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Addressing the factors causing inefficiency of fossil fuel power generation in Saudi Arabia

沙特阿拉伯化石燃料发电效率低下的因素研究

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Abstract - **The Efficiency of fossil fuel generation has improved significantly over the last decade and still has a potential for further improvement. The type of fuel and technologies have played a crucial role in this trend, but several factors can affect the efficiency with different impacts, such as equipment aging, operation, maintenance and fuel subsidies, as well as others. This paper aims to identify the main factors causing the current relatively low-efficiency level in fossil power generation in Saudi Arabia. First, generation efficiency was calculated to determine the average level according to the fuel type and technology in use. Second, the results were benchmarked against other countries to determine the actual gap. Third, actual detailed data related to the power plants' performance was collected and critically analyzed. In conclusion, we found that the average efficiency of fossil power generation in the country is below the international average. Between 2007 and 2013 the country's average was around 28% and in 2014 it was about 31%. The results show that the power plants' operation is a primary cause of the current level of efficiency. In addition, the available generation stock has a potential to reach higher than the current level.**

Keywords - **Efficiency, Electricity, Generation, Fossil Fuel.**

I. Introduction

Saudi Arabia (SA) is the largest oil producer in the world and possess around one fifth of the world's proven oil reserves [1]. The kingdom's economy relies heavily on oil exports in its annual budget. Oil represents 85% of the country's export earnings [1]. 8.6 Million barrels of oil per day were exported in 2013 out of a total production of 11.6 Million barrels per day [2]. SA is the world's twelfth energy consumer [3]. Oil consumption has doubled during the last decade and reached 3 Million barrels of oil [4], resulting in the country becoming the sixth largest oil and gas consumer in the world [5]. Recently, local consumption has reached 38% of total primary energy in the kingdom, according to the Saudi Deputy Minister of Energy [6].

Electricity generation consumes 39% [7] of local oil consumption and 43% of total produced natural gas and the rest are distributed in other sectors such as transport, industry and others. Fossil fuel is the sole source of electricity generation (47% gas and 53% oil as of 2013), 1.6 Million Barrel of Oil Equivalent (BOE) are burned every day in power plants [8]. This figure is growing on an annual basis. As a result, the share of export could be reduced by 3 Million barrels per day by 2028 [9] if the current situation continues, which will undoubtedly affect the national economy.

Electricity demand in SA is increasing on a yearly basis. In 2013, a 9.1% increase was recorded in peak demand [10]. On average, there was an annual growth of 8% during the previous decade [11], compared to 2.1% globally. This trend is projected to continue for the next few years, leading to the doubling of the current amount of primary energy by 2030, as the Department of Petroleum and Mineral Resources in SA has warned [6].

Generation efficiency has not shown a significant improvement during the last decade, whilst new power plants are built yearly to meet the demand. Official reports have not seriously considered this topic, although limited publications and some external reports mention the low efficiency in Saudi Arabia. In general, generation efficiency in Saudi Arabia is considered among the lowest countries in the world

The remainder of this paper is organised as follows. Section II provides the background of the electricity industry in SA and Section III discusses the efficiency trend and losses in the country in the past and exposes the main causes leading to inefficiency. Section IV describes the data collection, efficiency calculation and analysis applied in this paper. The main results and findings are presented and discussed in Section V. Finally, Section VI concludes the paper.

II The Power sector in Saudi Arabia

In Saudi Arabia, electricity is generated utilizing fossil fuels only. Heavy Fuel Oil (HFO), Light Fuel Oil (LFO), diesel and gas are the primary source of power as shown in Fig. 1 with an equal share of oil and gas [12]. Coal is not used for power generation. The Saudi Electricity Company (SEC) is the primary electricity provider in SA. It is 81% owned by the government. It owns the transmission and distribution networks and around 70% of the existing power plants. It generates 70% of the country's total demand.

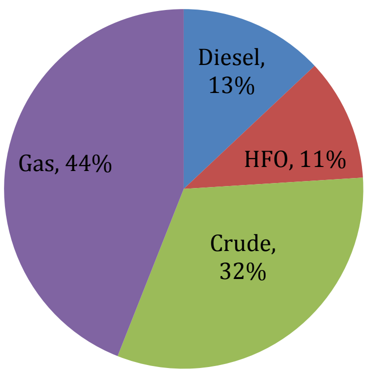

Fig. 1, Annual fuel consumption in electricity generation in SA by fuel type.

A remarkable rise in peak load recorded on an annual basis with projection to reach 75 (GW) by 2020 [12] as presented in Fig. 2. This upsurge demands massive investment in infrastructure expansion with an estimated 500 Billion Saudi Riyals for the next ten years [13]. As a result, 40% of the generation capacity is less than six years old and only 4% have operated for more than 35 years [12], as shown in Fig. 3.

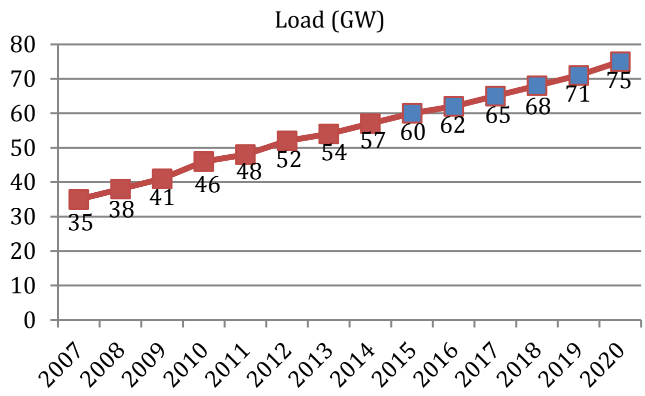

Fig. 2, Actual and projected load in SA.

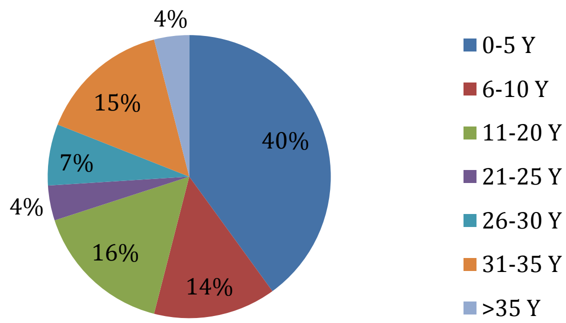

Fig. 3, Age of generation units in SA based on capacity.

2.1 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 are less than 1% of total generation stock, therefore, they are not considered here. Gas turbine has some advantages over others. First, the cost of investment is less than CC and ST. Second, it does not require long hours to start up which means quick response to demand. Nevertheless, it does not operate with high efficiency (30%-35%) [11]. Steam turbine can operate at higher efficiency (35%-40%). However, it is not suitable to respond to peak load quickly. It requires more hours to warm up. Combined cycle is the most efficient available technology, and it can reach 50% or more, but its investment cost is very high. In Saudi Arabia, gas turbines represent half of the generation stock (47%), followed by 40% steam turbines, 12% combined cycles and 1% diesel generators [12], as shown in Fig. 4.

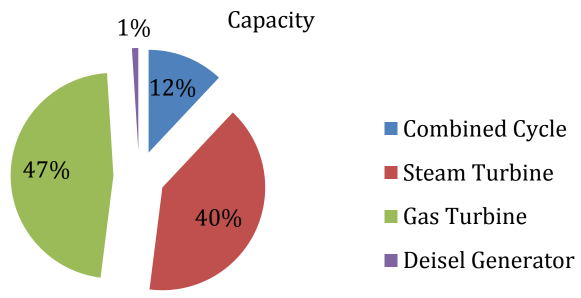

Fig. 4, Generation units by technology type.

Operation optimisation requires demand be satisfied by operating units with the lowest cost. However, the selection of power plants takes into consideration the load type (base, peak) and chooses the optimum technology to operate. Usually, power plants are ranked according to their operation cost. This order is called “merit order” [11] and is used in operation. For instance, when the demand increases, a new unit with higher cost is introduced. Nevertheless, merit order can change in some circumstances, such as maintenance schedules.

2.2 Fuel Subsidies

Electricity providers receive significant discount on petroleum fuel prices [16], as shown in TABLE 1. This is considered to be the compensation to avoid financial losses, since the tariff is determined by the government. Subsidies were literally introduced as a tool to promote equality in society and support low income households. Nevertheless, it has been proved those high income households are utilising subsidies more than the targeted segment [14]. On the supply side, it does not encourage service providers to invest in more efficient technologies and prevents them from competitive pressure [15]. In addition, it does not generate real data about the actual cost of production; as a result, operation decisions can be affected negatively.

TABLE 1 COMPARISON OF FOSSIL-FUELPRICES PAID BY ELECTRICITY PROVIDERS IN SA WITH INTERNATIONAL PRICES.

Fuel Type	Price (US $ / million BTU)	
	Local	International
HFO	0.43	15.43
Gas	0.75	9.04
Diesel	0.67	21.67
LFO	0.73	19.26

III. Historic Trend in Energy Efficiency

Globally, generation efficiency has shown significant improvement during the last decades. For instance, a study by Graus [17] aims to build a benchmark indicator for fossil fuel generation efficiency. The study was based on 14 countries[1] that consume two thirds of global fossil fuel power production. The results shows fossil fuel generation efficiency is around 35% in 2003. India has the lowest with 30% and the United Kingdom recorded the highest efficiency of 40%. However, based on the type of fuel, the efficiency of power plants that utilise gas varies from 35% in Australia up to 47% in India. In addition, the efficiency of coal fired power plants ranges from 41% in Japan to 29% in India. Finally, oil fired power plants range from 28% in India to 42% in Japan. Fig. 5 shows the weighted average efficiency of countries covered by Graus’s study based on fuel type from 1990 to 2003. Natural gas efficiency jumped from 34% to 40% while oil and coal remained at the same level, around 36% and 34% respectively.

In the European Union countries (EU)[2] 55% of power is generated from fossil fuel as of 2005 [18]. Coal contributes the largest share with 30%, followed by gas 20% and oil 4%. Between the years 1990 and 2005, the efficiency of gas fired power plants improved from 30% to 45% and coal from 33% to 39%.

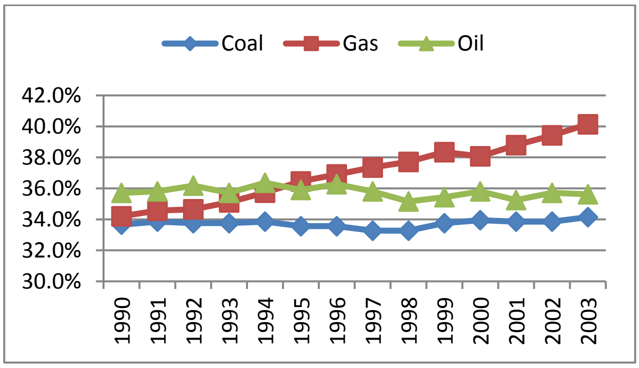

Fig. 5, Average efficiency of selected countries based on fuel type

Fig. 6 shows 3 years average efficiency of EU countries for different fuel types [18]. A three-year average efficiency shows fossil fuel fluctuates between 51% in Luxembourg and 28% in Bulgaria. Spain is the top efficient producer using gas with 50%, while Bulgaria has the least efficiency of 27%. Coal fired power plants range from 27% in Slovak Republic to 42% in Denmark. The top efficient generation utilising oil is 43% in Italy, while Czech Republic has the lowest at 21%. On average, EU countries achieved 39% for fossil power generation in 2005 [19].

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

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

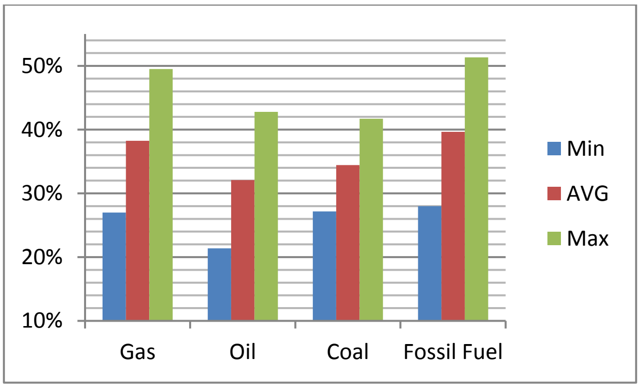

Fig. 6, Average efficiency in EU countries (2003-2005)

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, the efficiency in 2005 of fossil fuel generation was 31%, with 31% for coal, 30% for natural gas and 31.6% for oil [19]. According to Graus, it is predicted, to reach 50% on average by 2050.

3.1 Efficiency Analysis in Saudi Arabia

SA relies completely on oil and gas and does not utilise coal, which is the least efficient fossil fuel resource. But many studies either discuss the optimum energy mix and the utilisation of renewable resources [20] or focus on efficiency efforts on the demand side [21], with less attention paid to improving fossil fuel generation efficiency and limited research found on this topic. This can be related to the lack of published information of average efficiency by the governing body and the efficiency based on fuel used in power plants. The only available data was published in SEC reports from 2011 to 2013 with an average efficiency of 32%, as shown in TABLE 2. This information represents SEC power plants which accounts for 70% of the total production.

In general, SA is considered to be among the countries that have the lowest generation efficiency [22]. The generation efficiency was recorded as 30% in 2009 and 2010 [23]. Another study 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 are 29.5% and 38.6% respectively [24]. From 1990 to 2010, SA average generation efficiency has improved by 0.15 percent point per year (26%-29%) compared to 41%-46% in the EU countries [10]. On the other hand, reports published by ABB [25] have shown that SA generation efficiency increased from 27% to 32% between (1990-2011), as can be seen in Fig. 7.

TABLE 2 HEAT RATE IN SA (2010-2013)

	SEC HR (BTU/kwh)[3]	SEC efficiency (C)[4]	SA efficiency (ABB)[5]
1990	N/A	N/A	27.5%
2000	N/A	N/A	29.1%
2009	N/A	N/A	31%
2010	10,920	31.25%	31%
2011	10,585	32.23%	32%
2012	10,452	32.64%	N/A
2013	10,375	32.89%	N/A

It has been suggested to increase the share of CC units to improve the efficiency since it has the lowest heat rate compared to other fossil fuel generation technologies [24]. ABB reports linked the limited improvement of efficiency in Saudi Arabia to the increasing share of natural gas in generation and CC units [25]. However, CC power plants have increased significantly between 2012 and 2013 without achieving remarkable improvement. The share of CC turbines jumped from 5.4% to 13.8%, while heat rate decreased by only 0.7% [26]. In addition, the share of production of SEC has decreased with the intervention of private firms, which are supposed to be new power plants, yet no significant improvement in efficiency has been observed.

A reduction in heat rate leads to a significant saving of fuel consumed in power plants. For example, 106 million Saudi Riyal (SR) ($28.3M)[6] was saved in 2011 by reducing the average heat rate in SEC power plants by only 0.001% [27]. Moreover, in 2014, the SEC reported a 1% reduction in heat rate results in saving 12 MBOE [28]. However, both reports have not revealed the main reasons for these improvements.

[3] [26], [27], [42]

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

[5] [25]

[6] 1 US$ = 3.75 SR

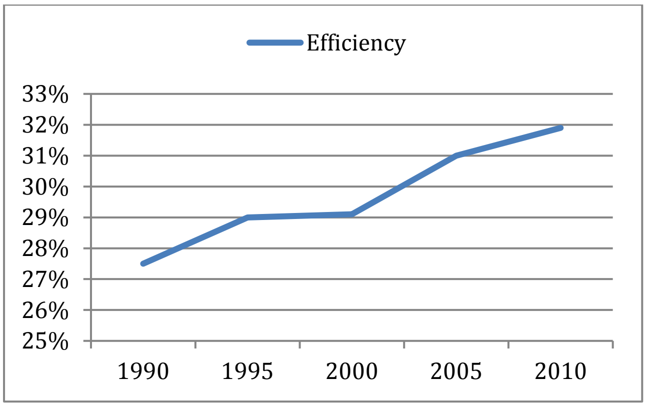

Fig. 7, Generation efficiency in SA (1990-2011)

3.2 INTERNAL CONSUMPTION AND LOSSES

The Type of fuel used in the power plant has an impact on the amount of auxiliary consumption. The largest consumption often appears in coal power plants which consume 6-8% of its gross production. On the other hand, gas based power plants have the lowest auxiliary consumption of around 2-3% and oil power plants usually 4-6% [29]. Globally, around 5% of total power production in 2007 was consumed as an auxiliary consumption. For instance, China power plants consume around 8% of their gross production as one of the highest figure in the world, followed by Russia and India with about 7% in both country [30]. On the other hand, SA power plants consume only 3% of their total production as shown in Fig. 8 [16] [17]. These figures could be linked to the fuel mix being used in producing electricity.

The world average transmission and distribution losses from 2006 to 2012 are around 8.3% [37], as shown in Fig. 9. Losses vary between countries: India has the highest loss of 20.68% and Korea the lowest at 3.54%. On the other hand, Saudi Arabia fluctuates between 8 and 10% in the last decade with an average of 8.8%. Network losses in the kingdom are among the world average range [12][25].

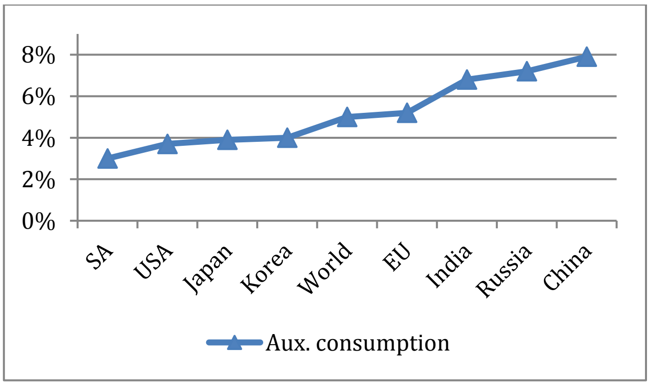

Fig. 8, Auxiliary consumption in power plants as a percentage of total production in 2007.

Electricity consumed within the power plants and power losses in networks including transmission and distribution in Saudi Arabia are within the international average.

3.3 FACTORS INFLUENCING EFFICIENCY.

Design efficiency or the so called name plate efficiency is the ideal efficiency. However, practically during operation, it is usually lower and known as operational efficiency. This can be linked to several factors such as operation practices, maintenance, fuel quality, cooling methods, size of power plant, environment and pollution control, as shown in Fig**.** 9 [31]. These factors have been classified into controllable and uncontrollable [32]. Operation and maintenance are considered to be controllable factors while the rest are uncontrollable, such as age deterioration, weather conditions etc. (500-1000 BTU/kWh) per power plant can be recovered by paying attention to controllable factors. Specifically, load hours is considered as the most significant factor affecting efficiency [31]. On average, maintenance can have a negative impact on efficiency by 0.5% but in some cases poor maintenance can reduce efficiency up to 5% [31].

Partial load operation and frequent shut down and start up consume more fuel and lead to lower operational efficiency [33] [34] [35]. Losses in efficiency are sensitive to the capacity utilization of plants. For instance, 5%-7% less than design efficiency is a result of the power plant operating at 30% of its capacity, while increasing operational capacity to 85% can reduce the losses to only 1-2% [31]. On average, 3-4% is estimated for half load operation [18]. This drop can vary according to technology. The efficiency of CC units operating at half load is 45%, instead of 52% efficiency if operated at full load [36].

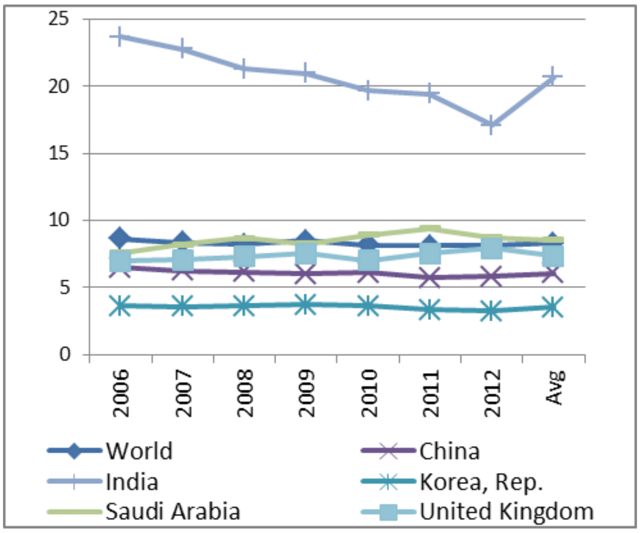

Fig. 9, Transmission and Distribution loses (%) 2006-2012

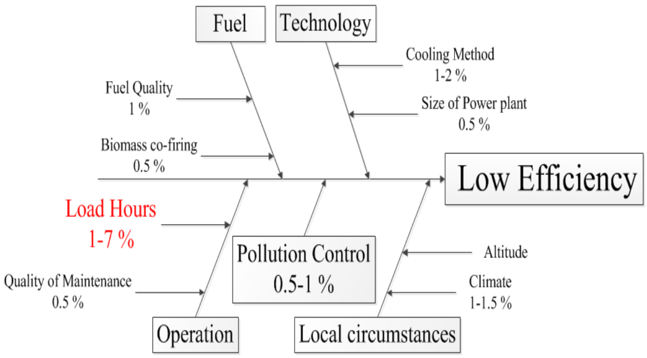

Fig. 9, Factors influencing efficiency

IV. Calculation and Analysis

This section provides a summary of the calculation and analysis performed in this study and the data used. First, the data for efficiency calculation was collected from different sources and checked. Second, efficiency is calculated utilizing the same method applied in several researches [17]. Finally, an in-depth analysis carried out to identify the causes leading to the current level of efficiency in Saudi Arabia.

4.1 Data Collection

Data of fuel used in power plants and electricity generation were taken from Electricity and cogeneration regulatory Authority in Saudi Arabia reports for the last ten years [38] and International Energy Authority website [39]. Input energy is based on gross calorific value (GCV)[7]. Output electricity is based on gross production [8]. This means auxiliary consumption, transmission and distribution losses are not considered.

In addition, detailed data of SEC's power plants was only collected from the ECRA, including the power plants' name, technology type, nominal capacity heat rate and gross generation as in 2011.

Calculating Efficiency

Efficiency is defined as "the ratio of the useful outputs energy to the input energy" [40]. The equation used for efficiency calculation is shown in Eq. (1):

$$E = \frac{P}{I} \qquad (1)$$

Where E is the efficiency, P is the generated electricity and I is the fuel used in power plants. The efficiency is based on Higher Heating Value (HHV). This is recommended by the energy efficiency experts network, since it provides a clear picture of inefficiency [41]. Alternatively, heat rate (HR) is used to measure the amount of BTU required for generating single kWh. Nevertheless HR is an efficiency measure as presented in Eq. (2):

$$E = \frac{3412}{HR} \qquad (2)$$

4.3 Data Analysis

The generation efficiency in Saudi Arabia was calculated for the last few years. This result was benchmarked with the UK to determine the gap. The collected data of power plants from ECRA was further analyzed in detail to determine the main causes leading to the current level of efficiency, as presented in the next section.

V. Results and Discussions

The results show that the generation efficiency in Saudi Arabia is below 30% from 2007 to 2012 with no significant change. Noticeable development was achieved in 2014 by reaching 31% Fig. 10. This change is not linked to any reason in official reports, but it can be related to the new units added to the generation assets with a total capacity of 7 GW.

The amount of fuel used in electricity production was shared equally between oil and gas and remained the same during the last decade with limited change every year. The type of generation units has changed slightly as shown in Table 3. CC units have doubled from 6% to 12% during the last 6 years, GT power plants shares has decreased from 52% to 47% and ST remained the same on average.

The average age of generation units in Saudi Arabia is 14 years old, similar to the UK fossil fuel power plants which are generating at an efficiency above 45% on average as shown in Fig 12. By comparing the efficiency of the same fuel type in both countries, we found gas fueled units in SA are far below those in the UK.

SA has a potential to achieve a higher efficiency than the current level according to the existing generation stock and type of fuel in use. By considering the average efficiency of the available resources, the average could be 37%-38%.

[7] Gross calorific value (GCV) or higher heating value (HHV) provides lower efficiency than if net calorific value (NCV) or lower heating value (LHV) is used. The variance is about 7% for oil (3 percent point) and 10% for natural gas (5-6 percent point) [43].

[8] Gross production= Net production + AUX consumption + T&D losses

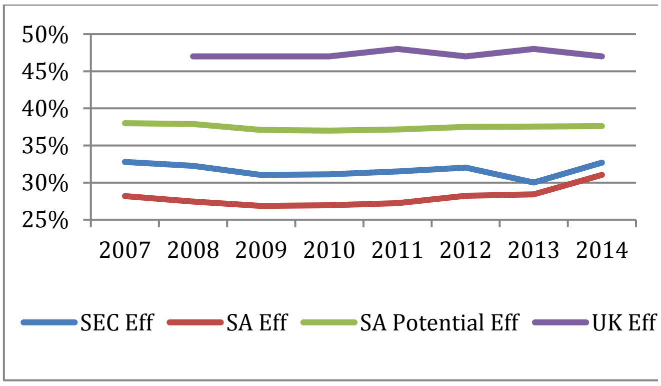

Fig. 10, Efficiency trend in SA and UK

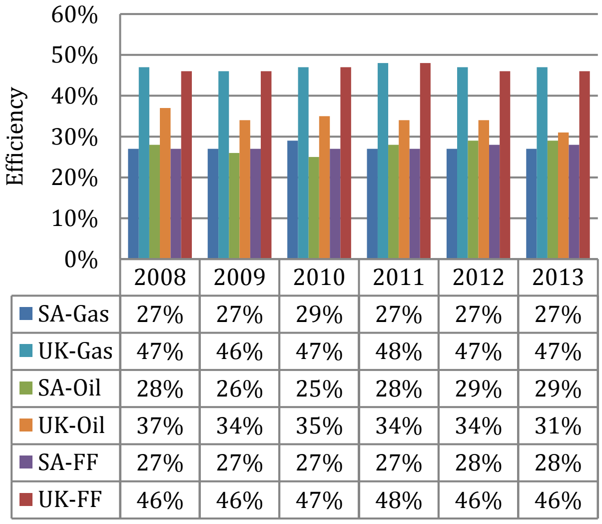

Fig. 11, Generation efficiency in SA & UK based on fuel type

TABLE 3 GENERATION UNITS' TYPE IN SABASED ON NOMINAL CAPACITY

	2009	2010	2011	2012	2013	2014	AVG
GT	52%	53%	52%	50%	50%	47%	51%
ST	41%	40%	40%	39%	36%	40%	40%
CC	6%	6%	6.1%	9.9%	12%	12%	9%
Potential Efficiency	36%	36%	36%	37%	37%	37%	37%

On the other hand, SEC generates 70% of total electricity transmitted through the networks. Its power plants' efficiency fluctuates between 32% and 31% between 2007 and 2014 higher than the country average. In terms of type of fuel consumed, oil is used more than gas with 60% against 40% respectively.

The analysis shows power plants that operate at high efficiency are being operated less than other units with lower efficiency, as shown in Fig 13. In addition, the existing most efficient technology, CC power plants, are showing an extremely low efficiency in operation compared to its design efficiency. On average, steam turbine power plants are the most utilized type by 67%, higher than combined cycle units which are used by only 52% during the year, followed by 41% for GTs. As a result, Gas turbines generate 44% of the total electricity produced by SEC. STs contribute 43% of the total production, while CCs generate only 13%.

Generation assets are not operating as efficiently as they could be and efficiency improvement is not considered as the primary objective in operation. This is related to the analysis of data showing the priority and high utilization of the least efficient units over other efficient ones.

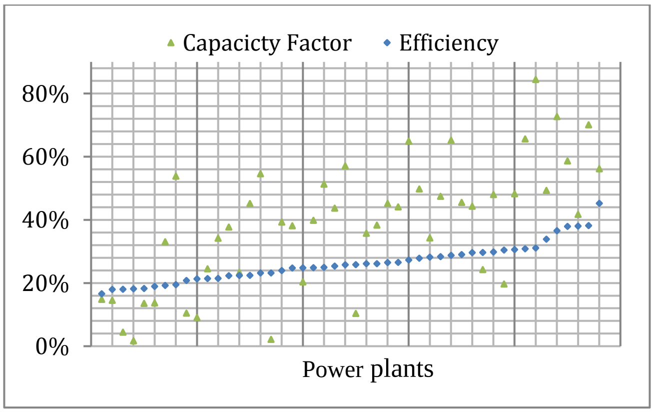

Fig. 12, Capacity factor vs. efficiency per power plant

VI. Conclusion

In this paper, the generation efficiency in Saudi Arabia's electricity sector was calculated and investigated for the years 2007 to 2014. A detailed analysis was carried out to identify the reasons affecting the efficiency.

Electricity generation efficiency in Saudi Arabia is far below the international average level. Recent research suggested that the increase in the share of high efficient units for improvement, which means further investment. This analysis shows that the existing generation technologies and type of fuel used could be utilized better to achieve a higher level of efficiency. Moreover, the operation of power plants represents a major cause of the current situation. In future, operation models will be developed and simulated to improve the electricity generation efficiency in Saudi Arabia.

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