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Techno-Economic Evaluation and Optimization of Grid Connected PV and Wind Generating System for Riyadh City

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Abstract

The risks and challenges faced by human society at the moment are global warming, climate change and pollution. In addition to their effect on the atmosphere, the quantity of fossil fuels is beginning to decrease, and countries have taken steps to encourage greater use of renewable energy resources. This article explores the feasibility of supplying electricity from a hybrid power system (HPS) comprising wind/photovoltaic (PV) and batteries. Taking into account residential buildings that consume the largest portion of energy in Saudi grid, Saudi Arabia, Riyadh is the preferred city with distinctive geographical and climatic conditions. The hourly electricity demand data must be over 8760 hours during a 1-year analysis in order to assess the optimum design and operational planning of the HPS. The economic analysis is carried out by applying HOMER software on the basis of net present cost (NPC), energy cost (COE) and the renewable fraction for all situations. In addition, to specify the effect of fuel costs on the scheme, sensitivity tests are carried out by considering two separate tariff rates for residential consumers. The results of the economic analysis show that current tariff is not economic to use HSP under warm and temperate climate conditions compare to using electricity from grid and the expected forecasted tariff shows it's economic to use HSP compare to grid electricity.

Keywords

Solar, Grid, Optimization, Cost, HOMER Pro® Software

1. Introduction

The energy demand has increased due to population growth. As a result, meeting energy requirements is a growing concern for governors. Under such cir-

cumstances, finding an alternative, clean, and low-cost source of energy is of the utmost importance. Limited reserves of fossil fuels, sustainability enhancement, diversification of energy supplies and environmental impacts of fossil fuels have led to increased utilization of renewable energies.

Moreover, the renewable technologies provide a sustainable and cost-effective alternative for fighting carbon pollution. Consequently, the significant advancement in the global clean energy sector stems from renewable energy sources and they are one of the fastest-growing industries [1]. Given the fact that global energy consumption has been growing rapidly, it is predicted that the electricity generated from renewable energy sources will surpass natural gases and nuclear power, and renewables will become dominant in energy production by the end of 2040. The strategic energy planning process is a framework that can be modified to meet each community's need. World energy consumption is increasing substantially, according to International Energy Agency the world energy consumption in 2018 is 25,721 TWh where almost 60% of the produced energy around the world emits carbon dioxide (CO_2). We can calculate the contribution of the average citizen of each country by dividing its total emissions by its population. This gives us CO_2 emissions per capita [1].

Saudi Arabia has a growing economy. The energy consumption per capita is increased throughout the country with a substantial percentage. The reason of significant energy consumption is the decline in the exports of fossil fuels. The previous decade experienced much energy consumption equivalent to more than 500 million barrels of oil. It is expected that the total consumption of energy could be double in 2030. Evidently, as per given data of Saudi Electric Company, the total share of hydrocarbon i.e. oil is 63% and gas is 37%. The data further integrated and demonstrated that the in 2008 the total hydrocarbon consumption is 1766 TWh to fulfill the energy needs of different sectors. The growth of primary energy demand from 2004-2008 is 1366 TWh, and with the current consumption ratio in 2020 (2035 TWh), it will increase up to 2593 TWh in 2030. It will lead to further decline in the fossil fuel [2].

The world's largest per capita CO_2 emitters are the major oil producing countries; this is particularly true for those with relatively low population size. Most are in the Middle East: In 2017 Qatar had the highest emissions at 49 tonnes (t) per person, followed by Trinidad and Tobago (30t); Kuwait (25t); United Arab Emirates (25t); Brunei (24t); Bahrain (23t) and Saudi Arabia (19t). Figure 1 shows carbon dioxide per person in year for Saudi Arabia. In the visualization we see the differences in per capita emissions across the world [3].

Various research work has been done on modeling hybrid systems that can generate much less emissions and can eventually replace the traditional way of producing electricity.

An off-grid solar-wind hybrid system is proposed for a university campus in Pakistan that will operate during power supply unavailability or shedding scenario. The University campus model has very low energy (COE) and Net Present
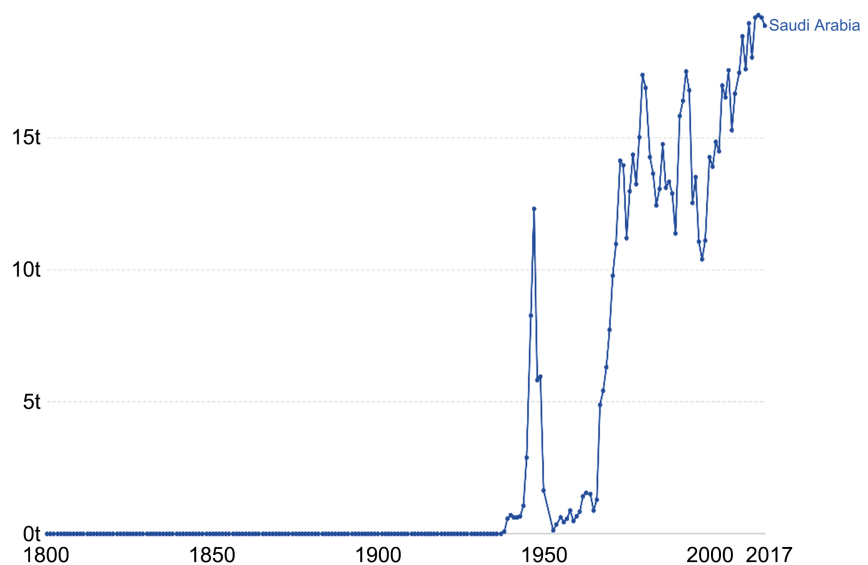
Figure 1. CO_2 emissions per capita (Source: our world in data [3]).

Cost (NPC) costs [4]. Hybrid energy system focused on PV-generator batteries for Aha Village, Morotai Island, North Maluku. Here, the authors considered two forms of loads for the village, *i.e.* communal and administrative. The results of the optimization show that both types of load can be easily satisfied by the proposed hybrid model [5]. Off-grid PV-wind battery hybrid system for three regions of Morocco that easily meets the load of those areas. The result also shows that the hybrid method can only be used if significant resources are available [6].

Study shows that among the cities considered in the study, Kish Island has mild and temperate climate, highest solar radiation and the lowest value for COE is the most economically and environmentally feasible city to meet the energy needs of all three types buildings. In addition to the substantial decrease in diesel fuel consumption, emission of CO_2, NPC and COE prices, this shows that renewable energy is more environmentally friendly and cost-effective than traditional energy sources [7].

2. Overview of the Electricity Sector in Saudi Arabia

Electricity generation capacity in 2018 reach 85.556 GW with 79 power plant of different producers, in between 2013-2018 around 49.4 GW have been added to the power system likely, due to increased consumption and higher energy demand in the kingdom. Based on International Energy Agency, Saudi Arabia generate electricity by using oil and gas on steam turbines (41%), gas turbines (41), diesel generator (1%) and combined cycle unite (17%) as it mentioned below (**Figure 2**).

Energy consumption by source, Saudi Arabia
Energy consumption is measured in terawatt-hours (TWh). Here an inefficiency factor has been applied for fossil fuels. meaning the shares by each energy source give a better approximation of final energy consumption.
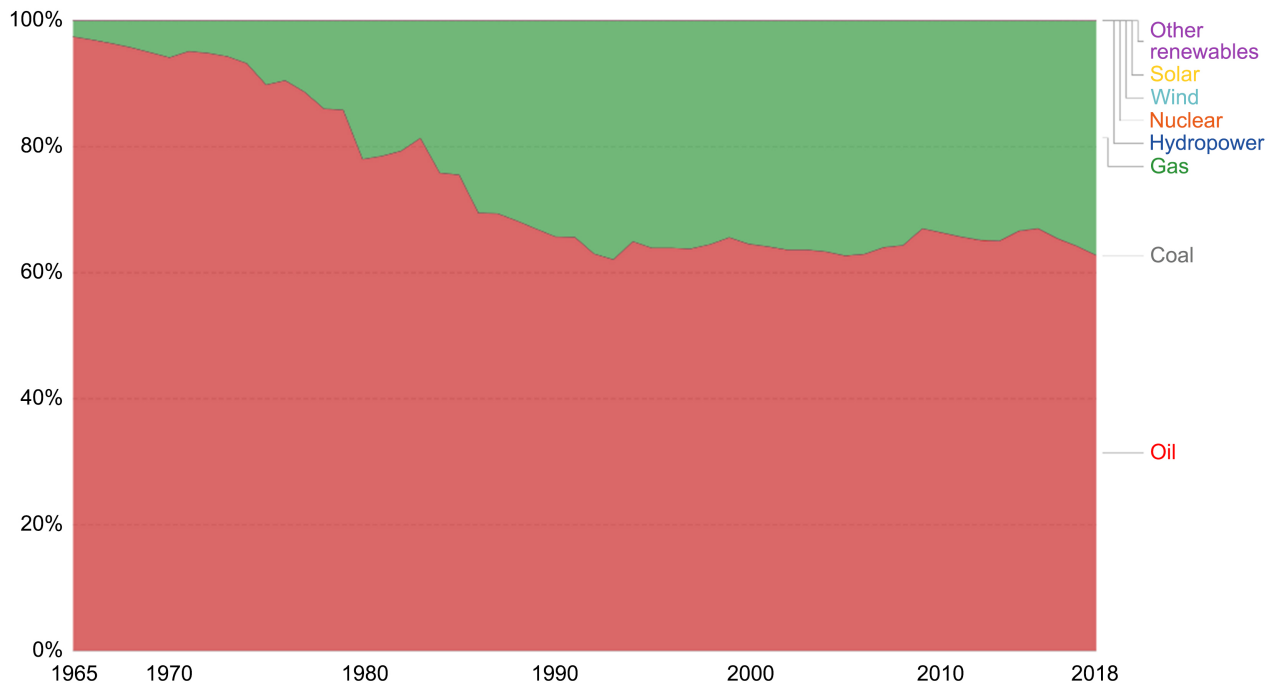
Source: BP Statistical Review of World Energy (2019)   OurWorldInData.org/energy • CC BY
Note: "Other renewables" includes geothermal, biomass and waste energy.

Figure 2. Energy consumption by source in Saudi Arabia (Source: our world in data [3]).

Integration of power sources in power system has the upside of decreasing greenhouse gas emanation, henceforth helping with settling an unnatural global warming issue. It additionally helps decline our reliance on non-renewable energy source in power areas. Accordingly, renewable energy resources are viewed as a piece of the answer for alleviate ecological issues brought about by the utilization of traditional vitality assets. Right now, assets offer clean energy generations, permitting the charge of no-associated and remote zones, add to diminish reliance on non-renewable energy sources. They additionally have improved their innovations and diminished expenses. Nevertheless, the capital expense of sustainable force plant is exceptionally high contrasted with conventional power sources. However, the operating cost is less expensive than the one for conventional source and will keep on declining with modern technical improvement [8].

Since the greater part of sustainable resources are discontinuous in nature, it is invaluable to use more than one asset when accessible. Hybridizing of inexhaustible assets improves the energy system reliability, proficiency and economy, particularly in places with great attributes of sun and wind.

3. Renewable Energy in Energy Portfolio

The geographic location of KSA is well placed for capitalizing solar energy with

the average daily solar radiation level between 5.69 - 6.62 kWh/m² and 80% - 90% of clear sky days over the year as shown in **Figure 3** [9] [10]. High availability of neutral sources like solar and wind guide the world trending to use renewable energy and identify valuable opportunities to further reduce future energy costs and CO_2. Hence, according to Vision 2030, Saudi Arabia aims to boost its renewable energy resources in its total energy share by producing nearly 9.5 GW of energy from sustainable energy sources by 2023, of which solar photovoltaic (PV) generation comprises a considerable portion [9].

In addition to the solar over the kingdom, It shows that minimum and maximum wind speed over the Saudi Arabia 6 m/s and 10 m/s repetitively as shown in **Figure 4**.
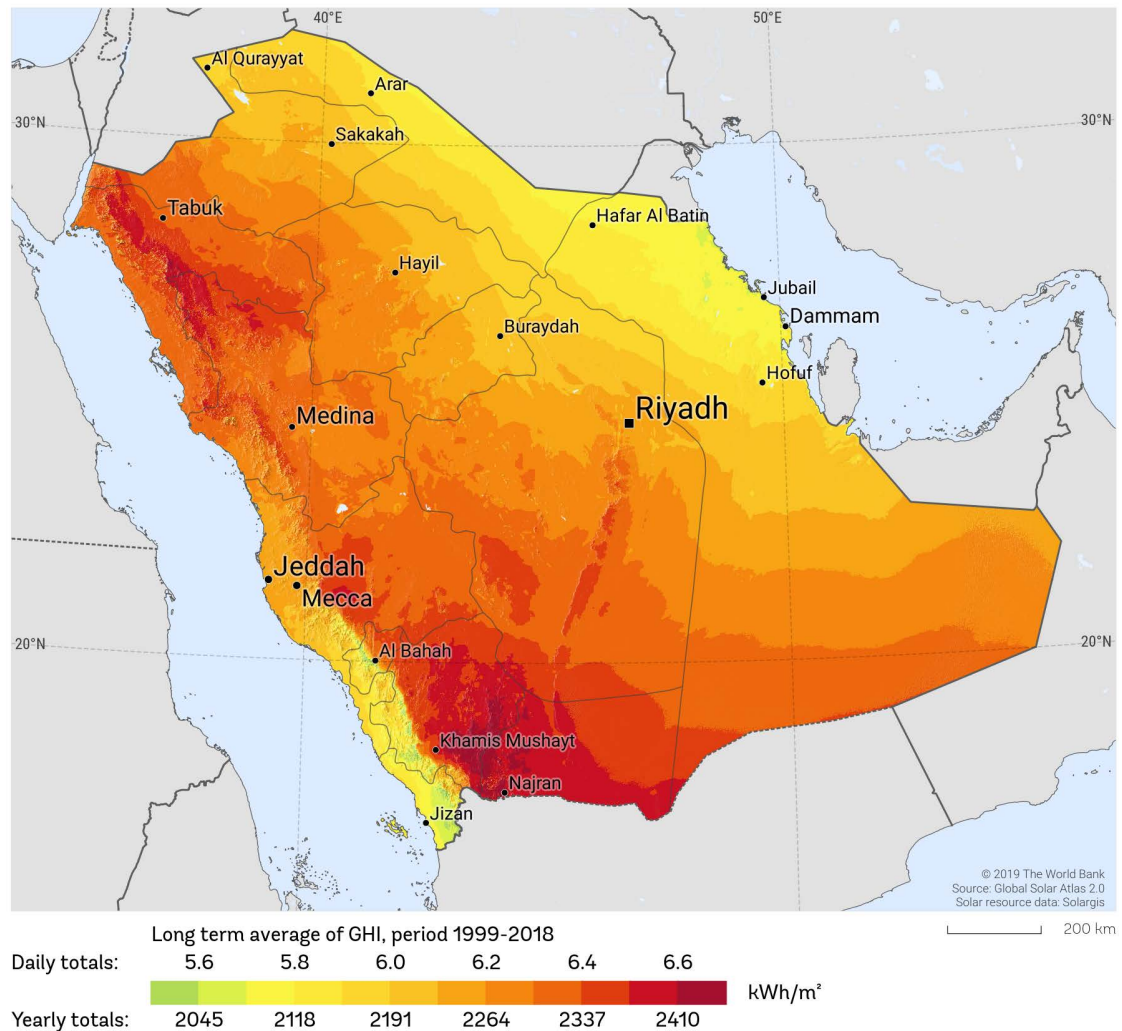

Figure 3. Global horizontal irradiation overt the kingdom (source: Global Solar Atlas [10]).

Potential Renewable Energy Systems in Chosen Location in Different Areas in KSA

Kingdom of Saudi Arabia is an Arab country and it is the largest nation in the Middle Orient and it is primarily situated in the southwest of the continent of Asia and forms the largest region of the Arab Peninsula with a latitude and length of approximately two million square km (23°43'00''N 44°07'00''E), respectively, and it has a diverse climate and a particular topographic character in this analysis. Riyadh city has been considered. The location Riyadh in Saudi Arabia is shown in Figure 5.
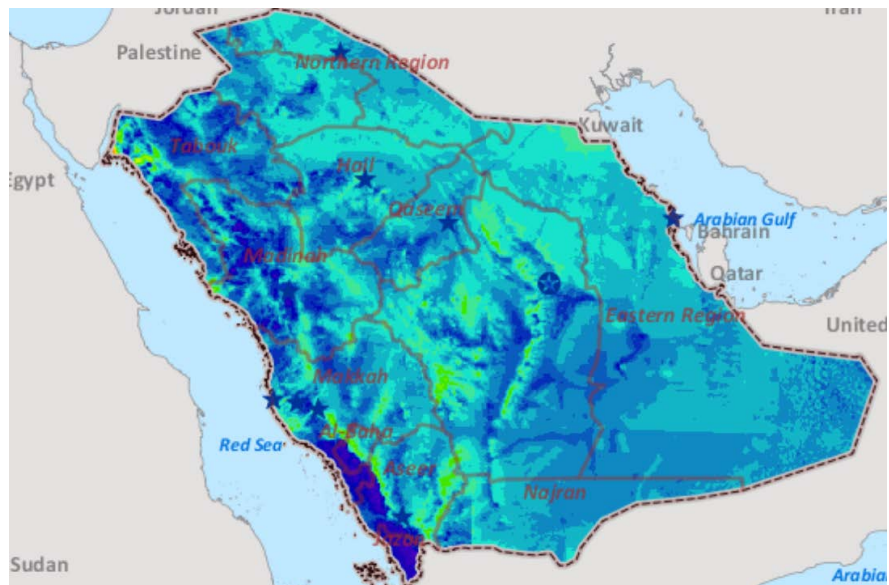

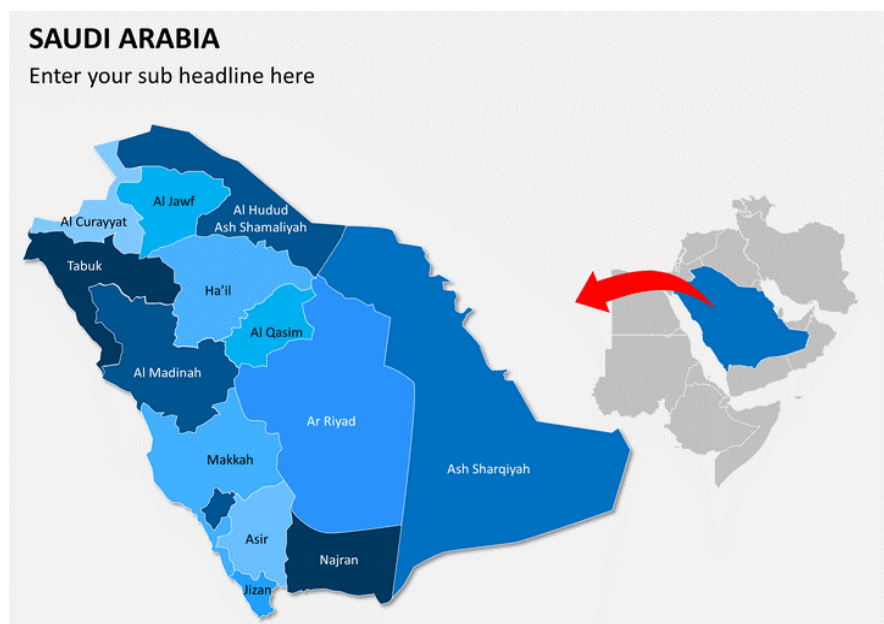**Figure 4.** Yearly average wind speed overt the kingdom (source: K.A.CARE [11]).

Figure 5. Riyadh city location.

4. Site Characterization

4.1. System Design

Mathematical model: PV [12]

$$P_{PVA} = N_{PV} V_{PV} I_{PV} \tag{1}$$

Mathematical model: Wind Turbine

Two or more binomial expressions are used to ensure fitting accuracy. The fitting equation of the wind generator output characteristic can be expressed as [12]:

$$P_{WG}(V) = \begin{cases} 0 & \text{for } V < V_{ci} \\ a_1 V^5 \cdots b_1 V^2 + c_1 V + d_2 & \text{for } V_c \leq V_c < V_1 \\ a_2 V^5 \cdots b_2 V^2 + c_2 V + d_2 & \text{for } V_1 \leq V < V_2 \\ a_3 V^5 \cdots b_3 V^2 + c_3 V + d_3 & \text{for } V_2 \leq V < V_f \\ 0 & \text{for } V > V_{co} \end{cases} \tag{2}$$

(V) is wind speed at the hub height.

(V_{ci}) is the cut-in wind speed.

(V_{Co}) is the cut-off wind speed.

Mathematical model: Batteries.

Where the total output of PV and wind generators is larger than the demand for load during the charging period, the available battery bank capacity can be represented by [12]:

$$C_{Bat}(t) = C_{Bat}(t-1) \times (1-\sigma) + \left(E_{PV}(t) + E_{WG}(t) - \frac{E_L(t)}{\eta_{inv}} \right) \eta_{Bat} \tag{3}$$

where:

$C_{Bat}(t)$ and $C_{Bat}(t-1)$ are the charge quantities of battery bank at the time (t) and (t − 1).

$E_{PV}(t)$ is the total energy generated by PV array.

$E_{WG}(t)$ is the total energy generated by wind Turbine.

$E_L(t)$ is load demand at the time (t).

(σ) is hourly self-discharge rate of the battery bank.

Mathematical model: System Performance.

As the lowest energy cost of these projects is more concerned, an economic model for the hybrid PV/ ind power generation system based on a leveled energy cost (COE) concept is developed [12].

$$COE = \frac{TPV + CRF}{E_{load}} \tag{4}$$

(CRF) is the cumulative present value of the actual cost of all components of the system including the replacement cost of hybrid system components as mentioned below [12].

$$TRF = C_{PV} + C_{Batt} + C_{wind} + C_{grid} \tag{5}$$

4.2. System Schematic

Figures 6-8 display the schematic configuration of the photovoltaic/wind/battery hybrid system for this analysis. As the demand for load is not constantly the same as solar panel and wind turbine power, battery banks are used to store energy in excess and then to use it when more energy is required. Moreover, any device that includes both AC and DC elements needs a converter to produce enough electricity.
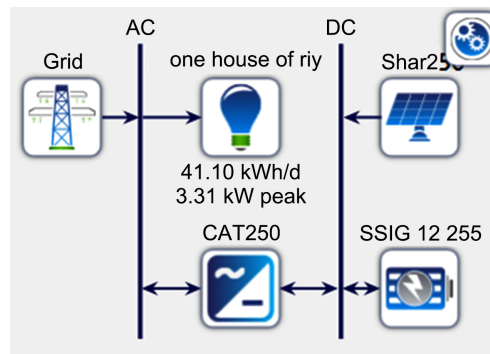

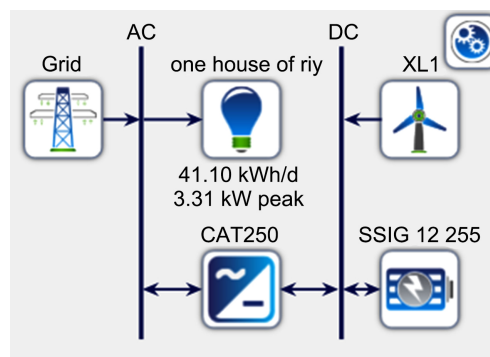**Figure 6.** Schematic of PV-Battery.
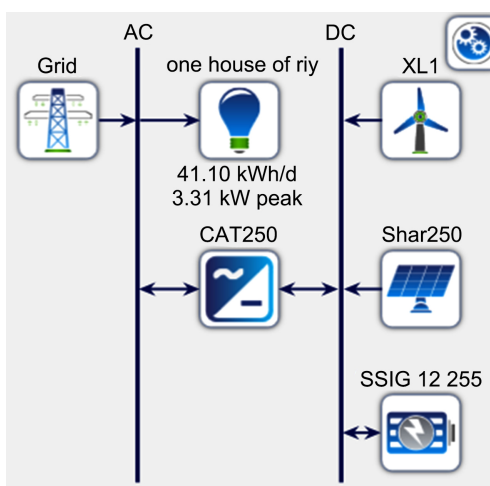

Figure 7. Schematic of Wind-Battery.

Figure 8. Schematic of PV-Wind-Battery.

System #1: PV-Battery Generation system
System #2: Wind-Battery Generation system
System #3: PV-Wind-Battery Generation system
Components technical and economic specification:

The emissions g/kWh consider in Saudi Arabia about 929.85 where this is the carbon gram per kilo watt hour for Petroleum according to U.S. electric utility and independent power electricity generation and resulting CO_2 emissions by fuel in 2018 [13].

4.3. Load Profile Assessment

This hybrid system has been planned to meet Riyadh City's energy needs for a residential load. The current demand for residential power in urban areas is strong, because of air conditioning. Energy use is strong in residential communities. In the current case the main energy consumption is due to the Ac units. Electric load evaluation was conducted carefully considering household load requirements for the summer peak season for residential requirements. The residential load estimates are mentioned in Table 1. The load profile of the residential community's monthly average electricity consumption is shown in the Figure 9, with highest consumption of electricity between May and Oct. The AC units run and the warm temperature in the city of Riyadh.

Table 1. Monthly load profile of typical consumer in Riyadh City.

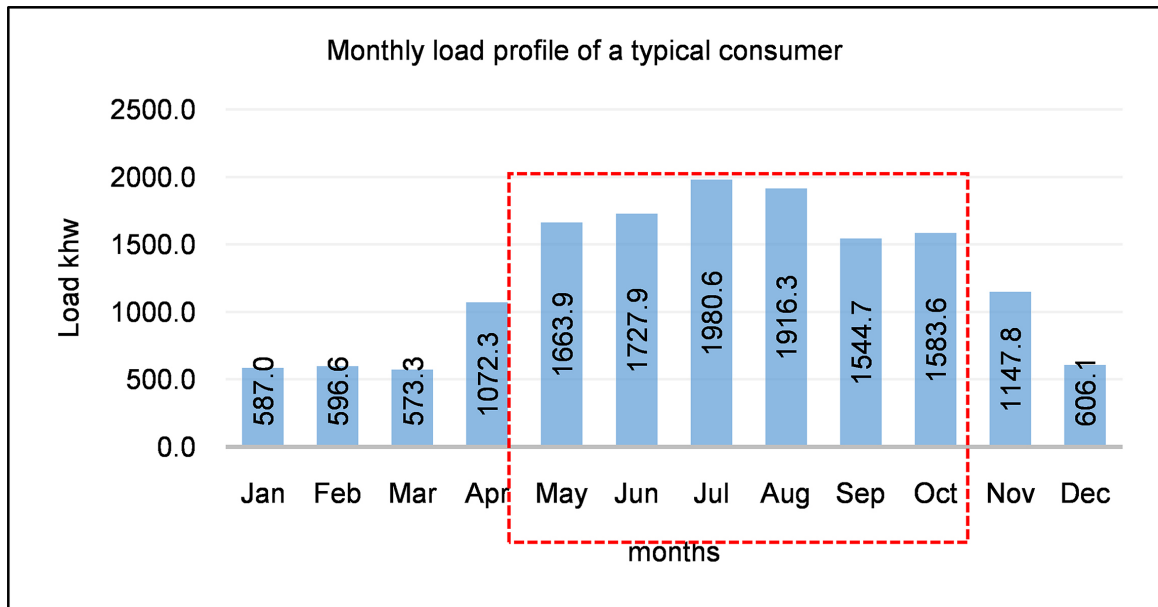| Month	Consumption kWh
Jan	587.0
Feb	596.6
Mar	573.3
Apr	1072.3
May	1663.9
Jun	1727.9
Jul	1980.6
Aug	1916.3
Sep	1544.7
Oct	1583.6
Nov	1147.8
Dec	606.1
Total	15,000

Figure 9. Monthly load profile of a typical consumer Riyadh city kWh.

4.4. Available Resources Assessment

In the present case, the hybrid solar/wind power system was taken into account. Therefore, the full assessment of the wind and solar resources available is given below:

4.4.1. Available Solar Radiation Data

Solar radiation data obtained by using HOMER software for the locations of Riyadh city from "Atlas website by K.A.CARE" **Figure 10** [11]. The maximum solar radiations were found to be 6.95 kWh/m²/day. Data shows that the location has good solar potential and can produce power in efficient way using photovoltaic (PV) panels. Below sampled of one day of a year in MAY. Using measured Global horizontal irradiation form Al-Uyaynah Research Station 24°54'36.0"N 46°24'36.0"E which considered the advanced solar measurement station in the world shown in **Figure 11**.

4.4.2. Available Wind Speed Data

Wind speed data obtained by using HOMER software for the location of Riyadh city from "Atlas website by K.A.CARE". **Figure 12** [11] displays the monthly mean wind speed data, measured at 40 m above the ground level. The data have been obtained from the meteorological database for 3 yr period of 2013-2016. The annual mean wind speed of is estimated to be 7.64 m/s at 40 m height which demonstrates that the city benefits from the abundant wind resource. Using measured wind speed data City site station at Riyadh city 24°34'35.1"N 46°21'10.0"E which considered the advanced solar measurement station in the world Shown in **Figure 13**.
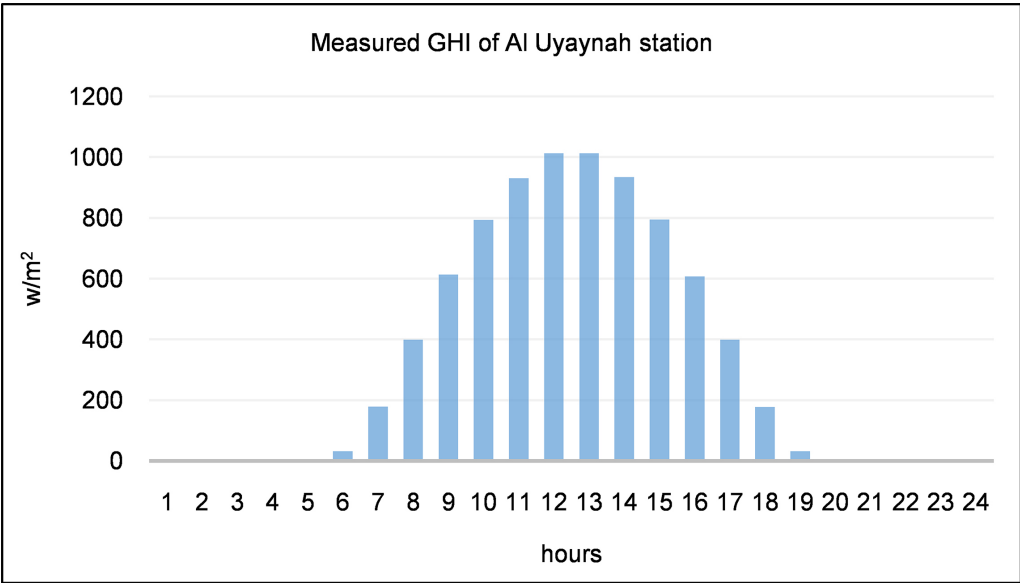
Figure 10. Global horizontal irradiation of Al Uyaynah station sample day in May [11].
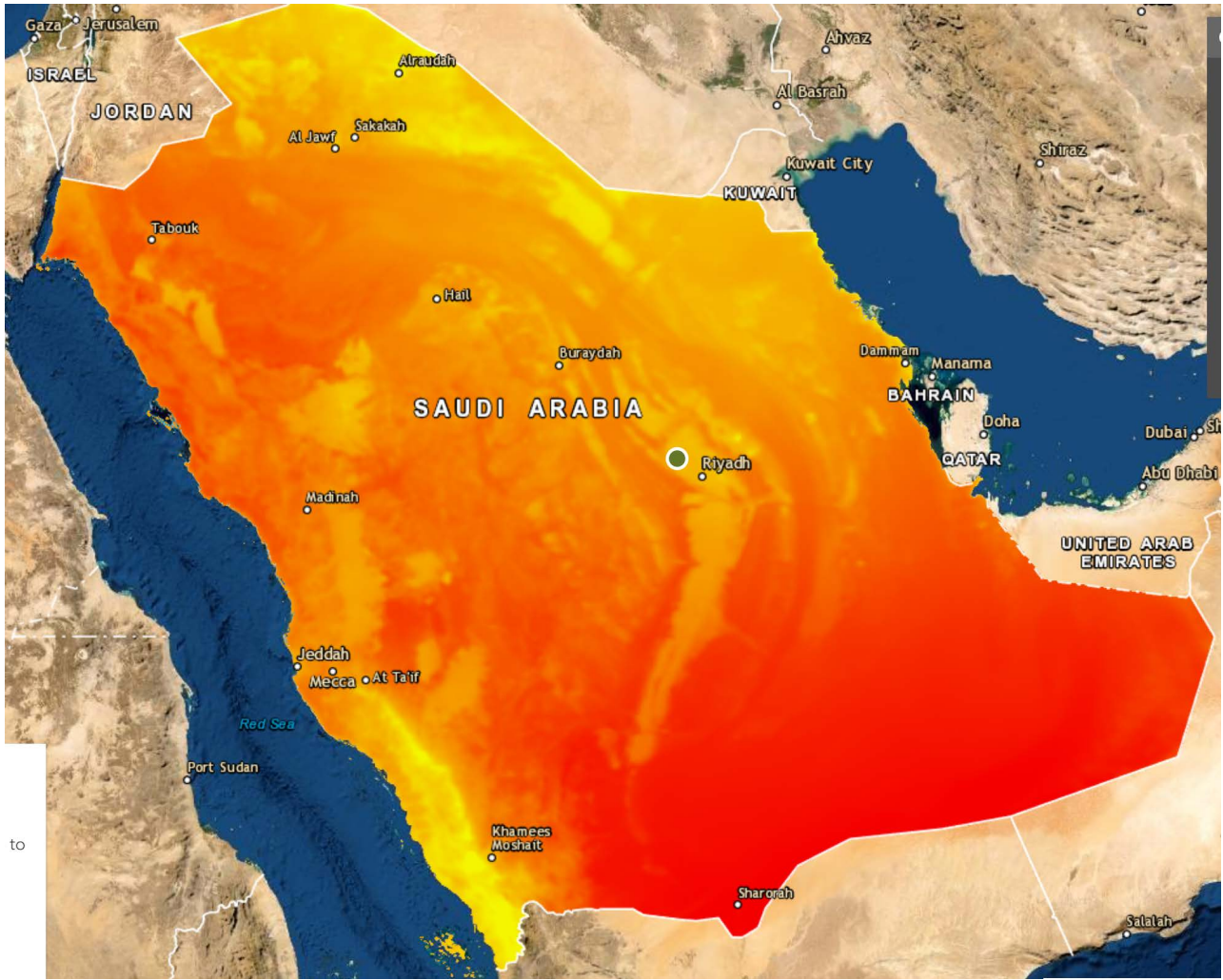

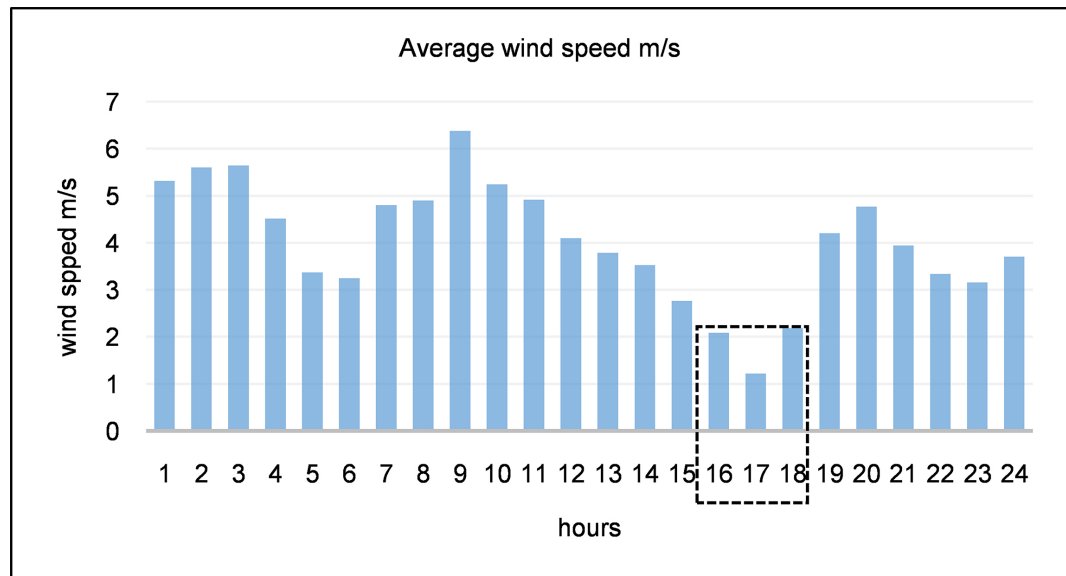**Figure 11.** Al Uyaynah Research Measurement Station location in Saudi Arabia.

Figure 12. Average wind speed of city site station at Riyadh city Sample day of January [11].

Figure 13. Wind Measurement Station location in Saudi Arabia [11].

5. Methodology

For optimal design and evaluation of the techno-economic feasibility of hybrid systems, HOMER software Pro 3.14.3 produced by NREL (National Renewable Energy Laboratory, USA) has been employed. This software is a powerful tool for the optimum design, scale and planning of renewable hybrid energy systems through technical and economic analysis of off-grid and on-grid power systems. It requires inputs such as electrical or heating loads to simulate the system or hybrid part combinations based on various set-ups and generates optimized systems sorted in terms of COE and NPC methodology of optimization presented in Figure 14 [15]. Device architecture configurations are optimized by limiting the objective feature to the limitations. In this analysis, the objective function is COE which is the current device expense, except the amount of the revenue. Battery charging and unloading, power balance and other technological limitations are the limitations. By making energy balance for an hour, HOMER simulates the system configurations and takes the electric or thermal loads per hour that can be supplied to the system [14].

This study shows the effect on COE and NPC of renewable penetration and storage. As HOMER analyzes and optimizes the pre-feasibility of the micro-grid systems before implementation. Typically, three tasks can be done with HOMER: simulations, sensitivity analysis and the simulated machine optimization [13].

Loads, modules and grids are three primary types of equipment for hybrid renewable systems. The electric loads for this analysis include PV, generators, batteries and converters. Tables 2-5 define the characteristics of these components which are modeled on HOMER.
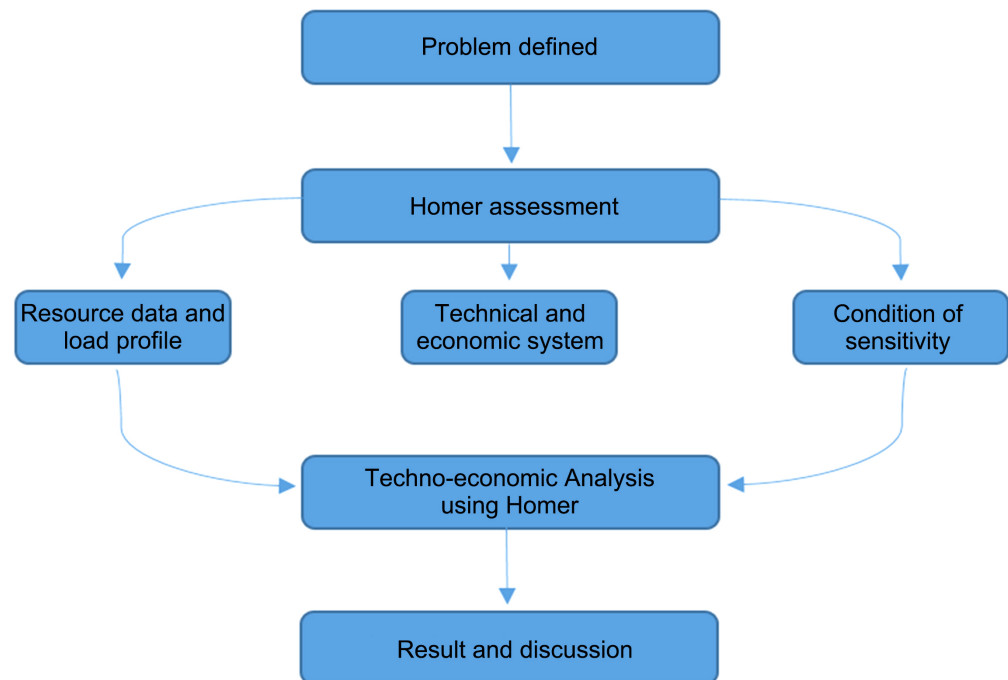

Figure 14. A schematic diagram indicating methodology utilized for analysis [15].

Table 2. Parameters of the hybrid system components in Homer.

Component	Model	Life time	Initial cost	Replacement cost	Maintenance cost
Grid	-	-	-	-	-
Battery Bank	SSIG 12 255		300$/Battery	300$/Battery	4.5$/year
PV module	ND-250QCS	25	850$/kW	800$/kW	80.5$/year
Wind Turbine	BWC XL.1	20	1500$/turbine	1200$	50$/year
Power Converter	BDP250	25	900$/Converter	800$/Converter	0$/year

Table 3. Technical data used by the HOMER software.

Efficiency	96%
Wind turbine cut-in	2.5 m/s
Wind turbine cut-off	12.5 m/s
Project life time	25 years
Grid Electricity price	0.048 and 0.08 $/kWh

Table 4. Technical Specifications of Bergey XL.1 - 1 kW.

Start-up Wind Speed	3 m/s (6.7 mph)
Cut-in Wind Speed	2.5 m/s (5.6 mph)
Rated Wind Speed	11 m/s (24.6 mph)
Rated Power	1000 watts
Furling Wind Speed	13 m/s (29 mph)
Max. Design Wind Speed	54 m/s (120 mph)
Type	3 Blade Upwind
Rotor Diameter	2.5 m (8.2 ft.)
Over speed Protection	AUTOFURL

Table 5. Technical Specifications of ND-250QCS 250 W.

Maximum Power (Pmax)*	250 W
Tolerance of Pmax	+5%/−0%
PTC Rating	223.6 W
Type of Cell	Polycrystalline silicon
Cell Configuration	60 in series
Open Circuit Voltage (Voc)	38.3 V
Maximum Power Voltage (Vpm)	29.8 V
Short Circuit Current (Isc)	8.90 A
Maximum Power Current (Ipm)	8.40 A
Module Efficiency (%)	15.3%
Maximum System (DC) Voltage	600 V
Series Fuse Rating	15 A

Optimization Method

The optimization of the system has been done according to the leveled cost of energy (COE) concepts and compare to SEC tariff prices for residential consumers (two tariff has been considered for the electricity coming from the grid) The terms "Total NPC" and "Total NPC" for all schemes, including the initial capital cost final price of operating costs in addition to CO_2 emissions per system, for electricity tariff prices of US$ 0.08/kWh have been considered in Table 6 shows that the optimum configuration of the optimization of renewable energy was the lowest NPC and COE for PV-Grid system. The system does not need batteries due to the consumer's load behavior. using batteries would increase the capital cost of the system and increasing COE as it mentioned in the second system in Table 6 and is not the highest prices due to the price of PV-Battery system would be also less than the price of electricity grid where the electricity of the grid coming in the third table where first tire 1 - 6000 kWh cost 0.048 $/kWh and second tariff is >6000 kWh cost 0.08 $/kWh.

6. Result

Table 6, Table 7 shows the results of the simulations of the optimal systems for each case study and the economic assessments based on NPC and COE parameters. Sensitivity case studies in Saudi Arabia often take into account the current price of electricity in the residual categorization prices of $0.048/kWh and the potential projected prices of $0.08/kWh. Systems in various configurations are tested. PV-Grid 2. PV-Battery-Grid 3. Wind-Grid 4. Wind-Battery-Grid 5. PV-Wind-Grid 6. PV-Wind-Battery-Grid. In Table 7 for the Total NPC and Total NPC, plus the initial expense of the operating cost, for both systems. In addition to the emission of CO_2 per device, only the 0.048$/kWh tariff price of Table 7 is considered. Also, show optimum systems optimization. Table 7 shows that the use of renewables is not economical for a typical Riyadh user with an annual consumption of 15,000 kWh per year, because of a COE scheme than electricity for the grid. so, it is obvious the grid coming as the economic NPC and COE as it shows in Table 7.

Table 6. Generalization of renewable energy systems optimization in riyadh for electricity tariff of 0.08$.

PV	WIND	Battery	Grid	NPC	COE	operating cost	Cost/Initial capital ($)	System/Ren Frac (%)	emmsion kg/yr
2.036			on	16215.990	0.075	963.832	2631.788	21.0768	7601
1.982		1	on	16492.320	0.077	965.914	2878.783	20.70087	7631
			on	16912.740	0.080	1200.000	0.000	0	9480
1.963	1		on	18113.440	0.084	995.881	4077.545	23.66246	7356
1.891	1	1	on	18389.850	0.086	998.934	4310.935	23.19167	7393
	1		on	18973.440	0.090	1232.888	1597.181	2.528687	9240
	1	1	on	19233.290	0.091	1224.962	1968.750	3.053514	9191

Table 7. Generalization of renewable energy systems optimization in riyadh for electricity tariff of 0.048$.

PV	WIND	Battery	Grid	NPC	COE	operating cost	Cost/Initial capital ($)	System/Ren Frac (%)	emmsion kg/yr
			on	10147.640	0.048	720.000	0	0	9480
0.056			on	10162.170	0.048	716.220	67.801	0.531	9430
0.066		1	on	10441.900	0.049	713.131	391.066	0.735	9410
	1		on	12380.080	0.059	765.316	1593.750	2.488	9244
0.382	1	1	on	12649.170	0.060	728.906	2376.004	7.362	8782
	1	1	on	12656.330	0.060	762.302	1912.500	2.681	9226
0.723	1		on	12849.960	0.061	759.264	2148.927	3.409	9157

The critical factors (for example, the size of the PV, converter and the number of wind turbines and batteries) that are required to provide the electricity demand are distinct from the environment parameters of a selected area at Riyadh, and they could have a profound effect on the cost of the system as well. It is primarily due to the fluctuation of the city's primary parameters, such as solar radiation and wind speed, to determine the solar panel size and the amount of solar radiation power turbines used and the optimum application of the wind speed. Higher irradiation or wind speeds may result in the load needed without using grid electricity and reduce the electricity used by the grid.

7. Conclusion

As a conclusion, several changes in electricity prices in the Kingdom has been done and recently in 2018 was the last change in the electricity tariff in the Kingdom, especially for the residential sector which aims to make several reforms to the electricity sector in the Kingdom, implicitly in the goals of Vision 2030 for the Kingdom where the electricity tariff for the residential sector became for the first and second tiers (1 - 6000-kilowatt hours (kWh) and (6001-kilowatt-hours and higher) at a value of $0.048/kilowatt-hour and $0.08/kWh respectively, which ultimately aims to link electricity prices to global energy prices. The cost of electricity today in the Kingdom is considered a non-incentive for the acquisition of a renewable energy system, as the electricity tariff from the grid in Saudi Arabia is cheaper than its cost than the renewable energy systems. But in the event that electricity prices are raised in the Kingdom and it is expected that electricity prices in the Kingdom will rise to become similar to the prices of commercial categories in the next 10 years $0.08/kWh, it is possible that the renewable energy system is economical and the cost of electricity is cheaper than acquiring it from the grid to meet the needs of the residential consumer in the Kingdom. where it shows that PV-Grid system can provide electricity with a price of 0.075 $/kWh cheaper than electricity from the grid of 0.08 $ per each kWh.

8. Data Availability

1) The data that support the findings of this study are openly available in Global Atlas at https://globalsolaratlas.info/map, reference number [10].

2) The data that support the findings of this study are available from [K.A.CARE. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors upon reasonable request and with the permission of K.A.CARE [11].

3) The data that support the findings of this study are openly available in EIA at https://www.eia.gov/tools/faqs/faq.php?id=74&t=11, reference number [16].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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