Implementing renewable energy technologies in the city of Jeddah

Montaser Shaban Kabakibou
Department of Engineering and Design,
School of Engineering and Informatics,
University of Sussex,
Brighton, United Kingdom
Ms812@sussex.ac.uk

Chris Chatwin
Department of Engineering and Design,
School of Engineering and Informatics,
University of Sussex,
Brighton, United Kingdom
c.r.chatwin@sussex.ac.uk

Abstract—This research investigates the possibility of implementing different renewable energy technologies in a city and integrating them into the electrical supply grid. A system model is created using Simulink to explore and manage the different technologies. Several energy storage systems are used to compensate for the fluctuations caused by the inconsistency of the different renewable sources.

Keywords—Renewable Energy, Power, Energy Storage

I. INTRODUCTION

In a world where countries are trying to transform themselves to be more sustainable and environmentally conscious, implementing renewable energy technologies is vital to keep up with the way countries are evolving and progressing with their sustainable development. If transition is possible then a city can thrive, reducing electricity costs, providing jobs, spreading environmental awareness, reducing pollution and saving money, which means that the government would not have to raise taxes or the price of goods. Power generation in the Saudi Kingdom relies on natural gas (61%) and crude oil (39%) [1] It is the world’s sixth largest consumer of oil [2]. Not only is the country producing a large carbon footprint but also it uses more energy than is actually needed [3]; due to this, the demand on its oil reserves is large and the country might be forced to reduce its exports and hence reduce its main source of income.

Energy consumption relies on crude oil (62%) and natural gas (38%) [1] [4], not to confuse consumption with generation. Having an alternative method of generating power is beneficial; however, social awareness is required if any city is to be truly transformed. There is an average increase in energy demand in Saudi of 5-8% annually [3], so the government in conjunction with the Saudi Energy Efficiency Center (SEEC – formed in 2010), ministry, regulatory authorities, and other major companies launched the Saudi Energy Efficiency Program (SEEP) in 2012. Moreover, as part of the 2030 vision the Kingdom has decided that by the year 2032, 30% of the energy generated should be from an array of renewable sources, namely 25 GW via concentrated solar power (CSP), 16 GW through solar photovoltaic (PV), 17.6 GW nuclear, 9 GW by wind, 3 GW through waste energy and 1 GW through geothermal based generation. [5]

Cities in the Middle East are an interesting location for sustainable transition and smart city implementations. The Sunlight is abundant and the desert is large and several cities have the advantage of being adjacent to the Gulf and the Red sea, giving them opportunities for offshore wind.

The vast hot desert is an ideal place for solar projects. However, considerations such as dust as well as other factors compromising the efficiency of the solar arrays must be considered. Some Middle Eastern countries still rely heavily on oil and gas, which is not a sustainable way of getting energy as the carbon footprint is relatively high, furthermore, the cost of current energy production is high and over time it will affect the economic state of the countries and the cost of living.

II. RESEARCH METHODOLOGY

A. Energy demand estimation

The population of Jeddah in 2032 was estimated using the growth rate and the compound interest formula; this was used to predict the energy per capita for 2032. The total energy demand for the population of Jeddah (residential) in 2032 was estimated to be 110 TWh. This energy demand was divided among the different renewable energy plants.

As can be seen below in Fig.1 there will be seven power plants, divided into three categories based on their technologies. The first category is the CSP technology, the two plants have different systems, one uses parabolic troughs and the other uses a solar tower. The photovoltaics also differ in that one uses monocrystalline panels and the other uses thin-film panels. The three wind turbine plants are similar to each other but are built in three different locations.
B. Energy to Power

For brevity only an example of the Photovoltaic energy to power conversion will be shown. As illustrated in Fig.1 each of the two solar parks would need to satisfy a demand of 15.4 TWh.

1) Power demand:

\[ \text{Energy} = \text{Capacity factor} \times \text{Power} \times 24 \times 365 \quad (1) \]

\[ \text{Power} = \frac{\text{Energy}}{\text{Capacity factor} \times 24 \times 365} \quad (2) \]

\[ \text{Power} = \frac{15.4 \text{TWh}}{0.3 \times 24 \times 365} = 5.86 \text{ GW} \approx 6 \text{ GW} \quad (3) \]

The 24 and 365 in all three equations above are the hours in a day and the days in a year, respectively.

2) Power in Photovoltaic solar panels (First Solar’s series 6 model type: FS-6445A.):

\[ \text{Irradiance} \times \text{Area} \times \text{Efficiency of the panel} = \text{Power} \quad (4) \]

\[ 1000 \text{ W/m}^2 \times 2.475 \text{ m}^2 \times 18\% = 445.5 \text{ W} \quad (5) \]

If 15 million panels were used in the first park each with a power of just over 445 Watts (W) then the power of the park would be 6.675 GW, which is sufficient to meet the power requirement as calculated above. However, taking into consideration the hot weather in Jeddah the efficiency of the panels would decrease from 18% to 17% because of the temperature coefficient, which is explained later in this paper. This changes the power of the panel from 445 W to 420 W, which causes the total power of the 15 million panel park drop to 6.3 Gigawatts (GW), which is still more than the required 6 GW.

The above was for the thin-film photovoltaic plant, and if the maximum power (as seen in each of the graphs in the following figures) of each of the 2 CSP plants, the 2 PV plants and the 3 wind plants were added then this will manage to deliver the maximum required power demand for the population of Jeddah in 2032, which is 69.65 GW

C. Design Implementation

Simulink was used to create a control system, which integrates the different renewable energy systems. The control system is configured to facilitate maintenance of the city’s connection to the grid. As the city gets its power from the different renewable sources the control system will ensure that whenever any of the sources is not up to the required power demand the backup is turned on.

The goal of the Simulink model is to simulate how the different systems will interact and complement each other and how they can be controlled automatically by the programmable software. The amount of energy needed from each renewable energy plant is known to the control system. This allows the control system to regulate the amount of energy that is drawn from the combined plants. For example: if on a certain day clouds were covering the Sun and the solar plant was unable to obtain its required power then the control system will use the hot oil reserve and generate more electricity using the steam turbine to make up for the energy that the solar sector was unable to provide. If on one day the wind speed was below the threshold and the wind turbines were underperforming, then the control system would “pull” the energy required from another source, whether it is batteries or stored hot salts or even turn on the combined cycle power plant.

The control system is programmed to adjust the amount of electricity coming from the different sectors in response to the data feeding in. These data are information such as wind speed at the wind turbine plant’s actual geographical location or how clear the weather is at the solar plant’s location.

D. Combined cycle power plant:

Conventional power plants use gas turbines, which rely on the Brayton cycle on the other hand steam turbines rely on the Rankine cycle. The thermal efficiency of a Rankine cycle can be increased by increasing the temperature difference in the cycle. Meaning that the inlet temperature would be increased and the outlet temperature would be decreased. Other methods such as reheaters and regeneration could be used. An interesting method is using combined cycle power plants. Where both gas turbines and steam turbines are used, so the Rankine cycle and the Brayton cycle in one power plant. Other research shows the possibility of using two turbines but of the same type, so both would be steam. This could mean the plant would use renewable technology to obtain the heat required to run the power plant.

Combined cycle power plants are being used because they combine two different power cycles that complement each other. The gas turbine which uses the Brayton cycle is set up first. Air is compressed and gas is added in the turbine and both the pressure and the temperature of the fluid are increased significantly and the combustion of the fluid and its movement (kinetic energy) turns the turbine shaft which is connected to the generator. As the fluid moves or passes through the turbine, instead of going to waste it is used, the...
exhaust of the gas turbine goes into a heat exchanger where it is used as a heating fluid to heat up another fluid and generate steam. The steam is used in the steam turbine which relies on the Rankine cycle. [6]

An example of this is in Turkey where Siemens built a 1350 MW combined cycle power plant. It was the first commercially operating thermal plant in the world able to achieve about 52.5% efficiency. It has six 150 MW gas turbines and three 173 MW steam turbines. [7]

E. Energy Storage

Accompanying the seven plants will be a combined cycle power plant (CCPP) and different storage technologies

the following are the different energy storage technologies

1) Pumped Hydroelectric Energy Storage (PHES):
This system not only can be used to generate power but it can be used with renewable energy systems such as wind turbine plants. When integrated the PHES acts as a complementary system for optimisation purposes and to ensure the wind turbine plant delivers the required output at all times eliminating any fluctuations. Making renewable energy plants more reliable and desirable. PHES can be used to level the daily load on the electricity network between day and night. The disadvantage of PHES is the location and geography of the location, in order to build the storage system two reservoirs are needed and quite a large head is needed, the vertical distance between them needs to be significant, for example 300 metres. This puts some cities at an disadvantage. [8], [9],[10]

2) Sodium Sulphur Batteries:
Sodium Sulphur batteries have an average round trip energy efficiency of 86% to 89%. These renewable projects are moving towards a greener future and NaS batteries are created from materials that are abundant, inexpensive, and 99% of the battery is recyclable. [10]

3) Lithium-Ion Battery Energy Storage: They have a high power density and a high efficiency.[11]

4) Molten Salts For The CSP Plant

It stores hot liquids such as molten salts, or a heat transfer fluid if it’s a parabolic trough. The interesting and advantageous part about these fluids is that they are reusable unlike coal or natural gas.

In a solar tower when the receiver absorbs the heat reflected by the heliostats, the heat is used in a boiler and heat exchanger and turns water into steam, which is used in the steam turbine, however, another route is that the heated fluid (whether it is a molten salt mix, like sodium nitrate and potassium nitrate or a type of oil as a heat transfer fluid in a parabolic trough system) goes to the storage tank instead of the heat exchanger to generate steam. Some of the heated fluids go to storage so that when the Sun is down the hot fluids, which have retained their energy can be used in a heat exchanger to generate steam to be used in the steam turbine at night.

As for time, the molten salts lose one degree of temperature per day, so technically they can be stored and topped up for months however this never happens since it is best to use them daily to get the highest efficiency out of the power plant. As for their “age,” they can be used for at least 30 years and naturally the tank would need repairs, so at this point the salts would be cooled off for a couple of months, but after that they can continue to work for another 3 decades. [12]

5) Hydrogen Energy Storage System (HESS):
Hydrogen energy storage is divided into 3 different processes:

a) Hydrogen production: production via electrolysis is the greenest and most economical way to make hydrogen. This process has an 85% efficiency [11], Energy is needed in an electrolyser to split water into oxygen and hydrogen, hydrogen is stored while oxygen is released as a by-product.

b) Hydrogen storage:
After producing hydrogen, it can be stored by compressing or liquifying it or by using metal hydride [13]

c) Hydrogen usage: Energy is obtained from hydrogen when it is used in fuel cells or internal combustion engines.

III. RESULTS

The 2 cases presented show the power at different times of the year, summer and winter have been chosen since these two seasons would have the biggest difference in the number of hours of sunlight during a day.

A. Case 1: Winter

Fig.2 above shows the two concentrated solar power plant’s power capacity. The orange line represents the parabolic trough which ideally generates 29 GW of power when working at maximum capacity, the blue line represents the solar tower which ideally generates 19.2 GW of power when working at maximum capacity. The Horizontal X-axis represents time and the vertical Y-axis represents Power, this is the same for all the graphs in the figures.

It can be seen that during peak hours when the sun is out and well above the ground the power generation is at its
maximum, during the late days of winter power generation starts at 7:00 in the morning and gets to its maximum power generation capacity at 8:30, although the Sun comes out before 8:30 it is not high or strong enough to help generate enough power to reach the required capacity. As long as the Sun is up and there is nothing obstructing the path from the Sun to the mirrors, power generation continues and as the Sun starts to set the power generation starts declining, so until 16:00 it is possible to get a significant amount of power however, from there on it declines until it stops at 17:00. The way the graph is shaped is very straightforward, the straight horizontal lines at the top are the hours when the sun is up during the day and the straight horizontal line at the bottom are the hours when the Sun is down and it is night-time. The semi-vertical lines are the hours when the sun is either starting to come up or starting to set and go down and power generation is only partial at those hours.

Fig. 3 next shows the power fluctuations during the day for both photovoltaic plants however since they were both designed to have the same capacity the lines are overlapping and it appears as there is only one line (the orange line), the efficiency and size of the solar panels used in each of the plants are different since they are from different companies and one is made of monocrystalline silicon and the other is made from thin film (Cadmium Telluride). The graph shows a similar pattern to the CSP graph, power is generated during the day, but the plants produce nothing during the night.

Unlike CSP technology the PV panels convert the energy from the Sun directly into electricity that is transported to the grid, but in the case of the CSP technology the Sun’s rays are focused and reflected to be used as heat in a heat exchange process where steam is created to drive a steam turbine.

The graph in Fig 4 is the graph for the wind plants, although one graph is shown there will be three wind plants. The advantage that the wind plants have is that power is generated ideally all the time, whether it is night or day, the wind will continue blowing, however, there are fluctuations in how fast the wind is during a full day as can be seen in Fig 4, moreover the advantage that the solar plants have is that in Saudi irradiance levels are at their highest and amongst the highest levels in the world [14], [15],[16] [17] whereas with wind although it is possible to harness wind energy in Saudi [18], [19],[20], it is not as efficient as wind plants with high wind speeds over 10 m/s such as in some European countries.

As it has been mentioned earlier the advantage of wind plants over solar plants is that when the sun goes down wind plants still work unlike the solar plants, however the Sun does play a role in how fast the wind is blowing, from morning to afternoon wind speeds increase as a result of solar heating, the sun heats the surface of the earth however unevenly plus the sea does not absorb heat as much as land the unevenness of temperatures and pressure gradients forces air to move thus creating more wind. This can be seen below as wind speed increases, from the hours of 12:00 till 15:00, power generation is at its highest.

**Fig. 4. Power capacity during a two day period**

**Fig. 3. Power capacity during a two day period**

**Fig. 5. Power capacity during a two day period**

### B. Case 2 June (Summer)

Although summer days are longer and the Sun is up for longer hours, which is advantageous for the solar plants, the weather gets very hot which causes people to turn on their air conditioning all day and all night which puts a heavy load on the electrical grid. One advantage that CSP has over PV technology is that the hotter the weather gets and the stronger the Sun is, the better it is for CSP technology since all the heat is used to create steam so the hotter the better however in the case of PV technology different solar panels have different temperature coefficients, so for example if a panel has a temperature coefficient of -0.3% and an efficiency of 20% then it loses 0.3% of its 20% efficiency for every 1 degree over 25 degrees Celsius [21]. Fig. 5 shows the CSP power capacity for two days in June.
Fig. 6 below shows the power capacity for the two PV plants. Compared to the winter graphs in the figures in Case 1 power generation starts earlier and stops later than that in the winter. It is unlike the UK where there is almost a five hour difference between winter and summer Sunsets. So because of Saudi’s geological location the difference is not as big as in the UK, so the impact of the summer and winter day time change is not a huge one in Saudi.

![PV](image1)

**Fig. 6. Power capacity during a two day period**

![Wind Power](image2)

**Fig. 7. Power capacity during a two day period**

Fig. 7 shows the wind power capacity and although it changes it does not reach zero as do the solar technologies, nevertheless, as can be seen from the graph above in Fig. 7 the wind does fluctuate and it does get higher during the day for the reasons that were explained previously.

IV. CONCLUSION

Comparing the wind for the two different seasons it can be seen that because of the hotter weather and longer period of sunlight, high wind speeds stay for a bit longer during the day compared to the winter season. In other cities in other countries wind speed could be much higher during winter than in the summer due to the harsh winter weather, however, in Jeddah the winter season does not have a harsh windy or rainy period, nevertheless wind technology can function properly on Jeddah’s Offshore, as [20], [22], [23] showed, the power law wind profile helps calculate wind speeds at different heights.

In order to take advantage of all the technologies that are available and to compensate for the disadvantages of some of the technologies, different technologies are used and integrated together, the parabolic trough concentrated solar power plant, the solar tower concentrated solar power plant, the photovoltaic monocrystalline silicon plant, the photovoltaic thin-film Cadmium Telluride plant all together with the addition of the three wind plants are used to provide power to the city and to make sure the electricity supply is smooth and does not fluctuate. A combined cycle power plant is used during emergencies or when needed, moreover the five different storage systems are also integrated to provide and compensate in case of any power shortage occurring at any of the seven plants.

The data used to create the graphs are only a fraction of the entire year’s data and the Simulink control system processes all these values and knows when to store excess energy and when to use the batteries and stored energy. The control system has sensors at all the seven plants and whenever there is a drop below the threshold to any value e.g. wind speed level or irradiance level, the control system will automatically calculate the percentage of power loss and compensate for it using the storage systems and the combined cycle power plant.

REFERENCES


