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Abstract

In Saudi Arabia, fossil-fuel is the main source of power generation. Due to the huge economic and demographic growth, the electricity consumption in Saudi Arabia has increased and should continue to increase at a very fast rate. At the moment, more than half a million barrels of oil per day is used directly for power generation. Herein, we assess the power generation situation of the country and its future conditions through a modelling approach. For this purpose, we present the current situation by detailing the existing generation mix of electricity. Then we develop a optimization model of the power sector which aims to define the best production and investment pattern to reach the expected demand. Subsequently, we will carry out a sensitivity analysis so as to evaluate the robustness of the model's by taking into account the integration variability of the other alternative (non-fossil fuel based) resources. The results point out that the choices of investment in the power sector strongly affect the potential oil's exports of Saudi Arabia.

Keywords: Electricity Generation Model; Saudi Arabia; Power Generation Mix

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1. Introduction

Saudi Arabia with around one-fifth of the world's proven oil reserves is the biggest oil producer in the Organization of Petroleum Exporting Countries (OPEC). With important investments in the oil sector and low production costs, Saudi Arabia is likely to remain the world's largest net oil exporter. Thus, the Saudia oil production is 544 million of tons (Mt) in 2011 and the net exports reach 355 Mt for the same year (IEA, 2012)

Over the next two decades, Saudi's power generation capacity is predicted to reach 120 gigawatt-electric (GWe) (SEC 2010). The combination of Saudi Arabia's rapidly expanding population and industrial infrastructure, along with low electricity tariffs, has increased the demand on electricity utilities (averaging 8% annual growth over the period). This dramatic load increase has led to shortages, brownouts, blackouts and power rations in various parts of the country. Electricity demand which now stands at around 50GWe, around 200 terawatt hours (TWh) of yearly production, is predicted by the government to increase from 80GWe by 2020 to more than 120GWe by 2030.[1] Figure 1, illustrates this increase of power production.

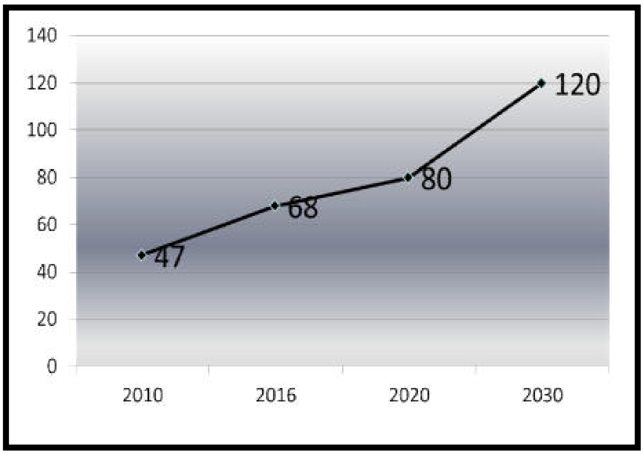

Figure 1: Power generation growth forecast in GW for Saudi Arabia

(Source: SEC/KACARE 2010)

[1] Electricity and cogeneration regulatory authority 2010.

For the time being in Saudi Arabia, 100% of power generation is based on the fossil fuel sources (oil & gas). Figure 2 and figure 3 show respectively the share of different power units and fuels in the power generation mix of the country. Increasing oil and gas domestic consumption and the resulting impact on export revenues is not a very good option for the Saudi government due to both economic and political reasons. In this paper, we evaluate the present and future potential of using non-fossil fuel based energy in the power sector of this country.

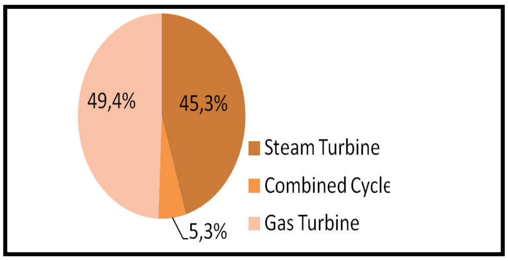

Figure 2: Existing generation capacity profile in Saudi Arabia

(Source: SEC 2010)

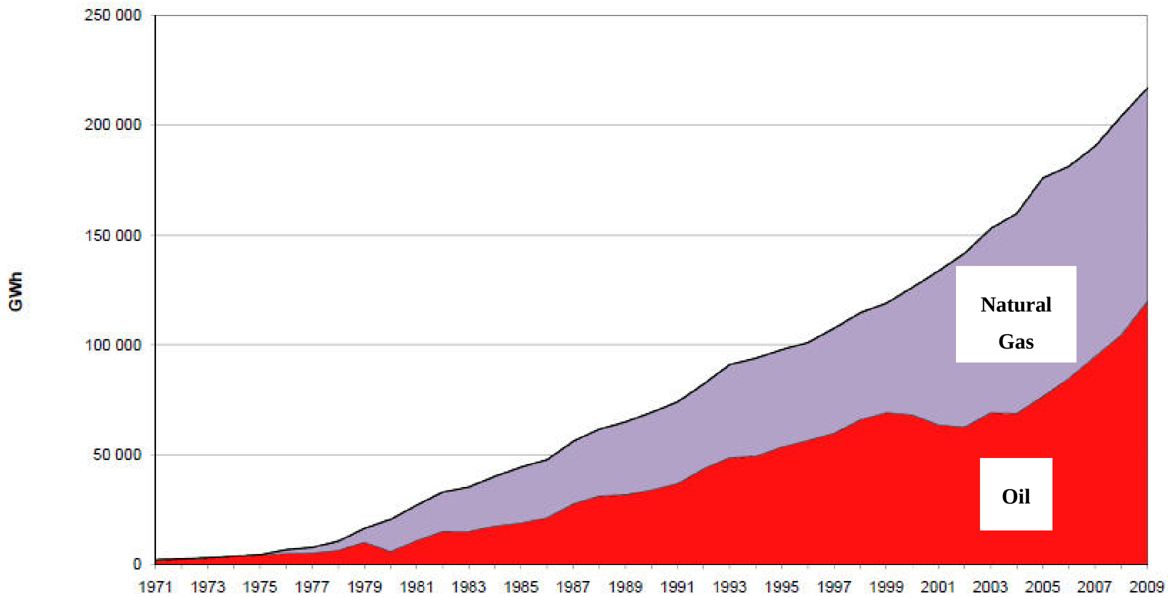

Figure 3: Electricity generation by fuel in Saudi Arabia (Source: OECD/IEA 2011)

A linear programming optimization framework was used to assess the costs and savings of expanding the role of non-fossil fuel based power sources in electricity supply. LP (Linear programming) cost minimizing is an approach that systematically evaluates potential power supply to satisfy the demand at the best societal cost. In this study, we analyse what the incremental cost would be if each sources of power generation were to integrate the electricity supply of the country. In pursuit of this objective, we provide a review of relevant non-fossil and fossil based power unit choices on the basis of resource potential, cost and economic benefits. Several choices of technologies that are or are expected to be technically and economically feasible over the next two decades have been identified and incorporated into the modelling effort.

2. Methodology

Electricity generation should be provided by a large set of power plants which are characterized by different technologies associated to a very large spectrum of fixed and running (variable) costs. Consequently, this leads to an optimal usage and investments so as to satisfy the current and future demand. Optimizing the overall electricity cost of production from different types of plants enables us to rank the existing production units. Indeed, when the electricity demand increases and the available power (in the lowest cost category) is not enough, producer must switch to the generation unit whose cost category is just one step above the previous one. In other words, we rank the use of power plants according to their growing variable cost (so-called "merit-order" process).

The main contribution of this study is to analyse an optimal pattern of the Saudi power generation mix through an LP model (based on the above-mentioned structure) and to reveal the impact of renewable and nuclear integration into the electric system under different penetration-range scenarios. Afterwards, the financial and economic gains (or perhaps losses) will be quantified by looking at the amount of fossil-fuel probably released and injected to the market instead of internal/national usage in the power sector.

Total electricity generation cost minimization, is one of the main modelling approaches in power generation modelling. Examples of such models include POLES[2] (Criqui 2001), MARKAL[3] and TIMES[4] (Loulou et al. 2004). The main idea of these models is to explain electricity prices from the marginal generation cost. In this case, assumption over the future electricity prices does not have to be made. Focusing on minimum generation cost implies minimizing the cost to be transferred to the final consumers, irrespective of the electricity price. The key advantage of this method is to analyse the producer behaviour facing with a mix of deferent types of constraints such as economic, technical and environmental ones. Our approach is similar, in the way that we develop a model where the total costs are to be minimized under certain constraints and scenarios developed in the next section.

3. Power Generation Means in Saudi Arabia

Before the power generation model construction, we analyse the potential of different non-fossil fuel based technologies such as geothermal, wind, solar and nuclear in Saudi Arabia. Feasibility studies have been realized in order to identify the most suitable and reliable technologies for this region based on the technical, economic and geographical characteristics. Due to the climate and regional properties of this country, some power units are not supposed to be useful and adapted to the national generation mix. In the following, we analyse each technology in detail and try to find out those who can be considered for the Saudi power generation mix from climatic, economic and technological point of view. Finally, the existing thermal power units in Saudi Arabia have been described.

[2] Prospective Outlook on Long term Energy Systems
[3] MARKet ALlocation
[4] The Integrated MARKAL-EFOM System

3.1. Geothermal Energy

While not really abundant, geothermal energy potential does exist in Saudi Arabia (Alnatheer 2006). This technology is not entirely a renewable resource since the geothermal wells can be depleted over time. These resources belong to two types of technology, either hydrothermal or hot dry rock. Binary and flash technologies are the main approaches generally used to extract heat from geothermal wells. Although initial investment costs of the plant are relatively high, geothermal energy could become economically competitive (on a life cycle basis) to other sources of power generation (Boyle 2004).

Some studies have suggested the potential of combined solar and geothermal power so as to provide water and electricity in Saudi Arabia (Oktun & Sayigh 1976). Saudi Arabia is somehow rich in terms of various geological features, with around 10 hot springs located in the regions of Gizan and Al Lith in the southern part of the country (Taleb 2009). Some of these thermal springs could be utilized for electricity generation, even though none have yet been exploited (Lund et al. 2005). Alnatheer (2006) argued that the exploitation of geothermal energy in Saudi Arabia is not cost-effective, even when compared with other renewable sources such as solar and wind power. Moreover, a set of renewable power sources scenarios were developed for Saudi Arabia in a study provided by Al-Saleh et al. (2008) in which the prospects of geothermal energy (both power and heat) were not considered as being sufficiently viable. Taleb (2009) identified both technical and non-technical barriers of geothermal energy utilization in Saudi Arabia. The most important reasons which are claimed are the uncertainty regarding available resources (the lack of technical feasibility studies), the lack of financial incentives and high capital cost of this technology (compared to the power generation based on oil), and the poor public acceptance of renewable energy sources in general and particularly geothermal one and lack of neither academic nor professional training in this field.

At last, due to the above mentioned arguments and existing barriers for the development of this technology in Saudi Arabia, we don't consider the integration of geothermal energy as an option for the future energy mix of the country (neither in the optimization model nor in its associated scenarios).

3.2. Wind Energy

There are many locations in Saudi Arabia that the annual speed of wind (averaged) goes beyond 4 m/s at a height of around 20m. Al-Abbadi (2004) showed that the wind annual average speed can reach even 5.7m/s and 5.4m/s in Dhulum and Arar sites respectively for speeds higher than 5m/s for around 50% of the time. In spite of this rather high potential wind power in Saudi Arabia (compare to the other Persian Gulf CCG countries) there is not an upright future for this energy in this country, at least in the short and medium terms. In fact, the highest and most optimistic wind energy potential in Saudi Arabia was estimated to yield around 20 TWh per year (Alnaser 2009). This is a considerable amount seeing the climatic conditions of the region but compare to the other renewable options such as solar (both concentrated and photovoltaic); it does not represent even 1% of their estimated potential.

Therefore in this study we won't consider wind energy as a high potential option for the future power generation mix of the country due to its negligible potential and huge costs (currently) compare to conventional plants. Moreover, there has not been any official declaration from the government or any energy authority regarding a vast investment in this area up to now. And the existing projects are all at a very small scale (decentralized) or are just under R & D and pilot stages.

3.3. Solar Energy

Solar energy has been accepted as a key source of energy for the future in Saudi Arabia. Saudi Arabia has enormous potential for exploiting solar energy. Its geographical location, widespread unused desert land and clear skies, make it an excellent candidate for this technology. The average solar radiation falling on the Arabian Peninsula is around 2200KWh/m² per year (Hepbasli & Alsuhaibani 2011).

According to the Saudi Solar Radiation Atlas which is a governmental document concerning the solar radiation of the country, Saudi Arabia has vast areas subject to strong GHI[5] and fractions of DNI[6] which are respectively ideal for Photovoltaic (PV) and Concentrating Solar Power (CSP) technologies.

Just for giving an example, within about 2000 KWh/m²/y of DNI, it has been estimated that the potential annual energy yield of CSP technology in Saudi Arabia is around 124,560 TWh.[7] This amount represents around 650 times the total electricity consumption of the country in 2009. This reflects the fact that CSP technology must be considered between the most suitable renewable technologies in the Saudi's future energy mix. Hence, in this study and in our model's scenarios we do consider solar option in the future electricity generation mix of the country. Load factors considered for both PV and CSP technologies in the model are respectively equal to 0.2 and 0.34 (K.A. CARE 2010).

3.4. Nuclear Power

Nuclear power generation provides around 7% of the world primary energy supply and about 14.7% of the electric power generation.[8] Increasing improvements in safety means, using experience, plant availability and of course economy, made nuclear energy competitive with other means of electricity generation. For the time being 436 nuclear reactors generate around 370 GW of electric power all around the world (IEA 2011). While there are many reactors in operation in the US, Europe, Japan and China, the other regions of the world do not use this

[5] Global Horizontal Irradiance which is equal to the total solar radiation.
[6] Direct Normal Irradiance which is equal to direct beam radiation.
[7] German Aerospace Center (DLR) report, 2010. *Concentrating Solar Power*.
[8] Nuclear Energy Outlook 2008.

technology within a significant amount. In Africa, it is only South African Republic which has two operating reactors providing only 1.8GWe of electricity. In the Middle-East only one nuclear power plant with the capacity of 1GWe is operating in Iran. Despite of the large diversity in term of design, only two types of reactor dominate nuclear power generation. 85% of operating reactors are the light water type reactors including the Russian RBMK reactor. Majority of these reactors are Pressurized Water type reactors and the rest of it are boiling water ones. Both technologies use slightly enriched Uranium (3-5%) as fuel which does not create any potential proliferation risk. Nuclear fuel, in contrary to oil and gas resources, has extended life time and is not considered as a depleting resource.

Therefore, this technology is not a negligible source of electric power choice for Saudi Arabia as an energy source (the model will tell us more about its economic viability) and we consider it in our model's scenarios. Moreover, Saudi government has recently announced its intention to use this technology for the future power generation. According to the government officials, Saudi Arabia plans to build about 16 nuclear power reactors, with the capacity of around 20GWe, over the next 20 years by spending around $7 billion on each plant. This $112 billion investment plan (total 16 reactors) is supposed to provide one-fifth of the Saudi Arabia electricity generation for residential and industrial usage and in some cases for desalination of sea water which is very critical for this country. Most likely, the reactor locations will be along the Persian Gulf or Red Sea.

3.5. Thermal fossil-fuel-based power plants and their situation

Currently, electricity production in Saudi Arabia comes thoroughly from thermal equipment family, except coal and nuclear ones. Hence, the current electricity supply system in our optimization model is composed of only this type of power plants. Their operating principle is as following: combustion can heat a fluid which produces, in a turbine, mechanical energy converted into electrical one by a generator. There are currently three main types of thermal fossil-fuel-based power plant in Saudi Arabia:

First, the gas turbines whose exhaust gases produced directly goes for the energy required to drive the alternator. Efficiency of this mode of production is relatively low (15 to 30%) and operating costs, including fuel which accounts for most of them, are very important. However, gas turbine power plant has two major advantages over competing modes of production: first the investment cost is relatively low and secondly they have the distinction of being immediately available with a very low starting time. Gas turbine is an ideal element when used for a short period, when it is necessary to significantly and rapidly increase the production capacity to meet the demand. Hence, they are very adapted to be used during peak loads. Hail-2 power plant located in the Hail in Saudi Arabia is an example of this sort of thermal unit.

Second type is the combined cycle, which consists of installing counter-pressure (steam turbine) in addition to the gas turbine so as to maximize the electricity production. Indeed, it offers the opportunity to at least triple the production of electricity for the same heat, which can lead to overall efficiency of 50 to 60%. Ras Tanura power plant located in the Ash Sharqiyah belongs to this family of thermal units.

Finally the conventional thermal stations with two versions: the thermal oil and thermal coal. The operating principle consists of burning oil or coal to heat a fluid (most often it is the water steam) and then expansion of this fluid through a turbine that drives a generator. Despite a low overall efficiency (electricity produced is only 30-35% of energy input); it remains higher than that of Gas Turbines. In addition, operating costs are relatively low and allow to partially offsetting the heavy investment costs. However, these plants are very slow to start and ramp up, so they are not suited to respond quickly to a sudden increase in demand.

Shuaibah power plant with the capacity of 3*400 MW (gross) is an example of thermal oil units.

Figure 4 shows the locations of these power plants for all the four operating areas in Saudi Arabia: Eastern, Central, Western and Southern.

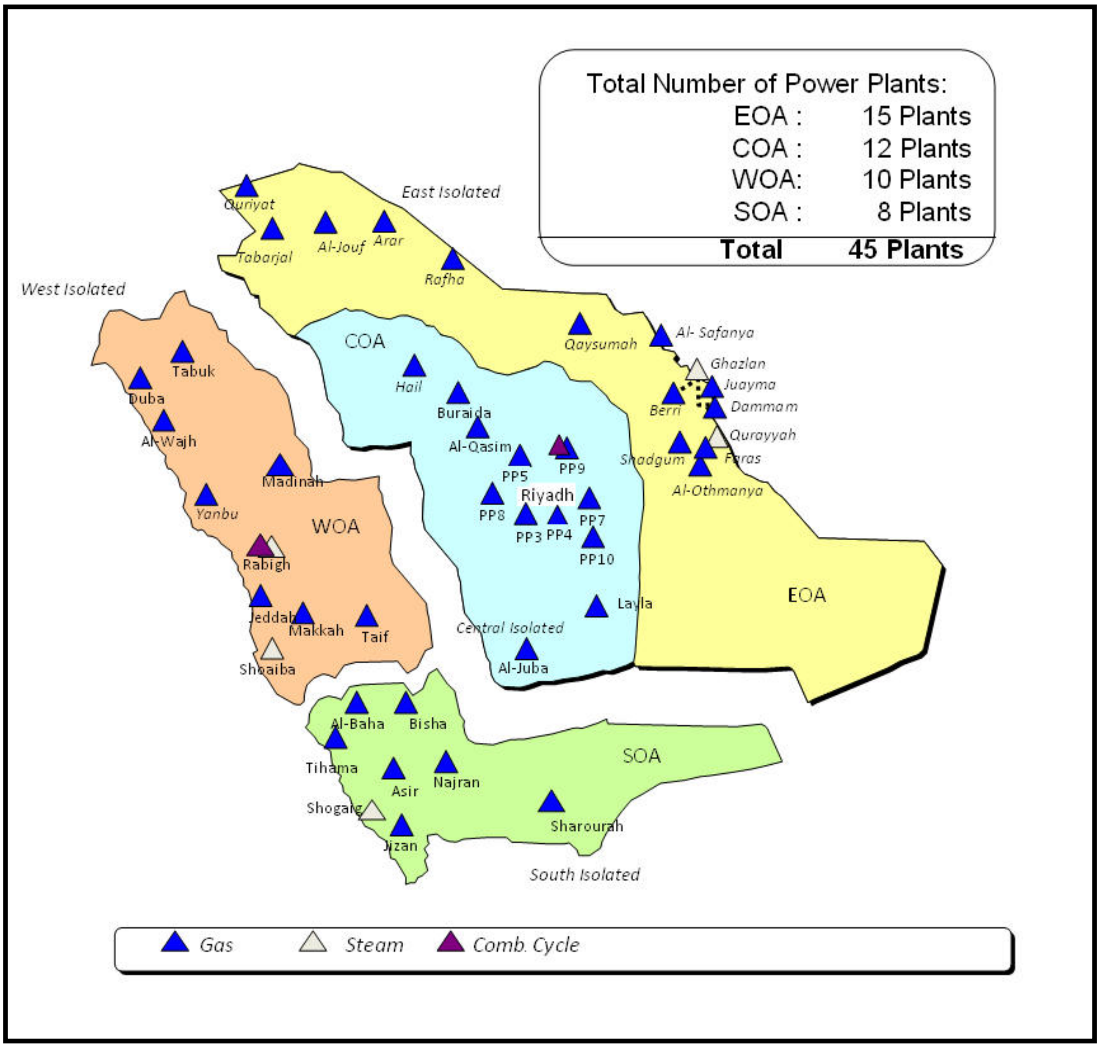

Figure 4: Existing power plants in Saudi Arabia (Source: Saudi Electricity Company 2009)

4. Modelling frame-work

We model the current power generation mix structure of the country by using GAMS (General Algebraic Modelling System) software. This cost minimization model contains the objective cost function that must be minimized and the demand constrains that have to be satisfied. For static short-term optimization (base year 2010), the production capacities must be respected and in the case of long-term optimization, investments are allowed. The model structure is as following:

$$\text{Min} \left[\sum_i \sum_s H_s \times E_{it} \times p_{ist} + \sum_i I_{it} C_{it} \right]$$

$$\frac{1}{\tau_{is}} P_{ist} \leq C_{it}$$

$$\sum_i P_{ist} \geq D_{st} - AP_t$$

In which,

P_{ist} is the Power loaded on the grid by each equipment of type *i*, for the season *s* in year *t* (MW)

C_{it}: The capacity of the equipment of type *i* in year t (MW)

H_s: Length of the season *s* (hours)

I_{it}: Investment cost of each unit of production ($/kW)

E_{it}: Variable cost of production for each equipment *i* ($/kWh)

D_{st}: Called power on the grid for the season *s* (MW)

τ_{is}: Coefficient of availability in each season for each equipment *i*

AP_t: Supply of the must-run or auto-producers (MW) if there is any

The variables of the model are the powers loaded, coming from each type of unit (i) for each season (s) in year (t).

4.1. Demand

We know that the most important feature of electric power is its almost non-storability. This implies that production must be adjusted instantaneously to the consumption and ensures that equipment is functioning at full capacity at the time of peak demand, and even extreme spikes. Therefore, the load curve, which represents the continuing evolution of the power demand over time, is one of the fundamental elements of the power system optimization model.

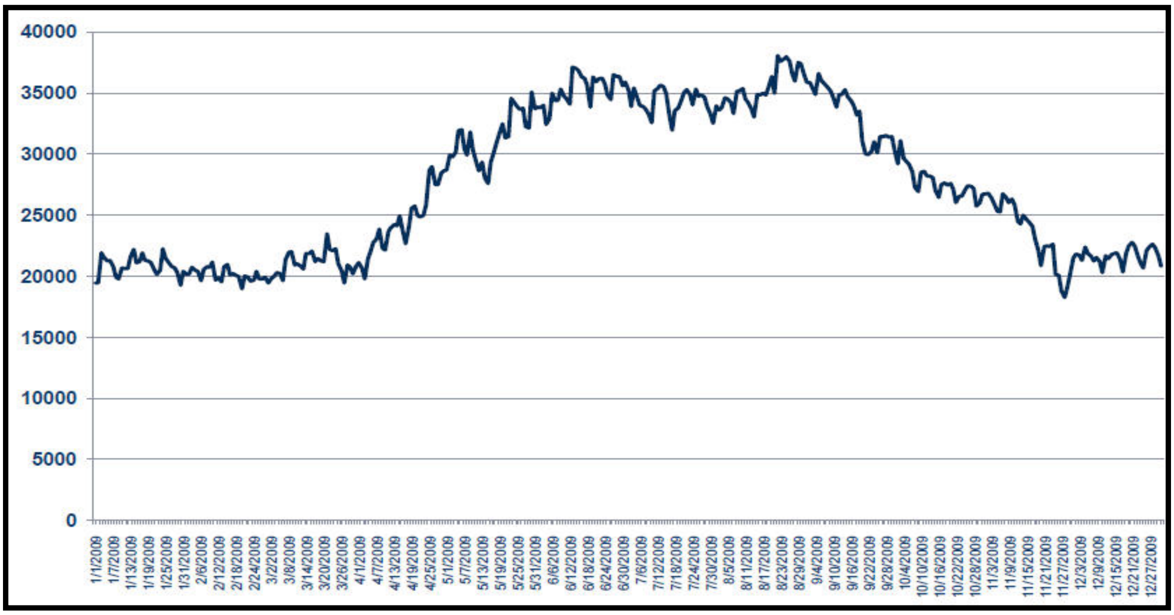

Figure 6: Annual load curve for Saudi Arabia in 2009

(Source: Electricity & Co-generation Regulatory Authority)

Figure 6 represents the load curve of Saudi Arabia during year 2009. This demand structure has been used in the model for simulating the current generation mix of the country. As it was mentioned before, the total electricity demand of the country will reach 80GWe in 2020 and 120GWe in 2030 (SEC 2009 and ECRA 2010). Hence, future demand curves considered in the models for the year 2020 and the year 2030 increase proportionally to this demand structure up to the before-mentioned amounts.

The overall demand for electricity in Saudi Arabia has been refined by different seasons. They are defined in Table 1.

Model's parameter	Seasonal periods in Saudi Arabia
S1	Summer
S2	Spring and Autumn
S3	Winter

Table 1: Seasonal definition

Demand corresponding to each season will be the demand to be met by using the available generation capacity. The reason for which three periods have been defined is the fact that in each period, the load behaviour is quite uniform. This seasonal division is shown in the Figure 5.

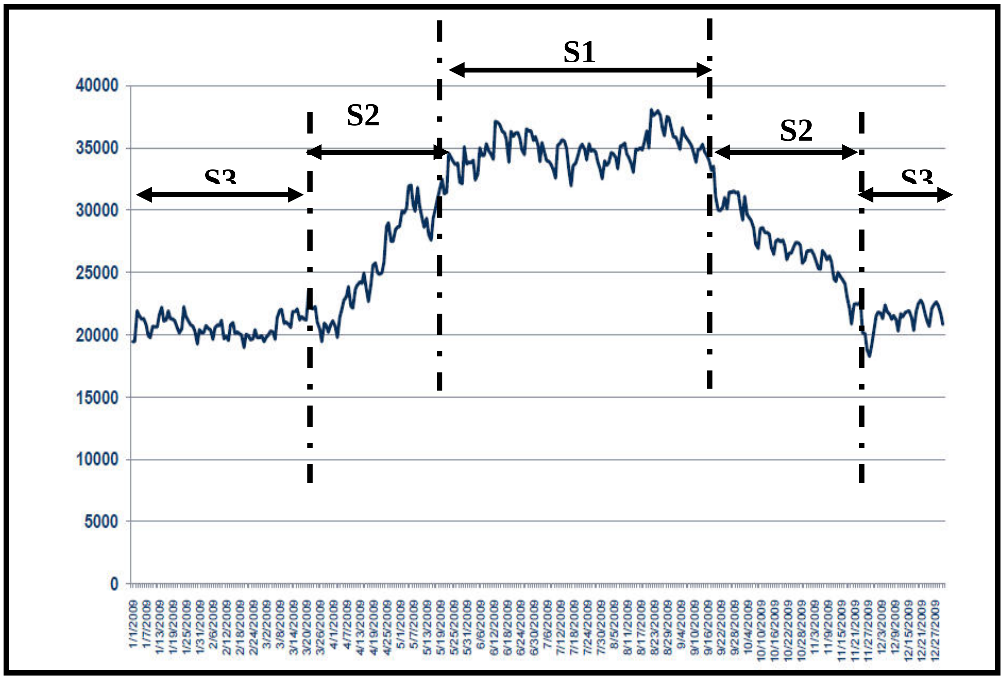

Figure 5: Seasonal periods' definition over an annual loading curve of Saudi Arabia's power sector (ECRA 2010)

Seasons

* Winter (S3): December, January, February, March

* Spring & autumn (S2): April, May, October and November

* Summer (S1): June, July, August and September

In Saudi Arabia, periods when electricity demand is the highest correspond to the months of June, July and August and up to the end of September (S1). In our model we presume the same amount of hour for each season (S1, S2 & S3) which is not far from the reality.

$$S1 = S2 = S3 = \left(\frac{8760}{12}\right) \times 4 = 2920h$$

4.2. Load factors and Back-up Plants

The annual load factor of an electrical power plant demonstrates the ratio of the power generated by a plant and the theoretical maximum that could be produced over the year (8760 hours). For the nuclear and fossil-fuelled units, this annual load factor is simply determined by planned unavailability due to the maintenance or refuelling or shutdowns when the plant is not considered for dispatching. Assuming base-load generation, in this study we applied a generic 85% load factor for our nuclear and fossil-fuel based power units. Nevertheless, for solar sources, the output of the plant is impacted not only by the aforementioned unavailability factors but also by site-specific availability of solar irradiation. In this study, as it was already said in the section 3.3, we consider the load factors of 20% and 34% respectively for PV and CSP sites.

Moreover, in an attempt to cover the risk related to the intermittent production of solar power plants, we have introduced in the model a necessary investment in the fossil-fuel power plants that play the back-up role in case of insufficient capacity factor that could happen during peak consumption. In most of the regions around the world, lowest values of capacity factor for the intermittent technologies are observed during peak demand periods. On the contrary, in Saudi Arabia the capacity factor of solar technologies does not vary too much during peak hours because of the climatic characteristics of the country. Peak hours generally take place around 3 p.m. in summer when we have proper shining factor for the solar technologies.

In our model the absence of production from intermittent means is compensated by combined cycle plants and/or gas and fuel turbines which have around 100% of availability (capacity factor equals to 1) except for the ex-ante planned maintenance. So the total yearly cost of power generation, for the renewable-integrated power mix, includes these back-up costs.

4.3. Fuel costs

Fuel costs are calculated per MWh on the basis of price information available for gas, oil and uranium (IEA 2011 and World Bank 2011). In the case of gas price, we considered the average price of large gas producing countries like Canada, USA, Australia and Russia (6 $/MMBtu), where domestic prices of natural gas can decouple from international market prices. This averaged price could be a good representative of international gas price for Saudi power sector, although the real (strongly subsidized) domestic gas price is much lower for the Saudi power producers. And for oil, Dubai dated average price over the last 4 years has been considered (80 $/bbl), even if sometimes we use oil products in power generation which are more or less expensive than the crude itself. Despite the fact that in this study we assume stable fuel prices for the matter of simplicity; this should not be considered or interpreted as any sort of prediction of stable energy markets.

In the case of uranium the task is entirely different because the price of U_3O_8 (so-called yellow cake) only counts for about 5% of the total cost of power production and therefore any volatility in the price has very small impact on the total cost of electricity generation. Spot-market plays a very limited role for the nuclear fuel (at different stages) and most of the activities are carried out under long term contracts. In the model we assume the nuclear fuel price of 7 $/MWh until fuel fabrication process, plus 2.5 $/MWh more for transport, storage and eventually reprocessing and final disposal (IEA & NEA 2010).

4.4. Technical properties and other costs

Apart from fuel costs, which have already been described, the other variable and fixed costs of each type of power plant are also essential for the decision making process of the model. Plants' life-time and efficiency should also be incorporated in the model so as to be able to evaluate the potential amount of electricity (from technical point of view) that each power plant could produce. Table 2 provides the techno-economic properties of various thermal power plants used in the model. These values are derived from the studies of IEA and NEA (2010) on power generation costs.

Techno-economic data for each type of power plant					
Plant type	*Nuclear Plant*	*CCGT Plant*	*Fuel Plant*	*Solar PV*	*CSP*
Efficiency (%)	33	57	38	*	*
Investment cost ($/Kwe)	2050	534	364	3400	3000
Life cycle (years)	60	30	30	25	25
Fix O&M cost ($/Kwe)	46	8	8	50	60
Variable O&M cost ($/MWh)	0.8	1	0.3	0.5	0.5

Table 2 (Source: IEA 2010 Median Case)

4.4. Model's Scenarios

In our model we attempt to analyse the future situation of Saudi Arabia generation mix under different scenarios, respectively ten and twenty years forward. To do so, we assume the most probable scenarios for the electric mix of the country for years 2020 and 2030. Then we calculate the total yearly cost of optimal electricity generation for each specific year and scenario. Figure 10 illustrates different assumed scenarios integrated to the model.

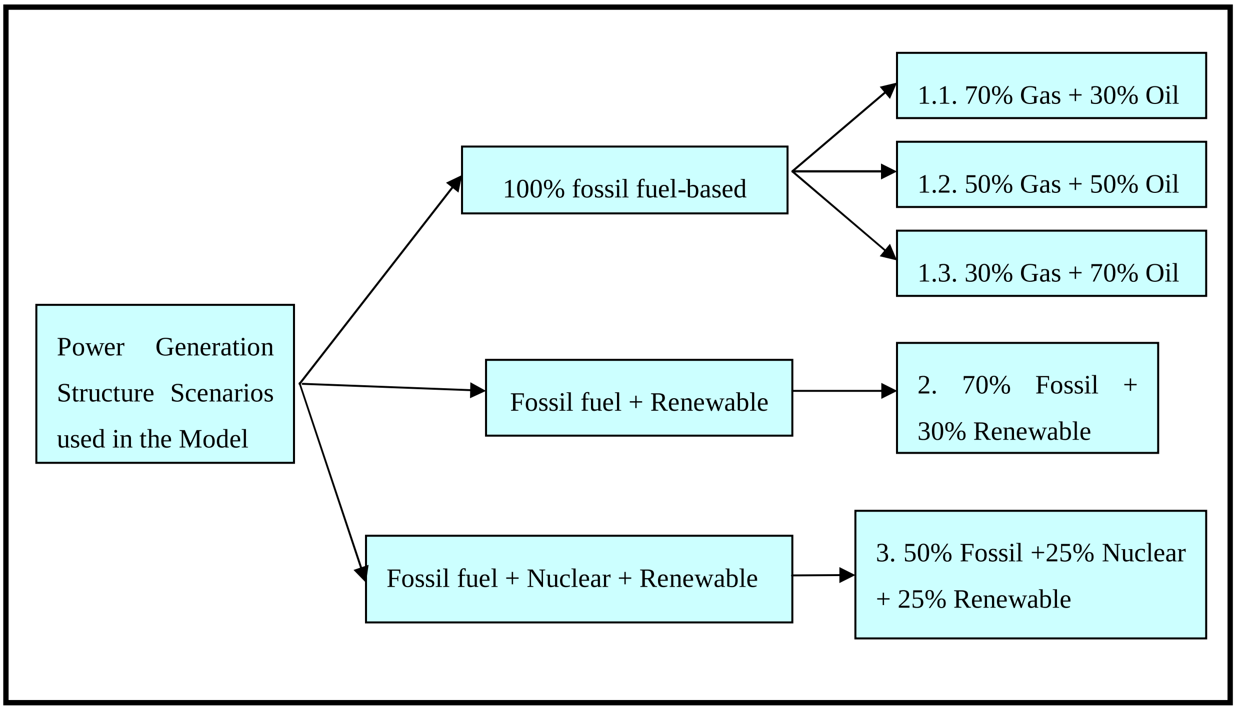

Figure 10: Scenarios considered for the electric power generation mix model of Saudi Arabia

Three main scenarios, including three sub-scenarios, have been considered for the future electricity mix of the country. In first scenario, which is our business as usual and most probable scenario, we continue the power generation of Saudi Arabia by using 100% of fossil-based (Oil & Gas) power plants in years 2020 and 2030. Therefore, there is no investment or construction plan for nuclear and renewable energies. Investments only go for oil-based and gas-based thermal power plants. For this scenario we have defined three sub-scenarios which are as following:

Gas oriented mix (1-1): In which we consider 70% of the electricity production from gas-based power plant and the remaining 30% is provided by oil-based plants.

Fifty-fifty fossil fuel mix (1-2): This is our middle case sub-scenario in which half of the power production is provided by gas–based plants and the other half of it by oil-based ones. This scenario is too similar to the current power generation situation of Saudi Arabia.

Oil oriented mix (1-3): Finally, the last assumed sub-scenario is based on the massive usage of fuel power plants. In this scenario 70% of power is generated by Oil-based plants and the remaining part would be satisfied by Gas consuming power plants.

Our second scenario for the future mix of the country contains both fossil-based and renewable resources. We assume 30% integration of renewable sources in the total generation mix of Saudi Arabia. Only solar power plants, both PV and CSP have been integrated to the model due to their remarkable efficiencies under the climatic situation of Saudi Arabia. The rest of the electric power is afforded by the fossil-based (50%Oil & 50%Gas) thermal power plants.

Finally our third scenario contains all the possible resources of electricity generation (Fossil, Renewable & Nuclear). In this scenario, we assume that half of the generated power is provided by non-fossil based power plants, both Nuclear and Renewable. The share of each technology in the generation mix is equal to 25% of installed capacity.

5. Simulation Results

To calibrate and verify the reliability of the model, we compared the results on a reference year with the observed data provided by IEA Electricity Information and BP Electricity Generation Statistics. Table 3 shows the amount of power production in our base case (reference year 2010) generation mix and those of BP and IEA.

Source	*Power generation*
BP Statistics	*240 TWh*
IEA Electricity Information	*240.3 TWh*
Model Base Case	*239 TWh*

Table 3: Model's base case result validation: power production in 2010

Thereafter we run the model for all the pre-defined scenarios. Figure 11 illustrates the total costs of power generation per year for different structures of generation mix.

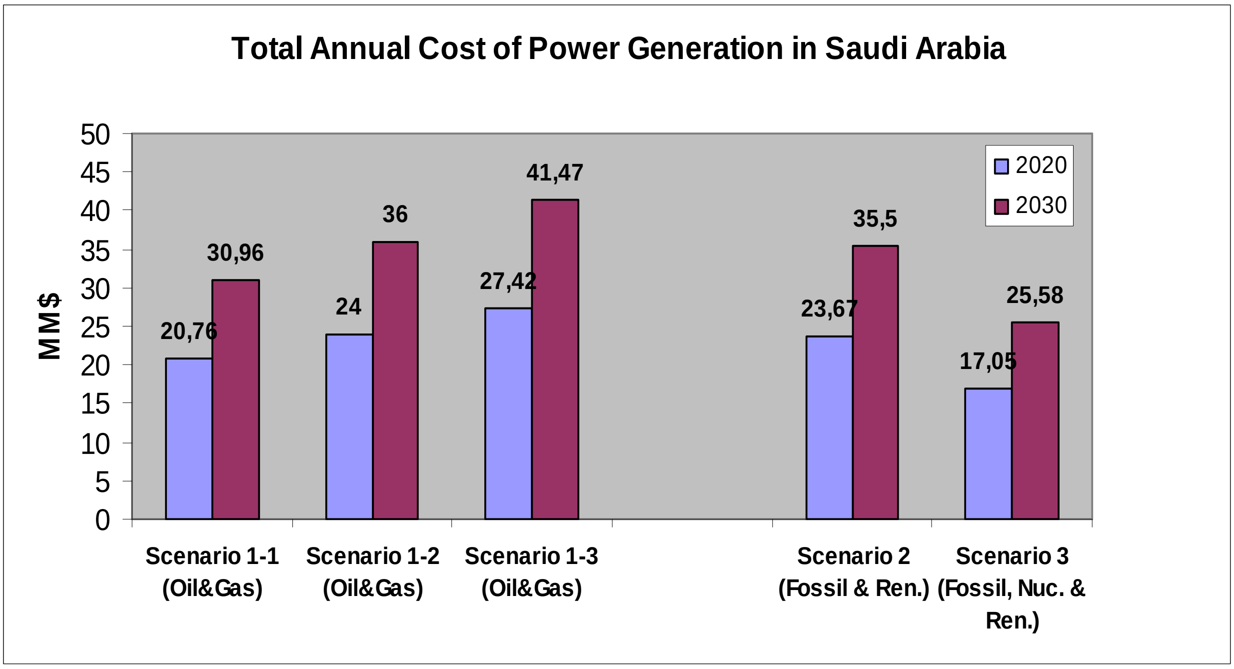

Figure 11

The first scenario (and its three related sub-scenarios) shows us the cost of electricity production during years 2020 and 2030 by using only fossil fuel based power plants. The total cost of generation (minimum and optimal cost of-course) increases dramatically when the integration rate of oil rises in the national generation mix.

Moreover, the cost difference between year 2020 and year 2030 also increases when we switch to more oil dependent mixes. The results for scenario 2, in which we consider 30% of renewable share in the national generation mix, are not far from those of scenario 1-2 suggesting 50% of oil-consuming power plants in the system. However, it is essential to state that, this conclusion is only based on the pure economic insight and if we include also environmental externalities then the result would be different and renewable integration will certainly have more success.

Finally the result concerning scenario 3, both nuclear and renewable integration to the national mix, illustrates the dramatic impact of nuclear plants on the total cost of power generation. For instance, the cost difference between scenario 3 and scenario 1-1 (which consumes mostly gas compare to more expensive oil) has been estimated by the model to be around 3.7 billion dollars in 2020 and even higher in 2030 (5.38 billion USD).

6. Sensitivity & Break-even Analysis

In order to perform a reasonable sensitivity analysis, we have chosen to test the impact of changes in the discount rate on a total generation cost calculation. The reason behind this choice is the fact that the discount rate has more significant impact on the generation cost for capital intensive centralized generation units and at the same time it is the most uncertain factor in the case of Saudi Arabia. Oil and gas technologies and their associated O&M and fuel costs are already very well known in Saudi Arabia and therefore we are looking for a factor (which is the discount rate in our study) that can remarkably impact the new power units such as renewable and nuclear ones. Sensitivity analysis over the other underlying parameters of generation cost, such as fuel costs, has not been considered in our study because of their rather negligible influence over the total cost of nuclear & solar power units. In the particular case of solar plants, generally load factor variation has the most important weight in the total cost sensitivity analysis and to a lesser extent the construction cost. However, in the case of Saudi Arabia as the load factor is somehow stable (due to the regional climatic condition and important share of CSP) we focus more on the construction and initial investment costs.

The discount rate that we have considered in our model is equal to 8% based on a set of governmental studies and information regarding investments in power sector in Saudi Arabia (KACARE 2010). Sensitivity analysis has been performed for all the three scenarios. The impact of several discount rates on total annual generation cost for these three scenarios is shown in the Figure 12 for discount rates ranging from 5% to 15%.

Logically, within higher capital cost, the total cost for all scenarios increases. On one hand, we see a relative stability of fossil-based (gas and fuel) power plants cost and therefore their almost insensitivity to cost of capital changes. On the other hand, nuclear power units, in spite of having a lower initial investment cost ratio rather than solar technologies, are the most sensitive units to discount rate changes, too simply because they have much longer construction times than any other power unit. The construction time for a nuclear plant in the model is equal to 5 years while for solar plants is only 1 year. This high sensitivity of nuclear power units compare to solar ones can be easily revealed by comparing the sensitivity results (comparative growth rate of each chart) of the two non-fossil based plants integration scenarios (2 & 3). Therefore, financing structure and capital costs are of significant importance to investments in nuclear capacity.

Break-even analysis has also been performed for aforementioned scenarios at different discount rates. The outcome will help us to make a more rational (from economic point of view) technology choice for the national power generation. As it is shown in figure 12, at the discount rate of 8%, our pure fossil based scenario intersects the 30% renewable penetration scenario. It means that at the discount rates greater than 8%, a fossil-based generation mix is more economic than that of scenario 2. However, scenario 3 (with both nuclear and renewable penetration) remains the most economical solution. This situation continues until the discount rate of 13%. Thereafter, the fossil-based scenario becomes again the best scenario (economically speaking) compare to the other two. It is important to remark that with a higher integration of gas plants in to the system this second break-even point could be pushed even more to the left. In other words, higher percentage of gas power plants in the pure fossil-based national mix will promote the first scenario (under the current gas price assumptions of-course).

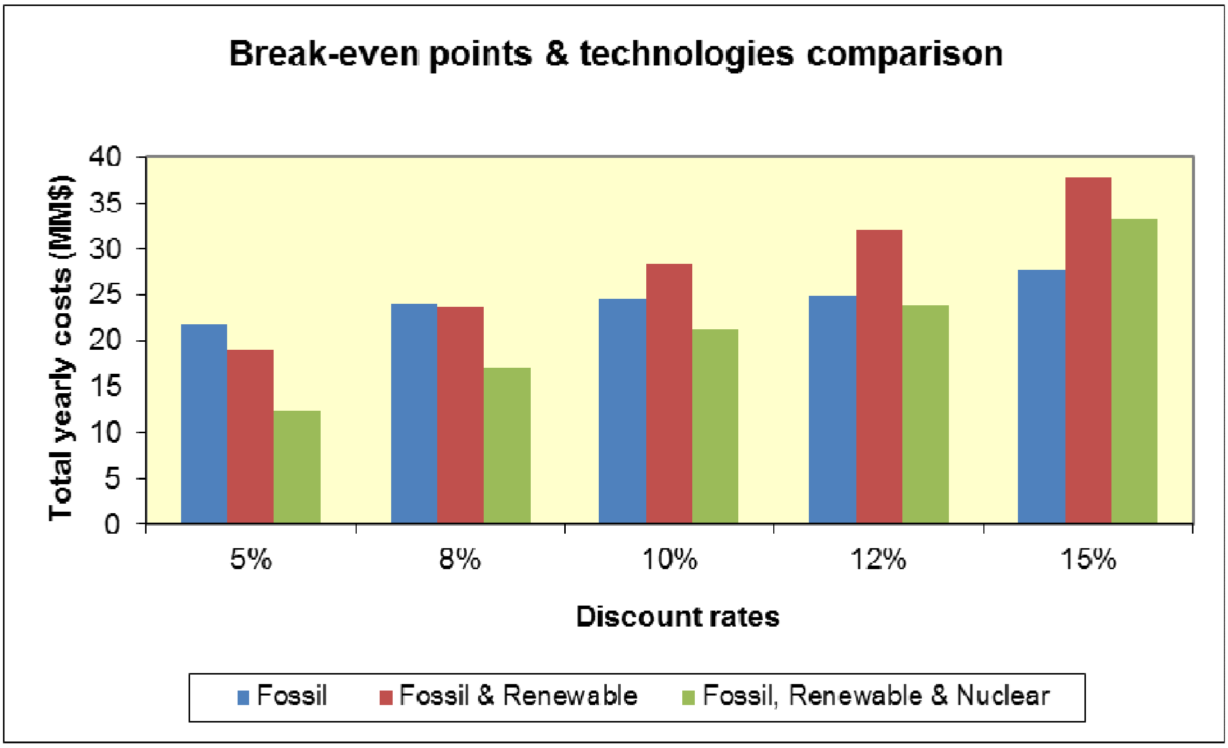

Figure 12

There is another interesting observation for our two non-fossil based scenarios at the discount rate of 12%. From this point the distance between the two scenarios becomes narrower. It shows the fact that after 12% of discount rate the profitability of scenario 3 over the 2nd one becomes less and less significant. It confirms the higher sensitivity of nuclear power plants to discount rates than that of renewable energies such as solar in our case.

7. Economic Analysis and Interpretation

Figure 13 shows us the important share of oil consumption in the Saudi Arabia's total oil production. In 2010, around one third of the total oil consumption went for power generation via fuel power plants.

1000b/d

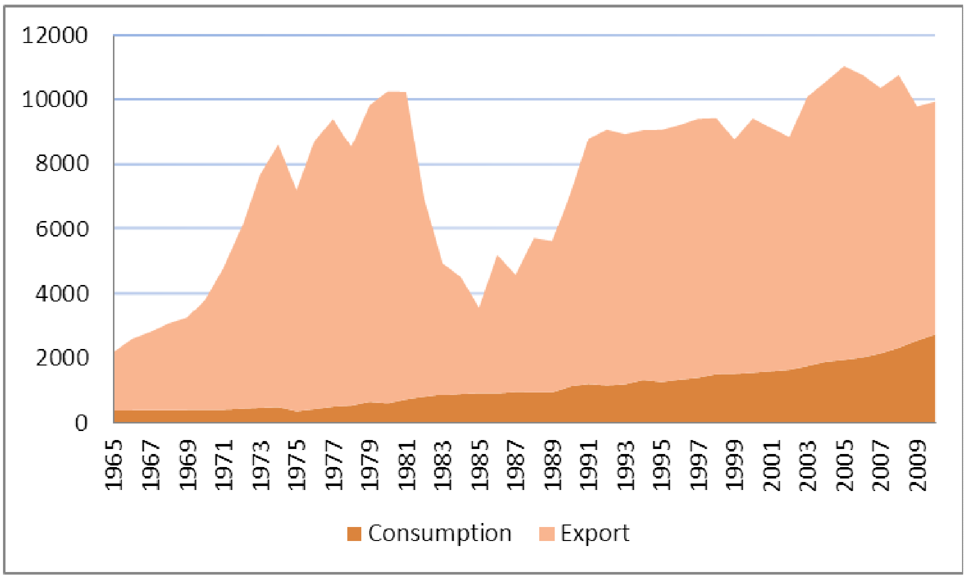

Figure 13: Saudi Arabia's oil production since 1965

(Source: BP, 2011)

This amount will proportionally increase if Saudi Arabia continues to generate electricity under its current production structure. That means, keep using oil-consuming power plants for 55% of the total electricity generation of the country.

Under the before-mentioned demand increase scenarios, total oil consumption of Saudi Arabia for power generation will reach 1.5 mbd and 2.25 mbd, respectively in 2020 and in 2030. These numbers can become even higher if the share of oil-fired power plants goes beyond 55% of the national generation mix. As a matter of fact, Saudi Arabia can release at least 1mbd of crude oil by decarbonising its power generation. For instance, under scenario 2, (30% of renewable integration into the generation mix) Saudi Arabia will be able to put aside around 1.05 mb per day in 2020. This number could be easily doubled if the generation mix moves toward scenario 3 and even tripled by going beyond 25% of nuclear integration.

Eventually, switching from first group scenarios (1-1, 1-2 & 1-3) to non-fossil fuel based scenarios will not only reduce the generation cost of electricity but will also remarkably increase the oil export revenue of Saudi Arabia.

8. Conclusion

The results of the simulations of the power sector in Saudia Arabia shows us that for various scenarios of fossil-based power plant replacement, by both renewable & nuclear ones, we can observe a remarkable cost reduction in the total power generation cost of Saudi Arabia. The same thing does not happen in the case of generation mix extension by using only renewable power plants.

By exporting the amount of oil extracted out of the generation mix (released thanks to the fuel power plant replacement) Saudi Arabia can make a massive financial and political benefits. Financial benefits, not only because of the considerable reduction in the total generation cost of electricity, but also, by raising the amount of crude oil export. Political benefits, due to an increase in their spare capacity of oil production (providing more flexibility for Saudi Arabia in terms of oil production) and consequently, an increase in its role in the OPEC and international oil market.

At the end we should emphasize on the fact that these benefits could be realized only in the case that we give an opportunity cost to the fuel that we use in the power plants. Without this hypothesis (e.g. cheaper fuel cost compare to the international market price due to subsidies) the major part of the variable cost will be vanished in the model and the benefits would become negligible.

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