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

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Abstract. The efficiency of fossil power generation has improved during the last decades and technology development has played a significant role in this improvement. However, several factors can affect the efficiency level, such as operation, maintenance and environment, etc. The economic growth in Saudi Arabia in recent years has increased the demand for electricity. On the supply side, despite the reinforcement of generation stock with new units, the generation efficiency of fossil fuel has not improved significantly and is considered as being amongst the lowest in the world. This, as a result, means further consumption of resources and more emissions being produced. For this study, a new merit order has been produced using mathematical models to optimise the operation of power plants and improve the average efficiency. In addition, a simulation model was built to verify the enhancement. The results of the first stage show, on average, 3.5% improvement in generation efficiency and around a 4.95 Mtonnse reduction in total CO2 produced. In the second stage, the efficiency improved by 6% and the emissions rate dropped by 5.7%.

Keywords: Efficiency · Electricity · Generation · Fossil fuel · Saudi Arabia

1 Introduction

In Saudi Arabia, electricity demand has been growing continuously. A 9.1% rise in peak load was recorded 2013 [1] and around 8% on average during the last decade [2], compared with 2.1% globally. This trend is anticipated to last for the next few years, thus resulting in the need to double the existing generation capacity [3]. Oil and gas are the main sources of electricity in Saudi Arabia. The growing demand for electricity has increased the local consumption of primary energy and Saudi Arabia has become the world's twelfth biggest energy consumer. In addition, local oil consumption has doubled and reached around 38% of total primary energy, making the country the sixth largest oil consumer [4]. 39% and 43% of oil and gas, respectively, are consumed in electricity generation.

The average generation efficiency in the kingdom did not improve significantly during the last two decades, although the generation assets are being reinforced by new units on a yearly basis. Nevertheless, several researchers have reported Saudi Arabia as

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being among the poorest performing countries in terms of generation efficiency [5, 6]. Regarding which, the average efficiency in the country improved from 26% to 29% (1990–2010), with an annual average of 0.15 of a percentage point. On the other hand, average efficiency in the EU countries reached 46% in the same period [1]. Globally, average efficiency of fossil power generation was 35% in 2003, whilst gas fueled units reached 40% and oil 36% [7].

Efficiency improvement can have significant financial and environmental impact. For instance, the Saudi Electricity Company (SEC), the largest electricity producer in the kingdom, reported 0.12% heat rate reduction in 2011 and 1% in 2014 compared with the previous year. As a result, the fuel saved was worth $28.3 million in 2011 and 12.1 million barrels of oil equivalent in 2014 [8, 9]. This is based on 70% of the country gross electricity produced. Environmentally, achieving 0.1 higher efficiency would reduce the total CO2 emissions produced by 0.18% to 0.24% [10].

In Saudi Arabia, efficiency has been discussed from a different point of view. The majority of attention has been focused on the consumption side aimed at controlling and reducing the increasing demand [11, 12]. On the supply side, the adoption of renewable energy has been a widely discussed topic [13–15] in relation to mitigating the consumption of fossil fuel in electricity generation. In order to improve the level of generation efficiency, increasing the share of combined cycle (CC) units has been proposed, since they have the ability to generate electricity at a lower heat rate [1, 6] compared to other technologies. However, this option has not shown any significant improvement, for after the doubling of the capacity share of CC units between 2011 and 2013, no marked improvement was observed [16, 17].

The literature has reported several factors that can affect generation efficiency in power plants. Operation is pointed to as the most influencing factor, with up to 7% loss in efficiency, followed by maintenance, subsidies, environment etc. [18–21]. Likewise, among all the influencers, operation has shown the strongest association with the current low efficiency level in Saudi Arabia [22]. It shows high utilisation of less efficient units when compared to the top efficient power plants. In addition, it is acknowledged that the existing generation stock has the potential of reaching a higher level of efficiency. This paper is aimed at improving the efficiency by optimising the operation of power plants in Saudi Arabia and examining the improvement proposed.

The remainder of this paper is structured as follows. Section 2 provides a background, whilst Sects. 3 and 4 describe the methodology employed. Section 5 presents the results obtained and discussion. Finally, Sect. 6 concludes this paper.

2 Operating Criteria of Power Plants

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 electricity. Units with the lowest cost of production are located at the top and have priority in operation. This ranking is known as "Merit- Order" [2]. In Saudi Arabia, power plant operation is planned based on the cost of electricity units produced. The main objective is to ensure sufficient production under minimum cost within the security limits. This rule has some exceptions to avoid interruptions, such as shortage in supply, sudden low voltage or unexpected increase on the demand side. The operation of the network is controlled by an LDC (Load Dispatch Centre) located within the SEC, which theoretically means efficiency is a major criterion in operation, since it is related to cost.

3 Simulation

"Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system" [23]. Simulation does not provide solutions; it shows the outcomes of applying different alternatives (scenarios) to the system. This can support the decision makers in evaluating the performance of each choice and acting with high confidence. The main purpose of utilising simulation is to avoid unexpected results in the real world as it predicts system behaviours and outcomes subsequent to any change. Simulation has achieved a 92% satisfaction factor as a tool in supporting decision making [24]. It can be considered as providing risk reduction, efficiency improvement, operation and capital cost saving along with other financial benefits. Furthermore, it is a useful tool for examining hypotheses so as to understand the reasons for a particular phenomenon [23].

A discrete event simulation model has been designed tested and justified following the steps and approach from several studies [25–29]. It was run several times utilising real data obtained from the Electricity and Cogeneration Regulatory Authority (ECRA) in SA [30]. However, only the data for SEC's power plants during the year 2011 were deployed. The data for the simulation comprised 48 power plant names, type, merit order, heat rate and gross actual generation. It is important to mention that this represents around 70% of total production in the kingdom.

The obtained data do not provide exact details of internal consumption (auxiliary) at each power plant. Therefore, 3% was considered as the average for all of them and 10% losses in the transmission and distribution networks, as mentioned in ECRA reports [17, 31]. Fuel consumed and annual load profile was also collected from ECRA annual reports. Finally, the emissions produced and the total cost of fuel were found in [32, 33]. This data will be used to verify the model results.

The simulation report illustrates similar results to the real system by consuming the same amount of fuel and generating a similar amount of electricity at identical efficiency for each unit and on average. Nevertheless, the analysis shows no relation between merit order, efficiency and the actual capacity factor (see Fig. 1). This could be related to the existence of fuel subsidies, which tend to favour less efficient units that are negatively reflected in the average efficiency [1].

In addition, fuel subsidies do not reflect the actual cost of production on the supply side and generate a distorted price pattern [34], which does not support effective decision making for better utilisation of national resources [21, 35, 36], as well as having significant consequences regarding the efficiency. Consequently, a new merit order is

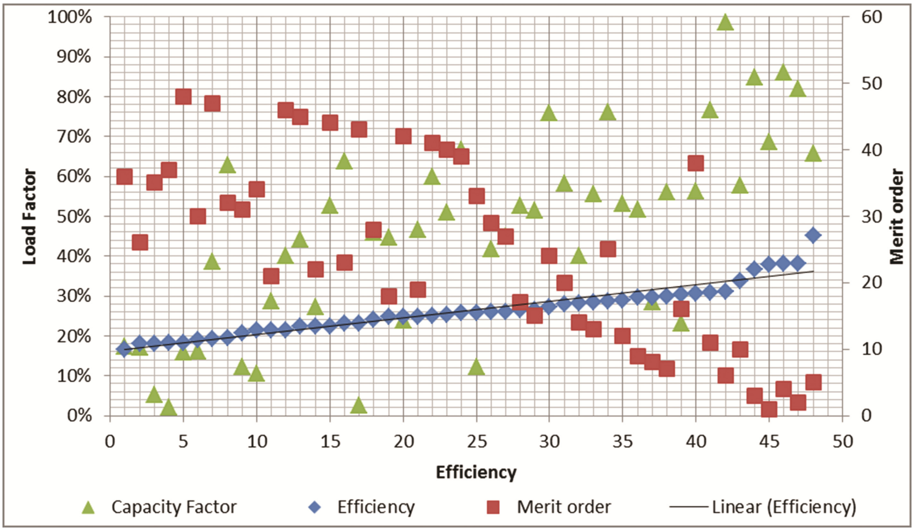

Fig. 1. Efficiency vs capacity factor and merit order

proposed here grounded in a combination of efficiency and a capacity factor using a mathematical model.

4 Mathematical Model in the Electric Power Industry

A mathematical model is a powerful method for helping to understand system performance through equations [37]. It has been utilised to solve issues by recognising the relations within the system or predicting the outcomes of specific variables [38]. Employing such a model requires in depth understanding of the problem to ensure that it is designed appropriately.

4.1 Model 1

In this study, we develop a new merit order by utilising the efficiency (E) and load factor (LF). The mathematical model has been used in order to identify the weight of each factor.

$$E = \sum_{i=1}^{k} (ciei) \tag{1}$$

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:

$$c = \frac{PPGP}{TP} \tag{2}$$

Where TP is total production, PPGP is the power plant gross production.

$$PPGP = LF * NC * 7500h \tag{3}$$

Where NC is the nominal capacity and 7500 is the maximum operating hours per year for the unit.

$$e = \frac{3412}{HR} \tag{4}$$

Where HR is the Heat Rate. Hence, we have:

$$E = \sum_{(i=1)}^{k} \frac{LFi*NCi\,3412 * 7500}{(HRi\,TP)} \tag{5}$$

The actual nominal capacity, total production and average heat rate of the power plants are applied in Eq. (5) to determine the weight both factors in Eq. (6).

$$S = E + (F*LF) \tag{6}$$

S is the new merit order. By applying Eq. (6) 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.

4.2 Model 2

Alternatively, improvement can be designed based on estimating the required production from each unit that will provide maximum system efficiency.

(1) Total production has been classified into two categories in Eq. (7). Electricity is produced by efficient and non-efficient power plants. The criterion used in classifying the units is the average generation efficiency.

$$TP = \text{Efficient production(EP)} + \text{Non efficient production(NEP)} \tag{7}$$

(2) Efficient production can be calculated using Eq. (8).

$$EP = \sum_{i=1}^{n} (TPppi) = \sum_{i=1}^{n} (NCppi\ *7500h) \tag{8}$$

This means efficient units will be utilised to the maximum

(3) Non-efficient production can be calculated using Eq. (9).

$$NEP = TP - EP \tag{9}$$

(4) NEP will be distributed to non-efficient units according to their efficiency

Equation (10), which is one of the constraints.

$$EP = \sum_{i=(n+1)}^{m} (NCppi*7500h) \geq Demand \quad (10)$$

The results will 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. Specifically, nonlinear mathematical programming is used to provide the optimum output needed by each power plant to fulfil the total production requirement. The constraints include that the electricity generated by each unit should not exceed its maximum capacity and that there is no less than the minimum needed production to fulfil the load profile. Total production also should not exceed demand by more than 10%. The objective to be minimized is the average heat rate using Eq. (11), which is calculated according to the suggested production by 48 variables.

$$HR = \sum_{i=1}^{k} (cihri) \quad (11)$$

5 Results and Discussion

The original data have been used on the first mathematical model and generated a new merit order that has been utilised in operating the power plants. This can be used to generate unlimited scenarios regarding implementation by changing the loading hours for each unit. To identify the most optimum scenario, Eq. 7 was applied several times to obtain the required loading hours for each unit. Then, the original simulation model was run and new results were generated. The simulation report shows 3.5% improvement in average generation efficiency. As a result, about 66,189 billion BTU of fuel was saved, worth around one billion US dollars. In addition, the average CO2 emissions produced per kWh generated were decreased by 3.3%, amounting to 4.95 Mtonnes reduction in the total CO2 produced by fossil fuel generation.

The second mathematical method combined with the optimisation tool was applied to maximise the utilisation of efficient units and minimise it in the least efficient power plants, without affecting the demand. The obtained utilisation factor was applied to the simulation model and new results were obtained. The second simulation report demonstrates better results than the previous method and the efficiency has improved by 6% compared to the reference scenario. This improvement saves around 1.8 billion US $ by reducing the total fuel consumed by 114 T.BTU (−5.7%). Furthermore, the reduction in the emissions rate is 0.449 kg per kWh, which represents a decrease of 8.5 Mtonnes in CO2.

Table 1 summarises the results of both methods and compares them to the reference scenario. As can be seen, 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 an electricity unit has been reduced to 0.158 $/kWh.

Table 1. Results summary

	Reference scenario S1	1st method improvement	2nd method improvement
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 emissions (kg/kwh)	0.7888	0.7623	0.7439
Reduction (%)	-----	3.4	5.7
CO2 emissions (M.Ton)	149.696	144.750	141.176
Reduction (M.Ton)	-----	4.95	8.52
Efficient PP Avg. utilisation factor (%)	78%	82%	100%
NEP PP Avg. utilisation factor (%)	40%	30%	25%
Cost ($)/kWh	0.167	0.162	0.158
Discount (%)	-----	3	5.4

The calculation of average efficiency is affected by the amount of electricity produced by each generating unit (contribution) under specific efficiency. This means that the presence of highly efficient units is not sufficient to improve the average efficiency unless they make a significant contribution, because the increase in the share of production of less efficient units will result in reducing the average efficiency and vice versa. The analysis of the first simulation results show that 52% of gross production was generated by power plants with above average efficiency, but these units were only utilised 78% during the year. On the other hand, several power plants with efficiency below average were being used more than those with high efficiency. This means that SEC's generation assets are not being deployed as efficiently as they could be, which is the main contributor to the low level of average efficiency.

Whilst significant improvement was generated during the implementation of stage 2 and 3, nevertheless, further improvement can be made. According to several studies, the increase in load factor can have significant impact on the unit average efficiency [39, 40]. This study is based on the provided figures of the heat rate for each unit and it was assumed the average figure was fixed in all the scenarios proposed. The results of the new methods indicate higher load hours of the efficient units. This has the potential to increase the average efficiency of each power plant by (1–7% points) or to reduce the fuel consumed by 25%, on average and as a result, this will be positively reflected in the average efficiency. This can open a window for future research.

6 Conclusion

In this paper, the operation of SEC power plants has been analysed using simulation. The results have shown that existing generation stock is not being operated efficiently. Consequently, new merit order has been proposed, using a mathematical model that combines the quality and quantity so as to produce a single measure for operation. Subsequently, simulation models were utilised to implement the new merit order. The average efficiency of power plants improved significantly by optimising the operation. The proposed mathematical model and simulation could be employed in the future with the addition of further parameters.

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References

1. Groissböck, M., Pickl, M.J.: An analysis of the power market in Saudi Arabia: retrospective cost and environmental optimization. Appl. Energy **165**, 548–558 (2016)
2. Farnoosh, A., Lantz, F., Percebois, J.: Electricity generation analyses in an oil- exporting country transition to non-fossil fuel based power units in Saudi Arabia. Energy **69**, 299–308 (2014)
3. Sulman, A.: Local consumptiopn of energy represents 38% of the kingdom total production. Aleqtisadiah, RIYADH, 08 February 2016
4. El-katiri, L., Fattouh, B.: A brief political economy of energy subsidies in the middle east and North Africa. Oxford Inst. Energ Study, February 2015
5. Fattouh, B.: Summer Again: The Swing in Oil Demand in Saudi, pp. 1–8, July 2013
6. Alyousef, Y., Abu-ebid, M.: Energy Efficiency Initiatives for Saudi Arabia on Supply and Demand Sides (2012)
7. Graus, W.: Power of Efficiency International comparisons of energy efficiency and CO2 emissions of fossil-based power generation (2010)
8. SEC: Annual Report. RIYADH (2011)
9. SEC: Annual Report. RIYADH (2014)
10. EURELECTRIC: Efficiency in Electricity Generation. Brussels (2003)
11. Khan, S.: Energy efficiency: the first renewable. Oxford (2014)
12. Fattouh, B., El-katiri, L.: Energy and Arab Economic Development (2012)
13. Alnatheer, O.: The potential contribution of renewable energy to electricity supply in Saudi Arabia. Energy Policy **33**(18), 2298–2312 (2005)
14. Aljarboua, Z.: The national energy strategy for Saudi Arabia. World Acad. Sci. Eng. Technol. **3**(9), 472–481 (2009)
15. Al-Saleh, Y.: Renewable energy scenarios for major oil-producing nations: the case of Saudi Arabia. Futures **41**(9), 650–662 (2009)
16. ECRA: Annual Statistical Booklet for Electricity and Sea Water Desalination Industries. RIYADH (2013)
17. ECRA: Annual Statistical Booklet on Electricity and Sea Water Desalination Industries. RIYADH (2011)
18. (Ron) Chan, H.S., Cropper, M.L., Malik, K.: Why are power plants in India less efficient than power plants in the United States? Am. Econ. Rev. **104**(5), 586–590 (2014)

19. Farouk, N., Sheng, L., Hayat, Q.: Effect of ambient temperature on the performance of gas turbines. Int. J. Comput. Sci. Issues **10**(1), 439–442 (2013)
20. De Sa, A., Al Zubaidy, S.: Gas turbine performance at varying ambient temperature. Appl. Therm. Eng. **31**(14–15), 2735–2739 (2011)
21. Krane, J.: Stability versus Sustainability: Energy Policy in the Gulf Monarchies (2013)
22. Althaqafi, M., Yang, Q.: Addressing the factors causing inefficiency of fossil fuel power generation in Saudi Arabia. North Sea Conf. J. **3**(3) (2016)
23. Shannon, R.: Introduction to the art and science of simulation. In: Proceedings of the 1998 Winter Simulation Conference, WSC 1998, vol. 53, pp. 7–14 (1998)
24. Hollocks, B.W.: The impact of simulation in manufacturing decision making. Control Eng. Pract. **3**(1), 105–112 (1995)
25. Banks, J.: Introduction to simulation. In: Proceedings of the 2000 Winter Simulation Conference, no. Riis 1995, pp. 9–16 (2000)
26. Wyland, B., Buxton, K., Fuqua, B.: Simulating the supply chain. IIE Solut. **32**(1), 37–42 (2000)
27. Altiok, T., Melamed, B.: Simulation Modeling and Analysis with ARENA. Academic Press, Burlington (2010)
28. Robinson, S., Brooks, R., Kotiadis, K., Van der Zee, D.-J.: Conceptual Modelling for Discrete-Event Simulation. CRC Press, Boca Raton (2010)
29. Fishwick, P.A.: Simulation Model Design And Execution, 1st edn. Prentice Hall, Upper Saddle River (1995)
30. ECRA: Installed Generation Capacity (2012)
31. ECRA: Activities & Achievements of the Authority (English) (2011)
32. International Energy Agency: CO2 Emissions from Fuel Combustion Highlights (2013)
33. SEC: Annual Report. RIYADH (2012)
34. International Monetary Fund: Energy Subsidies in the Middle East and North Africa: Lessons for Reform. Washington, D.C. (2014)
35. Alyousef, Y., Stevens, P.: The cost of domestic energy prices to Saudi Arabia. Energy Policy **39**(11), 6900–6905 (2011)
36. Fattouh, B., El-katiri, L.: Energy Subsidies in the Arab World. Oxford (2012)
37. El-Haik, B., Al-Aomar, R.: Simulation-based Lean Six-Sigma and Design for Six- Sigma. Wiley, Hoboken (2006)
38. Giordano, F., Weir, M., Fox, W.: A First Course in Mathematical Modelling. Nelson Education (2013)
39. Graus, W., Roglieri, M., Jaworski, P., Alberio, L.: Efficiency and capture- readiness of new fossil power plants in the EU. Utrecht (2008)
40. Graus, W., Worrell, E.: Trend in efficiency and capacity of fossil power generation in the EU. Energy Policy **37**(6), 2147–2160 (2009)
41. ECRA: Revised final report updated generation planning for the Saudi electricity sector (executive summary). Riyadh (2006)