Operation Optimisation towards Generation Efficiency Improvement in Saudi Arabia Using LSS, Simulation and Mathematical Programming

By

Mohammad Althaqafi

Student ID: 0839747

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Abstract

The efficiency of fossil power generation has improved in recent decades with the different types of fuel and advancing technologies playing a crucial role in this trend. The Kingdom of Saudi Arabia (KSA) is considered among the lowest countries in the world in terms of generation efficiency. As a consequence, recent studies have proposed upgrading the generation stock with highly efficient units, and increasing the share of natural gas over oil to improve the average efficiency. However, despite efforts being made in that direction in the past few years, they have not had a significant impact and there have been few studies in the literature aimed at tackling what the real issues are in the kingdom.

This research explores the causes leading to the current level of energy efficiency in KSA using Lean Six Sigma (LSS) and a simulation model, subsequent to which a new framework is developed aimed at delivering sustained continuous improvement. Firstly, LSS is applied to identify the primary area of waste and secondly, the actual efficiency is measured using real data collected from KSA. Subsequently, the outcomes are analysed through utilising a simulation model that has been designed and tested to ensure accurate results are obtained. Following this, an improvement plan is proposed using mathematical models and mathematical programming, which was implemented using a simulation model. Finally, controlling the obtained improvement is included for sustaining its continuity.

The main contribution of this thesis lies in the integration of LSS and a simulation model to identify the most influential factors in relation to the generation efficiency level in KSA in terms of their impact on fuel and emissions. Moreover, this research involves developing a new merit order using a mathematical model and mathematical programming for optimisation. The novelty can be seen in combining the quality and quantity of production to generate a single operation measure.

The results show that the power plants' operation is a primary cause of the current level of efficiency, while the generation stock has the potential to deliver higher efficiency levels. Around 3.5 and 6% improvement in efficiency have been achieved over the two research stages. This figure has resulted in a fuel saving worth \$1.8 billion, significant reduction in subsidies and 8.5 Mtonnes reduction in the total CO_2 produced. Finally, this thesis provides a framework based on incentives for power providers that can ensure continuous improvement.

Dedication

I dedicate this thesis to the soul of my father, Taher Abed, and to my wonderful mother, Afaf Jamal, to my wife, Lama and to my dear children, Sara, Sultan and Sahl.

Acknowledgements

I would like to acknowledge my limitless gratitude to Allah Almighty for granting me countless blessings. Without His blessings, I would not have been able to complete this thesis. Infinite praises are due to Allah, and may endless peace and blessings be upon His beloved Messenger Mohammed.

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To my life journey partner and loving wife, Lama. She has been a devoted and patient partner throughout my involvement with the research project, and this has been greatly appreciated. Indeed, her devotion made this journey a memorable story. I would like to express my utmost love for her.

To my brothers, sisters and lovely children, Sara, Sultan and Sahl for their love and hope that infuses in my soul every day when writing this thesis.

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Author's Declaration

I hereby declare and confirm that this thesis is my own work and efforts. Also, it has not been submitted before for any award. Where other sources of information have been used, they have been acknowledged.

Mohammad Althaqafi
March 2017

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List of Abbreviations

AUX: Auxiliary

BOE: Barrel of Oil Equivalent

BTU: British Thermal Unit

CC: Combine Cycle

CCGT: Combined Cycle Gas Turbines

CO_2: Carbon Dioxide

DT: Diesel Turbine

ECRA: Electricity & Cogeneration Regulatory Authority

EIA: US Energy Information Administration

EP: Efficient Production

FF: Fossil Fuel

g/kwh: Grams per Kilowatt-hour

GCV: Gross Calorific Value

GT: Gas Turbine

GW: Gigawatt

H_2O: Water

HFO: Heavy Fuel Oil

HH: Halalah

HHV: Higher Heating Value

HR: Heat Rate

IEA: International Energy Agency

KACARE: King Abdullah City for Atomic and Renewable Energy

kJ: Kilojoule

kV: Kilovolt

kW: Kilowatt

kWh: Kilowatt-hour

LCOE: Levelized Cost of Energy

LFO: Light Fuel Oil

LHV: Lower Heating Value

mbpd : Million Barrels per Day

MP: Mathematical Model

NCV: Net Calorific Value

NEEP: The National Energy Efficiency Programme

NEP: Non Efficient Production

NG: Natural Gas

OCED: The Organisation for Economic Co-operation and Development

PP: Power Plant

SA: Saudi Arabia

SAR: Saudi Arabian Riyal

SEC: Saudi Electricity Company

SEEC: The Saudi Energy Efficiency Centre

ST: Steam Turbine

Chapter 1 Introduction

1.1 Research Introduction

Electricity is a fundamental part of human life and essential for any country's economy. The power sector has been evolving over the last decades in terms of structure, technology and resources. It has been affected by industrial revolutions, climate change and the intervention of renewables in electricity production. The industry consists of several stages, including fuel supply, generation, transmission and distribution. Variability in demand is considered as being the most challenging issue in this business, which requires quick response in supply along the whole chain. Fuel price and emissions regulation are another challenge to fossil power generation.

Efficiency has been a primary focus for scholars. It has been frequently called the "first fuel" of energy, since it is available for any country and one of the most significant ways to achieve sustainability (IEA, 2016). It is a powerful tool that can serve several objectives with less cost. It can reduce the amount of emissions produced by power plants, decrease the quantity of fuel consumption, provide energy security improvement and lead to energy bills reduction. For instance, it was reported that around a 0.33% improvement in efficiency saved about 12.1 M BOE in Saudi Arabia (SEC, 2014). As a consequence, investment in efficiency improvement has been attracting more attention than previously.

In Saudi Arabia, fossil fuel is the sole source of electricity and fuel prices are heavily subsidised by the government, in particular, to provide access to low income people. The increasing consumption of electricity has increased the financial burden on the national budget. Moreover, efficiency has been mentioned consistently in recent years. Accordingly, significant effort has been devoted to improving the efficiency on the demand side by promoting awareness among consumers. However, on the supply side the country has been located among the less efficient countries in terms of generation efficiency.

The Electricity and Cogeneration Regulatory Authority (ECRA) is the governing and legislator body of the electricity sector in the kingdom. It has reported, on an annual basis, the growth and required investment to cope with the demand. In addition, reforming the sector represents a high priority for ECRA, according to the reports. Efficiency improvement on the generation side has been mainly triggered by reinforcing the generation stock with new units.

Nevertheless, the outcome has not shown significant improvement despite the injected investment.

1.2 Background to the Research

Fossil fuels represented around 81.6% of energy supply in the world, as of 2013 and this figure is projected to reach 82% by 2030 (IEA, 2015). They have been a primary source in power generation. Around two third of global electricity is generated by them, followed by hydroelectric (16.6%), nuclear (10.6%) and 4.2% by renewables (IEA, 2014). Fuel price has played a role in changing the share of each type of fossil fuel, accordingly. During the twentieth century, electricity production relied heavily on oil due to its low price, particularly between 1920 and 1973. Later on, the increase in oil price resulted in a significant shift to natural gas and coal (Yergin, 1993). Between 1990-2007, oil's share dropped from 28% to 7%, while gas jumped from 12% to 31% (IEA, 2009).

Globally, electricity demand has been growing by 2.8% since 1980 and the same growth is projected until 2030 (IEA, 2007b). India and China's growth were 6.2% and 5.1%, respectively, over the same period. Saudi Arabia has been encountering unprecedented demand for electricity (8-9%) since the beginning of the 21st century and this is expected to continue in coming years, as shown in Figure 1-1 (Groissböck & Pickl, 2016; Alawaji, 2012; Woertz, 2013). The European countries, on the other hand, experienced the slowest groth rate in the world at 1.3%. In general, the developing countries have experienced the highest figures of around 4.6%.

Saudi Arabia (SA) is the largest oil producer in the world and possesses around one fifth of the world's proven oil reserves (OPEC, 2016). The kingdom's economy relies heavily on oil exports in its annual budget, with it representing 85% of the country's export earnings (OPEC, 2016). 8.6 million barrels of oil per day (mbpd) were exported in 2013 out of a total production of 11.6 million barrels per day (EIA, 2013) and SA is the world's twelfth energy consumer (El-katiri & Fattouh, 2015). Oil consumption has doubled during the last decade, reaching 3 million barrels per day (Khan, 2014), thus resulting in the country becoming the sixth largest oil and gas consumer in the world with around a 7% annual increase (Chaoul, 2013). Recently, local consumption has reached 38% of total primary energy in the kingdom, according to the Saudi Deputy Minister of Energy (Sulman, 2016).

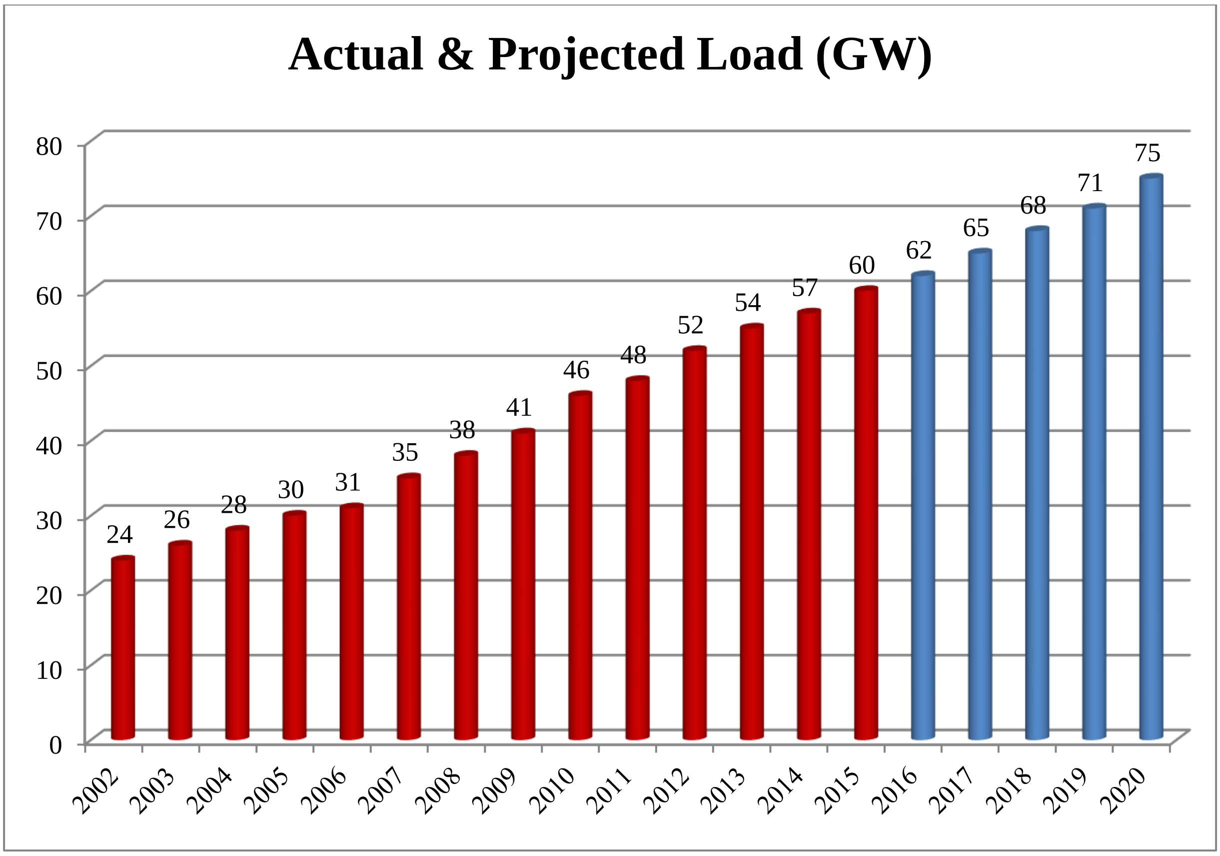

Figure 1-1 Actual and projected load in Saudi Arabia (ECRA, 2013b) (ECRA, 2014b)

Electricity generation consumes 39% (Alowaidh, 2010) of local oil consumption and 43% of total produced natural gas, with the rest being distributed in other sectors, such as transport, industry, among others. Electricity was generated by 47% gas and 53% oil, as of 2013,with 1.6 million barrels of oil equivalent (MBOE) being burned every day in power plants (ECRA, 2013b) and this figure is growing on an annual basis. The share of exports could be reduced by 3 MBOE by 2028 (Alhoweish & Orujov, 2016) if the current situation continues, which will undoubtedly affect the national economy.

The Power Sector in Saudi Arabia

In Saudi Arabia, electricity is generated utilising several type of fossil fuels, heavy fuel oil (HFO), light fuel oil (LFO), diesel and natural gas, as shown in Figure 1-2 (ECRA, 2014b). Coal is not used for power generation. The Saudi Electricity Company (SEC) is the primary electricity provider in SA. It was established in 2000 by the merging of all electricity firms (Ministry of Water and Electricity 2015). It is 81% owned by the government. It owns the transmission and distribution networks and around 70% of the existing power plants, generating about 70% of the country's total demand.

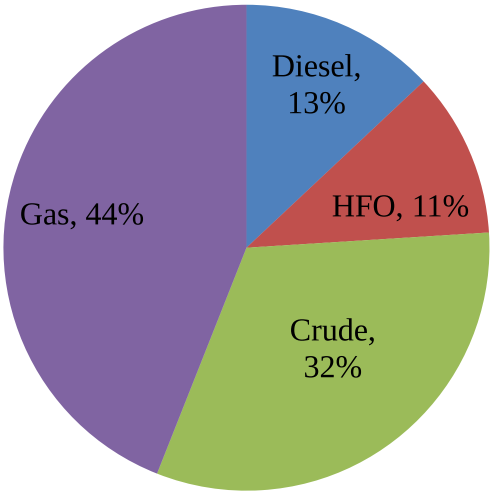

Figure 1-2 Annual fuel consumption in electricity generation in SA by fuel type

SA is the 20th largest country in the world in terms of electricty production and consumption (Alyousef & Abu-ebid, 2012). There has been a remarkable rise in the peak load in recent years, recorded on an annual basis, with a projection that will reach 75GW by 2020. This upsurge requires massive investment in infrastructure expansion with an estimated value of 500 billion Saudi Riyals for the next ten years (Al- Hossein, 2016). As a result, 40% of the generation capacity is less than six years old and only 4% have operated for more than 35 (ECRA, 2014b), as shown in Figure 1-3.

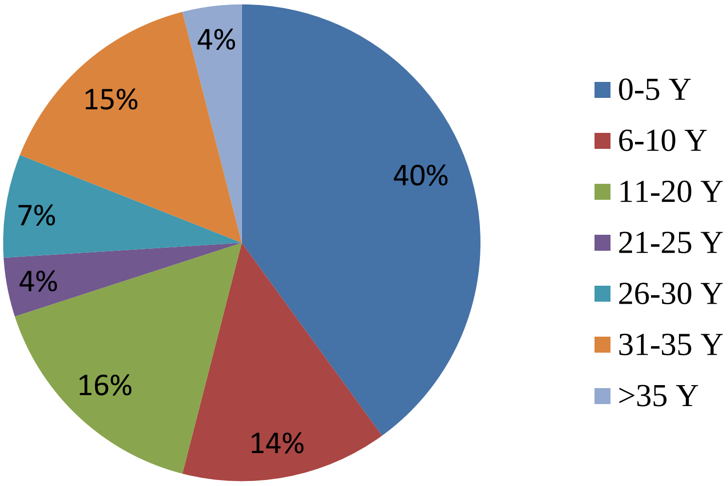

Figure 1-3 Age of generation units in SA based on capacity

Fossil fuel power plants characteristics

There are three main types of technologies used in the kingdom: gas turbines (GT), steam turbines (ST) and combined cycle turbines (CC). Diesel turbines represent less than 1% of the total generation stock and therefore, they are not considered here. A gas turbine has some advantages over others. First, the cost of investment is less than for CC and ST. Second, it does not require long hours to start up, which means it provides a quick response to demand. Nevertheless, it does not operate with high efficiency (30%-35%) (Farnoosh et al., 2014). A steam turbine can operate at higher efficiency (35%-40%), however, it is not able to respond to peak load quickly, because requires more hours than a GT to warm up. The combined cycle is the most efficient available technology, being able to reach 50%, but its investment cost is very high. In Saudi Arabia, GT represent half of the generation stock (47%), followed by 40% ST, 12% CC and 1% diesel generators (ECRA, 2014b), as shown in Figure 1-4.

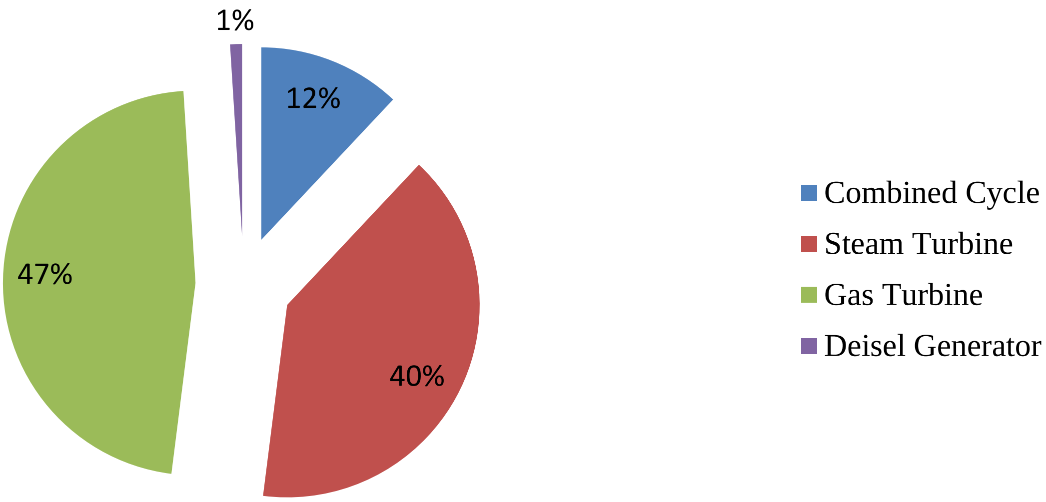

Figure 1-4 Generation units by technology type

Concerns of fossil fuel usage in electricity generation

Notwithstanding the advantages of fossil fuel in generating electricity, energy security and environment are widely discussed as concerning factors. Despite the existence of reserves that could last for at least fifty years (BP, 2016), as aforementioned, annual consumption is increasing on a yearly basis. Prior to the depletion of fossil fuel, the price could be affected significantly. Environmentally, the CO_2 produced by the combustion of fossil fuel is a major issue for environment. Coal accounts for 46% of the total CO_2 produced followed by oil and gas with 34% and 19%, respectively (IEA, 2014). Improving energy efficiency in power plants is one of the suggestions proposed in order to mitigate these concerns (Graus, 2010).

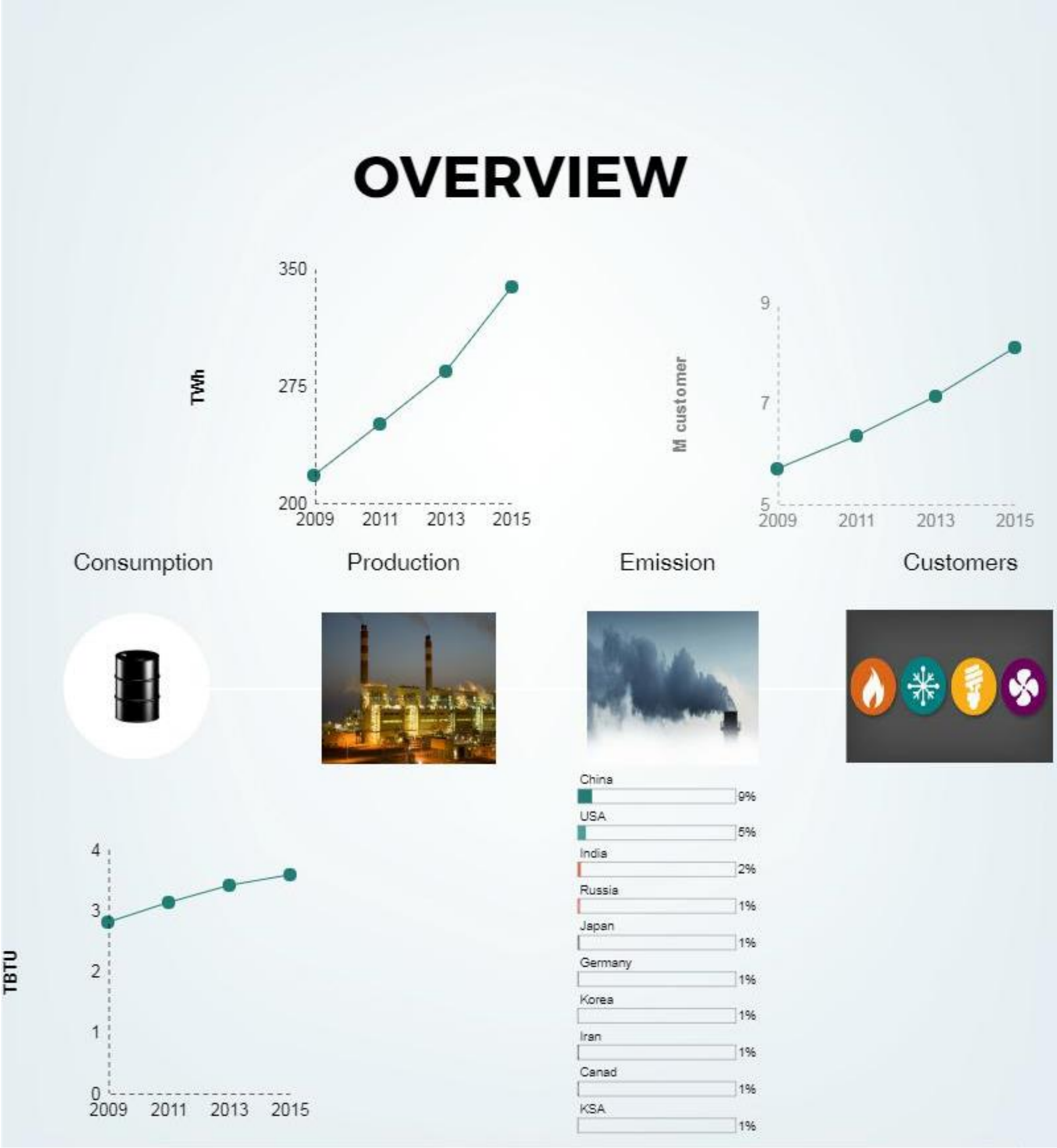

Figure 1-5 Overview of the electricity system in Saudi Arabia

1.3 Problem Statement

Efficiency improvement is a primary objective in the electricity sector due to its significant financial and environmental impact. Consequently, authorities are working with service providers in several programmes and implementing them to achieve the goal. In Saudi Arabia, despite some improvement having been achieved in the electricity market, some issues still need to be considered. Primarily, SA is classified among the poorest countries in terms of generation efficiency. As a result, the level of emissions produced by fossil power generation is considered among the highest globally. Second, the kingdom has one of the highest growth rates in electricity demand. This has increased the consumption of oil and gas in power plants as they are the sole source of electricity production in the country. Third, huge investment has been injected into the power sector in recent years for expansion, but no significant improvement in efficiency has been achieved. Fourth, most of the effort was focused on the consumer side. All of these constitute serious warnings that could turn into problems. In particular, the supply side is experiencing massive waste that is having a significant impact.

1.4 Research Significance

Efficiency of fossil power generation is a vital measure for understanding how resources are being utilised. A low efficiency level means heavy fuel consumption, which no doubt will be reflected in cost and emissions levels. In addition, the existence of fuel subsidies and the current market structure, in Saudi Arabia, does not encourage competition among electricity providers owing to the lack of incentives. Most of the previous studies that targeted efficiency improvement proposed new plans that require further investment and additional cost. The massive investment combined with the slow improvement in efficiency has motivated this research to analyse the available assets so as to identify issues regarding efficiency and subsequently, to proposes an optimum solution without the need for further investment. This improvement will lead to fuel saving and emissions reduction, as shown in Figure **1-6**. In addition, this will bridge the gap of efficiency loss by providing a sustainable framework based on incentives and competition.

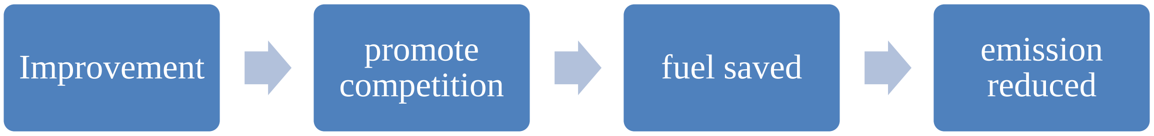

Figure 1-6 Research motivations

1.5 Aims and Objectives of this Research

This research aims to improve the efficiency of the electricity industry in Saudi Arabia by developing a model that integrates Lean Six Sigma, simulation and a mathematical model in order to establish a sustainable and effective implementation framework for application.

The research objectives are:

- To assess the current system losses;
- To benchmark the current efficiency level with other similar country;
- To classify the main factors influencing efficiency;
- To identify the causes leading to the current efficiency in Saudi Arabia;
- To develop a mathematical model to optimse the operation;
- To develop a simulation model to examine and justify the improvement;
- To validate the model by implementation;
- To develop a framework for application in the power industry to sustain continuous improvement and promote competition.

Research Question

How can fossil power generation efficiency be improved in Saudi Arabia?

Sub-questions:

- What is the current trend regarding electricity in Saudi Arabia?

- How was energy efficiency addressed in the past?
- What are the main factors influencing energy efficiency of fossil-fuel generation?
- What are the initiatives available for improving fossil fuel efficiency?
- How can fossil fuel generation efficiency be improved?
- To what degree will efficiency improvement contribute to fuel saving and emissions reduction?

1.6 Researcher Contributions

This section provides the contributions to knowledge, a brief about the methodology applied in this study and the challenges experienced by the researcher.

Contributions to Knowledge

This research has made contributions to the area of fossil power generation by integrating Lean Six Sigma, a mathematical model and simulation. The contributions can be summarised as follows:

- Study of the efficiency of fossil power generation and identifying the most influencing factors and the impact on fuel and emissions by carrying out a literature review of this area;
- The development and presentation of a sound methodology and model to integrate LSS, simulation and mathematical modelling in the power industry;
- The integrated model has been implemented and validated utilising real data. Its appropriateness and effectiveness in the power sector have been justified;
- Simulation model development with the ability of easily changing any inputs and variables;
- Identification of the causes leading to the low efficiency level in Saudi Arabian fossil fuel generation;
- Developing a new merit order using a mathematical model. The novelty can be seen in combining the quality and quantity of production to generate a single measure;
- Optimisation of power plant operation using mathematical programming to maximise the efficiency and to mitigate fuel consumption, thereby reducing carbon emissions;
- Creation of a competitive model among providers grounded in new criteria for subsidy entitlement to promote continuous improvement and to stimulate sustainability.

Research Methodology

In order to achieve the research aims and objectives, the following methodology is employed:

- Published literature reviewed;
- Apply Lean Six Sigma framework;
- Classify the most wasteful areas in the system and identify the gap;
- Develop a computer-based simulation model. The model will be utilised to assess the current situation in order to extract the factors that are affecting efficiency. In addition, it will be used for testing and justifying the future means of enhancement;
- Develop a mathematical model for improvement;
- Develop mathematical programming for optimisation;
- Validate the model through implementation using real data to examine its effectiveness in delivering improvement.

Challenges

Development of a model to simulate the electricity sector can be challenging. These challenges can be summarised as follows:

- Availability of data: Most of the published data is general and does not suit the requirements of this research. Only the Electricity and Cogeneration Regulatory Authority (ECRA) has the type of data that are necessary for this project. After several visits, which involved travel to Saudi Arabia and the exchange of emails, a one year efficiency report was sent, which has been used in this study. Unfortunately, this delay in response meant the research was stalled for a long time.
- Simulation model: Several materials were utilised to gain an understanding of the ideal approach for designing a model, including course materials, videos, books and manuals. In addition to the time consumed in the model design, run and troubleshooting the errors, some limitations held back progress as several modifications were required.
- Model run: To justify the results, several runs were applied. Each run last for nearly a couple of hours and impeded the PC from being used for other work.

1.7 Organisation of the Thesis

This thesis is divided into six chapters. Chapter 1 contains the introduction, motivation and background to the electricity sector in Saudi Arabia. It has also covered the historical trend of fossil fuel production/consumption for that nation, the aims and objectives, the challenges and the thesis outline. Chapter 2 provides a comprehensive review of extant literature relating to the study. This includes efficiency in power sector, influencing factors, Lean Six Sigma, simulation and mathematical models. Chapter 3 describes the methodology used in this research. It covers the rationale behind the selection of the methodology as well as the collected data and presents the integrated framework. Chapter 4 covers the implementation of the proposed model, whilst chapter 5 discusses the results in detail. Finally, the conclusion and limitations of the study are presented along with proposals for future work in chapter 6.

1.8 Author’s Publications

The following conference and journal papers have been published:

Journal:

- Althaqafi, M. & Yang, Q., 2016, Addressing the factors causing inefficiency of fossil fuel power generation in Saudi Arabia, Journal of Energy Challenge & Mechanics, 3(3), pp.100-108.

Conference paper:

- Althaqafi, M. and Yang, Q., 2017, August. Operation Optimisation Towards Generation Efficiency Improvement in Saudi Arabia, Using Mathematical Programming and Simulation. In *Smart Grid Inspired Future Technologies: Second EAI International Conference, SmartGIFT 2017, London, UK, March 27–28, 2017, Proceedings* (Vol. 203, p. 49). Springer.

Conferences attended:

- Althaqafi, M. & Yang, Q., 2013, Improving Efficiency in Electricity Usage in the Residential Sector in Saudi Arabia, In *ResCon13*, Brunel University, London, UK.
- Althaqafi, M. & Yang, Q., 2014, Factors Affecting Efficiency of Electricity Generation in Saudi Arabia, In *ResCon14*, Brunel University, London, UK
- Althaqafi, M. & Yang, Q., 2016, Addressing the Factors Causing Inefficiency in the Saudi Arabian Power Supply Industry, In *6th International Symposium on Energy Challenge & Mechanics*, Inverness, Scotland.

Chapter 2 Literature Review

2.1 Introduction

This chapter discusses the role of efficiency in the power system and the significance of efficiency improvement. The aim is to identify the most influencing factors on the efficiency of fossil power generation and the impact on fuel and emissions.

2.2 Impact of Efficiency

Energy efficiency has been an interesting topic for researchers for several decades, because it affects important concerns, including the economy, environment and energy security. “**Energy Efficiency is one of the fastest, easiest and cheapest ways to make our economy stronger and cleaner**” (Obama 2009; Aman 2013). This is because enhanced energy efficiency leads to a reduction in primary energy consumption (IEA 2006), which contributes to energy security and emissions reduction (Khan et al. 2015). Consequently, it is considered as being the most crucial factor for developing sustainability in electricity market (Chen et al. 2013).

Energy efficiency is a major tool for adding value (Bellman et al. 2007). It can significantly mitigate the increasing demand for fossil fuels and thus, lead to reduced emissions (IEA 2014). Fossil fuel is the main source of energy in the world, representing around 80% of energy supply in 2005 and the volume will continue up until 2030 (Graus et al. 2011). Moreover, it accounts for 75% of the CO_2 produced. Between 30 and 60% of the total demand in the world will be produced by fossil fuel and around 50% in Europe by 2040, based on IEA scenarios (VGB Powertech 2015). Consequently, efficiency improvement of fossil power generation is the key to reducing the consumption of fossil fuel and minimising CO_2 emissions.

In general, electricity markets have various challenges, such as fluctuating fuel price on the supply side, annual growth on peak load and variable load on the demand side. Moreover, massive investment is needed for continuous expansion in production and delivery to cope with the demand. Nevertheless, investment in energy infrastructure could be reduced by adopting and applying efficient production (Farrell et al. 2008). The international energy agency (2006) indicates that, investing in improving efficiency could save up to half the investment required in generation expansion (including generation, transmission and distribution) in the Organisation for Economic Co-operation and Development (OCED) countries, while in developing countries up to two thirds could be saved. O'reilly (Chevron former CEO) stated the same view, contending that energy efficiency is the most economical available form of energy (Farrell et al. 2008).

2.3 The Definition of Efficiency

Energy efficiency is defined as “usable energy output divided by energy input” (Eurelectric 2003), which includes all useful output from a power plant, including electricity, heat etc. in its calculations. It can be also be termed “energy conversion efficiency”. Economic efficiency pertains to the cost of production, with the focus being on optimising a power plant’s process and production by taking into consideration energy efficiency as an indicator. It is quite common to have high economic efficiency while energy efficiency is below the average (IEA 2010a). Operational efficiency relates the energy output to the maximum achievable output and is also called the “capacity factor” or load factor (IEA 2010a).

Thermal efficiency relates to the transformation of heat content in fuel into just electricity (Department of Energy & Climate Change 2014). While “power plant efficiency is generally defined as the electricity produced per energy input” (Chen et al. 2013) or the quantity of heat (BTU) for every (kWh) produced (Bellman et al. 2007). However, these relations do not consider other outputs such as electricity consumed in power plants, CO2 emission produced, workforce and installed capacity. It only focuses on the usable electricity delivered.

Generation efficiency refers to the percentage of usable electricity output from the energy value of input fuel at a specific power plant within a particular timeframe (Eurelectric 2003). In power plants, efficiency is not static, but changeable, according to many factors, such as weather, load profile, operation practice etc. Therefore, taking in account a specified time period for measurement would provide average efficiency, which is more appropriate.

Achieving the required amount of production by consuming less input is another way of defining energy efficiency (Lawrence Berkeley National Laboratory 2016) (Bahgat 2012). Efficiency has several names and detailed definitions according to the context, but the concept can simply be defined as:

“**The ratio of the useful output energy to the input energy**” (Harvey 2011)

And is represented by the formula:

$$E = P/I \qquad (1)$$

where:

- E: Energy Efficiency
- P: Power production (based on gross output, including auxiliary consumption) (kJ)
- I: Fuel input (based on average gross calorific value) (kJ)

Efficiency has no specific unit and is generally presented as a percentage or in terms of the heat rate (HR), which pertains to the amount of BTUs or kilojoules needed to generate a single unit of energy (kWh). Consequently, reducing heat rate means improving efficiency and vice versa. Where:

- Heat Rate = Energy Input (fuel: BTU, kJ) / Energy Output (electricity: kWh)

$$\text{Efficiency} = \frac{3412}{\text{HR (BTU/kWh)}} = \frac{3600}{\text{HR (kJ/kWh)}}$$

(1 kWh = 3600 kJ = 3412 BTU)

2.3.1 Gross Efficiency and Net Efficiency

There are two measures of efficiency depending on which type of electricity output is being considered. Gross efficiency refers to utilising gross or “sent-out” electricity in efficiency calculations, including that consumed in auxiliaries. Whereas measuring net efficiency pertains to the “gross-net” or “net output” power, which excludes the amount of power consumed within the power plants (IEA 2010a). Measuring gross efficiency is more straight forward when compared with net efficiency. Quantifying the latter is more complex, especially for large power plants that contain several generation units, because is possible to find auxiliaries being fed from other units or a common feeding point. In such cases, unit based efficiency can become inaccurate.

2.3.2 Design Efficiency and Operational Efficiency

Each power plant is designed to achieve a level of efficiency according to its specifications. This is called design efficiency or nameplate efficiency and requires specific criteria in operation to achieve it. However, design efficiency is affected by operational circumstances, which leads to lower efficiency than that planned. Consequently, operational efficiency, which is a year round measure of efficiency and invariably lower than design efficiency is considered a more practical benchmark for evaluating a power plant’s performance (Graus & Worrell 2009).

2.3.3 Net Calorific Value (NCV) and Gross Calorific Value (GCV)

Energy contained in a fuel can be expressed in two forms, GCV and NCV, as shown in Table 2-1. This relates to the amount of energy produced by burning the fuel and the physical state of H_2O prior the combustion process. As a result, efficiency usually is expressed in two forms, either the lower heating value (LHV), which is based on the net calorific value (NCV) of the fuel or higher heating value (HHV), which is based on gross calorific value (GCV). The efficiency calculation based on gross calorific value (GCV) is lower than that pertaining to net calorific value (NCV) (Graus & Worrell 2009) and the difference varies according to the type of fuel used. The difference for oil is around 7%, natural gas 10% and for coal about 3% (ibid). The difference between them is based on the chemical state of the H_2O produced by the combustion process and the energy content. For NCV, it is assumed that the H_2O produced from the combustion is in gaseous state and its contained energy is seen a loss since it cannot be restored. On the other hand, regarding GCV, the H_2O resulting from the transformation is assumed to be in liquid form (Bellman et al. 2007).

Reporting efficiency varies depending on the fuel type used and country. For instance, the efficiency of coal power plants is usually expressed using HHV in the United States, while the majority of other countries, including Europe, employ LHV (Eurelectric 2003). Whilst natural gas is commonly presented in LHV in reports. However, the energy efficiency experts network prefers using HHV more than LHV, as it reflects a clearer picture of losses (inefficiency) from the energy efficiency analysis point of view (Phylipsen et al. 1997).

Graus et al. (2008) proposed efficiency conversion factors for GCV to NCV according to the fuel type, using IEA published data (IEA 2007). Regarding which, the conversion factor for coal is 0.96-0.97, while those for natural gas and oil are 0.9 and 0.93 respectively.

Table 2-1 Difference in energy content between GCV and NCV (Eurelectric 2003)

	GCV	NCV
Heavy fuel oil (HFO)	42.6 MJ/kg = 10,175 kcal/kg	40.57 MJ/kg = 9,690 kcal/kg
Light fuel oil (LFO)	43.3 MJ/kg = 10,342 kcal/kg	41.2 MJ/kg = 9,840 kcal/kg
Natural gas (NG)	42.0 MJ/kg = 10,032 kcal/kg	37.9 MJ/kg = 9,052 kcal/kg
Hard coal	35.4 MJ/kg = 8,448 kcal/kg	34.1 MJ/kg = 8,145 kcal/kg

2.4 Efficiency of Electricity Sector in SA

Efficiency has not received sufficient attention in Saudi Arabia (Al-Ajlan et al. 2006). This has resulted in the current high and growing consumption of fossil fuel in power plants, which threatens the country’s natural resource reserves (Fattouh & El-katiri 2012a). Some studies have proposed diversification of resources in electricity generation by utilising alternative technologies, such as nuclear, solar; wind etc. (El-katiri 2014) (Alnatheer 2005) (Al-Saleh

2009; Aljarboua 2009; Bachellerie 2012; Alyousef & Abu-ebid 2012) to mitigate the consumption of natural resources. This opinion is supported by the availability of sunlight for long hours during the year, which could be sustainable source of energy. Despite the development of renewable energy, the global average growth was only around 2.6% annually for the period 2000-2012, which represents around 13.5% of total used energy in 2012 compared to 13%in 1971. This is due to the growth in non-renewable resources (Crijns-Graus 2016).

The kingdom has a plan to produce around 50% of total generated electricity from alternative sources (nuclear, solar, wind, geothermal) by 2030 (Yamani 2012). Based on the levelised cost of energy (LCOE), nuclear is the most competitive source of electricity and has the potential to compete with fossil fuel based on international fuel price. However, El-katiri (2012) believes that nuclear power does not seems to be a cost effective option compared to oil and gas for an oil exporting country, based on capital and operational costs. The lack of financial motivation for renewables (Al-Saleh 2009) and the existing subsidised price of fossil fuel weaken the chances of the former competing, which as a result has not attracted investors (Alnatheer 2005; Aljarboua 2009; El-katiri 2013). Furthermore, subsidies and low electricity tariffs are considered as key obstacles to growth in renewables unless they receive similar financial support (Beck & Martinot 2004; El-katiri 2013). Moreover, in one study it is argued that generating electricity from renewable resources does not a represent top priority option for the kingdom owing to the availability of fossil fuel in the kingdom, which could last for hundreds of years (Aljarboua 2009).

The intervention of new technologies with no doubt will enhance the energy market by diversifying the generation assets and mitigating the consumption of oil. However, the aforementioned plan does not show how renewables can be sustainable given the current tariff and discounted price for oil and gas. They require enormous capital investment and subsidies to sustain them under the current situation. Alternatively, the elimination of existing subsidies would incur a huge jump in operation cost for current providers, which may result in bankruptcy under the current tariff. Both options require in depth analysis to identify the optimum scenario. On the other hand, taking into consideration the availability of fossil fuel in the kingdom, the cheapest and fastest approach to reduce fuel consumption and subsidies is through efficiency improvement, which will support the intervention of alternative resources.

On the consumption side, the majority of studies have focused on promoting efficient consumption. Smart meters and a smart grid, for example, are considered to have the potential to reduce consumption, develop awareness among end users (Aman 2014) and to improve the whole system efficiency (CESI & ATKearney 2012) by building two way communications between supply and demand. This can save the extra production and help the supplier to generate the needed electricity, in addition to benefiting the end users through in their bills. However, this requires a huge long-term investment in upgrading the current infrastructure to generate results. In another study, it is believed that efficiency should start with promoting awareness among consumers (Alyousef & Abu-ebid 2012), while others have suggested that increasing the tariff is the fastest way to force consumers to use electricity more cautiously and to avoid wasteful usage (El-katiri 2013; Khan 2014; Fattouh & Mahadeva 2014).

The National Energy Efficiency Programme (NEEP) was established in 2003, for three years as a short-term programme, aimed at improving the efficiency of both the supply and demand side (Al-Saud 2014). Later on, in 2010, the Saudi Energy Efficiency Centre (SEEC) was launched to take the responsibility for efficiency improvement on the demand side, whilst abandoning supply side efficiency. The main objectives of this centre are to propose a long term plan for efficiency improvement, design policies of energy efficiency, improve awareness and to take part in the implementation of efficiency programmes (SEEC 2015). However, in some studies it is argued that all these efforts are inconsistent and will not be effective in the long term without the existence of a national energy policy approved by law (Al-Ajlan et al. 2006).

Generation efficiency has not received significant attention to date. A study has pointed out that all Gulf countries, including Saudi Arabia, are below the international average in terms of such efficiency (Saudi Arabia, Kuwait, UAE, Bahrain, Oman and Qatar) (El-katiri 2013) (Fattouh & El-Katiri 2013). The author related this issue to the lack of incentives for electricity producers to become more efficient. Other research has evaluated the efficiency in Saudi Arabia as being one of the lowest countries, at around 30%, in terms of electricity production (Fattouh & El-katiri 2012b; Fattouh 2013). Whilst other scholars have claimed that, nominal power plants efficiency in the kingdom is far below the world average generation efficiency, by comparing Saudi Arabia with the United Kingdom, which stand at 29.5% and 38.6%, respectively (Alyousef & Abu-ebid 2012). Similarly, efficiency studies carried out by ABB, have stated that the kingdom is still considered amongst the lowest countries in the world in terms of efficiency performance (ABB 2011) (ABB 2012). Lack of efficient generation units and fuel type in use were the associated causes highlighted in these studies leading to the current level of efficiency in Saudi Arabia. Efficiency figures have never been published in ECRA's official reports, to the best of my knowledge. However, SEC, which is the largest producer of electricity in the country and generates around 70% of total production, has shown an inconsistent[1] annual heat rate between 2010 and 2013, as shown in Table 2-2 below, with limited improvement and major corrections.

Table 2-2 Available data of HR in SEC power plants in SA

	2010	2011	2012	2013
SEC HR (BTU/kwh)	10,920	10,907 - 10,585	10,452 - 10,533	10,375
SEC efficiency (C)[2]	31.25%	31.28% - 32.23%	32.65% - 32.39%	32.89%

In general, the current efficiency level is considerably below the average, as claimed by many reports and a potential saving of 850 thousands BOE per day could be achieved by improving the efficiency (Sulman 2016). Since less effort has been devoted to efficiency improvement on the supply side in Saudi Arabia, it is more significant to focus on it and the next section discusses it in detail.

2.4.1 Major Types of Losses in the Electricity System

During the production of electricity and delivery, each stage has different level of efficiency that affect the whole system efficiency. Given the fact that efficiency in the electricity system in SA is below the average, this means losses are high in certain points. this section examines where these emanate from.

1. Generation Stage

Generation is the primary phase in the electricity system. It starts with fuel injection, which accounts for more than half of the energy production cost and around three quarters of the cost of operation (Bushnell & Wolfram 2005). Fuel combustion is a crucial process in determining the generation efficiency during the transformation. It is usually expressed as a heat rate (HR), which assigns the required amount of heat in BTU to generate a single unit of electricity (kWh). The HR level depends basically on the turbine type. Power plant facilities consume some of its gross production and send out its net generation, which is usually followed by the transmission

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[1] (SEC 2012) stated HR = 10,907 in 2011 compared to 10,920 in 2010, while (SEC 2013) reported HR = 10,451.83 in 2012 compared to 10.585 in 2011. Moreover, (SEC 2014) indicated HR = 10375 in 2013 compared to 10,533 in 2012.

[2] Equivalent efficiency= $\frac{3412}{\text{HR}}$

phase. However, in some cases it is linked to a distribution network or to bulk customers directly.

Generation efficiency is often pointed out as major determinant of system efficiency, since it involve the largest amount of losses (Graus et al. 2011). Graus found that generation losses in power plants fuelled by fossil fuel account for 75% of total losses occurring on the power supply side, which includes refineries, generation, transmission and distribution firms. Consequently, potential saving can be obtained by increasing the efficiency level in the generation phase.

Generation efficiency in Saudi Arabia has improved from 26% in 1990 to 29% in 2010, i.e. by 5.8% (0.15 PP) per year (Groissböck & Pickl 2016). According to ABB, it improved from 27% to 31% in the same period (ABB 2013). On the other hand, efficiency of fossil power generation in the European Union countries was 41%-46% over the same period. Generally, the type of fuel used in power generation can affect the average efficiency significantly (Graus 2010). Natural gas has a high level of efficiency compared to coal or oil. Saudi Arabia relies completely on oil and gas and does not utilise coal, which is the least efficient fossil fuel resource. However, the unavailability of detailed data of efficiency based on each fuel type does not facilitate accurate assessment of the current situation. Technology type has a significant role in efficiency improvement, as suggested by several researchers. For example, increasing the share of combined cycle gas turbines (CCGT) can improve the average efficiency and save a significant amount of fuel, since it has lower HR compared to other fossil fuel generation technology (Alyousef & Abu-ebid 2012) (Groissböck & Pickl 2016). In addition, ABB reports have linked the limited improvement of efficiency in Saudi Arabia to the increase in utilising natural gas over oil in power plants and CCGT units (ABB 2013).

A study by Graus (2010) aimed to build a benchmark indicator for fossil fuel generation efficiency. His study was based on 14 countries[3] that consume two thirds of global fossil fuel power production. In 2003, the results showed fossil fuel generation efficiency was around 35%. India had the lowest with 30% and the United Kingdom recorded the highest efficiency at 40%. Moreover, based on type of fuel, power plants fuelled with natural gas vary from 35% in Australia up to 47% in India. In addition, efficiency of power plants utilising coal ranged

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[3] Australia, China, Denmark, Finland, France, Germany, India, Japan, Norway, South Korea, Sweden, the United Kingdom and Ireland, and the United States.

from 41% in Japan to 29% in India. Finally, oil fired power plants spanned from 28% in India to 42% in Japan. Figure 2-1 shows the weighted average efficiency of countries covered by Graus's (2010) study based on fuel type from 1990 until 2003. Natural gas efficiency jumped from 34% to 40%, while oil and coal remained at the same level, around 36% and 34%, respectively.

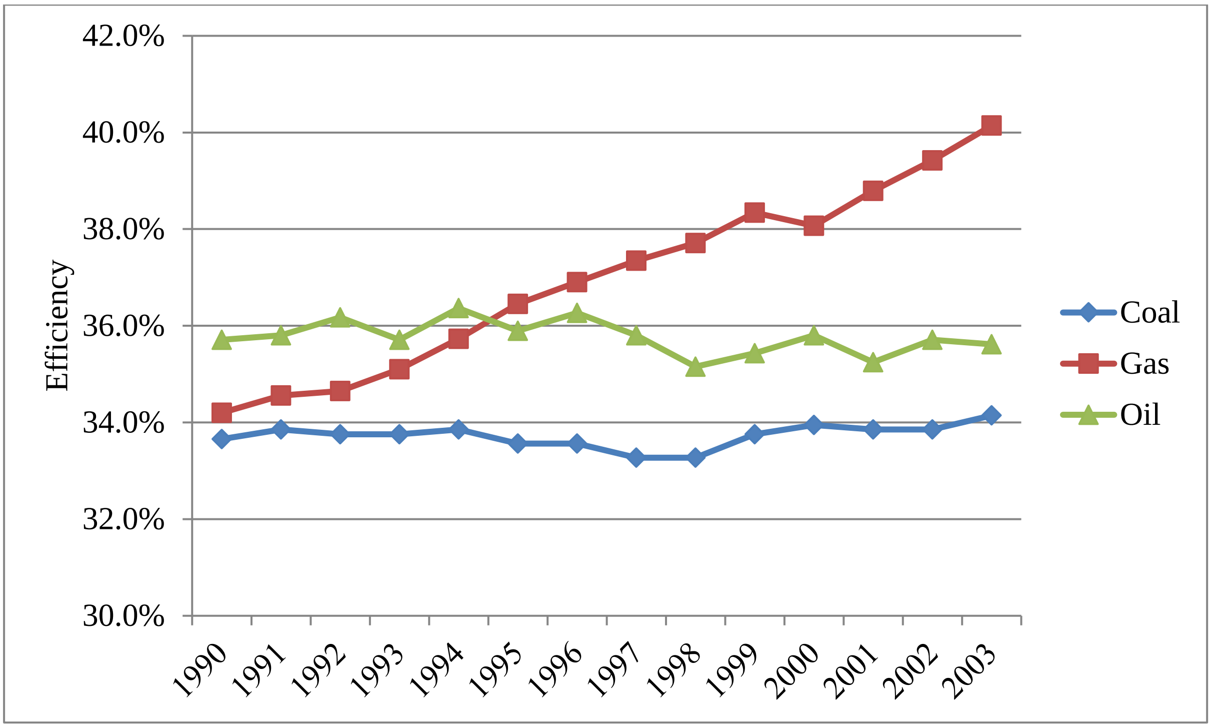

Figure 2-1 Weighted average efficiencies of selected countries based on fuel type

In the European Union countries[4], 55% of power was generated from fossil fuel in 2005 (Graus & Worrell 2009). Coal contributed the largest share with 30%, followed by gas with 20% and only 4% was produced from oil. Between 1990 and 2005, the efficiency of gas fired power plants improved from 30% to 45% and coal from 33% to 39%. Figure 2-2 shows the 3 year average efficiency of EU countries for different fuel type. In general, efficiency fluctuates between 50% and 21%. In detail, Spain was the most efficient producer, using gas with 50%, whilst 27% was the lowest efficiency and found in Bulgaria. For coal fired power plants, this ranged from 27% in the Slovak Republic to 42% in Denmark. The top efficient generation

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[4] Germany, the United Kingdom, France, Italy, Spain, Sweden, Poland, the Netherlands, Belgium, the Czech Republic, Finland, Austria, Greece, Romania, Portugal, Bulgaria, Denmark, Hungary, Slovak Republic, Ireland, Slovenia, Lithuania, Estonia, Latvia, Cyprus, Luxembourg, Malta.

utilising oil was 43% in Italy and the Czech Republic had the lowest at 21%. On average, EU countries achieved 39% efficiency for fossil power generation in 2005 (Graus et al. 2011).

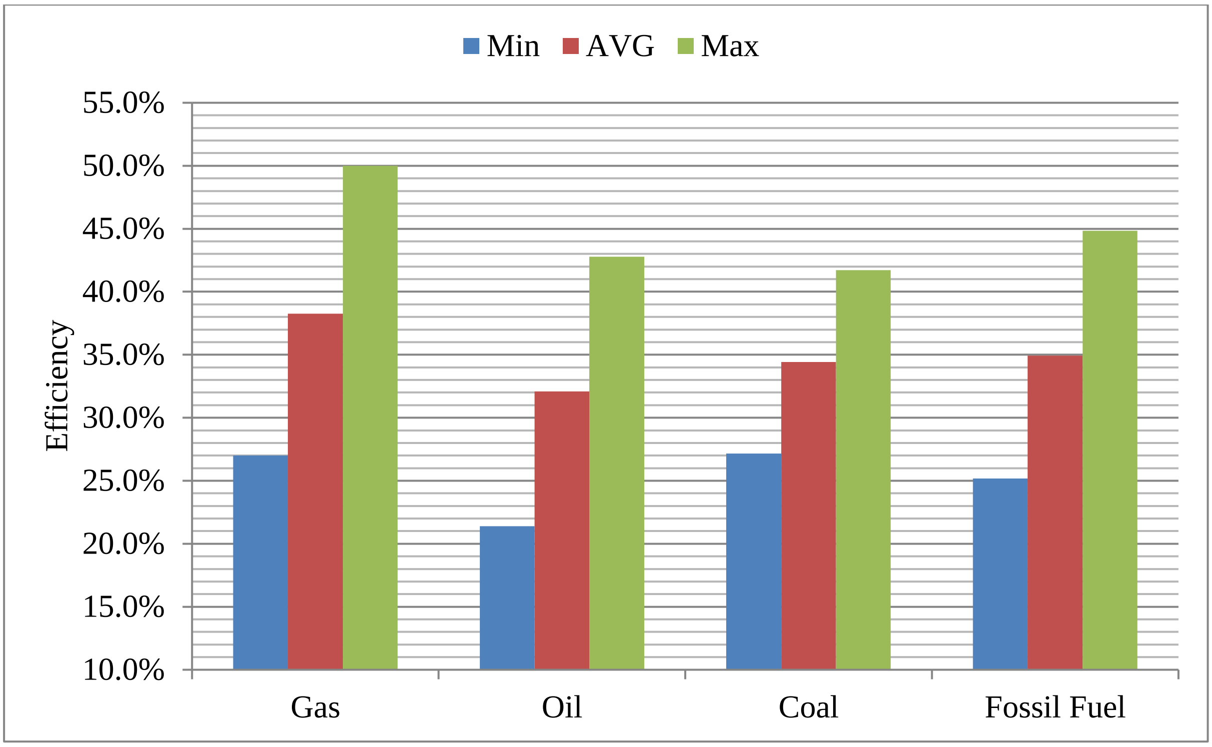

Figure 2-2 Minimum, average and maximum efficiency in EU countries (2003-2005) (Graus & Worrell 2009)

In 2005, coal accounted for the largest share of electricity production in the world, with 40%, followed by natural gas 20% and only 7% from oil. On average, efficiency of fossil fuel generation in that year was 31%, with 31% for coal, 30% for natural gas and 31.6% for oil (Graus et al. 2011). It is predicted, Graus claimed, to achieve 50%, on average, by 2050.

2. Auxiliary consumption

The amount of electricity used to feed any equipment within the boundaries of the power plant is called auxiliary consumption. It is the differentiating factor between gross and net production, being usually expressed as a percentage of total production. Auxiliary can be pumps, pollution control equipment, fans, staff facilities etc. The amount of consumption varies according to several factors. For example, reducing emissions by applying pollution control equipment can consume between 0.5-2% of the total power generation (Graus 2010). In general, auxiliary consumption varies between 3% up to 15% of total electricity generated depending on the fuel type used, size of fans and/or pumps (ABB 2009). The largest consumption often appears in coal power plants, which consume 6-8% of gross production. On the other hand, gas based power plants are the lowest in terms of auxiliary consumption, standing at around 2-3% and for oil power plants this figure is usually between 4 and 6% (Graus et al. 2007). In 2007, the world average electricity consumed as auxiliary equipment was around 5% of gross production. Figure 2-3 shows the percentage of consumed electricity in power plants in relation to fuel type in several countries. China can be seen at the top, consuming slightly below 8% of its gross production within it power plants, while, Saudi Arabian plants consume nearly 3%, which is the lowest figure (Graus 2010). These figures could well be due to the absence of coal in the fuel being used. In Saudi Arabia power plants are fed with oil and natural gas. The average auxiliary consumption in the last six years was around 3.2%. 3.45% was the highest recorded in 2014 (ECRA 2015a) and the lowest consumption occurred in 2010, with 3.01% (ECRA 2011a). In sum, power plants in the kingdom are among the lowest countries in terms of auxiliary consumption, is most likely related to the fuel mix in use.

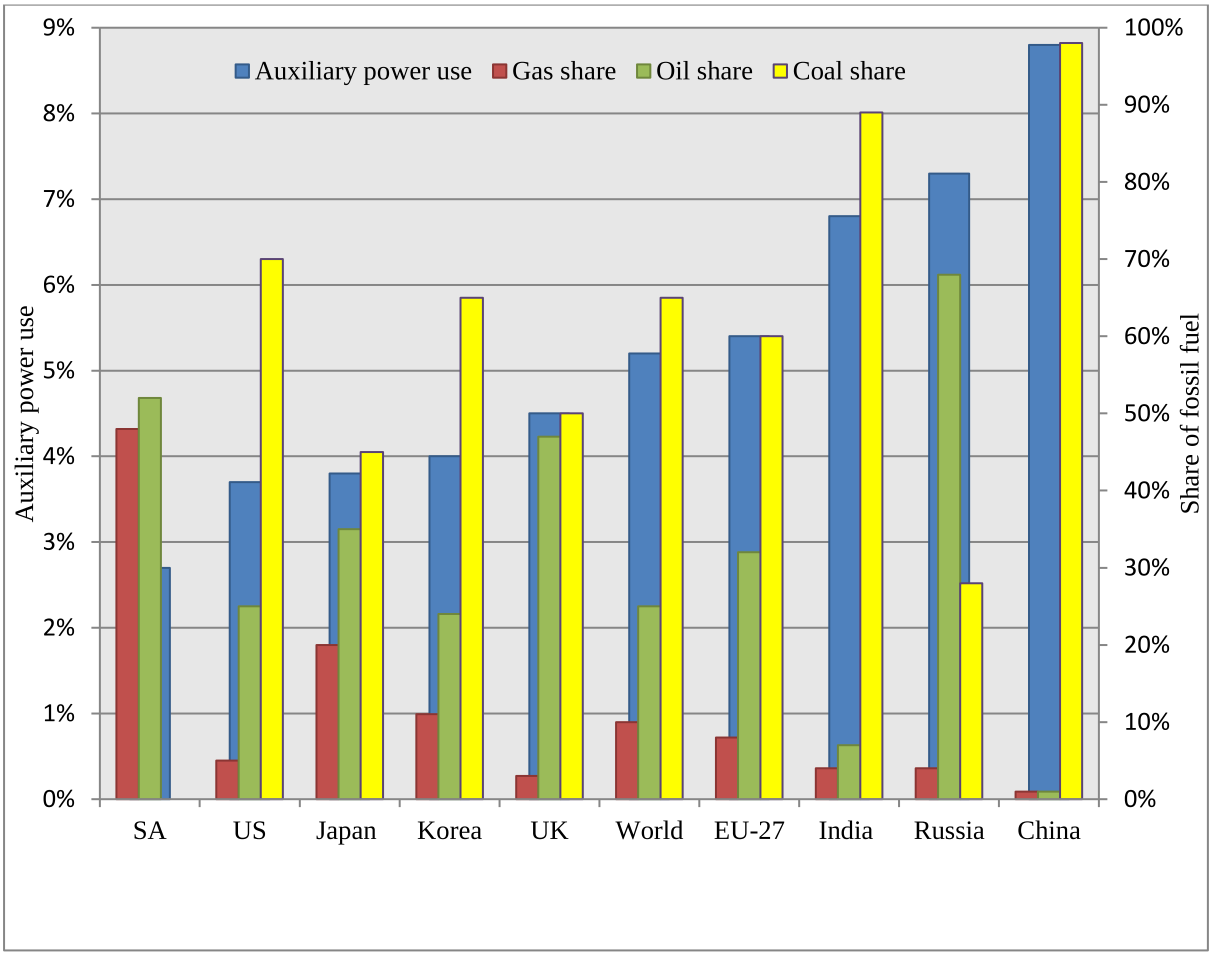

Figure 2-3 Auxiliary consumption in power plants as a percentage of total production in 2007 (Graus 2010)

3. Transmission and distribution losses

The transmission and distribution phases are the bridge between supply and demand through overhead network or underground cables. Substations are used as a share points between the different stages to change voltage level. Transmission lines are used to transfer power over long distances at high voltage, which can be between countries, regions or cities and the voltage range varies across countries. In Saudi Arabia, the voltage range of transmission networks varies between 110-380 kV. Distribution networks either link the transmission with consumers or in some cases link directly to power plants. They are used to link villages together depending on the distance and inside cities and villages to feed customers' meters. Distribution voltage varies according to the requirements. In Saudi Arabia, it varies from 69kV to 380/220 volts.

Losses in transmission and distribution networks are usually expressed together and fluctuate between 5-20% (Chowdhury et al. 2009). Overloaded networks leading to outages and theft are pointed out as reasons for high network losses in some countries, such as India (Zengh 2007; Graus 2010). The world average transmission and distribution losses from 2006 to 2012 were around 8.3%, as shown in Figure **2-4**. Losses vary between countries. For instance, India was the highest with 20.68% and Korea the lowest, with 3.54%. Whilst the figure for Saudi Arabia has fluctuated between 8 and 10% in the last decade, with an average 8.8%. Therefore, network losses in the kingdom are considered as being about the world's average (ECRA 2014b; ABB 2013).

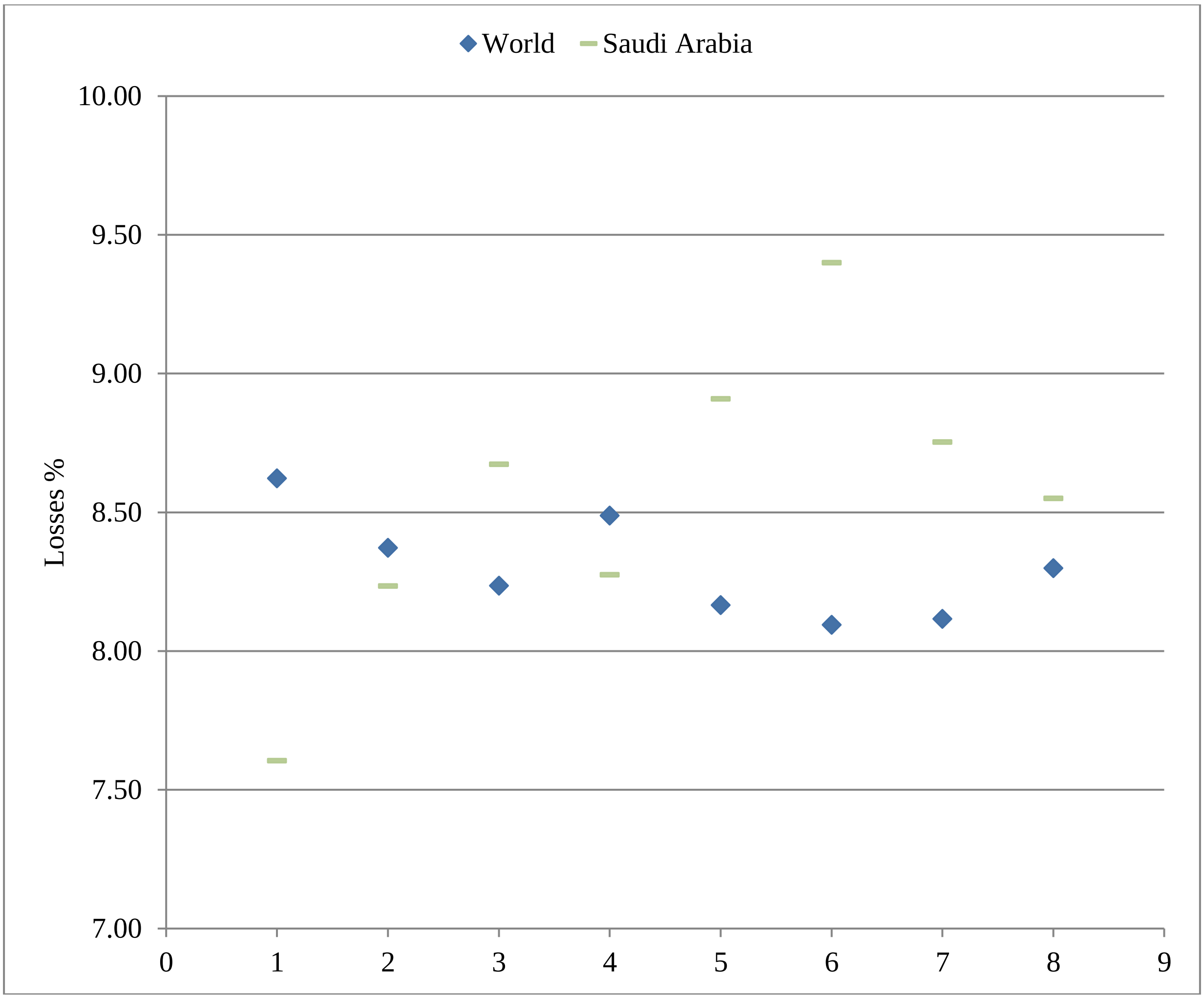

Figure 2-4 Transmission and distribution losses 2006-2012 (The World Bank 2014)

2.4.2 Supply Side Efficiency

Among the discussed type of losses in the system, as aforementioned, the generation stage accounts for the greatest amount. Figure **2-5** shows the average efficiency of different stages in power supply sector in Saudi Arabia. As can be seen, losses in the generation phase represent the largest share in the system. In addition, generation efficiency is below the global average level, while auxiliary, transmission and distribution losses are either within or better than the international average. Therefore, this research is focused on generation efficiency. Before addressing this, it is worthwhile drawing on knowledge of the expected return of efficiency improvement as found in the literature.

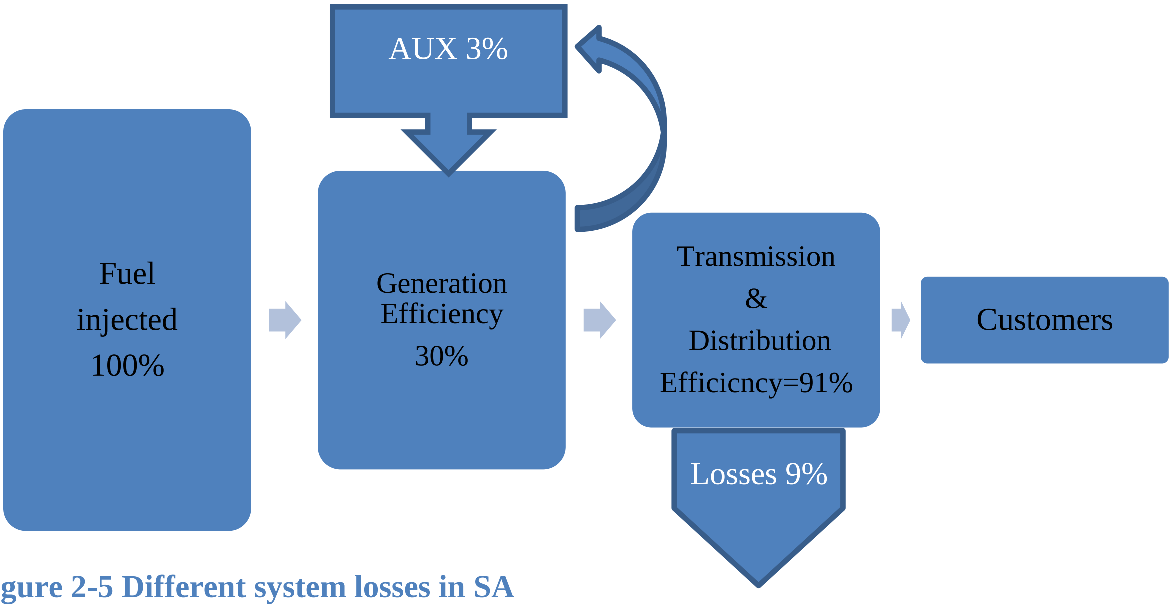

Figure 2-5 Different system losses in SA

2.4.3 The Cost of Inefficiency and the Gain of Efficiency

This section evaluates the economic losses of low efficiency and the potential gain of efficiency improvement. Heat rate reduction has significant economic and environmental impact. Efficient production leads to less emissions being produced and reduction in the amount of fuel consumed in fossil fuel generation. In fact, the cost of fuel can reach 90% of the production cost (Yamani 2012). To illustrate, a study on the impact of efficiency improvement shows that generating the same amount of electricity with 0.1 higher efficiency[5], can lead to 0.24% reduction in the fuel needed and CO_2 produced as shown in Table **2-3** (Eurelectric 2003).

In Saudi Arabia, SEC stated that HR improved by 1% in 2014 compared to the previous year, without stating the exact figure, resulting in a saving 12.1 million (BOE) (SEC 2015). This means SEC's HR had reached a new record of 10,271 (BTU/kWh) down from 10,375 (BTU/kWh) in 2013 (SEC 2014). Moreover, in 2011, HR decreased to 10,907 (BTU/kWh) down from 10,920 (BTU/kwh) in 2010 (SEC 2012)**,** which resulted in saving fuel worth 106 million SAR[6] (£17.67 million)[7]. The massive saving from the previous limited improvement indicates the significance and the need for more effort being devoted to improving the efficiency during the generation phase.

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[5] The study is based on LHV

[6] USD 1 = 3.75 SAR, £ 1= 6 SAR (approximately)

[7] (Calculation based on 60 $/ barrel

Table 2-3 The Impact of energy improvement (Eurelectric 2003)

	Coal	+0.01% Efficiency	Oil	+0.01% Efficiency	Gas- CC	+0.01% Efficiency
Capacity (MW)	800	---	500	---	300	---
Load factor (h/y)	6,000	---	1,000	---	4,500	---
Total production (MWh)	4,800,000	---	500,000	---	1,350,000	---
Efficiency	42.0%	42.1%	44.0%	44.1%	57.0%	57.1%
Fuel consumption (t/y)	1,400,000	-3,382	98,000	-200	189,000	-331
CO2 emission (t/y)	3,800,000	-8,938	341,000	-800	451,000	-790

2.5 Factors Influencing Efficiency in Power Plants Systems

Generation efficiency in any country is the outcome of the available technologies. Each technology, under specific conditions, is designed to operate with a specific heat rate, which, as aforementioned, is known as the design efficiency or nameplate efficiency. However, actual efficiency during operation is normally below the design efficiency. There are several factors for why this is so, such as equipment aging, quality of fuel, local circumstances, operation conditions and maintenance, which are discussed in detail next.

2.5.1 Age (deterioration)

Generally, the average age of fossil fuel power plants in the world is around 30-40 years (Platts 2008) and over such a period, power plants efficiency decline due to several mechanical factors (ABB 2009; Chan et al. 2014). A study analysed the relation between efficiency and the average age of power plants fuelled by gas and coal in European countries (Graus et al. 2008). Both types' efficiencies were found to be affected by aging, but coal units showed less decline in efficiency compared to gas, as shown in Figure **2-6**. This could be related to the average age of coal power plants, which are considerably higher than gas units in Europe. On average, heat loss in turbines is around 0.25% per year. It appears fast during the first years of operation, and can reach 2% just in the first two years (IEA 2010a). Moreover, aging affects both efficiency and reliability, which are the most important indicators in operation. On average, the outage rate increases every five years and HR reduces by 2% every ten years (General Electric 1996). Figure **2-7** shows the change in HR over years for fossil fuel power plants plants. As can be seen, there are two type of HR deterioration, recoverable and unrecoverable. The former can be obtained through applying the required maintenance on time and according to the manufacturer's plan, while the other type cannot be restored. In both cases, "AS NEW" efficiency is not achievable over years.

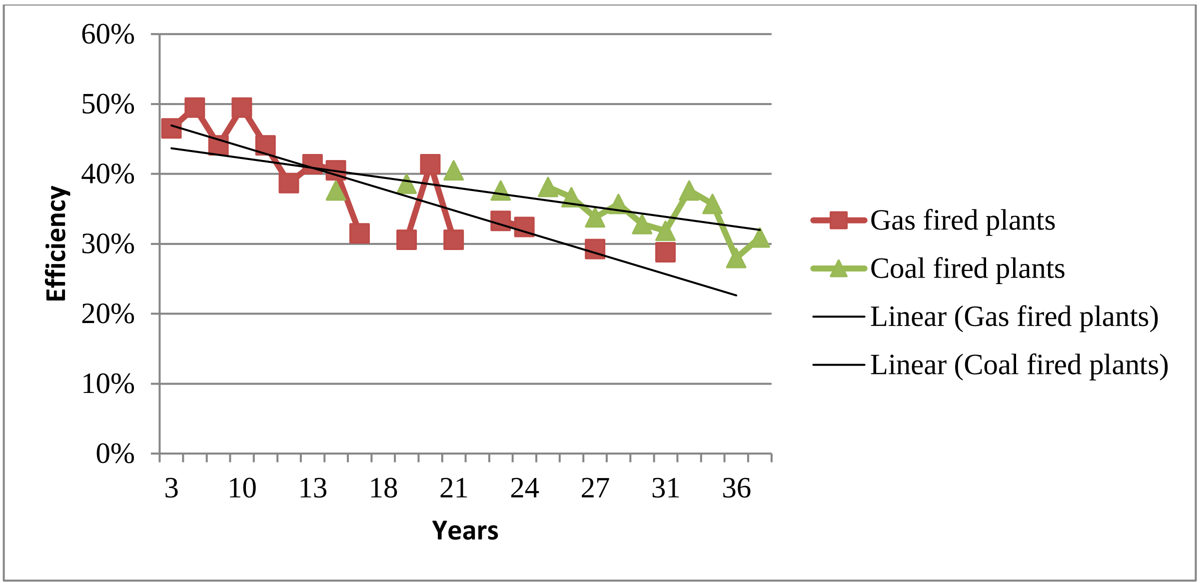

Figure 2-6 Average efficiency and average age of power plants in the EU 2005 (Graus et al. 2008)

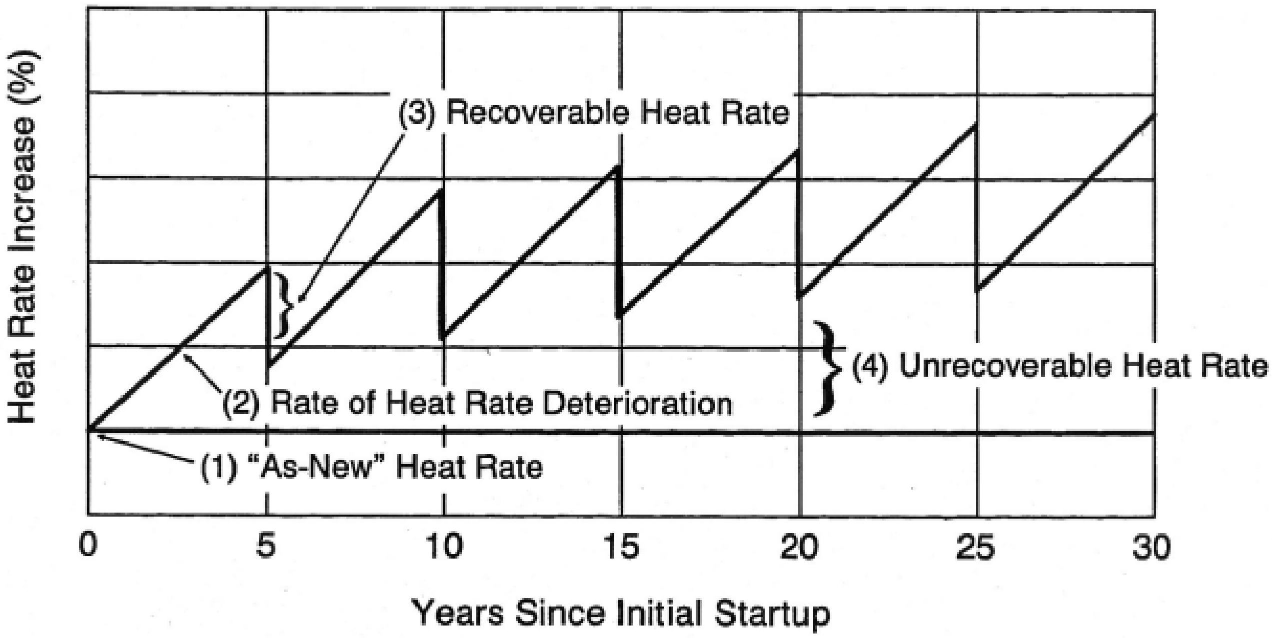

Figure 2-7 Age vs heat rate (General Electric 1996)

2.5.2 Environment Impact

It has been proved that changes in weather have a direct relation with turbine output and generation efficiency. Turbine performance is affected by the variation in ambient temperature in two ways: cooling water and mass flow of air. Colder water utilised in the cooling system leads to higher efficiency. A report estimated the loss in efficiency due to the rising water temperature can reach 2.5% (KEMA 2004). In addition, the rate of air mass flow decreases as temperature rises, which involves consuming additional power to compress the air and as a result, decrease turbine efficiency (Farouk et al. 2013). Research based on gas turbines located in the United Arab Emirates, elicited that a single degree increment[8] in temperature can lead to 0.1% reduction in efficiency and also reduces the turbine gross output by 1.47MW (De Sa & Al Zubaidy 2011). On the other hand, in a recent study it is argued that this correlation is not generic to all power plant types and that, in fact, it is specifically in relation gas turbines only (Colman 2013), since they are naturally very sensitive to weather changes (Wärtsilä 2015). The claim is based on two criteria, first, an increase in temperature reduces the energy needed in boilers. For example, if the outside temperature is 40°C the energy required to reach combustion temperature, is less than if it was -10°C. Second, for a specific volume of air, the quantity of oxygen is less in high temperatures than during cold weather and less oxygen injected means less efficiency. In fact, the author found that the impact on efficiency can fluctuate between +0.02 (increase) and -0.03 (decrease) percentage points per degree Celsius. In a different study, it was claimed that an increase in temperature from 5°C to 40°C decreases the rate of air flow mass by 11%. This results in a drop of net power output of 24% for a gas turbine, 9% for a steam turbine and 18% for combined cycle power plants, whilst efficiency decreased only for the GT, by 9% (Singh & Kumar 2012). However, in a more recent study it claimed that there is a reduction in efficiency per every single increase °C in ambient temperature, these values being: (0.03-0.07%) for gas turbines and 0.04% for combined cycles (Tiwari et al. 2013). Furthermore, altitude has an impact on efficiency. Specifically, power plants based in sea level cities provide higher efficiency than those located at a higher altitude due to the ambient pressure (Bellman et al. 2007). Nevertheless, the impact of altitude is small and can be neglected according to Arrieta & Lora (2005).

2.5.3 Fuel quality

The quality of fuel has an impact on power plant efficiency. For instance, the amount of ash contained in coal plays a role in this. By way of illustration, power plants that utilise coal with higher amount of ash can be less efficient than when coal with lower quantities of ash are used (Bellman et al. 2007). In addition, the efficiency of CCGT utilising natural gas is higher than if other types of gas are used, such as industrial process gas (Graus et al. 2008). In general, the impact if fuel quality is assumed not to exceed one percentage point.

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[8] The study considered ISO conditions as a standard reference.
Gas turbines (ISO 3977) standard reference conditions are: 15°C (59°F) and 101.3 kPa (14.7 psia), whilst combustion engines reference conditions (ISO 3046) are: 25°C (77°F) and 99 kPa (14.4 psia). (Wärtsilä 2015)

2.5.4 Pollution

The new regulations in many countries towards pollution abatement are having an impact on efficiency (Bellman et al. 2007), whereby controlling it requires the installation of equipment in power plants. This will increase the amount of internal electricity consumption, which affects the net efficiency in terms of an average of 2% for coal fired plants and 1% for power plants fuelled with gas, while gross efficiency can be affected by 1% (Worrell & Graus 2006).

2.5.5 Maintenance

Maintenance practice has a direct impact on power plant efficiency (Chan et al. 2014). Applying maintenance schedules according to standards and on time can ensure the unit's performance reliability, reduce outages and mitigate for the aging deterioration. Maintenance impact is estimated not to exceed 0.5 percentage point, according to Graus et al. (2008). However, they added, poor maintenance can reduce efficiency by up to 5 percentage points in some special cases.

2.5.6 Operation

Power plants operate according to the demands on the consumption side. However, demand changes at different times of the day, is affected by weather condition and varies across seasons. Furthermore, scheduled maintenance and forced outages affect the availability of generation units and consequently, their operation. These factors play a significant role in determining the units' usage intensity (capacity utilisation) which is known as the load factor (Department of Energy & Climate Change 2013). This can be defined as the percentage of the electricity produced by the unit in relation to the theoretical maximum that can be generated over a specific period (Farnoosh et al. 2014) and it is usually measured based on a full year (8,760 hours). However, power plants require shut down for maintenance, therefore, 85% load hour is considered as the maximum limit or 100%, if based on 7,500 hours per year. Inconsistent operation, such as partial load as well as frequent start up and shut down of generation units, consumes more fuel for electricity production and as a result, has an impact on efficiency (Chan et al. 2014; IEA 2010a).

Load operation of generation units has a significant impact on generation efficiency (Graus & Worrell 2009; Bellman et al. 2007; ABB 2009). Hiebert (2002) claimed the existence of strong evidence linking the load factor of power plants utilising fossil fuel and efficiency. That is, the increases in load factor are positively reflected in operation efficiency and vice versa (Hiebert 2002). For instance, the new regulation in the UK to cut down the amount of CO_2 arising from fossil fuel generation has accomplished this by decreasing the load factor of coal power plants

(1996-1997). This action has led to a slight decline in the thermal efficiency of these plants (Graus et al. 2007). Moreover, in France, fossil fuel efficiency fluctuates on yearly basis. The reason underlying this is related to the changes in load factor of fossil power generation, as illustrated by Graus (2009).

Losses in efficiency are sensitive to the load factor of plants. For instance, (5-7) percentage points less than the design efficiency is the result of a power plant operating at 30% of its full capacity, while increasing the operational load to 85% can reduce these losses to just (1-2) percentage points (Graus et al. 2008). On average, (3-4) percentage points is estimation for half load operation (Graus & Worrell 2009), as shown on Figure **2-8**. This drop can vary according to technology type. For instance, the efficiency of CCGT operating at half load is 45%, instead of 52% efficiency, if operated at full load (IEA-ETSAP 2010). Alternatively, fuel consumption per electricity unit generated is affected by loading, such that half load can increase fuel consumption by 6% in coal fired and 25% in CCGT units. There is even greater consumption if loading drops to 25%, reaching 28% and 79% in coal and gas units respectively, as shown in Figure **2-9**.

Whilst coal fired power plants are affected by part loading, they are less sensitive to it compared to CCGT. That is, gas fired CCGT efficiency can drop to 40% instead of 50%, if operated at half load. By definition, an increase in fuel consumption per generated electricity unit means lower efficiency and higher emissions. In other research, it has been claimed that half load operation could result in 5-10% reduction in operational efficiency compared to design efficiency (Bellman et al. 2007). These authors added, among all factors influencing efficiency, the only two that can be controlled are operation and maintenance. They can reduce HR by (500-1000 BTU/kWh). In sum, load hours is considered as the most significant factor affecting efficiency (Graus et al. 2008).

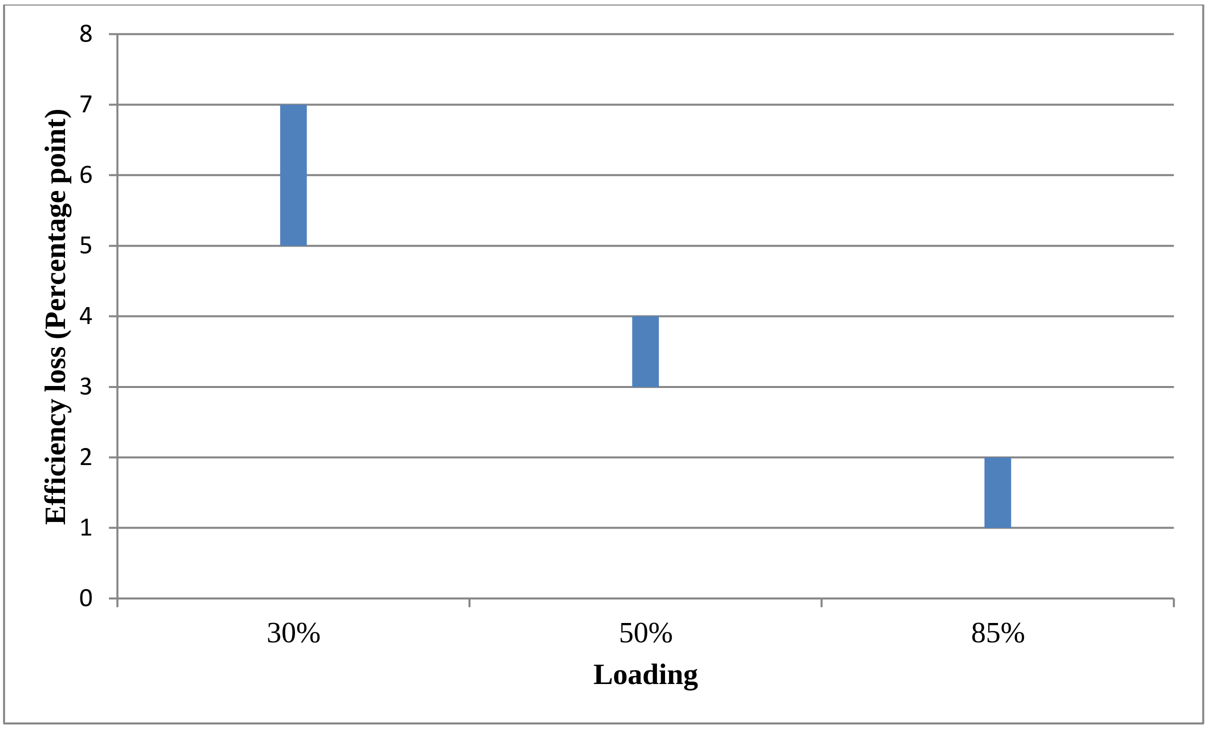

Figure 2-8 The impact of loading hours on operational efficiency

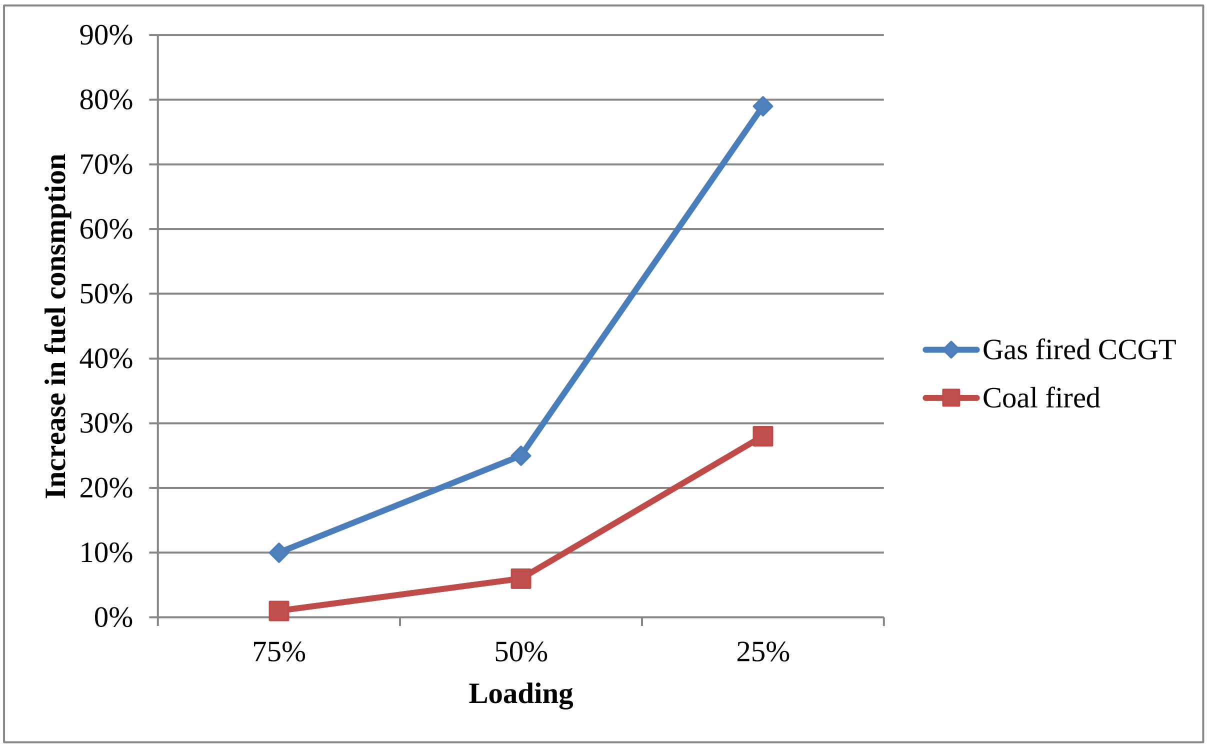

Figure 2-9 Impact of loading on fuel consumption (Flextricity 2013)

In SA, demand is fed through a mix of different types of power plants with different characteristics and different costs of production. To obtain the optimum operation, power plants are classified according to their cost in generating power. Units with the lowest cost of production are located on the top and have the priority in terms of operation. This ranking is known as the “Merit- Order” (Farnoosh et al. 2014). Literally, the “Merit Order” of operating the power plants in SA is planned based on the cost of unit HH/kWh (SEC, 2011), with the calculation being based on the cost of consumed fuel per unit (HH/BTU). The main objective is to insure sufficient production under minimum cost within the security limits. This rule has some exceptions so as to avoid interruptions, such as shortage in supply, sudden low voltage or unexpected increase in demand side etc. The operation of the network is controlled by an LDC (Load Dispatch Centre) located within the SEC. Theoretically, this means efficiency is a major criterion of operation since it is related with cost.

2.5.7 Subsidy

Subsidy has different definitions depending on the context. Bacon & Robert (2014) defined subsidy as "**a feature of those markets where prices are controlled by the government, rather than being set by a free market**". While "**a consumer subsidy is defined as the difference between the actual price paid by a consumer for an item, and the price at which that item would be sold in a free market**" (Bacon 2014). Alyousef & Stevens (2011) defined it as the "**difference between the market price and the real opportunity cost of the commodity, therefore it's called negative taxes**."

Subsidies have been introduced to support low income people in getting access to electricity, which they could not do without it. They are aimed at promoting quality of life, social fairness and energy security for such individuals (World Bank 2010). However, in some cases, they can serve against their mission, for since more energy is consumed by those with high incomes, then more subsidies are received by them compared to the segment that they are designed for (Bacon 2014). Several reports found this to be the case (International Monetary Fund 2014; IEA 2011). To illustrate, 50% of total energy subsidies are obtained by the top 20% income families in Sudan, for example, while the poorest 20% houses, which should receive the largest share of support, do not exceed more than 3% of total subsidies granted. This scenario applies to several countries that subsidise energy. Worldwide, in 2010, the International Energy Agency reported that the lowest 20% income households receive no more than 8% of total money spent on fossil fuel subsidies (IEA 2011). Consequently, energy subsidies are not achieving their goal of supporting low income families and hence, they do not provide social fairness.

Applying subsidies without restrictions (for all end users with different income) has led to an increasing burden on the governments' budget every year. This applies to both supply side if fuel is being subsidised and the demand side if the tariff is discounted by the authorities.

Economically, subsidies mask the actual cost of resources, thereby generating a distorted price pattern (International Monetary Fund 2014) which hinders the correct decision making for better utilisation of national resources (Alyousef & Stevens 2011; Krane 2013). In addition, fuel subsidies do not reflect the actual cost of production on the supply side, which also leads to price distortion and has significant consequences regarding the efficiency and deployment of available assets (Fattouh & El-katiri 2012b). Moreover, subsidies make privatisation of the electricity sector unattractive since the market does not have a sense of competition (Fattouh & El-Katiri 2013). It has also been contended that they are a main cause for inefficient consumption of resources (Institute for Energy Research 2011). Finally, the world bank (2010) has added that subsidies affect the efficiency of both sides, i.e. electricity providers and end user, negatively.

On the supply side, subsidies discourage any investment, by suppliers in improving efficiency (IEA 2014; Krane 2012). In addition, they lead to underinvestment in infrastructure, including generation capacity, transmission and distribution networks, which can reduce whole system reliability and increase the level of emissions (Bacon 2014). Moreover, it tends to favour GT over CC units in operation, which will be negatively reflected in the average efficiency (Groissböck & Pickl 2016). Finally, renewable energy cannot compete in the presence of fossil fuel subsidies (World Bank 2010; Fattouh & El-katiri 2012a).

On the demand side, subsidies lead to unsustainable, wasteful and rapidly growth of electricity consumption and encourage smuggling (Gelan 2014; International Monetary Fund 2014; Bacon 2014; World Bank 2010; Krane 2013). Research by Fattouh and El-Katiri (2012) found that energy subsidies are one of the main causes of inefficient consumption of energy and they diminish the value of saving (Farrell et al. 2008). Worldwide, subsidies removal could lead to 10% saving in fossil fuel consumption, as estimated by the International Energy Agency and this would lead to a decrease in emissions by a similar amount by 2050 (World Bank 2010).

Saudi Arabia subsidises fuel prices heavily for all consumers in different sectors (electricity, transport, industry…etc.) In fact, it is the second largest fuel subsidising country in the world (IEA 2011), with local consumers paying less than one third of the international fuel price. The World Energy outlook estimated that the economic value of fossil fuel subsidies in Saudi Arabia was US$ 35 billion in 2009 (IEA 2010b) and this jumped to US$ 43 billion in 2010 (IEA 2011). In the electricity sector, there are two different types of subsidies, with the first being fossil fuel subsidies, whereby the price paid by electricity providers is far below the international price, as shown in Table **2-4**.

Table 2-4 Local and international fuel price in Saudi Arabia US$ (ECRA 2013a)

		Price ($/M.BTU)		
Fuel	Consumption	Local price (SA)	International	Discount
Gas	46%	0.75	9.04	92%
Crude	31%	0.73	19.26	96%
Diesel	15%	0.67	21.67	97%
HFO	8%	0.43	15.43	97%

The selling price of electricity units is determined by the government at a discounted price as a subsidy for the end users and suppliers are compensated according to the difference between the selling price and production costs. Alyousef & Stevens (2011) have estimated the cost of end users' subsidies around US $13.3 billion (SAR 49,882 million), as shown on Table **2-5**. This estimation is based on the different between the average costs of production per electricity unit given by SEC (37.2 HH/KWh) and the selling price per sector.

Table 2-5 Average sales price and total subsidies per sector in SA (2010) (Alyousef & Stevens 2011).

Sector	Average sales price (HH[9]/KWH)	Subsidies (million SAR)
Residential	7.5	-32,262
Commercial	20	-5,041
Governmental	26	-2,746
Industrial	15	-8,562
Agricultural	12	-912
Other	20	-1,311
Total	---	49,882

According to the Electricity and Co-Generation Regulatory Authority reports. the total subsidies in electricity sector paid by the government in 2013 was SAR150 Billion (£25 Billion) (ECRA 2014a). This figure is increasing every year owing to the increase in the amount of fuel consumed in producing electricity.

In Saudi Arabia, subsidies seem to be one of the main causes leading to rapid growth on the demand side (Alyousef & Stevens 2011). In addition, the delay in utilising alternative resources in electricity generation is related to the existence of fossil fuel subsidies (Bachellerie 2012). For instance, nuclear can only compete with fossil fuel under international prices (Yamani

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[9] SAR 1=100 HH

2012). Therefore applying the international fuel price would be the more attractive for alternative energy resources, including renewables (Groissböck & Pickl 2016).

There have been calls for the elimination of subsidies on both the supply and demand sides. This involves consideration of several political, economic and social aspects, which not among the goals of this study. Nevertheless, subsidies have been illustrated as having an impact on generation efficiency. Fuel subsidies are given to electricity providers with the aim of providing support in selling electricity with low tariffs and to avoid losses. However, cheap (subsidised) fuel prices is one of the factors affecting the generation efficiency in Saudi Arabia.

2.6 The Role of Industry Reform

Restructuring the electricity sector has been implemented in several countries in recent decades. The movement from a monopolised traditional vertical market to more privatised divested firms was driven by several technical and financial reasons, as mentioned by several authors (Bacon & Besant-Jones 2001; IEA 1999; Patterson 1999). Service interruption, high cost of production, inefficiency and increasing financial demand by the electricity providers for subsidies and loans to build and upgrade the existing infrastructure have pressurised governments into restructuring. In addition, governments would generate revenue from reform instead of consuming the national income. Consequently, the main objectives have been to attract investment, encourage competition as well as improving operation and efficiency (Malik et al. 2011; Borenstein & Bushnell 2000), which will lead to reduced unit cost (Chan et al. 2013; Al-Ajlan et al. 2006).

Any reform should contain the basic criterea which will enable it to achive its goals, as described by Bacon & Besant-Jones (2001):

1- Commitment to profitable operation;
2- Promote a competitive market especially in the generation sector to promote efficiency;
3- Unbundling the electricity activities generation, transmission and distribution to operate independently.
4- Privatisation of power plants into several generation companies and distribution firms;
5- Policy implementation should be managed by an independent organisation, not by the government, to ensure transparency.
6- The government should focus on legislation while operation should be undertaken by investors.

In 2007, ECRA announced a comprehensive long term plan reform for the electricity market in the country by unbundling the main activities into several entities so as to promote a competitive market and diminish monopoly (ECRA 2009a). This plan consists of different stages. The first stage includes unbundling SEC into three different companies: generation, transmission and distribution. Then, the generation and distribution were to be broken up into several firms and retaining the transmission as a channel between generation and distribution entities, as shown in Figure 2-10.

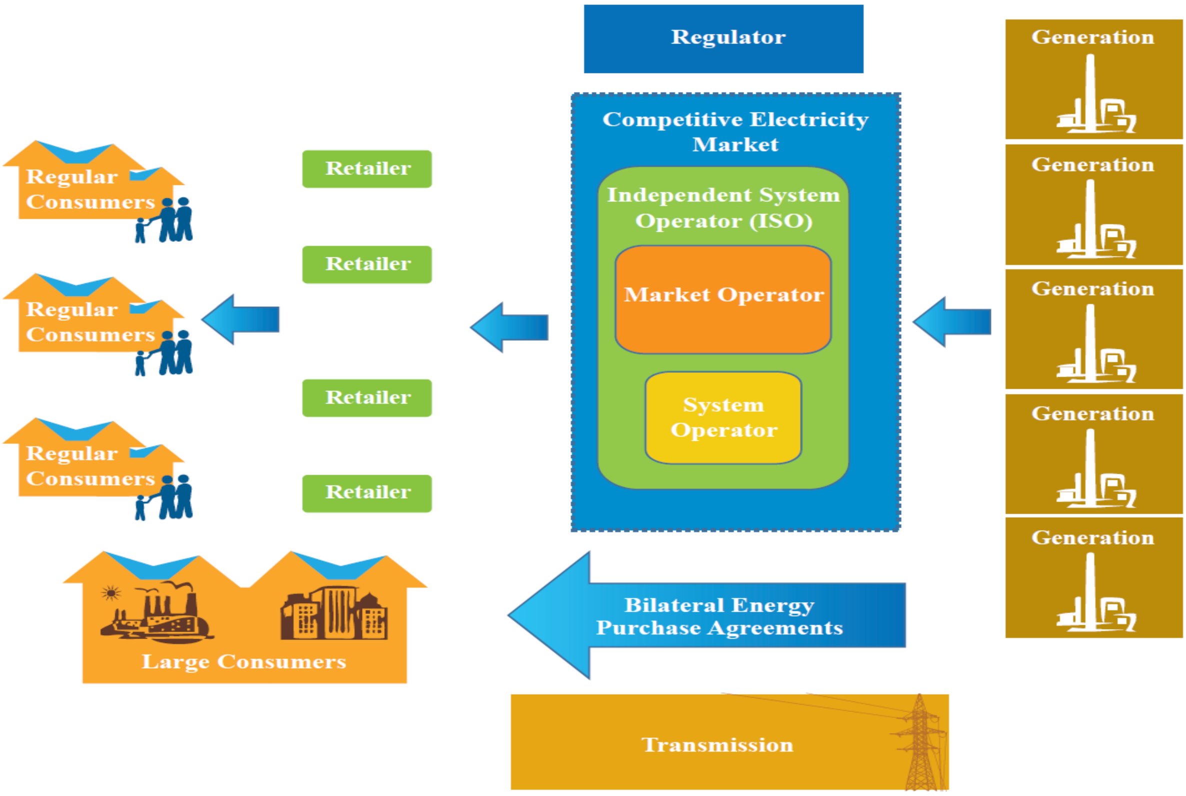

Figure 2-10 Final stage of the electricity sector structure in SA (ECRA 2014a)

Some research conducted in different sectors, such as aviation, power, water telecommunication etc. has reported efficiency improvement following reform implementation (Newbery & Pollitt 1997; Ng et al. 2001; Saal & Parker 2001). Nevertheless, efficiency gains presented in these works were mainly in relation to manpower productivity. For instance, some studies have shown that, firms that have been exposed to reform gained 3-12% savings, which has been achieved through reduced forced outages, workforce reduction and reducing expenditure, but was not related to fuel consumption (Markiewicz et al. 2004). Moreover, in India for example, reform has led to an increase in system availability by 10% and 25% reduction in service interruptions and unit cost, but the generation heat rate did not fall (Malik et al. 2011).

The existence of heavily subsidised fuel, offered to power plants, results in lack of incentive to upgrade to more efficient technology (Matar et al. 2014) or to improve efficiency (Groissböck & Pickl 2016). This issue represents an obstacle to electricity market reform in Saudi Arabia, hindering it from becoming a liberalised and competitive market or improving efficiency. Bushnell and Wolfram (2005) believe incentive is more important in promoting efficiency than reform. For instance, "The incentives for improving fuel efficiency and maintaining equipment to prevent breakdown depends on how plants are compensated" (Malik et al. 2011). Moreover, A study by Knittel (2002) pointed out that any programme that is grounded on incentives, based on fuel consumed in generation has positively improved technical efficiency, because it promotes initiatives by providers. On the other hand, the absence of fuel based incentives in regulations result in less motivation for power plants to reduce heat rate or avoid penalties for poor efficiency (Knittel 2002).

The current scheme of subsidies in SA and absence of motivation do not support the reform objectives of pressurising providers into operating competitively and engaging in more efficient production. However, subsidies can be utilised as a tool of an incentive scheme.

2.7 Emissions

The increasing concentration of CO_2 has triggered the attention of governments across the world of the need to tackle this issue. A report published by the International Energy Agency shows energy use accounts for 68% of global emissions including (CO_2, CH_4 and N_2O) and fossil fuel represents 82% of the total energy supply in the world. Oil represents 31% of total primary energy supply in the globe, followed by coal and gas with 29% and 21%, respectively. Moreover, coal is the source of 46% of the total CO_2 emissions in the world, followed by oil with 33% and gas with 20% (IEA 2015). Electricity and heat produce the largest share, 42%, of total CO_2, whilst the transport and industry sectors are the second and third largest sources of CO_2, with 23% and 19%, respectively.

The quantity of CO_2 released per unit of electricity (g/kwh) is known as CO_2 intensity of power generation (Graus 2010). It varies according to the fuel type, as shown in Table **2-6**. In general, coal has the highest intensity followed oil and natural gas is the least CO_2 emitter. Nevertheless, the emissions rate of each product can vary according to the type of cycle in power plant, as show on Figure **2-11**. For instance, a gas fuelled turbine can range from 360 in CC up to 580 g CO_2/kWh in single cycle units.

Table 2-6 Average carbon dioxide rate for selected fuel type in electricity generation in OECD countries (IEA 2013)

Fuel type	g CO2 / kWh
Lignite	1,005
Sub- bituminous coal	925
Bituminous coal	860
Peat	745
Diesel	715
Fuel oil	670
Crude oil	635
Natural gas	400

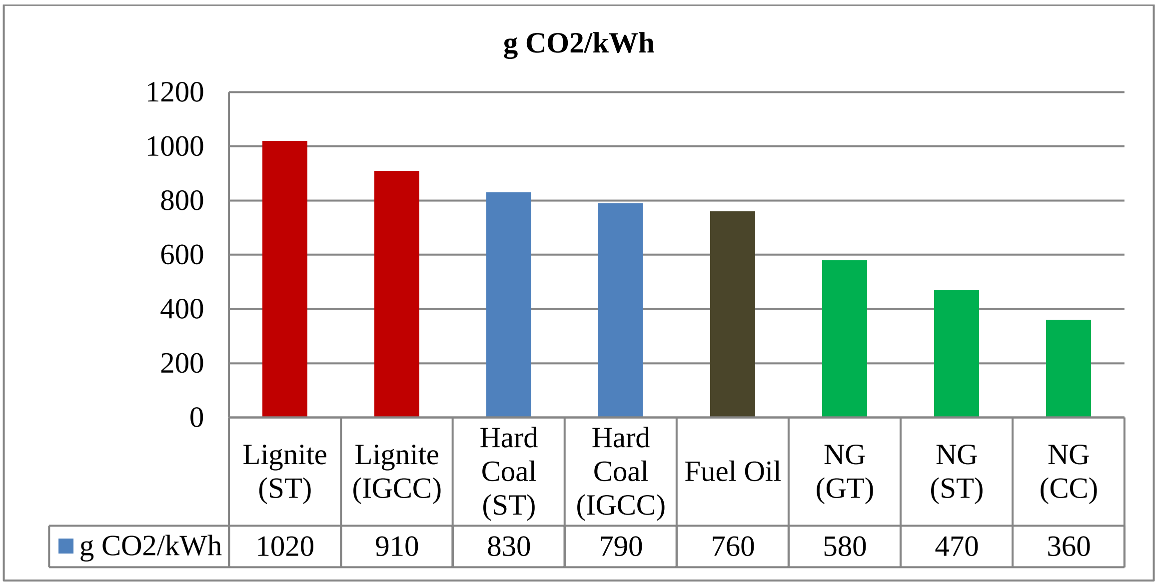

Figure 2-11 Average CO2/ kWh based on unit type (VGB powertech 2004) (VGB Powertech 2015)

Saudi Arabia is the tenth largest CO_2 emitter country in the world (UCSUSA 2011; Aman 2015). CO2 emissions from the consumption of fossil fuel energy have jumped from 393 Mtonnes in 2007 to 520 Mtonnes in 2011 (The World Bank 2015). This can be linked to the country's heavy and increasing reliance on oil and natural gas in generating electricity, transport and industry. The average CO_2 emissions are around 17 tonnes per capita, similar to the USA, compared to 7 tonnes in the EU, 6 tonnes in China, which are above the global average standing at 5 tonnes per capita (Nachet & Aoun 2015). A study has shown that CO_2 produced from power generation in Saudi Arabia was around 328 Mtonnes in 2008 and is expected to reach 655 Mtonnes by 2030 (Alyousef & Abu-ebid 2012).

The global average CO_2 stemming from electricity production from 1990-2011 was around 533g/kWh, while in SA was far above this, being 749-796g/kWh (Brander et al. 2011). In 2011, electricity produced in SA accounted for 41% of the total CO_2 produced in the country (IEA

2013). Fossil fuel, as a major source of emission, is the sole source of electricity in the kingdom and combined with low efficiency, results in a higher rate of emissions. It has been reported that, 0.1% efficiency improvements in a 500 MW power plant, can reduce annual emissions by up to 800 tonnes in oil and gas power plants, as shown in Table **2-7**. Consequently, improving generation efficiency, which is the aim of this research, will contribute to a reduction of CO_2 emissions in Saudi Arabia.

Table 2-7 Impact of improving efficiency on emissions (Eurelectric 2003)

	Oil	+0.01% Efficiency	Gas- CC	+0.01% Efficiency
Capacity (MW)	500	---	300	---
Load factor (h/y)	1000	---	4500	---
Total production (MWh)	500,000	---	1,350,000	---
Efficiency	44.0%	44.1%	57.0%	57.1%
Fuel consumption (t/y)	98,000	-200	189,000	-331
CO_2 emission (t/y)	341,000	-800	451,000	-790

2.8 Methodology

An improvement method must deliver it continuously and includes “improvement initiatives that increase successes and reduce failure” ,as stated by Deming (Juergensen 2000). Among all improvement philosophy, Lean and Six Sigma are used widely and considered among the top of the list. The prosperity gained from the previous successful implementation in several industries with persistent and determined to continuous improvement by utilising their own tools and techniques.

2.8.1 Lean, Six Sigma and Lean Six Sigma

Lean is defined as a “**dynamic process of change, driven by a set of principles and best practices aimed at continuous improvement**” (Womack et al. 1990, cited in Svensson et al. 2015). It has been known widely as a quality tool invented by Taichi Ohno in the 1940s and the first implementation was by the Toyota Motor Corporation (Furterer & Elshennawy 2005). Lean aims to minimise the final product or service cost by eliminating waste from the process (Muda in Japanese) to improve efficiency (Antony 2011; Salah et al. 2010). It involves focusing on an obvious problem with a more efficient approach so as to create value with less investment (Womack et al. 1990). The seven aspects of waste are:

- Over production
- Defects
- Unnecessary inventory
- Inappropriate processing

- Excessive transportation
- Waiting
- Unnecessary motion

Lean is aimed at removing any non-value added activity or transforming it to add value to the process. This can be applied using the framework VVFPP (Identify value, Identify value stream, Flow, Pull and Perfection) (Mousa 2013) and by utilising its tools and techniques, such as standardisation, Poka-yoka 5S (sort, set in order, shine standardise and sustain), Kaizen, Value Stream Mapping etc., However, some researchers have contended that Lean is not suitable for application in all businesses (Andersson et al. 2006).

Six Sigma is "**a well-established approach that seeks to identify and eliminate defects, mistakes or failures in business processes or systems by focusing on those process performance characteristics that are of critical importance to customers**"(Antony 2008). It was developed by Mikel Harry in the 1980s and applied by B. Smith in 1987 in the Motorola Corporation (Salah et al. 2010), followed by the General Electric Corporation in the 1990s, Caterpillar, JPMorgan, GMAC Mortgage, AIG, LG Chemicals, DOW Chemicals and DuPont (Sharma 2003). Six Sigma is more suitable when the root causes are unknown (Svensson et al. 2015), because it applies statistical and analytical methods in tackling and revealing these root causes to problems, with the aim of minimising defects through variations reduction and continuous improvements (Andersson et al. 2006; Corbett 2011). Pepper & Spedding (2010) defined a defect as a product or service that does not satisfy the end user requirements.

There are two main frameworks that can be used in applying Six Sigma (Andersson et al. 2006). The first methodology is DMAIC (Design, Measure, Analyse, Improve and Control), which is widely known regarding its implementation. The second approach is DMADV (Define, Measure, Analyse, Design, Verify), which is normally used when the DMAIC does not achieve an acceptable level of success in terms of customer satisfaction or business strategies (Mousa 2013), since the second one concentrates on redesigning and more verification to achieve the required goals. Several tools can be used such as Pareto analysis, a cause and effect diagram, control chart etc., however, the use of these tools varies according to the project requirements (Salah et al. 2010).

Six Sigma has justified its appropriateness to different industries, including manufacturing and services (De Mast 2004). The driving force for implementing Six Sigma relates to the significant financial impact that can occur. For instance, the Swedish car manufacturer Volvo gained more than 55 million euro in two years after adopting Six Sigma in 2000 (Mousa 2013). The goal of Six Sigma in this case was reducing the percentage of error with no more than 3.4 per million products (Mousa 2013). Nevertheless, Andersson et al. (2006) believe that Six Sigma lacks a comprehensive view of the system, since it focuses on solving a problem in a specific part of the organisation and hence, the proposed solution may affect other related divisions negatively.

According to Pophaley & Vyas (2015) Six Sigma has passed through different stages over the years. Prior 1990, which is known as the first generation, defects elimination, cost reduction, quality of product and process improvement were the focus. In the second generation, between 1990 and 2000, it became more comprehensive and was concentrated on the quality of the whole business instead of the product. Since 2000, the third generation emerged named Lean Six Sigma. “Lean and Six Sigma”, “Lean Six Sigma” or “Lean Sigma” is considered the most significant continuous improvement approach for accomplishing operational and service distinction in any industry (Salah et al. 2010). LSS is defined as **“a business strategy and methodology that increases process performance resulting in enhanced customer satisfaction and improved bottom line results”** (Snee 2010)**.** It is the latest enhancement methodology that has been utilised widely around the world. Its effective process is supported by several tools and techniques to solve problems and achieve enhancements, have resulted in being the choice of any improvement plan (Snee 2010)**.**

The integration of Lean and Six Sigma has become a more effective tool leading to continuous improvement (Smith 2003), reduced costs of production (Albliwi & Antony 2013) and expediting enhanced outcomes more than any system can achieve alone with less time and effort (Bhuiyan & Baghel 2005; Antony 2011), because they are integrated with each other (Andersson et al. 2006; Zhang et al. 2012). The combination of LSS has evolved to cover the gaps, disadvantages and to avoid the chance of failure of applying each methodology separately (Arnheiter & Maleyeff 2005). In sum, it is a balanced approach between variation reduction and waste elimination for achieving continuous improvement.

The main difference between the two is that Six Sigma emphasises defects reduction, while Lean concentrates on eliminating waste (George, Rowlands and Kastle 2003; Andersson et al. 2006). However, there is a similarity in their concepts, since Six Sigma aims to eliminate defects, which can be considered as a waste from a Lean point of view since it requires reworking. Both of them are quality methodologies, but each has a different point of view in relation to quality improvement and therefore, different techniques are used (Pepper & Spedding 2010).

Several research endeavours have demonstrated that the integration of Lean with Six Sigma does not lead to any of their concepts conflicting (Salah et al. 2010) and there is clear evidence of the suitability of their combination (Corbett 2011). However, Bendell (2006) has opined that the professed compatibility is philosophical and not practical, because some evidence of inappropriateness appeared in applying the two methodologies. Therefore, a unified approach in implementation could solve this issue.

Less attention has been paid to the implementation process of Lean Six Sigma (LSS) (Zhang et al. 2012). As a result, there is no specific implementation guide or framework to be applied or clear explanation of the tools and techniques that should be used (Albliwi & Antony 2013; Kumar et al. 2006; Proudlove et al. 2008; Pepper & Spedding 2010). In response to this, Laureani & Jiju (2011) have called for the establishment of a recognised body for LLS, with the aim of building an international standard. Some researchers have proposed different implementation frameworks that combine Lean with Six Sigma. For example, Salah et al. (2010) have suggested using DMAIC as a framework for implementation. Regarding which, Six Sigma tools, techniques and frameworks could be implemented to deliver lean concepts more effectively and increase the success rate (Sharma 2003). In general, the nature of the business and the project can best determine the most appropriate implementation method (Antony 2014).

Many organiations have applied LSS to obtain its advantages, with aim being to improve service quality and process efficiency by removing waste and decreasing variations (Furterer & Elshennawy 2005; Zhang et al. 2012). Its implementation at Caterpillar Inc. in 2001, for example, achieved significant financial savings and substantial growth in revenue through exploring innovative solutions and process restructuring (Byrne et al. 2007). The first integration of LSS appeared in 1986, deployed by the George group in the United States of America (Albliwi & Antony 2013), then it was developed by BAE Systems Controls in 1997, titled Lean Sigma (Phillips 2014) and this was followed by the Maytag Corporation in 1999, Northrop Grumman, Lockheed Martin Aeronautical Systems (Furterer & Elshennawy 2005) General Electric, Honeywell and Motorola (Timans et al. 2012). LSS has been used in different manufacturing sectors and several quality specialists have proposed its appropriateness in other areas, such as services and government sectors (Zhang et al. 2012; Bossert & Grayson 2002).

2.8.2 Mathematical Modelling

Mathematical modelling is a method of understanding system behaviours by utilising equations to express and formulate the relationship in any system (El-Haik & Al-Aomar 2006). It is a powerful tool that has been applied in different subjects to identify the future value of variables or to provide an in depth view by understanding the proportionality in the system to solve problems (Giordano et al. 2013). Using mathematical modelling requires understanding of the problem that needs to be solved and having the required data prior to formulating the model. Then, the model is built and analysed to generate a mathematical conclusion. Subsequently, explanation and/or relations between variables can be determined, or prediction can be produced by interpretation. Applying real data to verify the model is the final stage, as shown in Figure **2-12**.

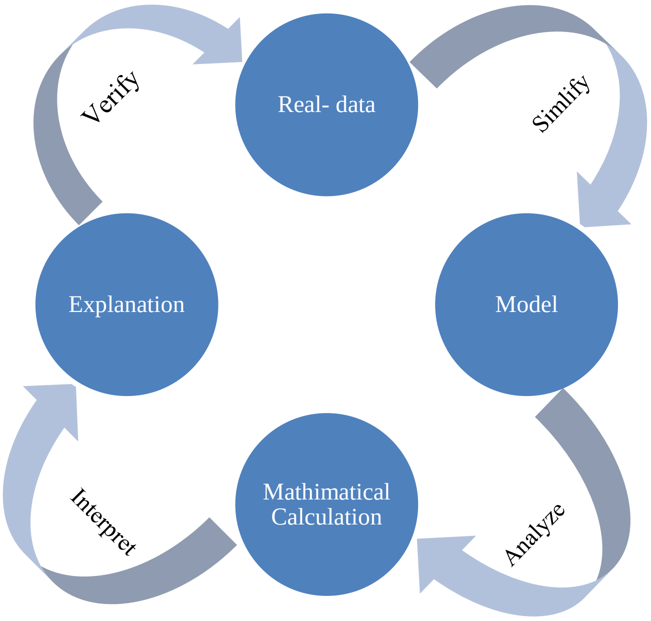

Figure 2-12 modelling process (Giordano et al. 2013)

In the power sector, mathematical model has been used widely in relation to various aspects. For instance, issues related to demands, water flow and fuel have justified the appropriateness of applying mathematical model in solving problems relating to that industry (Edwards & Hamson 2007) .

2.8.3 Mathematical Programming

Mathematical programming (MP) is a planning tool for delivering the optimum option based on predefined requirements, which Liberti (2009) defined as “**descriptive language used to**

formalise optimisation problems by means of parameters, decision variables, objective functions and constraints, while such diverse settings as combinatorial, integer, continuous, linear and nonlinear optimisation problems can be defined precisely by their corresponding formulations”. There are four stages to developing a mathematical model, as proposed by Hassanzadeh (2016). First, determine the decision problem, which is important for building the MP, which consists of constraints, variables and objectives. Second, the data needed to be utilised in the model are collected. Third, there is problem solving to generate the optimum option. Finally, sensitivity analysis is performed to avoid any errors and consider any changes, proactively.

There are several types of MP, with each having its own characteristics. Linear programming (LP) is used to maximise or minimise a specific objective by changing the value of some variables under certain constraints based on linear relationships. If the relationships are nonlinear then nonlinear programming (NLP) can be applied. Regarding integer programming, variables are limited to integers only. Under goal programming (GP), several criteria are considered at the same time instead of a specific objective (Nejadi 2016). MP has been widely used in different sectors, such as research, business, government, marketing, manufacturing etc.

2.9 Summary

The increasing demand for electricity has led to a great deal of pressure on natural resources consumption. Despite the development of alternative resources, fossil fuel remains the primary source of energy. The efficiency of fossil fuel generation has improved considerably in the last decade. However, this improvement varies according to fuel type and the technology utilised. The amount of waste is still enormous, which happens mostly during the generation stage, but this does have the potential to be mitigated. This would lead to a significant saving in fuel consumption and emissions reduction. There are several factors that can lead to inefficiency in generation, with the load factor being the most salient. Subsidies are also considered as being a serious indirect cause of inefficiency. Privatisation has been proposed as having a positive impact in terms of attracting investment and developing competition in the electricity market. However, this does not lead to efficiency improvement, unless incentives regulations are included.

In Saudi Arabia, efficiency has not received sufficient attention. Regarding the generation phase, it is considered among the lowest performing countries in the world, whereas its losses in transmission and distribution networks are about the global average. Lack of consistent data of annual efficiency in the official reports do not support adequate and consistent comparisons. Limited research has analysed the main reasons causing inefficiency in the kingdom or proposed ways of tackling it. Technology type and lack of efficient units have been mentioned as primary reasons. As a result, further investment has been recommended for improving the average level of efficiency in the kingdom.

To the best of this researcher's knowledge, no previous studies have examined in depth the main causes leading to the current level of efficiency and proposed a comprehensive improvement plan without seeking additional fund. In this study, a mix of methods approach is adopted to meet this challenge of delivering improvement in electricity production efficiency without any further investment. That is, the aim of this research is to improve the generation efficiency in the electricity sector by identifying the main causes of inefficiency and proposing solutions for tackling them. This requires identifying the current level of efficiency. The next chapter will discuss in detail the methodology utilised in this research.

Chapter 3 Methodology

3.1 Introduction

The literature review revealed that Saudi Arabia is amongst the least efficient countries in the world in terms of electricity generation. In addition, several causes were mentioned regarding efficiency loss. This research is aimed at improving and sustaining the level of efficiency by identifying and proposing solutions to the most relevant and influential factors leading to low efficiency in the kingdom. Finding these causes requires in depth analysis of previous efficiency figures of power plants in SA. However, the unavailability of consistent data in official reports regarding efficiency figures, means that it is necessary to calculate estimates of the current level of efficiency to determine the current situation.

The viability of any proposed changes requires implementation to justify it. However, their actual implementation is not possible, due to the scale of the targeted sector and sensitivity. Hence, an alternative implementation plan is needed to justify future improvement. Therefore, this study requires a methodology that can fulfil the research requirements and overcome the challenges. In this chapter, a methodology that involves building a model that integrates LSS, simulation and mathematical modelling is presented and explained.

3.2 Need for a Comprehensive Methodology

Improved efficiency means extra production or less fuel consumption, which results in waste reduction (Bellman et al. 2007). The aim of this study can be seen as quality improvement of the electricity system and any such improvement process requires measurement to determine the existing level of efficiency. In this study, calculated efficiency is considered as the quality measure. Inefficiency results in consuming additional fuel, which is considered as waste under the Lean philosophy. Prior to any improvement plan, the gap should be measured and major reasons must be identified. Then, the causes should be eliminated to enable the achievement of a significant change and sustainability. On the other hand, with the Six Sigma perspective, the focus is on variation and tackling the root causes, which is one of the objectives of this study.

The low level of efficiency in SA resulting in high consumption of fuel and subsidies can be considered as a waste, according to the Lean concept. These consumptions are not adding value to the system and could be mitigated to reduce cost, increase the value of the whole process and to improve efficiency. The main objective of Six Sigma is clearly related to the aims of this research, for one of which is to examine the root causes leading to the variation in the power plants' heat rate that is affecting the average level of generation efficiency in the kingdom.

The main reason for choosing Lean Six Sigma is that it can help fulfil the requirements of this research. The aim is to improve system efficiency and to reduce fuel consumption by identifying the main causes leading to inefficiency as well as proposing a sustainable framework for delivering continuous improvement. Lean's main objective is waste removal and efficiency improvement. However, efficiency cannot be improved unless the main causes are revealed and treated. Therefore, there is a need to address the main causes leading to low efficiency. Six Sigma is a problem focused methodology. It utilises the data to distinguish the main reasons leading to the problems and under it, the assumption is that system output can be improved, if process variation is reduced (Nave 2002).

3.3 Lean Six Sigma Implementation

How to implement Lean Six Sigma is a matter that is contested. Bhuiyan & Baghel (2005) have suggested starting by applying Lean as a first stage to eliminate waste, then following this with Six Sigma to reduce variation, which the authors argue can simplify the determination of variants. On the other hand, Bendell (2006) opposes this form of implementation, because starting with waste removal can lead to some obstacles when applying the Control stage in Six Sigma. Crawford (2004) recommends starting by applying Six Sigma to maximise process effectiveness, followed by Lean to develop system efficiency. Snee (2005) believes, whether starting with Lean then applying Six Sigma or vice versa, are both useful, with each having its advantages and disadvantages. However, it is not recommended to be used in isolation (Svensson et al. 2015) and Salah et al. (2010) contend that to achieve better outcomes they must be applied concurrently. These authors identify six different ways of applying Lean and Six Sigma. First, implement the Lean methodology as a main framework and use Six Sigma as a tool within it. Second, apply Six Sigma as a major methodology and utilise Lean techniques within DMAIC. Third, use both methodologies completely independently, with each focusing on different issues. Fourth, Lean and Six Sigma can be deployed unconnectedly in parallel to tackle the same problem at the same time. Fifth, apply Lean first completely and then Six Sigma or vice versa to address the same problem. Finally, the most preferred option is merging the two methods and apply them simultaneously.

There is no standard framework for applying Lean Six Sigma, and there are different opinions as to the selection of which tools to be used during the implementation. For instance Corbett

(2011) suggests that the selection of tools to be used in applying Lean Six Sigma depends on the nature of the industry and the project requirements. Furthermore, Pepper & Spedding (2010) recommend that the framework should be well balanced between the two approaches and carefully designed to solve the main problem.

3.4 Lean Six Sigma Framework

DMAIC is selected as the primary framework to fulfil the research requirements. The reasons for this are its appropriateness in improvement projects and its successful implementation across several industries. Specifically, its ability in identifying and eliminating the root causes of problems and sustaining continuous improvement. In order apply it in this research, the following steps have been applied:

Definition Stage

The goal of this step is to provide an overview of the problem, process, necessity and the area of improvement.

- Problem definition
- Process definition
- Define the necessity for improvement
- Identify the area of improvement
- Assign the concerned department to handle or manage this improvement

Measurement Stage

The aim of this step is to understand the current situation by measuring the efficiency and identifying the real gap and losses.

- Current situation
- Data collection
- Calculate efficiency
- Benchmark performance
- Quantify waste financially
- Potential efficiency gain

Analysis Stage

The aim of this step is to evaluate the outcome of the previous step and investigate the main causes affecting the efficiency.

- Measurement analysis
- Root causes
- Improvement opportunity
- Standardise and optimise: design standard process

Improvement Stage

The goal in this phase is to apply the proposed enhancement, measure the outcomes and report all the changes made.

- Implementation phase
- Measure the outcomes
- Validate effectiveness of implemented solution
- Documentation phase

Control Stage

The objective of this stage is to sustain continuous improvement.

- Design continuous improvement process (Sustainability)
- Implement
- Reward and recognition

3.5 Simulation Methodology

Efficiency improvement should be justified. However, the criticality and size of the targeted industry (electricity sector) are obstacles to implementing any actual changes or modifications. Alternatively, a simulation model can be utilised as an implementation tool. Applying the ideal method throughout the simulation stages will generate trustworthy results. Consequently, the simulation approach utilised in this study is based on a combination of several prior research works (Banks 2000; Wyland et al. 2000; Altiok & Melamed 2010; Robinson et al. 2010; Shannon 1998; Fishwick 1995).

The first step is problem explanation and clarifying the main goal for using simulation. The aim of this study is to improve the system efficiency, which cannot be achieved without addressing the main causes leading to the current situation. Hence, Simulation is used in two stages. The first stage is to provide an in depth view during the measurement phase for detecting the root causes leading to the current level of efficiency. The second stage, is to examine the proposed modification and identify any potential improvement.

The second step is the project plan. Planning a simulation project requires determining the time frame, the start and end point, level of complexity and assumption. Despite power production being a continuous event, it has been considered in this model as a discrete event to enable Arena software to simulate it for 24 hours for 365 days. The model starts from the moment of fuel injection up until electricity delivery to the end users. Transforming fuel into electricity (BTU to kWh) in the power plants is based on heat rate (HR) factors. 3% of the gross generation is assumed, on average, to be consumed within the plants as auxiliary consumption and the net production is sent to consumers through the network. 10% of transmitted power is lost prior to delivery, based on ECRA reports.

Third step pertains to the model characteristics. This step is tasked with defining constraints and boundaries of the system. For instance, there are 48 power plants used in this module, each unit has its own maximum capacity of production per hour that cannot be exceeded based on its nominal capacity. Furthermore, the model is restricted to providing the required amount of electricity, according to the given data. Moreover, the HR is fixed for each unit and not variable. The total output should fulfil the required load profile over the year considering different load in each season. Total fuel consumption is controlled.

The conceptual model is the fourth step. Building a preliminary model using a block diagram or flow chart is useful for understanding the logical flow and the required functions to be used. Figure **3-1** shows the basic flow chart of this model.

Fifth step is the initial design. It is important to determine the required output from the simulation from the beginning. This can help the model designer to consider several aspects, which can save time and effort, instead of modifying the model at later stage to generate specific information from a previous phase. The simulation report must provide detailed information about the operation of each power plant, including fuel consumed, efficiency, auxiliary consumption and actual load factor. In addition, total CO_2 emissions, average generation efficiency, average system efficiency, transmission and distribution losses cost of fuel consumed, cost of fuel subsidies and delivered electricity data are required.

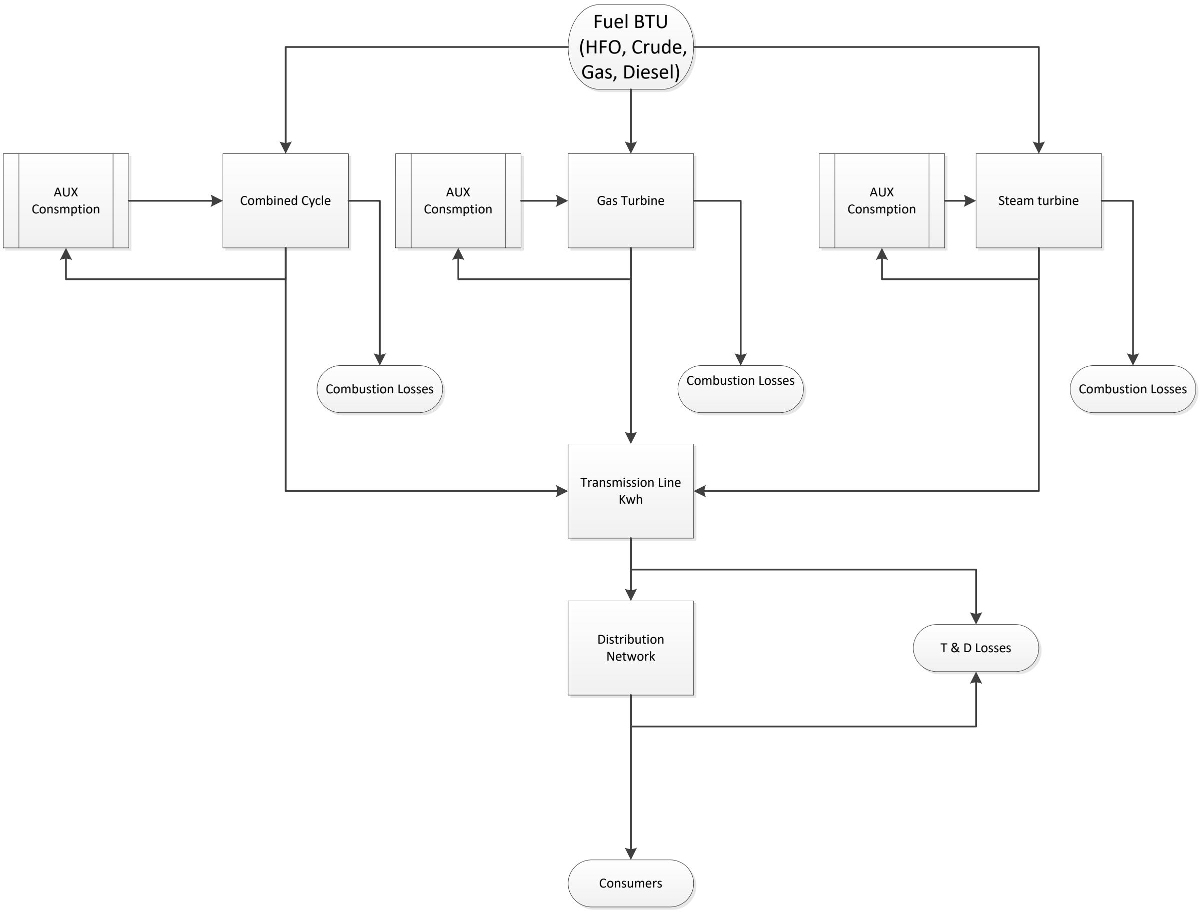

Figure 3-1 Conceptual model of the electricity system (flowchart)

The sixth step is about determining the required data needing to be collected. This simulation requires collecting detailed data about all power plants in Saudi Arabia. This includes HR, total production, technology type, nominal capacity for each power plant, total fuel consumed, annual load profile, fuel consumption and sold electricity. The seventh step pertains to model formulation into a simulation language. Rockwell Arena software was selected to build the model, which contains around one thousand elements. Several basic and advanced functions were utilised, including attributes, processes, resources schedules, records, statistics, expressions, hold, batch, plotting, routes and station. The main model consists of 48 sub models, representing a single power plant. The eighth step is debugging, which refers to verifying the model's credibility, whereby it is required to run until the end of the set time without receiving errors and producing valid and acceptable results. Validation is performed by comparing the results to the real system and will be presented and discussed in the next chapter in detail.

The ninth step is design testing. This means conducting more runs for the simulation to ascertain that same results are provided or this can be done by having different scenarios and comparing the outcomes. In other words, this step is aimed at building generic or global model that can be used to simulate a similar case in a different location to that which has been considered for this model’s construction. The tenth step is experimentation, which involves running the model to produce the required output and deciding whether further run(s) is/are needed based on the results. The eleventh step, analysis, pertains to analysing the results in tables, charts or as discussion is a significant step as this provides understanding of the main causes that have led to the current situation. In addition, it helps to optimise the system if the problem revealed has had a suitable solution proposed. This step is presented in the results and discussion chapters in detail. The final step is reporting and implementation. This involves drawing conclusions about the outcomes of the simulation results and utilising them to optimising the system, which is provided in this study. The simulation results are used to identify the root causes of low efficiency in the system in the first stage. At the next stage, they are utilised to justify the viability of the improvement.

3.6 Arena Software

Arena is a discrete event modelling (DES) program owned by Rockwell Automation since 2000 (Arenasimulation.com). It contains enormous varieties of defined functions that help users to build the model by linking these blocks in different methods. In addition, it has the feature of coding new functions. It generates statistical reports that help users to identify problems or bottlenecks in the system by providing detailed information for any specified process or entity in the system. It contains several characteristics that enable it to adapt to different types of businesses as well as public and private sector requirements. It has been widely utilised in areas such as manufacturing, the supply chain, healthcare, logistics, retail, packaging, services etc. For this research, Arena version 14.5 was utilised as simulation software, being deployed within the main methodology (DMAIC). First model represents the current situation, whilst the second, applies the proposed modifications.

3.7 Mathematical Modelling

Mathematical modelling will be used during the improvement stage. The outcome of the analysis stage and simulation will be utilised in building a model to identify the relationship between efficiency and the root causes, precisely. Equations will be used in relation to proposing improvement. Moreover, the Lean concept PULL has been engaged with to estimate the required production by each unit and mathematical programming used to optimise the results of the model.

Mathematical Programming

Mathematical programming (MP) has been applied to maximise the average generation efficiency by providing the optimum production needed from each power plant, specifically those with low efficiency. Since the mathematical models could not take into consideration the load profile accurately, MP was needed to estimate (minimise) the production on the least efficient units without affecting the demand. This can be obtained by defining the minimum required operating hours from each unit according to the load profile. Several constraints were taken into consideration. First, total production should neither be less than the demand nor exceed it. Second, production per unit should not exceed its maximum capacity and must be no less than the minimum requirements regarding to the demand. The (MP) outcome will be utilised in the simulation model.

3.8 CO_2 Calculation

The amount of CO_2 produced from electricity generation depends on the fuel type, with each having its own average emissions factor. For example, gas has lower emissions factor compared to oil. There are several methods for emissions calculation. It can be measured per unit of electricity produced (g/kWh) (Graus 2010). However, this method is not suitable in this study, because it does not consider the HR or fuel consumed. As a result, any potential improvement in HR or reduction in fuel consumed will not be reflected in the CO_2 calculations.

Alternatively, this study utilises the emissions factor based on energy consumed (kg/MM BTU), as presented on Table **3-1**. It can be used to calculate the total CO_2 emitted by multiplying the emissions factor by the total fuel consumed. Otherwise, it is possible to obtain the average emissions factor per kWh generated by considering HR instead of consumed fuel, as suggested by US Energy Administration Information (EIA 2015). This method is used within the simulation model to show the reduction in total emissions by improving the average efficiency.

Table 3-1 CO_2 emission factor (The Climate Registry 2015)

Fuel Type	CO_2 Emissions factor (kg/MMBTU)
Natural gas	53.02
Crude oil	74.49

3.9 Data Collection

This research requires the average efficiency of Saudi Arabian power plants during the last decade. The literature review mentioned the efficiency level in the kingdom among the lowest globally. Nevertheless, there are no consistent and reliable figures to rely on in this study. Published reports and official websites do not provide any efficiency data. Consequently, the researcher has had to calculate the efficiency after collecting the required data. For the first stage of this process, the total fuel consumed, gross electricity production, auxiliary consumption, networks losses and power plant capacities were collected from official websites and reports published online by ECRA and SEC. The second stage involved collecting detailed data of power plant productions and HR figures were collected through emails from ECRA after official visits to their offices in Riyadh, Saudi Arabia. In the third Stage, the CO_2 emissions rate utilised in the simulations, was obtained from the International Energy Agency. All these data were utilised on in this research during the measurement, analysis and improvement stages

3.10 Framework for Lean Six Sigma, Simulation and Mathematical Programming (LSSSMP)

In this research, a modified framework based on the nature of the focal sector and the project's requirements has been proposed as shown in Figure **3-2**. Its application involves utilising several LSS tools and techniques through the DMAIC framework (see Table **3-2**), as published in several journals (Shahada & Alsyouf 2012; Furterer 2004 Kumar et al. 2006; Furterer & Elshennawy 2005). First, it starts by defining the problem, process, area of improvement and its significance. Second, it understands the existing situation by measuring the current performance of the system and comparing it to the potential achievable limit based on the available resources. This step includes identifying the gap and the financial losses of the current situation. Then, Arena software is used to simulate the current situation to assure the model provides similar results to the real system and to provide in depth measurement. Third, the measurement output and simulation report are analysed to understand the issue and identify the main causes of low efficiency. Subsequently, improvement is proposed and designed utilising mathematical modelling. Different scenarios are implemented using simulation, and mathematical programming is deployed for optimisation. Finally, a framework is proposed to retain and control the gained improvement.

Table 3-2 Stages, activities and tools used in this study

Stage	Activities	Tools
Define	• Problem definition • Process definition • Define the necessity for improvement • Identify the area of improvement • Assign the concerned department	Brainstorming Process mapping
Measure	• Current situation • Data collection • Calculate efficiency • Benchmark performance. • Quantify waste financially. • Potential efficiency gain.	Value stream mapping Pareto analysis Cause and effect diagram Trend chart Cost/benefit analysis Simulation
Analyse	• Measurement analysis • Root Causes • Improvement opportunity • Standardise and optimise	Histogram Scatter graph
Improve	• Propose improvement • Implementation phase • Measure the outcomes • Documentation phase	Brainstorming Mathematical model Simulation Mathematical programming
Control	• Design continuous improvement process (Sustainability) • Implement • Reward and recognition	Control chart Performance management Education and training

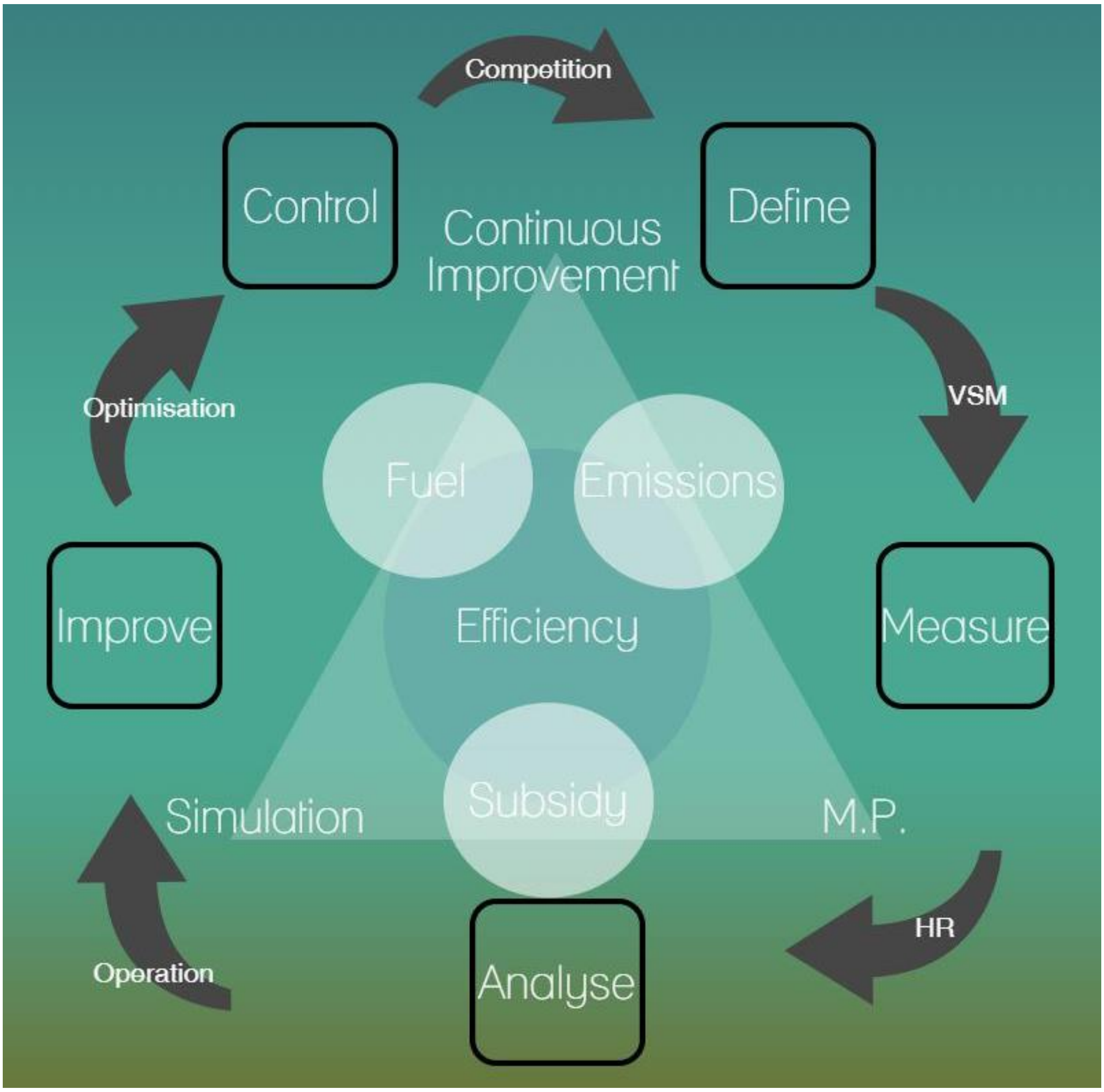

Figure 3-2 Framework for implementing Lean Six Sigma with Simulation and mathematical programming (LSSSMP)

3.11 Conceptual Model

This study is divided into several stages, starting with the conducting of an in depth search on the topic. Then, the methodological stance is explained and shaped to fit the aims of the study. The approach adopted involves different phases, each of which is examined and the results validated, for the outcomes of each phase are used in the next stage. Finally, the overall results are presented with a discussion. A summary of activities performed during this research is presented in Figure 3-2.

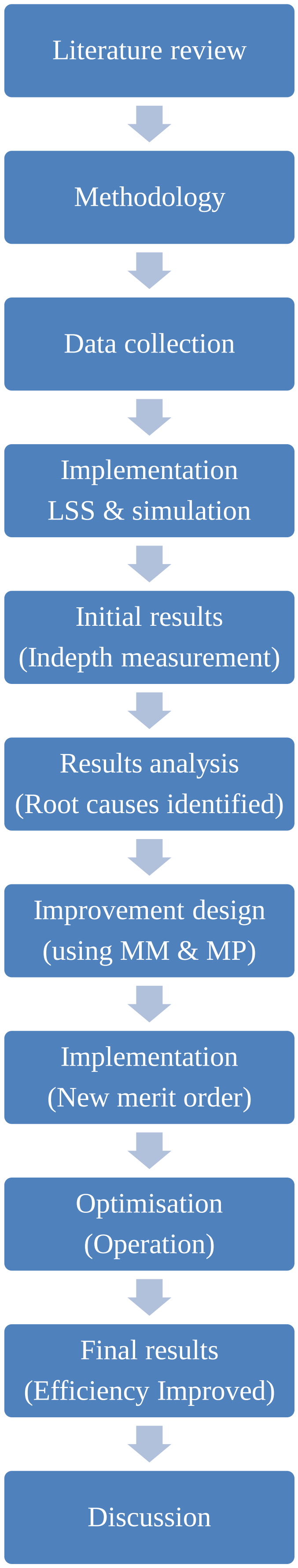

Figure 3-3 Research flowchart

3.12 Summary

The objective of this research is to improve the generation efficiency in Saudi Arabia power plants, which requires measuring the current efficiency. Then, there is analysis to identify the root causes leading to inefficiency and discussion on tackling the main ones. Subsequently, an improvement aimed at generating the required electricity using less fuel is designed. In addition, this model aims to control improvement through deployment of continuous improvement. It was decided that Lean thinking would be utilised to identify waste in line with the Six Sigma steps (DMAIC), as a primary framework. Furthermore, mathematical modelling is used during the improvement phase and simulation is deployed during the measurement and the final proposed modification to justify its credibility. The researcher validates the methodology by complete implementation in the next chapter and the final results will be presented and discussed in chapter 5.

Chapter 4 Implementation

4.1 Introduction

This chapter implements the methodology which integrates Lean Six Sigma, simulation and mathematical model, as proposed in the previous chapter. The DMAIC framework has been followed during the implementation. Historical data have been gathered, revised and utilised during the measurement phase. In the analysis stage, the root causes were identified and the solution evolved. The proposed solution has been implemented and tested in the improvement phase and the gained improvement was controlled during the last stage. The results of the implementation will be presented and discussed in the next chapter.

4.2 Stage 1 of DMAIC: Define

Prior to any improvement plan, it is important to define the project scope and goals through obtaining comprehensive understanding of the problem size, impact and the system process. This step helps to acquire sufficient knowledge to identify the needed improvement and the most wasteful area of the system.

- Problem definition

Low level of efficiency in generating electricity is harming the kingdom’s economy, environment and fuel reserve. It causes additional consumption (waste) of natural resources (oil and natural gas) and as a result, produces extra emissions. In addition, primary energy is heavily subsidised by the government, which means further costs incurred by the national economy. Consequently, improving the average level of efficiency means retaining natural resources, reducing subsidies and decreasing emissions.

- Process definition

In order to grasp an understanding of the existing state of power production, a process map has been developed to highlight the related factors, as shown in Figure **4-1**. It starts by injecting the different fuel types (including gas, diesel, HFO and LFO) into the power plants. There are four different types of turbine in SA: gas turbine, steam turbine, combined cycle and diesel turbine. Each type has its own operational characteristics. It should be noted that all data needed will be discussed in detail during the measurement stage.

The next stage is the transmission phase, which delivers electricity from power plants to distribution networks. Different levels of voltage are used in these networks based on the distances and technical requirements. Step up and step down transformers are located at both ends of the transmission networks for voltage conversion. Distribution networks are connected to transmission transformers to deliver electricity to consumers. There are several voltage levels in the distribution. according to customer requirements. This research has not involved considering the supply chain stage prior the generation or end user consumption habits, since they are beyond the scope of this study.

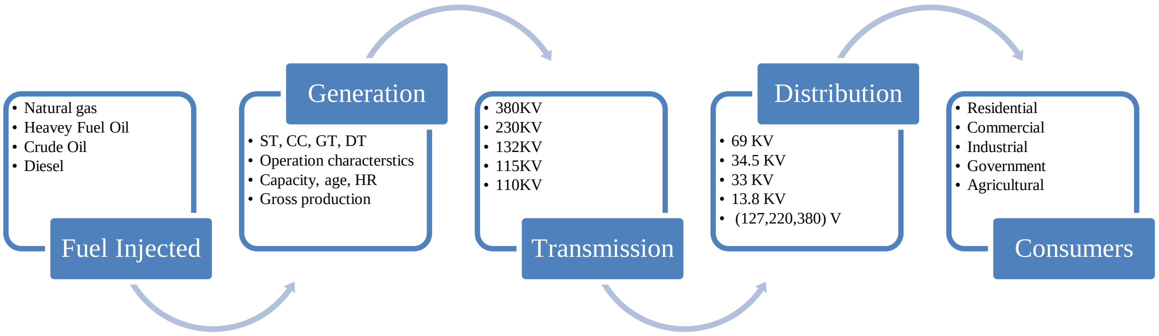

Figure 4-1 Process map

- Define the necessity for improvement

Improving the efficiency can lead to potential savings of fossil fuel and significant reduction in emissions. Saved fuel could be used in petrochemical manufacturing, exported at higher prices to benefit the national budget or retained for future generations.

- Identify the area of improvement (scope of work, goal)

First, for this research the sources of losses in the process leading to efficiency reduction are determined. Second, the main causes are classified and prioritised. Third, a model is proposed that can improve the efficiency and finally, the model is tested to validate the solution.

- Assign the concerned department to handle or manage this improvement

A high level of management must adopt the project to succeed and monitor the results on monthly basis. The concerned departments mainly are the Power Plants Operation and Load Dispatch Centre (LDC).

4.3 Stage 2 of DMAIC: Measure

In this step efficiency is measured after collecting the required data. Then, the performance is benchmarked to identify the gap and the potential gain. Finally, simulation is utilised to identify the root causes.

1- Current situation

Currently, there are three main points that are affecting the system efficiency, as presented in Figure **4-2**. Two of them are during the generation phase and the third pertains to the transmission and distribution stages. First, loss occurs during the transformation of fuel into electricity and the energy consumed by the auxiliaries is the second point. Third, power is lost in the transmission and distribution networks before it is delivered to end users. The average system efficiency can be calculated based on measuring the efficiency of each stage. To estimate these losses, the required data are collected in the next step.

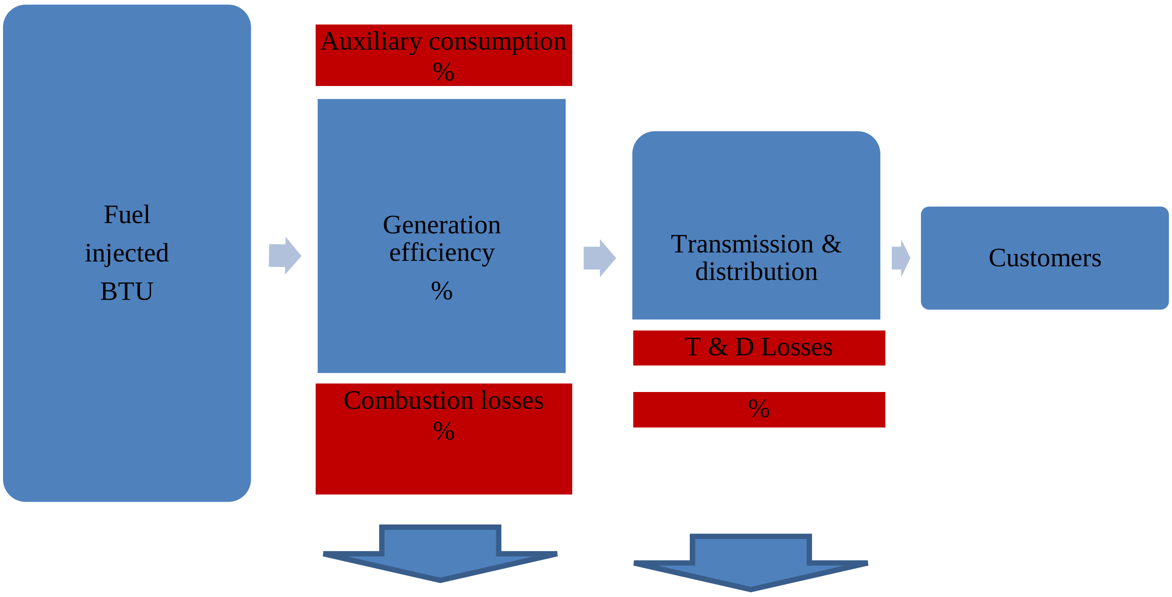

Figure 4-2 Losses points (VSM)

2- Data collection

Fuel consumed[10], generated and sold energy, unit age, power plant type, auxiliary consumption, transmission and distribution losses[11] data were obtained by the Electricity and Cogeneration Regulatory Authority in Saudi Arabia for between 2006 and 2015. Electricity produced from

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[10] (ECRA 2009b), (ECRA 2010b), (ECRA 2011c), (ECRA 2012a), (ECRA 2013b), (ECRA 2014b),(ECRA 2015b)

[11] (ECRA 2007), (ECRA 2008), (ECRA 2009a), (ECRA 2010a), (ECRA 2011a), (ECRA 2011b), (ECRA 2013a), (ECRA 2014a), (ECRA 2015a), (ECRA 2016)

each fuel type was collected from the International Energy Agency. All these data are utilised in the next step.

3- Calculate efficiency

The equation used for the efficiency calculation:

$$E = P/I \tag{2}$$

where:

E = Efficiency

P = the generated electricity

I = the total fuel used in the power plants

The produced electricity is based on the gross generation, which means auxiliary consumption and losses in the networks have not been subtracted. Fuel inputs are based on the higher heating value (HHV) or gross calorific value (GCV). Please note that the efficiency calculation based on HHV is lower than if it is based on LHV. The variance is approximately 7% for oil and 10% for gas (Graus & Worrell 2009). Efficiencies that have been calculated are presented in Table **4-1**.

Table 4-1 Input, output & efficiencies of electricity generation in Saudi Arabia

Year	Fuel T.BTU	Generated power GWh	AUX cons.	T&D losses	Delivered GWh	Generation efficiency	System efficiency
2015	3,581	338,336	3.7%	7.7%	286,037	32.24%	27.25%
2014	3,427	311,807	3.45%	9.8%	274,502	31.04%	27.33%
2013	3,410	284,008	3.3%	7.5%	256,688	28.42%	25.68%
2012	3,286	271,756	3.23%	9.3%	240,288	28.22%	24.95%
2011	3,134	250,069	3.16%	9.95%	219,622	27.23%	23.91%
2010	3,041	239,891	3.01%	9.4%	212,263	26.94%	23.82%
2009	2,776	217,082	3.02%	8.5%	193,472	26.86%	23.78%
2008	2,538	204,200	N/A	11.3%	181,098	27.45%	24.35%
2007	2,343	190,535	N/A	11.1%	169,303	28.18%	24.65%
2006	N/A	181,434	N/A	10.1%	163,151	--------------	-------------
Avg	-------	--------------	3.3%	9.4%	-------------	28.5%	25.23%

From 2007 until 2015 the average generation efficiency was 28%. The net system output represents around 25% of the total injected fuel, as shown in Table **4-1**, which means the typical loss 75%. It is important to identify the area where the largest amount of waste exists and then to study it in detail. On average, auxiliaries consume 3% of total production before transmission, and the electricity lost in the transmission and distribution networks is approximately 9%, whilst the average generation efficiency is 28 %, (see Figure **4-3**). In other words, the generation stage is the most wasteful area and hence, requires further investigation, as shown in Figure **4-4**.

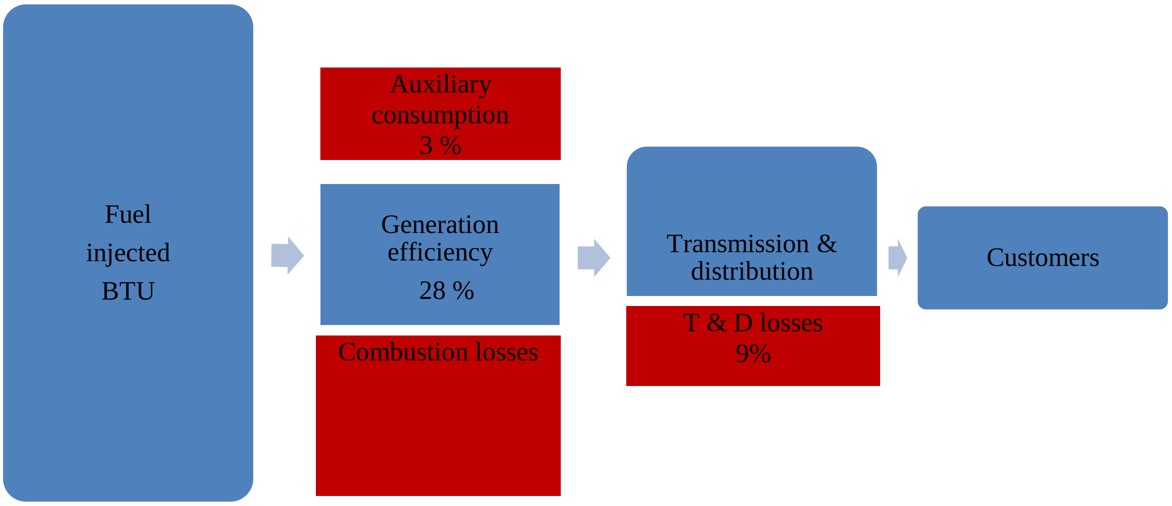

Figure 4-3 Average system losses

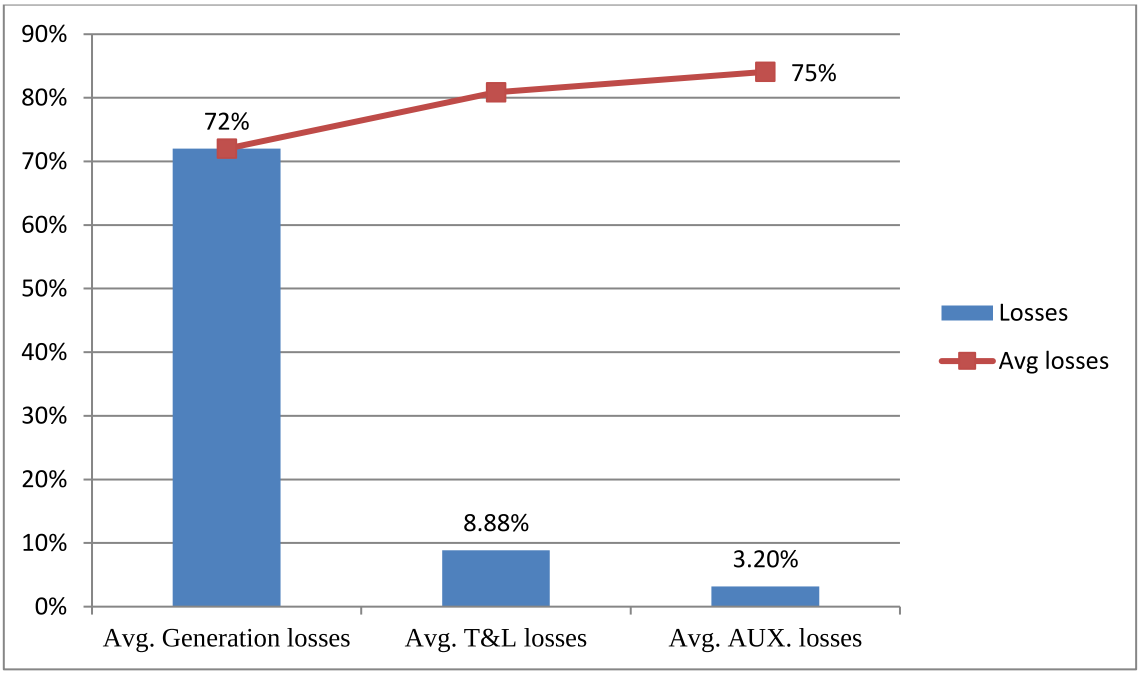

Figure 4-4 Pareto chart for average losses in the system (2006-2014)

SEC Efficiency

The calculations show that the generation efficiency of power plants owned by SEC, which is the largest power producer in the kingdom, is higher than the country's average (see Table **4-2**). Between 2007 and 2015, 31.81% was the average efficiency in SEC units. However, it is still well below the international average, and has not shown any particular improvement since 2007, with a maximum of 32%. In fact, in 2009 it decreased by 1 percentage point to 31% and remained there until 2011. In 2013, a significant reduction occurred without clear justification in the reports. However, 6% reduction appeared in SEC's total production compared to 2012.

Table 4-2 Calculated HR of SEC power plants based on ECRAs' reports from 2007 to 2015

	Efficiency[12]	SEC calculated HR (BTU/kwh)	SEC (GWh)
2007	32.78%	10,409	165,342
2008	32.26%	10,576	178,430
2009	31.02%	11,000	186,725
2010	31.12%	10,965	189,415
2011	31.50%	10,833	193,952
2012	32.03%	10,652	211,604
2013	30.01%	11,386	198,891
2014	32.68%	10,441	219,133
2015	32.88%	10,377	215,670
Average	31.8%	----	----

It is important to collect additional data about power plants in Saudi Arabia, such as, the amount of fuel used and total production from each fuel type, type of technology used, the age of the generation units, heat rate and the production of each power plant. Then, benchmark is necessary to determine the actual gap and to assess the chance of improvement.

Fuel based comparison

Figure **4-5** illustrates the amount of each type of fuel consumed, the total amount of electricity generated and the efficiency, based on fuel type, in Saudi Arabia between 2007 and 2014. On average, gas and oil represented 46% and 54% of total fuel consumption and produced 48% and 51% of total electricity, with 29% and 27% average efficiency, respectively. Gas consumed in power plants decreased from 52% to 44%, while total production increased from 50% to 51%, which shows significant improvement in efficiency, reaching 36.1% from 27.8% within 7 years. In contrast, between 2010 and 2011, electricity generated by oil increased by 12 percent with only a 2 percentage point increase in fuel consumption, which resulted in improving the

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[12] The quantity of fuel consumed in electricity production used in this calculation can be found on "ANNUAL STATISTICAL BOOKLET FOR ELECTRICITY AND SEAWATER DESALINATION INDUSTRIES 2009ECRA's reports (ECRA 2015b)(ECRA 2014b),(ECRA 2013b), (ECRA 2012a), (ECRA 2011c), (ECRA 2010b) and (ECRA 2009b). Total electricity production used on this calculation can be found on "Activities & Achievements of the Authority" reports(ECRA 2016) (ECRA 2015a) (ECRA 2014a), (ECRA 2013a), (ECRA 2011b)(ECRA 2011a), (ECRA 2010a),(ECRA 2009a) and (ECRA 2008)

efficiency from 25.1% to 27.5%. Nevertheless, both gas and oil efficiencies fluctuated on a yearly basis.

Figure **4-5** shows the minimum, maximum and average efficiency of power plants using fossil fuels (oil, gas and coal) from 1990 to 2003 in selected countries. These countries represent around 65% of the total electricity generated from such fuels in the world[13]. The maximum recorded efficiency in 2003 was 42% in Japan for oil and 47% in India for gas (Graus et al. 2007). This data is utilised to find out the potential efficiency in Saudi Arabia based on the type of fuel consumed (Table **4-3**).

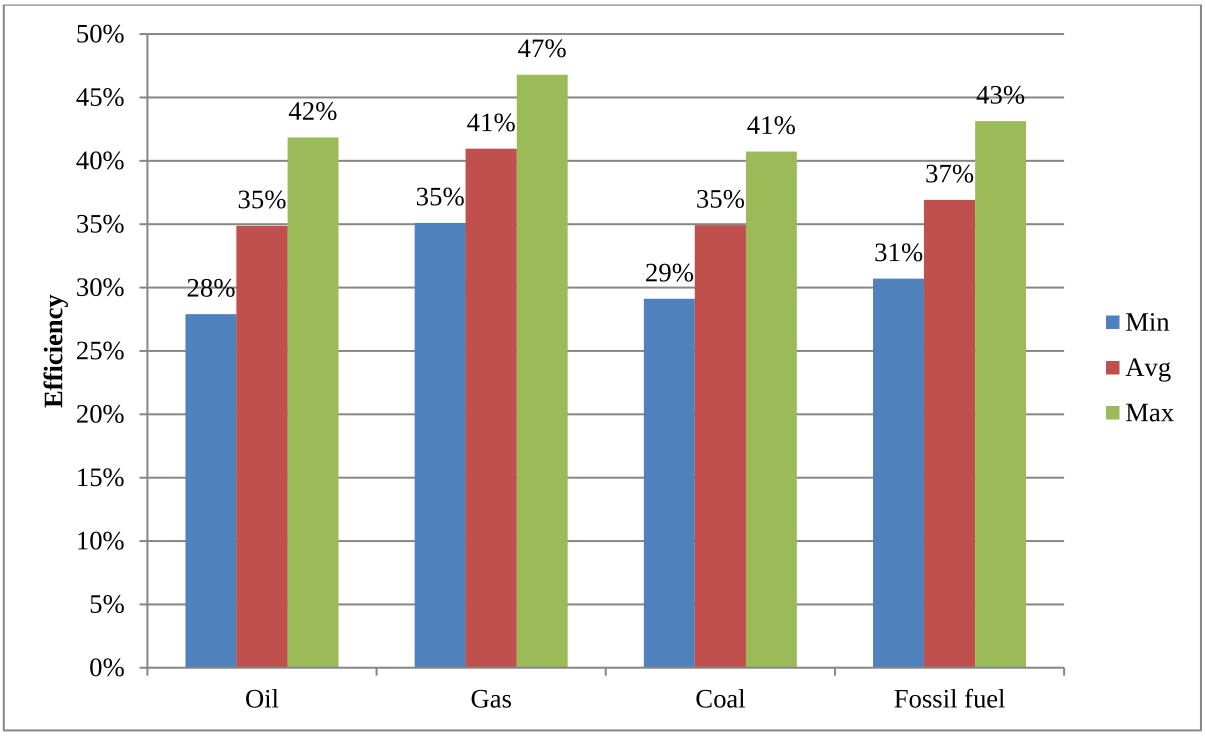

Figure 4-5 Global average efficiency of fossil fuel generation 1990-2003 converted from GCV to NCV14

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[13] Austria, China, France, Germany, India, Japan, Denmark, Finland, Sweden, Norway, South Korea, the United Kingdom, Ireland, and the United States of America

[14] Conversion factors are 0.9 for gas, 0.93 oil and 0.97 coal (Worrell & Graus 2006)

Table 4-3 Fuel consumed, electricity produced and efficiency of oil and gas in Saudi Arabia from 2007 to 2013.[15]

		2007	2008	2009	2010	2011	2012	2013	2014	Avg
Gas	Consumed (T.BTU)	1,212	1,273	1,222	1,284	1,377	1,512	1,605	1,506	---
	% of total fuel consumption	52%	50%	44%	42%	44%	46%	47%	44%	46%
	Electricity prod. (GWh)	98,732	99,707	97,285	110,773	108,383	121,402	149,824	159,520	---
	% of total production	50%	49%	45%	46%	43%	45%	53%	51%	48%
	Efficiency	27.8%	26.7%	27.2%	29.4%	26.9%	27.4%	31.9%	36.1%	29%
Oil	Consumed (T.BTU)	1,131	1,265	1,554	1,757	1,757	1,774	1,805	1,921	---
	% of total fuel consumption	48%	50%	56%	58%	56%	54%	53%	56%	54%
	Electricity prod. (GWh)	94,803	104,493	119,797	129,294	141,694	150,277	134,192	152,285	---
	% of total production	50%	51%	55%	45%	57%	55%	47%	49%	51%
	Efficiency	28.6%	28.2%	26.3%	25.1%	27.5%	28.9%	25.4%	27%	27%
FF efficiency		28.18%	27.45%	26.86%	26.94%	27.23%	28.22%	28.42%	31.04%	28%
Potential efficiency		38.0%	37.9%	37.5%	37.4%	37.5%	37.7%	37.7%	37.6%	37.7%

In comparison, using the collected data of fuel consumed and electricity produced, the calculations shows the average efficiency of oil and gas are 27% and 29% in SA, while globally the minimum were 28% and 35% respectively. Based on the international average efficiencies of fossil fuels and the shares of oil and gas in electricity generation in SA, the efficiency level is considered low. Efficiency in SA has the potential to improve up to 10 percentage points higher than the existing level, as shown on Table **4-3**. Nevertheless, the type of technology being used can play a significant role in the efficiency level, therefore it should be analysed prior to the final judgement.

Technology based comparison

Table **4-4** illustrates the share of each technology used in generation based on the installed capacity from 2009 until 2015 (diesel turbine is ignored since it represents only 1%). In general, gas turbines account for approximately half of the capacity with limited change during the period in question, followed by ST, which sustained about 40% and the rest are the CC units, which have been doubled in term of capacity. In 2013, CC had reached 12.3% and ST decreased to 36%, with only a 0.2% improvement in average efficiency. A year later, ST increased to 40% and showed significant efficiency improvement. The highest efficiency was achieved in 2015 without any substantial change in the generation stock.

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[15] (IEA 2013)

Table 4-4 Generation unit types in percentages, based on capacity (SA)

	2009	2010	2011	2012	2013	2014	2015	Avg
GT	52%	53%	52.4%	50.1%	50%	47%	47%	51%
ST	41%	40%	40.8%	39.3%	36.4%	40%	39%	40%
CC	6%	6%	6.1%	9.9%	12.3%	12%	13%	9%
Average efficiency	26.86%	26.94%	27.32%	28.22%	28.42%	31.04%	32.24%	28.72%
Potential efficiency	36.7%	36.6%	36.8%	37.3%	37.4%	37.6%	37.8%	37%

Figure 4-6 shows the minimum, maximum and average efficiency of each technology, globally. On average, CC units operate at 50% efficiency, while the figures for ST and GT are 38% and 35%, respectively. This information has been utilised to calculate the potential achievable efficiency based on the available assets. In SA, the average generation efficiency can reach around 37%, as shown in Table 4-4. This result supports the previous one based on fuel type. It is also important to consider the average age of power plants and to compare it with that of other countries.

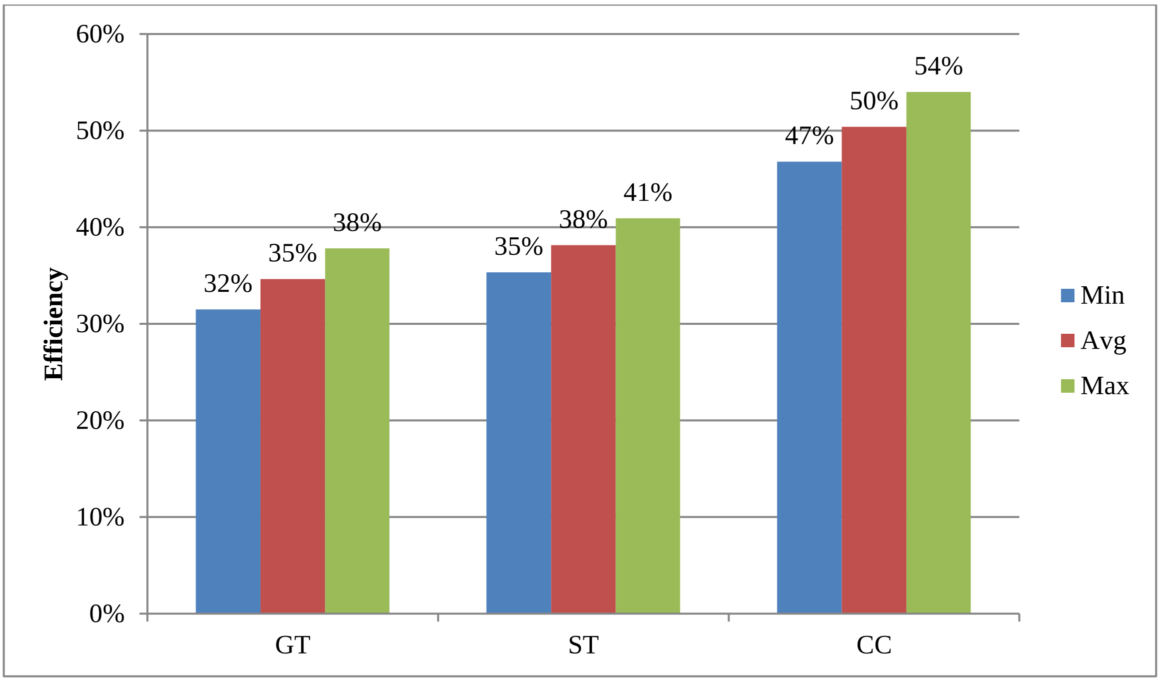

Figure 4-6 Efficiency based on unit type (Eurelectric 2003; IEA-ETSAP 2010)

Age based comparison

The average age of generation units in SA is around 14 years over the last five years, with more than half of the stock being less than 10 years in operation, as presented in Table **4-5**. 40% of the generation capacity is less than six years old; one fifth is older than 30 years, including 4% having operated for more than 35 years, as of 2015.

Table 4-5 Average age of generation units in SA (2011-2015)

Age of generation units	2011	2012	2013	2014	2015
0-5y	37%	36%	39%	40%	35%
6-10y	14%	16%	12%	14%	21%
11-20y	14%	14%	15%	16%	15%
21-25y	5%	5%	6%	4%	3%
26-30y	19%	15%	8%	7%	6%
31-35y	10%	12%	16%	15%	15%
>35y	1%	2%	4%	4%	5%
Avg age (years)	14.05	14.1	14.38	13.65	13.78

To find out what should be the average efficiency of units of such age, the average efficiency of gas fired power plants in 25 countries[16] from 2003-2005 was calculated by (Graus & Worrell 2009), based on their time in operation, as shown Figure 4-7. Based on that, the average efficiency gas turbines in SA can reach around 39%, according their time in operation.

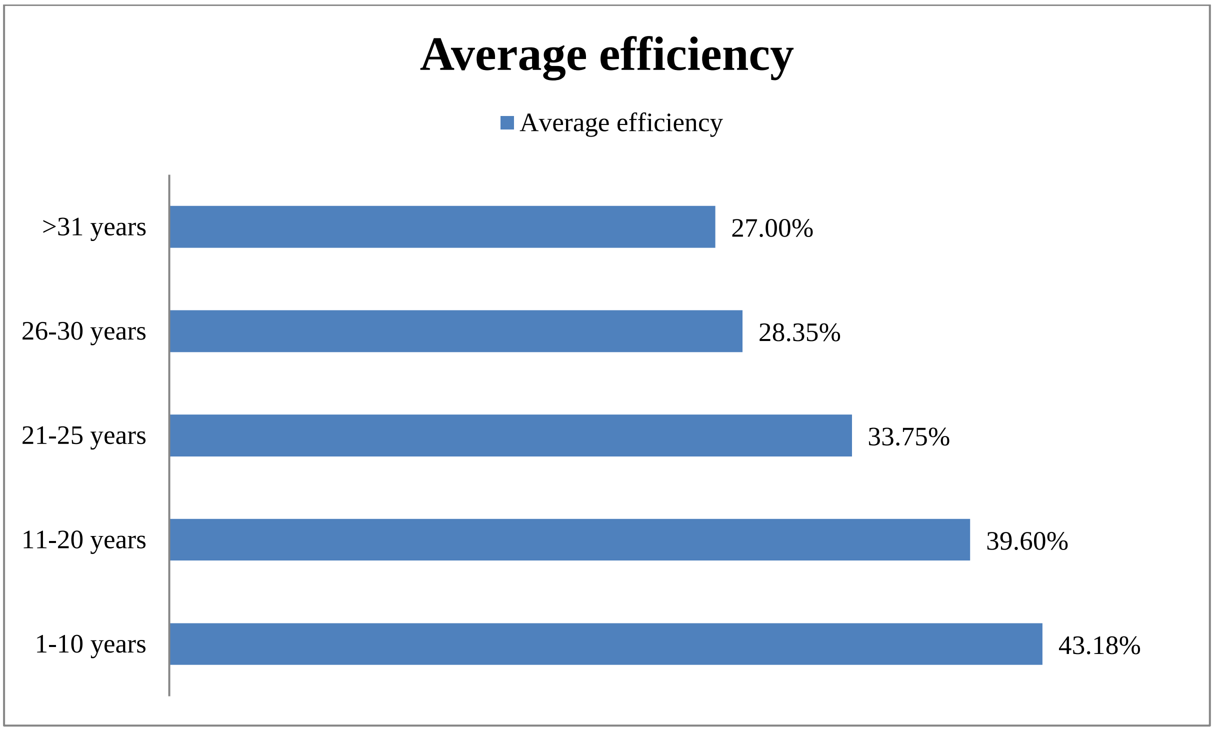

Figure 4-7 Average efficiency based on the average age of power plants in selected countries (Graus & Worrell 2009)

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[16] Poland, Spain, Portugal, Slovenia, Luxembourg, the United Kingdom, Belgium, France, Denmark, Italy, Finland, Greece, the Netherlands, Austria, Hungary, Ireland, the Czech Republic, Latvia, Germany, Sweden, Slovakia, Estonia, Bulgaria, Lithuania, Romania

In SA, 50% of power plants utilise gas in electricity generation. Their average age was 15.7 years, as of 2012, (ECRA, 2014) with 29% efficiency on average. 46% of the turbines were less than 10 years old and only 18% had been in operation for more than 30 years. This means age is not a key factor leading to the current level of efficiency.

4- Benchmark performance.

The United Kingdom's fossil fuel power plants have been selected to be used as a benchmark. The reason for this selection relates to the availability, accessibility, consistency of data of each type of fuel used and total power generated, which is very important for distinguishing the heat rate (HR) and efficiency. In addition, oil and gas are used in both countries for electricity generation.

As can be seen in Table **4-6**, using Eq. (1) the calculated efficiency of fossil fuel generation in the UK was 46%, with 13.23 years being the average age of power plants (Department of Energy & Climate Change 2013). As a result, the average ages of power plants in both countries are within the same range (10-15) years. Despite similar types of fuel being utilised, there is an enormous gap between the two countries in terms of efficiency, as can be seen in Figure **4-8** and the gap exists in both types of generation. This gap is smaller for oil, but gas fuelled units have improved recently and hence shrunk the gap. Generally, fossil fuel generation in SA is far below that of the UK.

Table 4-6 Input, output and efficiencies of electricity generation in the UK[17]

Year	Gas MTOE	Oil MTOE	T. Fuel MTOE[18]	Elec. gas GWh	Elec. oil GWh	Total elec. GWh[19]	Gas eff.	Oil eff.	Fossil fuel eff.
2015	18.313	0.618	18.931	100,035	2,133	102,168	47%	30%	45.7%
2014	18.779	0.53	19.309	100,928	1,881	102,809	46.35	30.5%	45.4%
2013	17.741	0.593	18334	96,028	2,091	98,119	46.6%	30.3%	45.5%
2012	18.620	0.727	19.347	100,160	2,571	102,371	46.3%	30.4%	45.1%
2011	26.577	0.783	27.360	146,520	3,117	149,637	47.4%	34.3%	47.2%
2010	32.428	1.178	33.606	175,656	4,803	180,459	46.65	35.1%	46.3%
2009	30.895	1.513	32.408	166,499	5,995	172,494	46.45	34.1%	45.7%
2008	32.400	1.582	33.982	176,215	6,711	182,926	46.8%	36.5%	46.4%
Avg									45.9%

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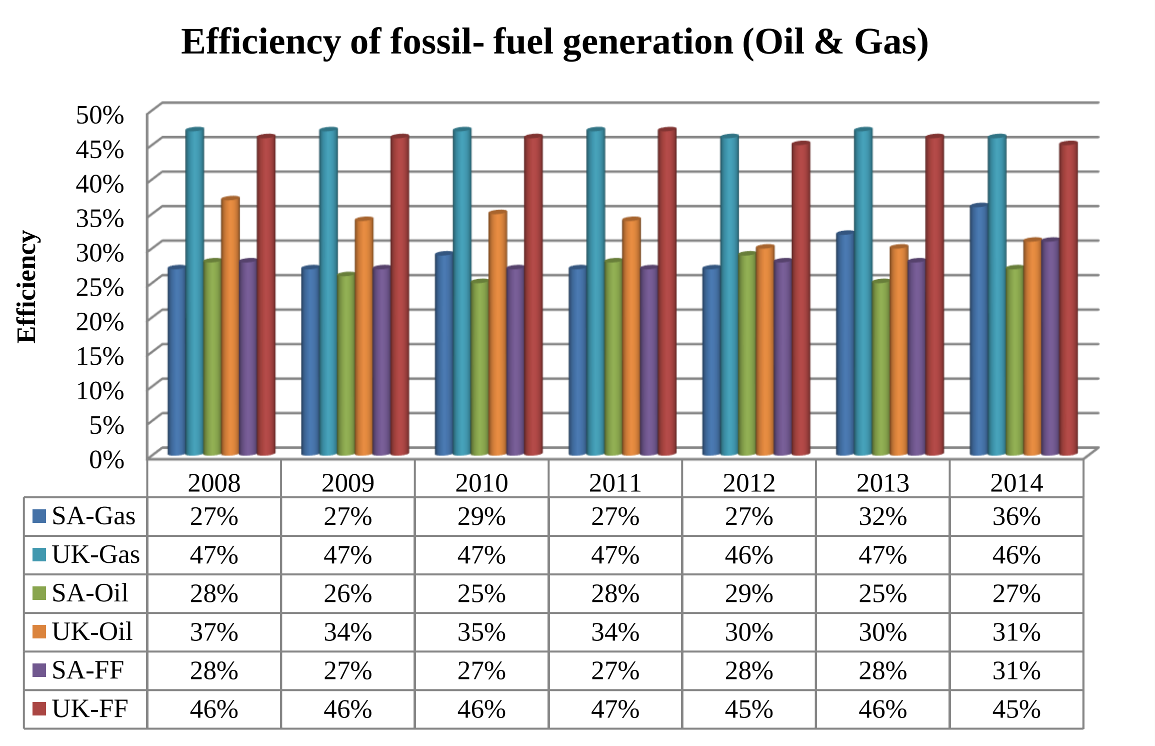
[17] Department of Energy & Climate Change 2016; Department of Energy & Climate Change 2015; Department of Energy & Climate Change 2014; Department of Energy & Climate Change 2013; and Department of Energy & Climate Change 2012.

[18] 1 M.TOE=39.68 T.BTU

[19] (IEA 2010)



	2008	2009	2010	2011	2012	2013	2014
SA-Gas	27%	27%	29%	27%	27%	32%	36%
UK-Gas	47%	47%	47%	47%	46%	47%	46%
SA-Oil	28%	26%	25%	28%	29%	25%	27%
UK-Oil	37%	34%	35%	34%	30%	30%	31%
SA-FF	28%	27%	27%	27%	28%	28%	31%
UK-FF	46%	46%	46%	47%	45%	46%	45%

Figure 4-8 Efficiency based on fuel type in SA and the UK

In general, the comparisons based on different criteria, show low efficiency in electricity production in SA. Nevertheless, the existing generation stock has the potential to achieve higher level based on its age, technology and fuel type, as shown in Figure 4-9.

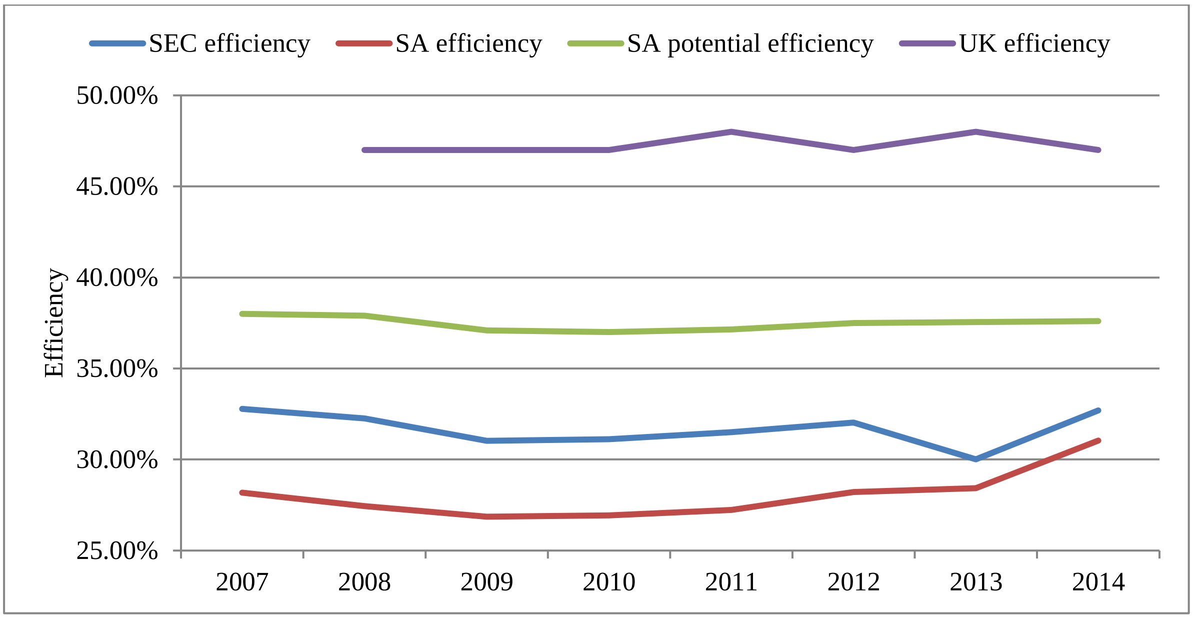


Figure 4-9 Efficiency trend (2007-2014)

5- Quantify waste financially

This step involves calculating the cost of losses financially and Figure **4-10** shows the accumulative useful output of the system, according to the losses occurred. Out of £30 billion that has been injected into the system as the cost of fuel, the useful output electricity was worth £7.4 billion. This assumption is based on the fuel price given by ECRA and not considering the selling price. Despite the maximum achievable efficiency not being able to exceed 50%, going by the UK figures, financial losses can be reduced significantly, as will be shown in the next step.

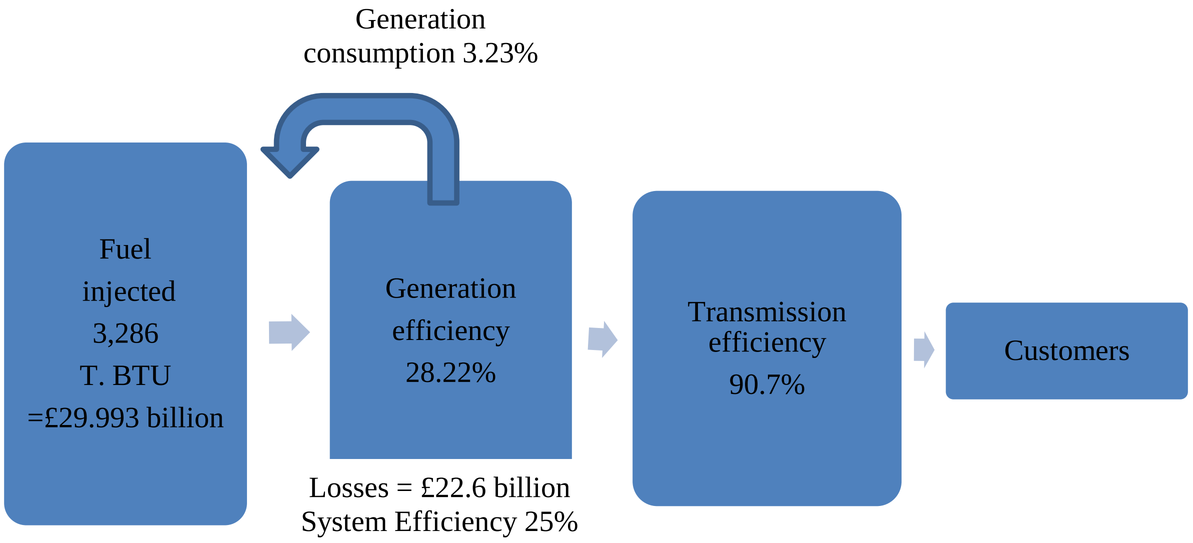


Figure 4-10 Accumulative losses for the system (2012)

6- Potential efficiency gain

Generation efficiency represents the largest share of losses in the system and to address this, different scenarios are proposed in Table **4-7**, with explanations of their significance in relation to improvement.

Table 4-7 Amount of saving if efficiency is improved, based on 2012 figures

Efficiency	Existing generation efficiency 28.22%	35% efficiency with same fuel amount	35% efficiency with less fuel amount
Fuel used (T. BTU)	3,286	3,286	2669
Fuel cost billion (£) int. price	29.993	29.993	24.361
Saving billion (£) int. price	N/A	N/A	5.63
Saving (%)	N/A	N/A	18.8%
Production (GWh)	271,756	337,075	273,784
Generation consumption (GWh)	8,778	10,888	8,843
Trans. & dist. losses (GWh)	24,641	30,335	24,639
Sales (GWh)	240,288	295,852	240,301
Income billion (£)	5.18	6.38	5.18
Additional sales (%)	N/A	23%	N/A

The table above presents the expected financial return or additional production in the case of efficiency being improved from 28% to 35%. The baseline efficiency is based on the average efficiency of SA during the last years (2007-2014). The selective figure (35%) is quite conservative, being below the international average of fossil generation efficiency and also below the potential efficiency that could be obtained based on fuel type or the available assets. Both of the above scenarios show impressive returns. The first, for which it is assumed that the same amount of fuel is being used and the efficiency is upgraded to 35%, demonstrates that 23% additional production can be attained, which would result to £1.2 billion additional income. Regarding the second, the suggestion is to produce the same amount of production at 35% efficiency, which would save 18.8% of total fuel consumed, worth £5.63 billion. Hence, both cases show the significance of efficiency improvement.

7- Reasons causing inefficiencies

The literature has found out several causes that lead to inefficiency with different effects, as shown in

Figure 4-11. However, it is important to identify the most relevant causes that relate to SA and to tackle them. Accordingly, simulation is utilised to provide detailed information about the system behaviour to help to identify the most salient impacting factors on efficiency.

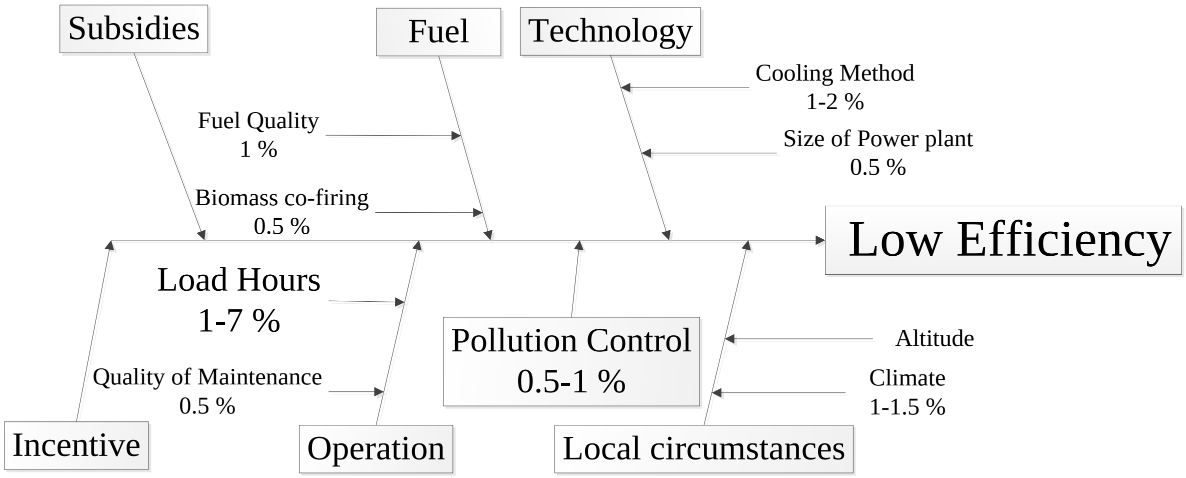


Figure 4-11Cause and effect diagram

Stage 1 Simulation Model

Simulation is used in this stage as a tool to provide an in-depth view of operation performance. It measures load hours, efficiency, fuel consumed and total production for each unit and in total. The outcomes will be evaluated in the analysis stage.

- Data collection and analysis.

One of the challenges of this study was the data collection as those needed are not available in reports or on official websites. So, they were collected through visits and direct communication with ECRA. However, the received data were limited to SEC’s power plant performance for the whole year 2011, as shown in Table 4-8. It contains 48 power plant names, type, merit order, HR and gross actual generation. Consequently, this simulation is based on the given year and SEC’s power plants. Nevertheless, it is important to mention that these data represent around 70% of total production in the kingdom. The nominal capacity of each power plant was obtained online through ECRA’s website (ECRA 2012b), details of which can be found in Appendix A.

The obtained data do not provide exact details of internal consumption (auxiliary) in each power plant. Hence, 3% was considered as an average in all power plants and 10% losses in the transmission and distribution networks, as mentioned in ECRA reports (ECRA 2011c) (ECRA 2011b). Fuel consumed and annual load profile were collected from ECRA annual reports. Finally, emissions produced and total cost of fuel were found at the International Energy Agency (2013) and SEC (2012). These data will be used to verify the model results. All data collected and prepared are available in Appendix B.

Table 4-8 HR and gross production of SEC's power plants for 2011. (Andejani, 2014)[20]

Power plant name	Gross annual HR (Btu/kWh)	Gross Actual generation (MWh)	Nominal capacity (MW)
PP9-CC	7,547	11,605,579	2,359
Rabigh-ST	8,934	9,654,490	1,572
Qurayaah-ST	8,965	16,109,600	2,500
Shaiba-ST	8,992	28,451,783	5,538
Ghazlan-ST	9,334	27,860,841	4,376
Rabigh-CC	10,071	4,841,234	1,120
PP9-GT	10,967	9,299,417	1,257
PP7	11,063	7,567,258	1,316
Tabuk-2	11,147	3,107,501	735
Rabigh-GT	11,204	2,897,265	1,680
Qurayah-CC	11,443	8,010,560	1,905
PP10	11,502	3,804,065	1,789
PP8	11,523	8,043,021	2,071
Assir	11,756	2,589,681	650
Bisha	11,853	1,992,580	349
JAZAN	12,041	5,566,690	1,339
Faras	12,088	3,994,813	1,330
Tihama	12,249	3,147,314	722
Najran	12,490	2,103,823	370
Madienah -2	12,862	1,097,551	284
Makkah	12,880	3,251,294	822
Hail – 2	13,056	1,753,204	522
Qassim	13,063	3,562,555	1,138
Albaha	13,218	60,514	67
Arar	13,230	1,231,238	246
Rafha	13,458	319,919	84
AL –Jouf	13,655	1,294,742	288
Jeddah No.3	13,732	6,313,340	1,808
Sharourah	13,758	225,322	126
PP4	13,775	1,123,874	337
PP5	14,230	2,093,177	608
Tabuk – 1	14,702	19,600	102
Layla	14,703	487,664	102
Guba	15,197	1,259,821	318
Yanbu	15,230	111,401	55
Tabargel	15,271	237,337	72
Duba	15,902	485,257	162
Shedgum	15,937	2,380,914	1,109
Berri	16,012	166,319	209
Taif	16,404	106,459	116
Qurayat	17,487	428,567	91
Al Wajh	17,751	239,406	83
Madienah -1	18,022	21,761	18
Buriedah	18,657	124,100	105
Safaniyah	18,762	6,739	44
Uthmaniyah	18,907	100,228	259
Dammam	18,972	440,417	346
Qaiesomah	20,539	186,585	144
Total	N/A	189,776,820	42641

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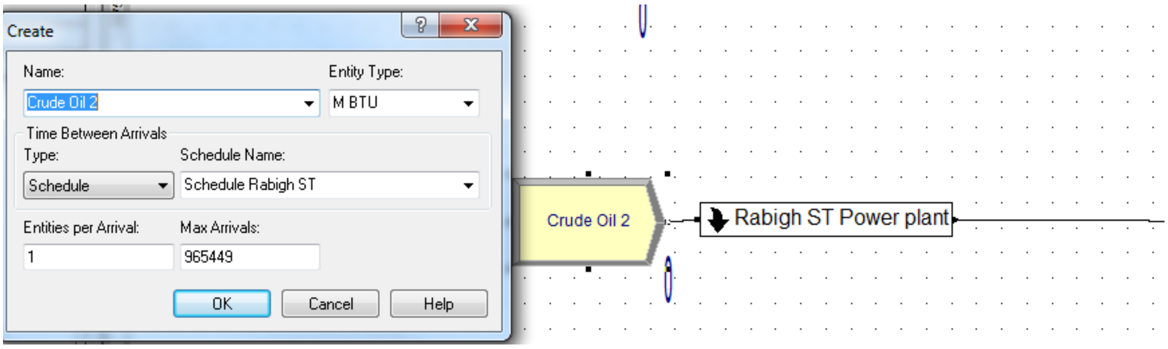
[20] Email

- Model building

The model was built using Arena software to simulate the operation of power plants in generating electricity on a discrete event simulation model. Due to the limitation of number of entities in the academic version of the software, an error message was presented while running the software. Consequently, a conversion factor is used within the model to reduce the number of entities without affecting the final results.

The model consists of several stages, fuel injection, transformation, transmission, and disposal or delivery. It starts with 48 create modules, which represent the fuel injection, measured in BTU. Power plant operation is based on schedules to control its operating capacity separately, according to the requirements and it has a maximum production limit, as shown in Figure **4-12**.



Name: Crude Oil 2
Entity Type: M BTU
Time Between Arrivals
Type: Schedule
Schedule Name: Schedule Rabigh ST
Entities per Arrival: 1
Max Arrivals: 965449

Figure 4-12 Fuel injection in power plants in BTU

The transformation stage calculates the efficiency of transforming fuel (BTU) to electricity (MWh). It contains 48 power plants represented by sub models, with each consisting of three recorders, as can be seen in Figure **4-13**. The first and second recorders are used to measure the total fuel consumed and the last, the total electricity generated. Capacity is controlled within the process. It contains the needed production time for each single unit to assure that this does not exceed its maximum capacity per hour. The assign module is used to assign every produced entity as MWh instead of BTU to be measured in the following steps.

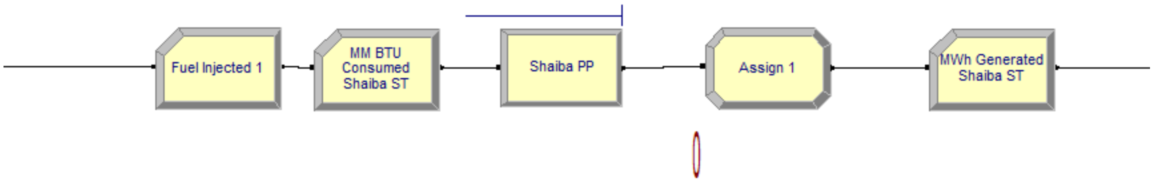


Figure 4-13 Sub model modules

The gross production of each power plant passes through a decide module, as shown in Figure **4-14**. On average, 3% of production is considered as auxiliary consumption of the power plants and disposed from the system after passing through the recorder for statistical use. 97% of the generated power from all the units is sent to a station named transmission line using several route modules.

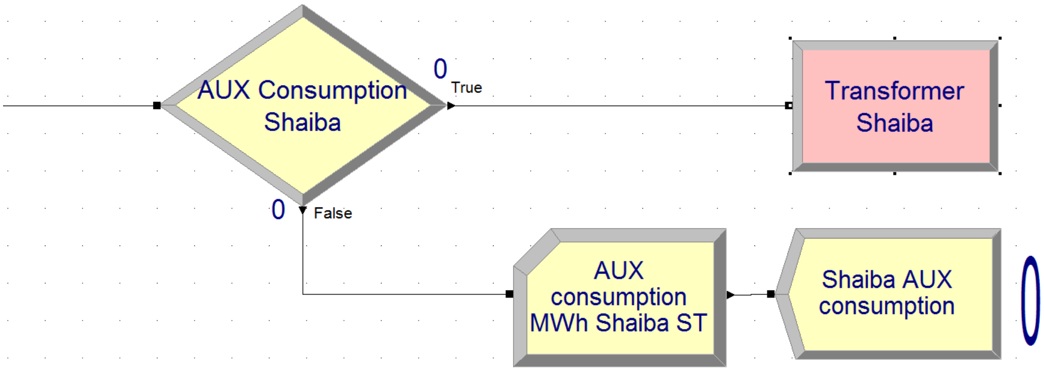


Figure 4-14 Auxiliary consumption

The transmitted electricity from all power plants passes through a decide module called T&D losses (see Figure **4-15**). 10% of production is lost in transmission and therefore, disposed after being recorded. 90% of the power passes through the batch, recorder and hold modules. Batch is used to merge entities and is represented in GWh instead of MWh. Hold is utilised for the purpose of plotting the output to show the delivered electricity per hour (Figure **4-15**) and finally, disposed. All entities are disposed from the system through 50 different disposing modules. On average, 3% of electricity generated is disposed through 48 (dispose modules) as auxiliary consumption and 10% represent transmission losses, whilst the rest is sent to customers.

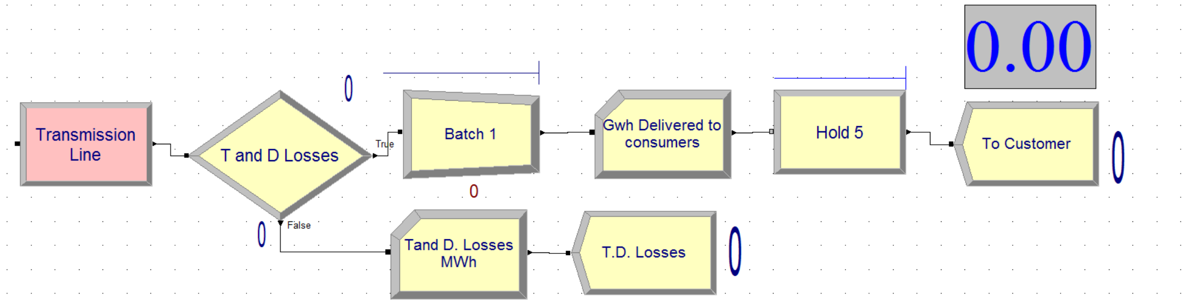


Figure 4-15 Transmission and distribution stage

Around 194 counters are used to record the fuel consumed, electricity generated, auxiliary consumption in each power plants, losses in transmission networks and total power sent to customers. The recorded values are used in the expressions and statistics functions. Equations are inserted in expressions and used for calculating the efficiency and load factor for each unit, overall BTU consumed and electricity generated, as. The expressions used in the model are presented below.

Capacity Factor:

- NC(MWh Generated Shaiba ST)/(Nominal Capacity Shaiba Mwh*7500)

Fuel cost M.USD International price:

- ((MM BTU Consumed)*15.81)/1,000,000

where, 15.81 is the average international price of fuel ($/MMBTU)

Fuel cost M.USD Local price

- ((MM BTU Consumed)*0.71)/1,000,000

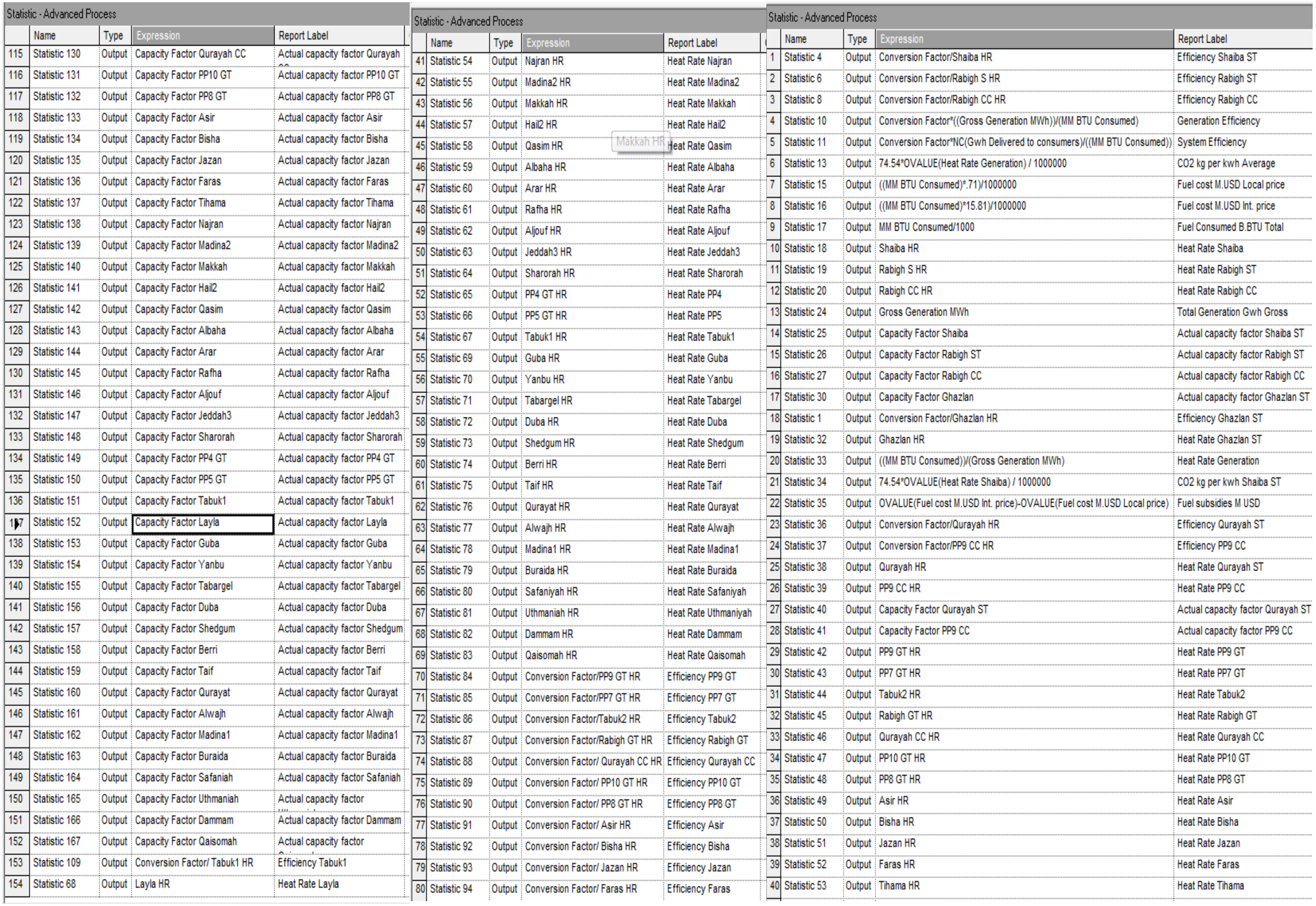
where, 0.71 is the average local price of fuel paid by electricity providers in SA ($/MMBTU)

Average CO_2 (kg/kWh)

- 74.54*OVALUE (Heat Rate Generation)/1,000,000

where, 74.54 is the emissions factor (kg CO_2/MMBtu)

About 154 statistics functions have been used to display the final results in the output report in Figure **4-16**. It contains the efficiency and load factor for each generating unit, cost of fuel, cost of subsidies, emissions rate, total fuel consumed, gross generated electricity, average efficiency and heat rate for all the power plants.



Statistic - Advanced Process

	Name	Type	Expression	Report Label
115	Statistic 130	Output	Capacity Factor Qurayah CC	Actual capacity factor Qurayah
116	Statistic 131	Output	Capacity Factor PP10 GT	Actual capacity factor PP10 GT
117	Statistic 132	Output	Capacity Factor PP8 GT	Actual capacity factor PP8 GT
118	Statistic 133	Output	Capacity Factor Asir	Actual capacity factor Asir
119	Statistic 134	Output	Capacity Factor Bisha	Actual capacity factor Bisha
120	Statistic 135	Output	Capacity Factor Jazan	Actual capacity factor Jazan
121	Statistic 136	Output	Capacity Factor Faras	Actual capacity factor Faras
122	Statistic 137	Output	Capacity Factor Tihama	Actual capacity factor Tihama
123	Statistic 138	Output	Capacity Factor Najran	Actual capacity factor Najran
124	Statistic 139	Output	Capacity Factor Madina2	Actual capacity factor Madina2
125	Statistic 140	Output	Capacity Factor Makkah	Actual capacity factor Makkah
126	Statistic 141	Output	Capacity Factor Hail2	Actual capacity factor Hail2
127	Statistic 142	Output	Capacity Factor Qasim	Actual capacity factor Qasim
128	Statistic 143	Output	Capacity Factor Albaha	Actual capacity factor Albaha
129	Statistic 144	Output	Capacity Factor Arar	Actual capacity factor Arar
130	Statistic 145	Output	Capacity Factor Rafha	Actual capacity factor Rafha
131	Statistic 146	Output	Capacity Factor Aljouf	Actual capacity factor Aljouf
132	Statistic 147	Output	Capacity Factor Jeddah3	Actual capacity factor Jeddah3
133	Statistic 148	Output	Capacity Factor Sharorah	Actual capacity factor Sharorah
134	Statistic 149	Output	Capacity Factor PP4 GT	Actual capacity factor PP4 GT
135	Statistic 150	Output	Capacity Factor PP5 GT	Actual capacity factor PP5 GT
136	Statistic 151	Output	Capacity Factor Tabuk1	Actual capacity factor Tabuk1
137	Statistic 152	Output	Capacity Factor Layla	Actual capacity factor Layla
138	Statistic 153	Output	Capacity Factor Guba	Actual capacity factor Guba
139	Statistic 154	Output	Capacity Factor Yanbu	Actual capacity factor Yanbu
140	Statistic 155	Output	Capacity Factor Tabargel	Actual capacity factor Tabargel
141	Statistic 156	Output	Capacity Factor Duba	Actual capacity factor Duba
142	Statistic 157	Output	Capacity Factor Shedgum	Actual capacity factor Shedgum
143	Statistic 158	Output	Capacity Factor Berri	Actual capacity factor Berri
144	Statistic 159	Output	Capacity Factor Taif	Actual capacity factor Taif
145	Statistic 160	Output	Capacity Factor Qurayat	Actual capacity factor Qurayat
146	Statistic 161	Output	Capacity Factor Alwajh	Actual capacity factor Alwajh
147	Statistic 162	Output	Capacity Factor Madina1	Actual capacity factor Madina1
148	Statistic 163	Output	Capacity Factor Buraida	Actual capacity factor Buraida
149	Statistic 164	Output	Capacity Factor Safaniah	Actual capacity factor Safaniah
150	Statistic 165	Output	Capacity Factor Uthmaniah	Actual capacity factor
151	Statistic 166	Output	Capacity Factor Dammam	Actual capacity factor Dammam
152	Statistic 167	Output	Capacity Factor Qaisomah	Actual capacity factor
153	Statistic 109	Output	Conversion Factor/ Tabuk1 HR	Efficiency Tabuk1
154	Statistic 68	Output	Layla HR	Heat Rate Layla

Statistic - Advanced Process

	Name	Type	Expression	Report Label
41	Statistic 54	Output	Najran HR	Heat Rate Najran
42	Statistic 55	Output	Madina2 HR	Heat Rate Madina2
43	Statistic 56	Output	Makkah HR	Heat Rate Makkah
44	Statistic 57	Output	Hail2 HR	Heat Rate Hail2
45	Statistic 58	Output	Qasim HR	Heat Rate Qasim
46	Statistic 59	Output	Albaha HR	Heat Rate Albaha
47	Statistic 60	Output	Arar HR	Heat Rate Arar
48	Statistic 61	Output	Rafha HR	Heat Rate Rafha
49	Statistic 62	Output	Aljouf HR	Heat Rate Aljouf
50	Statistic 63	Output	Jeddah3 HR	Heat Rate Jeddah3
51	Statistic 64	Output	Sharorah HR	Heat Rate Sharorah
52	Statistic 65	Output	PP4 GT HR	Heat Rate PP4
53	Statistic 66	Output	PP5 GT HR	Heat Rate PP5
54	Statistic 67	Output	Tabuk1 HR	Heat Rate Tabuk1
55	Statistic 69	Output	Guba HR	Heat Rate Guba
56	Statistic 70	Output	Yanbu HR	Heat Rate Yanbu
57	Statistic 71	Output	Tabargel HR	Heat Rate Tabargel
58	Statistic 72	Output	Duba HR	Heat Rate Duba
59	Statistic 73	Output	Shedgum HR	Heat Rate Shedgum
60	Statistic 74	Output	Berri HR	Heat Rate Berri
61	Statistic 75	Output	Taif HR	Heat Rate Taif
62	Statistic 76	Output	Qurayat HR	Heat Rate Qurayat
63	Statistic 77	Output	Alwajh HR	Heat Rate Alwajh
64	Statistic 78	Output	Madina1 HR	Heat Rate Madina1
65	Statistic 79	Output	Buraida HR	Heat Rate Buraida
66	Statistic 80	Output	Safaniyah HR	Heat Rate Safaniyah
67	Statistic 81	Output	Uthmaniah HR	Heat Rate Uthmaniyah
68	Statistic 82	Output	Dammam HR	Heat Rate Dammam
69	Statistic 83	Output	Qaisomah HR	Heat Rate Qaisomah
70	Statistic 84	Output	Conversion Factor/PP9 GT HR	Efficiency PP9 GT
71	Statistic 85	Output	Conversion Factor/PP7 GT HR	Efficiency PP7 GT
72	Statistic 86	Output	Conversion Factor/Tabuk2 HR	Efficiency Tabuk2
73	Statistic 87	Output	Conversion Factor/Rabigh GT HR	Efficiency Rabigh GT
74	Statistic 88	Output	Conversion Factor/ Qurayah CC HR	Efficiency Qurayah CC
75	Statistic 89	Output	Conversion Factor/ PP10 GT HR	Efficiency PP10 GT
76	Statistic 90	Output	Conversion Factor/ PP8 GT HR	Efficiency PP8 GT
77	Statistic 91	Output	Conversion Factor/ Asir HR	Efficiency Asir
78	Statistic 92	Output	Conversion Factor/ Bisha HR	Efficiency Bisha
79	Statistic 93	Output	Conversion Factor/ Jazan HR	Efficiency Jazan
80	Statistic 94	Output	Conversion Factor/ Faras HR	Efficiency Faras

Statistic - Advanced Process

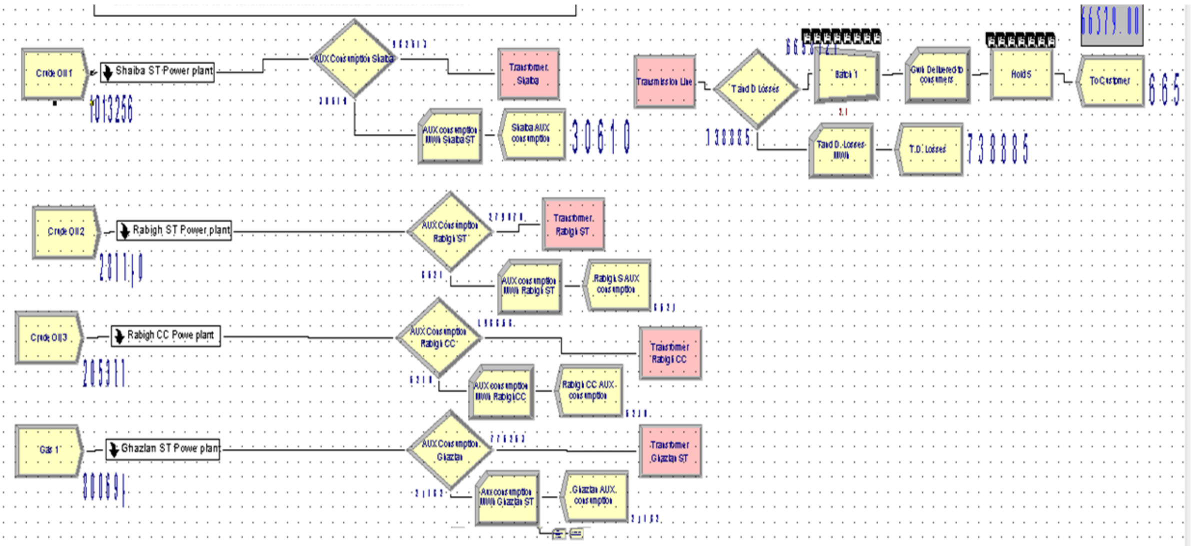
	Name	Type	Expression	Report Label
1	Statistic 4	Output	Conversion Factor/Shaiba HR	Efficiency Shaiba ST
2	Statistic 6	Output	Conversion Factor/Rabigh S HR	Efficiency Rabigh ST
3	Statistic 8	Output	Conversion Factor/Rabigh CC HR	Efficiency Rabigh CC
4	Statistic 10	Output	Conversion Factor*((Gross Generation MWh))/(MM BTU Consumed)	Generation Efficiency
5	Statistic 11	Output	Conversion Factor*NC(Gwh Delivered to consumers)/((MM BTU Consumed))	System Efficiency
6	Statistic 13	Output	74.54*OVALUE(Heat Rate Generation) / 1000000	CO2 kg per kwh Average
7	Statistic 15	Output	((MM BTU Consumed)*.71)/1000000	Fuel cost M.USD Local price
8	Statistic 16	Output	((MM BTU Consumed)*15.81)/1000000	Fuel cost M.USD Int. price
9	Statistic 17	Output	MM BTU Consumed/1000	Fuel Consumed B.BTU Total
10	Statistic 18	Output	Shaiba HR	Heat Rate Shaiba
11	Statistic 19	Output	Rabigh S HR	Heat Rate Rabigh ST
12	Statistic 20	Output	Rabigh CC HR	Heat Rate Rabigh CC
13	Statistic 24	Output	Gross Generation MWh	Total Generation Gwh Gross
14	Statistic 25	Output	Capacity Factor Shaiba	Actual capacity factor Shaiba ST
15	Statistic 26	Output	Capacity Factor Rabigh ST	Actual capacity factor Rabigh ST
16	Statistic 27	Output	Capacity Factor Rabigh CC	Actual capacity factor Rabigh CC
17	Statistic 30	Output	Capacity Factor Ghazlan	Actual capacity factor Ghazlan ST
18	Statistic 1	Output	Conversion Factor/Ghazlan HR	Efficiency Ghazlan ST
19	Statistic 32	Output	Ghazlan HR	Heat Rate Ghazlan ST
20	Statistic 33	Output	((MM BTU Consumed))/(Gross Generation MWh)	Heat Rate Generation
21	Statistic 34	Output	74.54*OVALUE(Heat Rate Shaiba) / 1000000	CO2 kg per kwh Shaiba ST
22	Statistic 35	Output	OVALUE(Fuel cost M.USD Int. price)-OVALUE(Fuel cost M.USD Local price)	Fuel subsidies M USD
23	Statistic 36	Output	Conversion Factor/Qurayah HR	Efficiency Qurayah ST
24	Statistic 37	Output	Conversion Factor/PP9 CC HR	Efficiency PP9 CC
25	Statistic 38	Output	Qurayah HR	Heat Rate Qurayah ST
26	Statistic 39	Output	PP9 CC HR	Heat Rate PP9 CC
27	Statistic 40	Output	Capacity Factor Qurayah ST	Actual capacity factor Qurayah ST
28	Statistic 41	Output	Capacity Factor PP9 CC	Actual capacity factor PP9 CC
29	Statistic 42	Output	PP9 GT HR	Heat Rate PP9 GT
30	Statistic 43	Output	PP7 GT HR	Heat Rate PP7 GT
31	Statistic 44	Output	Tabuk2 HR	Heat Rate Tabuk2
32	Statistic 45	Output	Rabigh GT HR	Heat Rate Rabigh GT
33	Statistic 46	Output	Qurayah CC HR	Heat Rate Qurayah CC
34	Statistic 47	Output	PP10 GT HR	Heat Rate PP10 GT
35	Statistic 48	Output	PP8 GT HR	Heat Rate PP8 GT
36	Statistic 49	Output	Asir HR	Heat Rate Asir
37	Statistic 50	Output	Bisha HR	Heat Rate Bisha
38	Statistic 51	Output	Jazan HR	Heat Rate Jazan
39	Statistic 52	Output	Faras HR	Heat Rate Faras
40	Statistic 53	Output	Tihama HR	Heat Rate Tihama

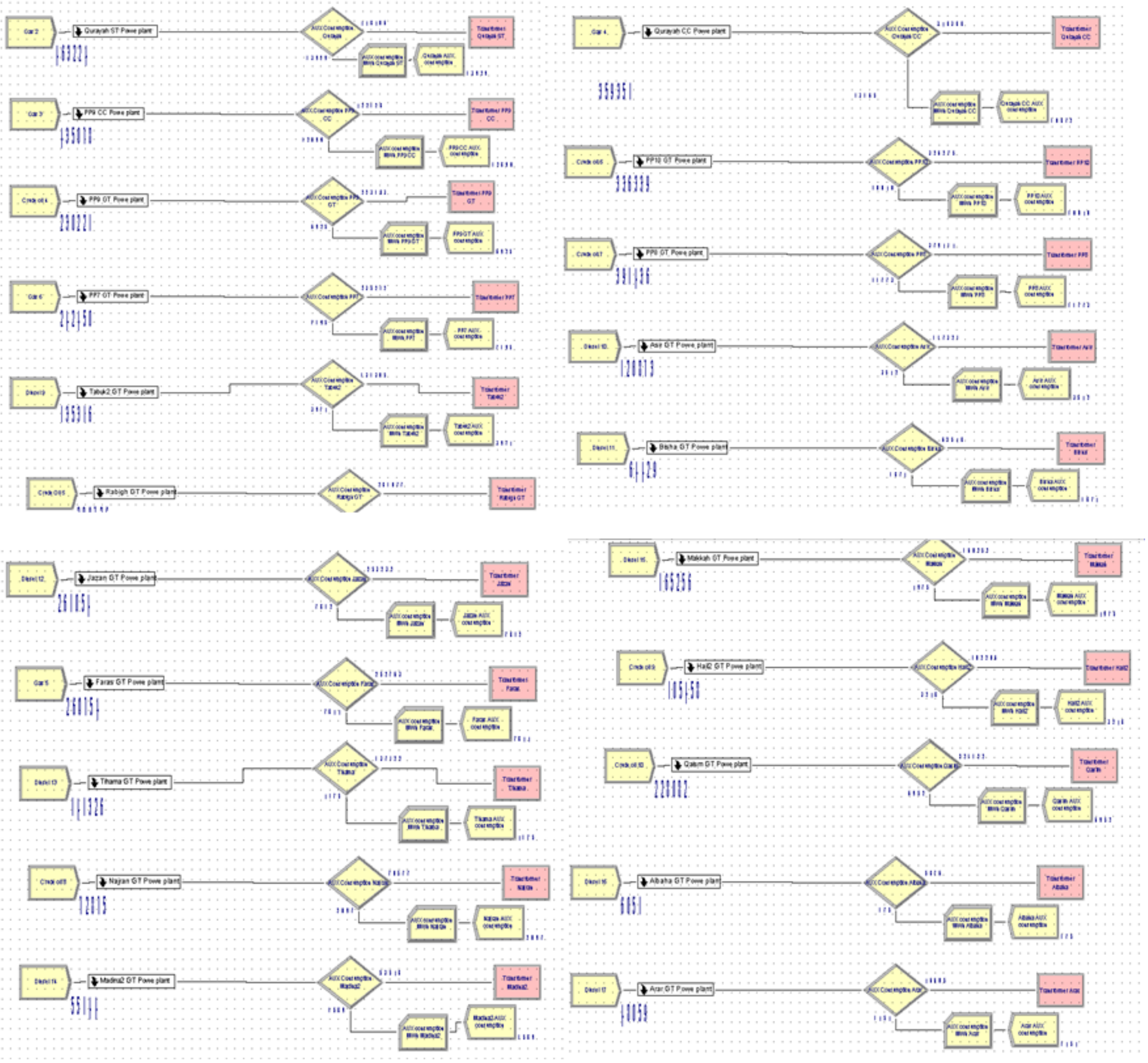
Figure 4-16 Statistics used in the model

All units passed through the transmission networks and delivered to consumers are plotted on an hourly basis to show the final net production. The final model shown in Figure **4-17** utilises 1,282 modules and functions, as shown in detail in Table **4-9**.

Table 4-9 Simulation model contents

Module	No. of modules
Create	48
Entity type	2
Assign	48
Sub model	48
Resource	48
Decide	49
Process	48
Schedule	48
Queue	50
Attribute	97
Statistics	154
Expression	98
Record	194
Variable	198
Route	48
Station	1
Hold	1
Batch	1
Plot	1
Dispose	50
Total	1,282


Crude Oil 1
Shaiba ST Power plant
AUX Consumption Shaiba
Transformer Shaiba
AUX consumption MWh Shaiba ST
Shaiba AUX consumption
30610
Transmission Line
T and D Losses
Batch 1
Gwh Delivered to consumers
Hold 5
To Customer
66579.00
T and D Losses MWh
T.D. Losses
738885
Crude Oil 2
Rabigh ST Power plant
AUX Consumption Rabigh ST
Transformer Rabigh ST
AUX consumption MWh Rabigh ST
Rabigh S AUX consumption
Crude Oil 3
Rabigh CC Powe plant
AUX Consumption Rabigh CC
Transformer Rabigh CC
AUX consumption MWh Rabigh CC
Rabigh CC AUX consumption
Gas 1
Ghazlan ST Powe plant
AUX Consumption Ghazlan
Transformer Ghazlan ST
Aux consumption MWh Ghazlan ST
Ghazlan AUX consumption


Qurayah ST Powe plant
Qurayah CC Powe plant
PP9 CC Powe plant
PP10 GT Powe plant
PP9 GT Powe plant
PP8 ST Powe plant
PP7 GT Powe plant
Asir GT Powe plant
Tabuk2 GT Powe plant
Baha GT Powe plant
Rabigh GT Powe plant
Jazan GT Powe plant
Makkah GT Powe plant
Farasi GT Powe plant
Hail2 GT Powe plant
Tihama GT Powe plant
Qasim GT Powe plant
Najran GT Powe plant
Albaha GT Powe plant
Madina2 GT Powe plant
Arar GT Powe plant

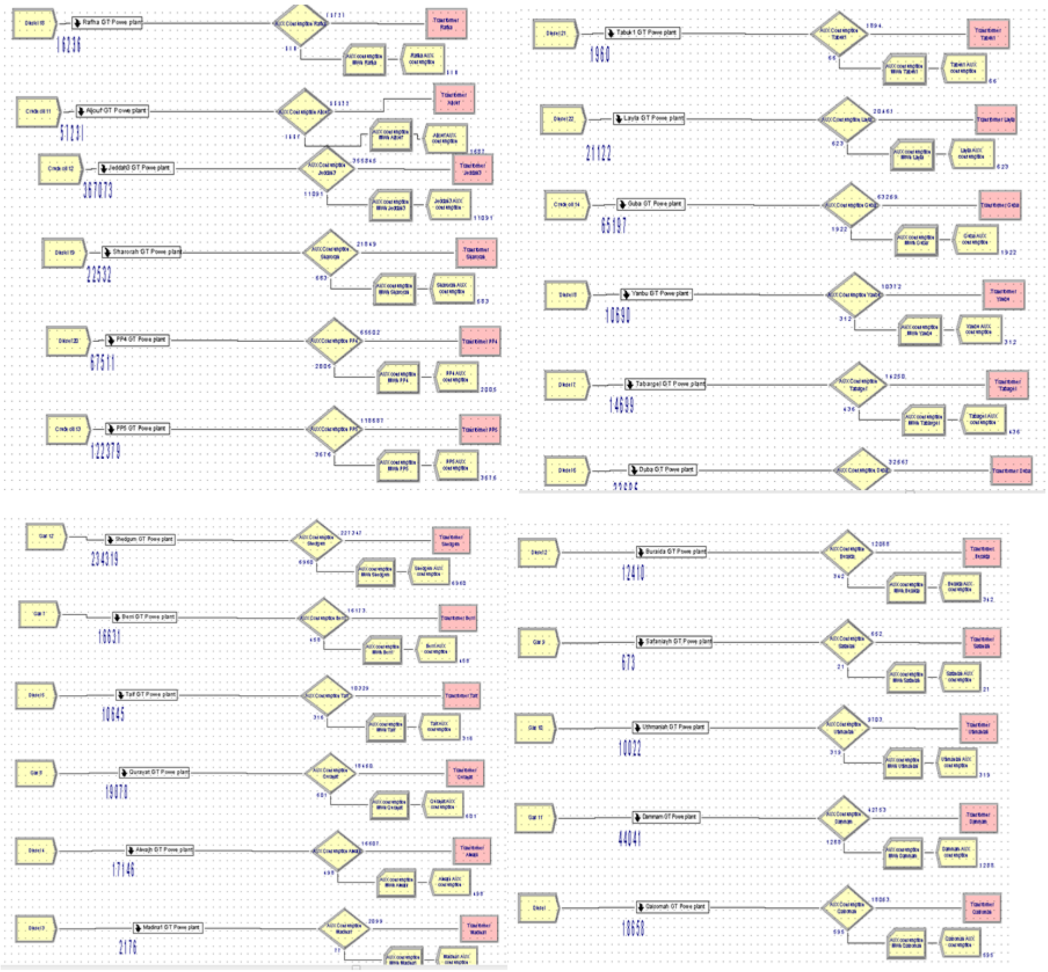


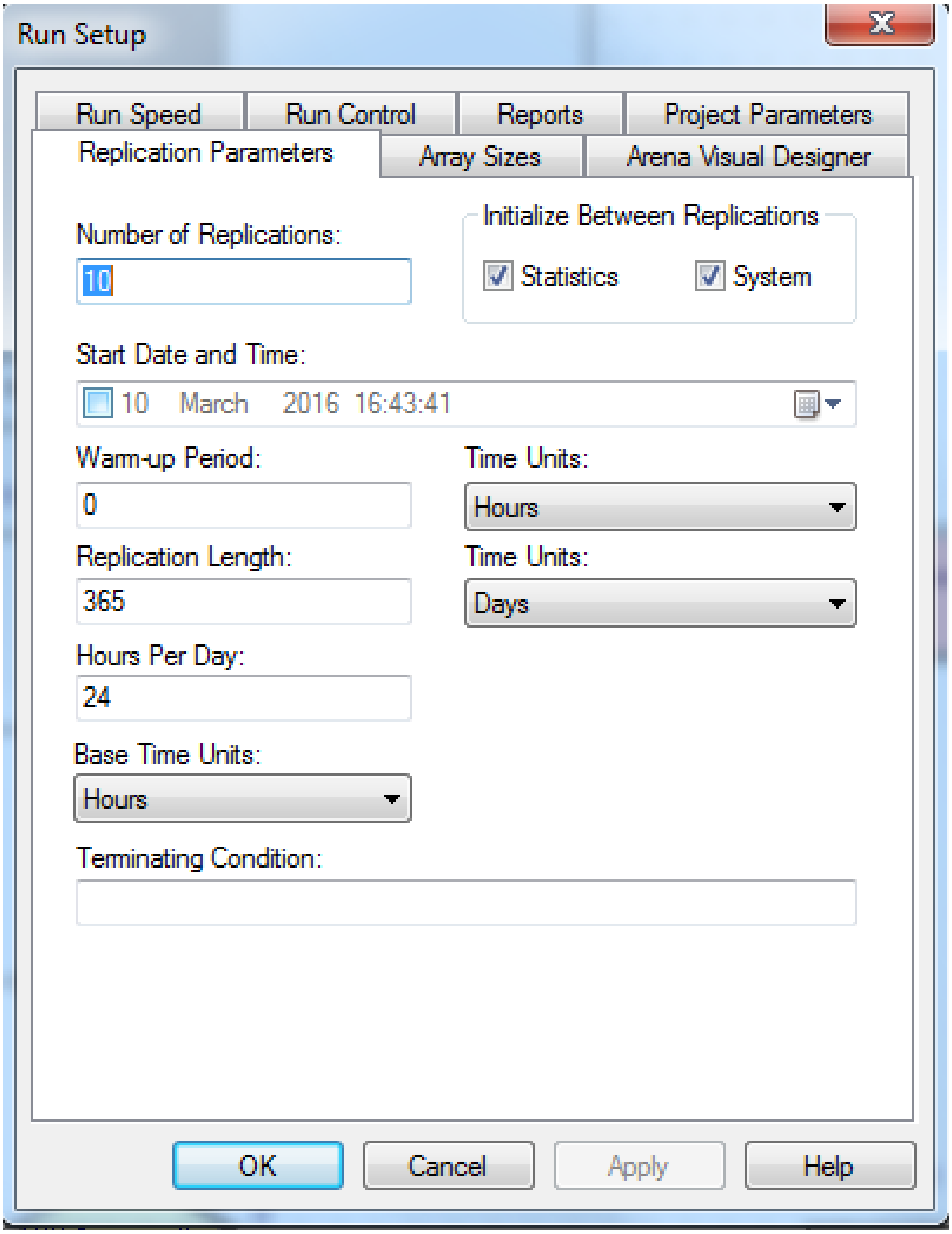
Figure 4-17 Simulation model blocks

- Verify and Validate

The model was verified after solving all the errors; reducing the amount of entities using conversion factor. A complete run was undertaken including several replications without showing any error messages. In addition, outcomes were validated by generating similar results in the real system.

- Run Setup

The model configuration was set to run 10 replications and both the system and statistics were set to be initialised during each replication. The length of each run was 365 days for 24 hours a day to simulate a complete year cycle and the goal when choosing this length was to test whether the simulation generated results that match the real data. The "base time units" were set to hours, as shown in Figure **4-18**.



Number of Replications: 10

Initialize Between Replications: ☑ Statistics ☑ System

Start Date and Time: ☐ 10 March 2016 16:43:41

Warm-up Period: 0

Time Units: Hours

Replication Length: 365

Time Units: Days

Hours Per Day: 24

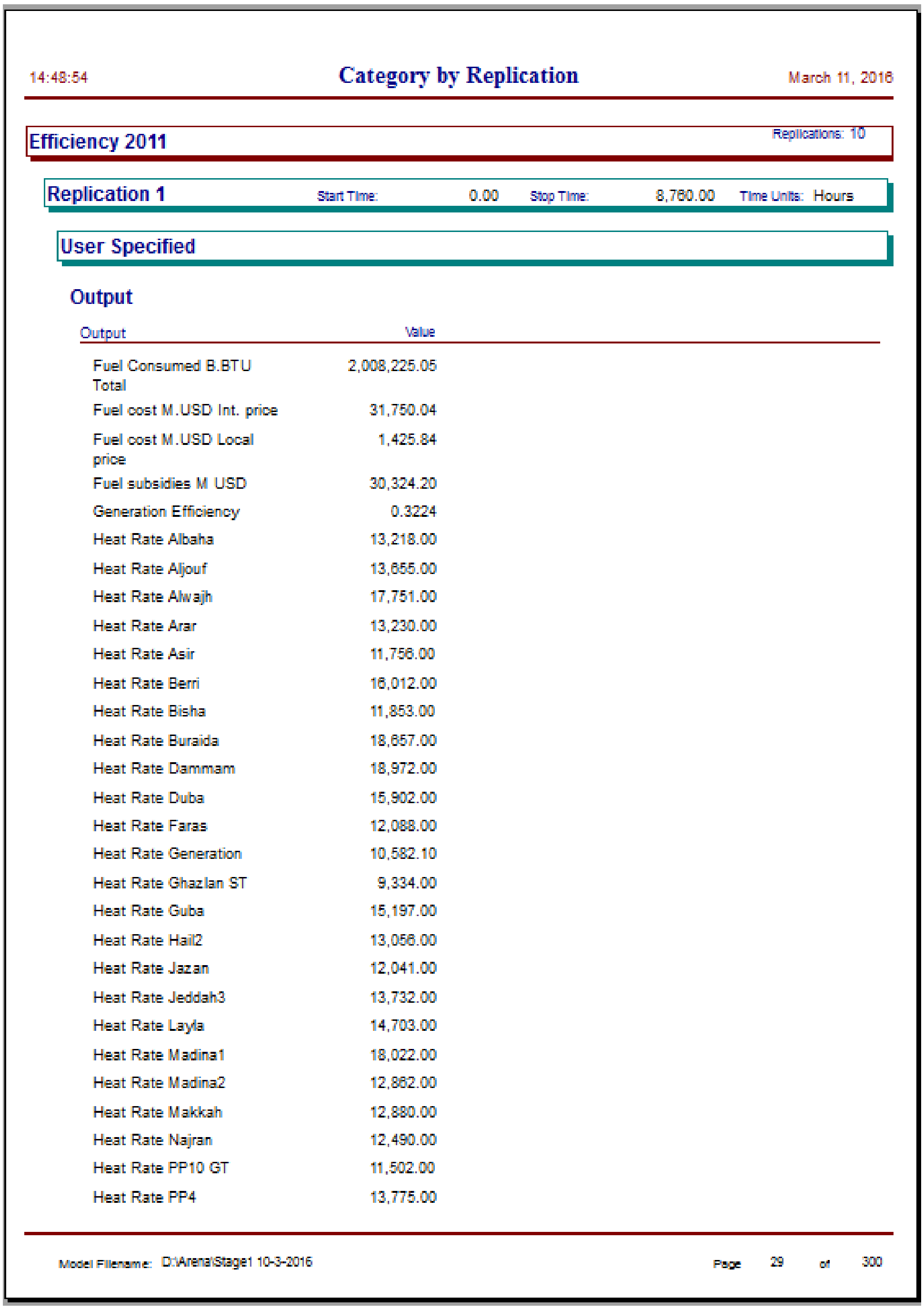
Base Time Units: Hours

Terminating Condition:

Figure 4-18 Run setup configuration

- Simulation Results (current situation)

After running the model, the software generates the results in a report, as shown in Figure **4-19**. The results can be classified in two types. The first, can be compared to the actual data to insure the credibility of the system, such as overall fuel consumed, gross production per unit and total production. The second type are those results which will be used in the analysis stage, such as load factor, efficiency for each unit and the average HR. There are additional data that cannot be used on this stage, but will be utilised during the final step as measures for quantifying any potential improvement, including average CO_2 produced, cost of fuel consumed, subsidies, net production and annual load profile. In general, the simulation l results represent the real system in terms of total fuel consumed, HR per unit and gross production. The average generation efficiency of SEC power plants was 32.24% in 2011. Power plants consumed 2008 T. BTU and produced 189,776 GWh, which is similar to the figures mentioned in the SEC report of 2011. Finally, the average CO_2 emitted was 788 g/kWh. Full reports are available in Appendix D.



14:48:54 **Category by Replication** March 11, 2016

Efficiency 2011 Replications: 10

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

User Specified

Output

Output	Value
Fuel Consumed B.BTU Total	2,008,225.05
Fuel cost M.USD Int. price	31,750.04
Fuel cost M.USD Local price	1,425.84
Fuel subsidies M USD	30,324.20
Generation Efficiency	0.3224
Heat Rate Albaha	13,218.00
Heat Rate Aljouf	13,655.00
Heat Rate Alwajh	17,751.00
Heat Rate Arar	13,230.00
Heat Rate Asir	11,756.00
Heat Rate Berri	16,012.00
Heat Rate Bisha	11,853.00
Heat Rate Buraida	18,657.00
Heat Rate Dammam	18,972.00
Heat Rate Duba	15,902.00
Heat Rate Faras	12,088.00
Heat Rate Generation	10,582.10
Heat Rate Ghazlan ST	9,334.00
Heat Rate Guba	15,197.00
Heat Rate Hail2	13,056.00
Heat Rate Jazan	12,041.00
Heat Rate Jeddah3	13,732.00
Heat Rate Layla	14,703.00
Heat Rate Madina1	18,022.00
Heat Rate Madina2	12,862.00
Heat Rate Makkah	12,880.00
Heat Rate Najran	12,490.00
Heat Rate PP10 GT	11,502.00
Heat Rate PP4	13,775.00

Model Filename: D:\Arena\Stage1 10-3-2016 Page 29 of 300

Figure 4-19 Sample of the model results

4.4 Stage 3 of DMAIC: Analyse

In this stage, measurement outcomes and simulation reports are analysed in detail. The most relevant root cause is identified and improvement opportunities are proposed.

- Measurement Analysis

The measurement stage has led to a more in depth view about the issue. It shows that the generation stage appears to be the least efficient and most wasteful area in the electricity system in Saudi Arabia. The current generation efficiency is below the global average. Notably, the existing generation stock can achieve higher efficiency of up to 38%, based on its age, fuel mix and available technology mix as proved on the measurement stage. The gap is wide between the current and potential level, which means massive savings could be made.

The calculated efficiency in SA was around 28% during the last decade with a notable jump to 31% in 2014. This change can be related to the intervention of new steam turbines that increased their nominal capacity to 40% in 2014, compared to 36% in the previous year and the retirement of old gas turbines, which resulted in reducing their capacity by 3%. On the other hand, the largest power producer in the kingdom (SEC) has shown 32% average efficiency, slightly higher than the country's average. Regarding the total fuel consumed and electricity produced, oil and gas are equally consumed in power generation. Both show a low level of efficiency, with 29% for gas and 28% for oil, on average. The technology mix was mainly the same up until 2011, with 52% GT, 41% ST and 6% CC. In two years, the nominal capacity of combined cycle units doubled reaching to 12.3% in 2013, but this change was not reflected in the average level of efficiency. This can be used as evidence that building new combined cycle power plants is not sufficient to improve the average efficiency, as suggested in the literature.

Notably, the merit order of operating power plants does not represent the optimum sequence, as the most efficient power plants are not on the top of the list and less efficient units have priority over them. The existing merit order is based on the cost of total fuel consumed per unit of energy generated, as stated in the literature. This means efficient units should be in lead position since they require less energy per kWh produced, which is not the case in the current order. The reason for the current order can be linked to the methodology used in cost calculations. Considering the kWh cost of each power plant based on its total fuel consumption and total production of the previous year can have negative impact, if load factor is not considered. For example, the Rabigh-CC power plant has been utilised to only 58% of its total capacity. This means it has operated on partial load with several start-ups and shut downs according to demand. Consequently, it consumed more fuel than it should have done during the start-up and owing to partial load, according to the literature. Without doubt, if it is assessed based on this performance, it will not show any evidence of reduction in unit cost and as a result, it will not be promoted in the merit order, which would allow more hours of operation. In addition, inconsistent operation could also be the reason for underperforming in terms of efficiency. Consequently, it will be located on the same rank of operation for the coming year. Several units have the potential to perform better in terms of efficiency, if they operate consistently by having priority of operation, as will be discussed on the simulation results.

The simulation utilised the data gathered for SEC power plants in 2011. The report shows similar outcomes compared to the actual data in official reports in terms of gross production and fuel consumption. This means the model is running successfully and can be used with confidence in the analysis and to examine any proposed changes in the next step. Nevertheless, it shows no relation between the load factors of units, efficiency and merit order. The poor utilisation of units would thus appear to have resulted in a significant loss in efficiency in some power plants.

The calculation of average efficiency is affected by the quantity of electricity produced by each generating unit (contribution) under specific efficiency. This means that the existence of high efficient units is not sufficient to improve average efficiency unless they have contributed significantly to the total production. That is, increasing the share of production of less efficient units will result in reducing the average efficiency and vice versa. To illustrate, 52% of gross production was generated by power plants with above average efficiency. However, these units were utilised only 74% of the time and represent 41% of the generation capacity. On the other hand, several power plants with efficiency below average were utilised more than those with higher efficiency (see Figure 4-20). This means SEC's generation assets are not being deployed as efficiently as they could be. As a result, this is a main contributor to the low level of average efficiency. One possible explanation could be the fuel subsidies, which tend to favour less efficient units, as discussed in the literature.

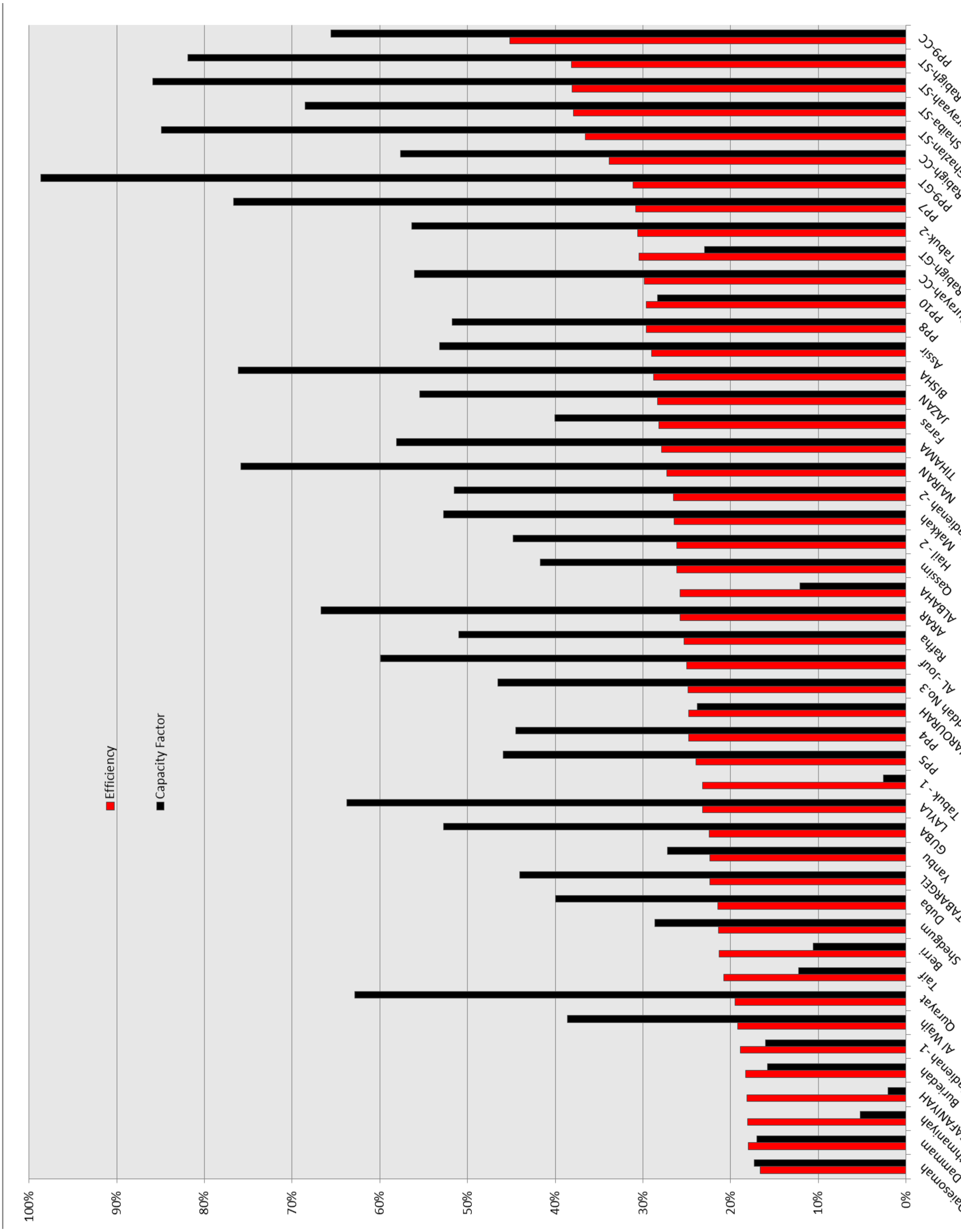


Figure 4-20 Efficiency and utilisation for each power plant

By analysing the generation stock according to the technology type and gross production, important observations have emerged Figure **4-21**, shows that 87% of gross production was generated by ST and GT in equal shares, while CC generated only 13% only. On average, the most utilised technology was ST (79%), followed by CC (61%) and then, GT (56%). Theoretically, combined cycles are more efficient (up to 50%) than steam turbines (38-40%) and gas turbines (32-38%) (World Bank 2008; IEA, 2010). It has been claimed that one of the main reasons of low efficiency is the lack of efficient technology, such as CCPP, Nevertheless, the simulation report shows 30% and 34% efficiency for some existing CCPP's, which is far below the design efficiency for this type of technology. One possible explanation for this could be linked to the nature of operation and load factor, which is affected by its merit order. That is, the first ranked units have more chance to operate continuously at high capacity with less shut down compared to the middle ranked turbines.

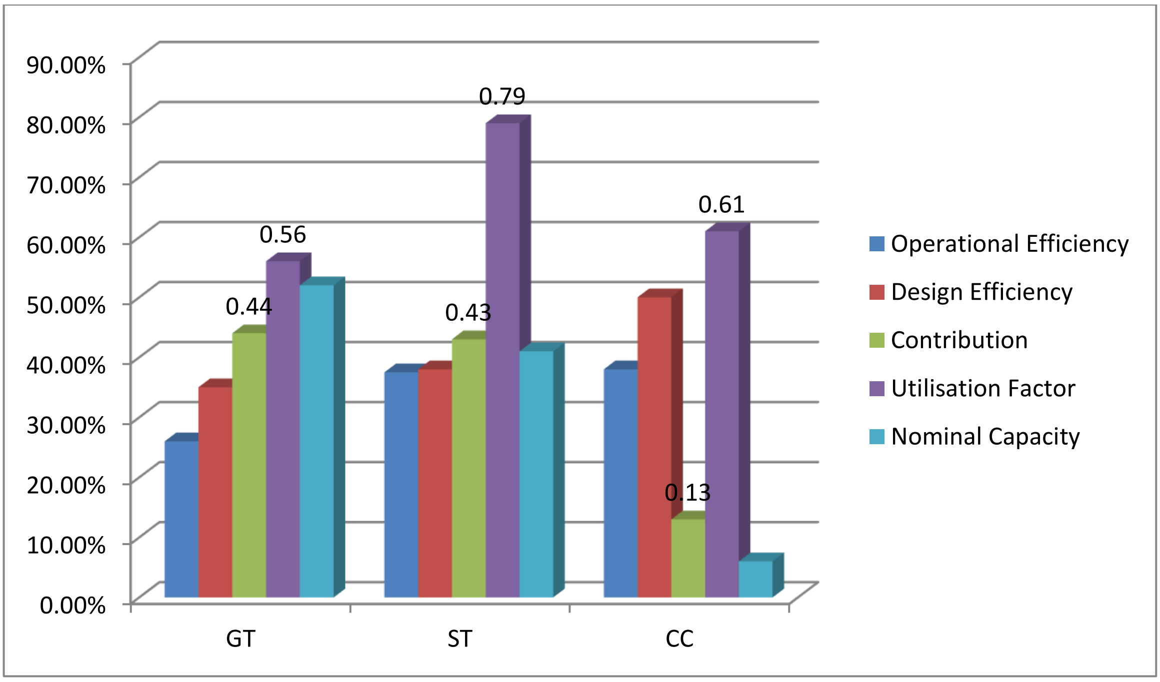


Figure 4-21 Technology based comparison

The current merit order locates CCPPs in the middle order behind STs, while theoretically the former are designed to operate with higher efficiency. In addition, several GT units ranked above CC units. As a result, the simulation report shows only 58% and 56% utilisation factors for two CCPPs, while other STs reached 86% operation and 99% for GT. This means the merit order is linked to the issue of interest and the existence of efficient technology (CC) power plants will not improve the average efficiency in the kingdom unless operation is optimised.

Table **4-10** shows the order of all power plants according to load factor, HR and current merit order. It can be seen that merit orders do not match with either the HR level or the utilisation factor. This could be a potential significant cause of low efficiency in Saudi Arabia. For instance, Shaiba-ST is the fourth most efficient power plant with an average of 38%. However, it is ranked first on the merit order, which means it should be fully utilised in operation. In operation, it has been utilised only 69%, being the eighth most utilised power plant. Another example can be seen with PP9–GT, which is seventh in terms of efficiency and sixth in the merit order. However, it was the most utilised unit at 99%, more than all CCPPs and STPPs. This means it was operated for at least 7,500 hours at full load. Notably, it is the most efficient GTPP and the following GTs were less loaded and less efficient. Likewise, PP9-CC is the top available efficient power plant, with 45% efficiency, followed by Rabigh-ST, with 38%. Noticeably, it is ranked fifth in merit order following Qurayaah-ST, with 38% efficiency. As a result, it was utilised only 66%, i.e. only as the tenth. PP7 is another example of different ranking in each type of order. In general, the current merit order operation does not show any consistency between load factor and efficiency, as shown in Figure **4-22**.

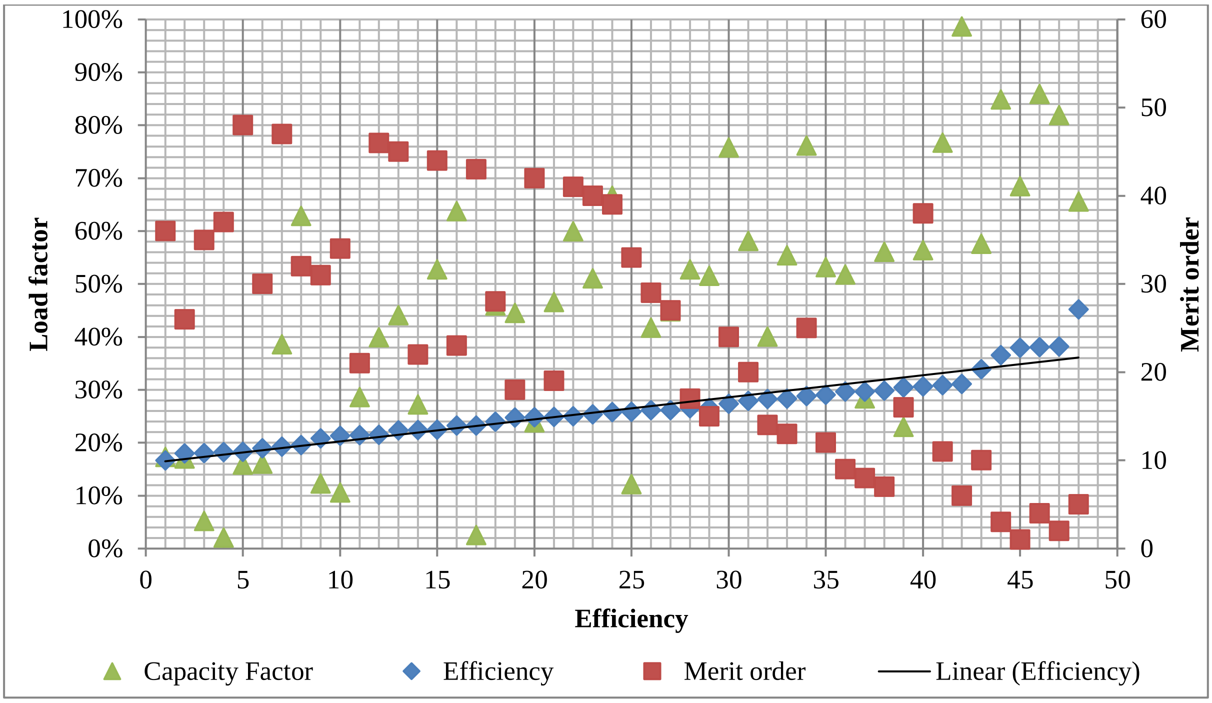


Figure 4-22 Efficiency vs load factor and merit order

Two further assumptions can be linked to the current situation. Since service providers are not paying the real price of fuel, this can lead to the value of saving being underestimated and the efficiency being underplayed, which results in fuel over consumption. This can affect the merit order calculation and lead to the current distortion, even if the merit order is based on the international fuel cost. In addition, lack of competition between providers can be a reason for the plateauing of efficiency since cost of fuel has been frozen at a very low level for a long time.

Table 4-10 Power plants ranked based on efficiency

Fuel	Location	Turbine type	Age	PP name	HR (Btu/kWh)	Gross generation (MWh)	Contribution	Efficiency	Nominal capacity MW	Capacity factor	Merit order
Crude/D	Central	CC	9	PP9-CC	7,547	11,605,579	6.12%	45.21%	2,359.44	66%	5
HFO/crude	Western	ST	24	Rabigh-ST	8,934	9,654,490	5.09%	38.19%	1,572.00	82%	2
Gas	Eastern	ST	22	Qurayaah-ST	8,965	16,109,600	8.49%	38.06%	4,405.00	86%	4
HFO/crude	Western	ST	6	Shaiba-ST	8,992	28,451,783	14.99%	37.94%	5,538.00	69%	1
Gas	Eastern	ST	21	Ghazlan-ST	9,334	27,860,841	14.68%	36.55%	4,376.00	85%	3
Crude/D	Western	CC	18	Rabigh-CC	10,071	4,841,234	2.55%	33.88%	1,120.44	58%	10
Crude&Gas	Central	GT	6	PP9-GT	10,967	9,299,417	4.90%	31.11%	1,257.00	99%	6
Gas/D	Central	GT	26	PP7	11,063	7,567,258	3.99%	30.84%	1,315.72	77%	11
Diesel	Northern	GT	12	Tabuk-2	11,147	3,107,501	1.64%	30.61%	735.20	56%	38
Crude/D	Western	GT	2	Rabigh-GT	11,204	2,897,265	1.53%	30.45%	1,680.00	23%	16
Gas/D	Eastern	CC	3	Qurayah-CC	11,443	8,010,560	4.22%	29.82%	1,905.00	56%	7
Crude/D	Central	GT	2	PP10	11,502	3,804,065	2.00%	29.66%	1,788.80	28%	8
C&G/D	Central	GT	22	PP8	11,523	8,043,021	4.24%	29.61%	2,071.38	52%	9
Diesel	Southern	GT	24	Assir	11,756	2,589,681	1.36%	29.02%	649.50	53%	12
Diesel	Southern	GT	19	Bisha	11,853	1,992,580	1.05%	28.79%	349.00	76%	25
Diesel	Southern	GT	16	Jazan	12,041	5,566,690	2.93%	28.34%	1,339.00	55%	13
Gas	Eastern	GT	23	Faras	12,088	3,994,813	2.11%	28.23%	1,329.80	40%	14
Diesel	Southern	GT	14	Tihama	12,249	3,147,314	1.66%	27.86%	722.00	58%	20
Crude/D	Southern	GT	18	Najran	12,490	2,103,823	1.11%	27.32%	370.00	76%	24
Diesel	Western	GT	27	Madienah -2	12,862	1,097,551	0.58%	26.53%	284.00	52%	15
Diesel	Western	GT	34	Makkah	12,880	3,251,294	1.71%	26.49%	821.86	53%	17
Crude/D	Central	GT	18	Hail - 2	13,056	1,753,204	0.92%	26.13%	521.85	45%	27
Crude/D	Central	GT	22	Qassim	13,063	3,562,555	1.88%	26.12%	1,138.06	42%	29
Diesel	Southern	GT	31	Al-Baha	13,218	60,514	0.03%	25.81%	66.50	12%	33
Diesel	Northern	GT	17	Arar	13,230	1,231,238	0.65%	25.79%	246.20	67%	39
Diesel	Northern	GT	14	Rafha	13,458	319,919	0.17%	25.35%	83.60	51%	40
Crude	Northern	GT	17	AL -Jouf	13,655	1,294,742	0.68%	24.99%	288.00	60%	41
Diesel	Western	GT	26	Jeddah No.3	13,732	6,313,340	3.33%	24.85%	1,808.08	47%	19
Diesel	Southern	GT	14	Sharourah	13,758	225,322	0.12%	24.80%	126.20	24%	42
Diesel	Central	GT	36	PP4	13,775	1,123,874	0.59%	24.77%	336.45	45%	18
Crude/D	Central	GT	32	PP5	14,230	2,093,177	1.10%	23.98%	608.00	46%	28
Diesel	Northern	GT	33	Tabuk - 1	14,702	19,600	0.01%	23.21%	102.00	3%	43
Diesel	Central	GT	25	Layla	14,703	487,664	0.26%	23.21%	102.00	64%	23
Crude/D	Central	GT	18	Guba	15,197	1,259,821	0.66%	22.45%	318.43	53%	44
Diesel	Western	GT	29	Yanbu	15,230	111,401	0.06%	22.40%	54.59	27%	22
Diesel	Northern	GT	23	Tabargel	15,271	237,337	0.13%	22.34%	71.80	44%	45
Diesel	Northern	GT	12	Duba	15,902	485,257	0.26%	21.46%	162.00	40%	46
Gas	Eastern	GT	31	Shedgum	15,937	2,380,914	1.25%	21.41%	1,108.80	29%	21
Gas	Eastern	GT	35	Berri	16,012	166,319	0.09%	21.31%	209.40	11%	34
Diesel	Western	GT	33	Taif	16,404	106,459	0.06%	20.80%	115.85	12%	31
Diesel	Northern	GT	16	Qurayat	17,487	428,567	0.23%	19.51%	90.90	63%	32
Diesel	Northern	GT	23	Al Wajh	17,751	239,406	0.13%	19.22%	82.70	39%	47
Diesel	Western	GT	36	Madienah -1	18,022	21,761	0.01%	18.93%	18.10	16%	30
Diesel	Central	GT	33	Buriedah	18,657	124,100	0.07%	18.29%	104.50	2%	48
Gas	Eastern	GT	38	Safaniyah	18,762	6,739	0.00%	18.19%	44.30	5%	37
Gas	Eastern	GT	38	Uthmaniyah	18,907	100,228	0.05%	18.05%	256.60	17%	35
Gas/D	Eastern	GT	28	Dammam	18,972	440,417	0.23%	17.98%	345.70	17%	26
Diesel	Eastern	GT	30	Qaiesomah	20,539	186,585	0.10%	16.61%	143.80	66%	36

- Potential Efficiency

To identify the loss in efficiency, the generation stock was categorised into four main groups, according to the operation and utilising the simulation reports. Figure **4-23** shows that only three power plants, which account for 19% of generation capacity, were utilised by more than

85% during the year and contributed 28% to total production. On the other hand, 15 power plants utilised less than 30% and the remaining 30 varied between 30% and 85%. By linking these statistics to the literature, around 70% of the total production has the potential to be generated at higher efficiency. In other words, up to 7% loss in efficiency is experienced by more than half of the power plants due to the operation.

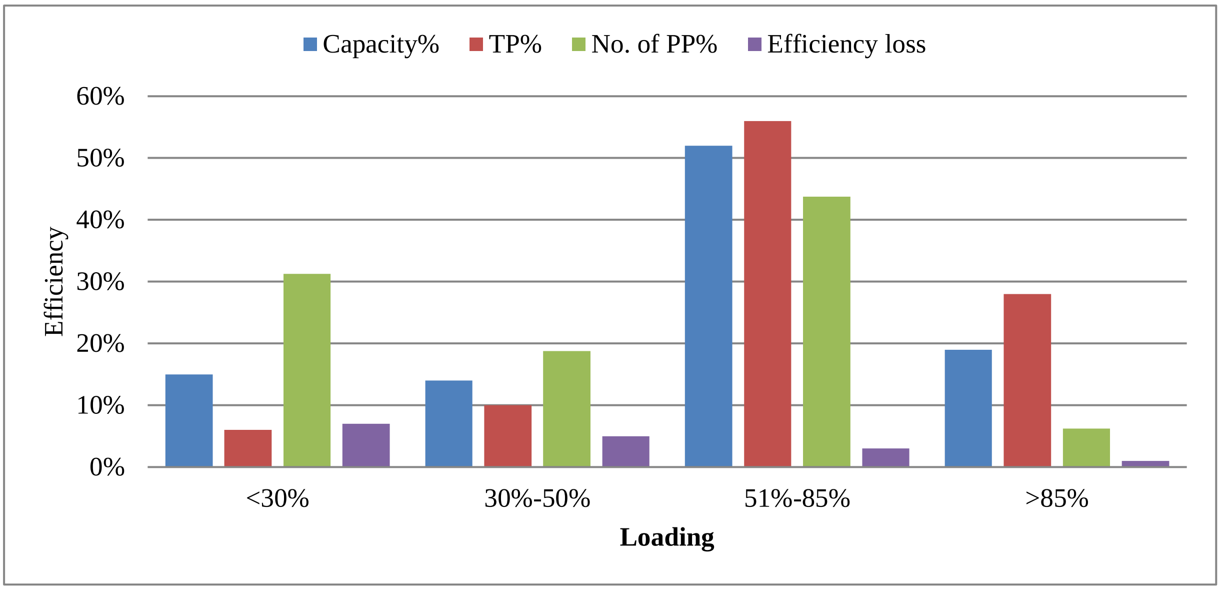


Figure 4-23 Power plants' loading in relation to capacity

- Root Causes

The literature review illustrated several factors that can have an impact on the generation efficiency level. Among these influencers, loading hours has been pointed out as being a high impact factor, which is controlled by the merit order. The analysis shows that operation has a direct impact on average generation efficiency for SEC. First, high utilisation of less efficient units compared to those having higher efficiency by generating more electricity, has a negative impact on the average efficiency. Second, the cost of fuel consumed in generation is considered as the sole criteria in designing the merit order. This is the major cause of underestimating top class technology units, which led to them being middle ranked and hence, less utilised, thereby resulting in a significant loss in operational efficiency. In the next step, a novel design for operation is proposed.

- Identify Waste

Waste is known as any activity or process that adds cost to production without further value to customers. Low level of generation efficiency results in consuming extra fuel, which means higher cost of generation, without adding value to the final product or making a difference to consumers. Therefore, improving efficiency can save a significant amount of fuel and thus, reduce cost whilst producing the same product.

- Improvement Opportunity

The analysis has proven that building new power plants with high efficiency has no significant impact and that operation is the key to any improvement plan. That is, optimising the operation of existing generation stock has the potential to deliver improvement and does not require any further investment. Since operation is based on merit order, there is a need to design a new one based on different criteria.

The improvement plan is based on two factors:

- Better optimisation of high efficient units;
- Designing a new merit order to fulfil the required optimisation.

However, this plan should take into account several constraints:

- Total production should not exceed demand;
- Each power plant should not operate for more than 7,500 hours per year;
- The improvement should consider demand’s peak (seasonality);
- HR level will be fixed to the available data.

- Standardise and optimise: design a standard process

Designing a new merit order, for maximum utilisation of the most efficient power plants, requires selecting different metrics. Accordingly, two important measures have been used to generate a new merit order for each power plant: quality of generation and production quantity for each unit. Quality refers to efficiency and quantity is the gross production. The idea of using these two factors is to build a method that is balanced between how capable the power plant is of operating continuously and efficiently. Highly efficient units should be able to operate for long hours to achieve a higher score under the new measure, for such efficiency without reliability or vice versa will not achieve a high rank in the new merit order. The most crucial part in this method is identifying the weight of quality and quantity in the new merit order. The next part will elaborate upon the method used to establish this.

4.5 Stage 4 of DMAIC: Improve

In this stage, improvement is designed mathematically and optimised. Then, it is implemented using simulation.

- Constraints to improvement

It is important to define the boundaries of any modifications:

- ❖ Operating hours for each power plant should not exceed 7,500 hours during the year due to the maintenance requirements. In addition, SEC reported an 86.4% average availability factor in 2011 for all units (SEC, 2011);
- ❖ The peak load should not be affected. For example, there are peak hours during the year that require the operation of all power plants to avoid any service interruption.

- Improvement Plan:

The planned improvement consists of two parts. The first one, new merit order for operation is proposed, while the second pertains to estimating the units' production according to required demand (Pull). Both methods will be implemented using simulation.

- Mathematical Model 1

The new merit order is developed by utilising the efficiency (E) and load factor (LF). A mathematical model has been used in order to identify the weight of each factor.

$$E = \sum_{i=1}^{k} (c_i e_i) \qquad (2)$$

where, E is the average generation efficiency, k is the number of power plants, e is the efficiency of each power plant and c is the percentage contribution for each power plant, as shown below:

$$c = PPGP/TP \qquad (3)$$

where, TP is total production and PPGP is power plant gross production.

$$PPGP = LF * NC * 7500h \qquad (4)$$

where, NC is the nominal capacity and 7,500[21] is the maximum operating hours per year for a unit.

$$e = 3412/HR \qquad (5)$$

---

[21] 4 & 6 weeks are needed every year for maintenance of GT & ST units (consecutively) (ECRA 2006)

Hence:

$$E = \sum_{i=1}^{k} \left(\frac{LFi \ * NCi}{HRi} \right) \left(\frac{3412 \ * 7500}{TP} \right) \tag{6}$$

The actual nominal capacity, total production and average HR of the power plants are applied in Eq. (6) to determine the weight of the factor (F) in Eq. (7).

$$S = E * (F * LF) \tag{7}$$

where, S is the proposed new merit order. By applying Eq. (7) for each power plant individually, using the efficiency and load hours, a new merit order is generated that can be used for operating the power plants. In addition, they can be utilised as an average utilisation factor for the unit over a year. However, total production can exceed the demand and therefore, to reduce the production F=0 is assumed for the least efficient units.

- Mathematical Model 2

Alternatively, improvement can be designed based on the Lean concept (Pull). This means estimating the required production from each unit that provides maximum system efficiency.

1) Total production has been classified into two categories in Eq. (8): electricity produced by efficient and non-efficient power plants. The criterion used in classifying the units is the average generation efficiency.

$$TP = \ Efficienct \ Production \ (EP) + Non \ Efficienct \ Production (NEP) \tag{8}$$

2) Efficient production can be calculated using Eq. (9).

$$EP = \sum_{i=1}^{n} (TP_{ppi}) = \sum_{i=1}^{n} (NC_{ppi} * 7500h) \tag{9}$$

This means efficient units will be utilised to the maximum

3) Non-efficient production can be calculated using Eq (10).

$$NEP = \ TP - EP \tag{10}$$

4) NEP will be distributed to non-efficient units according to their efficiency, according to Eq. (11), which is one of the constraints.

$$EP + \sum_{i=(n+1)}^{m} \left(NC_{ppi} * 7500h\right) \geq \ Demand \tag{11}$$

The results would show the required production from each power plant. Nevertheless, this method does not take into consideration the load profile, which can be seen as a drawback and hence, mathematical programming is applied to overcome this issue

- Mathematical Programming

Non-linear MP is used to provide the optimum MWh needed by each power plant to fulfil the total production. The constraints include the electricity generated by each unit should not exceed its maximum capacity and there should be no less than the minimum production needed to fulfil the load profile. Total production also should not exceed the demand by more than 10%. The objective to be minimised is the average HR, using Eq. (12) which is calculated according to the suggested production by 48 variables.

$$HR = \sum_{i=1}^{k} (c_i hr_i) \tag{12}$$

where, HR is the average heat rate for all units, c is the contribution for each power plant, as shown in Eq. (3) and hr is the heat rate of each power plant.

- Implementation: Stage 2 Simulation Model

Justifying the viability of any improvement requires examining it through implementation to generate new output that satisfy the studies objectives. The improvements proposed by the mathematical model suggest altering the power plants’ operation based on new measures to maximise the efficiency without affecting the total production or changing the load profile. The original simulation model utilised during the measurement stage with the same setup was run for 365 days for 24 hours a day. However, some modifications in operation were applied to fulfil the new requirements and different operating scenarios were considered during implementation. Two results are considered as the main contributions of this research and will be presented and discussed in next chapter in details. The results are based on the following limitations:

- ➢ All units are available for operation for at least 7,500 hours during the year with maximum capacity;
- ➢ No emergency shutdown or major breakdown occurs during operation;
- ➢ The used HR represents the average during the year.

- Measure the Outcomes

The data obtained from ECRA and simulated during the measurement stage is considered as the baseline scenario in this study. The results provided by the simulation show significant differences in average system efficiency, CO_2 emissions rate and fuel consumption, compared to this baseline scenario.

- Documentation Phase

The improvement plan pertains to designing a new merit order based on different measures. Efficiency and load hours are used simultaneously to generate the new merit order. The improvement can be obtained by applying the new measure as the merit order in power plant operation. Alternatively, designing and estimating the production per unit by maximising the top ranked and minimising the least ranked units according to the new order can also lead to improvement. However, demand must be met without causing any interruptions.

4.6 Stage 5 of DMAIC: Control

The control stage is very important since it sustains the enhancement and guarantees continuous improvement. Performance measures should be established based on continuous measurement of efficiency through an independent entity on weekly, monthly, quarterly and yearly bases as well as being monitored on a control chart. This data must be analysed in depth, with the outcomes documented and reported to the board. Control has to be a daily activity and under the supervision of top management. In addition, training is a key factor for successful application of LSS project (Coronado & Antony 2002).

- Design and Implement Continuous Improvement Process Measures

Efficiency improvement should be considered as a major objective for each power plant individually and for the whole system. HR performance should be analysed per unit to determine the reasons for improvement or deterioration in line with utilisation and considered in future operation. The new merit order generated by the mathematical model can be used in planning the operation of the generation stock and in promoting competition among electricity providers. Moreover, the merit order should be calculated annually based on the recent unit performance to reflect any change in the system.

Another aspect regarding sustaining continuous efficiency improvement is promoting competition among providers. This could be achieved through utilising subsidies to encourage power plants to improve their efficiency, instead of applying fixed subsidies to all providers equally. For instance, subsidies could be linked to the performance of providers based on the new merit and continuous implementation of this process would result in continuous improvement.

- Reward and Recognition

Applying the new continuous improvement process will lead to rewarding the high performing entities with subsidies and extra operating hours. In addition, the planning departments that will have a crucial and significant role to play in this process, deserve rewards and recognition based on their achieving higher average efficiency.

4.7 Summary

Operation has been highlighted as a major issue in the current low level of efficiency in power plants in the Saudi Electricity Company. Power plants operate according to their ranking in the merit order. To tackle this issue causing efficiency loss, operation needs to be viewed from a different prospective and consequently a new model has been proposed. It has been implemented successfully, showing promising results. In the next chapter, the results obtained from the implementation will be presented and discussed in detail.

Chapter 5 Results Analysis and Discussion

5.1 Introduction

This research is aimed at improving the efficiency of fossil fuel generation in Saudi Arabia. This chapter illustrates and discusses the results and outcomes of this study after applying the proposed methodology to justify and validate the improvement.

5.2 Results Analysis

The implementation of the first mathematical model, developed in the previous chapter, was applied using the original data and generated new merit order for each power plant, as shown in Figure 5-1 and Appendix C. The original simulation model was run in accordance with the new merit order. Since the loading hours for each unit is flexible, unlimited scenarios can be generated. Consequently, to find the optimum implementation of the merit order in the simulation model, a more specific guide was needed to determine the loading hours for each power plant. To identify optimum scenario, the original equation (Eq.8) in chapter four was applied several times to provide the needed loading hours for each unit, as shown in Figure 5-2. Then, the original simulation model was run (Figure 5-3) and the new results generated, as shown in Figure 5-4 and a full report can be found in Appendix D.

The simulation report shows 3.5% improvement in average generation efficiency reaching 33.36% compared to the reference scenario. These results were obtained by optimising the operation of power plants without affecting the total production or the load profile. The average utilisation factor regarding the efficient units was increased form 78% to 82%. On the other hand, the less efficient units were utilised by 30% instead of 40% previously. As a result, about 66,189 billion BTU of fuel was saved, worth around one billion US dollars. This saving has reduced the cost of production per electricity unit by 3%. In addition, average CO_2 emissions produced per kWh generated decreased by 3.4%, which represents 4.95 Mtonnes reduction in total CO_2 produced by fossil fuel generation. Nevertheless, these outcomes have the potential to further improvement and will be implanted on the next stage improvement.

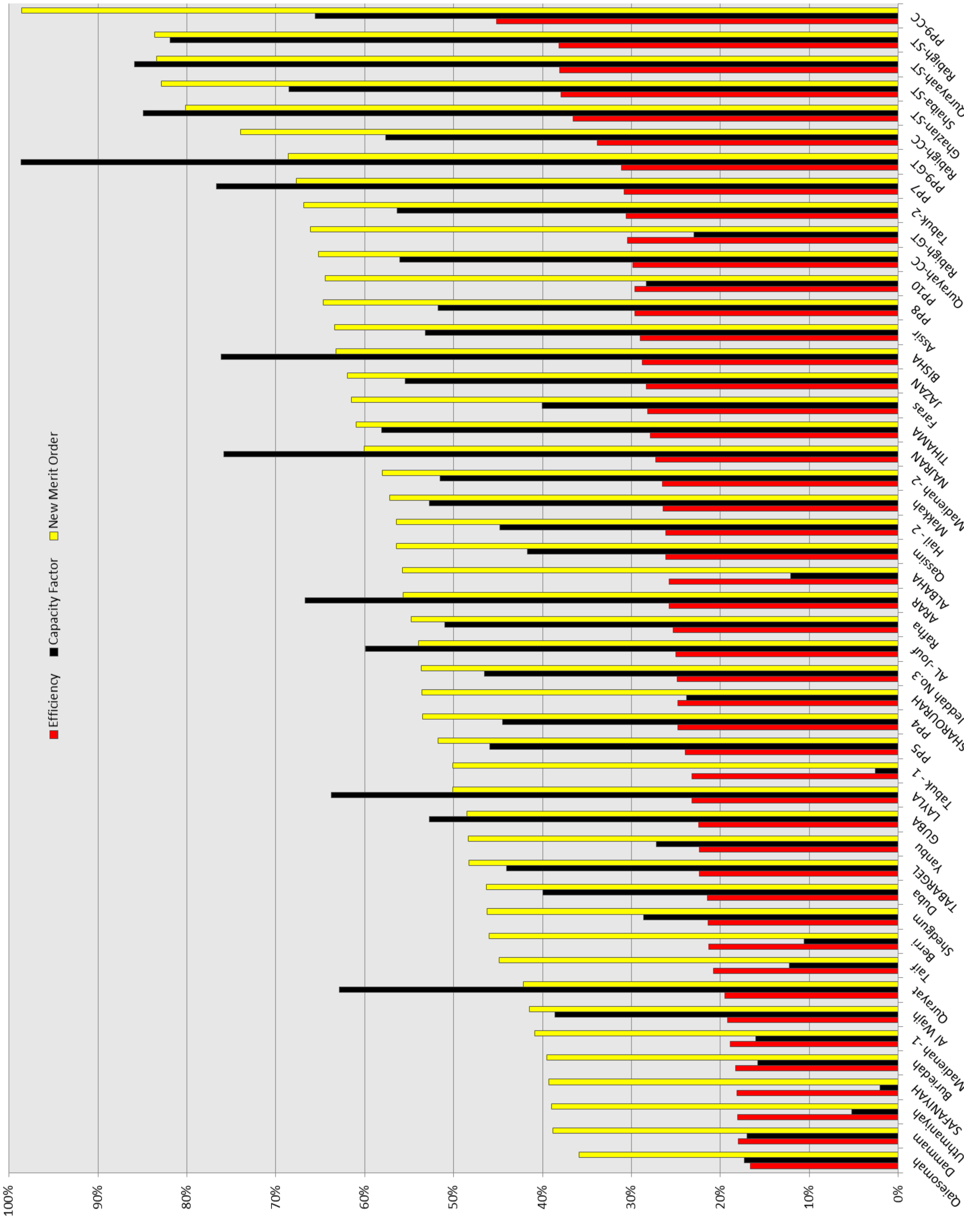


Figure 5-1 New merit order of operation

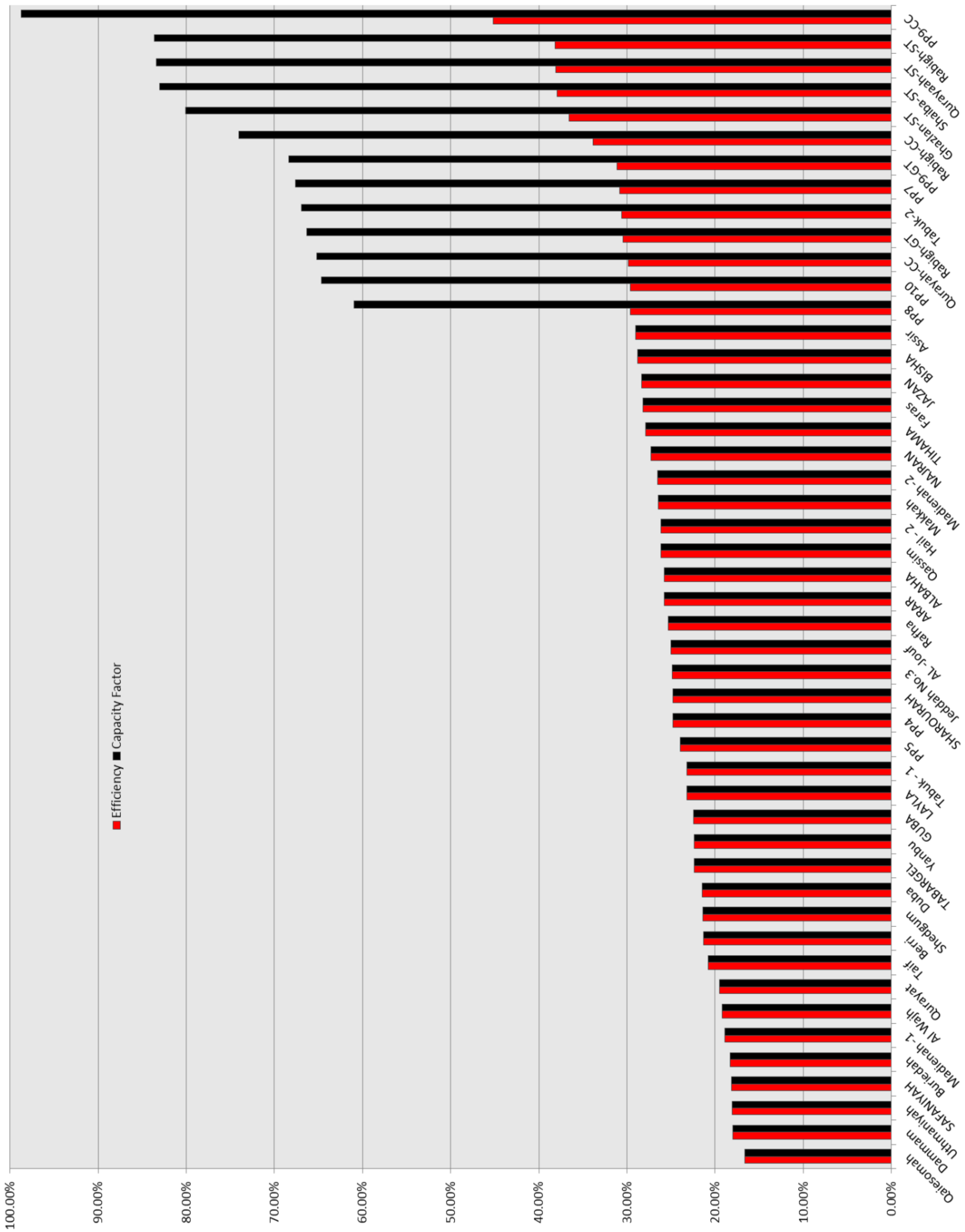


Figure 5-2 New load factor (Stage 2)

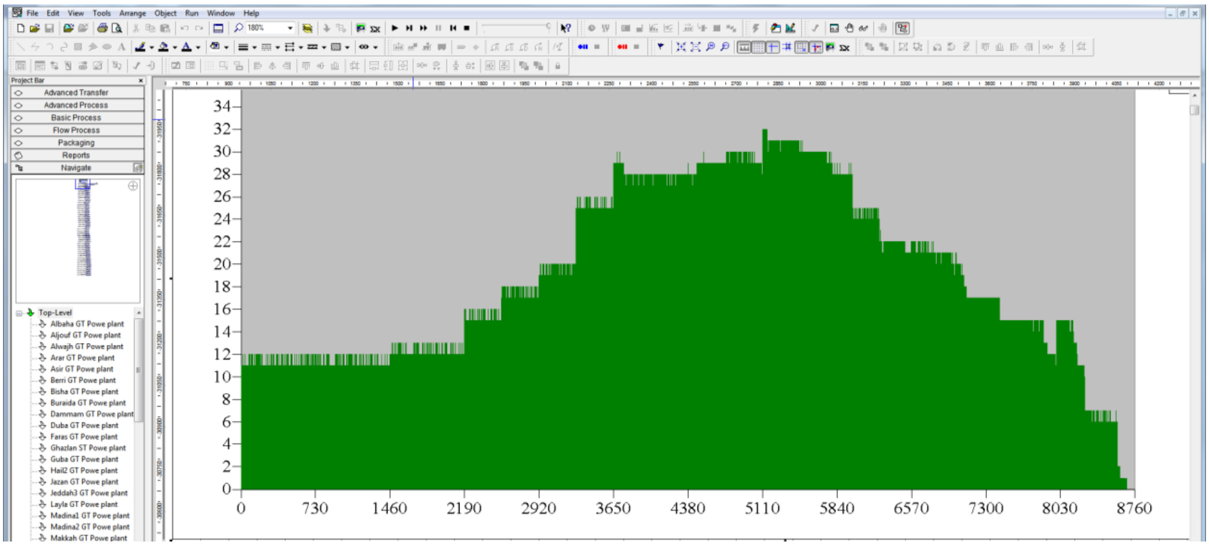
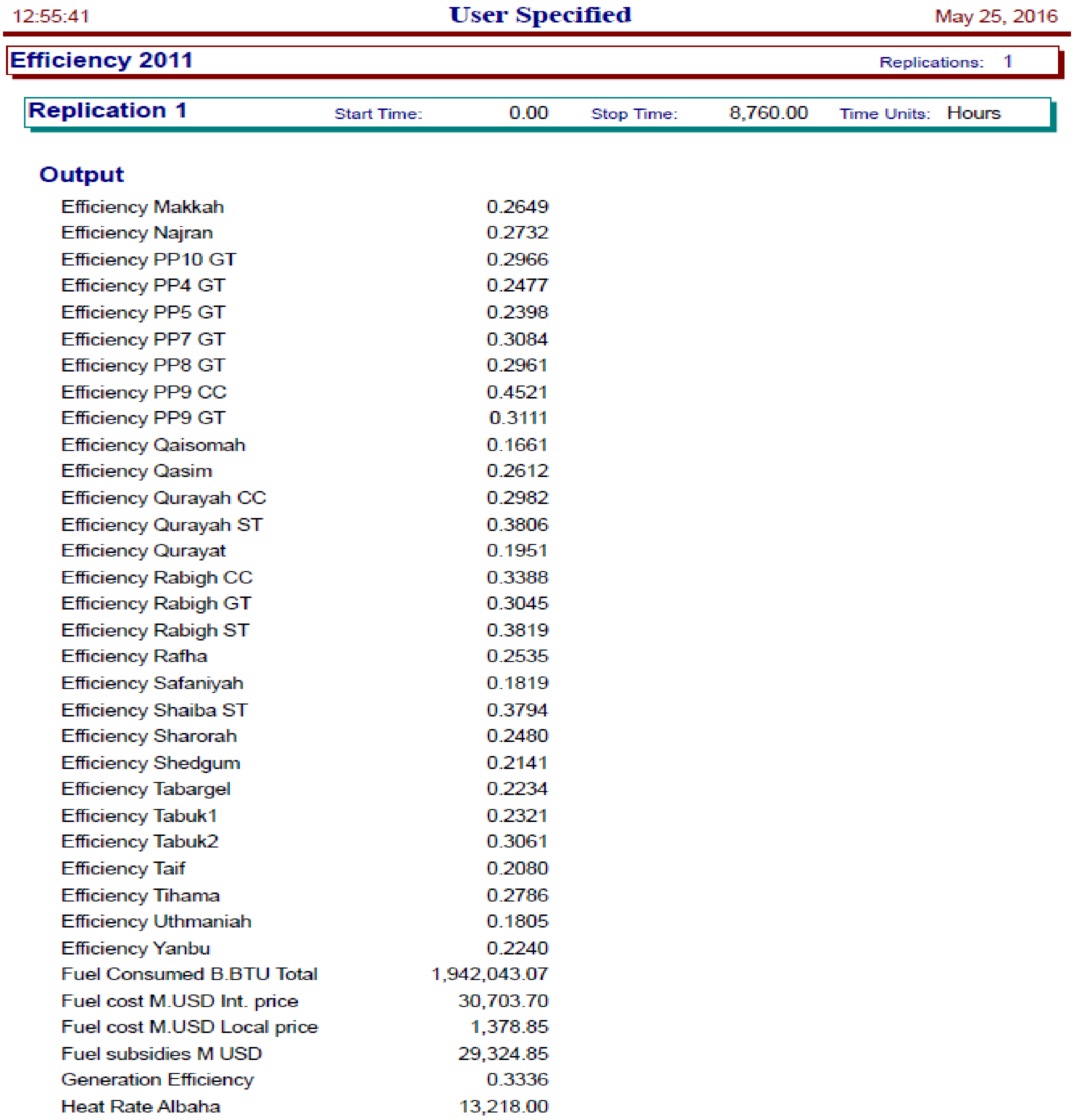


Figure 5-3 Stage 2 load profile



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12:55:41                     User Specified                      May 25, 2016

Efficiency 2011                                          Replications:   1

Replication 1        Start Time:      0.00   Stop Time:   8,760.00   Time Units:  Hours

Output
    Efficiency Makkah                        0.2649
    Efficiency Najran                        0.2732
    Efficiency PP10 GT                       0.2966
    Efficiency PP4 GT                        0.2477
    Efficiency PP5 GT                        0.2398
    Efficiency PP7 GT                        0.3084
    Efficiency PP8 GT                        0.2961
    Efficiency PP9 CC                        0.4521
    Efficiency PP9 GT                        0.3111
    Efficiency Qaisomah                      0.1661
    Efficiency Qasim                         0.2612
    Efficiency Qurayah CC                    0.2982
    Efficiency Qurayah ST                    0.3806
    Efficiency Qurayat                       0.1951
    Efficiency Rabigh CC                     0.3388
    Efficiency Rabigh GT                     0.3045
    Efficiency Rabigh ST                     0.3819
    Efficiency Rafha                         0.2535
    Efficiency Safaniyah                     0.1819
    Efficiency Shaiba ST                     0.3794
    Efficiency Sharorah                      0.2480
    Efficiency Shedgum                       0.2141
    Efficiency Tabargel                      0.2234
    Efficiency Tabuk1                        0.2321
    Efficiency Tabuk2                        0.3061
    Efficiency Taif                          0.2080
    Efficiency Tihama                        0.2786
    Efficiency Uthmaniah                     0.1805
    Efficiency Yanbu                         0.2240
    Fuel Consumed B.BTU Total          1,942,043.07
    Fuel cost M.USD Int. price            30,703.70
    Fuel cost M.USD Local price            1,378.85
    Fuel subsidies M USD                  29,324.85
    Generation Efficiency                    0.3336
    Heat Rate Albaha                      13,218.00
```

Figure 5-4 Sample of a stage 2 simulation report

The second mathematical method combined with an optimisation tool was applied to maximise the utilisation of efficient units and to minimise the deployment of the least efficient power plants, without affecting the demand. The obtained utilisation factor (

Table 5-1) is presented in Figure **5-5** and applied in the simulation model (see Figure **5-6**) and the results obtained are shown in Figure **5-7**.

Table 5-1 Optimisation results

Power plant	HR	Nominal capacity	Min production	New CF	Power generated	Max kwh	Efficiency	Old production	Old CF
Qaiesomah	20,539	143.80	179,216	17%	179,216	1,078,500	16.62%	186,585	17%
Dammam	18,972	345.70	466,290	18%	466,290	2,592,750	17.98%	440,417	17%
Uthmaniyah	18,907	258.60	350,007	18%	350,007	1,939,500	18.05%	100,228	5%
Safaniyah	18,762	44.30	60,422	18%	60,422	332,250	18.19%	6,739	2%
Buriedah	18,657	104.50	143,333	18%	143,333	783,750	18.29%	124,100	16%
Madienah -1	18,022	18.10	25,701	19%	25,701	135,750	18.93%	21,761	16%
Al Wajh	17,751	82.70	119,221	19%	119,221	620,250	19.22%	239,406	39%
Qurayat	17,487	90.90	133,021	20%	133,021	681,750	19.51%	428,567	63%
Taif	16,404	115.85	180,724	21%	180,724	868,875	20.80%	106,459	12%
Berri	16,012	209.40	334,658	21%	334,658	1,570,500	21.31%	166,319	11%
Shedgum	15,937	1,108.80	1,780,397	21%	1,780,397	8,316,000	21.41%	2,380,914	29%
Duba	15,902	162.00	260,696	21%	260,696	1,215,000	21.46%	485,257	40%
Tabargel	15,271	71.80	120,317	22%	120,317	538,500	22.34%	237,337	44%
Yanbu	15,230	54.59	91,724	22%	91,724	409,425	22.40%	111,401	27%
Guba	15,197	318.43	536,199	22%	536,199	2,388,225	22.45%	1,259,821	53%
Layla	14,703	102.00	177,527	23%	177,527	765,000	23.21%	487,664	64%
Tabuk - 1	14,702	102.00	177,539	23%	177,539	765,000	23.21%	19,600	3%
PP5	14,230	608.00	1,093,375	24%	1,093,375	4,560,000	23.98%	2,093,177	46%
PP4	13,775	336.45	625,028	25%	625,028	2,523,375	24.77%	1,123,874	45%
Sharourah	13,758	126.20	234,733	25%	234,733	946,500	24.80%	225,322	24%
Jeddah No.3	13,732	1,808.08	3,369,412	25%	3,369,412	13,560,600	24.85%	6,313,340	47%
Al Jouf	13,655	288.00	539,723	25%	539,723	2,160,000	24.99%	1,294,742	60%
Rafha	13,458	83.60	158,963	25%	158,963	627,000	25.35%	319,919	51%
Arar	13,230	246.20	476,210	26%	476,210	1,846,500	25.79%	1,231,238	67%
Al Baha	13,218	66.50	128,744	26%	128,744	498,750	25.81%	60,514	12%
Qassim	13,063	1,138.06	2,229,423	26%	2,229,423	8,535,450	26.12%	3,562,555	42%
Hail - 2	13,056	521.85	1,022,836	26%	1,022,836	3,913,875	26.13%	1,753,204	45%
Makkah	12,880	821.86	1,632,872	26%	1,632,872	6,163,950	26.49%	3,251,294	53%
Madienah -2	12,862	284.00	565,041	27%	565,041	2,130,000	26.53%	1,097,551	52%
Najran	12,490	370.00	758,070	27%	758,070	2,775,000	27.32%	2,103,823	76%
Tihama	12,249	722.00	1,508,366	28%	1,508,366	5,415,000	27.86%	3,147,314	58%
Faras	12,088	1,329.80	2,815,154	28%	2,815,154	9,973,500	28.23%	3,994,813	40%
Jazan	12,041	1,339.00	2,845,695	28%	2,845,695	10,042,500	28.34%	5,566,690	55%
Bisha	11,853	349.00	753,473	29%	753,473	2,617,500	28.79%	1,992,580	76%
Assir	11,756	649.50	1,413,806	29%	1,413,806	4,871,250	29.02%	2,589,681	53%
PP8	11,523	2,071.38	4,600,071	30%	4,600,071	15,535,350	29.61%	8,043,021	52%
PP10	11,502	1,788.80	3,979,777	30%	3,979,777	13,416,000	29.66%	3,804,065	28%
Qurayah-CC	11,443	1,905.00	4,260,155	30%	4,260,155	14,287,500	29.82%	8,010,560	56%
Rabigh-GT	11,204	1,680.00	3,837,130	30%	3,837,130	12,600,000	30.45%	2,897,265	23%
Tabuk-2	11,147	735.20	1,687,788	31%	1,687,788	5,514,000	30.61%	3,107,501	56%

Table 5-1 (Continued)

Power plant	HR	Nominal capacity	Min production	New CF	Power generated	Max kwh	Efficiency	Old production	Old CF
PP7	11,063	1,315.72	3,043,413	37%	3,699,591	9,867,900	30.84%	7,567,258	77%
PP9-GT	10,967	1,257.00	2,933,038	100%	9,427,500	9,427,500	31.11%	9,299,417	99%
Rabigh-CC	10,071	1,120.44	8,403,300	100%	8,403,300	8,403,300	33.88%	4,841,234	58%
Ghazlan-ST	9,334	4,376.00	32,820,000	100%	32,820,000	32,820,000	36.55%	27,860,841	85%
Shaiba-ST	8,992	5,538.00	41,535,000	100%	41,535,000	41,535,000	37.94%	28,451,783	69%
Qurayaah-ST	8,965	2,500.00	18,750,000	100%	18,750,000	18,750,000	38.06%	16,109,600	86%
Rabigh-ST	8,934	1,572.00	11,790,000	100%	11,790,000	11,790,000	38.19%	9,654,490	82%
PP9-CC	7,547	2,359.44	17,695,800	100%	17,695,800	17,695,800	45.21%	11,605,579	66%
				Total_pro	189,794,026	319,804,125		189,776,820	
				Demand2	189,776,820	14,136			
					Heat rate	9,980	Efficiency	34.19%	

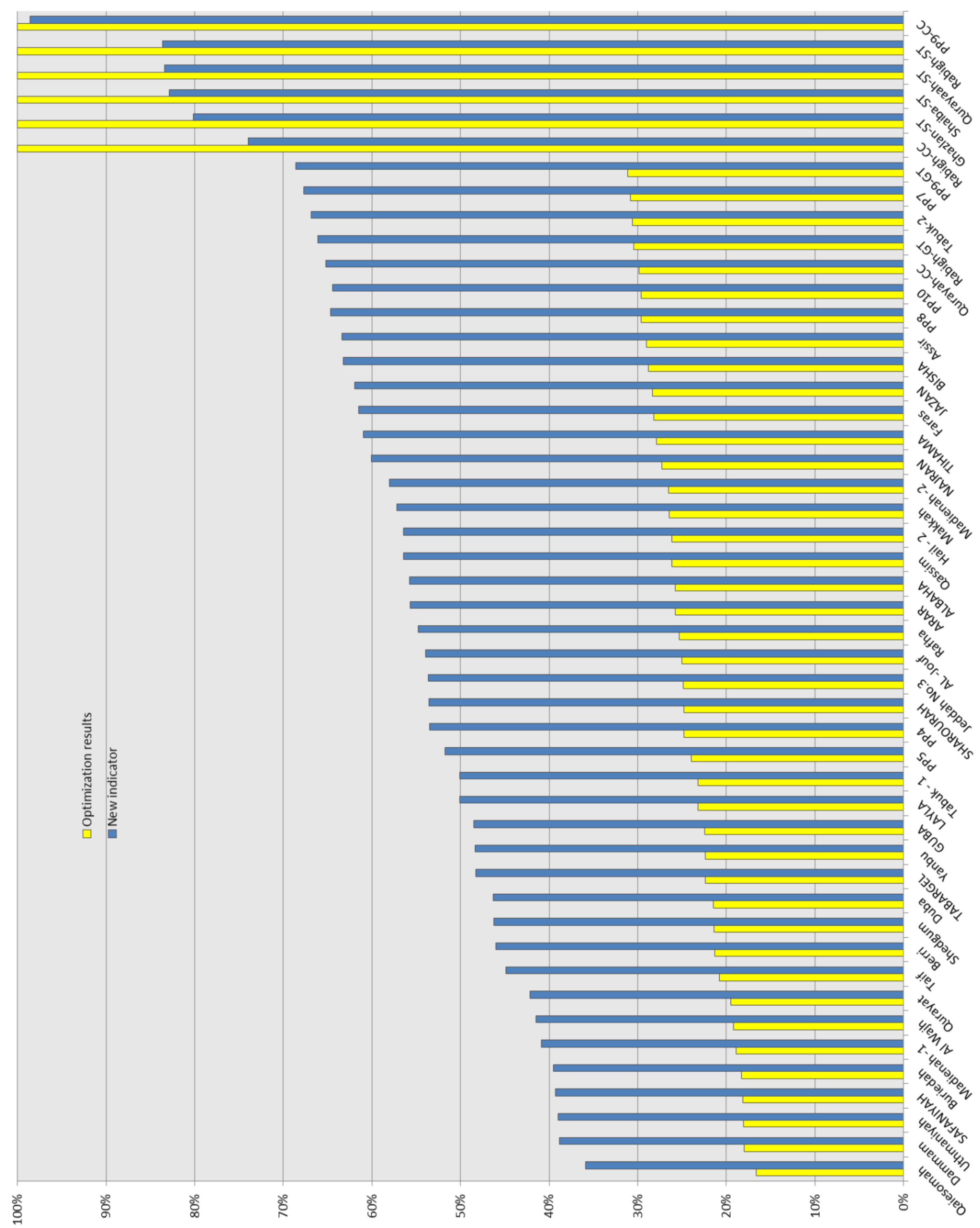


Figure 5-5 New load factor (Stage 3)

The second simulation report demonstrates better results than the previous method. Efficiency has improved by 6% (2 percentage points) compared to the baseline scenario. This improvement saved around US $ 1.8 billion by reducing the total fuel consumed by 114 T.BTU (-5.7%). Furthermore, the emissions rate dropped by 0.0449 kg per kWh produced. which results in reducing total CO_2 emissions by 8.5 Mtonnes.

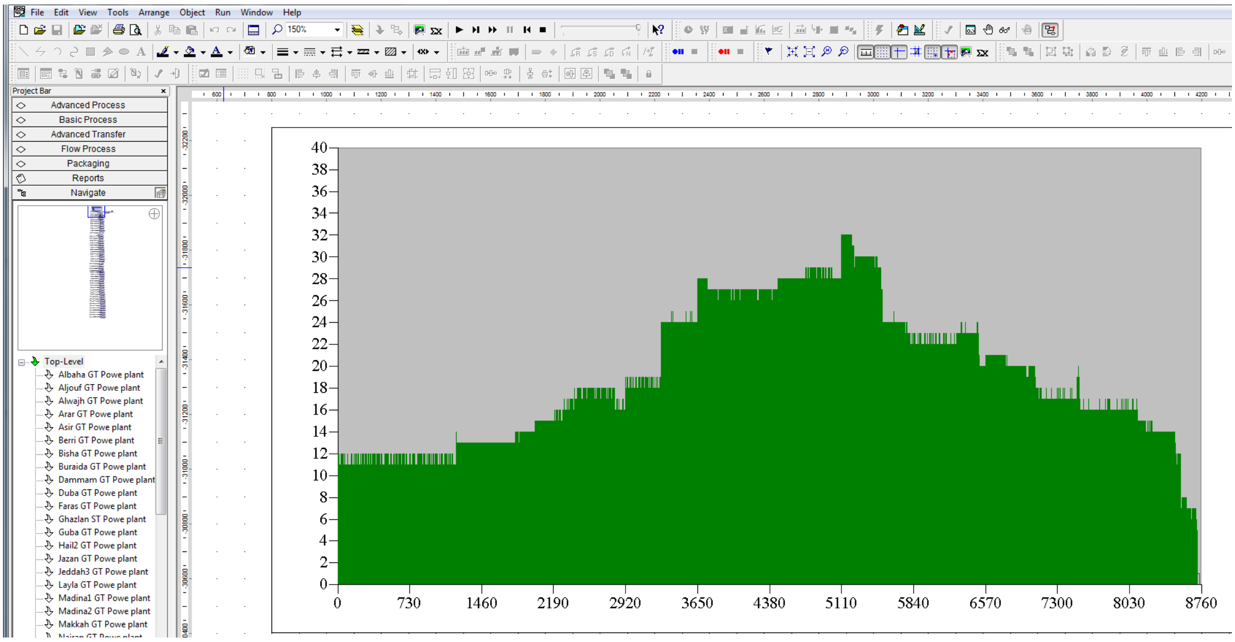
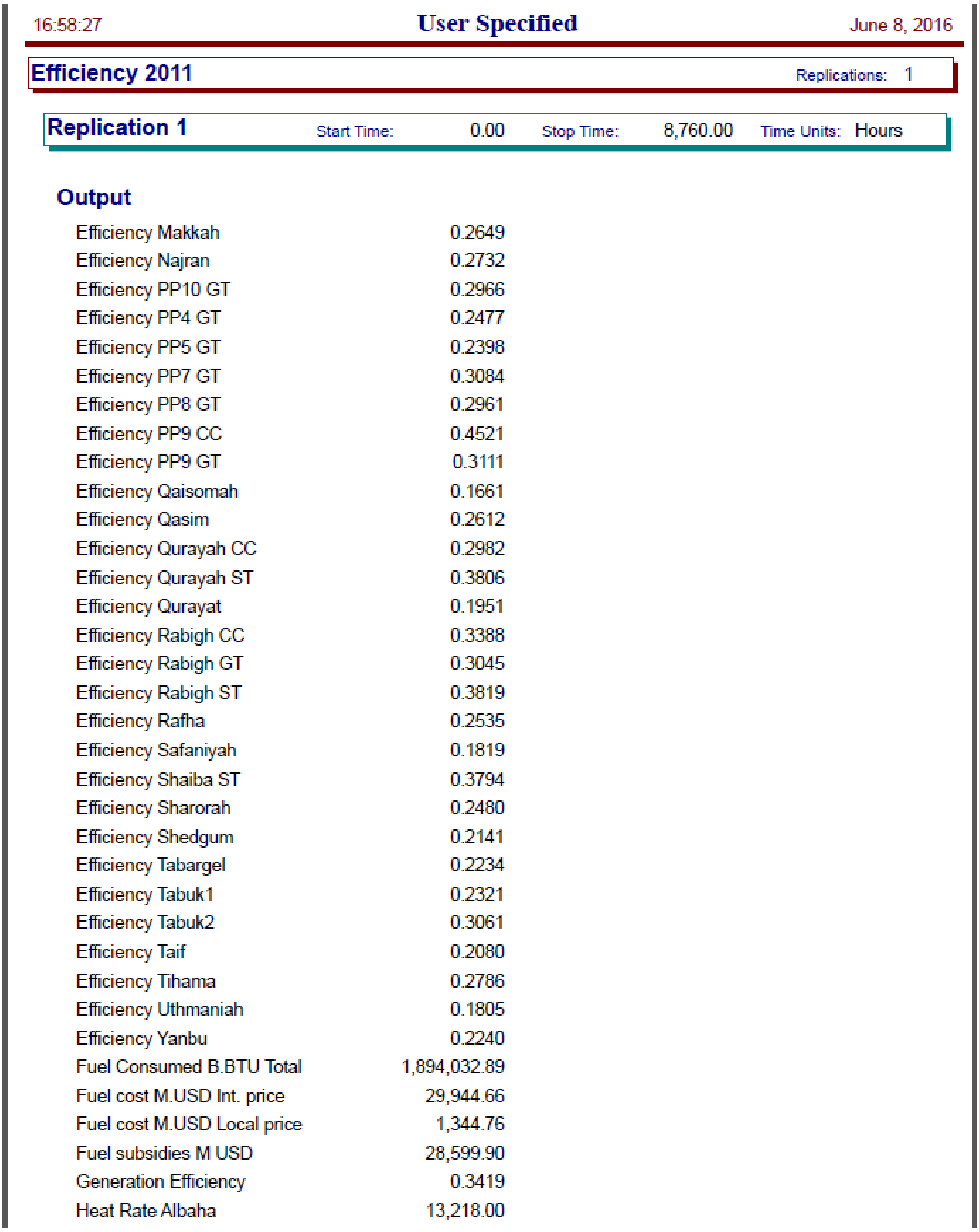


Figure 5-6 Stage 3 load profile



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16:58:27                         User Specified                         June 8, 2016

Efficiency 2011                                                    Replications:   1

  Replication 1        Start Time:        0.00    Stop Time:      8,760.00   Time Units:  Hours

   Output
      Efficiency Makkah                         0.2649
      Efficiency Najran                         0.2732
      Efficiency PP10 GT                        0.2966
      Efficiency PP4 GT                         0.2477
      Efficiency PP5 GT                         0.2398
      Efficiency PP7 GT                         0.3084
      Efficiency PP8 GT                         0.2961
      Efficiency PP9 CC                         0.4521
      Efficiency PP9 GT                         0.3111
      Efficiency Qaisomah                       0.1661
      Efficiency Qasim                          0.2612
      Efficiency Qurayah CC                     0.2982
      Efficiency Qurayah ST                     0.3806
      Efficiency Qurayat                        0.1951
      Efficiency Rabigh CC                      0.3388
      Efficiency Rabigh GT                      0.3045
      Efficiency Rabigh ST                      0.3819
      Efficiency Rafha                          0.2535
      Efficiency Safaniyah                      0.1819
      Efficiency Shaiba ST                      0.3794
      Efficiency Sharorah                       0.2480
      Efficiency Shedgum                        0.2141
      Efficiency Tabargel                       0.2234
      Efficiency Tabuk1                         0.2321
      Efficiency Tabuk2                         0.3061
      Efficiency Taif                           0.2080
      Efficiency Tihama                         0.2786
      Efficiency Uthmaniah                      0.1805
      Efficiency Yanbu                          0.2240
      Fuel Consumed B.BTU Total           1,894,032.89
      Fuel cost M.USD Int. price             29,944.66
      Fuel cost M.USD Local price             1,344.76
      Fuel subsidies M USD                   28,599.90
      Generation Efficiency                     0.3419
      Heat Rate Albaha                       13,218.00
```

Figure 5-7 Sample of a stage 3 simulation report

Table **5-2** summarises the results of both methods and compares them to the baseline scenario. As can be seen, all scenarios are set to generate similar electricity to enable a fair comparison. The difference in the utilisation factor of the efficient units has increased significantly from 78% to 82% in stage 2 and 100% in stage 3. On the other hand, the utilisation of less efficient power plants, has decreased from 40% to 30% in stage 2 and finally, to 25% in stage 3. As a result, the cost of the units has been reduced by 3% in stage 2 and 5.4% in stage 3. Subsidies have also decreased significantly by 1 and 1.7 (billion USD) for each scenario, respectively.

Table 5-2 Results summary

	Baseline scenario S1	1st method improvement S2	2nd method improvement S3
Total production (GWh)	189,776.63	189,889.33	189,778.23
Fuel consumed (T.BTU)	2,008	1,942	1,894
Fuel saved (T.BTU)	-----	66	114
Cost of fuel (M.USD)	31,750.15	30,703.70	29,943.79
Saving (M.USD)	-----	1,046.45	1,806.36
Efficiency (%)	32.24	33.36	34.19
Improvement (%)	-----	3.5	6.1
CO2 emission (kg/kwh)	0.7888	0.7623	0.7439
Reduction (%)	-----	3.4	5.7
CO_2 emission (Mtonne)	149.696	144.750	141.176
Reduction (M tonne)	-----	4.95	8.52
Efficient PP Avg utilisation factor (%)	78%	82%	100%
Non efficient PP utilisation factor (%)	40%	30%	25%
Cost ($) / kWh	0.167	0.162	0.158
Discount (%)	-----	3	5.4
Subsidies saved (M. USD)	-----	999.5	1,725

5.3 Discussion

In this research, an efficiency improvement model by applying an LSS framework and simulation has been proposed. Efficiency is a hugely important topic and can be considered from several aspects. Several studies have presented efficiency improvement on the demand side or by proposing a new fuel mix on the supply side. However, studying the existing generation assets and identifying the root causes of losses and tackling them have not received sufficient attention, especially in Saudi Arabia. This can be linked to the shortage of data officially published, which also has limited this research from performing further analysis.

The comprehensiveness of the DMAIC framework has been useful in defining the problem, measuring the current performance and analysing the outcomes so as to identify the losses and root causes to be addressed in the improvement phase. The proposed improvement model is not just aimed at a temporary improvement, for the objective is to build a continuous improvement environment, which is the primary idea underpinning LSS. This can be achieved by encouraging competition around improving the efficiency of production on a yearly basis.

The simulation model was built initially to simulate the real situation using the collected data in the measurement phase. During improvement stage, it was used to examine different scenarios.

Whilst significant improvement was achieved during the implementation stage, nevertheless, further improvement could be made. According to several studies, the increase in load factor can lead to a significant reduction in unit average HR (Graus et al. 2008; Graus & Worrell 2009). This study is based on the HR collected from ECRA and the same figures were assumed during the implementation in all the scenarios proposed. The results of the new methods indicate higher load factor in the high efficient units. As a result, a potential improvement can be obtained in the average efficiency of each power plant by 1-7 percentage points or a reduction in fuel consumption by 25%, which can be positively reflected in the average efficiency. This opens the window for future research.

One of the primary challenges of this study was to develop new criteria of operation (merit order) in light of the current market structure and the existence of fuel subsidies. Merit order is affected by data distortion caused by subsidies, as proven in the literature. The easiest way to address this would appear to be to propose new model with the removal of fuel subsidies, as some research has suggested. However, such a model is not applicable for implementation in SA, because it would result in the providers' bankruptcy with the current tariff or massive increases in customers' bills. Consequently, for this research, the decision was taken to avoid this option and instead, to investigate the hidden causes of low levels of efficiency and to resolve them.

Increasing the use of natural gas in power plants and building new units with high efficiency are not sufficient to improve the average level of efficiency without being well utilised. Therefore, the concept of the proposed improvement is based on utilising the most efficient power plants and reducing the hours of operation of units that generate at a low level of efficiency without affecting the demand, through a new model of operation. In addition, the number of hours in operation has been h taken into account for this model to ensure that reliable units that proved their ability to operate for long hours at high efficiency are at the top of the merit ranking. That is, the improvement model has combined these two factors to generate a new measure for each unit to be used for the merit order. This method aims to offer high efficient units more hours to operate and as a result improve the average efficiency. The current merit order relies on cost of production only, which is estimated based on international fuel price. The disadvantage of this method is that it does not consider the average operating hours for each unit, which affects the amount of fuel consumed and as a result, has an impact on production costs.

Fuel subsidies or low cost of fuel paid by providers in line with lack of incentives are considered as primary causes of inefficiency in several studies. However, to examine this factor in SA, the total fuel burned in each power plant needs to be examined against its total production, for which the data are not available to be applied. Alternatively, subsidies could be restructured based on performance. Regarding which, providers could pay the full cost of fuel and be compensated later based on their performance, according to the new measures. This approach would require several years of implementation to assess its outcome and consequently, it has not included in this research, but being planned for future study.

One of the significant outcomes of this study can be seen in the huge saving of fuel usage. The results have saved more than all the ongoing efforts on efficiency improvement, which is expected to reach 2.25 MBOE by 2030 (Sulman 2016). In addition, reduction in emissions has been delivered through this study without requiring any investment, which is not the case with other researches proposals.

5.4 Validation and Verification

The model can be verified through its logical steps. It started with an efficiency definition and utilised real data. In addition, the simulation model on the first stage can be considered as a verification tool since real input data has been used and the results match the same output data. Actual implantation could not be applied due to the size of targeted sector. Consequently, the original simulation model was used to examine the proposed improvements.

To validate the final results, an experts' review was carried out with consultants, managers and senior staff in the electricity sector in Saudi Arabia. A group of specialists was chosen to discuss the topics: "How viable is the proposed model? What could be the main obstacles in implementing the model? The aim was to obtain their feedback after presenting the purpose of this research, the methodology applied and the final results.

Soliman El-Salamouni, power generation consultant, SEC.
The current merit order is based on economical operation. Currently, any change in merit order is based on the changes in costs. Once the new model has proved significant saving without affecting the network's reliability then it will be feasible for use. This can be verified by presenting the cost of production per unit in different scenarios. One of the main challenges in operation is the changes of fuel type in power plants due to the suppliers. As a result units' efficiency can be affected according to fuel type.

Haider Al-Hertani, Managing director, Wärtsilä Saudi Arabia.
Efficiency improvement is a major goal of the Saudi 2030 vision and therefore, any initiative will be supported at the top managerial level. The model is applicable in reality since it does not include major changes to operation and it focuses on best available choices to fulfil demand. It shows promising and significant outcomes. However, maintenance schedules of units and transmission lines capacities could represent obstacles at peak times, which could be managed and solved. The existing market structure could lead to resistance to any changes, but the new ongoing reform will overcome this issue.

Sami Alharbi, GM Business development, Wärtsilä Saudi Arabia.
The selection of technology type in operation is a very crucial factor affecting system efficiency which has applied in this research. The massive saving resulted from this study is well worth the effort of implementing it. To avoid any resistance to change, training is needed for all involved staff to insure their readiness and to reduce the chance of failure. In addition, the

implementation could be scheduled in stages on a yearly basis, with each stage being focused on specific areas. This can minimise the chances of failure.

Seraj Allaf, Senior generation Engineer, SEC.
To insure successful implementation, maintenance departments must be involved in advance. This can help them in planning their annual maintenance plan of all units, according to demand requirements. Furthermore, shortage in a specific fuel type can affect the operation decisions. Sudden increase in demand could be a challenge for grid operation (LDC). However, training could solve this issue

Jamil Al-Matrafi, Supporting Systems Operation Manager, Shoiba Power plant, SEC.
I strongly support the view that operation has one of the highest impacts on the efficiency level in power plants in Saudi Arabia and this can make a significant difference, if operated properly. I can't see major obstacles in this model. But to insure more accurate results of the model, I suggest an independent department should be appointed to measure the efficiency of units based on total fuel supplied and gross power generated to the grid.

Yosef Alwafi, Acting operation manager stage 3 & CC, Shoiba Power plant, SEC.
Improving generation efficiency and reducing the emissions has become a major goal for the top management in the SEC. This research's results show the potential for saving of fuel and significant reduction in emissions could be gained by implementing this model. Nevertheless, transmission lines maintenance can be seen as an obstacle. In addition, the supply chain of fuel can represent a minor issue in some power plants but in the past these units were being operated with alternative fuels.

In conclusion, the discussion shows positive feedback in general. The study has triggered the most significant factor affecting efficiency in Saudi Arabia and the results obtained were promising. Merit order can be changed if required and justified. The raised concern regarding changes in fuel type did not affect any unit from operation in the past, which means it is not a major obstacle for this model and can be considered in future studies. Transmission line capacities have been upgraded and connected and can sustain the demand, according to ECRA (Saudi Electricity Company 2014). Annual maintenance of power plants and transmission lines can be scheduled based on load requirements. Finally, training of staff and involvement of all concerned departments as well as awareness of the project outcomes is a mandatory step for success.

5.5 Summary

The obtained results validate the appropriateness of the applied methodology and indicate successful implementation of the framework. The proposed merit order does not interfere with the current one in use. Its usefulness in optimising the available assets in generating the required electricity with less fuel and reduced emission has been proven and as a result, could have a significant financial and environmental impact. The experts' point of view regarding the proposed model and the results was encouraging and supportive. The raised concerns can be addressed in future work as they do not constitute major issues.

Chapter 6 Conclusion and Future Work

6.1 Introduction

This chapter presents the key conclusions of this study that are drawn from the research outcomes. It also provides the research contributions to knowledge in the field. Finally, it concludes with limitations and suggestions for future work.

6.2 Conclusion

Energy efficiency of electricity generation using fossil fuel in Saudi Arabia was the focus of this study. The aim was improving the efficiency by integrating Lean Six Sigma, simulation and a mathematical model, to provide an effective framework that sustains continuous improvement. The increasing demand for electricity has led to a great deal of pressure on natural resources consumption. Efficiency improvement would lead to a significant saving in fuel consumption and emissions reduction. There are several factors that can lead to inefficiency in generation, with the load factor being the most salient. Subsidies are also considered as being a serious indirect cause of inefficiency. Privatisation has been proposed as having a positive impact in terms of attracting investment and developing competition in the electricity market. However, this does not lead to efficiency improvement, unless incentives regulations are included.

In Saudi Arabia, efficiency has not received sufficient attention and the country is considered among the lowest performing in the world, whereas its losses in transmission and distribution networks are about the global average. Lack of consistent data of annual efficiency in the official reports does not support adequate and consistent comparisons. Limited research has analysed the main reasons causing inefficiency in the kingdom or proposed ways of tackling it. Technology type and lack of efficient units have been mentioned as primary reasons. As a result, further investment has been recommended for improving the average level of efficiency in the kingdom.

In this study, a mix of methods approach was adopted to meet this challenge of delivering the required electricity using less fuel and reducing emissions by improving efficiency without any further investment. The objectives of this research were to measure the current level of efficiency, identify the root causes, propose a framework for improvement and to sustain the enhancement through deployment of continuous improvement. It was decided that Lean thinking would be utilised to identify waste in conjunction with Six Sigma steps (DMAIC), as a primary framework. Furthermore, mathematical modelling was used during the improvement phase and simulation was utilised during the measurement and the final proposed modification, to justify its credibility.

The measurement stage proved the low level of generation efficiency in SA and during the analysis, operation was identified as a major issue leading to efficiency loss. Consequently, a new model of operation was developed, optimised using mathematical programming and implemented utilising simulation. In addition, an incentive programme that utilises subsidies was proposed to sustain continuous improvement. The obtained results demonstrated significant financial and environmental impact, thereby validating the proposed improvement. The outcome of this study justified the effectiveness of the applied methodology in achieving the research aim. Finally, the experts' point of view regarding the proposed model and results was encouraging and supportive. The raised concerns could be addressed in future work and they do not represent major issues.

6.4 Research Limitations

This research has involved implementing the optimisation model on one power system only, but it can be applied to any. The simulation model has a maximum number of objects that can be reached in the academic version of Arena software and as a result, a conversion factor had to be utilised to overcome this issue. Running the simulation model consumed the computer processor and memory and it took a long time to generate results. Consequently, the number of trials was decreased. Finally, the unavailability of other years' data has limited the implementation to the obtained information.

6.5 Future Work

For future research, this study can be extended to include several years' data, more power plants, transmission networks and load profile. This can open new windows for other issues that have not appeared before. Furthermore, considering the availability factor and emergency shutdown rate within the simulation for each unit can provide significant enhancement to the model. In addition, fuel supply challenges to be taken into consideration in the future. Finally, developing new standards for operation and designing a dynamic measure of efficiency within the simulation model has the potential to provide an in-depth view of the system behaviours.

References

ABB, 2009. *Power generation: energy efficient design of auxiliary systems in fossil-fuel power plants.* Available at: *https://library.e.abb.com/public/5e627b842a63d389c1257b2f002c7e77/Energy%20Efficiency%20for%20Power%20Plant%20Auxiliaries-V2_0.pdf.*

ABB, 2012. *Saudi Arabia Energy efficiency report*. Available at: https://library.e.abb.com/public/e291ae8c76ef33d448257a2300521bab/Saudi Arabia Energy efficiency Report.pdf.

ABB, 2013. *Saudi Arabia Energy efficiency report.* Available at: https://library.e.abb.com/public/3286e88f2467b11dc1257be80055df20/Saudi%20Arabia.pdf.

ABB, 2011. *Saudi Arabia Energy efficiency report the period 2000-2005.* Available at: https://library.e.abb.com/public/f90e53733342b472c125786400519e97/Saudi%20Arabia.pdf.

Al- Hossein, A., 2016. الذروة لأحمال تفادياً مليار 500 بقيمة مشاريع لتنفيذ بحاجة المملكة. *Alekhbariya*. Available at: http://www.alekhbariya.net/ar/node/5732# [Accessed February 9, 2016].

Al-Ajlan, S. A., Al-Ibrahim, A. M., Abdulkhaleq, M. & Alghamdi, F., 2006. Developing sustainable energy policies for electrical energy conservation in Saudi Arabia. *Energy Policy*, 34(13), pp.1556–1565. Available at: http://www.sciencedirect.com/science/article/pii/S0301421504003672.

Alawaji, S., 2012. Saudi Arabia: a proactive approach to energy. Available at: http://www.energy.siemens.com/ru/pool/hq/energy-topics/publications/living-energy/pdf/issue-07/Living-Energy-7-Essay-Saudi-Arabia-proactive-approach-to-energy.pdf.

Albliwi, S. & Antony, J., 2013. Implementation of a lean six sigma approach in the manufacturing sector: a systematic literature review. In *International Conference on Manufacturing Research*, p.6. Available at: http://www.uksacb.org/sites/default/files/The 11th International Conference on Manufacturing Research.pdf.

Alhoweish, B. & Orujov, C., 2016. Promoting an effective energy efficiency programme in Saudi Arabia: challenges and Introduction: economic challenges in Saudi Arabia. In M. Abdel Raouf & M. Luomi, eds. *The green economy in the Gulf*. New York: Routledge, pp. 100–122. Available at: http://cdn.intechopen.com/pdfs/31602.pdf.

Aljarboua, Z., 2009. The national energy strategy for Saudi Arabia. *World Academy of Science, Engineering and Technology*, 3(9), pp.472–481. Available at: http://www.waset.org/publications/3157.

Alnatheer, O., 2005. The potential contribution of renewable energy to electricity supply in Saudi Arabia. *Energy Policy*, 33(18), pp.2298–2312. Available at: http://www.sciencedirect.com/science/article/pii/S0301421503003719.

Alowaidh, M. & Alnutifi, A., 2010. Technology-Based Improvement for KSA Energy Intensity, Saudi Aramco.

Al-Saleh, Y., 2009. Renewable energy scenarios for major oil-producing nations: the case of Saudi Arabia. *Futures*, 41(9), pp.650–662. Available at: http://www.sciencedirect.com/science/article/pii/S0016328709000615#.

Al-Saud, A., 2014. *A brief on Saudi Arabia's Energy Efficiency Program*, Oxford. Available at: http://www.oxfordenergy.org/2014/06/oxford-energy-forum-issue-96/.

Altiok, T. & Melamed, B., 2010. *Simulation modeling and analysis with ARENA*, Academic Press.

Alyousef, Y. & Abu-ebid, M., 2012. *Energy Efficiency Initiatives for Saudi Arabia on Supply and Demand Sides*. Available at: http://cdn.intechopen.com/pdfs/31602/InTech-Energy_efficiency_initiatives_for_saudi_arabia_on_supply_and_demand_sides.pdf.

Alyousef, Y. & Stevens, P., 2011. The cost of domestic energy prices to Saudi Arabia. *Energy Policy*, 39(11), pp.6900–6905. Available at: http://dx.doi.org/10.1016/j.enpol.2011.08.025.

Aman, E., 2013. *Energy efficiency in MENA – A tool to reduce GHG emissions*. Available at: http://www.ecomena.org/energy-mena/.

Aman, E., 2015. *Energy efficiency perspectives for MENA*. Available at: http://www.ecomena.org//?s=Energy+Efficiency+Perspectives+for+MENA.

Aman, E., 2014. *Smart grid – key to managing energy demand in Saudi Arabia*. Available at: http://www.ecomena.org/smart-grid-saudi-arabia/.

Andersson, R., Henrik, E. & Håkan, T., 2006. Similarities and differences between TQM, six sigma and lean. *The TQM Magazine*, 18(3), pp.282–296. Available at: http://www.emeraldinsight.com/doi/full/10.1108/09544780610660004.

Antony, J., 2008. Can Six Sigma be effectively implemented in SMEs? *International Journal of Productivity and Performance Management*, 57(5), pp.420–423.

Antony, J., 2014. Readiness factors for the Lean Six Sigma journey in the higher education sector, *International Journal of Productivity and Performance Management*, 63(2), pp.257–264.

Antony, J., 2011. Six Sigma vs Lean: some perspectives from leading academics and practitioners. *International Journal of Productivity and Performance Management*, 60(2), pp.185–190. Available at: http://www.emeraldinsight.com/10.1108/17410401111101494 [Accessed June 9, 2014].

Arena Simulation Software by Rockwell Automation, n.d., *About us*. Available at: http://www.arenasimulation.com/About_Us_About_Us.aspx [Accessed May 15, 2015].

Arnheiter, E.D. & Maleyeff, J., 2005. The integration of lean management and Six Sigma. *The TQM Magazine*, 17(1), pp.5–18. Available at: http://www.emeraldinsight.com/doi/full/10.1108/09544780510573020.

Arrieta, F.R.P. & Lora, E.E.S., 2005. Influence of ambient temperature on combined-cycle power-plant performance. *Applied Energy*, 80(3), pp.261–272. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261904000601.

Bachellerie, I., 2012. *Renewable energy in the GCC countries: resources, potential and prospects*. Available at: http://library.fes.de/pdf-files/bueros/amman/09008.pdf.

Bacon, R., 2014. *Devising an energy pricing strategy for GCC countries*, Oxford. Available at: http://www.oxfordenergy.org/2014/06/oxford-energy-forum-issue-96/.

Bacon, R.W. & Besant-Jones, J., 2001. Global electric power reform, privatization, and liberalization of the electric power industry in developing countries. *Annual Review of*

Energy and the Environment, 26(1), pp.331–359. Available at: http://www.annualreviews.org/doi/pdf/10.1146/annurev.energy.26.1.331.

Bahgat, G., 2012. Will Saudi Arabia face an energy crisis? *The Journal of Social, Political and Economic Studies*, 37(2), pp.181–198.

Banks, J., 2000. Introduction to simulation. In *Proceedings of the 2000 Winter Simulation Conference*. IEEE, pp.9–16. Available at: http://staff.unak.is/andy/Year 3 Simulation/DirectedReading/IntroSimulationBanksWSC2000.pdf.

Beck, F. & Martinot, E., 2004. Renewable energy policies and barriers. *Encyclopedia of Energy*, pp.365–383. Available at: http://www.martinot.info/Beck_Martinot_AP.pdf.

Bellman, D., Blankenship, B., Imhoff, C., DiPietro, J., Rederstorff, B. & Zheng, X., 2007., *Topic Paper #4: Electric Generation Efficiency.* Washington, DC: National Petroleum Council.

Bendell, T., 2006. A review and comparison of Six Sigma and the lean organisations. *The TQM Magazine*, 18(3), pp.255–262. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/09544780610659989.

Bhuiyan, N. & Baghel, A., 2005. An overview of continuous improvement: from the past to the present. *Management Decision*, 43(5), pp.761–771. Available at: http://www.emeraldinsight.com/doi/pdfplus/10.1108/00251740510597761.

Borenstein, S. & Bushnell, J., 2000. *Electricity restructuring: deregulation or reregulation?* Competition Policy Center. Available at: http://escholarship.org/uc/item/22d2q3fn#page-1.

Bossert, J. & Grayson, K., 2002. Your opinion. *Six Sigma Forum Magazine*, 2(1).

BP, 2016. *BP statistical review of world energy*. Available at: http://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf.

Brander, M., Sood, A., Wylie, C., Haughton, A & Lovell, J., 2011. Electricity-specific emission factors for grid electricity. *Ecometrica*, (August), pp.1–22.

Bushnell, J.B. & Wolfram, C., 2005. *Ownership change, incentives and plant efficiency: the divestiture of U.S. electric generation plants*. University of California Energy Institute (March). Available at: http://faculty.haas.berkeley.edu/wolfram/papers/Divest_0331.pdf.

Byrne, G., Lubowe, D. & Blitz, A., 2007. Using a Lean Six Sigma approach to drive innovation. *Strategy & Leadership*, 35(2), pp.5–10. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/10878570710734480.

CESI & ATKearney, 2012. *Smart metering and smart grids strategy for the Kingdom of Saudi Arabia*, ECRA, Riyadh. Available at: http://www.ecra.gov.sa/ar-sa/ECRAStudies/ECRAStudies/Smart Metering and Smart Grids Strategy.pdf.

Chan, H.R., Fell, H., Lange, I. & Li, S., 2013. Efficiency and environmental impacts of electricity restructuring on coal-fired power plants. *SSRN Electronic Journal*. Available at: http://www.ssrn.com/abstract=2223408.

Chan, H.S. (Ron), Cropper, M.L. & Malik, K., 2014. Why are power plants in India less efficient than power plants in the United States? *American Economic Review*, 104(5), pp.586–590. Available at: http://pubs.aeaweb.org/doi/abs/10.1257/aer.104.5.586.

Chaoul, H., 2013. *Saudi Arabia budget 2013*, Jeddah. Available at:

http://www.alkhabeer.com/sites/default/files/Saudi Budget 2014 - English.pdf.

Chen, T., Yeh, T. & Lee, Y., 2013. *Comparison of power plants efficiency among 73 Countries*. Available at: http://www.hindawi.com/journals/jen/2013/916413/.

Chowdhury, S.P., Chowdhury, S.P. & Crossley, P., 2009. *Microgrids and active distribution networks*, London: The Institution of Engineering and Technology.

Colman, J., 2013. 'The effect of ambient air and water temperature on power plant efficiency', MSc Thesis, Duke University, Durham, NC, USA

Corbett, L.M., 2011. Lean Six Sigma: the contribution to business excellence. *International Journal of Lean Six Sigma*, 2(2), pp.118–131. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/20401461111135019.

Coronado, R.R.B. & Antony, J., 2002. Critical success factors for the successful implementation of Six Sigma projects in organisations. *The TQM Magazine*, 14(2), pp.92–99. Available at: http://dx.doi.org/10.1108/09544780210416702\nhttps://www.scopus.com/inward/record.uri?eid=2-s2.0-0036178544&partnerID=40&md5=014c78fe1775e86f9c28da1839257ce3\nhttp://www.emeraldinsight.com/doi/pdf/10.1108/09544780210416702\nhttp://www.emeraldinsight.com/j.

Crawford, R., 2004. *Ammunition enterprise excellence: ready for Tomorrow?* Available at: http://www.dtic.mil/ndia/2004munitions/Crawford.pdf [Accessed October 28, 2015].

Crijns-Graus, W., 2016. Renewable energy: past trends and future growth in 2 degrees scenarios. *Energy Procedia*, 100, pp.14–21. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1876610216311006.

De Mast, J., 2004. A methodological comparison of three strategies for quality improvement. *International Journal of Quality & Reliability Management*, 21(2), pp.198–213. Available at: http://www.emeraldinsight.com/doi/full/10.1108/02656710410516989.

Department of Energy & Climate Change, 2012. *Digest of United Kingdom Energy Statistics (DUKES) Chapter (5)* Electricity, Department for Business, Energy & Industrial Strategy, London, UK.

Department of Energy & Climate Change, 2014. *Digest of United Kingdom Energy Statistics (DUKES) Chapter (5) Electricity*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/337649/chapter_5.pdf.

Department of Energy & Climate Change, 2013. *Digest of United Kingdom Energy Statistics (DUKES) Chapter (5) Electricity*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/279523/DUKES_2013_published_version.pdf.

Department of Energy & Climate Change, 2016. *Digest of United Kingdom Energy Statistics (DUKES) Chapter (5) Electricity*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/552059/Chapter_5_web.pdf.

Department of Energy & Climate Change, 2015. *Digest of United Kingdom Energy Statistics (DUKES) Chapter (5) Electricity*. Available at:

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/447632/DUKES_2015_Chapter_5.pdf.

De Sa, A. & Al Zubaidy, S., 2011. Gas turbine performance at varying ambient temperature. *Applied Thermal Engineering*, 31(14-15), pp.2735–2739. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1359431111002468 [Accessed March 25, 2014].

ECRA, 2006. *Revised final report updated generation planning for the Saudi electricity sector* (Executive summary), Riyadh.

ECRA, 2007. *Activities & achievements of the authority*, Riyadh. Available at: http://ecra.gov.sa/reports.aspx#.U_8_AvmwLKM.

ECRA, 2008. *Activities & achievements of the authority*, Riyadh. Available at: http://ecra.gov.sa/reports.aspx#.U_8_AvmwLKM.

ECRA, 2009a. *Activities & achievements of the authority*, Riyadh. Available at: http://ecra.gov.sa/reports.aspx#.U_8_AvmwLKM.

ECRA, 2009b. *Annual statistical booklet on electricity industry*, Riyadh. Available at: http://ecra.gov.sa/NationalRegistry.aspx.

ECRA, 2010a. *Activities & achievements of the authority*, Riyadh. Available at: http://ecra.gov.sa/reports.aspx#.U_8_AvmwLKM.

ECRA, 2010b. *Annual statistical booklet on electricity industry*, Riyadh. Available at: http://ecra.gov.sa/NationalRegistry.aspx.

ECRA, 2011a. *Activities & achievements of the authority*, Riyadh. Available at: http://ecra.gov.sa/reports.aspx#.U_8_AvmwLKM.

ECRA, 2011b. *Activities & achievements of the authority* (English). Available at: http://ecra.gov.sa/reports.aspx#.U_8_AvmwLKM.

ECRA, 2011c. *Annual statistical booklet for electricity and sea water desalination industries*, Riyadh. Available at: http://ecra.gov.sa/NationalRegistry.aspx.

ECRA, 2012a. *Annual statistical booklet for electricity and sea water desalination industries*, Riyadh. Available at: http://ecra.gov.sa/NationalRegistry.aspx.

ECRA, 2012b. *Installed generation capacity*, Riyadh. Available at: http://www.ecra.gov.sa/ar-sa/DataAndStatistics/NationalRecord/StationCapacities/Pages/Home.aspx

ECRA, 2013a. *Activities & achievements of the authority*, Riyadh. Available at: http://ecra.gov.sa/reports.aspx#.U_8_AvmwLKM.

ECRA, 2013b. *Annual statistical booklet for electricity and sea water desalination industries*, Riyadh. Available at: http://ecra.gov.sa/upload/ecra_ebook2013.pdf.

ECRA, 2014a. *Activities & achievements of the authority*, Riyadh. Available at: http://ecra.gov.sa/reports.aspx#.U_8_AvmwLKM.

ECRA, 2014b. *Annual statistical booklet for electricity and sea water desalination industries*, Riyadh.

ECRA, 2015a. *Activities & achievements of the authority*, Riyadh. Available at: http://www.ecra.gov.sa/documents/Annual reports/ECRA Activities Report Ar For

Web.pdf.

ECRA, 2015b. *Annual statistical booklet for electricity and sea water desalination industries,* Riyadh. Available at: http://www.ecra.gov.sa/ar-sa/MediaCenter/doclib2/Pages/SubCategoryList.aspx?categoryID=5.

ECRA, 2016. *Activities & achievements of the authority,* Riyadh. Available at: file://acfs5/empg/empgmta/Downloads/true (1).pdf.

Edwards, D. & Hamson, M., 2007. *Guide to mathematical modelling,* Second edition, New York: Industria Press, Inc.

EIA, 2013. *Saudi Arabia estimated petroleum net export (1980-2013).* Available at: http://www.eia.gov/countries/country-data.cfm?fips=sa#pet [Accessed January 1, 2015].

EIA, 2015. *How much carbon dioxide is produced per kilowatthour when generating electricity with fossil fuels?* Available at: https://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11 [Accessed June 20, 2015].

El-Haik, B. & Al-Aomar, R., 2006. *Simulation-based Lean Six-Sigma and design for Six-Sigma*, New Jersey: John Wiley & Sons.

El-katiri, L., 2012. *The GCC and the nuclear question,* The Oxford Institute for Energ Study. Available at: http://www.oxfordenergy.org/wpcms/wp-content/uploads/2012/12/The-GCC-and-the-Nuclear-Question.pdf.

El-katiri, L., 2013. *Energy sustainability in the Gulf States: The why and the how*, The Oxford Institute for Energ Study. Available at: http://www.oxfordenergy.org/2013/03/energy-sustainability-in-the-gulf-states-the-why-and-the-how/.

El-katiri, L., 2014. *A roadmap for renewable energy in the Middle East and North Africa,* The Oxford Institute for Energ Study. Available at: http://www.oxfordenergy.org/wpcms/wp-content/uploads/2014/01/MEP-6.pdf.

El-katiri, L. & Fattouh, B., 2015. *A brief political economy of energy subsidies in the Middle East and North Africa*, The Oxford Institute for Energ Study. Available at: http://www.oxfordenergy.org/2015/02/brief-political-economy-energy-subsidies-middle-east-north-africa/.

Eurelectric, 2003. *Efficiency in electricity generation,* Brussels.

Farnoosh, A., Lantz, F. & Percebois, J., 2014. Electricity generation analyses in an oil-exporting country transition to non-fossil fuel based power units in Saudi Arabia. *Energy,* 69, pp.299–308. Available at: http://www.sciencedirect.com/science/article/pii/S0360544214002795.

Farouk, N., Sheng, L. & Hayat, Q., 2013. Effect of ambient temperature on the performance of gas turbines. *Internatioanl Journal of Computer Science Issues,* 10(1), pp.439–442. Available at: http://www.ijcsi.org/papers/IJCSI-10-1-3-439-442.pdf.

Farrell, D., Remes, J., Bressand, F., Laabs, M. & Sundaram, A., 2008. *The case for investing in energy productivity,* San Francisco. Available at: http://www.mckinsey.com/insights/energy_resources_materials/the_case_for_investing_in_energy_productivity.

Fattouh, B., 2013. *Summer again: the swing in oil demand in Saudi Arabia*, The Oxford

Institute for Energ Study, Oxford. Available at: https://www.oxfordenergy.org/publications/summer-again-the-swing-in-oil-demand-in-saudi-arabia/.

Fattouh, B. & El-katiri, L., 2012a. *Energy and Arab economic development*. Available at: http://www.arab-hdr.org/publications/other/ahdrps/ENGFattouhKatiriV2.pdf.

Fattouh, B. & El-katiri, L., 2012b. *Energy subsidies in the Arab world*, Oxford. Available at: http://www.arab-hdr.org/publications/other/ahdrps/Energy Subsidies-Bassam Fattouh-Final.pdf.

Fattouh, B. & El-Katiri, L., 2013. Energy subsidies in the Middle East and North Africa. *Energy Strategy Reviews*, 2(1), pp.108–115. Available at: http://linkinghub.elsevier.com/retrieve/pii/S2211467X12000399 [Accessed May 23, 2014].

Fattouh, B. & Mahadeva, L., 2014. *Price reform in Kuwait's electricity & water: assessing the benefits*, Oxford. Available at: http://www.oxfordenergy.org/2014/06/oxford-energy-forum-issue-96/.

Fishwick, P.A., 1995. *Simulation model design and execution*, First edition, New Jersey: Prentice Hall.

Furterer, S. & Elshennawy, A.K., 2005. Implementation of TQM and lean Six Sigma tools in local government: a framework and a case study. *Total Quality Management & Business Excellence*, 16(10), pp.1179–1191. Available at: http://www.tandfonline.com/doi/pdf/10.1080/14783360500236379.

Furterer, S.L., 2004. *A framework roadmap for implementing Lean Six Sigma in local governmental entities*, University of Central Florida. Available at: https://login.libweb.lib.utsa.edu/login?url=http://search.proquest.com/docview/305082274?accountid=7122\nhttp://uq5sd9vt7m.search.serialssolutions.com/?genre=article&sid=ProQ:&atitle=A+framework+roadmap+for+implementing+Lean+Six+Sigma+in+local+governmenta.

Gelan, A., 2014. *Simulating Impacts of reducing subsidies to Kuwait electricity sector*, Oxford. Available at: http://www.oxfordenergy.org/2014/06/oxford-energy-forum-issue-96/.

General Electric, 1996. *Upgradable opportunities for steam turbines*, p.22. Available at: https://powergen.gepower.com/content/dam/gepower-pgdp/global/en_US/documents/technical/ger/ger-3696d-upgradable-opportunities-steam-turbines.pdf.

George, M., Rowlands, D. & Kastle, B., 2003. *What is Lean Six Sigma?*, New York, NY: McGraw-Hill Companies.

Giordano, F., Weir, M. & Fox, W., 2013. *A first course in mathimatical modelling*, Nelson Education.

Graus, W. Roglieri, M., Jaworski, P. & Alberio, L., 2008. *Efficiency and capture-readiness of new fossil power plants in the EU*, Ecofys, Utrecht. Available at: http://www.ecofys.com/files/files/rptenergy-efficiencyandcarboncaptureinnewpowerplantsenfinal.pdf

Graus, W., 2009. *International comparison of fossil power efficiency and CO2 intensity*, Ecofys, Utrecht. Available at: http://www.ecofys.com/files/files/ecofys-internationalcomparisonfossilpowerefficiency_2009_final.pdf

Graus, W., 2010. 'Power of efficiency international comparisons of energy efficiency and CO2 emissions of fossil-based power generation', PhD thesis, Utrecht University, Utrecht.

Graus, W., Blomen, E. & Worrell, E., 2011. Global energy efficiency improvement in the long term: a demand- and supply-side perspective. *Energy Efficiency*, 4(3), pp.435–463. Available at: http://link.springer.com/article/10.1007/s12053-010-9097-z/fulltext.html.

Graus, W. & Worrell, E., 2009. Trend in efficiency and capacity of fossil power generation in the EU. *Energy Policy*, 37(6), pp.2147–2160. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421509000688 [Accessed March 25, 2014].

Graus, W.H.J., Voogt, M. & Worrell, E., 2007. International comparison of energy efficiency of fossil power generation. *Energy Policy*, 35(7), pp.3936–3951. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421507000213 [Accessed March 25, 2014].

Groissböck, M. & Pickl, M.J., 2016. An analysis of the power market in Saudi Arabia: retrospective cost and environmental optimization. *Applied Energy*, 165, pp.548–558. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261915016591.

Harvey, D., 2011. *Energy efficiency and the demand for energy services*, London: Cromwell Press Group. Available at: http://books.google.co.uk/books?hl=en&lr=&id=ryIkwDg8BegC&oi=fnd&pg=PR3&dq=energy+efficiency+and+the+demand+for+energy+services,+book&ots=ggMhF0rgXI&sig=XKuhtS5J8zIRuUa-C65qXrMf_Yc#v=onepage&q=energy efficiency and the demand for energy services, book&f=f.

Hassanzadeh, S., 2016. *A cloud manufacturing based approach to suppliers selection and its implementation and application perspectives*. Brunel University.

Hiebert, L.D., 2002. The determinant of the cost efficiency of electric generating plants: a stochastic frontier approach. *Southern Economic Journal*, 68(4), pp.935–946. Available at: http://www.jstor.org/stable/pdf/1061501.pdf?acceptTC=true.

Hollocks, B.W., 1995. The impact of simulation in manufacturing decision making. *Control Engineering Practice*, 3(1), pp.105–112. Available at: http://www.sciencedirect.com/science/article/pii/096706619400070W.

IEA, 2007a. *Fossil fuel-fired power generation: Case studies of recently constructed coal- and gas-fired power plants.* Available at: https://www.iea.org/publications/freepublications/publication/fossil_fuel_fired.pdf.

IEA, 2007b. *World energy outlook*, Paris. Available at: https://www.iea.org/publications/freepublications/publication/weo_2007.pdf.

IEA, 2009. *Energy balances of OECD countries 1960-2007 and of non-OECD countries 1971-2007,* Paris. Available at: http://www.iea.org/statistics/topics/energybalances/

IEA, 2010a. *Power generation from coal: measuring and reporting efficiency performance and CO2 emissions.* Available at: https://www.iea.org/ciab/papers/power_generation_from_coal.pdf.

IEA, 2010b. *World energy outlook 2010*. Available at: http://vnk.fi/tiedostot/julkinen/talousneuvosto/muistiot/TN-esitykset_14-04-07.pdf\nhttp://www.worldenergy.org/documents/weo_2010_berlin_birol.pdf.

IEA, 2011. *World energy outlook 2011*. Available at: http://www.iea.org/publications/freepublications/publication/weo2011_web.pdf.

IEA, 2013. *Saudi Arabia: electricity and heat*. Available at: http://www.iea.org/statistics/statisticssearch/report/?country=SAUDIARABI&product=electricityandheat&year=2013 [Accessed May 20, 2014].

IEA, 2014. *IEA energy atlas*. *Statistics*. Available at: http://energyatlas.iea.org/#!/tellmap/-1118783123 [Accessed February 6, 2017].

IEA, 2015. *World energy trends*, Paris. Available at: https://www.iea.org/publications/freepublications/publication/WorldTrends_NonOECD_countries2015.pdf.

IEA, 2016. *Energy efficiency market report 2016*, Paris. Available at: https://www.iea.org/eemr16/files/medium-term-energy-efficiency-2016_WEB.PDF

IEA-ETSAP, 2010. *Gas-fired power*. Available at: http://www.iea-etsap.org/web/E-TechDS/PDF/E02-gas_fired_power-GS-AD-gct.pdf.

IEA, 1999. *Electricity market reform*, Paris: OECD/IEA. Available at: http://www.oecd-ilibrary.org/energy/electricity-market-reform_9789264180987-en\npapers2://publication/doi/10.1787/9789264180987-en.

IEA, 2006. *World energy outlook*. Available at: http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/WEO2006.pdf.

IEA, 2010. *United Kingdom: electricity and heat 2009*. Available at: http://www.iea.org/statistics/statisticssearch/report/?country=UK&product=electricityandheat&year=2009.

IEA, 2013. *CO2 emissions from fuel combustion highlights*. Available at: http://www.indiaenvironmentportal.org.in/files/file/CO2EmissionsFromFuelCombustionHighlights2013.pdf.

IEA, 2014. *World energy outlook*. Available at: https://www.iea.org/publications/freepublications/publication/WEO2014.pdf

IEA, 2015. *CO2 emissions from fuel combustion*. Available at: http://www.iea.org/publications/freepublications/publication/CO2EmissionsTrends.pdf.

Institue for Energy Research, 2011. *IEA review shows many developing countries subsidize fossil fuel consumption, creating artificially lower prices*. Available at: http://instituteforenergyresearch.org/analysis/iea-review-shows-many-developing-countries-subsidize-fossil-fuel-consumption-creating-artificially-lower-prices/.

International Monetary Fund, 2014. *Energy subsidies in the Middle East and North Africa: lessons for reform*, Washington, D.C. Available at: https://www.imf.org/external/np/fad/subsidies/pdf/menanote.pdf.

Juergensen, T., 2000. *Continuous improvement: mindsets, capability, process, tools and results*, Indianapolis, IN: The Juergensen Consulting Group, Inc.

KEMA, 2004. *Influence of cooling water temperature on power and efficiency of combined cycle, coal fired and combi power plant*, KEMA 50331044-KPS/TPE 03-1112, Ploumen, P.J., and Rijen, S.P.N. van,
February 2004.

Khan, S., 2014. *Energy efficiency: the first renewable*, Oxford. Available at: http://www.oxfordenergy.org/2014/06/oxford-energy-forum-issue-96/.

Khan, S., Abdo, H. & Al-ghaban, A., 2015. Investigating consumer awareness of energy efficiency in Saudi Arabia. *Energy Research Journal*, pp.0–5. Available at: http://thescipub.com/PDF/ofsp.9818.pdf.

Knittel, C.R., 2002. Alternative regulatory methods and firm efficiency: stochastic frontier evidence from the U.S. electricity industry. *Review of Economics and Statistics*, 84(3), pp.530–540. Available at: http://www.mitpressjournals.org/doi/pdf/10.1162/003465302320259529.

Krane, J., 2012. *Energy policy in the Gulf Arab states: shortage and reform in the world's storehouse of energy*. Available at: http://www.usaee.org/usaee2012/submissions/OnlineProceedings/KRANE_IAEE_Energy-Policy-in-the-Gulf_Sept2012.pdf.

Krane, J., 2013. *Stability versus sustainability: energy policy in the Gulf monarchies*. Available at: http://www.eprg.group.cam.ac.uk/wp-content/uploads/2013/10/1302-PDF.pdf.

Kumar, M., Antony, J., Singh, R. K., Tiwari, M. K. & Perry, D., 2006. Implementing the Lean Sigma framework in an Indian SME: a case study. *Production Planning & Control: The Management of Operation*, 17(4), pp.407–423. Available at: http://dx.doi.org/10.1080/09537280500483350.

Laureani, A. & Jiju, A., 2011. Standards for lean Six Sigma certification. *International Journal of Productivity and Performance Management*, 61(1), pp.110–120. Available at: http://www.emeraldinsight.com/doi/full/10.1108/17410401211188560.

Lawrence Berkeley National Laboratory, 2016. *What is energy efficiency?*. Available at: https://eetd.lbl.gov/ee/ee-1.html.

Liberti, L., 2009. Reformulations in mathematical programming: definitions and systematics. *RAIRO - Operations Research*, 43(1), pp.55–85.

Malik, K., Cropper, M., Limonov, A. & Singh, A., 2011. Estimating the impact of restructuring on electricity generation efficiency: the case of the Indian thermal power sector. *NBER working paper 17383*. Available at: http://www.nber.org/papers/w17383.pdf?new_window=1.

Markiewicz, K., Rose, N.L. & Wolfram, C., 2004. *Do markets reduce costs? Assessing the impact of regulatory restructuring on U.S. electric generation efficiency.* Available at: http://www.nber.org/papers/w11001.pdf.

Matar, W., Murphy, F., Pierru, A., & Rioux, B., 2014. Lowering Saudi Arabia's fuel consumption and energy system costs without increasing end consumer prices. *Energy Economics*, 49(March), pp.558–569. Available at: http://www.sciencedirect.com/science/article/pii/S0306261915016591.

Ministry of Water and Electricity, 2015. *Introduction to electricity sector*. Available at:

http://www.mowe.gov.sa/English/electricitysectorintro.aspx [Accessed August 27, 2015].

Mousa, A., 2013. Lean, Six Sigma and Lean Six Sigma overview. *International Journal of Scientific & Engineering Research*, 4(5), pp.1137–1153. Available at: http://www.ijser.org/researchpaper\Lean-six-sigma-and-lean-six-sigma-Overview.pdf.

Nachet, S. & Aoun, M., 2015. *The Saudi electricity sector: pressing issues and challenges.* Available at: https://www.ifri.org/sites/default/files/atoms/files/note_arabie_saoudite_vf.pdf.

Nave, D., 2002. How to compare Six Sigma, lean management, and the theory of constraints. *Quality Progress*, 35(3), pp.73–78. Available at: http://www.asq1530.org/images/Compare_Lean_Six_Sigma_TOC.pdf.

Nejadi, F., 2016. *Investigation on integration of sustainable manufacturing and mathematical programming for technology selection and capacity planning*. Brunel University.

Newbery, D.M. & Pollitt, M., 1997. The restructuring and privatisation of Britain's Cegb--was it worth it ? *Journal of Industrial Economics*, 45(3), pp.269–303.

Ng, K., C. & Seabright, P., 2001. Competition, privatisation and productive efficiency: evidence from the airline industry. *Economic Journal*, 111, pp.591–619.

Obama, B., 2009. *Remarks by the President on energy*. Available at: https://www.whitehouse.gov/the-press-office/remarks-president-energy.

OPEC, 2016. *Saudi Arabia facts and figures*. Available at: http://www.opec.org/opec_web/en/about_us/169.htm [Accessed February 1, 2016].

Patterson, W., 1999. *Transforming electricity*, London: Earthscan.

Pepper, M.P.J. & Spedding, T.A., 2010. The evolution of lean Six Sigma. *International Journal of Quality & Reliability Management*, 27(2), pp.138–155.

Phillips, A., 2014. *BAE Systems achieves excellence with lean Sigma*. Available at: http://www.manufacturingglobal.com/lean/297/BAE-Systems-achieves-excellence-with-lean-sigma.

Phylipsen, G.J.M., Blok, K. & Worrell, E., 1997. International comparisons of energy efficiency–methodologies for the manufacturing industry. *Energy Policy*, 25(7-9), pp.715–725.

Platts, 2008. *World electric power plant database (WEPP)*. Available at: http://www.platts.com/infostore/product_.

Pophaley, M. & Vyas, R.K., 2015. Fortification of plant maintenance management practices: tole of Six Sigma approach. *Brazilian Journal of Operations & Production Management*, 12(1), p.56.

Proudlove, N., Moxham, C. & Boaden, R., 2008. Lessons for lean in healthcare from using Six Sigma in the NHS. *Public Money and Management*, 28(1), pp.27–34.

Robinson, S., Brooks, R., Kotiadis, K., & Van der Zee, D., 2010. *Conceptual modelling for discrete-event simulation*, CRC Press.

Saal, D.S. & Parker, D., 2001. Productivity and price performance in the privatized water and sewerage companies of England and Wales. *Journal of Regulatory Economics*, 20(1999), pp.61–90.

Salah, S., Rahim, A. & Carrrtero, J.A., 2010. The integration of Six Sigma and lean management. *International Journal of Lean Six Sigma*, 1(3), pp.249–274. Available at: http://cm7ly9cu9w.scholar.serialssolutions.com/?sid=google&auinit=S&aulast=Salah&atitle=The+integration+of+Six+Sigma+and+lean+management&id=doi:10.1108/20401461011075035&title=International+journal+of+lean+six+sigma&volume=1&issue=3&date=2010&spage=249&is.

Sarraf, G., Gardner, T., Fayad, W. & Decker, C., 2010. *The future of IPPs in the GCC new policies for a growing and evolving electricity market*. Available at: http://www.strategyand.pwc.com/media/file/The_Future_of_IPPs_in_the_GCC.pdf.

Saudi Electricity Company, 2014. *Electrical data (2000-2013)*, Riyadh. Available at: https://www.se.com.sa/en-us/Pages/ElectricalData.aspx.

SEC, 2012. *Annual report*, Riyadh. Available at: http://www.se.com.sa/SEC/English/Panel/Reports/.

SEC, 2013. *Annual report*, Riyadh. Available at: http://www.se.com.sa/SEC/English/Panel/Reports/.

SEC, 2014. *Annual report*, Riyadh. Available at: https://www.se.com.sa/en-us/Pages/AnnualReports.aspx.

SEC, 2015. *Annual report*, Riyadh. Available at: https://www.se.com.sa/ar-sa/Pages/AnnualReports.aspx.

SEEC, 2015. Saudi Energy Efficiency Program overview. Available at: http://www.seec.gov.sa/2013/08/04/%D8%A7%D9%84%D9%85%D9%87%D8%A7%D9%85-%D8%A7%D9%84%D8%B1%D8%A6%D9%8A%D8%B3%D9%8A%D8%A9-%D9%84%D9%84%D9%85%D8%B1%D9%83%D8%B2/?lang=en.

Shahada, T.M. & Alsyouf, I., 2012. Design and implementation of a Lean Six Sigma framework for process improvement: a case study. In *International Conference on Industrial Engineering and Engineering Management (IEEM)*, Hong Kong: IEEE, pp.80–84.

Shannon, R., 1998. Introduction to the art and science of simulation. In *Proceedings of the 1998 Winter Simulation Conference, WSC '98*, Los Alamitos, CA, USA: IEEE Computer Society Press, pp.7–14. Available at: http://delivery.acm.org/10.1145/300000/293175/p7-shannon.pdf?ip=134.83.1.241&id=293175&acc=ACTIVE SERVICE&key=BF07A2EE685417C5.E5A0F962EEDC4F14.4D4702B0C3E38B35.4D4702B0C3E38B35&CFID=562525466&CFTOKEN=11055325&__acm__=1448289976_21e0f91932ca9c8100b207bd26.

Sharma, U., 2003. Implementing Lean principles with the Six Sigma advantage: how a battery company realized significant improvements. *Journal of Organizational Excellence*, 22(3), pp.43–52. Available at: http://doi.wiley.com/10.1002/npr.10078.

Singh, S. & Kumar, R., 2012. Ambient air temperature effect on power plant. *International Journal of Engineering Science and Technology*, 4(08), pp.3916–3923. Available at: https://www.idc-online.com/technical_references/pdfs/mechanical_engineering/AMBIENT AIR

TEMPERATURE.pdf.

Smith, B., 2003. Lean and Six Sigma – a one-two punch. *Quality Progress*, (April), pp.37–41. Available at: http://www.tbmcg.com/acrobat/press_public/QP_-_Lean_and_Six_Sigma_-_One_Two_Punch.pdf.

Snee, R.D., 2010. Lean Six Sigma – getting better all the time. *International Journal of Lean Six Sigma*, 1(1), pp.9–29. Available at: file://acfs5/empg/empgmta/Downloads/Lean_Six (1).pdf.

Snee, R.D., 2005. When worlds collide: lean and Six Sigma. *Quality Progress*, 38(9), pp.63–65. Available at: http://asq.org/quality-progress/2005/09/3.4-per-million/when-worlds-collide--lean-and-six-sigma.html.

Sulman, A., 2016. الاستهلاك المحلي للطاقة يشكل 38% من إنتاج المملكة. *Aleqtisadiah*. Available at: https://www.aleqt.com/2016/02/08/article_1028401.html [Accessed February 8, 2016].

Svensson, C., Antony, J., Ba-Essa, M. & Bakhsh, M., 2015. A Lean Six Sigma program in higher education. *International Journal of Quality & Reliability Management*, 32(9), pp.951–969.

The Climate Registry, 2015. *Default factors for calculating CO2 emissions from fossil fuel and biomass combustion*. Available at: http://www.theclimateregistry.org/wp-content/uploads/2016/03/2015-TCR-Default-EFs.pdf.

The World Bank, 2015. *CO2 emissions*. Available at: http://data.worldbank.org/indicator/EN.ATM.CO2E.KT/countries/SA?display=graph [Accessed December 1, 2015].

The World Bank, 2014. *Electric power transmission and distribution losses*. Available at: http://search.worldbank.org/all?qterm=transmission+and+distribution+losses&language=EN&op=&_Top/date=2014 [Accessed December 15, 2015].

Timans, W., Antony, J., Ahaus, K. & Van Solingen, R., 2012. Implementation of Lean Six Sigma in small- and medium-sized manufacturing enterprises in the Netherlands. *Journal of the Operational Research Society*, 63(3), pp.339–353. Available at: http://dx.doi.org/10.1057/jors.2011.47.

Tiwari, A.K., Hasan, M.M. & Islam, M., 2013. Effect of operating parameters on the performance of combined cycle power plant. *Oriental Journal of Chemistry*, 29(1), pp.121–122. Available at: http://www.tcsme.org/Papers/Vol37/Vol37No4Paper10.pdf.

UCSUSA, 2011. *Each country's share of CO2 emissions*. Available at: http://www.ucsusa.org/global_warming/science_and_impacts/science/each-countrys-share-of-co2.html#.VmGu1nbhCUl [Accessed December 1, 2015].

VGB Powertech, 2015. *Electricty generation facts and figures*, VGB PowerTech e.V., Essen · Germany.

VGB Powertech, 2004. *Jahresnutzungsgrad von fossil befeuerten Kraftwerken gemäß den „besten verfügbaren Kraftwerkstechniken*, VGB Stellungnahme, August 2004.

Wärtsilä, 2015. *Combustion engine vs gas turbine: ambient temperature*. Available at: http://www.wartsila.com/energy/learning-center/technical-comparisons/combustion-engine-vs-gas-turbine-derating-due-to-ambient-temperature [Accessed December 23, 2015].

Woertz, E., 2013. *The domestic challenges in the Saudi energy market and their regional and geopolitical implecations*. Available at: https://www.ciaonet.org/attachments/24183/uploads.

Womack, J.P., Jones, D.T. & Roos, D., 1990. *Machine that changed the world,* New York: Simon and Schuster.

World Bank, 2008. *Republic of Lebanon: electricity sector public expenditure review*. Available at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2008/04/17/000333037_20080417083720/Rendered/PDF/414210REPLACEM1closed0April01502008.pdf.

World Bank, 2010. *Subsidies in the energy sector: an overview*. Available at: http://siteresources.worldbank.org/.

Worrell, E. & Graus, W., 2006. *Comparison of efficiency fossil power generation, Ecofys, Utrecht.* Available at: *http://www.ecofys.com/files/files/ecofyscomparison_fossil_power_efficiencyaug2006_02.pdf* .

Wyland, B., Buxton, K. & Fuqua, B., 2000. Simulating the supply chain. *IIE solutions*, 32(1), pp.37–42. Available at: http://cm7ly9cu9w.scholar.serialssolutions.com/?sid=google&auinit=B&aulast=Wyland&atitle=Simulating+the+supply+chain&title=IIE+solutions&volume=32&issue=1&date=2000&spage=37&issn=1085-1259.

Yamani, H., 2012. *Energy sustainability for future generations*. Available at: http://www.saudicrm.com/energy.gov.sa/sites/default/files/files/Presentation_MIT Meeting_Mar2012.pdf.

Yergin, D., 1993. *The price*, New York: Simon & Schuster.

Zengh, A.Y., 2007. *A smarter grid for India*. Available at: http://www.smartgridnews.com/artman/publish/article_303.html.

Zhang, Q., Irfan, M., Aamir, M. & Khattak, O., 2012. Lean Six Sigma: a literature review. *Interdisciplinary Journal of Contemporary Research in Business*, 3(10), pp.599–605. Available at: http://journal-archieves15.webs.com/599-605.pdf.

Appendix A

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
ALBAHA	SEC	AL-BAHA	1980	DIESEL	No Fuel	DG	32	4.25
ALBAHA	SEC	AL-BAHA	1980	DIESEL	No Fuel	DG	32	4.25
ALBAHA	SEC	AL-BAHA	1983	DIESEL	No Fuel	GT	29	8
ALBAHA	SEC	AL-BAHA	1983	DIESEL	No Fuel	GT	29	8
ALBAHA	SEC	AL-BAHA	1983	DIESEL	No Fuel	GT	29	8
ALBAHA	SEC	AL-BAHA	1980	DIESEL	No Fuel	DG	32	8.5
ALBAHA	SEC	AL-BAHA	1980	DIESEL	No Fuel	DG	32	8.5
ALBAHA	SEC	AL-BAHA	1980	DIESEL	No Fuel	DG	32	8.5
ALBAHA	SEC	AL-BAHA	1980	DIESEL	No Fuel	DG	32	8.5
TABARJAL	SEC	AL-JOUF	1983	DIESEL	No Fuel	DG	29	1.5
TABARJAL	SEC	AL-JOUF	1983	DIESEL	No Fuel	DG	29	1.5
TABARJAL	SEC	AL-JOUF	1983	DIESEL	No Fuel	DG	29	1.5
TABARJAL	SEC	AL-JOUF	1998	DIESEL	No Fuel	DG	14	1.5
TABARJAL	SEC	AL-JOUF	1974	DIESEL	No Fuel	GT	38	6
AL-QURAYYAT	SEC	AL-JOUF	1994	DIESEL	No Fuel	GT	Expired, out of service	6
AL-QURAYYAT	SEC	AL-JOUF	1994	DIESEL	No Fuel	GT	Expired, out of service	6
AL-QURAYYAT	SEC	AL-JOUF	1994	DIESEL	No Fuel	GT	Expired, out of service	6
AL-QURAYYAT	SEC	AL-JOUF	1994	DIESEL	No Fuel	GT	Expired, out of service	6
AL-QURAYYAT	SEC	AL-JOUF	1998	DIESEL	No Fuel	GT	14	16.3
AL-QURAYYAT	SEC	AL-JOUF	1998	DIESEL	No Fuel	GT	14	16.3
AL-QURAYYAT	SEC	AL-JOUF	1998	DIESEL	No Fuel	GT	14	16.3
AL-QURAYYAT	SEC	AL-JOUF	1993	DIESEL	No Fuel	GT	19	21
AL-QURAYYAT	SEC	AL-JOUF	1993	DIESEL	No Fuel	GT	19	21
AL-JOUF	SEC	AL-JOUF	1999	CRUDE	No Fuel	GT	13	24
AL-JOUF	SEC	AL-JOUF	1999	CRUDE	No Fuel	GT	13	24
AL-JOUF	SEC	AL-JOUF	1988	CRUDE	No Fuel	GT	24	24
AL-JOUF	SEC	AL-JOUF	1988	CRUDE	No Fuel	GT	24	24
AL-JOUF	SEC	AL-JOUF	1988	CRUDE	No Fuel	GT	24	24
AL-JOUF	SEC	AL-JOUF	1988	CRUDE	No Fuel	GT	24	24
AL-JOUF	SEC	AL-JOUF	1988	CRUDE	No Fuel	GT	24	24
TABARJAL	SEC	AL-JOUF	2002	DIESEL	No Fuel	GT	10	29.9
TABARJAL	SEC	AL-JOUF	2002	DIESEL	No Fuel	GT	10	29.9
AL-JOUF	SEC	AL-JOUF	2008	CRUDE	No Fuel	GT	4	60
AL-JOUF	SEC	AL-JOUF	2008	CRUDE	No Fuel	GT	4	60
AL-JOUF	SEC	AL-JOUF	2012	CRUDE	No Fuel	GT	0	60
AL-QURAYYAT	SEC	AL-JOUF	2012	DIESEL	No Fuel	GT	0	70
AL-QURAYYAT	SEC	AL-JOUF	2012	DIESEL	No Fuel	GT	0	70
ASIR	SEC	ASIR	1978	DIESEL	No Fuel	DG	34	8.5
ASIR	SEC	ASIR	1978	DIESEL	No Fuel	DG	34	8.5
ASIR	SEC	ASIR	1978	DIESEL	No Fuel	DG	34	8.5

PP name	**Provider**	**Area**	**Year of commission**	**Fuel**	**Alternative fuel**	**Unit type**	**Age**	Capacity (MW)
ASIR	SEC	ASIR	1978	DIESEL	No Fuel	DG	34	8.5
ASIR	SEC	ASIR	1978	DIESEL	No Fuel	DG	34	8.5
ASIR	SEC	ASIR	1978	DIESEL	No Fuel	DG	34	8.5
ASIR	SEC	ASIR	1978	DIESEL	No Fuel	DG	34	8.5
ASIR	SEC	ASIR	1978	DIESEL	No Fuel	DG	34	8.5
ASIR	SEC	ASIR	1978	DIESEL	No Fuel	DG	34	8.5
BISHA	SEC	ASIR	1984	DIESEL	No Fuel	GT	28	20
BISHA	SEC	ASIR	1984	DIESEL	No Fuel	GT	28	20
TIHAMA	SEC	ASIR	1986	CRUDE	DIESEL	GT	26	20
TIHAMA	SEC	ASIR	1986	CRUDE	DIESEL	GT	26	20
BISHA	SEC	ASIR	1984	DIESEL	No Fuel	GT	28	45
BISHA	SEC	ASIR	1984	DIESEL	No Fuel	GT	28	45
ASIR	SEC	ASIR	1985	DIESEL	No Fuel	GT	27	47
ASIR	SEC	ASIR	1985	DIESEL	No Fuel	GT	27	47
ASIR	SEC	ASIR	1986	DIESEL	No Fuel	GT	26	47
ASIR	SEC	ASIR	1996	DIESEL	No Fuel	GT	16	50
TIHAMA	SEC	ASIR	1986	CRUDE	DIESEL	GT	26	53
TIHAMA	SEC	ASIR	1986	CRUDE	DIESEL	GT	26	53
ASIR	SEC	ASIR	2002	DIESEL	No Fuel	GT	10	55
ASIR	SEC	ASIR	2003	DIESEL	No Fuel	GT	9	55
TIHAMA	SEC	ASIR	1991	CRUDE	DIESEL	GT	21	56
TIHAMA	SEC	ASIR	2009	CRUDE	DIESEL	GT	3	60
TIHAMA	SEC	ASIR	2007	CRUDE	DIESEL	GT	5	60
TIHAMA	SEC	ASIR	2007	CRUDE	DIESEL	GT	5	60
TIHAMA	SEC	ASIR	2003	CRUDE	DIESEL	GT	9	60
TIHAMA	SEC	ASIR	2003	CRUDE	DIESEL	GT	9	60
TIHAMA	SEC	ASIR	2009	CRUDE	DIESEL	GT	3	60
ASIR	SEC	ASIR	1997	DIESEL	No Fuel	GT	15	66
ASIR	SEC	ASIR	1998	DIESEL	No Fuel	GT	14	66
ASIR	SEC	ASIR	2005	DIESEL	No Fuel	GT	7	70
ASIR	SEC	ASIR	2006	DIESEL	No Fuel	GT	6	70
BISHA	SEC	ASIR	2005	DIESEL	No Fuel	GT	7	73
BISHA	SEC	ASIR	2006	DIESEL	No Fuel	GT	6	73
BISHA	SEC	ASIR	2005	DIESEL	No Fuel	GT	7	73
TIHAMA	SEC	ASIR	1999	DIESEL	No Fuel	GT	13	80
TIHAMA	SEC	ASIR	1999	DIESEL	No Fuel	GT	13	80
DAMMAM	SEC	EASTERN	1972	GAS	DIESEL	GT	40	13.5
DAMMAM	SEC	EASTERN	1972	GAS	DIESEL	GT	40	13.5
DAMMAM	SEC	EASTERN	1999	GAS	DIESEL	GT	13	13.5
DAMMAM	SEC	EASTERN	1999	GAS	DIESEL	GT	13	13.5
QAISUMAH	SEC	EASTERN	1980	DIESEL	No Fuel	GT	32	21
QAISUMAH	SEC	EASTERN	1980	DIESEL	No Fuel	GT	32	21
QAISUMAH	SEC	EASTERN	1977	DIESEL	No Fuel	GT	35	21

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
QAISUMAH	SEC	EASTERN	1983	DIESEL	No Fuel	GT	29	21
UTHMANIYAH	SEC	EASTERN	1973	GAS	No Fuel	GT	39	21.8
UTHMANIYAH	SEC	EASTERN	1973	GAS	No Fuel	GT	39	21.8
JUAYMAH	SEC	EASTERN	1974	GAS	No Fuel	GT	38	21.8
DAMMAM	SEC	EASTERN	1978	GAS	DIESEL	GT	34	23.8
DAMMAM	SEC	EASTERN	1978	GAS	DIESEL	GT	34	23.8
DAMMAM	SEC	EASTERN	1997	GAS	DIESEL	GT	15	23.8
DAMMAM	SEC	EASTERN	1973	GAS	DIESEL	GT	39	23.8
DAMMAM	SEC	EASTERN	1976	GAS	DIESEL	GT	36	26.1
DAMMAM	SEC	EASTERN	1976	GAS	DIESEL	GT	36	26.1
DAMMAM	SEC	EASTERN	1977	GAS	DIESEL	GT	35	26.1
DAMMAM	SEC	EASTERN	1977	GAS	DIESEL	GT	Expired, out of service	26.1
QAISUMAH	SEC	EASTERN	1985	DIESEL	No Fuel	GT	27	29.9
QAISUMAH	SEC	EASTERN	1985	DIESEL	No Fuel	GT	27	29.9
DAMMAM	SEC	EASTERN	1978	GAS	DIESEL	GT	34	30
UTHMANIYAH	SEC	EASTERN	1974	GAS	No Fuel	GT	38	43
UTHMANIYAH	SEC	EASTERN	1975	GAS	No Fuel	GT	37	43
UTHMANIYAH	SEC	EASTERN	1975	GAS	No Fuel	GT	37	43
UTHMANIYAH	SEC	EASTERN	1975	GAS	No Fuel	GT	37	43
UTHMANIYAH	SEC	EASTERN	1975	GAS	No Fuel	GT	37	43
DAMMAM	SEC	EASTERN	2000	GAS	DIESEL	GT	Expired, out of service	44.1
DAMMAM	SEC	EASTERN	1974	GAS	DIESEL	GT	38	44.1
DAMMAM	SEC	EASTERN	1965	GAS	DIESEL	GT	47	44.1
JUAYMAH	SEC	EASTERN	1974	GAS	No Fuel	GT	38	44.3
JUAYMAH	SEC	EASTERN	1976	GAS	No Fuel	GT	36	44.3
SAFANIYAH	SEC	EASTERN	1974	GAS	No Fuel	GT	38	44.3
SHEDGUM	SEC	EASTERN	1982	GAS	No Fuel	GT	30	57.8
SHEDGUM	SEC	EASTERN	1982	GAS	No Fuel	GT	30	57.8
SHEDGUM	SEC	EASTERN	1982	GAS	No Fuel	GT	30	57.8
SHEDGUM	SEC	EASTERN	1983	GAS	No Fuel	GT	29	57.8
SHEDGUM	SEC	EASTERN	1982	GAS	No Fuel	GT	30	57.8
SHEDGUM	SEC	EASTERN	1982	GAS	No Fuel	GT	30	57.8
SHEDGUM	SEC	EASTERN	1982	GAS	No Fuel	GT	30	57.8
SHEDGUM	SEC	EASTERN	1982	GAS	No Fuel	GT	30	57.8
FARAS	SEC	EASTERN	1985	GAS	No Fuel	GT	27	57.8
FARAS	SEC	EASTERN	1984	GAS	No Fuel	GT	28	57.8
FARAS	SEC	EASTERN	1984	GAS	No Fuel	GT	28	57.8
FARAS	SEC	EASTERN	1984	GAS	No Fuel	GT	28	57.8
FARAS	SEC	EASTERN	1984	GAS	No Fuel	GT	28	57.8
FARAS	SEC	EASTERN	1984	GAS	No Fuel	GT	28	57.8
FARAS	SEC	EASTERN	1984	GAS	No Fuel	GT	28	57.8
FARAS	SEC	EASTERN	1984	GAS	No Fuel	GT	28	57.8

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
SHEDGUM	SEC	EASTERN	1978	GAS	No Fuel	GT	34	69.8
SHEDGUM	SEC	EASTERN	1980	GAS	No Fuel	GT	32	69.8
BERRI (SEC)	SEC	EASTERN	1977	GAS	No Fuel	GT	35	69.8
BERRI (SEC)	SEC	EASTERN	1977	GAS	No Fuel	GT	35	69.8
BERRI (SEC)	SEC	EASTERN	1977	GAS	No Fuel	GT	35	69.8
FARAS	SEC	EASTERN	1980	GAS	No Fuel	GT	32	69.8
SHEDGUM	SEC	EASTERN	1979	GAS	No Fuel	GT	33	72.4
SHEDGUM	SEC	EASTERN	1978	GAS	No Fuel	GT	34	72.4
SHEDGUM	SEC	EASTERN	1978	GAS	No Fuel	GT	34	72.4
SHEDGUM	SEC	EASTERN	1978	GAS	No Fuel	GT	34	72.4
SHEDGUM	SEC	EASTERN	1980	GAS	No Fuel	GT	32	72.4
SHEDGUM	SEC	EASTERN	1980	GAS	No Fuel	GT	32	72.4
SHEDGUM	SEC	EASTERN	1981	GAS	No Fuel	GT	31	72.4
FARAS	SEC	EASTERN	1979	GAS	No Fuel	GT	33	72.4
FARAS	SEC	EASTERN	1979	GAS	No Fuel	GT	33	72.4
FARAS	SEC	EASTERN	1979	GAS	No Fuel	GT	33	72.4
FARAS	SEC	EASTERN	1981	GAS	No Fuel	GT	31	72.4
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2010	GAS	DIESEL	GT	2	127
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2009	GAS	DIESEL	GT	3	127
QURAYYAH- CC	SEC	EASTERN	2010	GAS	DIESEL	GT	2	127
QURAYYAH- CC	SEC	EASTERN	2010	GAS	DIESEL	GT	2	127
QURAYYAH- CC	SEC	EASTERN	2010	GAS	DIESEL	GT	2	127
QURAYYAH- CC	SEC	EASTERN	2010	GAS	DIESEL	GT	2	127
QURAYYAH- CC	SEC	EASTERN	2012	GAS	DIESEL	GT	0	127
QURAYYAH- CC	SEC	EASTERN	2012	GAS	DIESEL	GT	0	127
QURAYYAH- CC	SEC	EASTERN	2012	GAS	DIESEL	GT	0	127
FARAS	SEC	EASTERN	2009	GAS	No Fuel	GT	3	127
FARAS	SEC	EASTERN	2009	GAS	No Fuel	GT	3	127
FARAS	SEC	EASTERN	2009	GAS	No Fuel	GT	3	127
FARAS	SEC	EASTERN	2009	GAS	No Fuel	GT	3	127
GHAZLAN	SEC	EASTERN	1980	GAS	No Fuel	ST	32	430
GHAZLAN	SEC	EASTERN	1980	GAS	No Fuel	ST	32	430
GHAZLAN	SEC	EASTERN	1981	GAS	No Fuel	ST	31	430
GHAZLAN	SEC	EASTERN	1982	GAS	No Fuel	ST	30	430

PP name	**Provider**	**Area**	**Year of commission**	**Fuel**	**Alternative fuel**	**Unit type**	**Age**	Capacity (MW)
QURAYYAH -ST	SEC	EASTERN	1992	GAS	No Fuel	ST	20	625
QURAYYAH -ST	SEC	EASTERN	1992	GAS	No Fuel	ST	20	625
QURAYYAH –ST	SEC	EASTERN	1988	GAS	No Fuel	ST	24	625
QURAYYAH –ST	SEC	EASTERN	1989	GAS	No Fuel	ST	23	625
GHAZLAN	SEC	EASTERN	2001	GAS	No Fuel	ST	11	664
GHAZLAN	SEC	EASTERN	2002	GAS	No Fuel	ST	10	664
GHAZLAN	SEC	EASTERN	2002	GAS	No Fuel	ST	10	664
GHAZLAN	SEC	EASTERN	2003	GAS	No Fuel	ST	9	664
HAIL1	SEC	HAIL	1981	DIESEL	No Fuel	GT	Expired, out of service	8.3
HAIL1	SEC	HAIL	1983	DIESEL	No Fuel	GT	Expired, out of service	15.9
HAIL1	SEC	HAIL	1983	DIESEL	No Fuel	GT	Expired, out of service	15.9
HAIL2	SEC	HAIL	2007	CRUDE	DIESEL	GT	5	55.5
HAIL2	SEC	HAIL	2012	CRUDE	DIESEL	GT	0	63
HAIL2	SEC	HAIL	2012	CRUDE	DIESEL	GT	0	63
HAIL2	SEC	HAIL	2012	CRUDE	DIESEL	GT	0	63
HAIL2	SEC	HAIL	2012	CRUDE	DIESEL	GT	0	63
HAIL2	SEC	HAIL	2011	CRUDE	DIESEL	GT	1	63
HAIL2	SEC	HAIL	2011	CRUDE	DIESEL	GT	1	63
HAIL2	SEC	HAIL	1985	CRUDE	DIESEL	GT	27	68.07
HAIL2	SEC	HAIL	1985	CRUDE	DIESEL	GT	27	68.07
HAIL2	SEC	HAIL	1985	CRUDE	DIESEL	GT	27	68.07
HAIL2	SEC	HAIL	1985	CRUDE	DIESEL	GT	27	68.07
HAIL2	SEC	HAIL	1985	CRUDE	DIESEL	GT	27	68.07
JAZAN	SEC	JAZAN	1986	DIESEL	No Fuel	GT	26	15
JAZAN	SEC	JAZAN	1982	DIESEL	No Fuel	GT	30	15
JAZAN	SEC	JAZAN	1982	DIESEL	No Fuel	GT	30	15
JAZAN	SEC	JAZAN	1990	DIESEL	No Fuel	GT	22	15
JAZAN	SEC	JAZAN	1990	DIESEL	No Fuel	GT	22	15
JAZAN	SEC	JAZAN	1990	DIESEL	No Fuel	GT	22	15
JAZAN	SEC	JAZAN	1982	DIESEL	No Fuel	GT	30	16
JAZAN	SEC	JAZAN	1980	DIESEL	No Fuel	GT	32	16
JAZAN	SEC	JAZAN	1986	DIESEL	No Fuel	GT	26	17
JAZAN	SEC	JAZAN	1982	DIESEL	No Fuel	GT	30	17
JAZAN	SEC	JAZAN	1980	DIESEL	No Fuel	GT	32	17
JAZAN	SEC	JAZAN	1983	DIESEL	No Fuel	GT	29	20
JAZAN	SEC	JAZAN	1989	DIESEL	No Fuel	GT	23	50
JAZAN	SEC	JAZAN	1989	DIESEL	No Fuel	GT	23	50
JAZAN	SEC	JAZAN	2003	DIESEL	No Fuel	GT	9	60
JAZAN	SEC	JAZAN	2003	DIESEL	No Fuel	GT	9	60
JAZAN	SEC	JAZAN	1998	DIESEL	No Fuel	GT	14	60
JAZAN	SEC	JAZAN	2006	DIESEL	No Fuel	GT	6	66
JAZAN	SEC	JAZAN	2006	DIESEL	No Fuel	GT	6	66

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
JAZAN	SEC	JAZAN	2007	DIESEL	No Fuel	GT	5	66
JAZAN	SEC	JAZAN	2007	DIESEL	No Fuel	GT	5	66
JAZAN	SEC	JAZAN	2009	DIESEL	No Fuel	GT	3	66
JAZAN	SEC	JAZAN	2009	DIESEL	No Fuel	GT	3	66
JAZAN	SEC	JAZAN	2009	DIESEL	No Fuel	GT	3	66
JAZAN	SEC	JAZAN	2005	DIESEL	No Fuel	GT	7	66
JAZAN	SEC	JAZAN	2005	DIESEL	No Fuel	GT	7	66
JAZAN	SEC	JAZAN	2008	DIESEL	No Fuel	GT	4	66
JAZAN	SEC	JAZAN	2008	DIESEL	No Fuel	GT	4	66
JAZAN	SEC	JAZAN	1997	DIESEL	No Fuel	GT	15	70
JAZAN	SEC	JAZAN	1998	DIESEL	No Fuel	GT	14	70
MADINAH - 1	SEC	MADINAH	1976	DIESEL	No Fuel	GT	36	18.1
YANBU (SEC)	SEC	MADINAH	1982	DIESEL	No Fuel	GT	30	18.11
YANBU (SEC)	SEC	MADINAH	1983	DIESEL	No Fuel	GT	29	18.24
YANBU (SEC)	SEC	MADINAH	1983	DIESEL	No Fuel	GT	29	18.24
MADINAH - 2	SEC	MADINAH	1977	DIESEL	No Fuel	GT	35	20
MADINAH - 2	SEC	MADINAH	1977	DIESEL	No Fuel	GT	35	20
MADINAH - 2	SEC	MADINAH	1980	DIESEL	No Fuel	GT	32	20
MADINAH - 2	SEC	MADINAH	1981	DIESEL	No Fuel	GT	31	50
MADINAH - 2	SEC	MADINAH	1981	DIESEL	No Fuel	GT	31	50
MADINAH - 2	SEC	MADINAH	1998	DIESEL	No Fuel	GT	14	62
MADINAH - 2	SEC	MADINAH	1998	DIESEL	No Fuel	GT	14	62
TAIF	SEC	MAKKAH	1966	DIESEL	No Fuel	DG	Expired, out of service	1.1
TAIF	SEC	MAKKAH	1967	DIESEL	No Fuel	DG	Expired, out of service	1.6
TAIF	SEC	MAKKAH	1969	DIESEL	No Fuel	DG	Expired, out of service	1.6
TAIF	SEC	MAKKAH	1971	DIESEL	No Fuel	DG	Expired, out of service	2
TAIF	SEC	MAKKAH	1972	DIESEL	No Fuel	DG	Expired, out of service	2.2
TAIF	SEC	MAKKAH	1972	DIESEL	No Fuel	DG	Expired, out of service	2.2
MAKKAH	SEC	MAKKAH	1968	DIESEL	No Fuel	DG	44	5.24
MAKKAH	SEC	MAKKAH	1968	DIESEL	No Fuel	DG	44	5.24
JEDDAH NO.2	SEC	MAKKAH	1965	DIESEL	No Fuel	GT	Expired, out of service	6
MAKKAH	SEC	MAKKAH	1971	DIESEL	No Fuel	DG	41	7.86
MAKKAH	SEC	MAKKAH	1971	DIESEL	No Fuel	DG	41	7.86
MAKKAH	SEC	MAKKAH	1976	DIESEL	No Fuel	DG	36	8.65
MAKKAH	SEC	MAKKAH	1976	DIESEL	No Fuel	DG	36	8.65
TAIF	SEC	MAKKAH	1976	DIESEL	No Fuel	GT	36	15.95
MAKKAH	SEC	MAKKAH	1975	DIESEL	No Fuel	GT	37	18
TAIF	SEC	MAKKAH	1977	DIESEL	No Fuel	GT	35	19.5
TAIF	SEC	MAKKAH	1977	DIESEL	No Fuel	GT	35	19.5
TAIF	SEC	MAKKAH	1981	DIESEL	No Fuel	GT	31	20.3
TAIF	SEC	MAKKAH	1981	DIESEL	No Fuel	GT	31	20.3

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
TAIF	SEC	MAKKAH	1981	DIESEL	No Fuel	GT	31	20.3
MAKKAH	SEC	MAKKAH	1976	DIESEL	No Fuel	GT	36	22
MAKKAH	SEC	MAKKAH	1977	DIESEL	No Fuel	GT	35	22
JEDDAH NO.2	SEC	MAKKAH	1973	DIESEL	No Fuel	GT	Expired, out of service	24.95
JEDDAH NO.2	SEC	MAKKAH	1974	DIESEL	No Fuel	GT	Expired, out of service	24.95
JEDDAH NO.2	SEC	MAKKAH	1978	DIESEL	No Fuel	GT	Expired, out of service	25
JEDDAH NO.2	SEC	MAKKAH	1977	DIESEL	No Fuel	GT	Expired, out of service	28.9
MAKKAH	SEC	MAKKAH	1978	DIESEL	No Fuel	GT	34	40.3
MAKKAH	SEC	MAKKAH	1979	DIESEL	No Fuel	GT	33	40.3
MAKKAH	SEC	MAKKAH	1979	DIESEL	No Fuel	GT	33	40.3
MAKKAH	SEC	MAKKAH	1979	DIESEL	No Fuel	GT	33	40.3
JEDDAH NO.3	SEC	MAKKAH	1979	CRUDE	DIESEL	GT	33	44
JEDDAH NO.3	SEC	MAKKAH	1980	CRUDE	DIESEL	GT	32	44
JEDDAH NO.3	SEC	MAKKAH	1979	CRUDE	DIESEL	GT	33	44
JEDDAH NO.3	SEC	MAKKAH	1979	CRUDE	DIESEL	GT	33	44
JEDDAH NO.3	SEC	MAKKAH	1978	CRUDE	DIESEL	GT	34	44
JEDDAH NO.3	SEC	MAKKAH	1978	CRUDE	DIESEL	GT	34	44
JEDDAH NO.3	SEC	MAKKAH	1978	CRUDE	DIESEL	GT	34	44
JEDDAH NO.3	SEC	MAKKAH	1976	CRUDE	DIESEL	GT	36	44.6
JEDDAH NO.3	SEC	MAKKAH	1976	CRUDE	DIESEL	GT	36	44.6
JEDDAH NO.3	SEC	MAKKAH	1976	CRUDE	DIESEL	GT	36	44.6
JEDDAH NO.3	SEC	MAKKAH	1977	CRUDE	DIESEL	GT	35	44.6
MAKKAH	SEC	MAKKAH	1981	DIESEL	No Fuel	GT	31	46.3
MAKKAH	SEC	MAKKAH	1980	DIESEL	No Fuel	GT	32	46.3
MAKKAH	SEC	MAKKAH	1980	DIESEL	No Fuel	GT	32	46.3
MAKKAH	SEC	MAKKAH	1982	DIESEL	No Fuel	GT	30	48.5
MAKKAH	SEC	MAKKAH	1982	DIESEL	No Fuel	GT	30	48.5
JEDDAH NO.3	SEC	MAKKAH	1980	CRUDE	DIESEL	GT	32	51.7
JEDDAH NO.3	SEC	MAKKAH	1980	CRUDE	DIESEL	GT	32	51.7
JEDDAH NO.3	SEC	MAKKAH	1980	CRUDE	DIESEL	GT	32	51.7
JEDDAH NO.3	SEC	MAKKAH	1981	CRUDE	DIESEL	GT	31	51.7
JEDDAH NO.3	SEC	MAKKAH	1981	CRUDE	DIESEL	GT	31	51.7
JEDDAH NO.3	SEC	MAKKAH	1981	CRUDE	DIESEL	GT	31	51.7
JEDDAH NO.3	SEC	MAKKAH	1982	CRUDE	DIESEL	GT	30	51.7
JEDDAH NO.3	SEC	MAKKAH	1982	CRUDE	DIESEL	GT	30	51.7
JEDDAH NO.3	SEC	MAKKAH	1982	CRUDE	DIESEL	GT	30	51.7
JEDDAH NO.3	SEC	MAKKAH	1982	CRUDE	DIESEL	GT	30	51.7
JEDDAH NO.3	SEC	MAKKAH	1982	CRUDE	DIESEL	GT	30	51.7
JEDDAH NO.3	SEC	MAKKAH	1982	CRUDE	DIESEL	GT	30	51.7
JEDDAH NO.3	SEC	MAKKAH	1983	CRUDE	DIESEL	GT	29	51.7
JEDDAH NO.3	SEC	MAKKAH	1983	CRUDE	DIESEL	GT	29	51.7
JEDDAH NO.3	SEC	MAKKAH	1984	CRUDE	DIESEL	GT	28	51.7

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
JEDDAH NO.3	SEC	MAKKAH	1984	CRUDE	DIESEL	GT	28	51.7
MAKKAH	SEC	MAKKAH	1983	DIESEL	No Fuel	GT	29	53.21
MAKKAH	SEC	MAKKAH	1983	DIESEL	No Fuel	GT	29	53.21
MAKKAH	SEC	MAKKAH	1983	DIESEL	No Fuel	GT	29	53.21
MAKKAH	SEC	MAKKAH	1983	DIESEL	No Fuel	GT	29	53.21
MAKKAH	SEC	MAKKAH	1984	DIESEL	No Fuel	GT	28	53.21
MAKKAH	SEC	MAKKAH	1983	DIESEL	No Fuel	GT	29	53.21
RABIGH	SEC	MAKKAH	1991	CRUDE	DIESEL	CC	21	57.7
RABIGH	SEC	MAKKAH	1991	CRUDE	DIESEL	CC	21	57.7
RABIGH	SEC	MAKKAH	1990	CRUDE	DIESEL	CC	22	57.7
RABIGH	SEC	MAKKAH	1991	CRUDE	DIESEL	CC	21	57.7
RABIGH	SEC	MAKKAH	1991	CRUDE	DIESEL	CC	21	57.7
RABIGH	SEC	MAKKAH	1991	CRUDE	DIESEL	CC	21	57.7
RABIGH	SEC	MAKKAH	1991	CRUDE	DIESEL	CC	21	57.7
RABIGH	SEC	MAKKAH	1991	CRUDE	DIESEL	CC	21	57.7
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2010	CRUDE	DIESEL	GT	2	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60
RABIGH	SEC	MAKKAH	2009	CRUDE	DIESEL	GT	3	60

PP name	**Provider**	**Area**	**Year of commission**	**Fuel**	**Alternative fuel**	**Unit type**	**Age**	Capacity (MW)
RABIGH	SEC	MAKKAH	1997	CRUDE	DIESEL	CC	15	61.63
RABIGH	SEC	MAKKAH	1997	CRUDE	DIESEL	CC	15	61.63
RABIGH	SEC	MAKKAH	1997	CRUDE	DIESEL	CC	15	61.63
RABIGH	SEC	MAKKAH	1998	CRUDE	DIESEL	CC	14	61.63
JEDDAH NO.3	SEC	MAKKAH	2004	CRUDE	DIESEL	GT	8	61.81
JEDDAH NO.3	SEC	MAKKAH	2005	CRUDE	DIESEL	GT	7	61.81
JEDDAH NO.3	SEC	MAKKAH	2005	CRUDE	DIESEL	GT	7	61.81
JEDDAH NO.3	SEC	MAKKAH	2005	CRUDE	DIESEL	GT	7	61.81
JEDDAH NO.3	SEC	MAKKAH	2005	CRUDE	DIESEL	GT	7	61.81
JEDDAH NO.3	SEC	MAKKAH	2005	CRUDE	DIESEL	GT	7	61.81
JEDDAH NO.3	SEC	MAKKAH	2005	CRUDE	DIESEL	GT	7	61.81
JEDDAH NO.3	SEC	MAKKAH	2005	CRUDE	DIESEL	GT	7	61.81
RABIGH	SEC	MAKKAH	1994	CRUDE	DIESEL	CC	18	133.43
RABIGH	SEC	MAKKAH	1994	CRUDE	DIESEL	CC	18	133.43
RABIGH	SEC	MAKKAH	1998	CRUDE	DIESEL	CC	14	145.46
RABIGH	SEC	MAKKAH	1985	HFO	CRUDE	ST	27	260
RABIGH	SEC	MAKKAH	1985	HFO	CRUDE	ST	27	260
RABIGH	SEC	MAKKAH	1985	HFO	CRUDE	ST	27	260
RABIGH	SEC	MAKKAH	1985	HFO	CRUDE	ST	27	260
RABIGH	SEC	MAKKAH	1995	HFO	CRUDE	ST	17	266
RABIGH	SEC	MAKKAH	1996	HFO	CRUDE	ST	16	266
SHA'IBA (SEC)	SEC	MAKKAH	2001	HFO	CRUDE	ST	11	393
SHA'IBA (SEC)	SEC	MAKKAH	2002	HFO	CRUDE	ST	10	393
SHA'IBA (SEC)	SEC	MAKKAH	2002	HFO	CRUDE	ST	10	393
SHA'IBA (SEC)	SEC	MAKKAH	2003	HFO	CRUDE	ST	9	393
SHA'IBA (SEC)	SEC	MAKKAH	2003	HFO	CRUDE	ST	9	393
SHA'IBA (SEC)	SEC	MAKKAH	2011	CRUDE	HFO	ST	1	397
SHA'IBA (SEC)	SEC	MAKKAH	2011	CRUDE	HFO	ST	1	397
SHA'IBA (SEC)	SEC	MAKKAH	2011	CRUDE	HFO	ST	1	397
SHA'IBA (SEC)	SEC	MAKKAH	2007	HFO	CRUDE	ST	5	397
SHA'IBA (SEC)	SEC	MAKKAH	2007	HFO	CRUDE	ST	5	397
SHA'IBA (SEC)	SEC	MAKKAH	2007	HFO	CRUDE	ST	5	397
SHA'IBA (SEC)	SEC	MAKKAH	2006	HFO	CRUDE	ST	6	397
SHA'IBA (SEC)	SEC	MAKKAH	2006	HFO	CRUDE	ST	6	397
SHA'IBA (SEC)	SEC	MAKKAH	2006	HFO	CRUDE	ST	6	397
SHAROURA	SEC	NAJRAN	1988	DIESEL	No Fuel	DG	24	4.2
SHAROURA	SEC	NAJRAN	1988	DIESEL	No Fuel	DG	24	4.2
SHAROURA	SEC	NAJRAN	1988	DIESEL	No Fuel	DG	24	4.2
SHAROURA	SEC	NAJRAN	1988	DIESEL	No Fuel	DG	24	4.2
SHAROURA	SEC	NAJRAN	1988	DIESEL	No Fuel	DG	24	4.2
SHAROURA	SEC	NAJRAN	1988	DIESEL	No Fuel	DG	24	4.2
SHAROURA	SEC	NAJRAN	2000	DIESEL	No Fuel	DG	12	10
SHAROURA	SEC	NAJRAN	2000	DIESEL	No Fuel	DG	12	10

PP name	**Provider**	**Area**	**Year of commission**	**Fuel**	**Alternative fuel**	**Unit type**	**Age**	Capacity (MW)
SHAROURA	SEC	NAJRAN	2000	DIESEL	No Fuel	DG	12	10
SHAROURA	SEC	NAJRAN	2007	DIESEL	No Fuel	DG	5	10
SHAROURA	SEC	NAJRAN	2007	DIESEL	No Fuel	DG	5	10
SHAROURA	SEC	NAJRAN	2009	DIESEL	No Fuel	GT	3	17
SHAROURA	SEC	NAJRAN	2009	DIESEL	No Fuel	GT	3	17
SHAROURA	SEC	NAJRAN	2009	DIESEL	No Fuel	GT	3	17
NAJRAN	SEC	NAJRAN	1985	CRUDE	DIESEL	GT	27	22.5
NAJRAN	SEC	NAJRAN	1985	CRUDE	DIESEL	GT	27	22.5
NAJRAN	SEC	NAJRAN	1985	CRUDE	DIESEL	GT	27	22.5
NAJRAN	SEC	NAJRAN	1985	CRUDE	DIESEL	GT	27	22.5
NAJRAN	SEC	NAJRAN	1985	CRUDE	DIESEL	GT	27	22.5
NAJRAN	SEC	NAJRAN	2006	CRUDE	DIESEL	GT	6	51.5
NAJRAN	SEC	NAJRAN	1998	CRUDE	DIESEL	GT	14	51.5
NAJRAN	SEC	NAJRAN	2001	CRUDE	DIESEL	GT	11	51.5
NAJRAN	SEC	NAJRAN	2002	CRUDE	DIESEL	GT	10	51.5
NAJRAN	SEC	NAJRAN	2008	CRUDE	DIESEL	GT	4	51.5
RAFHA	SEC	NORTHERN BORDER	1998	DIESEL	No Fuel	DG	14	2.3
RAFHA	SEC	NORTHERN BORDER	1998	DIESEL	No Fuel	DG	14	2.3
RAFHA	SEC	NORTHERN BORDER	1998	DIESEL	No Fuel	DG	14	2.6
RAFHA	SEC	NORTHERN BORDER	1994	DIESEL	No Fuel	DG	18	4.6
RAFHA	SEC	NORTHERN BORDER	1994	DIESEL	No Fuel	DG	18	4.6
RAFHA	SEC	NORTHERN BORDER	1994	DIESEL	No Fuel	DG	18	4.6
RAFHA	SEC	NORTHERN BORDER	1994	DIESEL	No Fuel	DG	18	4.6
ARAR	SEC	NORTHERN BORDER	1985	DIESEL	No Fuel	GT	27	21
ARAR	SEC	NORTHERN BORDER	1985	DIESEL	No Fuel	GT	27	21
ARAR	SEC	NORTHERN BORDER	1985	DIESEL	No Fuel	GT	27	21
ARAR	SEC	NORTHERN BORDER	1996	DIESEL	No Fuel	GT	16	21
ARAR	SEC	NORTHERN BORDER	1996	DIESEL	No Fuel	GT	16	21
ARAR	SEC	NORTHERN BORDER	2001	DIESEL	No Fuel	GT	11	21
RAFHA	SEC	NORTHERN BORDER	2006	DIESEL	No Fuel	GT	6	29
RAFHA	SEC	NORTHERN BORDER	2006	DIESEL	No Fuel	GT	6	29
ARAR	SEC	NORTHERN BORDER	2006	DIESEL	No Fuel	GT	6	60.1
ARAR	SEC	NORTHERN BORDER	2006	DIESEL	No Fuel	GT	6	60.1
RAFHA	SEC	NORTHERN BORDER	2012	DIESEL	No Fuel	GT	0	69
RAFHA	SEC	NORTHERN BORDER	2012	DIESEL	No Fuel	GT	0	69
BURAIDAH	SEC	QASSIM	1977	DIESEL	No Fuel	GT	35	20.9

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
BURAIDAH	SEC	QASSIM	1977	DIESEL	No Fuel	GT	35	20.9
BURAIDAH	SEC	QASSIM	1977	DIESEL	No Fuel	GT	35	20.9
BURAIDAH	SEC	QASSIM	1981	DIESEL	No Fuel	GT	31	20.9
BURAIDAH	SEC	QASSIM	1982	DIESEL	No Fuel	GT	30	20.9
QASSIM CENTRAL	SEC	QASSIM	2010	CRUDE	DIESEL	GT	2	55.9
QASSIM CENTRAL	SEC	QASSIM	2010	CRUDE	DIESEL	GT	2	55.9
QASSIM CENTRAL	SEC	QASSIM	2010	CRUDE	DIESEL	GT	2	55.9
QASSIM CENTRAL	SEC	QASSIM	2010	CRUDE	DIESEL	GT	2	55.9
QASSIM CENTRAL	SEC	QASSIM	1999	CRUDE	DIESEL	GT	13	57.07
QASSIM CENTRAL	SEC	QASSIM	1999	CRUDE	DIESEL	GT	13	57.07
QASSIM CENTRAL	SEC	QASSIM	1999	CRUDE	DIESEL	GT	13	57.07
QASSIM CENTRAL	SEC	QASSIM	1999	CRUDE	DIESEL	GT	13	57.07
QASSIM CENTRAL	SEC	QASSIM	1999	CRUDE	DIESEL	GT	13	57.07
QASSIM CENTRAL	SEC	QASSIM	1999	CRUDE	DIESEL	GT	13	57.07
QASSIM CENTRAL	SEC	QASSIM	2012	CRUDE	DIESEL	GT	0	59
QASSIM CENTRAL	SEC	QASSIM	2012	CRUDE	DIESEL	GT	0	59
QASSIM CENTRAL	SEC	QASSIM	2012	CRUDE	DIESEL	GT	0	59
QASSIM CENTRAL	SEC	QASSIM	2012	CRUDE	DIESEL	GT	0	59
QASSIM CENTRAL	SEC	QASSIM	2012	CRUDE	DIESEL	GT	0	59
QASSIM CENTRAL	SEC	QASSIM	2012	CRUDE	DIESEL	GT	0	59
QASSIM CENTRAL	SEC	QASSIM	2012	CRUDE	DIESEL	GT	0	59
QASSIM CENTRAL	SEC	QASSIM	2012	CRUDE	DIESEL	GT	0	59
QASSIM CENTRAL	SEC	QASSIM	1982	CRUDE	DIESEL	GT	30	63.56
QASSIM CENTRAL	SEC	QASSIM	1983	CRUDE	DIESEL	GT	29	63.56
QASSIM CENTRAL	SEC	QASSIM	1982	CRUDE	DIESEL	GT	30	63.56
QASSIM CENTRAL	SEC	QASSIM	1983	CRUDE	DIESEL	GT	29	63.56
QASSIM CENTRAL	SEC	QASSIM	1983	CRUDE	DIESEL	GT	29	63.56
QASSIM CENTRAL	SEC	QASSIM	1983	CRUDE	DIESEL	GT	29	63.56
QASSIM CENTRAL	SEC	QASSIM	1983	CRUDE	DIESEL	GT	29	63.56
QASSIM CENTRAL	SEC	QASSIM	1983	CRUDE	DIESEL	GT	29	63.56
QASSIM CENTRAL	SEC	QASSIM	1983	CRUDE	DIESEL	GT	29	63.56
PP3	SEC	RIYADH	1969	DIESEL	No Fuel	GT	Expired, out of service	10

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
PP3	SEC	RIYADH	1970	DIESEL	No Fuel	GT	Expired, out of service	10
PP3	SEC	RIYADH	1972	DIESEL	No Fuel	GT	Expired, out of service	10
PP4	SEC	RIYADH	1977	DIESEL	No Fuel	GT	35	15.15
PP4	SEC	RIYADH	1977	DIESEL	No Fuel	GT	35	15.15
JUBA	SEC	RIYADH	2002	DIESEL	No Fuel	GT	10	16.54
JUBA	SEC	RIYADH	2002	DIESEL	No Fuel	GT	10	16.54
LAYLA	SEC	RIYADH	1987	DIESEL	No Fuel	GT	25	17
LAYLA	SEC	RIYADH	1987	DIESEL	No Fuel	GT	25	17
LAYLA	SEC	RIYADH	1987	DIESEL	No Fuel	GT	25	17
LAYLA	SEC	RIYADH	1987	DIESEL	No Fuel	GT	25	17
LAYLA	SEC	RIYADH	1987	DIESEL	No Fuel	GT	25	17
LAYLA	SEC	RIYADH	1987	DIESEL	No Fuel	GT	25	17
PP4	SEC	RIYADH	1975	DIESEL	No Fuel	GT	37	24.75
PP4	SEC	RIYADH	1975	DIESEL	No Fuel	GT	37	24.75
PP4	SEC	RIYADH	1975	DIESEL	No Fuel	GT	37	24.75
PP4	SEC	RIYADH	1975	DIESEL	No Fuel	GT	37	24.75
JUBA	SEC	RIYADH	1988	CRUDE	DIESEL	GT	24	25.05
JUBA	SEC	RIYADH	1988	CRUDE	DIESEL	GT	24	25.05
JUBA	SEC	RIYADH	1988	CRUDE	DIESEL	GT	24	25.05
JUBA	SEC	RIYADH	1988	CRUDE	DIESEL	GT	24	25.05
JUBA	SEC	RIYADH	1988	CRUDE	DIESEL	GT	24	25.05
JUBA	SEC	RIYADH	1988	CRUDE	DIESEL	GT	24	25.05
JUBA	SEC	RIYADH	1988	CRUDE	DIESEL	GT	24	25.05
PP4	SEC	RIYADH	1977	DIESEL	No Fuel	GT	35	41.43
PP4	SEC	RIYADH	1977	DIESEL	No Fuel	GT	35	41.43
PP4	SEC	RIYADH	1978	DIESEL	No Fuel	GT	34	41.43
PP4	SEC	RIYADH	1977	DIESEL	No Fuel	GT	35	41.43
PP4	SEC	RIYADH	1977	DIESEL	No Fuel	GT	35	41.43
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1983	CRUDE	DIESEL	GT	29	50
PP8	SEC	RIYADH	1984	CRUDE	DIESEL	GT	28	50

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
PP8	SEC	RIYADH	1984	CRUDE	DIESEL	GT	28	50
PP8	SEC	RIYADH	1984	CRUDE	DIESEL	GT	28	50
PP8	SEC	RIYADH	1986	CRUDE	DIESEL	GT	26	50
PP8	SEC	RIYADH	1986	CRUDE	DIESEL	GT	26	50
PP8	SEC	RIYADH	1985	CRUDE	DIESEL	GT	27	50
PP8	SEC	RIYADH	1985	CRUDE	DIESEL	GT	27	50
PP5	SEC	RIYADH	1982	CRUDE	DIESEL	GT	30	50
PP5	SEC	RIYADH	1982	CRUDE	DIESEL	GT	30	50
PP7	SEC	RIYADH	1981	GAS	DIESEL	GT	31	50
PP7	SEC	RIYADH	1981	GAS	DIESEL	GT	31	50
PP7	SEC	RIYADH	1981	GAS	DIESEL	GT	31	50
PP7	SEC	RIYADH	1981	GAS	DIESEL	GT	31	50
PP7	SEC	RIYADH	1981	GAS	DIESEL	GT	31	50
PP7	SEC	RIYADH	1981	GAS	DIESEL	GT	31	50
PP7	SEC	RIYADH	1981	GAS	DIESEL	GT	31	50
PP7	SEC	RIYADH	1981	GAS	DIESEL	GT	31	50
PP7	SEC	RIYADH	1980	GAS	DIESEL	GT	32	50
PP7	SEC	RIYADH	1980	GAS	DIESEL	GT	32	50
PP7	SEC	RIYADH	1980	GAS	DIESEL	GT	32	50
PP7	SEC	RIYADH	1980	GAS	DIESEL	GT	32	50
PP7	SEC	RIYADH	1980	GAS	DIESEL	GT	32	50
PP7	SEC	RIYADH	1980	GAS	DIESEL	GT	32	50
PP7	SEC	RIYADH	1980	GAS	DIESEL	GT	32	50
PP7	SEC	RIYADH	1980	GAS	DIESEL	GT	32	50
PP5	SEC	RIYADH	1979	CRUDE	DIESEL	GT	33	50.8
PP5	SEC	RIYADH	1979	CRUDE	DIESEL	GT	33	50.8
PP5	SEC	RIYADH	1979	CRUDE	DIESEL	GT	33	50.8
PP5	SEC	RIYADH	1979	CRUDE	DIESEL	GT	33	50.8
PP5	SEC	RIYADH	1979	CRUDE	DIESEL	GT	33	50.8
PP5	SEC	RIYADH	1979	CRUDE	DIESEL	GT	33	50.8
PP5	SEC	RIYADH	1979	CRUDE	DIESEL	GT	33	50.8
PP5	SEC	RIYADH	1979	CRUDE	DIESEL	GT	33	50.8
PP5	SEC	RIYADH	1980	CRUDE	DIESEL	GT	32	50.8
PP5	SEC	RIYADH	1980	CRUDE	DIESEL	GT	32	50.8
JUBA	SEC	RIYADH	2009	CRUDE	DIESEL	GT	3	55
JUBA	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	CC	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2008	CRUDE	DIESEL	GT	4	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	GT	5	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	GT	5	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	CC	5	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	CC	5	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	CC	5	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	CC	5	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	CC	5	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	CC	5	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	CC	5	55.5
PP9	SEC	RIYADH	2007	CRUDE	DIESEL	CC	5	55.5
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2011	CRUDE	DIESEL	GT	1	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP10	SEC	RIYADH	2010	CRUDE	DIESEL	GT	2	55.9
PP7	SEC	RIYADH	1994	GAS	DIESEL	GT	18	57.62
PP7	SEC	RIYADH	1994	GAS	DIESEL	GT	18	57.62
PP7	SEC	RIYADH	1994	GAS	DIESEL	GT	18	57.62
PP7	SEC	RIYADH	1994	GAS	DIESEL	GT	18	57.62
PP7	SEC	RIYADH	1994	GAS	DIESEL	GT	18	57.62
PP7	SEC	RIYADH	1994	GAS	DIESEL	GT	18	57.62
PP8	SEC	RIYADH	1996	GAS	DIESEL	GT	16	58.05
PP8	SEC	RIYADH	1996	GAS	DIESEL	GT	16	58.05
PP8	SEC	RIYADH	1996	GAS	DIESEL	GT	16	58.05
PP8	SEC	RIYADH	1996	GAS	DIESEL	GT	16	58.05
PP8	SEC	RIYADH	1995	GAS	DIESEL	GT	17	58.05
PP8	SEC	RIYADH	1995	GAS	DIESEL	GT	17	58.05
PP8	SEC	RIYADH	1995	GAS	DIESEL	GT	17	58.05
PP8	SEC	RIYADH	1995	GAS	DIESEL	GT	17	58.05
PP8	SEC	RIYADH	1995	GAS	DIESEL	GT	17	58.05
PP8	SEC	RIYADH	1995	GAS	DIESEL	GT	17	58.05
PP9	SEC	RIYADH	1998	GAS	DIESEL	CC	14	58.14
PP9	SEC	RIYADH	1998	GAS	DIESEL	CC	14	58.14
PP9	SEC	RIYADH	1998	GAS	DIESEL	CC	14	58.14
PP9	SEC	RIYADH	1998	GAS	DIESEL	CC	14	58.14
PP9	SEC	RIYADH	1997	GAS	DIESEL	CC	15	58.14
PP9	SEC	RIYADH	1997	GAS	DIESEL	CC	15	58.14
PP9	SEC	RIYADH	1997	GAS	DIESEL	CC	15	58.14
PP9	SEC	RIYADH	1997	GAS	DIESEL	CC	15	58.14
PP9	SEC	RIYADH	2000	GAS	DIESEL	CC	12	58.14
PP9	SEC	RIYADH	2000	GAS	DIESEL	CC	12	58.14
PP9	SEC	RIYADH	2000	GAS	DIESEL	CC	12	58.14
PP9	SEC	RIYADH	2000	GAS	DIESEL	CC	12	58.14
PP9	SEC	RIYADH	1999	GAS	DIESEL	CC	13	58.14

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
PP9	SEC	RIYADH	1999	GAS	DIESEL	CC	13	58.14
PP9	SEC	RIYADH	1999	GAS	DIESEL	CC	13	58.14
PP9	SEC	RIYADH	1999	GAS	DIESEL	CC	13	58.14
PP10	SEC	RIYADH	2012	CRUDE	DIESEL	GT	0	59
PP10	SEC	RIYADH	2012	CRUDE	DIESEL	GT	0	59
PP10	SEC	RIYADH	2012	CRUDE	DIESEL	GT	0	59
PP10	SEC	RIYADH	2012	CRUDE	DIESEL	GT	0	59
PP10	SEC	RIYADH	2012	CRUDE	DIESEL	GT	0	59
PP10	SEC	RIYADH	2012	CRUDE	DIESEL	GT	0	59
PP10	SEC	RIYADH	2012	CRUDE	DIESEL	GT	0	59
PP10	SEC	RIYADH	2012	CRUDE	DIESEL	GT	0	59
PP9	SEC	RIYADH	2004	GAS	DIESEL	GT	8	60
PP9	SEC	RIYADH	2004	GAS	DIESEL	GT	8	60
PP9	SEC	RIYADH	2004	GAS	DIESEL	GT	8	60
PP9	SEC	RIYADH	2004	GAS	DIESEL	GT	8	60
PP9	SEC	RIYADH	2004	GAS	DIESEL	GT	8	60
PP9	SEC	RIYADH	2004	GAS	DIESEL	GT	8	60
PP9	SEC	RIYADH	2004	GAS	DIESEL	GT	8	60
PP9	SEC	RIYADH	2004	GAS	DIESEL	GT	8	60
PP7	SEC	RIYADH	2005	GAS	DIESEL	GT	7	85
PP7	SEC	RIYADH	2005	GAS	DIESEL	GT	7	85
PP9	SEC	RIYADH	1999	GAS	DIESEL	CC	13	107.55
PP9	SEC	RIYADH	1998	GAS	DIESEL	CC	14	107.55
PP9	SEC	RIYADH	2000	GAS	DIESEL	CC	12	107.55
PP9	SEC	RIYADH	2000	GAS	DIESEL	CC	12	107.55
PP8	SEC	RIYADH	2009	GAS	DIESEL	GT	3	122.72
PP8	SEC	RIYADH	2009	GAS	DIESEL	GT	3	122.72
PP8	SEC	RIYADH	2009	GAS	DIESEL	GT	3	122.72
PP8	SEC	RIYADH	2009	GAS	DIESEL	GT	3	122.72
AL WAJH	SEC	TABUK	1985	DIESEL	No Fuel	DG	27	2.5
AL WAJH	SEC	TABUK	1985	DIESEL	No Fuel	DG	27	2.5
AL WAJH	SEC	TABUK	1985	DIESEL	No Fuel	DG	27	2.5
AL WAJH	SEC	TABUK	1985	DIESEL	No Fuel	DG	27	2.5
AL WAJH	SEC	TABUK	1977	DIESEL	No Fuel	DG	35	2.5
AL WAJH	SEC	TABUK	1977	DIESEL	No Fuel	DG	35	2.5
AL WAJH	SEC	TABUK	1985	DIESEL	No Fuel	DG	27	2.5
AL WAJH	SEC	TABUK	1985	DIESEL	No Fuel	DG	27	2.5
AL WAJH	SEC	TABUK	1993	DIESEL	No Fuel	DG	19	5
AL WAJH	SEC	TABUK	1993	DIESEL	No Fuel	DG	19	5
TABUK-1	SEC	TABUK	1978	DIESEL	No Fuel	DG	34	5.7
TABUK-1	SEC	TABUK	1978	DIESEL	No Fuel	DG	34	5.7
TABUK-1	SEC	TABUK	1978	DIESEL	No Fuel	DG	34	5.7
TABUK-1	SEC	TABUK	1978	DIESEL	No Fuel	DG	34	5.7

PP name	Provider	Area	Year of commission	Fuel	Alternative fuel	Unit type	Age	Capacity (MW)
TABUK-1	SEC	TABUK	1978	DIESEL	No Fuel	DG	34	5.7
TABUK-1	SEC	TABUK	1978	DIESEL	No Fuel	DG	34	5.7
AL WAJH	SEC	TABUK	2009	DIESEL	No Fuel	GT	3	16
TABUK-1	SEC	TABUK	1982	DIESEL	No Fuel	GT	30	16.8
TABUK-1	SEC	TABUK	1982	DIESEL	No Fuel	GT	30	16.8
TABUK-1	SEC	TABUK	1980	DIESEL	No Fuel	GT	32	17.1
TABUK-1	SEC	TABUK	1981	DIESEL	No Fuel	GT	31	17.1
DUBA	SEC	TABUK	2011	DIESEL	No Fuel	GT	1	18
DUBA	SEC	TABUK	2011	DIESEL	No Fuel	GT	1	18
DUBA	SEC	TABUK	1999	DIESEL	No Fuel	GT	13	18
DUBA	SEC	TABUK	1999	DIESEL	No Fuel	GT	13	18
DUBA	SEC	TABUK	2000	DIESEL	No Fuel	GT	12	18
DUBA	SEC	TABUK	2010	DIESEL	No Fuel	GT	2	18
DUBA	SEC	TABUK	1989	DIESEL	No Fuel	GT	23	18
DUBA	SEC	TABUK	1989	DIESEL	No Fuel	GT	23	18
DUBA	SEC	TABUK	1989	DIESEL	No Fuel	GT	23	18
AL WAJH	SEC	TABUK	2002	DIESEL	No Fuel	GT	10	18.3
AL WAJH	SEC	TABUK	2002	DIESEL	No Fuel	GT	10	18.4
TABUK-2	SEC	TABUK	1985	DIESEL	No Fuel	GT	27	27
TABUK-2	SEC	TABUK	1985	DIESEL	No Fuel	GT	27	27
TABUK-2	SEC	TABUK	1990	DIESEL	No Fuel	GT	22	31.2
TABUK-2	SEC	TABUK	1996	DIESEL	No Fuel	GT	16	57.7
TABUK-2	SEC	TABUK	1996	DIESEL	No Fuel	GT	16	57.7
TABUK-2	SEC	TABUK	1999	DIESEL	No Fuel	GT	13	60.1
TABUK-2	SEC	TABUK	2012	DIESEL	No Fuel	GT	0	61
TABUK-2	SEC	TABUK	2012	DIESEL	No Fuel	GT	0	61
TABUK-2	SEC	TABUK	2004	DIESEL	No Fuel	GT	8	61
TABUK-2	SEC	TABUK	2005	DIESEL	No Fuel	GT	7	61
TABUK-2	SEC	TABUK	2008	DIESEL	No Fuel	GT	4	65.5
TABUK-2	SEC	TABUK	2008	DIESEL	No Fuel	GT	4	65.5
TABUK-2	SEC	TABUK	2008	DIESEL	No Fuel	GT	4	65.5
TABUK-2	SEC	TABUK	2011	DIESEL	No Fuel	GT	1	78
TABUK-2	SEC	TABUK	2011	DIESEL	No Fuel	GT	1	78

Appendix B

Fuel	Location	Turbine Type	Age	P.P. Name	HR (Btu/kWh)	Gross Generation (MWh)	Contribution	Efficiency	Load Factor	Nominal Capacity GW
Gas	Eastern	GT	38	SAFANIYAH	18,762	6,739	0.00%	18.19%	2%	44.30
Diesel	Northern	GT	33	Tabuk - 1	14,702	19,600	0.01%	23.21%	3%	102.00
Gas	Eastern	GT	38	Uthmaniyah	18,907	100,228	0.05%	18.05%	5%	256.60
Gas	Eastern	GT	35	Berri	16,012	166,319	0.09%	21.31%	11%	209.40
Diesel	Southern	GT	31	ALBAHA	13,218	60,514	0.03%	25.81%	12%	66.50
Diesel	Western	GT	33	Taif	16,404	106,459	0.06%	20.80%	12%	115.85
Diesel	Central	GT	33	Buriedah	18,657	124,100	0.07%	18.29%	16%	104.50
Diesel	Western	GT	36	Madienah -1	18,022	21,761	0.01%	18.93%	16%	18.10
Gas/D	Eastern	GT	28	Dammam	18,972	440,417	0.23%	17.98%	17%	345.70
Diesel	Eastern	GT	30	Qaiesomah	20,539	186,585	0.10%	16.61%	17%	143.80
Crude/D	Western	GT	2	Rabigh-GT	11,204	2,897,265	1.53%	30.45%	23%	1,680.00
Diesel	Southern	GT	14	SHAROURAH	13,758	225,322	0.12%	24.80%	24%	126.20
Diesel	Western	GT	29	Yanbu	15,230	111,401	0.06%	22.40%	27%	54.59
Crude/D	Central	GT	2	PP10	11,502	3,804,065	2.00%	29.66%	28%	1,788.80
Gas	Eastern	GT	31	Shedgum	15,937	2,380,914	1.25%	21.41%	29%	1,108.80
Diesel	Northern	GT	23	Al Wajh	17,751	239,406	0.13%	19.22%	39%	82.70
Diesel	Northern	GT	12	Duba	15,902	485,257	0.26%	21.46%	40%	162.00
Gas	Eastern	GT	23	Faras	12,088	3,994,813	2.11%	28.23%	40%	1,329.80
Crude/D	Central	GT	22	Qassim	13,063	3,562,555	1.88%	26.12%	42%	1,138.06
Diesel	Northern	GT	23	TABARGEL	15,271	237,337	0.13%	22.34%	44%	71.80
Diesel	Central	GT	36	PP4	13,775	1,123,874	0.59%	24.77%	45%	336.45
Crude/D	Central	GT	18	Hail - 2	13,056	1,753,204	0.92%	26.13%	45%	521.85
Crude/D	Central	GT	32	PP5	14,230	2,093,177	1.10%	23.98%	46%	608.00
Diesel	Western	GT	26	Jeddah No.3	13,732	6,313,340	3.33%	24.85%	47%	1,808.08
Gas	Eastern	ST	22	Qurayaah-ST	8,965	16,109,600	8.49%	38.06%	49%	4,405.00
Diesel	Northern	GT	14	Rafha	13,458	319,919	0.17%	25.35%	51%	83.60
Diesel	Western	GT	27	Madienah -2	12,862	1,097,551	0.58%	26.53%	52%	284.00
C&G/D	Central	GT	22	PP8	11,523	8,043,021	4.24%	29.61%	52%	2,071.38
Diesel	Western	GT	34	Makkah	12,880	3,251,294	1.71%	26.49%	53%	821.86
Crude/D	Central	GT	18	GUBA	15,197	1,259,821	0.66%	22.45%	53%	318.43
Diesel	Southern	GT	24	Assir	11,756	2,589,681	1.36%	29.02%	53%	649.50
Diesel	Southern	GT	16	JAZAN	12,041	5,566,690	2.93%	28.34%	55%	1,339.00
Gas/D	Eastern	CC	3	Qurayah-CC	11,443	8,010,560	4.22%	29.82%	56%	1,905.00
Diesel	Northern	GT	12	Tabuk-2	11,147	3,107,501	1.64%	30.61%	56%	735.20
Crude/D	Western	CC	18	Rabigh-CC	10,071	4,841,234	2.55%	33.88%	58%	1,120.44
Diesel	Southern	GT	14	TIHAMA	12,249	3,147,314	1.66%	27.86%	58%	722.00
Crude	Northern	GT	17	AL -Jouf	13,655	1,294,742	0.68%	24.99%	60%	288.00
Diesel	Northern	GT	16	Qurayat	17,487	428,567	0.23%	19.51%	63%	90.90
Diesel	Central	GT	25	LAYLA	14,703	487,664	0.26%	23.21%	64%	102.00
Crude/D	Central	CC	9	PP9-CC	7,547	11,605,579	6.12%	45.21%	66%	2,359.44
Diesel	Northern	GT	17	ARAR	13,230	1,231,238	0.65%	25.79%	67%	246.20
HFO/crude	Western	ST	6	Shaiba-ST	8,992	28,451,783	14.99%	37.94%	69%	5,538.00
Crude/D	Southern	GT	18	NAJRAN	12,490	2,103,823	1.11%	27.32%	76%	370.00
Diesel	Southern	GT	19	BISHA	11,853	1,992,580	1.05%	28.79%	76%	349.00
Gas/D	Central	GT	26	PP7	11,063	7,567,258	3.99%	30.84%	77%	1,315.72
HFO/crude	Western	ST	24	Rabigh-ST	8,934	9,654,490	5.09%	38.19%	82%	1,572.00
Gas	Eastern	ST	21	Ghazlan-ST	9,334	27,860,841	14.68%	36.55%	85%	4,376.00
Crude&Gas	Central	GT	6	PP9-GT	10,967	9,299,417	4.90%	31.11%	99%	1,257.00
						189,776,820				

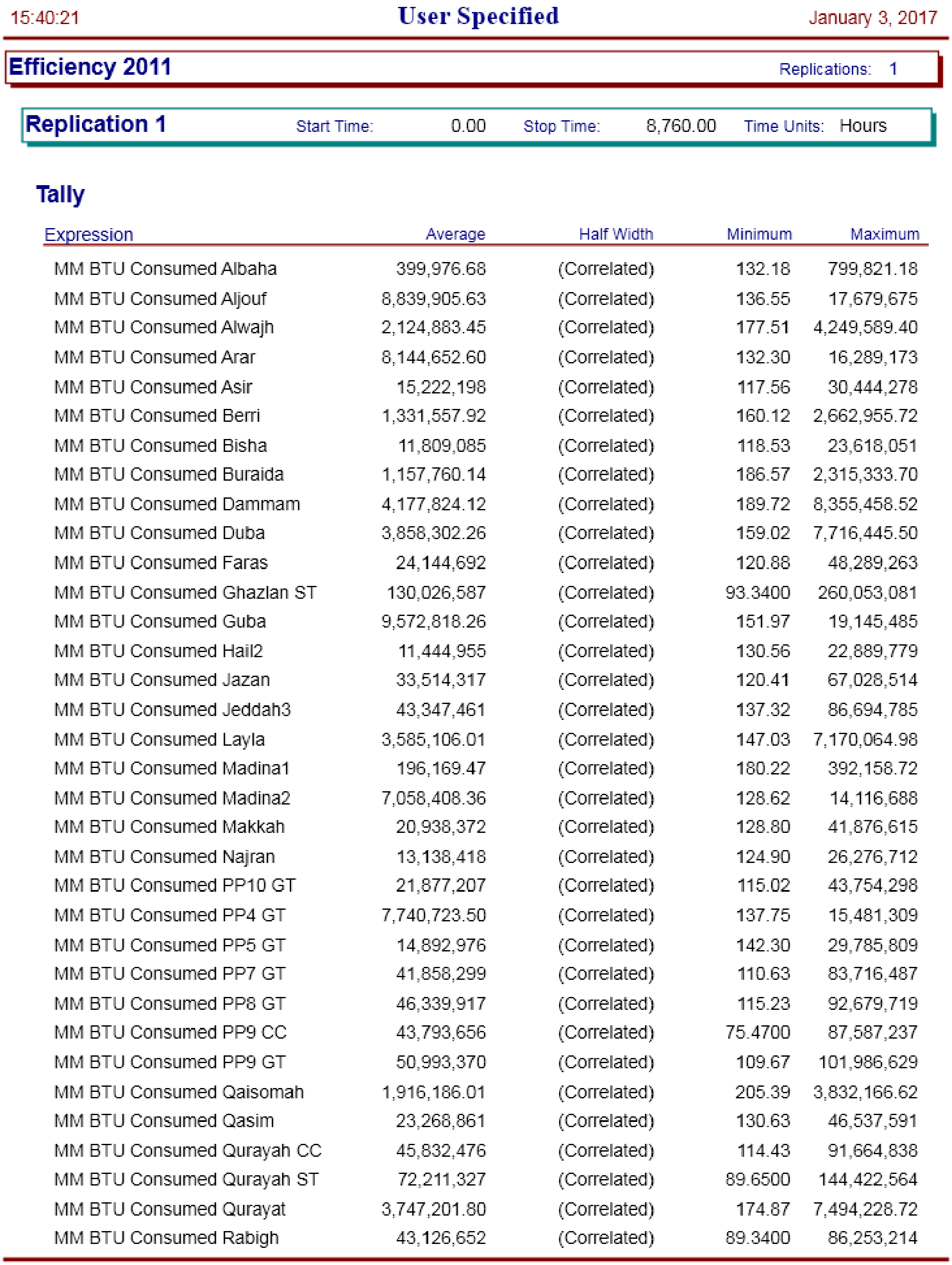
Appendix C

Power plant Name	Gross Generation (MWh)	HR (Btu/kWh)	Efficiency	Contribution	Nominal Capacity MW	Load Factor	Merit order	Indicators	S7 Simulated
PP9-CC	11,605,579	7,547	45.21%	6.12%	2,359.44	66%	5	81%	99%
Rabigh-ST	9,654,490	8,934	38.19%	5.09%	1,572.00	82%	2	83%	84%
Qurayaah-ST	16,109,600	8,965	38.06%	8.49%	2,500.00	86%	4	85%	83%
Shaiba-ST	28,451,783	8,992	37.94%	14.99%	5,538.00	69%	1	75%	83%
Ghazlan-ST	27,860,841	9,334	36.55%	14.68%	4,376.00	85%	3	83%	80%
Rabigh-CC	4,841,234	10,071	33.88%	2.55%	1,120.44	58%	10	65%	74%
PP9-GT	9,299,417	10,967	31.11%	4.90%	1,257.00	99%	6	85%	68%
PP7	7,567,258	11,063	30.84%	3.99%	1,315.72	77%	11	73%	68%
Tabuk-2	3,107,501	11,147	30.61%	1.64%	735.20	56%	38	61%	67%
Rabigh-GT	2,897,265	11,204	30.45%	1.53%	1,680.00	23%	16	43%	66%
Qurayah-CC	8,010,560	11,443	29.82%	4.22%	1,905.00	56%	7	60%	65%
PP10	3,804,065	11,502	29.66%	2.00%	1,788.80	28%	8	45%	65%
PP8	8,043,021	11,523	29.61%	4.24%	2,071.38	52%	9	58%	61%
Assir	2,589,681	11,756	29.02%	1.36%	649.50	53%	12	58%	29%
BISHA	1,992,580	11,853	28.79%	1.05%	349.00	76%	25	70%	29%
JAZAN	5,566,690	12,041	28.34%	2.93%	1,339.00	55%	13	58%	28%
Faras	3,994,813	12,088	28.23%	2.11%	1,329.80	40%	14	50%	28%
TIHAMA	3,147,314	12,249	27.86%	1.66%	722.00	58%	20	59%	28%
NAJRAN	2,103,823	12,490	27.32%	1.11%	370.00	76%	24	69%	27%
Madienah -2	1,097,551	12,862	26.53%	0.58%	284.00	52%	15	55%	27%
Makkah	3,251,294	12,880	26.49%	1.71%	821.86	53%	17	55%	26%
Hail - 2	1,753,204	13,056	26.13%	0.92%	521.85	45%	27	50%	26%
Qassim	3,562,555	13,063	26.12%	1.88%	1,138.06	42%	29	49%	26%
ALBAHA	60,514	13,218	25.81%	0.03%	66.50	12%	33	32%	26%
ARAR	1,231,238	13,230	25.79%	0.65%	246.20	67%	39	62%	26%
Rafha	319,919	13,458	25.35%	0.17%	83.60	51%	40	53%	25%
AL -Jouf	1,294,742	13,655	24.99%	0.68%	288.00	60%	41	58%	25%
Jeddah No.3	6,313,340	13,732	24.85%	3.33%	1,808.08	47%	19	50%	25%
SHAROURAH	225,322	13,758	24.80%	0.12%	126.20	24%	42	38%	25%
PP4	1,123,874	13,775	24.77%	0.59%	336.45	45%	18	49%	25%
PP5	2,093,177	14,230	23.98%	1.10%	608.00	46%	28	49%	24%
Tabuk - 1	19,600	14,702	23.21%	0.01%	102.00	3%	43	25%	23%
LAYLA	487,664	14,703	23.21%	0.26%	102.00	64%	23	58%	23%
GUBA	1,259,821	15,197	22.45%	0.66%	318.43	53%	44	51%	22%
Yanbu	111,401	15,230	22.40%	0.06%	54.59	27%	22	37%	22%
TABARGEL	237,337	15,271	22.34%	0.13%	71.80	44%	45	46%	22%
Duba	485,257	15,902	21.46%	0.26%	162.00	40%	46	43%	21%
Shedgum	2,380,914	15,937	21.41%	1.25%	1,108.80	29%	21	37%	21%
Berri	166,319	16,012	21.31%	0.09%	209.40	11%	34	27%	21%
Taif	106,459	16,404	20.80%	0.06%	115.85	12%	31	27%	21%
Qurayat	428,567	17,487	19.51%	0.23%	90.90	63%	32	54%	20%

Power plant Name	Gross Generation (MWh)	HR (Btu/kWh)	Efficiency	Contribution	Nominal Capacity MW	Load Factor	Merit order	Indicators	S7 Simulated
Al Wajh	239,406	17,751	19.22%	0.13%	82.70	39%	47	40%	19%
Madienah -1	21,761	18,022	18.93%	0.01%	18.10	16%	30	28%	19%
Buriedah	124,100	18,657	18.29%	0.07%	104.50	16%	48	27%	18%
SAFANIYAH	6,739	18,762	18.19%	0.00%	44.30	2%	37	19%	18%
Uthmaniyah	100,228	18,907	18.05%	0.05%	258.60	5%	35	21%	18%
Dammam	440,417	18,972	17.98%	0.23%	345.70	17%	26	27%	18%
Qaiesomah	186,585	20,539	16.61%	0.10%	143.80	17%	36	26%	17%

Appendix D

Stage 1



15:40:21 **User Specified** January 3, 2017

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Tally

Expression	Average	Half Width	Minimum	Maximum
MM BTU Consumed Albaha	399,976.68	(Correlated)	132.18	799,821.18
MM BTU Consumed Aljouf	8,839,905.63	(Correlated)	136.55	17,679,675
MM BTU Consumed Alwajh	2,124,883.45	(Correlated)	177.51	4,249,589.40
MM BTU Consumed Arar	8,144,652.60	(Correlated)	132.30	16,289,173
MM BTU Consumed Asir	15,222,198	(Correlated)	117.56	30,444,278
MM BTU Consumed Berri	1,331,557.92	(Correlated)	160.12	2,662,955.72
MM BTU Consumed Bisha	11,809,085	(Correlated)	118.53	23,618,051
MM BTU Consumed Buraida	1,157,760.14	(Correlated)	186.57	2,315,333.70
MM BTU Consumed Dammam	4,177,824.12	(Correlated)	189.72	8,355,458.52
MM BTU Consumed Duba	3,858,302.26	(Correlated)	159.02	7,716,445.50
MM BTU Consumed Faras	24,144,692	(Correlated)	120.88	48,289,263
MM BTU Consumed Ghazlan ST	130,026,587	(Correlated)	93.3400	260,053,081
MM BTU Consumed Guba	9,572,818.26	(Correlated)	151.97	19,145,485
MM BTU Consumed Hail2	11,444,955	(Correlated)	130.56	22,889,779
MM BTU Consumed Jazan	33,514,317	(Correlated)	120.41	67,028,514
MM BTU Consumed Jeddah3	43,347,461	(Correlated)	137.32	86,694,785
MM BTU Consumed Layla	3,585,106.01	(Correlated)	147.03	7,170,064.98
MM BTU Consumed Madina1	196,169.47	(Correlated)	180.22	392,158.72
MM BTU Consumed Madina2	7,058,408.36	(Correlated)	128.62	14,116,688
MM BTU Consumed Makkah	20,938,372	(Correlated)	128.80	41,876,615
MM BTU Consumed Najran	13,138,418	(Correlated)	124.90	26,276,712
MM BTU Consumed PP10 GT	21,877,207	(Correlated)	115.02	43,754,298
MM BTU Consumed PP4 GT	7,740,723.50	(Correlated)	137.75	15,481,309
MM BTU Consumed PP5 GT	14,892,976	(Correlated)	142.30	29,785,809
MM BTU Consumed PP7 GT	41,858,299	(Correlated)	110.63	83,716,487
MM BTU Consumed PP8 GT	46,339,917	(Correlated)	115.23	92,679,719
MM BTU Consumed PP9 CC	43,793,656	(Correlated)	75.4700	87,587,237
MM BTU Consumed PP9 GT	50,993,370	(Correlated)	109.67	101,986,629
MM BTU Consumed Qaisomah	1,916,186.01	(Correlated)	205.39	3,832,166.62
MM BTU Consumed Qasim	23,268,861	(Correlated)	130.63	46,537,591
MM BTU Consumed Qurayah CC	45,832,476	(Correlated)	114.43	91,664,838
MM BTU Consumed Qurayah ST	72,211,327	(Correlated)	89.6500	144,422,564
MM BTU Consumed Qurayat	3,747,201.80	(Correlated)	174.87	7,494,228.72
MM BTU Consumed Rabigh	43,126,652	(Correlated)	89.3400	86,253,214

15:40:21 **User Specified** January 3, 2017

Efficiency 2011

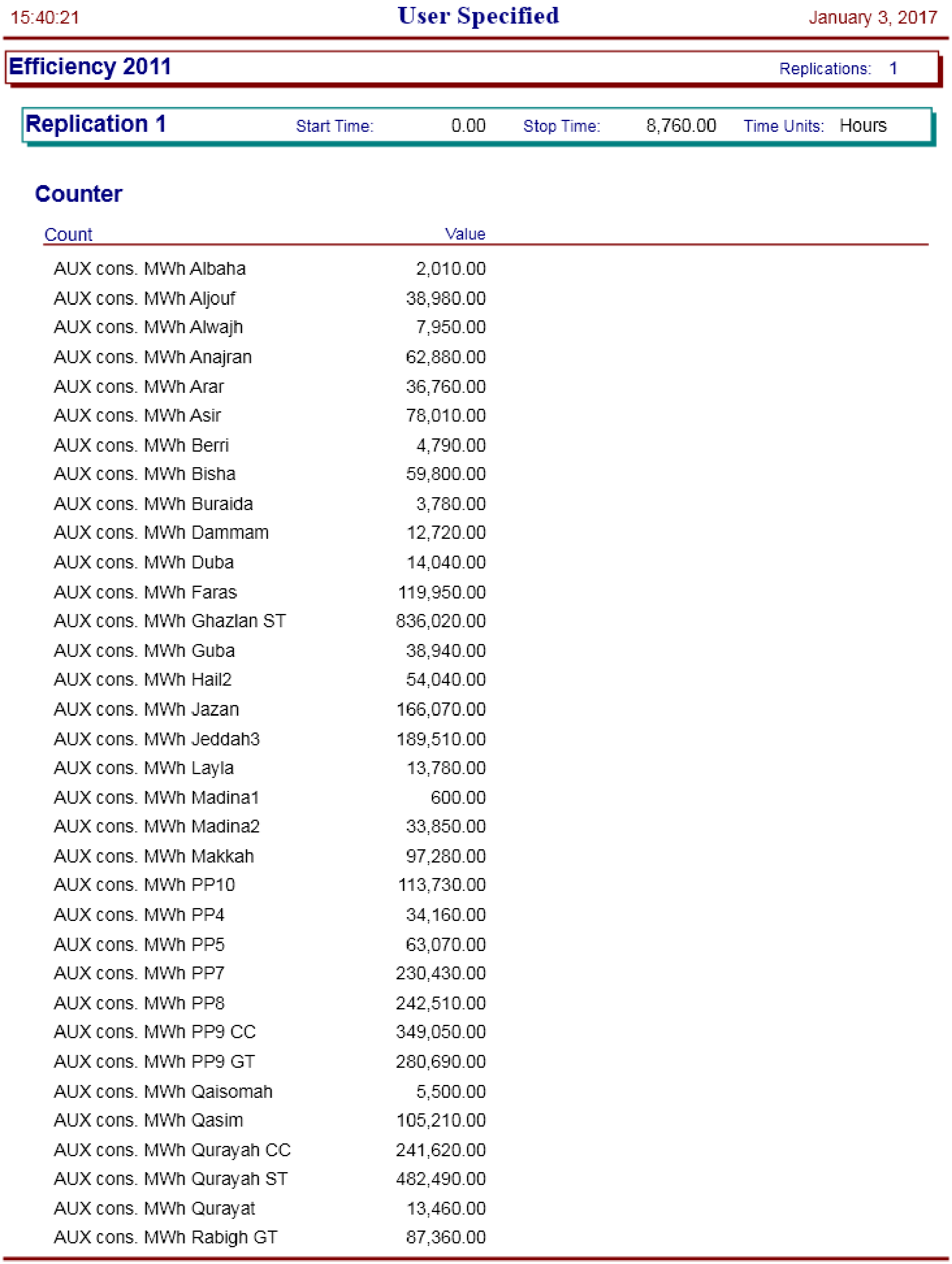
Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Tally

MM BTU Consumed Rabigh CC	24,378,064	(Correlated)	100.71	48,756,027
MM BTU Consumed Rabigh GT	16,230,507	(Correlated)	112.04	32,460,901
MM BTU Consumed Rafha	2,152,741.68	(Correlated)	134.58	4,305,348.78
MM BTU Consumed Safaniyah	63,227.94	(Correlated)	187.62	126,268.26
MM BTU Consumed Shaiba ST	127,919,248	(Correlated)	89.9200	255,838,406
MM BTU Consumed Sharorah	1,550,045.07	(Correlated)	137.58	3,099,952.56
MM BTU Consumed Shedgum	18,972,361	(Correlated)	159.37	37,944,563
MM BTU Consumed Tabargel	1,812,209.57	(Correlated)	152.71	3,624,266.43
MM BTU Consumed Tabuk1	144,153.11	(Correlated)	147.02	288,159.20
MM BTU Consumed Tabuk2	17,319,707	(Correlated)	111.47	34,639,303
MM BTU Consumed Taif	873,184.92	(Correlated)	164.04	1,746,205.80
MM BTU Consumed Tihama	19,275,761	(Correlated)	122.49	38,551,400
MM BTU Consumed Uthmaniah	947,524.31	(Correlated)	189.07	1,894,859.54
MM BTU Consumed Yanbu	848,387.15	(Correlated)	152.30	1,696,622.00



15:40:21 **User Specified** January 3, 2017

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

Count	Value
AUX cons. MWh Albaha	2,010.00
AUX cons. MWh Aljouf	38,980.00
AUX cons. MWh Alwajh	7,950.00
AUX cons. MWh Anajran	62,880.00
AUX cons. MWh Arar	36,760.00
AUX cons. MWh Asir	78,010.00
AUX cons. MWh Berri	4,790.00
AUX cons. MWh Bisha	59,800.00
AUX cons. MWh Buraida	3,780.00
AUX cons. MWh Dammam	12,720.00
AUX cons. MWh Duba	14,040.00
AUX cons. MWh Faras	119,950.00
AUX cons. MWh Ghazlan ST	836,020.00
AUX cons. MWh Guba	38,940.00
AUX cons. MWh Hail2	54,040.00
AUX cons. MWh Jazan	166,070.00
AUX cons. MWh Jeddah3	189,510.00
AUX cons. MWh Layla	13,780.00
AUX cons. MWh Madina1	600.00
AUX cons. MWh Madina2	33,850.00
AUX cons. MWh Makkah	97,280.00
AUX cons. MWh PP10	113,730.00
AUX cons. MWh PP4	34,160.00
AUX cons. MWh PP5	63,070.00
AUX cons. MWh PP7	230,430.00
AUX cons. MWh PP8	242,510.00
AUX cons. MWh PP9 CC	349,050.00
AUX cons. MWh PP9 GT	280,690.00
AUX cons. MWh Qaisomah	5,500.00
AUX cons. MWh Qasim	105,210.00
AUX cons. MWh Qurayah CC	241,620.00
AUX cons. MWh Qurayah ST	482,490.00
AUX cons. MWh Qurayat	13,460.00
AUX cons. MWh Rabigh GT	87,360.00

15:40:21 **User Specified** January 3, 2017

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

AUX cons. MWh Rabigh ST	290,370.00
AUX cons. MWh RabighCC	143,800.00
AUX cons. MWh Rafha	9,590.00
AUX cons. MWh Safaniah	190.00
AUX cons. MWh Shaiba ST	849,920.00
AUX cons. MWh Sharorah	6,700.00
AUX cons. MWh Shedgum	71,080.00
AUX cons. MWh Tabargel	7,130.00
AUX cons. MWh Tabuk1	710.00
AUX cons. MWh Tabuk2	93,030.00
AUX cons. MWh Taif	3,110.00
AUX cons. MWh Tihama	93,990.00
AUX cons. MWh Uthmaniah	2,840.00
AUX cons. MWh Yanbu	3,490.00
Fuel Injected 1	28,451,780
Fuel Injected 10	8,010,560.00
Fuel Injected 11	428,560.00
Fuel Injected 12	2,897,260.00
Fuel Injected 13	7,567,250.00
Fuel Injected 14	3,107,500.00
Fuel Injected 15	3,804,060.00
Fuel Injected 16	8,043,020.00
Fuel Injected 17	2,589,680.00
Fuel Injected 18	1,992,580.00
Fuel Injected 19	5,566,690.00
Fuel Injected 2	9,654,490.00
Fuel Injected 20	440,410.00
Fuel Injected 21	3,994,810.00
Fuel Injected 22	1,259,820.00
Fuel Injected 23	1,753,200.00
Fuel Injected 24	6,313,340.00
Fuel Injected 25	487,660.00
Fuel Injected 26	21,760.00
Fuel Injected 27	1,097,550.00
Fuel Injected 28	3,251,290.00

Efficiency 2011

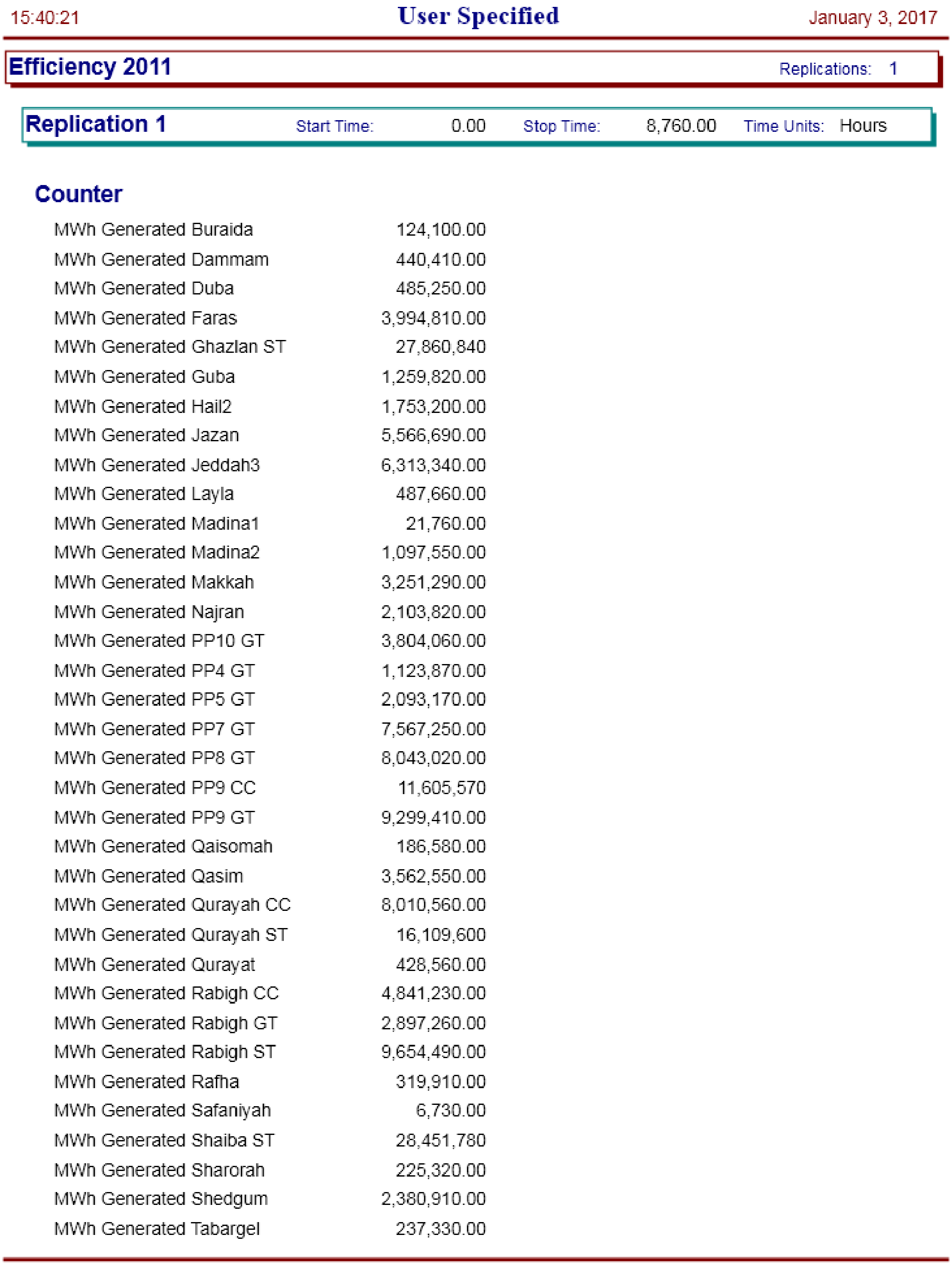
Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

Fuel Injected 29	2,103,820.00
Fuel Injected 3	4,841,230.00
Fuel Injected 30	1,123,870.00
Fuel Injected 31	2,093,170.00
Fuel Injected 32	319,910.00
Fuel Injected 33	6,730.00
Fuel Injected 34	225,320.00
Fuel Injected 35	2,380,910.00
Fuel Injected 36	237,330.00
Fuel Injected 37	19,600.00
Fuel Injected 38	106,450.00
Fuel Injected 39	3,147,310.00
Fuel Injected 4	27,860,840
Fuel Injected 40	100,220.00
Fuel Injected 41	111,400.00
Fuel Injected 42	60,510.00
Fuel Injected 43	1,231,230.00
Fuel Injected 44	1,294,740.00
Fuel Injected 45	485,250.00
Fuel Injected 46	166,310.00
Fuel Injected 47	239,400.00
Fuel Injected 48	124,100.00
Fuel Injected 5	16,109,600
Fuel Injected 6	11,605,570
Fuel Injected 7	9,299,410.00
Fuel Injected 8	3,562,550.00
Fuel Injected 9	186,580.00
Gwh Delivered to consumers	165,671.00
MWh Generated Albaha	60,510.00
MWh Generated Aljouf	1,294,740.00
MWh Generated Alwajh	239,400.00
MWh Generated Arar	1,231,230.00
MWh Generated Asir	2,589,680.00
MWh Generated Berri	166,310.00
MWh Generated Bisha	1,992,580.00



15:40:21 **User Specified** January 3, 2017

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

MWh Generated Buraida	124,100.00
MWh Generated Dammam	440,410.00
MWh Generated Duba	485,250.00
MWh Generated Faras	3,994,810.00
MWh Generated Ghazlan ST	27,860,840
MWh Generated Guba	1,259,820.00
MWh Generated Hail2	1,753,200.00
MWh Generated Jazan	5,566,690.00
MWh Generated Jeddah3	6,313,340.00
MWh Generated Layla	487,660.00
MWh Generated Madina1	21,760.00
MWh Generated Madina2	1,097,550.00
MWh Generated Makkah	3,251,290.00
MWh Generated Najran	2,103,820.00
MWh Generated PP10 GT	3,804,060.00
MWh Generated PP4 GT	1,123,870.00
MWh Generated PP5 GT	2,093,170.00
MWh Generated PP7 GT	7,567,250.00
MWh Generated PP8 GT	8,043,020.00
MWh Generated PP9 CC	11,605,570
MWh Generated PP9 GT	9,299,410.00
MWh Generated Qaisomah	186,580.00
MWh Generated Qasim	3,562,550.00
MWh Generated Qurayah CC	8,010,560.00
MWh Generated Qurayah ST	16,109,600
MWh Generated Qurayat	428,560.00
MWh Generated Rabigh CC	4,841,230.00
MWh Generated Rabigh GT	2,897,260.00
MWh Generated Rabigh ST	9,654,490.00
MWh Generated Rafha	319,910.00
MWh Generated Safaniyah	6,730.00
MWh Generated Shaiba ST	28,451,780
MWh Generated Sharorah	225,320.00
MWh Generated Shedgum	2,380,910.00
MWh Generated Tabargel	237,330.00

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15:40:21                         User Specified                         January 3, 2017

Efficiency 2011                                                      Replications:   1

  Replication 1          Start Time:        0.00    Stop Time:      8,760.00    Time Units:   Hours

   Counter

     MWh Generated Tabuk1                   19,600.00
     MWh Generated Tabuk2                3,107,500.00
     MWh Generated Taif                    106,450.00
     MWh Generated Tihama                3,147,310.00
     MWh Generated Uthmaniah               100,220.00
     MWh Generated Yanbu                   111,400.00
     Tand D. Losses MWh                    18,407,950
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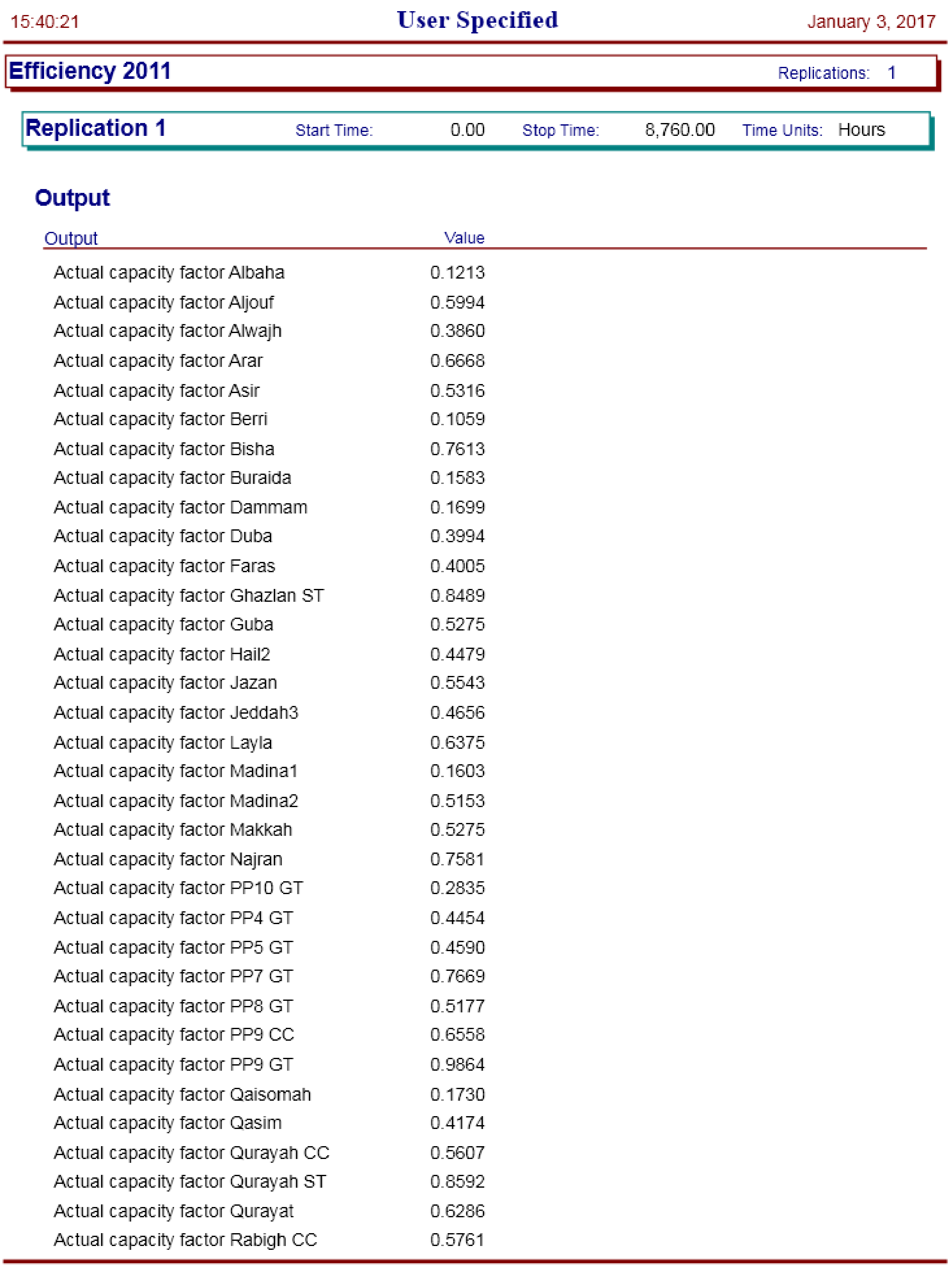


15:40:21 **User Specified** January 3, 2017

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Output	Value
Actual capacity factor Albaha	0.1213
Actual capacity factor Aljouf	0.5994
Actual capacity factor Alwajh	0.3860
Actual capacity factor Arar	0.6668
Actual capacity factor Asir	0.5316
Actual capacity factor Berri	0.1059
Actual capacity factor Bisha	0.7613
Actual capacity factor Buraida	0.1583
Actual capacity factor Dammam	0.1699
Actual capacity factor Duba	0.3994
Actual capacity factor Faras	0.4005
Actual capacity factor Ghazlan ST	0.8489
Actual capacity factor Guba	0.5275
Actual capacity factor Hail2	0.4479
Actual capacity factor Jazan	0.5543
Actual capacity factor Jeddah3	0.4656
Actual capacity factor Layla	0.6375
Actual capacity factor Madina1	0.1603
Actual capacity factor Madina2	0.5153
Actual capacity factor Makkah	0.5275
Actual capacity factor Najran	0.7581
Actual capacity factor PP10 GT	0.2835
Actual capacity factor PP4 GT	0.4454
Actual capacity factor PP5 GT	0.4590
Actual capacity factor PP7 GT	0.7669
Actual capacity factor PP8 GT	0.5177
Actual capacity factor PP9 CC	0.6558
Actual capacity factor PP9 GT	0.9864
Actual capacity factor Qaisomah	0.1730
Actual capacity factor Qasim	0.4174
Actual capacity factor Qurayah CC	0.5607
Actual capacity factor Qurayah ST	0.8592
Actual capacity factor Qurayat	0.6286
Actual capacity factor Rabigh CC	0.5761

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Actual capacity factor Rabigh GT	0.2299
Actual capacity factor Rabigh ST	0.8189
Actual capacity factor Rafha	0.5102
Actual capacity factor Safaniah	0.02025583
Actual capacity factor Shaiba ST	0.6850
Actual capacity factor Sharorah	0.2381
Actual capacity factor Shedgum	0.2863
Actual capacity factor Tabargel	0.4407
Actual capacity factor Tabuk1	0.02562092
Actual capacity factor Tabuk2	0.5636
Actual capacity factor Taif	0.1225
Actual capacity factor Tihama	0.5812
Actual capacity factor Uthmaniah	0.05167311
Actual capacity factor Yanbu	0.2721
CO2 kg per kwh Average	0.7888
CO2 kg per kwh Shaiba ST	0.6703
Efficiency Albaha	0.2581
Efficiency Aljouf	0.2499
Efficiency Alwajh	0.1922
Efficiency Arar	0.2579
Efficiency Asir	0.2902
Efficiency Berri	0.2131
Efficiency Bisha	0.2879
Efficiency Buraida	0.1829
Efficiency Dammam	0.1798
Efficiency Duba	0.2146
Efficiency Faras	0.2823
Efficiency Ghazlan ST	0.3655
Efficiency Guba	0.2245
Efficiency Hail2	0.2613
Efficiency Jazan	0.2834
Efficiency Jeddah3	0.2485
Efficiency Layla	0.2321
Efficiency Madina1	0.1893
Efficiency Madina2	0.2653

15:40:21 **User Specified** January 3, 2017

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Efficiency Makkah	0.2649
Efficiency Najran	0.2732
Efficiency PP10 GT	0.2966
Efficiency PP4 GT	0.2477
Efficiency PP5 GT	0.2398
Efficiency PP7 GT	0.3084
Efficiency PP8 GT	0.2961
Efficiency PP9 CC	0.4521
Efficiency PP9 GT	0.3111
Efficiency Qaisomah	0.1661
Efficiency Qasim	0.2612
Efficiency Qurayah CC	0.2982
Efficiency Qurayah ST	0.3806
Efficiency Qurayat	0.1951
Efficiency Rabigh CC	0.3388
Efficiency Rabigh GT	0.3045
Efficiency Rabigh ST	0.3819
Efficiency Rafha	0.2535
Efficiency Safaniyah	0.1819
Efficiency Shaiba ST	0.3794
Efficiency Sharorah	0.2480
Efficiency Shedgum	0.2141
Efficiency Tabargel	0.2234
Efficiency Tabuk1	0.2321
Efficiency Tabuk2	0.3061
Efficiency Taif	0.2080
Efficiency Tihama	0.2786
Efficiency Uthmaniah	0.1805
Efficiency Yanbu	0.2240
Fuel Consumed B.BTU Total	2,008,232.30
Fuel cost M.USD Int. price	31,750.15
Fuel cost M.USD Local price	1,425.84
Fuel subsidies M USD	30,324.31
Generation Efficiency	0.3224
Heat Rate Albaha	13,218.00

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Heat Rate Aljouf	13,655.00
Heat Rate Alwajh	17,751.00
Heat Rate Arar	13,230.00
Heat Rate Asir	11,756.00
Heat Rate Berri	16,012.00
Heat Rate Bisha	11,853.00
Heat Rate Buraida	18,657.00
Heat Rate Dammam	18,972.00
Heat Rate Duba	15,902.00
Heat Rate Faras	12,088.00
Heat Rate Generation	10,582.08
Heat Rate Ghazlan ST	9,334.00
Heat Rate Guba	15,197.00
Heat Rate Hail2	13,056.00
Heat Rate Jazan	12,041.00
Heat Rate Jeddah3	13,732.00
Heat Rate Layla	14,703.00
Heat Rate Madina1	18,022.00
Heat Rate Madina2	12,862.00
Heat Rate Makkah	12,880.00
Heat Rate Najran	12,490.00
Heat Rate PP10 GT	11,502.00
Heat Rate PP4	13,775.00
Heat Rate PP5	14,230.00
Heat Rate PP7 GT	11,063.00
Heat Rate PP8 GT	11,523.00
Heat Rate PP9 CC	7,547.00
Heat Rate PP9 GT	10,967.00
Heat Rate Qaisomah	20,539.00
Heat Rate Qasim	13,063.00
Heat Rate Qurayah CC	11,443.00
Heat Rate Qurayah ST	8,965.00
Heat Rate Qurayat	17,487.00
Heat Rate Rabigh CC	10,071.00
Heat Rate Rabigh GT	11,204.00

Efficiency 2011

Replications: 1

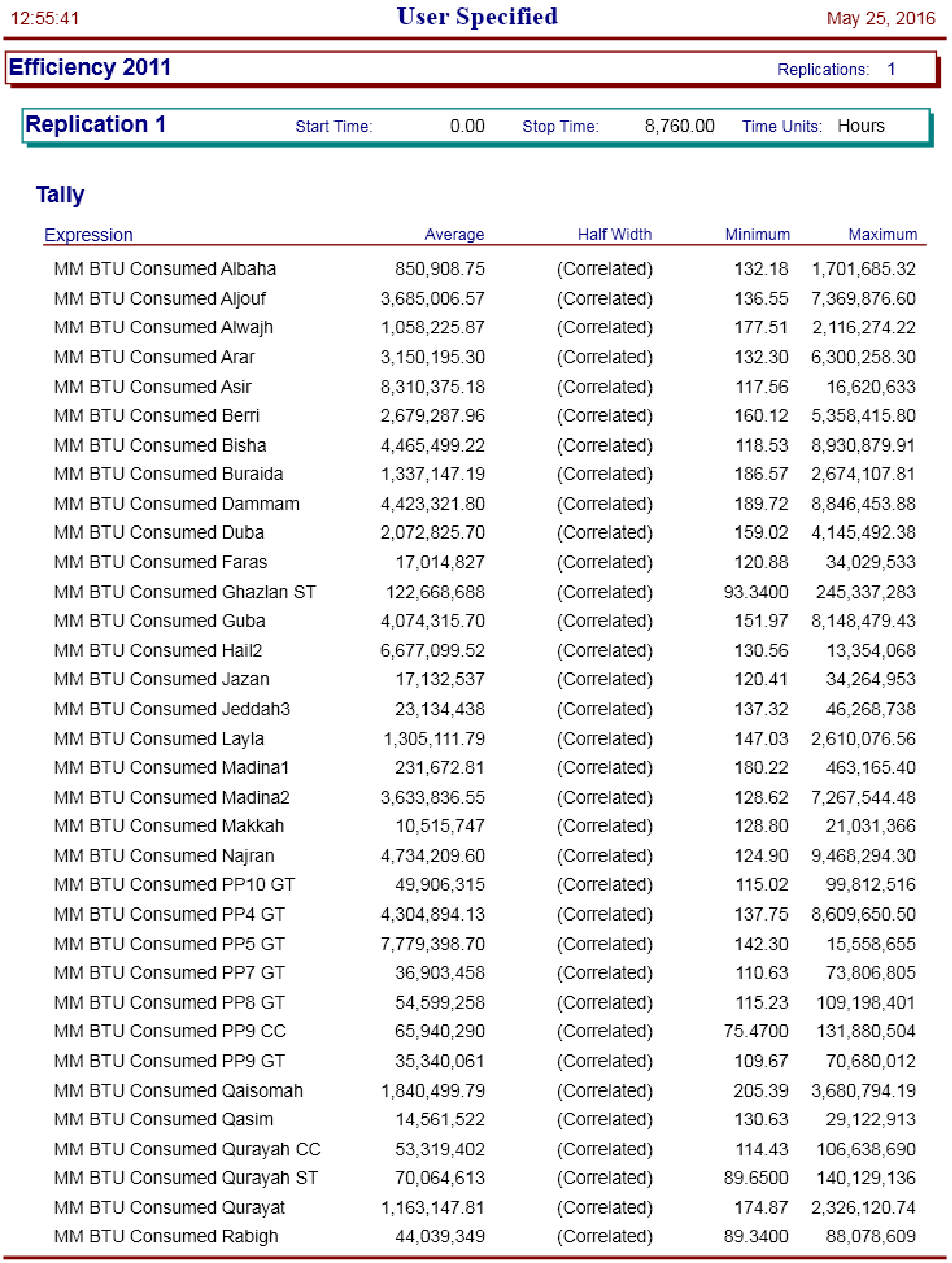
Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Heat Rate Rabigh ST	8,934.00
Heat Rate Rafha	13,458.00
Heat Rate Safaniyah	18,762.00
Heat Rate Shaiba	8,992.00
Heat Rate Sharorah	13,758.00
Heat Rate Shedgum	15,937.00
Heat Rate Tabargel	15,271.00
Heat Rate Tabuk1	14,702.00
Heat Rate Tabuk2	11,147.00
Heat Rate Taif	16,404.00
Heat Rate Tihama	12,249.00
Heat Rate Uthmaniyah	18,907.00
Heat Rate Yanbu	15,230.00
System Efficiency	0.2815
Total Generation Gwh Gross	189,776.63

Stage 2



12:55:41 **User Specified** May 25, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Tally

Expression	Average	Half Width	Minimum	Maximum
MM BTU Consumed Albaha	850,908.75	(Correlated)	132.18	1,701,685.32
MM BTU Consumed Aljouf	3,685,006.57	(Correlated)	136.55	7,369,876.60
MM BTU Consumed Alwajh	1,058,225.87	(Correlated)	177.51	2,116,274.22
MM BTU Consumed Arar	3,150,195.30	(Correlated)	132.30	6,300,258.30
MM BTU Consumed Asir	8,310,375.18	(Correlated)	117.56	16,620,633
MM BTU Consumed Berri	2,679,287.96	(Correlated)	160.12	5,358,415.80
MM BTU Consumed Bisha	4,465,499.22	(Correlated)	118.53	8,930,879.91
MM BTU Consumed Buraida	1,337,147.19	(Correlated)	186.57	2,674,107.81
MM BTU Consumed Dammam	4,423,321.80	(Correlated)	189.72	8,846,453.88
MM BTU Consumed Duba	2,072,825.70	(Correlated)	159.02	4,145,492.38
MM BTU Consumed Faras	17,014,827	(Correlated)	120.88	34,029,533
MM BTU Consumed Ghazlan ST	122,668,688	(Correlated)	93.3400	245,337,283
MM BTU Consumed Guba	4,074,315.70	(Correlated)	151.97	8,148,479.43
MM BTU Consumed Hail2	6,677,099.52	(Correlated)	130.56	13,354,068
MM BTU Consumed Jazan	17,132,537	(Correlated)	120.41	34,264,953
MM BTU Consumed Jeddah3	23,134,438	(Correlated)	137.32	46,268,738
MM BTU Consumed Layla	1,305,111.79	(Correlated)	147.03	2,610,076.56
MM BTU Consumed Madina1	231,672.81	(Correlated)	180.22	463,165.40
MM BTU Consumed Madina2	3,633,836.55	(Correlated)	128.62	7,267,544.48
MM BTU Consumed Makkah	10,515,747	(Correlated)	128.80	21,031,366
MM BTU Consumed Najran	4,734,209.60	(Correlated)	124.90	9,468,294.30
MM BTU Consumed PP10 GT	49,906,315	(Correlated)	115.02	99,812,516
MM BTU Consumed PP4 GT	4,304,894.13	(Correlated)	137.75	8,609,650.50
MM BTU Consumed PP5 GT	7,779,398.70	(Correlated)	142.30	15,558,655
MM BTU Consumed PP7 GT	36,903,458	(Correlated)	110.63	73,806,805
MM BTU Consumed PP8 GT	54,599,258	(Correlated)	115.23	109,198,401
MM BTU Consumed PP9 CC	65,940,290	(Correlated)	75.4700	131,880,504
MM BTU Consumed PP9 GT	35,340,061	(Correlated)	109.67	70,680,012
MM BTU Consumed Qaisomah	1,840,499.79	(Correlated)	205.39	3,680,794.19
MM BTU Consumed Qasim	14,561,522	(Correlated)	130.63	29,122,913
MM BTU Consumed Qurayah CC	53,319,402	(Correlated)	114.43	106,638,690
MM BTU Consumed Qurayah ST	70,064,613	(Correlated)	89.6500	140,129,136
MM BTU Consumed Qurayat	1,163,147.81	(Correlated)	174.87	2,326,120.74
MM BTU Consumed Rabigh	44,039,349	(Correlated)	89.3400	88,078,609

Efficiency 2011

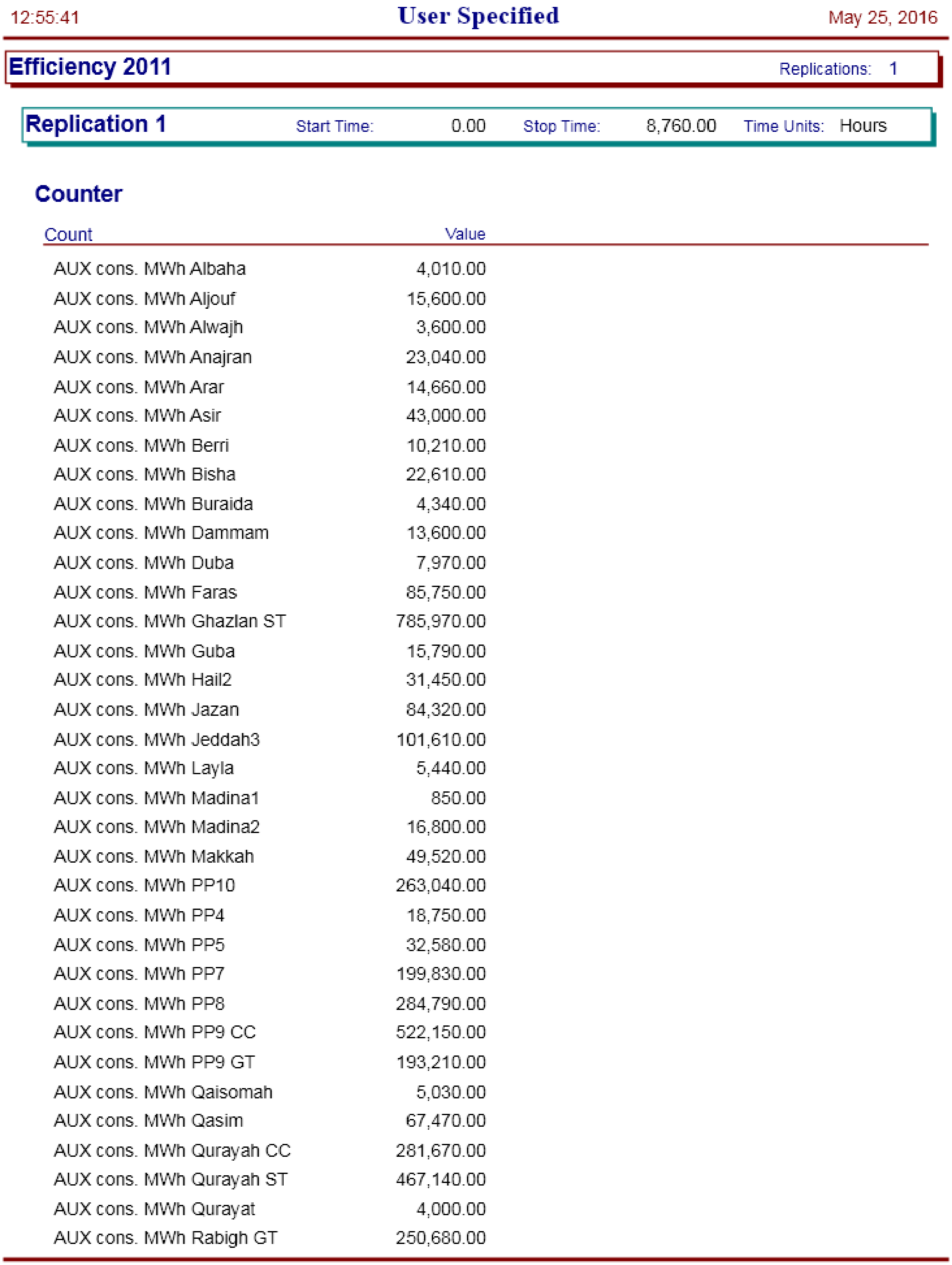
Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Tally

MM BTU Consumed Rabigh CC	31,340,650	(Correlated)	100.71	62,681,199
MM BTU Consumed Rabigh GT	46,838,098	(Correlated)	112.04	93,676,084
MM BTU Consumed Rafha	1,069,709.13	(Correlated)	134.58	2,139,283.68
MM BTU Consumed Safaniyah	566,893.83	(Correlated)	187.62	1,133,600.04
MM BTU Consumed Shaiba ST	154,963,722	(Correlated)	89.9200	309,927,354
MM BTU Consumed Sharorah	1,614,776.46	(Correlated)	137.58	3,229,415.34
MM BTU Consumed Shedgum	14,187,117	(Correlated)	159.37	28,374,075
MM BTU Consumed Tabargel	918,703.36	(Correlated)	152.71	1,837,254.01
MM BTU Consumed Tabuk1	1,305,096.54	(Correlated)	147.02	2,610,046.06
MM BTU Consumed Tabuk2	20,574,854	(Correlated)	111.47	41,149,596
MM BTU Consumed Taif	1,482,347.46	(Correlated)	164.04	2,964,530.88
MM BTU Consumed Tihama	9,238,012.07	(Correlated)	122.49	18,475,902
MM BTU Consumed Uthmaniah	3,308,819.54	(Correlated)	189.07	6,617,450.00
MM BTU Consumed Yanbu	698,523.95	(Correlated)	152.30	1,396,895.60



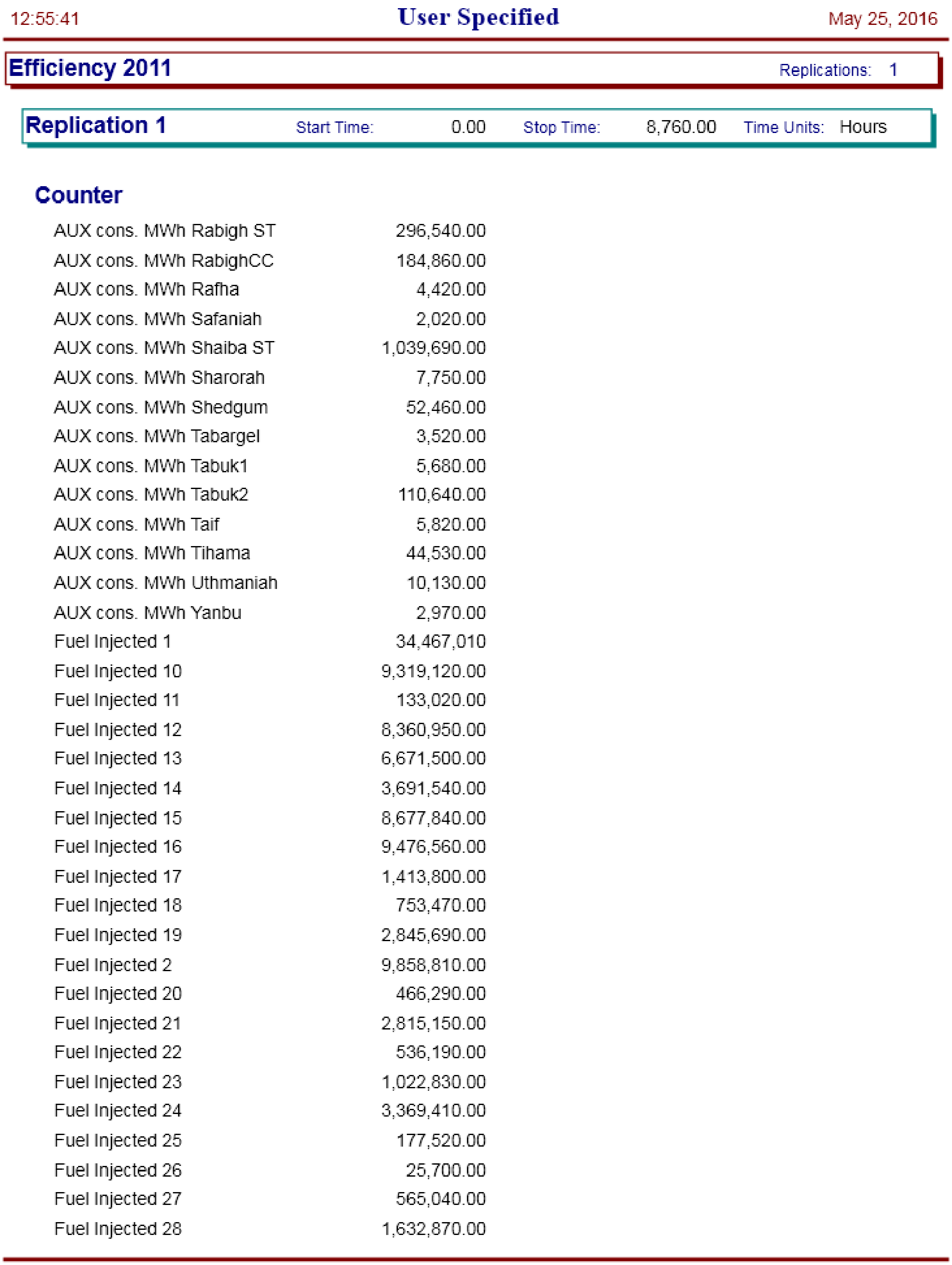
12:55:41 **User Specified** May 25, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

Count	Value
AUX cons. MWh Albaha	4,010.00
AUX cons. MWh Aljouf	15,600.00
AUX cons. MWh Alwajh	3,600.00
AUX cons. MWh Anajran	23,040.00
AUX cons. MWh Arar	14,660.00
AUX cons. MWh Asir	43,000.00
AUX cons. MWh Berri	10,210.00
AUX cons. MWh Bisha	22,610.00
AUX cons. MWh Buraida	4,340.00
AUX cons. MWh Dammam	13,600.00
AUX cons. MWh Duba	7,970.00
AUX cons. MWh Faras	85,750.00
AUX cons. MWh Ghazlan ST	785,970.00
AUX cons. MWh Guba	15,790.00
AUX cons. MWh Hail2	31,450.00
AUX cons. MWh Jazan	84,320.00
AUX cons. MWh Jeddah3	101,610.00
AUX cons. MWh Layla	5,440.00
AUX cons. MWh Madina1	850.00
AUX cons. MWh Madina2	16,800.00
AUX cons. MWh Makkah	49,520.00
AUX cons. MWh PP10	263,040.00
AUX cons. MWh PP4	18,750.00
AUX cons. MWh PP5	32,580.00
AUX cons. MWh PP7	199,830.00
AUX cons. MWh PP8	284,790.00
AUX cons. MWh PP9 CC	522,150.00
AUX cons. MWh PP9 GT	193,210.00
AUX cons. MWh Qaisomah	5,030.00
AUX cons. MWh Qasim	67,470.00
AUX cons. MWh Qurayah CC	281,670.00
AUX cons. MWh Qurayah ST	467,140.00
AUX cons. MWh Qurayat	4,000.00
AUX cons. MWh Rabigh GT	250,680.00



12:55:41 **User Specified** May 25, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

AUX cons. MWh Rabigh ST	296,540.00
AUX cons. MWh RabighCC	184,860.00
AUX cons. MWh Rafha	4,420.00
AUX cons. MWh Safaniah	2,020.00
AUX cons. MWh Shaiba ST	1,039,690.00
AUX cons. MWh Sharorah	7,750.00
AUX cons. MWh Shedgum	52,460.00
AUX cons. MWh Tabargel	3,520.00
AUX cons. MWh Tabuk1	5,680.00
AUX cons. MWh Tabuk2	110,640.00
AUX cons. MWh Taif	5,820.00
AUX cons. MWh Tihama	44,530.00
AUX cons. MWh Uthmaniah	10,130.00
AUX cons. MWh Yanbu	2,970.00
Fuel Injected 1	34,467,010
Fuel Injected 10	9,319,120.00
Fuel Injected 11	133,020.00
Fuel Injected 12	8,360,950.00
Fuel Injected 13	6,671,500.00
Fuel Injected 14	3,691,540.00
Fuel Injected 15	8,677,840.00
Fuel Injected 16	9,476,560.00
Fuel Injected 17	1,413,800.00
Fuel Injected 18	753,470.00
Fuel Injected 19	2,845,690.00
Fuel Injected 2	9,858,810.00
Fuel Injected 20	466,290.00
Fuel Injected 21	2,815,150.00
Fuel Injected 22	536,190.00
Fuel Injected 23	1,022,830.00
Fuel Injected 24	3,369,410.00
Fuel Injected 25	177,520.00
Fuel Injected 26	25,700.00
Fuel Injected 27	565,040.00
Fuel Injected 28	1,632,870.00

Efficiency 2011

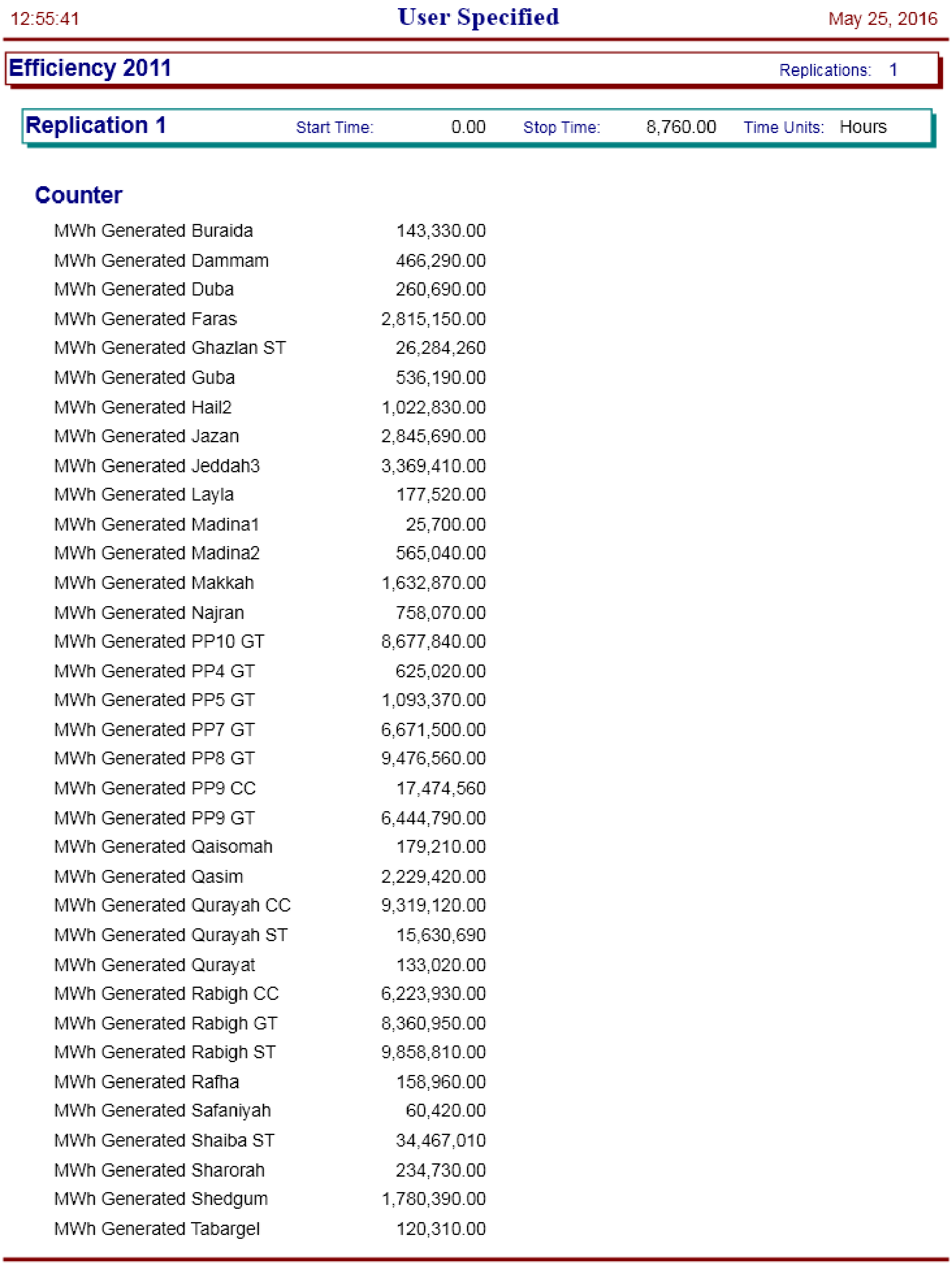
Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

Fuel Injected 29	758,070.00
Fuel Injected 3	6,223,930.00
Fuel Injected 30	625,020.00
Fuel Injected 31	1,093,370.00
Fuel Injected 32	158,960.00
Fuel Injected 33	60,420.00
Fuel Injected 34	234,730.00
Fuel Injected 35	1,780,390.00
Fuel Injected 36	120,310.00
Fuel Injected 37	177,530.00
Fuel Injected 38	180,720.00
Fuel Injected 39	1,508,360.00
Fuel Injected 4	26,284,260
Fuel Injected 40	350,000.00
Fuel Injected 41	91,720.00
Fuel Injected 42	128,740.00
Fuel Injected 43	476,210.00
Fuel Injected 44	539,720.00
Fuel Injected 45	260,690.00
Fuel Injected 46	334,650.00
Fuel Injected 47	119,220.00
Fuel Injected 48	143,330.00
Fuel Injected 5	15,630,690
Fuel Injected 6	17,474,560
Fuel Injected 7	6,444,790.00
Fuel Injected 8	2,229,420.00
Fuel Injected 9	179,210.00
Gwh Delivered to consumers	165,755.00
MWh Generated Albaha	128,740.00
MWh Generated Aljouf	539,720.00
MWh Generated Alwajh	119,220.00
MWh Generated Arar	476,210.00
MWh Generated Asir	1,413,800.00
MWh Generated Berri	334,650.00
MWh Generated Bisha	753,470.00



12:55:41 **User Specified** May 25, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

MWh Generated Buraida	143,330.00
MWh Generated Dammam	466,290.00
MWh Generated Duba	260,690.00
MWh Generated Faras	2,815,150.00
MWh Generated Ghazlan ST	26,284,260
MWh Generated Guba	536,190.00
MWh Generated Hail2	1,022,830.00
MWh Generated Jazan	2,845,690.00
MWh Generated Jeddah3	3,369,410.00
MWh Generated Layla	177,520.00
MWh Generated Madina1	25,700.00
MWh Generated Madina2	565,040.00
MWh Generated Makkah	1,632,870.00
MWh Generated Najran	758,070.00
MWh Generated PP10 GT	8,677,840.00
MWh Generated PP4 GT	625,020.00
MWh Generated PP5 GT	1,093,370.00
MWh Generated PP7 GT	6,671,500.00
MWh Generated PP8 GT	9,476,560.00
MWh Generated PP9 CC	17,474,560
MWh Generated PP9 GT	6,444,790.00
MWh Generated Qaisomah	179,210.00
MWh Generated Qasim	2,229,420.00
MWh Generated Qurayah CC	9,319,120.00
MWh Generated Qurayah ST	15,630,690
MWh Generated Qurayat	133,020.00
MWh Generated Rabigh CC	6,223,930.00
MWh Generated Rabigh GT	8,360,950.00
MWh Generated Rabigh ST	9,858,810.00
MWh Generated Rafha	158,960.00
MWh Generated Safaniyah	60,420.00
MWh Generated Shaiba ST	34,467,010
MWh Generated Sharorah	234,730.00
MWh Generated Shedgum	1,780,390.00
MWh Generated Tabargel	120,310.00

12:55:41 **User Specified** May 25, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

MWh Generated Tabuk1	177,530.00
MWh Generated Tabuk2	3,691,540.00
MWh Generated Taif	180,720.00
MWh Generated Tihama	1,508,360.00
MWh Generated Uthmaniah	350,000.00
MWh Generated Yanbu	91,720.00
Tand D. Losses MWh	18,432,510

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Output	Value
Actual capacity factor Albaha	0.2581
Actual capacity factor Aljouf	0.2499
Actual capacity factor Alwajh	0.1922
Actual capacity factor Arar	0.2579
Actual capacity factor Asir	0.2902
Actual capacity factor Berri	0.2131
Actual capacity factor Bisha	0.2879
Actual capacity factor Buraida	0.1829
Actual capacity factor Dammam	0.1798
Actual capacity factor Duba	0.2146
Actual capacity factor Faras	0.2823
Actual capacity factor Ghazlan ST	0.8009
Actual capacity factor Guba	0.2245
Actual capacity factor Hail2	0.2613
Actual capacity factor Jazan	0.2834
Actual capacity factor Jeddah3	0.2485
Actual capacity factor Layla	0.2321
Actual capacity factor Madina1	0.1893
Actual capacity factor Madina2	0.2653
Actual capacity factor Makkah	0.2649
Actual capacity factor Najran	0.2732
Actual capacity factor PP10 GT	0.6468
Actual capacity factor PP4 GT	0.2477
Actual capacity factor PP5 GT	0.2398
Actual capacity factor PP7 GT	0.6761
Actual capacity factor PP8 GT	0.6100
Actual capacity factor PP9 CC	0.9875
Actual capacity factor PP9 GT	0.6836
Actual capacity factor Qaisomah	0.1662
Actual capacity factor Qasim	0.2612
Actual capacity factor Qurayah CC	0.6523
Actual capacity factor Qurayah ST	0.8336
Actual capacity factor Qurayat	0.1951
Actual capacity factor Rabigh CC	0.7407

12:55:41 **User Specified** May 25, 2016

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Actual capacity factor Rabigh GT	0.6636
Actual capacity factor Rabigh ST	0.8362
Actual capacity factor Rafha	0.2535
Actual capacity factor Safaniah	0.1819
Actual capacity factor Shaiba ST	0.8298
Actual capacity factor Sharorah	0.2480
Actual capacity factor Shedgum	0.2141
Actual capacity factor Tabargel	0.2234
Actual capacity factor Tabuk1	0.2321
Actual capacity factor Tabuk2	0.6695
Actual capacity factor Taif	0.2080
Actual capacity factor Tihama	0.2786
Actual capacity factor Uthmaniah	0.1805
Actual capacity factor Yanbu	0.2240
CO2 kg per kwh Average	0.7623
CO2 kg per kwh Shaiba ST	0.6703
Efficiency Albaha	0.2581
Efficiency Aljouf	0.2499
Efficiency Alwajh	0.1922
Efficiency Arar	0.2579
Efficiency Asir	0.2902
Efficiency Berri	0.2131
Efficiency Bisha	0.2879
Efficiency Buraida	0.1829
Efficiency Dammam	0.1798
Efficiency Duba	0.2146
Efficiency Faras	0.2823
Efficiency Ghazlan ST	0.3655
Efficiency Guba	0.2245
Efficiency Hail2	0.2613
Efficiency Jazan	0.2834
Efficiency Jeddah3	0.2485
Efficiency Layla	0.2321
Efficiency Madina1	0.1893
Efficiency Madina2	0.2653

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Efficiency Makkah	0.2649
Efficiency Najran	0.2732
Efficiency PP10 GT	0.2966
Efficiency PP4 GT	0.2477
Efficiency PP5 GT	0.2398
Efficiency PP7 GT	0.3084
Efficiency PP8 GT	0.2961
Efficiency PP9 CC	0.4521
Efficiency PP9 GT	0.3111
Efficiency Qaisomah	0.1661
Efficiency Qasim	0.2612
Efficiency Qurayah CC	0.2982
Efficiency Qurayah ST	0.3806
Efficiency Qurayat	0.1951
Efficiency Rabigh CC	0.3388
Efficiency Rabigh GT	0.3045
Efficiency Rabigh ST	0.3819
Efficiency Rafha	0.2535
Efficiency Safaniyah	0.1819
Efficiency Shaiba ST	0.3794
Efficiency Sharorah	0.2480
Efficiency Shedgum	0.2141
Efficiency Tabargel	0.2234
Efficiency Tabuk1	0.2321
Efficiency Tabuk2	0.3061
Efficiency Taif	0.2080
Efficiency Tihama	0.2786
Efficiency Uthmaniah	0.1805
Efficiency Yanbu	0.2240
Fuel Consumed B.BTU Total	1,942,043.07
Fuel cost M.USD Int. price	30,703.70
Fuel cost M.USD Local price	1,378.85
Fuel subsidies M USD	29,324.85
Generation Efficiency	0.3336
Heat Rate Albaha	13,218.00

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Heat Rate Aljouf	13,655.00
Heat Rate Alwajh	17,751.00
Heat Rate Arar	13,230.00
Heat Rate Asir	11,756.00
Heat Rate Berri	16,012.00
Heat Rate Bisha	11,853.00
Heat Rate Buraida	18,657.00
Heat Rate Dammam	18,972.00
Heat Rate Duba	15,902.00
Heat Rate Faras	12,088.00
Heat Rate Generation	10,227.24
Heat Rate Ghazlan ST	9,334.00
Heat Rate Guba	15,197.00
Heat Rate Hail2	13,056.00
Heat Rate Jazan	12,041.00
Heat Rate Jeddah3	13,732.00
Heat Rate Layla	14,703.00
Heat Rate Madina1	18,022.00
Heat Rate Madina2	12,862.00
Heat Rate Makkah	12,880.00
Heat Rate Najran	12,490.00
Heat Rate PP10 GT	11,502.00
Heat Rate PP4	13,775.00
Heat Rate PP5	14,230.00
Heat Rate PP7 GT	11,063.00
Heat Rate PP8 GT	11,523.00
Heat Rate PP9 CC	7,547.00
Heat Rate PP9 GT	10,967.00
Heat Rate Qaisomah	20,539.00
Heat Rate Qasim	13,063.00
Heat Rate Qurayah CC	11,443.00
Heat Rate Qurayah ST	8,965.00
Heat Rate Qurayat	17,487.00
Heat Rate Rabigh CC	10,071.00
Heat Rate Rabigh GT	11,204.00

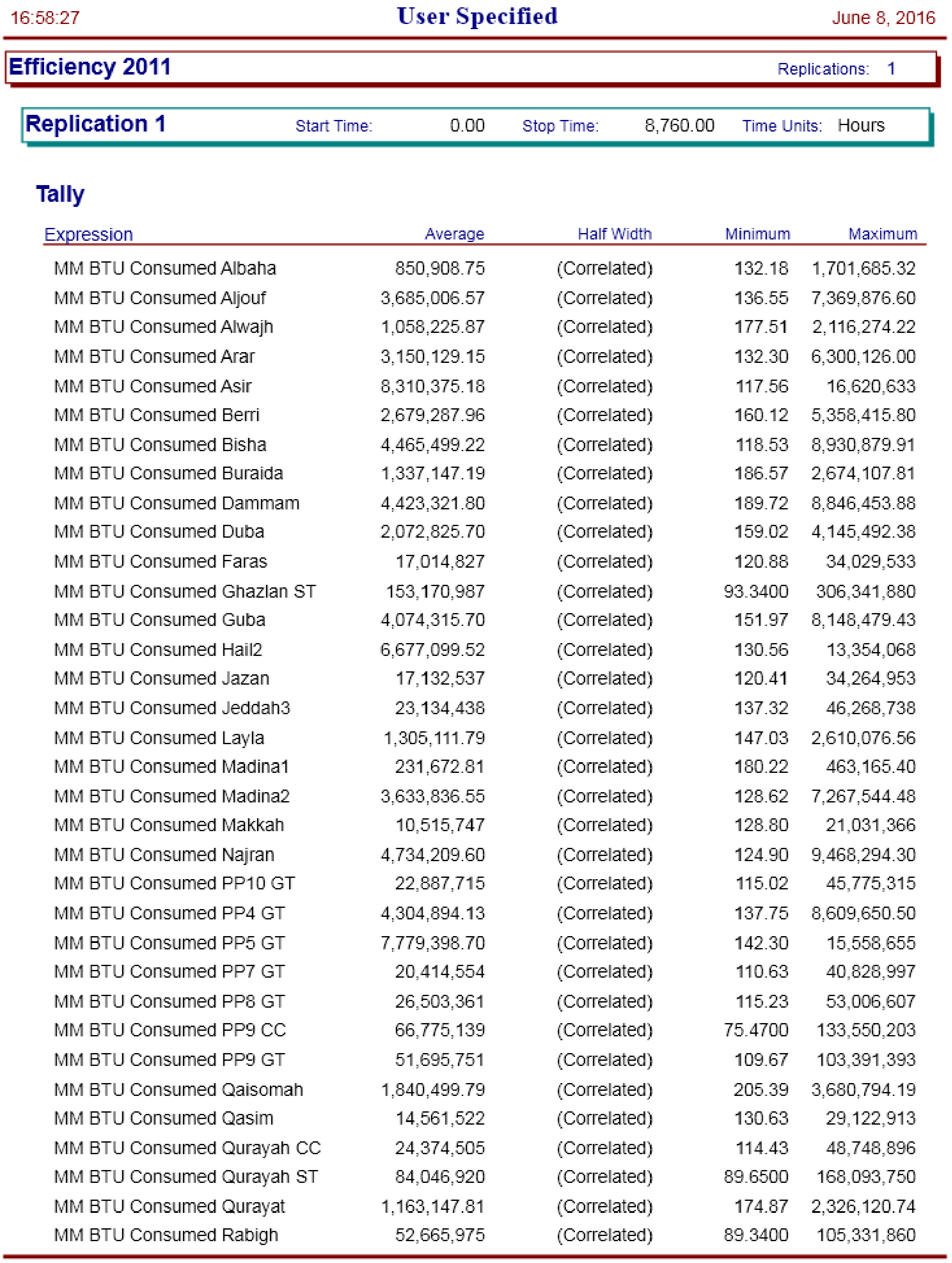
```
12:55:41                    User Specified                    May 25, 2016

Efficiency 2011                                          Replications:   1

  Replication 1      Start Time:      0.00   Stop Time:   8,760.00   Time Units:   Hours

   Output
     Heat Rate Rabigh ST                   8,934.00
     Heat Rate Rafha                      13,458.00
     Heat Rate Safaniyah                  18,762.00
     Heat Rate Shaiba                      8,992.00
     Heat Rate Sharorah                   13,758.00
     Heat Rate Shedgum                    15,937.00
     Heat Rate Tabargel                   15,271.00
     Heat Rate Tabuk1                     14,702.00
     Heat Rate Tabuk2                     11,147.00
     Heat Rate Taif                       16,404.00
     Heat Rate Tihama                     12,249.00
     Heat Rate Uthmaniyah                 18,907.00
     Heat Rate Yanbu                      15,230.00
     System Efficiency                      0.2912
     Total Generation Gwh Gross          189,889.33
```

Stage 3



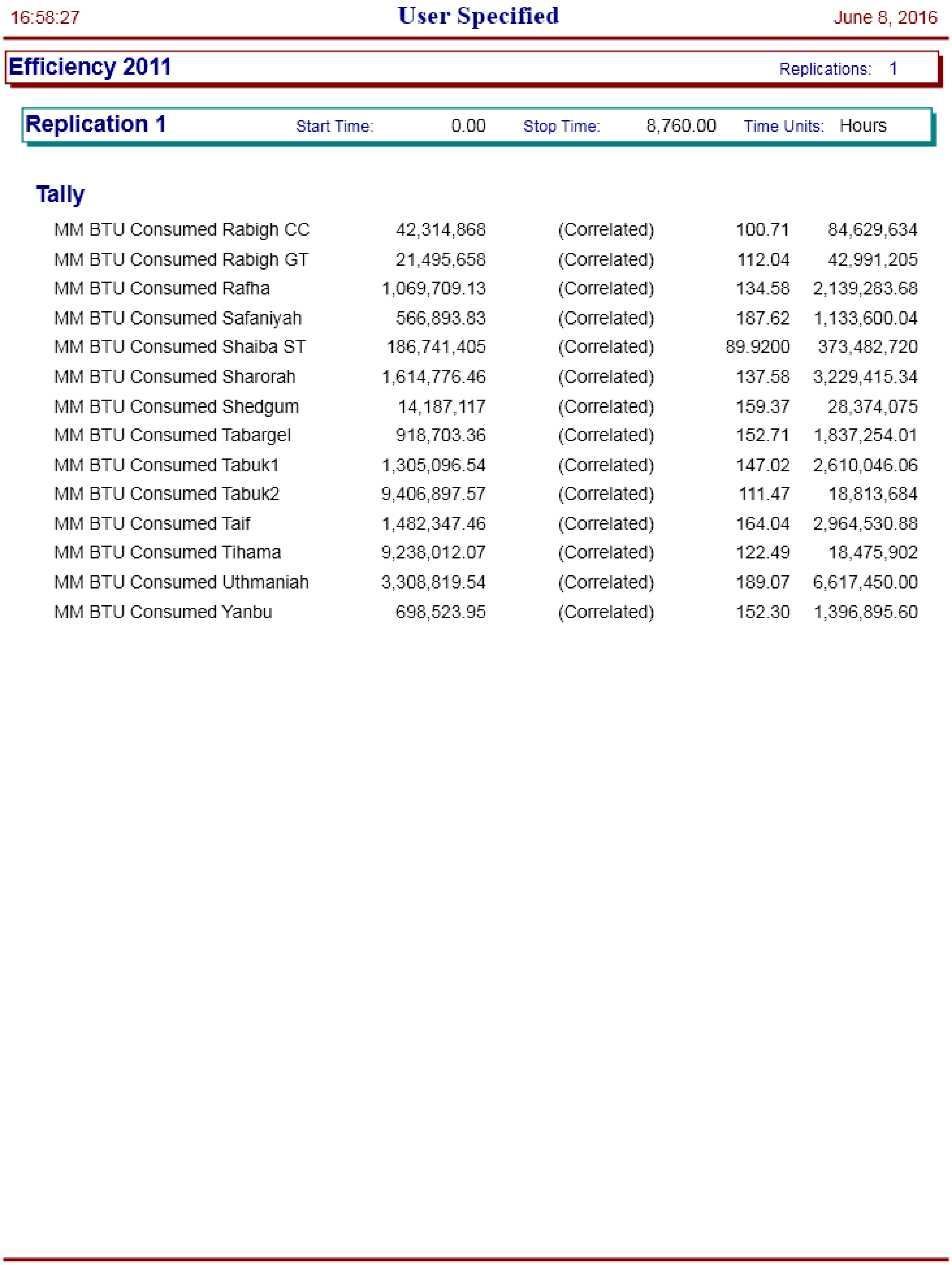
16:58:27 **User Specified** June 8, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Tally

Expression	Average	Half Width	Minimum	Maximum
MM BTU Consumed Albaha	850,908.75	(Correlated)	132.18	1,701,685.32
MM BTU Consumed Aljouf	3,685,006.57	(Correlated)	136.55	7,369,876.60
MM BTU Consumed Alwajh	1,058,225.87	(Correlated)	177.51	2,116,274.22
MM BTU Consumed Arar	3,150,129.15	(Correlated)	132.30	6,300,126.00
MM BTU Consumed Asir	8,310,375.18	(Correlated)	117.56	16,620,633
MM BTU Consumed Berri	2,679,287.96	(Correlated)	160.12	5,358,415.80
MM BTU Consumed Bisha	4,465,499.22	(Correlated)	118.53	8,930,879.91
MM BTU Consumed Buraida	1,337,147.19	(Correlated)	186.57	2,674,107.81
MM BTU Consumed Dammam	4,423,321.80	(Correlated)	189.72	8,846,453.88
MM BTU Consumed Duba	2,072,825.70	(Correlated)	159.02	4,145,492.38
MM BTU Consumed Faras	17,014,827	(Correlated)	120.88	34,029,533
MM BTU Consumed Ghazlan ST	153,170,987	(Correlated)	93.3400	306,341,880
MM BTU Consumed Guba	4,074,315.70	(Correlated)	151.97	8,148,479.43
MM BTU Consumed Hail2	6,677,099.52	(Correlated)	130.56	13,354,068
MM BTU Consumed Jazan	17,132,537	(Correlated)	120.41	34,264,953
MM BTU Consumed Jeddah3	23,134,438	(Correlated)	137.32	46,268,738
MM BTU Consumed Layla	1,305,111.79	(Correlated)	147.03	2,610,076.56
MM BTU Consumed Madina1	231,672.81	(Correlated)	180.22	463,165.40
MM BTU Consumed Madina2	3,633,836.55	(Correlated)	128.62	7,267,544.48
MM BTU Consumed Makkah	10,515,747	(Correlated)	128.80	21,031,366
MM BTU Consumed Najran	4,734,209.60	(Correlated)	124.90	9,468,294.30
MM BTU Consumed PP10 GT	22,887,715	(Correlated)	115.02	45,775,315
MM BTU Consumed PP4 GT	4,304,894.13	(Correlated)	137.75	8,609,650.50
MM BTU Consumed PP5 GT	7,779,398.70	(Correlated)	142.30	15,558,655
MM BTU Consumed PP7 GT	20,414,554	(Correlated)	110.63	40,828,997
MM BTU Consumed PP8 GT	26,503,361	(Correlated)	115.23	53,006,607
MM BTU Consumed PP9 CC	66,775,139	(Correlated)	75.4700	133,550,203
MM BTU Consumed PP9 GT	51,695,751	(Correlated)	109.67	103,391,393
MM BTU Consumed Qaisomah	1,840,499.79	(Correlated)	205.39	3,680,794.19
MM BTU Consumed Qasim	14,561,522	(Correlated)	130.63	29,122,913
MM BTU Consumed Qurayah CC	24,374,505	(Correlated)	114.43	48,748,896
MM BTU Consumed Qurayah ST	84,046,920	(Correlated)	89.6500	168,093,750
MM BTU Consumed Qurayat	1,163,147.81	(Correlated)	174.87	2,326,120.74
MM BTU Consumed Rabigh	52,665,975	(Correlated)	89.3400	105,331,860



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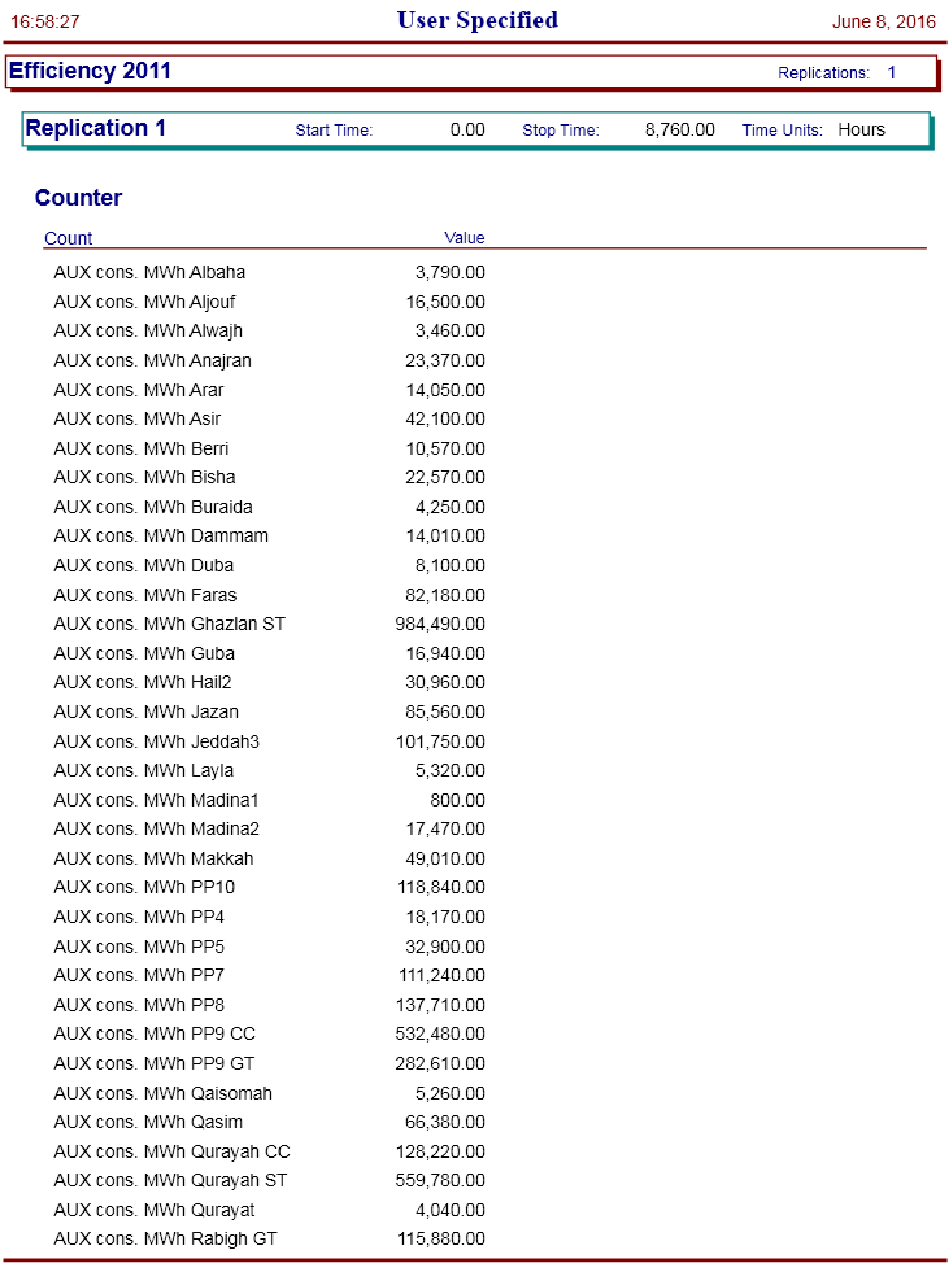
16:58:27                        User Specified                        June 8, 2016

Efficiency 2011                                                  Replications:   1

  Replication 1        Start Time:       0.00   Stop Time:     8,760.00   Time Units:  Hours

   Tally

     MM BTU Consumed Rabigh CC          42,314,868      (Correlated)      100.71     84,629,634
     MM BTU Consumed Rabigh GT          21,495,658      (Correlated)      112.04     42,991,205
     MM BTU Consumed Rafha            1,069,709.13      (Correlated)      134.58   2,139,283.68
     MM BTU Consumed Safaniyah          566,893.83      (Correlated)      187.62   1,133,600.04
     MM BTU Consumed Shaiba ST         186,741,405      (Correlated)     89.9200    373,482,720
     MM BTU Consumed Sharorah         1,614,776.46      (Correlated)      137.58   3,229,415.34
     MM BTU Consumed Shedgum            14,187,117      (Correlated)      159.37     28,374,075
     MM BTU Consumed Tabargel           918,703.36      (Correlated)      152.71   1,837,254.01
     MM BTU Consumed Tabuk1           1,305,096.54      (Correlated)      147.02   2,610,046.06
     MM BTU Consumed Tabuk2           9,406,897.57      (Correlated)      111.47     18,813,684
     MM BTU Consumed Taif             1,482,347.46      (Correlated)      164.04   2,964,530.88
     MM BTU Consumed Tihama           9,238,012.07      (Correlated)      122.49     18,475,902
     MM BTU Consumed Uthmaniah        3,308,819.54      (Correlated)      189.07   6,617,450.00
     MM BTU Consumed Yanbu              698,523.95      (Correlated)      152.30   1,396,895.60
```



16:58:27 **User Specified** June 8, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

Count	Value
AUX cons. MWh Albaha	3,790.00
AUX cons. MWh Aljouf	16,500.00
AUX cons. MWh Alwajh	3,460.00
AUX cons. MWh Anajran	23,370.00
AUX cons. MWh Arar	14,050.00
AUX cons. MWh Asir	42,100.00
AUX cons. MWh Berri	10,570.00
AUX cons. MWh Bisha	22,570.00
AUX cons. MWh Buraida	4,250.00
AUX cons. MWh Dammam	14,010.00
AUX cons. MWh Duba	8,100.00
AUX cons. MWh Faras	82,180.00
AUX cons. MWh Ghazlan ST	984,490.00
AUX cons. MWh Guba	16,940.00
AUX cons. MWh Hail2	30,960.00
AUX cons. MWh Jazan	85,560.00
AUX cons. MWh Jeddah3	101,750.00
AUX cons. MWh Layla	5,320.00
AUX cons. MWh Madina1	800.00
AUX cons. MWh Madina2	17,470.00
AUX cons. MWh Makkah	49,010.00
AUX cons. MWh PP10	118,840.00
AUX cons. MWh PP4	18,170.00
AUX cons. MWh PP5	32,900.00
AUX cons. MWh PP7	111,240.00
AUX cons. MWh PP8	137,710.00
AUX cons. MWh PP9 CC	532,480.00
AUX cons. MWh PP9 GT	282,610.00
AUX cons. MWh Qaisomah	5,260.00
AUX cons. MWh Qasim	66,380.00
AUX cons. MWh Qurayah CC	128,220.00
AUX cons. MWh Qurayah ST	559,780.00
AUX cons. MWh Qurayat	4,040.00
AUX cons. MWh Rabigh GT	115,880.00

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

AUX cons. MWh Rabigh ST	355,370.00
AUX cons. MWh RabighCC	251,330.00
AUX cons. MWh Rafha	4,590.00
AUX cons. MWh Safaniah	1,760.00
AUX cons. MWh Shaiba ST	1,245,730.00
AUX cons. MWh Sharorah	7,250.00
AUX cons. MWh Shedgum	52,630.00
AUX cons. MWh Tabargel	3,630.00
AUX cons. MWh Tabuk1	5,340.00
AUX cons. MWh Tabuk2	50,400.00
AUX cons. MWh Taif	5,410.00
AUX cons. MWh Tihama	46,220.00
AUX cons. MWh Uthmaniah	10,650.00
AUX cons. MWh Yanbu	3,090.00
Fuel Injected 1	41,535,000
Fuel Injected 10	4,260,150.00
Fuel Injected 11	133,020.00
Fuel Injected 12	3,837,130.00
Fuel Injected 13	3,690,590.00
Fuel Injected 14	1,687,780.00
Fuel Injected 15	3,979,770.00
Fuel Injected 16	4,600,070.00
Fuel Injected 17	1,413,800.00
Fuel Injected 18	753,470.00
Fuel Injected 19	2,845,690.00
Fuel Injected 2	11,790,000
Fuel Injected 20	466,290.00
Fuel Injected 21	2,815,150.00
Fuel Injected 22	536,190.00
Fuel Injected 23	1,022,830.00
Fuel Injected 24	3,369,410.00
Fuel Injected 25	177,520.00
Fuel Injected 26	25,700.00
Fuel Injected 27	565,040.00
Fuel Injected 28	1,632,870.00

16:58:27 **User Specified** June 8, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

Fuel Injected 29	758,070.00
Fuel Injected 3	8,403,300.00
Fuel Injected 30	625,020.00
Fuel Injected 31	1,093,370.00
Fuel Injected 32	158,960.00
Fuel Injected 33	60,420.00
Fuel Injected 34	234,730.00
Fuel Injected 35	1,780,390.00
Fuel Injected 36	120,310.00
Fuel Injected 37	177,530.00
Fuel Injected 38	180,720.00
Fuel Injected 39	1,508,360.00
Fuel Injected 4	32,820,000
Fuel Injected 40	350,000.00
Fuel Injected 41	91,720.00
Fuel Injected 42	128,740.00
Fuel Injected 43	476,200.00
Fuel Injected 44	539,720.00
Fuel Injected 45	260,690.00
Fuel Injected 46	334,650.00
Fuel Injected 47	119,220.00
Fuel Injected 48	143,330.00
Fuel Injected 5	18,750,000
Fuel Injected 6	17,695,800
Fuel Injected 7	9,427,500.00
Fuel Injected 8	2,229,420.00
Fuel Injected 9	179,210.00
Gwh Delivered to consumers	165,670.00
MWh Generated Albaha	128,740.00
MWh Generated Aljouf	539,720.00
MWh Generated Alwajh	119,220.00
MWh Generated Arar	476,200.00
MWh Generated Asir	1,413,800.00
MWh Generated Berri	334,650.00
MWh Generated Bisha	753,470.00

16:58:27 **User Specified** June 8, 2016

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

MWh Generated Buraida	143,330.00
MWh Generated Dammam	466,290.00
MWh Generated Duba	260,690.00
MWh Generated Faras	2,815,150.00
MWh Generated Ghazlan ST	32,820,000
MWh Generated Guba	536,190.00
MWh Generated Hail2	1,022,830.00
MWh Generated Jazan	2,845,690.00
MWh Generated Jeddah3	3,369,410.00
MWh Generated Layla	177,520.00
MWh Generated Madina1	25,700.00
MWh Generated Madina2	565,040.00
MWh Generated Makkah	1,632,870.00
MWh Generated Najran	758,070.00
MWh Generated PP10 GT	3,979,770.00
MWh Generated PP4 GT	625,020.00
MWh Generated PP5 GT	1,093,370.00
MWh Generated PP7 GT	3,690,590.00
MWh Generated PP8 GT	4,600,070.00
MWh Generated PP9 CC	17,695,800
MWh Generated PP9 GT	9,427,500.00
MWh Generated Qaisomah	179,210.00
MWh Generated Qasim	2,229,420.00
MWh Generated Qurayah CC	4,260,150.00
MWh Generated Qurayah ST	18,750,000
MWh Generated Qurayat	133,020.00
MWh Generated Rabigh CC	8,403,300.00
MWh Generated Rabigh GT	3,837,130.00
MWh Generated Rabigh ST	11,790,000
MWh Generated Rafha	158,960.00
MWh Generated Safaniyah	60,420.00
MWh Generated Shaiba ST	41,535,000
MWh Generated Sharorah	234,730.00
MWh Generated Shedgum	1,780,390.00
MWh Generated Tabargel	120,310.00

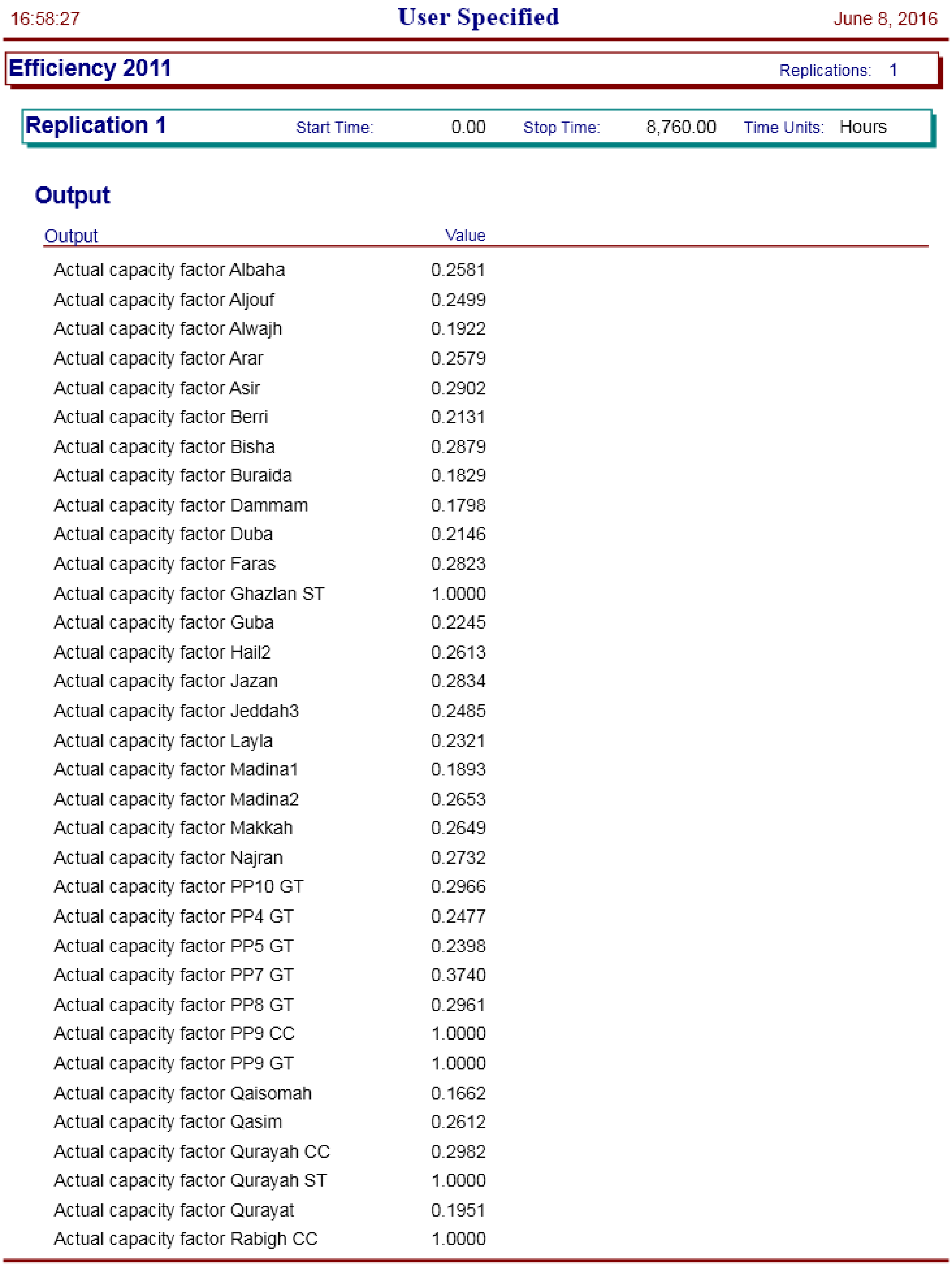
16:58:27 **User Specified** June 8, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Counter

MWh Generated Tabuk1	177,530.00
MWh Generated Tabuk2	1,687,780.00
MWh Generated Taif	180,720.00
MWh Generated Tihama	1,508,360.00
MWh Generated Uthmaniah	350,000.00
MWh Generated Yanbu	91,720.00
Tand D. Losses MWh	18,420,590



16:58:27 **User Specified** June 8, 2016

Efficiency 2011 Replications: 1

Replication 1 Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Output	Value
Actual capacity factor Albaha	0.2581
Actual capacity factor Aljouf	0.2499
Actual capacity factor Alwajh	0.1922
Actual capacity factor Arar	0.2579
Actual capacity factor Asir	0.2902
Actual capacity factor Berri	0.2131
Actual capacity factor Bisha	0.2879
Actual capacity factor Buraida	0.1829
Actual capacity factor Dammam	0.1798
Actual capacity factor Duba	0.2146
Actual capacity factor Faras	0.2823
Actual capacity factor Ghazlan ST	1.0000
Actual capacity factor Guba	0.2245
Actual capacity factor Hail2	0.2613
Actual capacity factor Jazan	0.2834
Actual capacity factor Jeddah3	0.2485
Actual capacity factor Layla	0.2321
Actual capacity factor Madina1	0.1893
Actual capacity factor Madina2	0.2653
Actual capacity factor Makkah	0.2649
Actual capacity factor Najran	0.2732
Actual capacity factor PP10 GT	0.2966
Actual capacity factor PP4 GT	0.2477
Actual capacity factor PP5 GT	0.2398
Actual capacity factor PP7 GT	0.3740
Actual capacity factor PP8 GT	0.2961
Actual capacity factor PP9 CC	1.0000
Actual capacity factor PP9 GT	1.0000
Actual capacity factor Qaisomah	0.1662
Actual capacity factor Qasim	0.2612
Actual capacity factor Qurayah CC	0.2982
Actual capacity factor Qurayah ST	1.0000
Actual capacity factor Qurayat	0.1951
Actual capacity factor Rabigh CC	1.0000

```
16:58:27                        User Specified                        June 8, 2016

Efficiency 2011                                                  Replications:   1

Replication 1        Start Time:        0.00   Stop Time:     8,760.00   Time Units:   Hours

Output
   Actual capacity factor Rabigh GT              0.3045
   Actual capacity factor Rabigh ST              1.0000
   Actual capacity factor Rafha                  0.2535
   Actual capacity factor Safaniah               0.1819
   Actual capacity factor Shaiba ST              1.0000
   Actual capacity factor Sharorah               0.2480
   Actual capacity factor Shedgum                0.2141
   Actual capacity factor Tabargel               0.2234
   Actual capacity factor Tabuk1                 0.2321
   Actual capacity factor Tabuk2                 0.3061
   Actual capacity factor Taif                   0.2080
   Actual capacity factor Tihama                 0.2786
   Actual capacity factor Uthmaniah              0.1805
   Actual capacity factor Yanbu                  0.2240
   CO2 kg per kwh Average                        0.7439
   CO2 kg per kwh Shaiba ST                      0.6703
   Efficiency Albaha                             0.2581
   Efficiency Aljouf                             0.2499
   Efficiency Alwajh                             0.1922
   Efficiency Arar                               0.2579
   Efficiency Asir                               0.2902
   Efficiency Berri                              0.2131
   Efficiency Bisha                              0.2879
   Efficiency Buraida                            0.1829
   Efficiency Dammam                             0.1798
   Efficiency Duba                               0.2146
   Efficiency Faras                              0.2823
   Efficiency Ghazlan ST                         0.3655
   Efficiency Guba                               0.2245
   Efficiency Hail2                              0.2613
   Efficiency Jazan                              0.2834
   Efficiency Jeddah3                            0.2485
   Efficiency Layla                              0.2321
   Efficiency Madina1                            0.1893
   Efficiency Madina2                            0.2653
```

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Efficiency Makkah	0.2649
Efficiency Najran	0.2732
Efficiency PP10 GT	0.2966
Efficiency PP4 GT	0.2477
Efficiency PP5 GT	0.2398
Efficiency PP7 GT	0.3084
Efficiency PP8 GT	0.2961
Efficiency PP9 CC	0.4521
Efficiency PP9 GT	0.3111
Efficiency Qaisomah	0.1661
Efficiency Qasim	0.2612
Efficiency Qurayah CC	0.2982
Efficiency Qurayah ST	0.3806
Efficiency Qurayat	0.1951
Efficiency Rabigh CC	0.3388
Efficiency Rabigh GT	0.3045
Efficiency Rabigh ST	0.3819
Efficiency Rafha	0.2535
Efficiency Safaniyah	0.1819
Efficiency Shaiba ST	0.3794
Efficiency Sharorah	0.2480
Efficiency Shedgum	0.2141
Efficiency Tabargel	0.2234
Efficiency Tabuk1	0.2321
Efficiency Tabuk2	0.3061
Efficiency Taif	0.2080
Efficiency Tihama	0.2786
Efficiency Uthmaniah	0.1805
Efficiency Yanbu	0.2240
Fuel Consumed B.BTU Total	1,894,032.89
Fuel cost M.USD Int. price	29,944.66
Fuel cost M.USD Local price	1,344.76
Fuel subsidies M USD	28,599.90
Generation Efficiency	0.3419
Heat Rate Albaha	13,218.00

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Heat Rate Aljouf	13,655.00
Heat Rate Alwajh	17,751.00
Heat Rate Arar	13,230.00
Heat Rate Asir	11,756.00
Heat Rate Berri	16,012.00
Heat Rate Bisha	11,853.00
Heat Rate Buraida	18,657.00
Heat Rate Dammam	18,972.00
Heat Rate Duba	15,902.00
Heat Rate Faras	12,088.00
Heat Rate Generation	9,979.90
Heat Rate Ghazlan ST	9,334.00
Heat Rate Guba	15,197.00
Heat Rate Hail2	13,056.00
Heat Rate Jazan	12,041.00
Heat Rate Jeddah3	13,732.00
Heat Rate Layla	14,703.00
Heat Rate Madina1	18,022.00
Heat Rate Madina2	12,862.00
Heat Rate Makkah	12,880.00
Heat Rate Najran	12,490.00
Heat Rate PP10 GT	11,502.00
Heat Rate PP4	13,775.00
Heat Rate PP5	14,230.00
Heat Rate PP7 GT	11,063.00
Heat Rate PP8 GT	11,523.00
Heat Rate PP9 CC	7,547.00
Heat Rate PP9 GT	10,967.00
Heat Rate Qaisomah	20,539.00
Heat Rate Qasim	13,063.00
Heat Rate Qurayah CC	11,443.00
Heat Rate Qurayah ST	8,965.00
Heat Rate Qurayat	17,487.00
Heat Rate Rabigh CC	10,071.00
Heat Rate Rabigh GT	11,204.00

Efficiency 2011

Replications: 1

Replication 1

Start Time: 0.00 Stop Time: 8,760.00 Time Units: Hours

Output

Heat Rate Rabigh ST	8,934.00
Heat Rate Rafha	13,458.00
Heat Rate Safaniyah	18,762.00
Heat Rate Shaiba	8,992.00
Heat Rate Sharorah	13,758.00
Heat Rate Shedgum	15,937.00
Heat Rate Tabargel	15,271.00
Heat Rate Tabuk1	14,702.00
Heat Rate Tabuk2	11,147.00
Heat Rate Taif	16,404.00
Heat Rate Tihama	12,249.00
Heat Rate Uthmaniyah	18,907.00
Heat Rate Yanbu	15,230.00
System Efficiency	0.2984
Total Generation Gwh Gross	189,784.85