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Role of renewable energy in decarbonisation process: Case study in KSA

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Abstract. Currently, most countries are replacing the fossil fuel electricity generation with renewable technologies for their crucial role in mitigating the greenhouse gas emissions. This paper discusses the implementation of three power plants in Al Aziziya in the eastern province of KSA by deploying three different renewable technologies 1) Photovoltaic 2) Solar thermal power and 3) Wind turbine. Both the energy performance and rate of electricity exported to grid were predicted when the capacity varies from 1000 to 1000,000 KW. In addition, the role of the three different renewable technologies in the decarbonization process has been evaluated.

Introduction

Over the last century, the greenhouse gases including atmospheric carbon dioxide (CO_2) have potentially grown with the energy production, especially by burning fossil fuels to generate electricity. In fact, fossil fuel materials like oil and gas stand behind 75% of the global greenhouse gas emissions and almost 90% of carbon dioxide emissions [1]. The data analysis in [2] have shown that greenhouse gas emissions were raised by 4298.05 (MTCO2e) between 1990 and 2016 due to the tremendous electric energy consumption, which accounts of 40% of the total GHG emissions. The Kingdom faces relatively high-energy demands of energy in industrial as well as residential spots. According to The King Abdullah Petroleum Studies and Research Center (KAPSARC) Residential Energy Model (REEM), a residential Villa in Dhahran area consumes an average of 24,900 KWh annually, while apartments use around 17,200 KWh [3]. Further, a study conducted in 2012 shows that the annual average electricity consumption hits 176.5 kWh/m², exceeding international energy-efficiency benchmarks. This translates to around 21,180 kWh per year for a 120-m² house [4]. Internationally, a household consumes, on average 9,600 to 12,000 kWh annually. This translates to an average daily energy consumption of about 26 to 33 kWh, equivalent to 26,000 to 33,000 watt-hours [5].

Hence, promoting the decarbonisation concept becomes a necessity. This process is achieved either by reducing the energy consumption, or by applying efficient practice and technologies through Renewable energy [6, 7]. For a one percent shift away from the usage of oil, it is possible to reduce the carbon emissions by 1.288 [8]. With the growth of Energy demand, the decarbonisation process consists of reducing or cutting the greenhouse gas emissions, which can be achieved through zero-carbon renewable energy sources such as wind, Solar, Hydropower, Geothermal and Biomass. Simultaneously, the available carbon and methane in the atmosphere shall be continually captured, and stored to counter balance the released toxic gases. The implementation of renewable technologies is required to be in correlation with the actual needs and peak demands of power. Currently, Wind and Solar are two main clean energy resources that can be used to generate electricity with zero carbon emissions and consequently less greenhouse effect. The deployment of key technologies such as solar PV or Wind turbines is on track in many countries and it proved to present a beneficial role in the decarbonisation process. According to

[9], the slice of renewables in power production will rise from around one-quarter in 2015 to around 60% by 2030 and 85% by 2050 for energy sector decarbonisation. In Russia, the implementation of wind and solar have contributed to more than 5 GW since 2013 which is likely to exceed the targeted capacity of 5.9 GW in 2024. For Middle Eastern countries, Turkey is urging to increase the share of solar and wind as well to cover its demand of imported energy [10].

The Kingdom of Saudi Arabia has ongoing plans to halt the rise of greenhouse gas emissions, and contribute to decarbonisation in order to reach the zero-carbon emission target by 2060. The main milestone for this is certainly to generate electric power by shifting away from petroleum and fossil fuel towards Renewable energy sources. Yet, such projects are still challenging and they are affected by many factors such as the location of the facility, meteorological parameters, connections to grid and mostly the efficiency of the technology. The scope of this paper is to discuss the implementation of electric power plant based on three renewable technologies 1) Photovoltaic 2) Solar thermal power and 3) Wind turbine in Al Aziziyah, located in Dhahran, the eastern province of Saudi Arabia. The performance of the three different power plants is predicted by using Retscreen Expert, a clean energy management software that has been validated by a team of experts in the Canadian government [11] in addition to HOMER Energy software. The analysis of the results presents evaluation of the electric power exported to the grid as well as the role of the three renewable technologies in the decarbonization process.

Renewable Energy Technologies

Photovoltaic

A Solar PV system consists of panels that convert electromagnetive wave of sunlight into electricity using the photovoltaic (PV) effect. The PV modules are made up of multiple (series and parallel) interconnected solar cells, which are typically formed of semiconductor material such as silicon. When sunlight hits these cells, it excites electrons, generating an electric current. Connecting cells in series increases the voltage and connecting them in parallel increases the current of the panel [12, 13]. Solar PV capacity has experienced a growth more than any other source of electricity generation [7]. In general, the PV size is chosen based on the energy and power consumption. The process of calculation of solar photovoltaic modular system involves the following steps: 1) Determine electricity consumption by calculating the total amount of electricity appliances to be powered in kilowatt-hours (kWh). An electricity bill provides a preliminary idea of the average monthly or yearly consumption. (2) Assess the solar irradiation which depends on the geographic location, time of year, and weather conditions. (3) Account for system losses: These can typically range from 10% to 20% including shading, wiring losses, inverter efficiency, etc. (4) Calculate the required capacity as in Eq. 1 and Eq. 2 (5) Determine the number of panels based on Eq. 3 [14, 15]. The efficiency of a solar panel refers to the amount of sunlight it can convert into electricity. The average efficiency for most commercial solar panels is ranging between 15% and 20%. The typical power output of a standard solar panel is around 250 to 400 watts [12, 13 & 16]. Advanced PV modules can produce over 400 watts power with maximum efficiency that reaches 40%.

$$\text{Required Capacity (kW)} = \frac{\text{Electricity Consumption(kWh)}}{\text{Solar irradiation} * \text{System Losses}} \quad (1)$$

$$\text{Solar Irradiation per day} = \frac{P}{A} = \epsilon\,\sigma T^4 \quad (2)$$

$$\text{Number of panels} = \text{Required Capacity(kW)}/\text{Panel power Output(kW)} \quad (3)$$

Where, P and A represent solar power and Area; €, σ and T indicate emissivity, Stefan-Boltzmann constant and surface temperature, respectively.

Solar Thermal Panel

A solar thermal panel absorbs the incoming solar radiation, converts it into heat [17, 18], and transfers this heat to a fluid (usually air, water, or oil) that flows and circulates (by mechanical component, such as a fan or pump) through the collector. A solar heating system utilizes solar heat (concentrated or not) without conversion in order to supply residential and commercial purposes [19]. The common types of solar panel or collectors are flat plate collector, integral collector-storage (ICS), double -glass solar collectors, compound parabolic collectors and evacuated tube collectors etc. [17, 18]. The concentration ratio, fluid flow velocity, and surface area would all have a significant influence on the collector's efficiency and heat removal factor. Compared to solar PV panels, solar thermal panels are more efficient, converting 70–90% of the energy input into heat, and they require less area. However, the capacity factor of the overall power utilization is in the range of 20 to 30% due to the intermittency of the naturel resources. Flat panel or collector, typically measuring one meter by two meters, is the most popular kind of solar thermal panel [20]. Figure 1 shows the system to convert sunlight to heat.

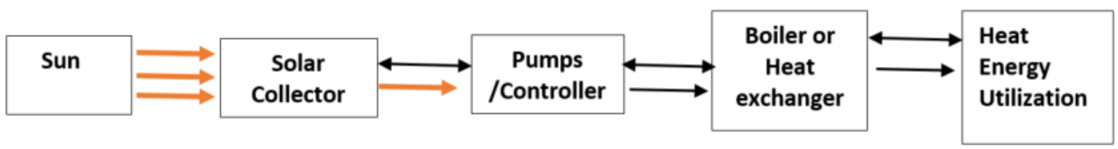

Figure 1 Converting sunlight to heat system

Again, concentrated solar power (CSP), a high temperature solar thermal system, uses groups of mirrors to concentrate solar energy at central collector. This produces a temperature high enough to generate steam, which then turns a turbine, driving a generator to produce electricity [19]. Electricity from a solar thermal system is an opto-caloric system that depends on solar radiation and its capture's capacity. Figure 2 shows the flow chart of electricity generation from solar radiation (by converting solar thermal radiation into electricity) with the support of a solar collector and other mechanical components.

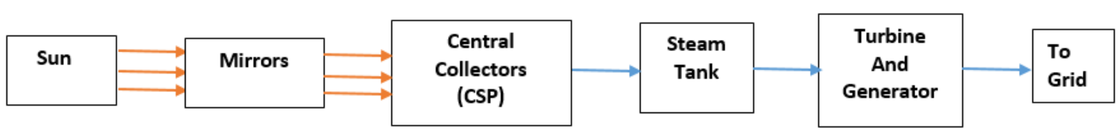

Figure 2 Electricity generation from solar radiation using solar heat

High temperatures that are required to achieve the utmost efficiency can be obtained by increasing the energy flux density of the solar radiation incident on a collector. According to Lupu et al. [20] energy efficiency of a solar thermal collector is:

$$n_{en} = \frac{\dot{Q}_u}{GA_C} \tag{4}$$

Q_u useful heat rate absorbed by the fluid; incident solar radiation, G (average 240W/m^2), A_c is area of the collector. C_p, m, and T are latent heat, mass of plate, and temperature, respectively. The useful heat rate absorbed by the fluid [20], Q_u, is

$$\dot{Q}_u = \dot{m}C_p(T_{fl,out} - T_{fl,in}) \tag{5}$$

Wind turbine
Wind turbines harness the naturel wind energy to generate electricity. The blades start to rotate when they are stimulated by the wind's kinetic energy. The resulting mechanical energy created over a drive shaft is then converted to electric energy through a generator. A basic wind speed of 3 to 5m/s at 10m height is usually sufficient to have potential wind resource. The efficiency of a wind turbine is measured by calculating its capacity factor as per Eq. (6) [21].

$$\mathrm{Cp} = \frac{\text{Actual Electricity Output (kWh)}}{\text{Maximum Electricity Output}} \tag{6}$$

$$\text{Maximum Electricity Output (kWh)} = \text{Capacity(kW)} * \text{hours per year} \tag{7}$$

The capacity factor indicates how fully the wind turbine capacity is used. It is affected by the availability of wind, the hub height, swept area of the unit and the size of its generator. The capacity factor ranges between 20 to 35% and it can go up to 52% for new giant devices.

Data Assessment
The potential electric power plants are located in Al-Aziziyah, in the vicinity of Dhahran, the eastern province of Saudi Arabia. The latitude and longitude for the facility location are 26.2 and 50.2 respectively. The climate zone is estimated to be extremely hot – Dry. The preliminary climate assessment is based on the meteorological data and NASA provided by RetScreen Expert Clean Energy Management Software platform. Fig.3 shows two meteorological parameters: the daily solar radiation and wind speed at 10m height above the ground.

The daily solar radiation ranges between 3.2 and 8 KWh/m². It is the global horizontal irradiance that presents the total solar radiation falling on a horizontal surface. The peak value of 7.8 KWh/m²/d attained in the month of June refers to 7.8 hours of sun received per day at 1 KWh/m² during this month. The extreme value of the annual average irradiance of 5.6 KWh/m²/d as per NASA as well as the high temperatures (above 30ºc) make the area an excellent resource for solar applications. The annual wind speed variation shows an average of 4.4 m/s, which favors the installation of wind turbines. Besides, Dhahran area belongs to the moderate to good wind resource as per [22].

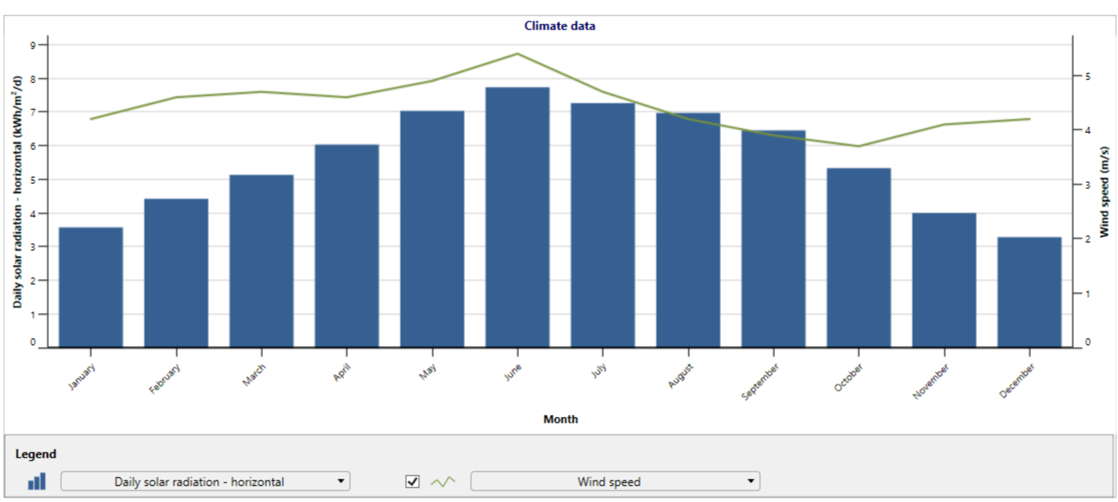

Figure 3- Daily Solar Radiation and Wind Speed in Dhahran area

RetScreen-Software based Simulation
The simulation of the three different renewable power plants has been conducted in RetScreen. Each RetScreen Technology model is developed within a workbook file that is been validated by

modelling experts and other simulation software. RetScreen evaluates the implementation of a renewable project based on several aspects: 1) Energy performance 2) Cost analysis 3) GHG emissions 4) Financial Summary and 5) Risk Analaysis. The input data is relatively small since RetScreen contains integrated products, cost and weather databases. The data that is required cover the location of the facility, climate data (hourly wind Speed for wind), selected technology (Manufacturer and model) and economic input data (Table 1). Other variables that are relevant to the energy pricing can also be filled by the user.

Table 1- Financial Indicators considered in RetScreen Simulation for the current simulation

Inflation rate: 2%	Debt Interest rate: 7%	Electricity Export rate: 0.10 $/kWh
Discount rate: 9%	Project Life: 20 years	Electricity Export Escalation rate: 2%

Results and Discussion

Renewable Energy Systems

Table 2 shows the technical specifications for the renewable technologies implemented in four potential power plants with different capacity each. Based on RetScreen predictions, the number of solar thermal and photovoltaic units is raised with the increase of the required capacity. For wind turbines, a larger electricity output is generated when the hub height increases and more turbines are added; which results in higher capacity factor. The gross energy production per turbine GE is different for each device model. For 1000,000 KW capacity, there is need for vast wind farm with 500 ENERCON 82 E2 2MW wind turbines at 138 m height. The solar thermal system presents the same performance for all capacities: 30% while photovoltaic cells have the least efficiency: the rate of miscellaneous losses considered is 15%, while the inverter capacity is 95%.

Table 2 – Technical Specifications for considered renewable based Power Plant

Capacity (KW)	Solar Thermal	Photovoltaic	Wind Turbine
1000	Abengoa Solar PS10 with parabolic mirrors Capacity factor: 30%	5000 units mono-Si Solar Collector: 3333 m² Efficiency: 17%	2 ENERCON 53 – 73m Capacity Factor: 25%
10,000	Abengoa Solar PS10 with parabolic mirrors Capacity factor: 30%	50,000 units mono – Si SP150 Capacity per unit: 150 W Solar Collector: 64103 m² Efficiency: 17.6%	5 ENERCON 82 E2 2MW – 78 m GE: 4771 MWh per turbine Capacity Factor: 24%
100,000	Abengoa Solar PS10 with parabolic mirrors Capacity factor: 30%	500,000 units mono – Si CS1H-320MS Capacity per unit: 320 W Solar Collector: 842105 m² Efficiency: 17.6%	44 ENERCON 82 E2 – 138 m GE: 5818 MWh per turbine Capacity Factor: 25%
1000,000	Abengoa Solar PS10 with parabolic mirrors Capacity factor: 30%	5,000,000 units mono – Si CS1H-320MS Capacity per unit: 320 W Solar Collector: 8421053 m² Efficiency: 17.6%	500 ENERCON 82 E2 2MW – 138 m GE: 5613 MWh per turbine Capacity Factor: 28%

Table 3 – Electricity outcome and CO_2 reduction for the three considered technologies

Designed Capacity (KW)	Electricity Exported to Grid (MWh)			GHG Emission Reduction (tCO_2)		
	Solar Thermal	Photovoltaic	Wind Turbine	Solar Thermal	Photovoltaic	Wind Turbine
1000	2,628	1,543	1,968	1,243	730	1,650
10,000	26,280	11,576	20,675	13,582	5,475	9,778
100,000	26,280,000	246,950	221,668	124,291	116,795	104,837
1000,000	262,800,000	2,469,205	2,432,350	1,242,910	1,167,949	1,150,377

Table 3 shows the electricity exported to Grid as well as the rate of carbon reduction in tons of CO_2 relevant to each technology. The production of electricity from both photovoltaic and wind turbines is comparable specifically when the capacity exceeds 10,000 KW. The solar thermal system provides the highest rate of total electricity output at a specific designed capacity. It can play a pivotal role in the electricity generation in the area due to the abundance of sun and consequently the generated heat will be used in electricity generation. The electricity exported to grid will reach 262,800,000 MWh for a 1000,000 KW power plant capacity, which surpasses the output from Photovoltaic and wind. The amount of greenhouse gas displaced in tons of CO_2 is in correlation with the increase of the designed capacity. The implementation of photovoltaic results in the lowest carbon reduction rate in comparison with the solar and wind at 10 MW and smaller.

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Figure 4 shows the greenhouse gas emissions displacement with respect to the three different renewable technologies (solar thermal, Photovoltaic and Wind Turbine) in function of the required power plant capacity. At capacities equal to or lower than 10,000 KW, the solar thermal has the ability to displace the highest rate of carbon dioxide, followed by the wind turbine and then the photovoltaic system. For 100,000 and 1000, 000-KW power plants, the three technologies will result in comparable amount of greenhouse gas emissions. This is due to the expansion in the number of photovoltaic units and higher wind turbines that will capture more sun and wind and consequently release clean energy. The amount of displaced greenhouse gas emissions when setting up a 1,000,000 KW renewable power plant capacity attains 1,242,910 tCO_2, which accounts for 2,890,487 Barrels of crude oil not consumed.

The process of electricity generation by using renewable technologies instead of the conventional methods has a great impact on the decarbonization as it halts the release of toxic substances in the air. In fact, coal, natural gas or petroleum combustion are more carbon-intensive in electric power production in comparison with wind and solar as shown in Table 4. Besides, Coal combustion produces more greenhouse gases than the combustion of any other fossil fuels.

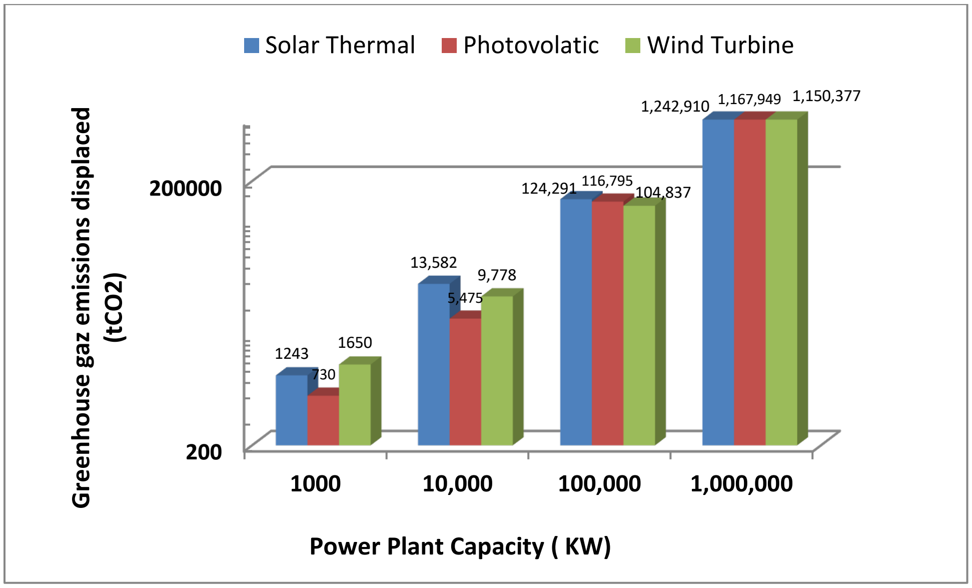

Figure 4 - Greenhouse emissions reduction with respect to renewable energy technologies (tCO_2)

Table 4 CO_2 emissions during electricity production for different energy sources (obtained from [23])

	Coal	Natural Gas	Fuel Oil	Wind	Solar	Petroleum
Electricity generation	0.88 kWh/Pound	0.13 kWh/cubic foot	12.90 kWh/gallon	2,4 kWh and 9,6 kWh/day	0.68 KWh/day	1.18 kWh/pound
CO_2 emissions	980 g CO_2/kWh	465 g CO_2/kWh	266.5 g CO_2/kWh	11 g CO_2/kWh	41 g CO_2/kWh	345.0 g CO_2/kWh

Reducing carbon emissions from the power industry is greatly impacted by moving electricity production from fossil fuel generation sources to renewable ones. Decarbonizing the grid is one potential option that calls for international cooperation and coordination between businesses and governments in order to reduce emissions as well as follow the Paris Agreement.

Conclusion

Renewable energy sources, particularly wind and solar, provide sustainable solutions to our power needs. They present a major role in the decarbonization process especially when used in the electricity generation process. A case study conducted in Al Aziziyah in the Kingdom of Saudi Arabia reveals the most beneficial impact on displacing the greenhouse gas emissions when implementing the Solar Thermal power plant. The area, prone to continuous extreme sunlight, and good wind potential offers an efficient and sustainable alternative for producing fossil fuel based electricity and facing the high demand with minimal environement effects. Finally, while renewable energy sources like wind and solar power significantly reduce greenhouse gas emissions, they are not entirely devoid of waste generation, particularly during the manufacturing and end-of-life stages.

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