2011, pp. 1-7.

[134] A. Faruqui, R. Hledik, and C. Davis, "Sizing up the Smart Grid," in *ISO New England Smart Grid Forum*, 2009.

[135] L. R. Varasquim and V. R. Oliveira, "The use of roadmaps for Smart Grid deployment - The practice," in *IEEE/PES Transmission and Distribution Conference and Exposition: Latin America*, 2010, pp. 380-387.

[136] M. McGranaghan, D. Von Dollen, P. Myrda, and E. Gunther, "Utility experience with developing a Smart Grid roadmap," in *IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 2008, pp. 1-5.

[137] S. Pullins, "West Virginia Smart Grid implementation plan," National Energy Technology Laboratory, US Department of Energy, DOE/NETL-2009/1386, 20 Aug. 2009.

[138] K. N. Hasan, T. K. Saha, D. Chattopadhyay, and M. Eghbal, "Benefit-based expansion cost allocation for large scale remote renewable power integration into the Australian grid," *Applied Energy,* vol. 113, pp. 836-847, 2014.

[139] I. Konstantelos, D. Pudjianto, G. Strbac, J. De Decker, P. Joseph, A. Flament*, et al.*, "Integrated North Sea grids: The costs, the benefits and their distribution between countries," *Energy Policy,* vol. 101, pp. 28-41, 2017.

[140] A. E. Boardman, D. H. Greenberg, A. R. Vining, and D. L. Weimer, *Cost-benefit Analysis: Concepts and Practice*: Prentice Hall, 2001.

[141] "Characterizing and quantifying the societal benefits attributable to smart metering investments," EPRI (Electric Power Research Institute), 1017006, Jul. 2008.

[142] W. S. Baer, B. Fulton, and S. Mahnovski, "Estimating the benefits of the GridWise initiative," DTIC Document, TR-160-PNNL, 2004.

[143] H. r. Zhao, T. y. Li, L. w. Fu, and D. Ou, "The research on comprehensive benefits evaluation of Smart Grid self-healing," in *International Conference on Electricity Distribution (CICED)*, China, 2012, pp. 1-12.

[144] L. Kannberg, M. Kintner-Meyer, D. Chassin, R. Pratt, and L. DeSteese, "The benefits of a transformed energy system," Pacific Northwest National Laboratory PNNL-14396, 2003.

[145] H. F. Campbell and R. P. Brown, *Benefit-Cost Analysis: Financial and Economic Appraisal Using Spreadsheets*: Cambridge University Press, 2003.

[146] Y. Qian, L. Loi Lei, and L. Chun Sing, "Methodology for cost benefit analysis of smart grid used in decision support," in *International Conference on Machine Learning and Cybernetics (ICMLC)*, 2013, pp. 104-107.

[147] Y. Liu, H. Xiong, H. Luo, and N. Song, "Investment-benefit analysis and evaluation model of the smart grid," in *International Conference on Electricity Distribution (CICED)*, China, 2010, pp. 1-5.

[148] Y. Song and J. Li, "Analysis of the life cycle cost and intelligent investment benefit of smart substation," in *IEEE PES Innovative Smart Grid Technologies*, 2012, pp. 1-5.

[149] N. Katic, V. Marijanovic, and I. Stefani, "Smart Grid solutions in distribution networks cost/benefit analysis," in *International Conference on Electricity Distribution (CICED)*, China, 2010, pp. 1-6.

[150] H. Zhang, J. Li, W. Yang, and Y. Zhao, "The study on evaluating indicator system of the pilot project of Smart Grid," in *International Conference on Electricity Distribution (CICED)*, China, 2010, pp. 1-7.

[151] M. Sullivan and J. Schellenberg. (2011) Smart Grid economics: the cost-benefit analysis. *Renew Grid.*

[152] C. Chardonnet and B. d. Boissezon, "GDF SUEZ - GreenLys WP2: Estimating the benefits and costs of a smart electrical system in French urban areas in 2020-2030," in *IEEE Grenoble Conference*, 2013, pp. 1-6.

[153] V. Giordano, S. Vitiello, and J. Vasiljevska, "Definition of an assessment framework for projects of common interest in the field of smart grids," JRC79445, 2014.

[154] D. R. V. Leite, H. Lamin, J. M. C. d. Albuquerque, and I. M. T. Camargo, "Regulatory impact analysis of smart meters implementation in Brazil," in *IEEE PES Innovative Smart Grid Technologies (ISGT)*, 2012, pp. 1-8.

[155] V. Giordano, I. Onyeji, G. Fulli, M. S. Jimenez, and C. Filiou, "Guidelines for conducting a cost-benefit analysis of Smart Grid projects," Publications Office of the European Union, EUR 25246 EN, 2011.

[156] M. Wakefield, "Guidebook for cost/benefit analysis of Smart Grid demonstration projects," Electrical Power Reseach Institute (EPRI), Dec 2012.

[157] W. Li and P. Choudhury, "Probabilistic planning of transmission systems: Why, how and an actual example," in *IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century*, 2008, pp. 1-8.

[158] C. Meili, Z. Yuan, N. Ruixin, and C. Yaoheng, "Study on the model of advanced asset management in Smart Grid," in *International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, 2011, pp. 781-785.

[159] D. Parker and K. Hartley, "Organizational status and performance: The effects on employment," *Applied Economics,* vol. 23, no.2, pp. 403-416, 1991.

[160] D. Besanko and R. Braeutigam, *Microeconomics*: John Wiley & Sons, 2010.

[161] T. J. A. Gallagher, Joseph D, *Financial Management: Principles and Practice*: Prentice Hall, 2010.

[162] R. Brealey and S. Myers, *Principles of Corporate Finance*, 6th ed. Boston: Irwin McGraw-Hill, 2000.

[163] J. Jin, L. Rothrock, P. L. McDermott, and M. Barnes, "Using the analytic hierarchy process to examine judgment consistency in a complex multiattribute task," *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans,* vol. 40, no.5, pp. 1105-1115, Sep 2010.

[164] Z. Ayağ and R. G. Özdemir, "A fuzzy AHP approach to evaluating machine tool alternatives," *Journal of intelligent manufacturing,* vol. 17, no.2, pp. 179-190, 2006.

[165] P. Dehghanian, M. Fotuhi-Firuzabad, S. Bagheri-Shouraki, and A. A. R. Kazemi, "Critical component identification in reliability centered asset management of power distribution systems via fuzzy AHP," *IEEE Systems Journal,* vol. 6, no.4, pp. 593-602, Dec 2012.

[166] C. K. Mechefske and Z. Wang, "Using fuzzy linguistics to select optimum maintenance and condition monitoring strategies," *Mechanical Systems and Signal Processing,* vol. 17, no.2, pp. 305-316, Mar 2003.

[167] W. Kangmao, C. K. Wang, and H. Chun, "Analytic hierarchy process with fuzzy scoring in evaluating multidisciplinary R&D projects in China," *IEEE Transactions on Engineering Management,* vol. 52, pp. 119-129, 2005.

[168] P. J. M. van Laarhoven and W. Pedrycz, "A fuzzy extension of Saaty's priority theory," *Fuzzy Sets and Systems,* vol. 11, no.1-3, pp. 229-241, 1983.

[169] K. K. F. Yuen, "Fuzzy cognitive network process: Comparisons with fuzzy analytic hierarchy process in new product development strategy," *IEEE Transactions on Fuzzy Systems,* vol. 22, no.3, pp. 597-610, Jun 2014.

[170] C. N. Elias and N. D. Hatziargyriou, "An annual midterm energy forecasting model using fuzzy logic," *IEEE Transactions on Power Systems,* vol. 24, pp. 469-478, Feb 2009.

[171] D. Y. Chang, "Applications of the extent analysis method on fuzzy AHP," *European Journal of Operational Research,* vol. 95, no.3, pp. 649-655, Dec 20 1996.

[172] S. A. Mian and C. X. Dai, "Decision-making over the project life cycle: An analytical hierarchy approach," 1999.

[173] B. L. Golden, E. A. Wasil, and D. E. Levy, "Applications of the Analytic Hierarchy Process: A Categorized, Annotated Bibliography," in *The analytic hierarchy process*, 1st ed: Springer, 1989, pp. 37-58.

[174] M. M. Gupta and A. Kaufmann, *Introduction to Fuzzy Arithmetic: Theory and Applications*: New York, NY: Van Nostrand Reinhold Company, 1985.

[175] H.-J. Zimmermann, *Fuzzy Sets, Decision Making, and Expert Systems* vol. 10: Springer Science & Business Media, 2012.

[176] A. J. Conejo, M. Carrión, and J. M. Morales, *Decision Making Under Uncertainty in Electricity Markets* vol. 1: Springer, 2010.

[177] T. Alaqeel and S. Suryanarayanan, "Ex ante cost-benefit analysis for optimal deregulation of electricity markets," in *IEEE Power & Energy Society General Meeting*, Boston, MA, 2016.

[178] T. Alaqeel and S. Suryanarayanan, "A decision analysis framework using analytic hierarchy process for the modernization of the Saudi electricity infrastructure," presented at the Energy Policy Research Conference, Santa Fe, NM, 2016.

[179] T. Alaqeel and S. Suryanarayanan, "A fuzzy analytic hierarchy process algorithm to prioritize Smart Grid technologies for the Saudi electricity infrastructure," *Sustainable Energy, Grids and Networks,* 2017 (Under Review).

[180] T. Alaqeel and S. Suryanarayanan, "A comprehensive cost-benefit economic analysis of the penetration of Smart Grid technologies in the Saudi Arabian electricity infrastructure," *IEEE Transactions on Engineering Management,* 2017 (Under Review).

[181] SEC, "SEC annual report (2013)," Saudi Electricity Company, Annual Report, 2014.

[182] ECRA, "Activities and achievements of the authority in 2014," Electricity & Cogeneration Regulatory Authority, , 2015.

[183] A. F. Ott and K. Hartley, *Privatization and Economic Efficiency: A Comparative Analysis of Developed and Developing Countries*: E. Elgar Pub., 1991.