Photovoltaic Power Plant Fossil Fuels Savings in an Isolated Electricity Generation System in Saudi Arabia

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Introduction

Overview

The Kingdom of Saudi Arabia is in possession of about 15.6% of the world's proven crude oil reserves, only second to Venezuela. The crude oil production of Saudi Arabia was at 585 Mt and the net exports exceeded 375 Mt in 2016 [BP (2017)], making Saudi Arabia by far the biggest crude oil producer in OPEC. It is also the biggest crude oil exporter in the world having significant investments in the oil sector and low production costs. In addition, crude oil is Saudi Arabia's main source of income and any problem that affects this precious natural resource can seriously harm its economy.

Moreover, Saudi Arabia has 4.5% of the world's proven natural gas reserves. It produced about 109.4 Bcm in 2016 [BP (2017)], although all Saudi natural gas is used domestically and not exported.

Nevertheless, there exists a serious energetic problem in the country. Crude oil and natural gas consumption in Saudi Arabia has grown at an average annual rate of 5.4% and 5.1% since the year 2000 reaching 167.9 Mt and 4.7 Bcm in 2016 respectively [BP (2017)], raising concerns over the ability of the country to maintain future crude oil exports or even becoming a net importer of crude oil in a little more than 20 years [Lahn and Stevens (2011)].

One of the main reasons for the increase in the local crude oil consumption is the fact that the absolute majority of electricity generation in Saudi Arabia is based on fossil fuel sources (Natural gas, Crude oil, Heavy fuel oil and Diesel) [ECRA (2016)].

Furthermore, the rapidly growing population and the expanding industrial infrastructure, along with low electricity tariffs, is continuously increasing the demand on electricity and consequently fossil fuels, see Figure 1.

The increase in electricity consumption and the huge consumption of fossil fuels has caused visible damage to the environment in various forms. The demand for electricity is predicted by the Electricity and Cogeneration Regulatory Authority of Saudi Arabia to increase from 80 GWe by 2020 to more than 120 GWe by 2030 [ECRA (2010)].

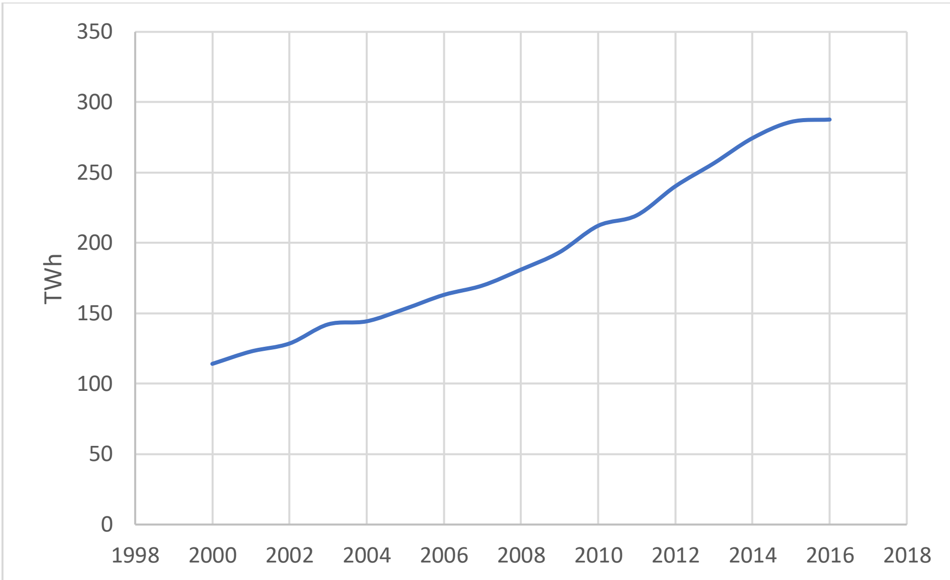

Figure 1 Evolution of SEC consumed energy. (Source: SEC 2014, ECRA 2016)

Research Objective

The objective of this research is to determine how much fossil fuel could be saved yearly by optimizing the power generation mix in an isolated electricity generation system of a certain city in Saudi Arabia by means of investing in a specific kind of sustainable utility scale grid connected renewable energy power plant without an energy storage facility.

Considering a 14-criteria evaluation model for the selection of a renewable energy technology in Saudi Arabia solar, photovoltaic solar energy is the best option [1].

Thus, a free standing fixed frame grid connected crystalline silicon photovoltaic power plant systems will be considered in this research, see Figure 2.

The year 2016 is chosen as a case study for the necessary calculations since it is the most recent year with available data.

In this research, the decision criteria are derived based on the study objective, the existing literature and accessibility to the electrical database. The raw data of this research is collected from different resources including governmental agencies, open sources, and related literature.

Photovoltaic Technology

Photovoltaic power plants, also known as solar parks, are large-scale photovoltaic systems designed for the supply of electricity into the grid at a utility scale.

Solar radiation is converted to DC electricity by means of photovoltaic modules following the photovoltaic effect. An inverter converts the array's power output from DC to AC, and connection to the utility grid is made through a high voltage, three-phase step up transformer.

This type of plants is considered to have a minimum life span of at least twenty-five years and has relatively low maintenance costs in comparison to other energy producing technologies.

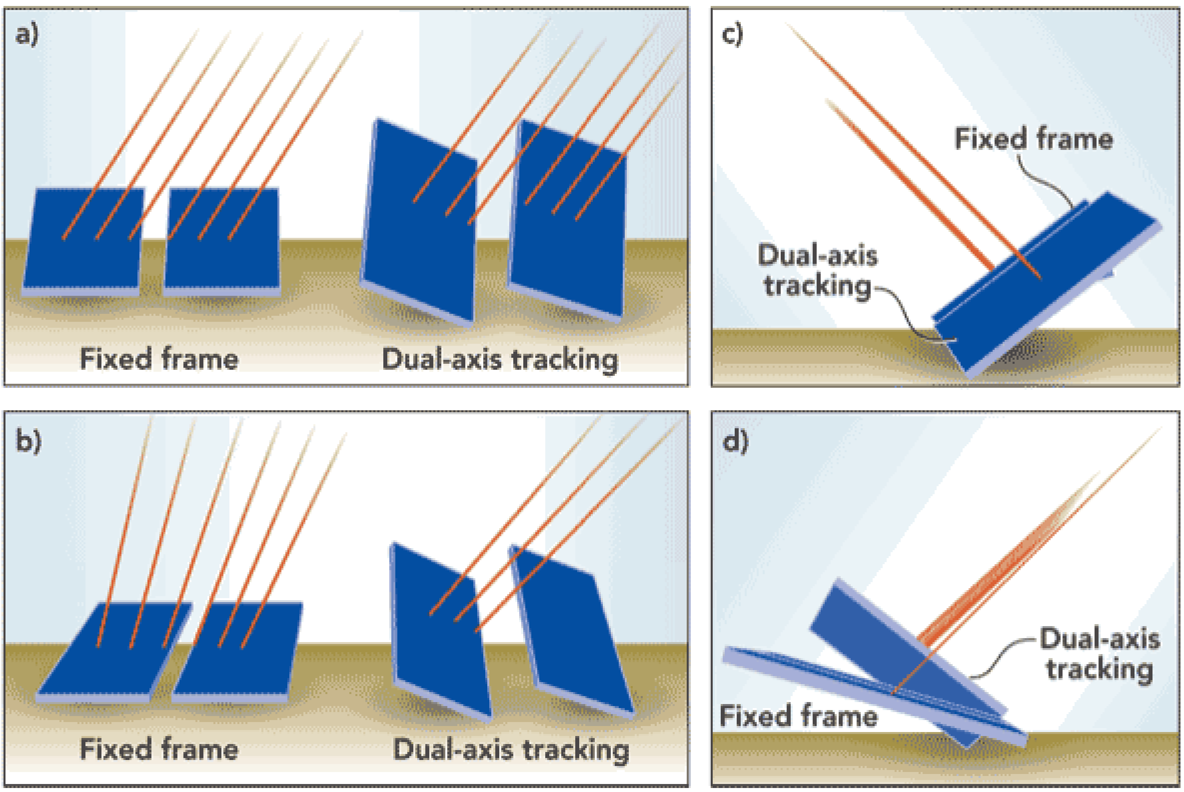

Figure 2 Free standing-static and a two-axis sun solar panels.

Structure of the Research

- In the first stage, the electricity generation mix, the distribution grid and the power consumption mix in Saudi Arabia will be determined and an isolated city electricity generation system will be chosen for analysis.
- In the second stage, the electricity demand, most used fossil fuels and the load curve of the chosen system shall be determined.
- In the third stage, possible fossil fuels savings opportunities, by adding a photovoltaic power plant to the electricity generation mix of the system, will be identified and quantified.
- Finally, discussion, conclusion and recommendations shall be presented.

Demographical and Geographical Features of Saudi Arabia

Saudi Arabia is located in southwest Asia with an area greater than 2,149,690 sq km. The country has five main metropolitan areas where over 75% of the country's approximately 32,000,000 residents live [GAS (2016)]. The main cities are Riyadh (capital city), Jeddah, Mecca, Medina, Qassim and Dammam. The rest of the population reside in medium sized and small cities scattered across Saudi Arabia. Some of these smaller cities are relatively remote.

The country's climate is majorly arid except at the Asir province in the southwest which is influenced by seasonal monsoons from the Indian Ocean.

Desert is the most prominent geographical feature of the Arabian Peninsula of which Saudi Arabia encompasses most of its area. Considerably, more than half the area of Saudi Arabia is desert. The country has three major deserts.

Rub' al Khali (The Empty Quarter) extends over much of the southeast and beyond the southern frontier. It is one of the largest sand deserts in the world. Rub' al Khali has an estimated area of about 650,000 sq km with lesser portions in Yemen, Oman, and the United Arab Emirates.

An Nafud or the Great Nafud is an upland desert of red sands covering an area of 64,000 sq km. It lies at an elevation of 900 meter in the northern part of the Arabian Peninsula, its frequent sandstorms shape immense dunes and is noted for its sudden violent winds.

Ad Dahna' is a narrow strip of sandy terrain. This reddish sandy desert is in the central part of Saudi Arabia, extending about 1,300 km southward from the northeastern edge of An Nafud to the northwestern borders of Rub' al-Khali. Thus, Ad-Dahna' links the other two deserts of Saudi Arabia.

The country lies in the zone between latitudes 16° and 33°N and longitudes 34° and 56°E, and receives about 5–9 kWh/m2/day. The potential for solar power electricity generation in this region is immense. Indeed, the average annual solar irradiation on Saudi Arabia is about 2200 KWh/m2, see Figure 3.

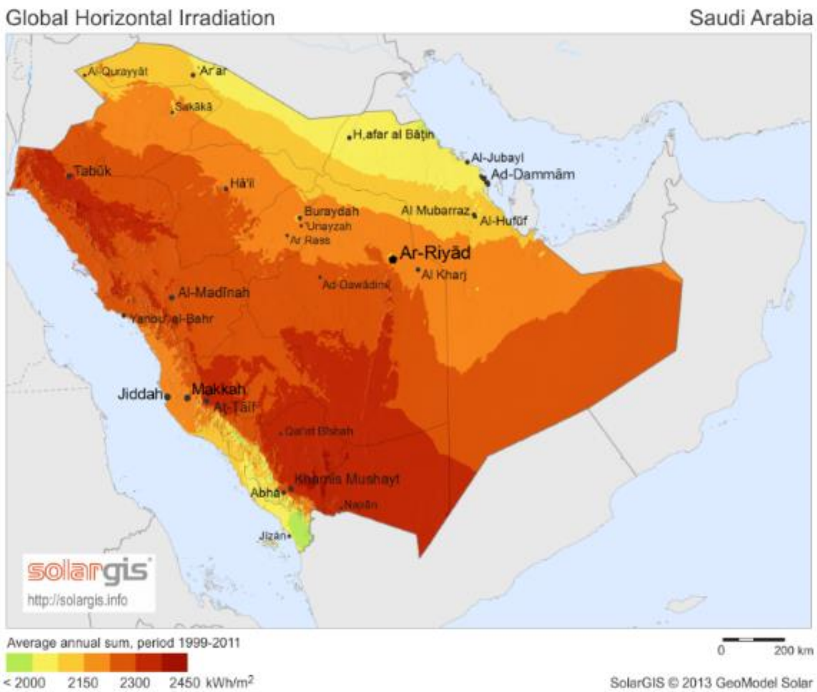

Figure 3 Global Horizontal Irradiation in Saudi Arabia. (Source: Solargis 2013)

Data source

The data discussed in this research, unless specifically mentioned, is mainly extracted from these sources:

- The statistical booklet of the Electricity and Cogeneration Regulatory Authority of Saudi Arabia.
- The historic electrical data of the Saudi Electricity Company.
- The annual reports of the Saudi Electricity Company.
- The Demography Survey of the General Authority of Statistics

Background and Case Study

In the following chapter, the number and type of licensed electricity power generators in Saudi Arabia will be defined. Also, the main technologies used by these power generators, the number of generation units and the capacities of different technologies shall be described and quantified.

Furthermore, the distribution grid and its divisions shall be characterized and the average installed capacity in each region determined. The number of power plants and their capacities shall also be described. Finally, an isolated city electricity generation system will be chosen as a case study for this research.

Background

Current Electricity Generation Mix in Saudi Arabia

In the year 2016, there were 19 different licensed electricity power generators in Saudi Arabia with a total installed electricity generation capacity of 87.8 GW and a total number of 81 power plants, see Table 1. The Saudi Electricity Company, being the biggest of them all, accounts for 67.9% of the installed electricity generation capacity with 44 operational power plants distributed across the country, see Figure 4 [ECRA (2016)].

Of the 19 different licensed electricity power generators in Saudi Arabia only two (Saudi Electricity Company and Marafiq) are service providers. The rest generate electricity for self-use.

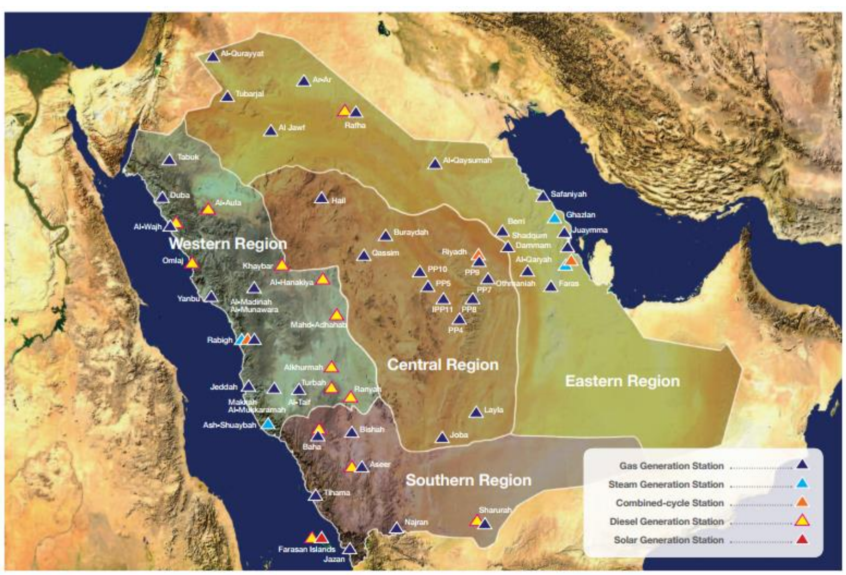

Figure 4 Existing SEC power plants in Saudi Arabia. (Source: SEC 2014)

Producer	Number of plants	Installed Capacity (GW)	Percentage
Saudi Electricity Company (SEC)	44	59.59	67.92
Power & Water Company for Jubail and Yanbu (Marafiq)	2	2.41	2.75
Jubail Water & Power Company	1	2.87	3.28
Shuaibah Water & Electricity Company	1	1.19	1.36
Shaqaiq Water & Electricity Company	1	1.02	1.16
Hajr for Electricity Production Company	1	4.09	4.67
Durmah Electric Company	1	1.75	2.00
Rabigh Electric Company	1	1.32	1.50
Saline Water Conversion Corporation (SWCC)	7	7.81	8.90
Saudi Aramco	8	2.24	2.56
Tihama Power Generation Company	4	1.64	1.87
Rabigh Arabian Water and Electricity	1	0.84	0.96
Jubail Energy Company	1	0.25	0.28
Saudi Cement Company	2	0.22	0.26
Ma'aden Wa'ad Al-shamal Phosphate (MWSPC)	1	0.16	0.18
Power Cogeneration Plant Company (PCPC)	1	0.16	0.18
Tuwairqi Energy Company	1	0.08	0.09
Saudi Aramco Shell Refinery	2	0.05	0.06
Obeikan Paper Industries Company	1	0.02	0.02
Total	81	87.80	100.00

Table 1 Electricity Power Generators in Saudi Arabia. (Source: ECRA 2016)

The electricity generation capacity of these power plants ranges from less than 200 MW to more than 2000 MW, see Figure 5 ,and the average electricity generation capacity of power plants in Saudi Arabia is approximately 1083 MW.

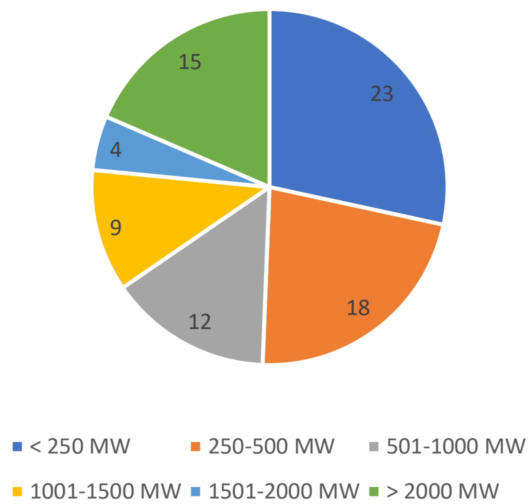

Figure 5 Number of power plants per generation capacity. (Source: ECRA 2016)

Electricity generation in Saudi Arabia is mainly based on thermal power plants, these plants operate according to the following principle:

Potential chemical energy of fossil fuels is converted into mechanical energy which is used to run a turbine or an engine that is coupled to a generator that is used to produce electrical energy.

The country depends on four main types of thermal fossil fuel power plants in Saudi Arabia, see Table 2:

- Diesel generator power plants.
- Gas turbines power plants.
- Steam turbines power plants.
- Combined cycle power plants.

Technology	Efficiency	Installed Capacity (GW)	Advantages	Disadvantages
Diesel generator power plants	30% - 40%	0.60	Low initial investment. Low starting time (immediately available).	Expensive fuel
Gas turbines power plants	20% - 35%	36.00	Low initial investment. Low starting time (immediately available).	High operating costs (mainly fuel).
Steam turbines power plants	30% - 40%	36.10	Low operating costs.	High initial investment. High starting time.
Combined cycle power plants	50% – 60%	15.10	High efficiency.	High initial investment. High operating costs (mainly fuel).

Table 2 Power Plant Technology comparison.

Power Plants Configuration

In the year 2016, there was a total of 113 combined cycle, 124 steam, 548 gas, 44 diesel installed generation units in different power plants in Saudi Arabia. The location of different power plants of the Saudi Electricity Company that operate according to the aforementioned technologies can be seen in Figure 4.

However, during the last couple of years a national trend of replacing gas and diesel units with combined cycle and steam units can be noticed as seen in Figure 6.

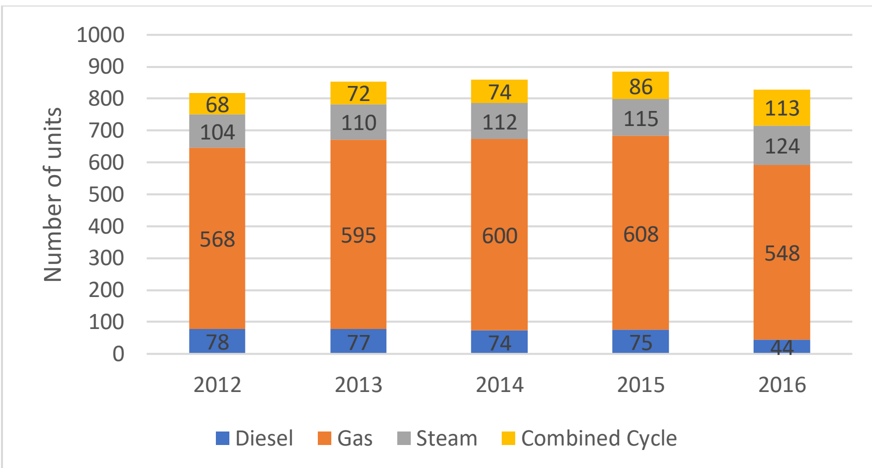

Figure 6 Number of units per power generation technology. (Source: ECRA 2016)

It is also worthy to note that 15.8 GW of the installed capacity is over 30 years old and would soon be out service. With 9.5 GW and 6.3 GW corresponding to gas and steam turbines respectively. The ages of the generation units by capacity and technology in the year 2016 are shown in Figure 7.

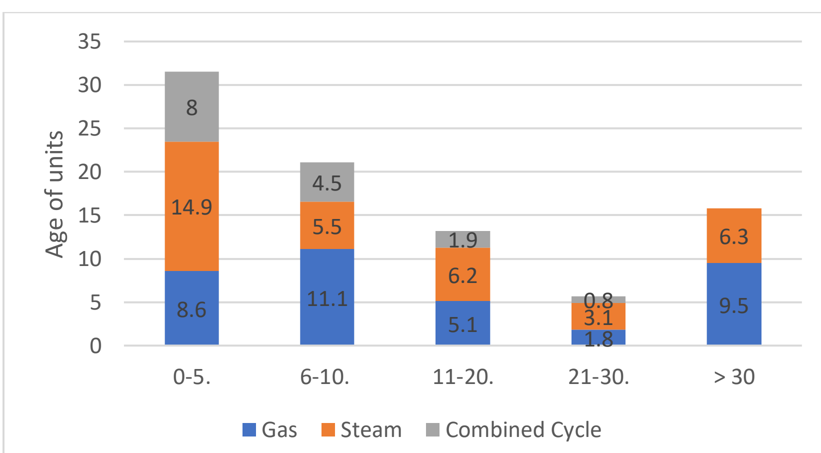

Figure 7 Generation units age by capacity and technology. (Source: ECRA 2016)

Electrical Grid of Saudi Arabia

The Saudi electrical grid can be divided into four interconnected regions (Central, Eastern, Western and Southern regions), see Figure 8.

41% of the installed electricity generation capacity is located in the eastern region and 38% in the western region, whereas 23% is located in the central region and only 6% in the southern region.

The average electricity generation capacity of power plants and the total installed electricity generation capacity per region can be seen in Table 3.

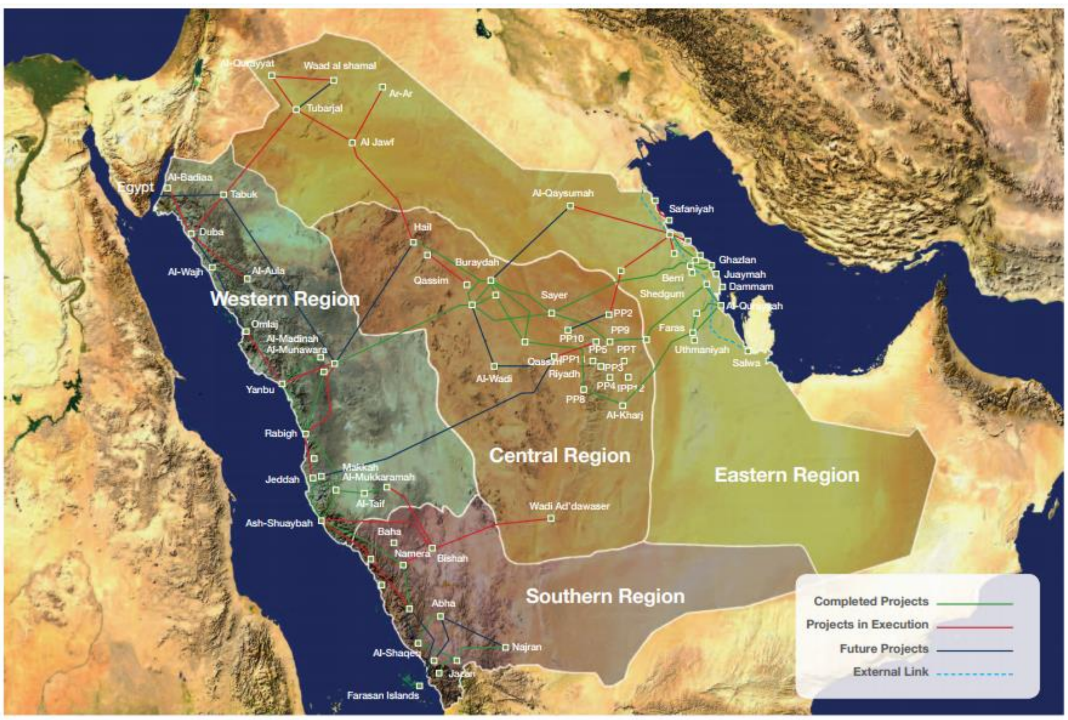

Figure 8 Electrical grid of Saudi Arabia. (Source: SEC 2014)

Region	Average plant capacity (MW)	Total installed capacity (GW)
Central	1427	19
Eastern	958	33
Western	1231	31
Southern	615	5

Table 3 Average and total capacity by region. (Source: ECRA 2016)

Case Study

City Selection

By analyzing Figure 4 and Figure 8, a number of cities in different regions are identified as possible case studies for this research, see Table 4. All of these cities share the following characteristics:

- Have an isolated electricity generation system.
- Have a plant that is operated by the Saudi Electricity company.
- There are no ongoing or future projects to connect these plants to the national electrical grid.
- High solar yearly irradiation.

City	Region	Estimated Population	Yearly in-plane irradiation [kWh/m2]
Sharoura	Southern	96701	2560
Rafha	Eastern	80544	2350
Al-hanakiya	Western	80000	2510
Mahd-Adhahab	Western	63000	2480
Khaybar	Western	53000	2560
Ranyah	Western	45942	2570
Turbah	Western	23235	2570
Farasan Islands	Southern	10527	2330

Table 4 Cities that have an isolated electricity generation system.

Bearing the aforementioned data in mind, the city of Sharoura is most suitable for selection as a case study for this research, for having the biggest population and the second highest yearly in-plane irradiation.

Sharoura

Sharoura is located in the Najran region of Saudi Arabia within the southern region of the electrical grid division, see Figure 4; being exactly located at latitude 17.5° and longitude 47.1°. The city is located at an elevation of 727 m from sea level and has a population approximately 96701 inhabitants.

Of the two service providers in Saudi Arabia only the Saudi Electricity Company is present in Sharoura. The city has a diesel generator power plant and two simple cycle gas turbine power plants with a total installed capacity of 261.52 MW. These power plants are located at latitude 17.330° and longitude 47.093° 18 km south to the city of Sharoura on Al-Wadia Road.

Figure 9 Saudi electricity company power plant in Sharoura.

For detailed information regarding generation units, their capacity, primary fuel and age of these power plants, see Table 5.

Unit type	Unit installation year	Primary Fuel	Back up Fuel	Age - years	Unit capacity MW
Diesel Generator	1988	Diesel	No Fuel	27	5.42
Diesel Generator	1988	Diesel	No Fuel	27	5.42
Diesel Generator	1988	Diesel	No Fuel	27	5.42
Gas Turbine	1988	Diesel	No Fuel	27	5.42
Gas Turbine	1988	Diesel	No Fuel	27	5.42
Gas Turbine	1988	Diesel	No Fuel	27	5.42
Diesel Generator	2000	Diesel	No Fuel	15	10
Diesel Generator	2000	Diesel	No Fuel	15	10
Diesel Generator	2000	Diesel	No Fuel	15	10
Diesel Generator	2007	Diesel	No Fuel	8	10
Diesel Generator	2007	Diesel	No Fuel	8	10
Gas Turbine	2009	Diesel	No Fuel	6	17
Gas Turbine	2009	Diesel	No Fuel	6	17
Gas Turbine	2009	Diesel	No Fuel	6	17
Gas Turbine	2014	Diesel	No Fuel	1	64
Gas Turbine	2014	Diesel	No Fuel	1	64

Table 5 Generation units of power plants in Sharoura. (Source: ECRA 2016)

Electricity Consumption and Fossil Fuel Used for Electricity Generation

In the following chapter, the electricity consumption in Saudi Arabia will be determined and analyzed highest consumer sectors and regions. In addition, the quantity of fossil fuels used for electricity generation in Saudi Arabia will be identified and analyzed for most used fuels and highest consumption sectors.

Furthermore, the electricity consumption, the quantity of fossil fuels used for electricity generation in the isolated electrical system in Sharoura are going to be estimated.

Saudi Arabia

Electricity Consumption

The electricity power consumption profile in Saudi Arabia in general can be divided to the following sectors:

- Residential
- Industrial
- Commercial
- Governmental
- Other

In 2016 the Saudi Electricity Company accounted for 97% of the 296.67 TWh sold to consumers in Saudi Arabia whereas Marafiq sold the rest of electricity [ECRA (2016)].

The amount of energy sold for each sector in 2016 in Saudi Arabia can be seen in Table 6 whereas the evolution of the Saudi Electricity Company consumed energy per sector during the las decade can be seen in Figure 10. The demand on electricity has grown at an average annual rate of 6.3% since the year 2000 [SEC (2014), ECRA (2016)].

Region	Residential (TWh)	Industrial (TWh)	Commercial (TWh)	Governmental (TWh)	Other (TWh)	Total (TWh)
Central	47.45 (16.00%)	6.33 (2.10%)	17.04 (5.70%)	15.06 (5.10%)	4.39 (1.50%)	90.29 (30.40%)
Eastern	26.92 (9.10%)	33.27 (11.20%)	8.97 (3.00%)	7.13 (2.40%)	4.35 (1.50%)	80.66 (27.20%)
Western	52.01 (17.50%)	13.22 (4.50%)	17.87 (6.00%)	11.69 (3.90%)	2.96 (1.00%)	97.77 (32.90%)
Southern	17.26 (5.80%)	0.75 (0.30%)	4.33 (1.50%)	4.61 (1.60%)	0.97 (0.30%)	27.95 (9.50%)
Total (TWh)	143.66 (48.40%)	53.59 (18.10%)	48.23 (16.20%)	38.50 (13.00%)	12.70 (4.30%)	296.67 (100.00%)

Table 6 Amount of energy sold to consumers per sector, region and percentage of total. (Source: ECRA 2016)

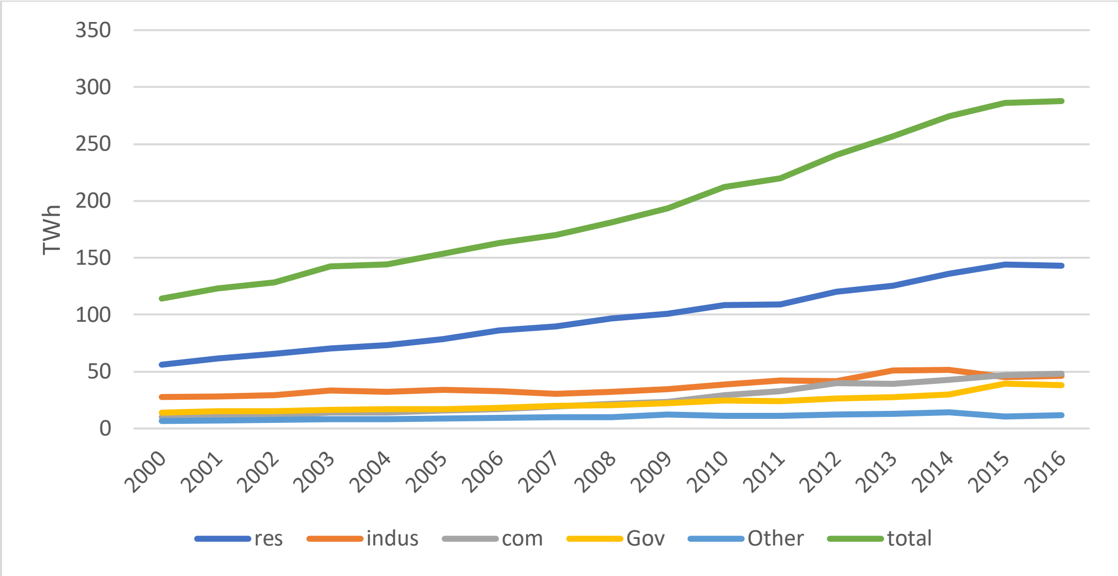

Figure 10 Evolution of SEC consumed energy. (Source: SEC 2014, ECRA 2016)

Fossil Fuel Used for Electricity Generation

The local consumption of fossil fuels for electricity generation purpose has increased drastically over the years reaching approximately 3840 TBTU of fossil fuels in 2016 [ECRA (2016)].

The majority of fossil fuels were used to generate electricity for the industrial sector as it can be seen in Figure 11. In other words, as deduced from Table 7 and Figure 11, 0.1% of the total number of customers is responsible for 57.4% of electricity consumption.

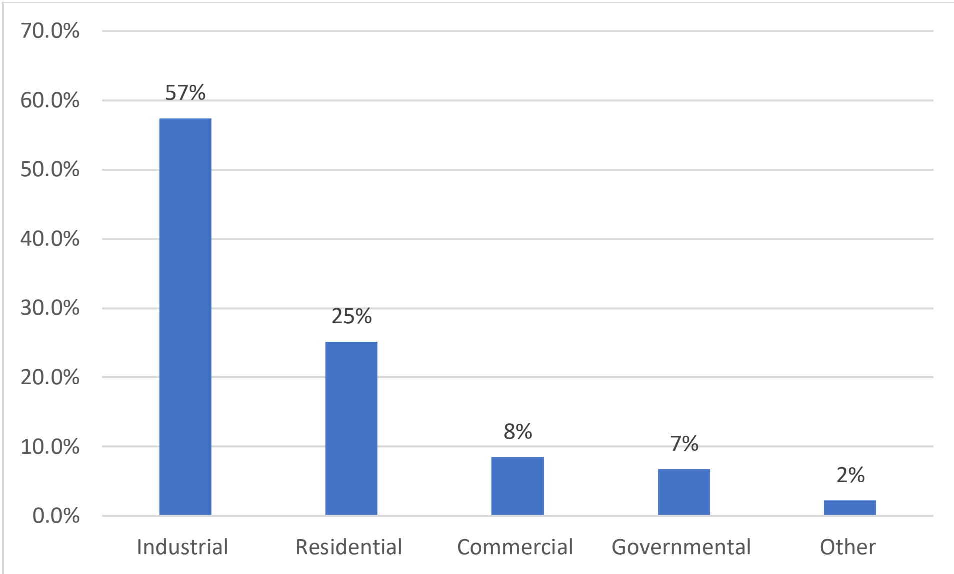

Figure 11 Percentage of consumed fossil fuels per sector. (Source: ECRA 2016)

	Number of Customers	Percentage (%)
Residential	6760629	78.5
Industrial	10184	0.1
Commercial	1466826	17.0
Governmental	263772	3.1
Other	105589	1.2
Total	8607000	100.0

Table 7 Number of customers, percentage per sector. (Source: ECRA 2016)

Natural gas was the most common fossil fuel to be used for electricity generation in 2016 followed by Crude oil, HFO and Diesel as shown in Figure 12.

Yet, if we consider the combined percentage of crude oil, HFO and diesel, since they are all derived from crude oil, we find that natural gas and the combined fossil fuels account for 50.7% and 49.3% of the used fossil fuels respectively.

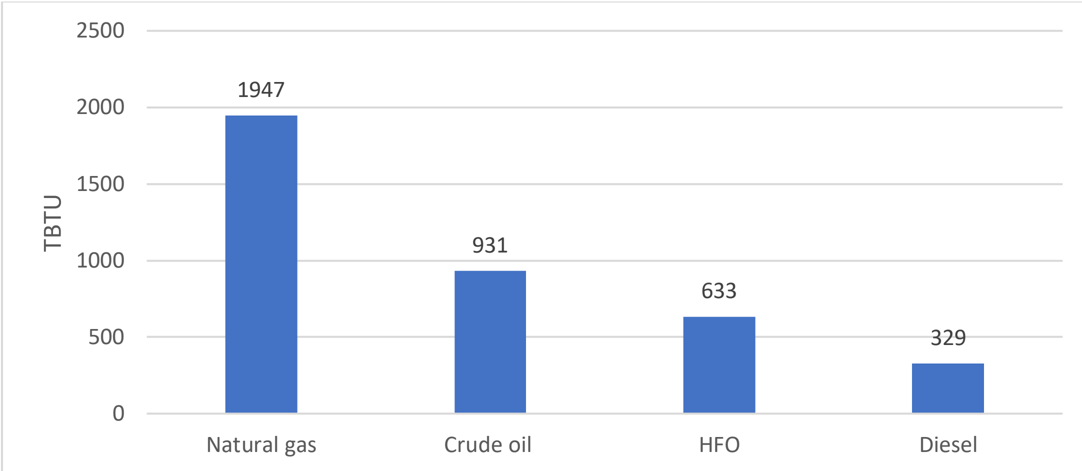

Figure 12 Quantity of fossil fuels used in 2016. (Source: ECRA 2016)

Analyzing Figure 13, at a simple glance, natural gas can be identified as the most used fuel type to generate electricity in all sectors. Whereas if we consider the combined fuels, this scenario differs and natural gas only continues to be the most used fuel type for electricity generation in the industrial sector.

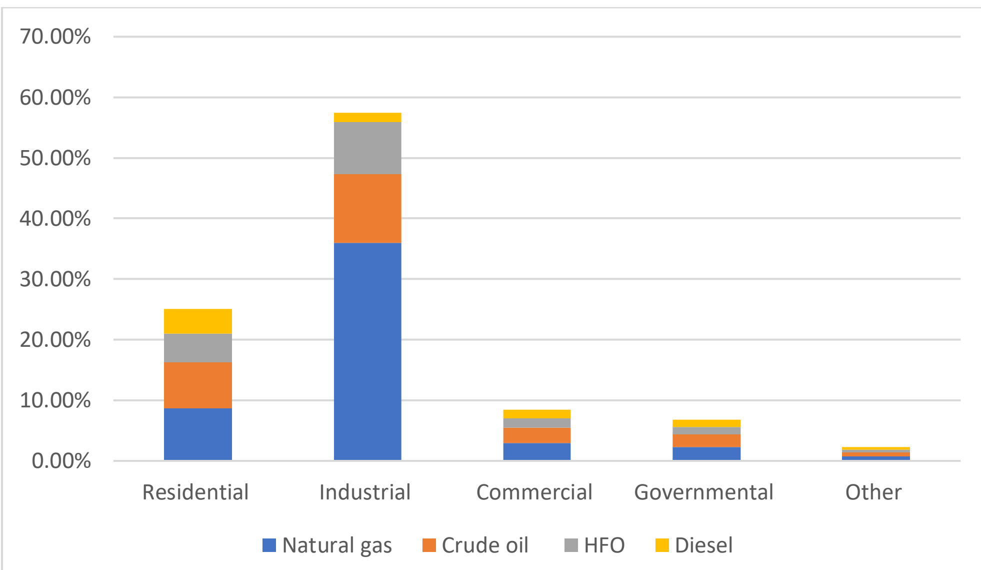

Figure 13 Percentage of consumed fossil fuels per type per sector. (Source: ECRA 2016)

Moreover, viewing Figure 14, Natural gas can be identified as the most used fuel type in the eastern and central regions whereas the use of crude oil is abundant the western region followed by the central and southern regions consecutively. Diesel can be identified as the most used fuel type in the southern region and HFO is exclusively used in the western region.

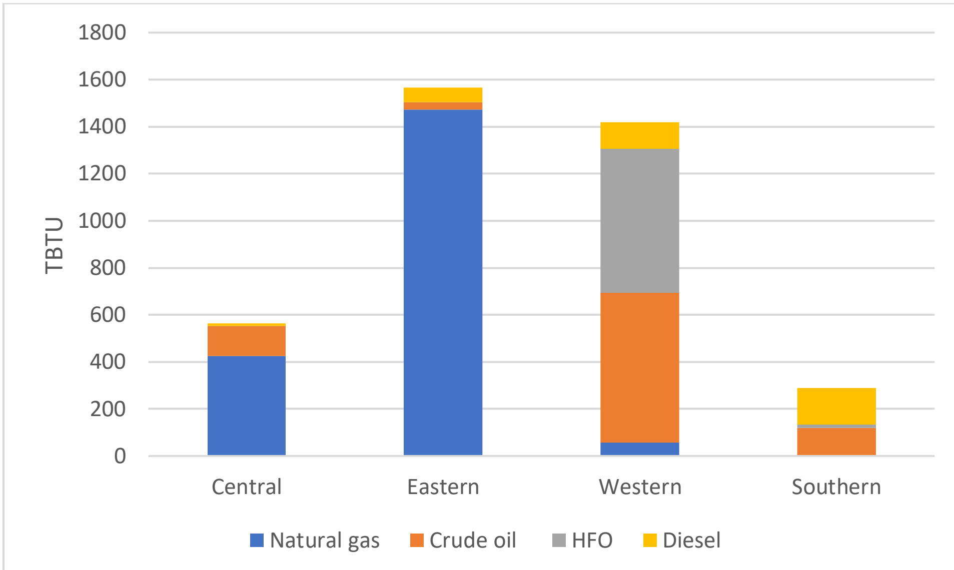

Figure 14 Quantity of fossil fuels used per region in 2016. (Source: ECRA 2016)

Combining the data retrieved from the Saudi electrical company with the data of the Electricity and Cogeneration Regulatory Authority of Saudi Arabia, it is possible to estimate the quantity of various fossil fuels used to generate electricity which was sold to different sectors in the year 2016 as shown in Table 8. [SEC (2014), ECRA (2016)].

	Natural gas (TBTU)	Crude oil (TBTU)	HFO (TBTU)	Diesel (TBTU)	Total (TBTU)
Residential	334.44	291.37	180.53	158.75	965.10
Industrial	1381.07	437.96	327.51	60.37	2206.91
Commercial	111.94	97.52	60.43	53.14	323.03
Governmental	89.83	78.26	48.49	42.64	259.22
Other	29.71	25.89	16.04	14.10	85.74
Total	1947.00	931.00	633.00	329.00	3840.00

Table 8 Quantity of fossil fuels used to generate electricity for each sector.

Sharoura Estimations

Estimating the Electricity Consumption

In order to estimate the electricity demand in Sharoura, the number of customers will be determined by means of an extrapolation based on the population of the city in relation to the total population of the southern region. The population of Sharoura represents 2.04% of the total population of the regions that are included in the southern region of the electrical grid division. Table 9 shows the total number of customers of the southern region and the estimated number of customers of Sharoura per sector in the year 2016.

	Residential	Industrial	Commercial	Governmental	Other	Total
Number of Customers Southern Region	987,000	500	154,000	58,300	4,500	1,204,300
Estimated Number of Customers Sharoura	20,164	10	3,146	1,191	92	24,603

Table 9 number of customers in the southern region and estimated number of customers in Sharoura. (Source: ECRA 2016)

Consequently, the estimated electricity demand in Sharoura would be the result of multiplying the estimated number of customers per sector by the average consumption of customers per sector respectively. The average consumption of customers per sector for the southern region and the estimated electricity demand in Sharoura are indicated in Table 10.

	Residential	Industrial	Commercial	Governmental	Other	Total
Average energy demand per customer southern region (MWh)	17.5	1674.28	28.14	79.07	111.91	
Estimated energy demand Sharoura (MWh)	352,870	16,743	88,528	94,172	10,296	562,609

Table 10 Consumption averages for the southern region and estimated consumption for Sharoura. (Source: ECRA 2016)

Fossil Fuel Used for Electricity Generation in Sharoura

In order to estimate the quantity of fossil fuel that was used for electricity generation in Sharoura in 2016, the type of used fossil fuels should be revealed. Table 5 indicates that diesel is the only fossil fuel that is used for electricity generation in Sharoura. In addition, Figure 14 shows that the total quantity of diesel used for electricity generation in the southern region in 2016 stood at 156.6 TBTU.

Furthermore, Table 5 shows the type of the existing generation units in Sharoura and Table 2 the efficiency range for each type of generation technology. Assuming that one MWh is equivalent to 100 liters of diesel and bearing in mind the yearly energy consumption of Sharoura (562,609 MWh/Year), the estimated quantity of diesel used for electricity generation in Sharoura would be 56,260,933 Liters/Year.

Estimating the Load Curve in Sharoura

Assuming that the climate in Sharoura is to some extent identical to the average climate in the southern region, it is correct to presume that the annual load curve for Sharoura is going follow a similar trend of the annual load curve for the southern region. Figure 15 shows the maximum, minimum and average loads for every month of 2016 in the southern region.

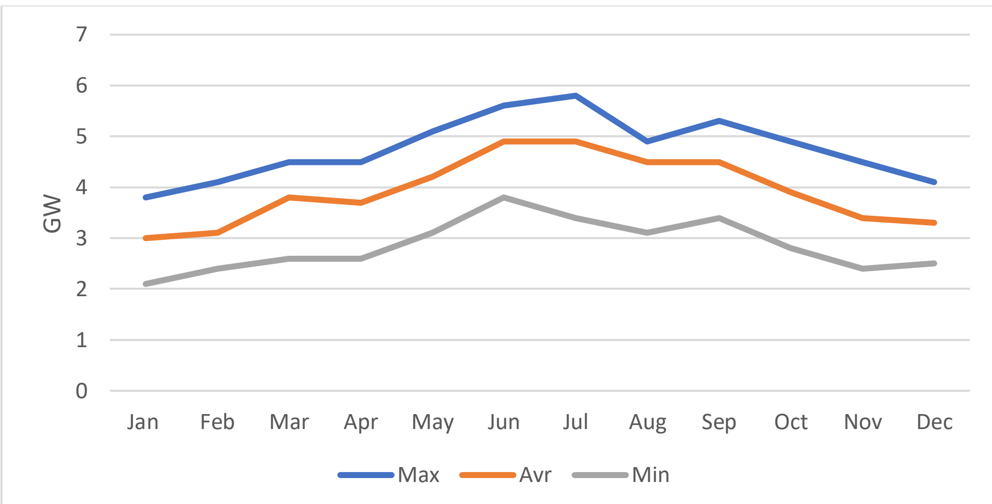

Figure 15 Southern region load curve. (Source: ECRA 2016)

In order to estimate the load curve for Sharoura, it is necessary to correct Figure 15 by multiplying the load value of every month by a correction coefficient. In this case, the coefficient can be calculated as the average between the percentage of the installed capacity in Sharoura in relation to the total installed capacity in the southern region (6.30%), the percentage of the population of Sharoura in relation to the total population of the southern region (2.04%) and the percentage of similarity between connected systems and isolated systems (3.81%).

Assuming that the numeric value of the correction coefficient is 0.404, Figure 16 shows the estimated load curve for Sharoura in 2016.

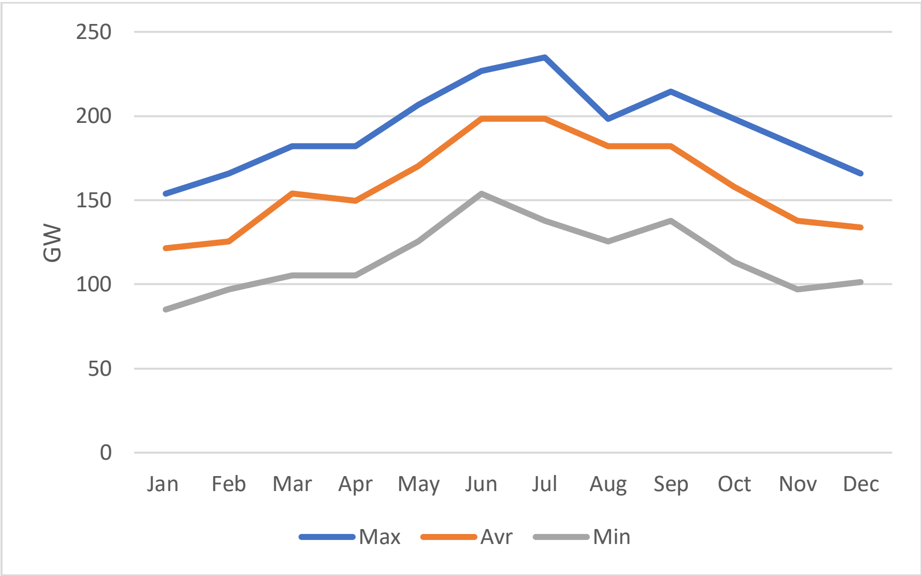

Figure 16 Estimated load curve for Sharoura.

Diesel Savings

In this chapter, the potential diesel savings, resulting from the construction of a free standing fixed frame polycrystalline silicon photovoltaic power plant system to entirely cover the electricity needs of Sharoura during the day is going to be quantified.

In addition, the combination of a smaller photovoltaic power plant system with the existing thermal plants is going to be studied for diesel savings and for the effect of the photovoltaic system on the load of the thermal plants and consequently the efficiency of the thermal plants.

Solar Power Plant Diesel Savings

A solar power plant is designed in order to cover the estimated electricity demand of Sharoura during the day for an optimum inclination angle of 20°. The monthly consumed energy was calculated by multiplying the estimated annual consumed energy by a correction coefficient for each month. This coefficient was calculated by multiplying the variability of the load by the weight of the load in relation to the sum of loads and assuming that the demand during the day is equivalent to 66% of the total demand.

The amount of solar irradiation is statistically modelled by photovoltaic geographical information system of the European commission. The calculation takes into account the solar radiation, temperature, wind speed and type of PV module [PVGIS (2017)], see Table 11.

Month	Optimum angle average irradiation (20°) (KWh / m2)	Estimated energy demand (MWh)	Correction coefficient
Jan	213	18001	0.032
Feb	213	19221	0.034
Mar	239	28881	0.051
Apr	184	27381	0.049
May	217	35281	0.063
Jun	203	48022	0.085
Jul	199	48022	0.085
Aug	209	40502	0.072
Sep	216	40502	0.072
Oct	242	30421	0.054
Nov	210	23121	0.041
Dec	217	21781	0.039

Table 11 Average solar irradiation, correction coefficient and estimated energy demand in Sharourah.

The most unfavorable month to take into consideration for design purposes is found to be July with an average irradiation of 199 KWh / m2 at an inclination of 20°, some average sunshine hours of 268.8 h and an estimated electricity demand of 48022 MWh.

Assuming a total 20% loss rate for the installation, a system of 298 MW at an inclination of 20° is sufficient to cover the energy demands of Sharoura by producing 972,276 MWh / Year, using 1,044,666 solar panels of 285 Wp.

Assuming an electricity tariff of 0.056 $ / Kwh and a local diesel price of 0.088 $/liter, Table 12 reveals the yearly solar power plant diesel plant savings and the yearly generated revenue.

Month	Diesel savings in liter	Diesel savings	Revenue
Jan	1,800,075.10	$ 158,497.18	$ 1,166,539.23
Feb	1,922,080.19	$ 169,239.76	$ 1,245,604.67
Mar	2,888,120.49	$ 254,299.92	$ 1,871,647.39
Apr	2,738,114.23	$ 241,091.82	$ 1,774,435.79
May	3,528,147.19	$ 310,654.47	$ 2,286,416.90
Jun	4,802,200.34	$ 422,835.25	$ 3,112,067.44
Jul	4,802,200.34	$ 422,835.25	$ 3,112,067.44
Aug	4,050,168.97	$ 356,618.65	$ 2,624,713.27
Sep	4,050,168.97	$ 356,618.65	$ 2,624,713.27
Oct	3,042,126.91	$ 267,860.23	$ 1,971,451.30
Nov	2,312,096.46	$ 203,580.82	$ 1,498,354.84
Dec	2,178,090.87	$ 191,781.59	$ 1,411,512.47
Yearly Total	38,113,590.06	$ 3,355,913.59	$ 24,699,524.02

Table 12 Photovoltaic plant diesel savings and revenue.

Combination of Solar Power Plant with Gas Turbines

Bearing in mind the estimated monthly consumed energy estimated before, a solar power plant is designed in a similar way to replace the older diesel generators and gas turbines shown in Table 5 and only cover the electricity demand of Sharoura for the lowest consumption month (January) during the day. In addition, this plant would run simultaneously with the remaining thermal power plants to supply the electricity demand of Sharoura during the rest of the year, see Table 13.

Unit type	Unit installation year	Primary Fuel	Back up Fuel	Age - years	Unit capacity MW
Diesel Generator	2007	Diesel	No Fuel	8	10
Diesel Generator	2007	Diesel	No Fuel	8	10
Gas Turbine	2009	Diesel	No Fuel	6	17
Gas Turbine	2009	Diesel	No Fuel	6	17
Gas Turbine	2009	Diesel	No Fuel	6	17
Gas Turbine	2014	Diesel	No Fuel	1	64
Gas Turbine	2014	Diesel	No Fuel	1	64

Table 13 Remaining generation units of power plants in Sharoura. (Source: ECRA 2016)

Assuming a total 20% loss rate for the installation, a system of 104 MW at an inclination of 20° is sufficient to cover the energy demands of Sharoura by producing 340,496 MWh / Year, using 365,848 solar panels of 285 Wp.

The approximate amount of energy to be produced by each technology is indicated in Table 14 whereas the quantity of diesel saved every year by the solar power plant and the yearly generated revenue is shown in Table 15, also assuming an electricity tariff of 0.056 $ / Kwh and a local diesel price of 0.088 $/liter.

Month	Energy produced by solar plant (MWh/Month)	Estimated energy to be produced by thermal plants (MWh/Month)	Estimated energy demand (MWh/Month)
Jan	27545	0	18001
Feb	26616	0	19221
Mar	27983	898	28881
Apr	27879	0	27381
May	31950	3332	35281
Jun	28276	19746	48022

Jul	28056	19966	48022
Aug	27409	13092	40502
Sep	29424	11078	40502
Oct	28996	1425	30421
Nov	29361	0	23121
Dec	27002	0	21781
Yearly Total	340497	69538	381136

Table 14 Approximate energy production.

Month	Diesel Savings in liter	Diesel Savings in US dollar	Revenue
Jan	2,754,494.10	$ 242,534.07	$ 1,250,576.13
Feb	2,661,599.08	$ 234,354.64	$ 1,310,719.54
Mar	2,798,332.21	$ 246,394.03	$ 1,863,741.50
Apr	2,787,894.56	$ 245,474.99	$ 1,778,818.96
May	3,194,962.66	$ 281,317.47	$ 2,257,079.89
Jun	2,827,557.61	$ 248,967.34	$ 2,938,199.53
Jul	2,805,638.56	$ 247,037.36	$ 2,936,269.55
Aug	2,740,925.17	$ 241,339.32	$ 2,509,433.95
Sep	2,942,371.69	$ 259,076.75	$ 2,527,171.37
Oct	2,899,577.35	$ 255,308.70	$ 1,958,899.77
Nov	2,936,109.10	$ 258,525.33	$ 1,553,299.35
Dec	2,700,218.36	$ 237,755.08	$ 1,457,485.96
Yearly Total	34,049,680.43	$ 2,998,085.07	$ 24,341,695.50

Table 15 Photovoltaic plant diesel savings and revenue.

Part Load Effect on the Efficiency of the Thermal Power Plants

It is important to take into account the fact that the thermal power plants are not going to be run on the highest load possible during the day from March to October.

Consequently, their efficiency is going to drop depending on the load and more diesel might be eventually used.

Thus, it is important to find the best combination of thermal power plants that would cover the energetic needs without reducing the load too much in order not to prejudice the efficiency. Assuming a minimum 15% over dimensioning factor, Table 16 indicates the combinations with the average necessary loads.

The criteria for choosing the combinations of power plants is based on generation unit capacity without combing more than two thermal power plant facilities at the same time. In regards to the generation units, the bigger generation units will be allowed to run on higher load.

Month	Combination	Necessary energy (MWh/Month)	Max energy produced (MWh/Month)	Average necessary load
Jan	-	0.00	-	
Feb	-	0.00	-	
Mar	One diesel generator (10 MW)	897.8	2681.0	33.5%
Apr	-	0.00	-	
May	Gas turbine generator (17 MW)	3331.8	5203.7	64.0%
Jun	Gas turbine generator (17 MW)	19746.4	4605.3	52.3%
	Gas turbine generator (64 MW)		17337.6	100.0%
Jul	Gas turbine generator (17 MW)	19965.6	4569.6	60.5%
	Gas turbine generator (64 MW)		17203.2	100.0%
	Gas turbine generator (17 MW)	13092.4	4464.2	97.8%
	Gas turbine generator (17 MW)		4464.2	97.8%
	Gas turbine generator (17 MW)		4464.2	97.8%
Sep	Gas turbine generator (17 MW)	11077.9	4792.3	77.1%
	Gas turbine generator (17 MW)		4792.3	77.1%
	Gas turbine generator (17 MW)		4792.3	77.1%
Oct	One diesel generator (10 MW)	1425.5	2778.0	51.3%
Nov	-	0.00	-	
Dec	-	0.00	-	

Table 16 Best combinations for surplus energy production.

Discussion

In addition to mitigating the environmental impact of burning diesel to produce electricity, diversifying the power generation mix in Sharoura would further decentralize and enhance the reliability of the isolated electrical system, increase the available time for the necessary maintenance of the thermal power plants and reduce their maintenance costs.

Performance

The construction of a free standing fixed frame polycrystalline silicon photovoltaic power plant system is certainly going to result in substantial diesel savings. The quantity of these savings directly depends on the size of the installation and the solar irradiation.

In case of opting for a 298 MW solar power plant to cover the entire electricity needs of Sharoura during the day, the diesel savings stand at approximately 38,113,590.06 liters every year representing 13.6% of the total revenue and accounting for 68% of the total quantity of diesel that would have been used.

In contrast, if running a 104 MW solar power plant is opted for, in order to cover the electricity needs of Sharoura during the lowest consumption month (January), in this case, the diesel savings represent 12.3% of the total revenue and account for 61% of the total quantity of diesel that would have been used standing at 34,049,680.43 liters every year.

The efficiency loss caused by running the diesel generators and gas turbines at lower loads in combination with this solar power plant during the rest of the year does not constitute a serious problem.

On the one hand, the smaller gas turbines, with a capacity of 17 MW, would always run on a relatively high average load, being the lowest average load 52.3% during the month of June, meaning that they would run at an approximate efficiency of 30%, see Figure 17.

On the other hand, the diesel generators, with a capacity of 10 MW, would run on lower loads 33.5% and 51.3% for the months of March and October respectively, meaning that they would run at an approximate efficiency between 31% and 34%, see Figure 17.

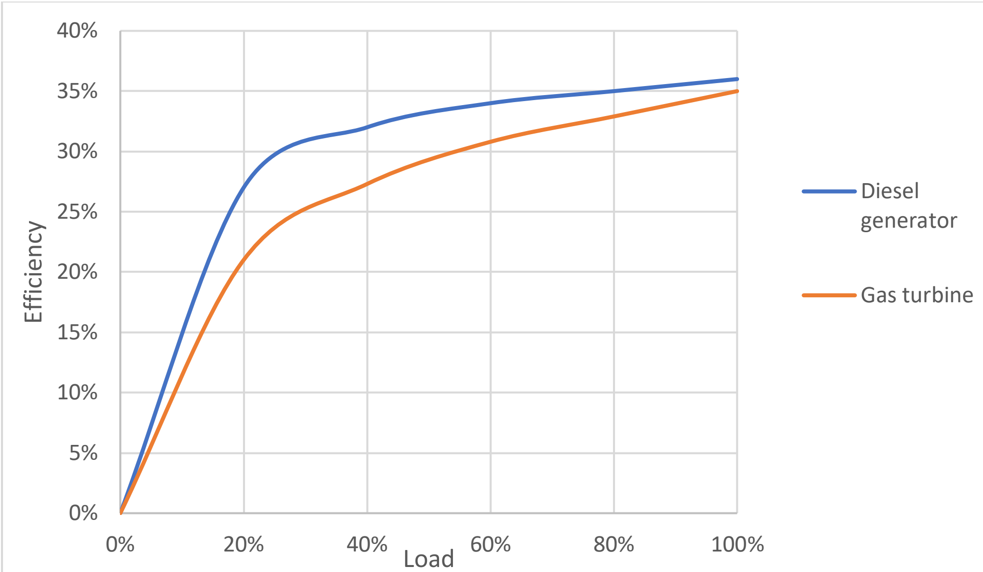

Figure 17 Partial load effect on efficiency on typica gas turbines and diesel generators.

Cost-Benefit

Comparing both systems, at a simple glance, it is obvious that opting for running a solar power plant in combination with existing thermal power plants is more attractive economically. For designing the solar power plant to cover the entire electricity needs of Sharoura during the day independently would only save an extra 7% of diesel at the cost of building a 2.8 times bigger solar power plant and only increase the yearly revenue by 1.3%.

Possible limitations and solutions

In Saudi Arabia large scale solar power plants projects are most probably going to be located near desert or arid areas and Sharoura is no exception. Consequently, sand and dust are expected to form a major problem. Solar power plants can lose up to 30% energy output within a few weeks of installation. Sand deposition rates is a big issue in Saudi Arabia. It is therefore essential to clean the solar panels regularly.

One of the most promising technologies to help automate the cleaning process and decrease the use of water is the use of electrostatic force to remove sand from the surface of solar panels. A single-phase high voltage is applied to parallel wire electrodes embedded in the cover glass plate of a solar panel. More than 90% of the adhering sand is repelled from the surface of the slightly inclined panel after the cleaning operation and the power consumption of this technology is practically zero, see Figure 18. [3]

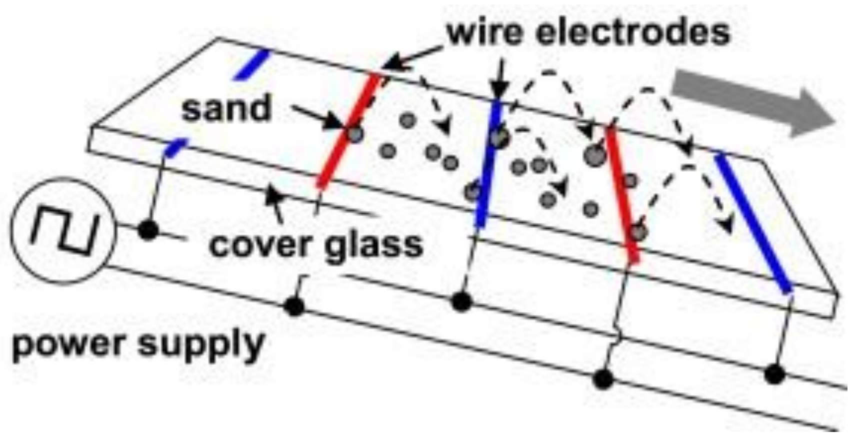

Figure 18 Schematic diagram of the electrostatic cleaning system (Source: [3]).

Conclusion

It is possible to meet the electricity needs of an entire isolated electrical system, estimated at 562,609 MWh, located in the city of Sharoura during the day by means of investing in a utility scale solar power plant.

The construction of 298 MW a free standing fixed frame polycrystalline silicon photovoltaic power plant system would result in substantial diesel savings (38,113,590.06 liters) worth 3,355,913.59 $.

In addition, it is also possible to invest in a substantially smaller scale system (104 MW) designed to only cover the electrical needs of the city during winter months (November to April) whereas this system would work simultaneously with existing thermal power plants during the rest of the year (May - October).

The efficiency loss caused by running the diesel generators and gas turbines at lower loads in combination with this solar power plant does not constitutes a serious problem.

This kind of photovoltaic power plant system would also result in substantial diesel savings (34,049,680.43 liters) worth 2,998,085.07 $.

Comparing both systems, a smaller scale system that works in combination with existing thermal power plants is economically more attractive.

Recommendations

It is recommended to quantify the exact amount of diesel increase that would be caused by the decrease of efficiency resulting from the combination of thermal power plants with solar power plants. In addition, it is also recommended to study the diesel savings resulting from opting for the construction of an energy storage facility to

Further research on the savings of other renewable energy technologies in the same location should be conducted.

Furthermore, further research on the cost and benefits of replacing other remote diesel power plants located in isolated electrical systems in Saudi Arabia with renewable energy power sources should be investigated.

Moreover, the feasibility of connecting these isolated electrical systems with the national grid should be studied.

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Units

Mt	millions of tons
GWe	Giga Watt electric
TWh	Tera Watt hours
MWh	Mega Watt hours
KWh	Kilo Watt hours
TOE	Tones of oil equivalent
MTOE	Million tons of oil equivalent
Bcm	Billion cubic meters

Acronyms

ECRA	Electricity and cogeneration regulatory authority
BP	British petroleum
IEA	International Energy Agency
GAS	General Authority for Statistics

SEC	Saudi Electricity Company
BOE	Barrel of oil equivalent
HFO	Heavy fuel oil