

Analysis of the Potential of Solar Energy Development in Saudi Arabia

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ABSTRACT

Saudi Arabia has been exploring the potential of renewable energy for many years. Saudi authorities, scientists, and researchers view the generation of renewable energy as a viable long-term energy strategy. Despite this, because Saudi Arabia is one of the leading oil producing nations and relies heavily on it as a form of energy and source of income, solar energy has not been given much serious consideration. However, it has become more and more evident that for the continuing prosperity of the nation and the inevitable gradual decline in long-term oil production, it is essential to explore and invest in alternative energy sources. The main objectives of this research are: i) to establish the potential of solar energy generation as a suitable, cost-effective alternative to petroleum products. ii) to establish the potential for maximizing renewable power generation to support the supply grid. This paper presents an examination of various economic and technological aspects of generating solar energy in Saudi Arabia. Using some existing data on the amount of solar radiation, a seasonal multiple linear forecasting method is used to generate forecasts for electric energy generation potential for 32 cities. Results of this research demonstrate the desirability and economic feasibility of installing solar panel farms and constructing distribution lines.

Keywords: Quantitative Forecasting, Renewable energy, Levelized Cost of Electricity (LCOE) generation model, Photovoltaic Generator

I. INTRODUCTION

Solar energy has been viewed by Saudi authorities, scientists, and researchers as a preferred this, the fact that Saudi Arabia is also one of the leading oil-producing nations and relies heavily on it as a form of energy, development, and distribution of electricity generated by solar power has not received serious consideration in the past. This research intends to examine the economic and technical aspect of solar energy development in Saudi Arabia and provides an approach to the analysis of investments needed to achieve a successful gradual transition to solar energy.

1.1 Problem Definition

The main objectives of this research are to study the potential of solar energy generation as a suitable, cost-effective alternative to petroleum products and to develop a methodology to evaluate the potential for maximizing renewable power generation to support the supply grid to Saudi cities. Using irradiation data collected from government

sources, we develop a forecasting model for the amount of solar energy that can be produced in 32 major cities of Saudi Arabia. The output of the forecasting model is then fed into an economic analysis model. The economic model employs estimates of the current cost of petroleum production, cost per unit production of solar energy and various other costs accrued during the production and distribution of the power generated using solar panels. This model can be used to identify regions in Saudi Arabia that have the most exposure to solar irradiation and can be considered as suitable solar energy production zones.

1.2 Status of Non-Renewable Energy in Saudi Arabia

Saudi Arabia's oil reserve is one of the largest in the world, which has led to significant development in this segment of the country's economy. Heavy focus on petroleum has partly been motivated by the fact that oil sales are high and form a major component of the country's income.

Statistics from 2010 indicate that income from oil made up about 90% of the country's total revenue. Saudi Arabia remains the largest exporter of petroleum-related products in the Middle East. Another major commodity is natural gas, for which Saudi Arabia was estimated to have the 4th largest reserves after Iran, Russia, and Qatar. Despite the rising interest and focus on renewable energy by consumers, research has shown that there is little motivation to explore and invest in alternative energy sources. The availability of non-renewable energy at a lower price places a barrier in the way of promoting renewable energy. High reliance on non-renewable energy sources among consumers coupled with the production advantage has resulted in the domestic prices in Saudi Arabia for petroleum products, such as gasoline and natural gas, to be about 40% less than international prices.

1.3 Status of Renewable Energy in Saudi Arabia

In Saudi Arabia, solar energy is the largest potential source of renewables. Despite the convergence of several factors that would seem to make solar power a viable source of energy, it remains largely unutilized or underutilized. The issue is not just the use of solar energy by the consumer, but also a significant lack of production capacity. Research shows that there is little investment in solar energy, especially by the state, in contrast to its heavy involvement and investment in petroleum products. This means that there is little motivation among state stakeholders, energy sector engineers, and other professionals in the sector to develop an effective policy that can be relied upon to push forward the widespread adoption of solar energy in Saudi Arabia.

The renewable energy issue in Saudi is further complicated by the high reliance among consumers on petroleum products. This is because of the current low cost of petroleum-based energy, as well as the high initial investment required to install solar energy production centers. It is worth noting that the average investment required for non-renewable energy surpasses that of renewable energy, which means that high consumption plays a role in driving the growth of non-renewable energy at the expense of solar energy. In fact, the majority of existing solar power generating ventures are funded by the private sector where, given the current state of technology, the costs end up being high and unsustainable in the long run.

II. LITERATURE REVIEW

Renewable energy, and specifically solar energy, have been the subject of various studies with different approaches. In this section, we discuss previous works on the potential for generating renewable energy in Saudi Arabia, the issues with

generating and distributing electricity from renewable sources and benefits associated with it.

Housing sector accounts for 52% of Saudi Arabia's total electricity consumption, and they propose Zero Energy Homes (ZEHs) as one of the ways in which the Saudi government can enhance sustainable housing practices in the country [1]. The study concluded that ZEHs do have the ability to withstand certain weather conditions, as well as the capability to produce energy that sustains and exceeds their consumption. Saudi Arabia has an immense wealth of solar exposure, having 2,200 thermal Kilowatts hours per square meter [2]. This article analyzes various projects that the country initiated and discusses the lessons learned from their operation and maintenance. The experience gained while applying quantitative assessment to the environmental benefits, costs, and savings that Saudi Arabia may receive from implementing large-scale solar energy projects [3]. Being in a location that is described as a sun belt, Saudi Arabia could become one of the largest producers of solar energy [4]. According to the article, photovoltaic cells can be used to generate clean solar energy, and there is a notable decrease in solar energy production cost making it economically viable compared to conventional fossil fuel.

The position of using photovoltaic power in the United States, China, and Japan. The study also seeks to discuss the subject countries' current and future policies regarding the use of such energy source. In a bid to promote the use of PV, European countries have introduced incentives for using PV panels. Germany and Spain lead in the use of PV as a percentage of their total energy production, while America holds the third position [5]. The lessons drawn from two Saudi Arabian solar projects, namely the Energy Research Institute (ERI) together with the King Abdulaziz Science and Technology City (KACST) [6]. They discuss activities such as PV, solar water heating, desalination, and solar hydrogen production, among others that were evaluated for solar energy applications. The paper notes that the main challenges in the deployment of solar energy include high cost as well as the lower conversion efficiency.

The determinants of the real cost of electricity are timing, location, and a few other characteristics. A controversy exists in the quantification of the non-market value of the reduced emissions since it is difficult to quantify; that is, the benefits that accrue from reduced emissions, e.g. a reduction in green gas emissions, cannot have a market value placed on them easily. Taxes on emissions, as well as a tradable permit system, represent some of the proposed market-based policies [7].

On the role of renewable sources in the protection of the environment, Panwar, ET al. review the use of renewable technologies. They state that renewable energy mitigates both the effects of pollution and the effects of global warming [8]. Other article studies the commitment that various countries have made to renewable energy sources. They focus on 24 European countries while applying panel dynamic estimators. The paper also seeks to find the determinants that promote or hamper the implementation of the commitments and finds a positive relation between previous uses of renewable energy with the assessed period's usage. However, it lacks evidence that awareness plays a significant part in the use of renewable sources. They conclude that it was not the market that hampered the optimal use of renewable energy, but other sources were more influential mostly because of lack of stability in fossil fuel prices [9].

III. METHODOLOGY

The methodology that was followed in this research is shown below.

1. Data collection: Information on the average solar irradiation in 32 selected cities in Saudi Arabia was collected. Various data regarding the cost of solar panels and construction of solar farms, as well the cost of transmission were also be gathered.
2. Construct and analyze an appropriate forecasting model for modeling the seasonal pattern of the amount of irradiation in the selected cities.
3. Use of the output of the forecasting model as in input to an economic analysis model to determine the cost of generation and transmission of solar power in the selected cities.

The following subsections discuss these steps in detail.

IV. DATA COLLECTION

This step included gathering the required data on the average solar irradiation in Saudi Arabia, the cost of solar panels, and other costs associated with the transmission of electricity from solar farms to consumer centers.

4.1 Average Solar Irradiation in Saudi Arabia

The amount of available solar irradiation varies across Saudi Arabia. Some regions of the country provide the highest potential in the world when it comes to solar energy production [10]. They study generated the map shown in Fig. 1 [10], indicating solar irradiation in different parts of Saudi Arabia.

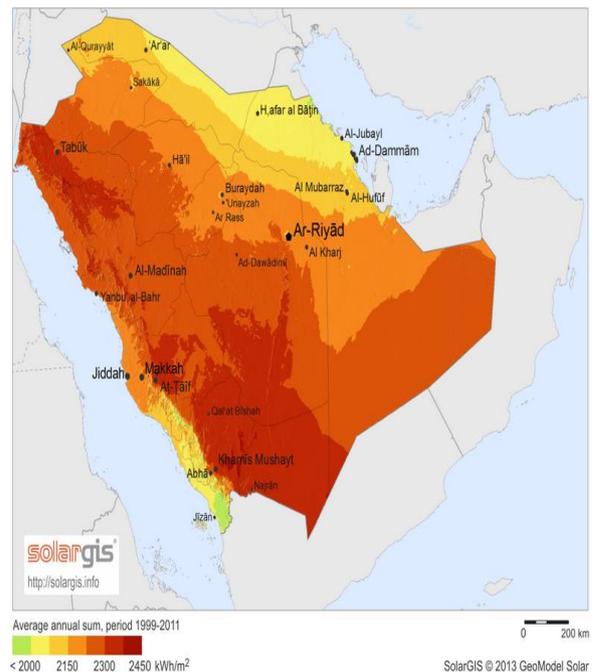


Fig. 1 Map Showing Solar Irradiation in Different Parts of Saudi Arabia [10]

From the map, it is clear that the regions of Tabuk, Hagl, and Taif receive the highest irradiation levels; hence, they are the best candidates for the installation of solar energy farms. TABLE 1 shows the average, maximum, and minimum direct normal irradiance for selected cities.

Table 1: Direct Normal Irradiance for Selected Cities [11]

City	kWh/m ² /day		
	Average	Maximum	Minimum
Afif	6.24	10.1	0.04
Al Aflaaj	5.98	9.56	0.26
Al Baha	7.54	10.21	1.01
Al Dawadmi	6.12	10.39	0
Al Hanakiyah	6.36	10.99	0
Al Jouf	5.17	7.99	0.22
Al Qunfudah	4.53	8.19	0.02
Al Uyaynah	5.76	10.34	0.01
Al Wajh	6.71	10.3	0.07
Arar	4.92	9.19	0.08
Duba	7.06	10.66	0.03
Hafar Al Batin	5.56	10.38	0
Jazan	4.51	6.82	0.45
Riyadh	5.97	10.27	0
Jeddah	5.15	9.33	0.1

Thuwal	5.46	9.6	0.01
Dammam	5.44	10.08	0
Al Ahsa	5.49	9.72	0
Majmah	5.86	10.37	0
Najran	6.59	10.37	0.01
Al Kharj	5.55	9.2	0.02
Qassim	6.1	10.27	0
Rania	6.68	9.65	0.26
Yanbu	5.65	8.52	0.5
Al Khafji	4.81	8.4	0.19
Farrasan	4.46	7.11	0.29
Hagl	6.9	11.15	0
Umluj	6.33	10.17	0
Al Jubail	5.39	9.93	0
Shagra	5.95	10.07	0.01
Tabuk	7.09	11.27	0
Taif	6.47	11.1	0.19
Timaa	7.07	10.38	0
Wadi Addawasir	6.18	9.68	0.06

Cost of Solar Panels

The cost of solar panels is market-dependent, and it reflects the level of consumption of solar power as a preferred choice of energy. A realistic estimate of the cost of solar panel installations per Watt of electricity generated. Figure 2 shows the decreasing trend of the price for crystalline Si panels from 1977 to 2013 [12].

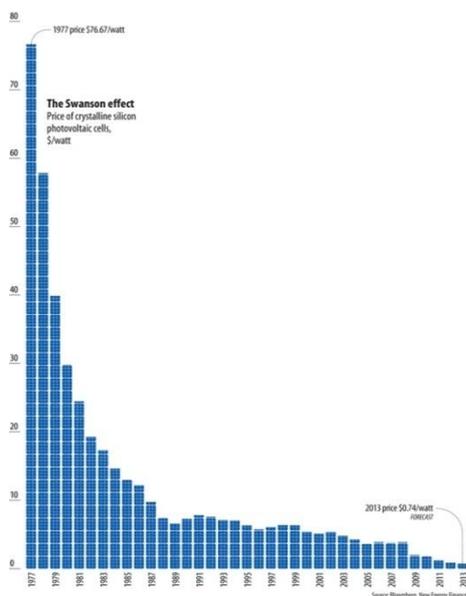


Fig. 2 Solar Panels Costs (1977-2013) [12].

Using the estimates provided in this article, it is possible to determine the cost of solar panels required based on the projected Watt capacity targeted by a specific solar project. From the graph, it is evident that in 2013 the average cost was US\$0.74 per Watt of solar electricity generated.

The cost of installation of solar power systems has gone down dramatically since 2008, leading to increasing affordability and exponential growth across different countries. The data presented in Fig. 3 shows the average cost of solar power system installation between 2006 and 2014 in different developed nations [13].

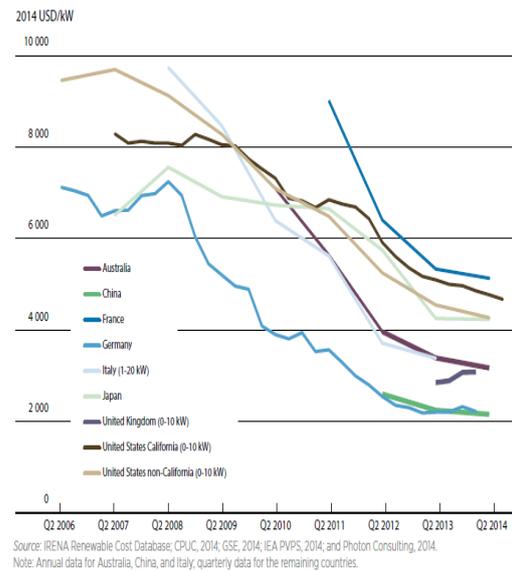


Fig. 3 Renewable Costs (2006-2014) [13].

3.2 Number of Solar Panels for a Solar Panel Farm

For a solar panel farm, solar panels are usually arranged in the form of parabolic trough collectors. This is the system that has already been installed in some solar panel farms in the Middle East region. TABLE 2 provides a breakdown of the associated civil and structural, solar field and their share in percentage for different components during solar energy production [13].

TABLE 2 Share in percentage for different components during solar energy production [13].

Component	Share (%)
Civil and Structural	5
Solar field preparation and solar field work	1
Solar collector pylon foundations	2
Power block and balance of plant structures	2
Solar Field	64
Health collector elements (HCE)	10
Reflectors	14
Metal support structures	20

Drivers, electronic and controls	2
Heat transfer fluid (HTF) piping between collectors	1
HTF header piping	2
HTF fluid initial filling	3
Transport, erection, and commissioning	11
Heat transfer fluid system, including solar heat exchangers	9
HTF heat exchangers and tanks	5
HTF pumps	2
Transport, erection, and commissioning	2
Power Block	23
Steam turbine generators	7
Cooling system including condenser	7
Fuel gas system including backup	1
Balance of plant	0
Waste water treatment	1
Fire protection	4
Electrical and Installation	2
Transport, erection and commissioning and other	2
TOTAL	100

4.2 Electricity Produced per Solar Panel

The amount of electricity produced per solar panel depends on the peak solar irradiation time. During low irradiation times, the amount of electricity generated is not the same as during high irradiation times [14]. Consequently, a typical solar panel produces an average of 200 W per day, but this depends on the efficiency and the size of solar panel being used. Liorens adds that an array of 25 panels can produce five kWh [15]. However, Energy Australia places the output at 3.84 - 4 kWh, while the Office of the Renewable Energy Regulator in Australia provides a figure of 3.79 kWh for Sydney [16]. This disagreement implies that it may not be possible to predict precisely the output that can be generated from a solar cell array. TABLE 3 provides an estimate of solar energy generated using solar panels in different parts of the world.

Table 3: Energy Production [14].

	Unit	Australia 2007-08	OECD 2008	World 2007
Primary Energy consumption^a	PJ	6.9	189.4	401.8
Share of total	%	0.12	0.09	0.08
Average annual growth, from 2000	%	7.2	4.3	9.6
Electricity generation				
Electricity output	GWh	0.1	8.2	4.8
Share of total	%	0.04	0.08	0.02
Average annual growth, from 2000	%	26.1	36.3	30.8
Electricity Capacity	GW	0.1	8.3	14.7

a: Energy production and primary energy consumption are identical

4.3 Cost of Transmission Lines

The estimates provided in this section were retrieved from Wartsila, leading manufacturing and energy Installations Company in Finland, specifically looking at estimates provided for the year 2011. The cost of building a transmission line largely depends on the model adopted for transmission. In the case of a tunnel transmission system, there will be fixed and variable costs associated with tunnel and shaft construction, tunnel boring machine costs, and overheads. The cost of a transmission line depends on whether it is an overhead or underground system. For the overhead system, there are single, double, and multiple circuits, all of which affect the cost of transmission [17].

The cost of an underground system is significantly higher than the cost of an overhead system, mainly due to trenching costs. TABLE 4 compares the cost of these two transmission systems for different voltage lines [18].

Table 4 Comparison of overhead and underground transmission costs [18]

Type	Overhead transmission	Underground transmission
69 kV single circuit transmission line	\$285,000 per mile	\$1.5 million per mile
138 kV single circuit transmission line	\$390,000 per mile	\$2.0 million per mile

Other substantive cost estimates for an overhead system, which would be the ideal choice in a solar energy transmission system [17]. According to these estimates, the costs for an overhead system will vary depending on the height of the tower. Juho adds that there are other costs associated with the civil construction process, such as earth excavation, earth filling, boxing work, concrete, iron fitting, land clearing costs (depending on the density of vegetation), engineering costs, and commissioning costs. Juho's illustration of the component costs for a typical transmission line can be seen in Fig. 4.

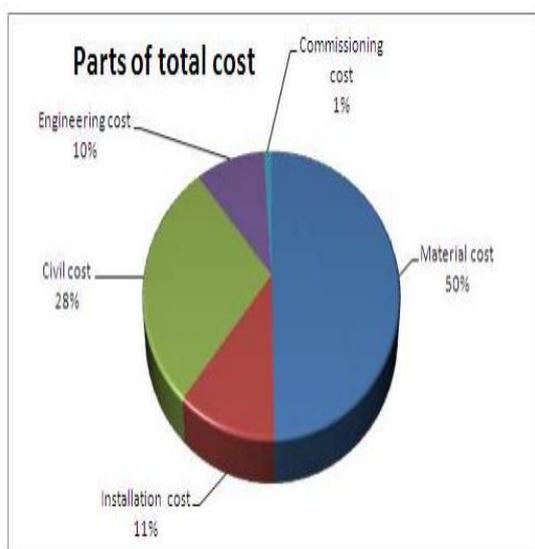


Fig. 4 Transmission cost estimate components for an 8 km transmission [17]

Fig. 5 shows the prices for different voltage models at a constant line length of 10 km.

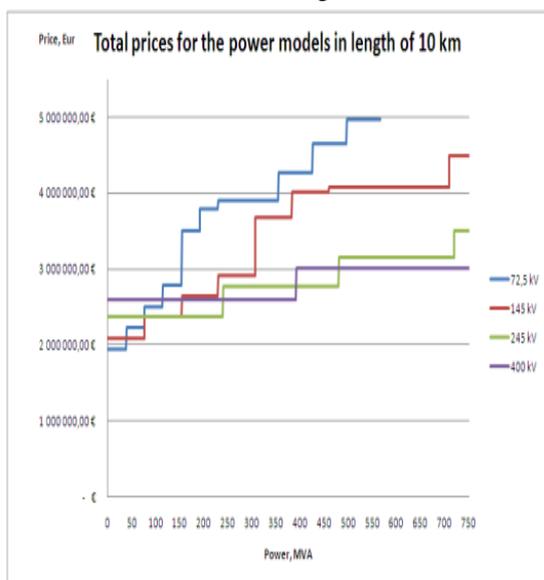


Fig. 5 Price for the Power Models [17]

Fig. 6 is an illustration of the cost per km and total costs for a 72.5 kV and 0-38 MVA.

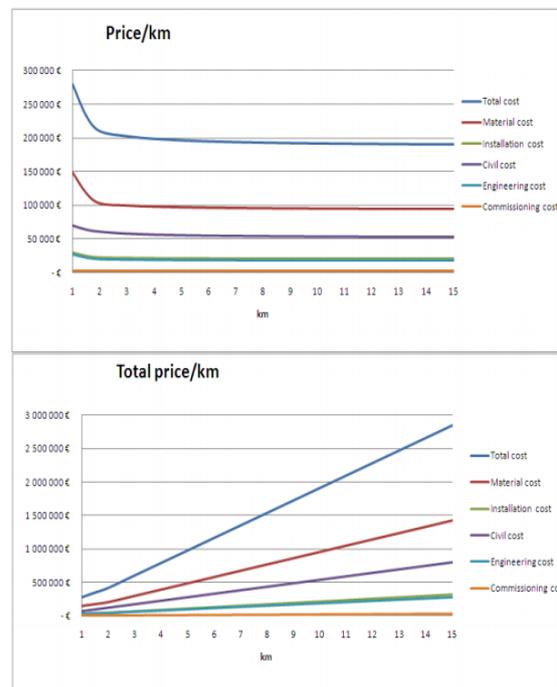


Fig. 6 Cost per Kilometer and Total Costs [17]

4.5 Transfer of Electricity through Transmission Lines to Consumers

The transfer of electricity through the transmission lines to consumers should be done by pursuing a model that lowers the civil, material, engineering, and commissioning costs associated with the transmission line. This should take into consideration the load, which is mostly determined by the number of consumers to be connected. It should also consider the uses for which the generated electricity will be used (e.g., residential or industrial), as each may have different demands from the system.

5.6 Status of Renewable Energy in Saudi Arabia

We use multiple linear regressions method of forecasting to predict the solar irradiation while considering the seasonality of the data. This approach analyzes a relationship between a dependent variable and several independent variables. To capture the seasonality of the irradiation data, sine and cosine functions have been included in the regression equation.

To illustrate the procedure for estimation of model parameters, we have used data from Tabuk City. The same process was then repeated for 31 other cities, and the regression coefficients for each city were estimated. We use the following linear regression model:

$$x_t = b_1 + b_2 \sin \frac{2\pi t}{12} + b_3 \cos \frac{2\pi t}{12} + \epsilon_t(1)$$

In this research, the objective is to forecast the irradiation for next two years which requires 28 observations. The irradiation data for Tabuk City over 28 periods, as shown in TABLE 5.

The least squares regression model estimate based on the data for Tabuk City was obtained as:

$$x_t = 7.47614 - 2.7241 \sin \frac{2\pi t}{12} - 2.406 \cos \frac{2\pi t}{12} + \epsilon_t(2)$$

Fig. 7 shows the actual data along with the forecast generated using equation 2. It is obvious that the seasonal regression equation fits the actual data reasonably well.

Table 5 Irradiation data of Tabuk City [19]

Observation Number	Irradiation of Tabuk City kWh/m ² /day
1	10.44
2	9.65
3	9.21
4	8.76
5	8.29
6	7.61
7	6.72
8	5.82
9	5.11
10	4.26
11	3.16
12	1.36
13	3.71
14	4.82
15	4.97
16	5.08
17	5.46
18	6.63
19	7.28
20	8.84
21	9.57
22	10.44
23	11.04
24	11.27
25	9.74
26	7.15
27	6.42
28	5.84

The same seasonal regression model was employed to generate a forecasting equation for the other 31 cities. Additionally, to gauge the accuracy of the forecast, we computed the Mean Squared Error (MSE) and Mean Absolute Percentage Error (MAPE) for each city using the following formulas:

$$MSE = \frac{\sum_{t=1}^T (x_t - \hat{x}_t)^2}{T-2} \quad (3)$$

$$MAPE = \frac{1}{T} \sum_{t=1}^T \left| \frac{x_t - \hat{x}_t}{x_t} \right| * 100(4)$$

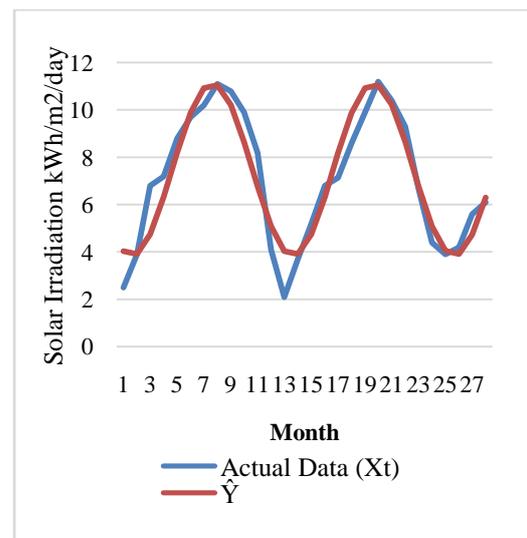


Fig. 7 Actual and Forecast Data for Tabuk City [19]

TABLE 6 shows the fitted regression model for each city and their corresponding MSE and MAPE.

Table 6 Seasonal Regression Equations, MSE, and MAPE for all cities

City	Seasonal Regression Equation	MSE	MAPE
Afif	$x_t = 7.15 - 1.93 \sin \frac{2\pi t}{12} - 1.77 \cos \frac{2\pi t}{12} + \epsilon_t$	47.21	659.70
Al Baha	$x_t = 7.80 - 2.29 \sin \frac{2\pi t}{12} - 2.60 \cos \frac{2\pi t}{12} + \epsilon_t$	55.29	778.40
Al Dawadmi	$x_t = 6.839 - 2.453 \sin \frac{2\pi t}{12} - 2.109 \cos \frac{2\pi t}{12} + \epsilon_t$	47.79	664.42
Al Hanakiyah	$x_t = 6.933 - 2.329 \sin \frac{2\pi t}{12} - 2.609 \cos \frac{2\pi t}{12} + \epsilon_t$	48.37	682.46
Al Qunfudah	$x_t = 7.44 - 2.188 \sin \frac{2\pi t}{12} - 1.953 \cos \frac{2\pi t}{12} + \epsilon_t$	43.27	542.63
Al Uyaynah	$x_t = 7.356 - 2.745 \sin \frac{2\pi t}{12} - 2.122 \cos \frac{2\pi t}{12} + \epsilon_t$	45.09	558.27
Al Wajh	$x_t = 7.773 - 2.233 \sin \frac{2\pi t}{12} - 2.920 \cos \frac{2\pi t}{12} + \epsilon_t$	50.54	748.75
Arar	$x_t = 7.207 - 2.533 \sin \frac{2\pi t}{12} - 1.844 \cos \frac{2\pi t}{12} + \epsilon_t$	28.23	436.00
Duba	$x_t = 7.611 - 1.917 \sin \frac{2\pi t}{12} - 2.806 \cos \frac{2\pi t}{12} + \epsilon_t$	26.38	421.53
Hafar Al Batin	$x_t = 7.866 - 2.295 \sin \frac{2\pi t}{12} - 2.003 \cos \frac{2\pi t}{12} + \epsilon_t$	39.26	509.64
Jazan	$x_t = 6.927 - 1.658 \sin \frac{2\pi t}{12} - 1.937 \cos \frac{2\pi t}{12} + \epsilon_t$	37.64	487.21
Riyadh	$x_t = 6.657 - 2.907 \sin \frac{2\pi t}{12} - 2.635 \cos \frac{2\pi t}{12} + \epsilon_t$	38.58	492.72
Jeddah	$x_t = 5.988 - 1.848 \sin \frac{2\pi t}{12} - 1.609 \cos \frac{2\pi t}{12} + \epsilon_t$	43.73	549.81
Thuwal	$x_t = 5.798 - 1.653 \sin \frac{2\pi t}{12} - 1.740 \cos \frac{2\pi t}{12} + \epsilon_t$	42.92	525.01
Dammam	$x_t = 7.625 - 2.193 \sin \frac{2\pi t}{12} - 2.596 \cos \frac{2\pi t}{12} + \epsilon_t$	48.47	688.74
Al Ahsa	$x_t = 5.681 - 1.397 \sin \frac{2\pi t}{12} - 1.732 \cos \frac{2\pi t}{12} + \epsilon_t$	47.85	661.30

Majmah	$x_t = 6.781 - 2.482 \sin \frac{2\pi t}{12} - 2.276 \cos \frac{2\pi t}{12} + \epsilon_t$	58.12	794.43
Najran	$x_t = 6.506 - 2.093 \sin \frac{2\pi t}{12} - 2.262 \cos \frac{2\pi t}{12} + \epsilon_t$	37.64	489.50
Al Kharj	$x_t = 7.561 - 2.732 \sin \frac{2\pi t}{12} - 2.483 \cos \frac{2\pi t}{12} + \epsilon_t$	35.27	458.23
Qassim	$x_t = 5.368 - 1.526 \sin \frac{2\pi t}{12} - 1.164 \cos \frac{2\pi t}{12} + \epsilon_t$	31.38	447.01
Rania	$x_t = 7.075 - 2.410 \sin \frac{2\pi t}{12} - 2.152 \cos \frac{2\pi t}{12} + \epsilon_t$	34.04	452.65
Yanbu	$x_t = 6.651 - 2.091 \sin \frac{2\pi t}{12} - 2.167 \cos \frac{2\pi t}{12} + \epsilon_t$	41.48	518.18
Al Khafji	$x_t = 6.374 - 2.324 \sin \frac{2\pi t}{12} - 1.946 \cos \frac{2\pi t}{12} + \epsilon_t$	45.80	559.70
Farrasan	$x_t = 5.831 - 1.329 \sin \frac{2\pi t}{12} - 1.402 \cos \frac{2\pi t}{12} + \epsilon_t$	39.24	506.14
Hagl	$x_t = 5.840 - 1.732 \sin \frac{2\pi t}{12} - 1.466 \cos \frac{2\pi t}{12} + \epsilon_t$	26.07	417.05
Umluj	$x_t = 6.722 - 2.572 \sin \frac{2\pi t}{12} - 2.171 \cos \frac{2\pi t}{12} + \epsilon_t$	29.37	442.71
Al Jubail	$x_t = 7.320 - 2.143 \sin \frac{2\pi t}{12} - 2.251 \cos \frac{2\pi t}{12} + \epsilon_t$	43.09	539.33
Shagra	$x_t = 5.779 - 1.683 \sin \frac{2\pi t}{12} - 1.458 \cos \frac{2\pi t}{12} + \epsilon_t$	44.56	548.09
Tabuk	$x_t = 7.47 - 2.72 \sin \frac{2\pi t}{12} - 2.416 \cos \frac{2\pi t}{12} + \epsilon_t$	23.02	389.46
Taif	$x_t = 6.637 - 2.276 \sin \frac{2\pi t}{12} - 2.126 \cos \frac{2\pi t}{12} + \epsilon_t$	48.09	676.01
Timaa	$x_t = 7.267 - 2.398 \sin \frac{2\pi t}{12} - 2.146 \cos \frac{2\pi t}{12} + \epsilon_t$	36.77	469.34
Wadi Addawasir	$x_t = 5.577 - 1.832 \sin \frac{2\pi t}{12} - 1.172 \cos \frac{2\pi t}{12} + \epsilon_t$	39.29	512.05

4.6 Modeling of Photovoltaic Generator Cost

It is important to understand what it costs to have a solar power system installed before any investment decision is made. Various models have been suggested to predict the cost of solar system installation. The most commonly used model is the Levelized Cost of Electricity (LCOE) generation model, which can be used to calculate the cost of installation of all renewable sources of energy [20]. The model makes use of the available information on solar radiation, ambient temperatures and manufacturer data for photovoltaic modules. Using this information and model input, the power output of the photovoltaic generator, P_{PV} can be calculated using the following equation:

$$P_{PV} = \eta_g N A_m G_t, \quad (5)$$

Where η_g represents the instantaneous PV generator efficiency, A_m is the area of a single module in m^2 , G_t is the global irradiance incident on the tilted plane in W/m^2 and N is the number of modules. The model assumes that there is zero loss of energy in the system. The instantaneous efficiency of the generator can be calculated using equation (6), below:

$$\eta_g = \eta_r \eta_{pt} [1 - \beta_t (T_c - T_r)] \quad (6)$$

Where η_r is the reference efficiency of the PV generator, η_{pt} is the efficiency of the power tracking equipment (which is equal to 1 if a perfect

maximum power point tracker is used), T_c is the temperature of the PV cell in Celsius, T_r is the PV cell reference temperature and β_t is the temperature coefficient of efficiency, ranging from 0.004 to 0.006 per $^{\circ}C$ for silicon cells. Based on the energy balance proposed by Duffie et al. (1991) [21], the PV cell temperature can be expressed as:

$$T_c = T_a + G_t \left(\frac{\tau \alpha}{U_L} \right), \quad (7)$$

Where T_a is the ambient temperature in Celsius, U_L is the overall heat loss coefficient in W per m^2 per $^{\circ}C$, τ represents the transmittance coefficient of the PV cells, and α represents the absorption coefficient of PV cells. The overall heat loss coefficient ($\tau \alpha / U_L$) can be estimated from the nominal operating cell temperature (NOCT) as follows [21]:

$$\left(\frac{\tau \alpha}{U_L} \right) = \frac{NOCT - 20}{800} \quad (8)$$

The instantaneous efficiency of the PV generator can, therefore, be expressed as follows:

$$\eta_g = \eta_r \eta_{pt} \left\{ 1 - \beta_t (T_a - T_r) - \beta_t G_t \left(\frac{NOCT - 20}{800} \right) (1 - \eta_r \eta_{pt}) \right\} \quad (9)$$

The parameters η_{pt} , β_t , NOCT, and A_m depend on the type of module and are provided by the manufacturer.

4.7 Estimation of the Number of Panels Needed in a Solar Power System

When planning for the installation of a solar power system for residential or industrial use, it is important to have a reasonably accurate estimate of the number of solar panels needed to meet the demand. This can help in estimating the total cost that is likely to be incurred in assembling the system. The following formula can be used in estimating the number solar panels required for a solar system installation:

Number of solar panels = solar radiation power \times surface area of panels in $m^2 \times$ efficiency \times average days with sunshine per month $\quad (10)$

An average of 4.5 $kWh/m^2/day$ of solar radiation is commonly used in the United States. The values for every state are available on a map provided by the National Renewable Energy Laboratory (NREL) Resource Assessment Program. Most solar panels work at efficiencies of 7-17%. To fully cover a monthly power usage of 1000 kW, divide the figure obtained from equation (10) by 1,000.

Estimation of the Cost of Solar Power

Despite the improved efficiency offered by modern solar power systems, many people throughout the world do not know what it costs to install a solar power system in their homes and are reluctant to do so due to the uncertainties involved. Residential solar systems typically range in size from 3-8 kW, which translates into a cost of between \$15,000 and \$40,000. In recent years, the cost per Watt, which includes the price of the parts of the system, labor costs, permitting fees, overhead costs, and profit, has been reduced significantly. The current cost per Watt stands at around \$6-8 per Watt in most parts of the US [20]. Solar power systems benefit significantly from economies of scale, meaning that larger systems translate into a lower cost per Watt. To find the total cost of a typical solar power system, one must consider all components such as the installation cost and operation and maintenance costs [22].

a) The Cost of Solar Panels

Solar panels usually account for approximately 30% of the total cost of a solar power system. A typical residential solar panel with a combined capacity of 3-8 kW costs between \$4,000 and \$16,000. It is important for solar power system users to know that the best solar panels are not necessarily the most expensive ones. The most reliable and most convenient way to rate the cost of solar panels is by considering their cost per Watt, the commonly accepted figure of merit. This is a reliable metric because it indicates the cost incurred in the acquisition of the solar panels as it relates to the power output. Due to widespread campaigns encouraging the use of renewable sources of energy, the cost of solar panels has been decreasing continually in recent years. Currently, the typical wholesale price of solar panels is well below \$0.70/W. For homeowners who buy small quantities at retail prices, this figure translates into approximately \$1.50/W [22].

b) Balance of System

"Balance of system" refers to all the components of the solar system except for the panels themselves. The balance of system includes components such as inverters, of which there may be one or several, the mounts, the wiring system and other electrical components of the system. The balance of system represents approximately 20% of the total cost of the system. For homeowners, the expected cost of assembling the balance of system ranges from \$3,000 to \$10,000 [22].

4.8 The Cost Model and Equations for Solar Systems

The preferred cost model for renewable sources of energy, according to the International Renewable Energy Agency (IRENA), is the LCOE model. This model is based on a discounted cash flow (DCF) analysis to a common basis, taking into account the effect of time on the value of money [23]. The fact that most renewable sources of energy require a huge initial capital investment followed by almost zero operational cost means that the weighted average cost of capital (WACC), or the discounted rate used to evaluate the project, has a critical impact on the Levelized Cost of Electricity (LCOE) [20]. The LCOE is defined mathematically as:

$$LCOE = \frac{TPV \cdot CRF}{E_{load}} \quad (11)$$

Where E_{load} is the yearly output in kWh, TPV and CRF are the Total Present Value of the actual cost of all system components and the Capital Recovery Factor, respectively, which can be expressed as follows [24]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (12)$$

And

$$TPV = C_{pv} \quad (13)$$

Where i is the annual discount rate, n is the system life in years, C_{pv} is the sum of the present value of capital and maintenance costs of the PV generator in system life. The configuration with the lowest LCOE is taken as the optimal one from the set of configurations which guarantee the required LPSP (Loss of Power Supply Probability, an indicator of power system reliability).

There are many potential trade-offs that have to be taken into consideration when developing an LCOE modeling approach to the cost of renewable energy. First, the model is a simplistic approach because it needs to be applicable to a wider range of technologies in different countries and regions [20]. The analysis method is, however, transparent and easily understood. Also, more detailed LCOE analysis results in a significantly higher overhead regarding the many assumptions that have to be made. This means that the equations are, probably, more accurate [20].

The overall formula used for the calculation of the LCOE in \$/kWh for renewable energy technology is [20]:

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (14)$$

Where LCOE is the average lifetime levelized cost of electricity generation, I_t is the investment expenditure in year t, M_t is the operation and maintenance expenditures in year t, F_t is the amount in fuel expenditures in year t, E_t is the electricity generation in year t, r is the discount rate, and n is the economic life of the system in years.

4.9 Applying the Cost Model to Tabuk City

As a demonstration of how the cost model works, we will use the data for Tabuk City and show the steps for cost modeling in detail for a solar farm consisting of 12,729 solar panels.

TABLE 7, below, provides the nameplate generation capacity of solar panels given in units of GW for Tabuk City. The second item given in the table is the capacity factor, which is the ratio of a power plant's actual power output to its potential output if it were possibly operating consistently at full nameplate capacity. The total electricity generation capacity by the solar panel is 25.8 MW, the capacity factor is 16%, and 36,161 GWh are produced annually using solar panels.

Table 7 Capacity, capacity factor, and generation for Tabuk City

	Units	Solar Panels
Nameplate Generation Capacity	MW	25.8
Capacity Factor	%	16
Annual Generation	GWh	36,161

Table 8 shows the capital cost calculations; it shows the capital cost rate, capital cost, capital cost for transmission and distribution additions, and the total capital cost for solar panels. The cost of capital describes the opportunity cost of making a particular investment. It is the rate of return that could have been earned by putting the same amount of money into a different investment with an equal amount of risk. In the same context, the capital cost of transmission and distribution refers to the opportunity cost of making the transmission and distribution of the solar panels.

table 8 Capital Cost for Tabuk City

Capital Cost	Units	Solar Panels
Capital Cost Rate	\$/kW	\$4,650
Capital Cost	\$Million	\$120
Capital Cost for Transmission & Distribution Additions	\$Million	\$95.12
Total Capital Cost	\$Million	\$215.12

Table 9 shows the LCOE, the cost of operating and building a generating plant for the period of an assumed financial life and duty cycle. This table provides the LCOE for both the system and technology in \$/MWh. It also shows the sum of the total cost of electricity for the transmission and distribution for solar panels and provides the total levelized cost in \$/MWh. For the technology LCOE, \$394/MWh is spent for solar panels, while \$164/MWh is spent on the system LCOE. The LCOE for transmission & distribution adds a total of \$60/MWh. Summing up the LCOE, a total of \$225/MWh results.

Table 9 Levelized Cost of Electricity (LCOE)

Levelized Cost of Electricity (LCOE), \$/MWh	Solar Panels
Technology	\$394
System	\$164
Transmission & Distribution Additions	\$60.68
Total	\$224.68

TABLE 10 contains the total gross plant cost, total sent out plant cost, plant size, capacity factor, auxiliary load, thermal efficiency, fuel cost, CO₂ transport and storage, fixed O&M, variable O&M, plant life in years, discount rate and capital recovery factor. Total gross plant cost is the amount paid for any owned asset. Plant size describes the physical dimensions of a plant. The auxiliary load is the device used to provide power for performing different functions. Fixed O&M is the cost used for the operation and maintenance of the plant. Plant life describes the duration of which the plant can survive and function properly. The capital recovery factor is the ratio of a constant annuity to the current value of acquiring that annuity for a specific duration of time. TABLE 9 below shows that the total (gross and sent out) plant cost of solar panels is \$4,650. The sizes of the solar panels are 1x5 and 10x5. The capacity factor of the solar panels is 16%. The auxiliary load is zero, which shows that neither uses any external device to provide power. The thermal efficiency, fuel cost, and CO₂ transport and storage are not available. The capital recovery factor of the solar panels is 0.1070.

Table 10 LCOE Inputs

LCOE Inputs	Units	Solar Panels
Total Plant Cost (gross)	\$/kW	4,650
Total Plant Cost (sent out)	\$/kW	4,650

Plant Size (MW)	MW	1x5, 10x5
Capacity Factor	%	16
Auxiliary Load	%	0
Thermal Efficiency (HHV)	%	N/A
Fuel Cost	\$/GJ	N/A
CO2 Transport and Storage		N/A
Fixed O&M	\$/kW-yr.	\$55
Variable O&M	\$/MWh	0
Plant Life	Years	20
Discount Rate	%	10.1
Capital Recovery Factor (CRF)		0.1070

Table 11 shows the LCOE calculator for solar panels. It includes capital charges, fixed and variable O&M costs, and fuel costs. Summing these all up, we can see that the solar panels require an investment of \$394/MWh.

Table 11 LCOE Calculator

LCOE Calculator, \$/MWh	Units	Solar Panels
Capital Charges	\$/MWh	\$355
Fixed O&M Cost	\$/MWh	\$39
Variable O&M Cost	\$/MWh	\$0
CO2 Transport and Storage	\$/MWh	-
Fuel Cost	\$/MWh	-
LCOE	\$/MWh	\$394

V. RESULTS AND DISCUSSION

The objectives of this research were:

- i. Develop forecasting model for the amount of irradiation that can be produced in 32 major cities of Saudi Arabia so that can be input to the economic analysis model.
- ii. Develop an economic analysis model to investigate the potential of solar energy as a cost-effective, suitable alternative to using petroleum products to generate power.

5.1 Forecasting and Solar Power Model

32 locations for solar stations were selected among all cities in Saudi Arabia. Details of the solar output of the selected locations are shown in TABLE 12 and depicted in Fig. 8. Also, model validation was done to assess the aptness of the forecasting models that were developed for each location. From the data collected for the demand at each city, the solar output and the number of required solar panels to meet the demand are shown for all 32 locations.

The model was run for different cities to report the output that can be generated from each location. Based on the model and the available data, users should be able to perform proper analysis to

reach accurate conclusions. For example, in these results, Riyadh City has the highest amount of solar output at 32.22 GW, which represents 19.89% of the total output of all 32 locations. This is due to the ever increasing demand for energy from the population and businesses in the city, which contains 7 million people. In total, 20% of the country's total electricity consumption is due to the demand from Riyadh City. A large portion of Saudi Arabia's electricity consumption is from the housing sector [1].

From Fig. 8, it is clear that the regions of Tabuk, Arar, Taif, Riyadh, Dammam, and Jeddah receive the highest output of solar irradiation levels; hence, they are best suited for the installation of solar energy farm.

Table 12 Summarized Solar Output in GW

City	Solar Output (GW)	Number of Solar Panel
Afif	2.252	4,093
Al Ahsa	22.910	17,484
Al Baha	0.838	1,966
Al Dawadmi	1.788	3,636
Al Hanakiyah	1.467	3,257
Al Jubail	0.970	2,426
Al Khafji	0.870	1,984
Al Kharj	2.108	3,983
Al Qunfudah	0.483	1,527
Al Uyaynah	0.862	1,972
Al Wajh	0.705	1,851
Arar	10.476	12,696
Dammam	31.763	36,428
Duba	0.750	1,897
Farrasan	0.237	980
Hafar Al Batin	1.463	3,238
Hagl	1.809	3,751
Jazan	0.824	1,907
Jeddah	17.637	14,953
Majmah	1.790	3,686
Najran	1.987	3,832
Qassim	2.955	4,981
Rania	1.557	3,462
Riyadh	32.228	39,519
Shagra	1.038	2,522
Tabuk	10.510	12,729
Taif	2.487	4,546
Thuwal	0.387	1,338
Timaa	2.745	4,743
Umluj	1.012	2,621
Wadi Addawasir	2.243	4,006
Yanbu	0.882	1,995

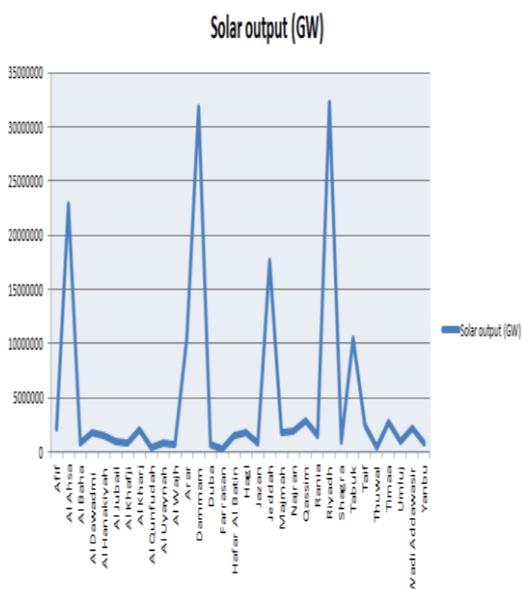


Fig. 8 Summarized Solar Output in GW

Table 13 shows the percentage of the total output of solar for each city. Riyadh and Dammam City have the highest values which are 19.89% and 19.603%, respectively.

Table 13 Percentage of Total output

City	Percentage of Total output %
Afif	1.390
Al Ahsa	14.139
Al Baha	0.517
Al Dawadmi	1.103
Al Hanakiyah	0.905
Al Jubail	0.599
Al Khafji	0.537
Al Kharj	1.301
Al Qunfudah	0.298
Al Uyaynah	0.532
Al Wajh	0.435
Arar	6.465
Dammam	19.603
Duba	0.463
Farrasan	0.146
Hafar Al Batin	0.903
Hagl	1.117
Jazan	0.508
Jeddah	10.885
Majmah	1.105
Najran	1.226

Qassim	1.824
Rania	0.961
Riyadh	19.890
Shagra	0.640
Tabuk	6.486
Taif	1.535
Thuwal	0.239
Timaa	1.694
Umluj	0.624
Wadi Addawasir	1.384
Yanbu	0.544

5.2 LCOE ANALYSIS

TABLE 14 shows that the total cost of solar energy generation is \$590.164 M/MWh, which represents the cost of generating that power in each city. The highest cost was from Farrasan, with \$90.775 M/MWh, which represents 15% of the total cost. The locations with the lowest costs are Dammam and Riyadh City, which have \$0.676 M/MWh, and \$0.667 M/MWh, respectively.

TABLE14 Summarized LCOE for Each City

City	LCOE (\$ M/MWh)
Afif	9.539
Al Ahsa	0.938
Al Baha	25.641
Al Dawadmi	12.017
Al Hanakiyah	14.648
Al Jubail	22.142
Al Khafji	24.696
Al Kharj	10.191
Al Qunfudah	44.480
Al Uyaynah	24.924
Al Wajh	30.485
Arar	2.051
Dammam	0.676
Duba	28.648
Farrasan	90.775
Hafar Al Batin	14.684
Hagl	11.874
Jazan	26.082
Jeddah	1.218
Majmah	12.001
Najran	10.813

Qassim	7.270
Rania	13.798
Riyadh	0.667
Shagra	20.702
Tabuk	2.044
Taif	8.637
Thuwal	55.524
Timaa	7.826
Umluj	21.238
Wadi Addawasir	9.577
Yanbu	24.364

TABLE 15 shows the annual electricity generation statistics for all 32 cities. According to these statistics, the total electricity generation by fuel is 45.1 GW. In total, the cost of producing that amount of power is \$2,300 M/MWh. Thus, the total cost of generating power by fuel represents just 25.6% of the total cost of generating power from solar panels. Using statistical analysis, it was demonstrated that building new farms of solar panels and wind turbines further reduce generation expenses. This recommendation, if adopted, could result in significant cost savings for Saudi Arabia.

Table 15 Summarized Average Levelized Cost of Production (Fuel)

Plant Name	Fuel Type	Average Levelized Cost of Production (\$/MWh)
Afif	Diesel	62.6
Al Ahsa	NG	58.7
Al Baha	Diesel	58.5
Al Dawadmi	Diesel	61.6
Al Hanakiyah	NG	58.6
Al Jubail	NG	59.2
Al Khafji	Crude	64.9
Al Kharj	Crude / Diesel	68.8
Al Qunfudah	Diesel	65
Al Uyaynah	Diesel	67.7
Al Wajh	Diesel	63.1
Arar	Crude	64.9
Dammam	Crude	67.5
Duba	NG	70.1

Farrasan	Diesel	78
Hafar Al Batin	Diesel	66
Hagl	NG	64.7
Jazan	Diesel	65.6
Jeddah	Diesel	70.1
Majmah	Diesel	69
Najran	NG	73.9
Qassim	NG	66.8
Rania	Diesel	74.6
Riyadh	Diesel	76.7
Shagra	Crude	74.5
Tabuk	Diesel	76.6
Taif	Diesel	105
Thuwal	Diesel	79.3
Timaa	Crude	88.5
Umluj	Diesel	93.1
Wadi Addawasir	Diesel	85.2
Yanbu	Diesel	101.9

VI. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

This research was aimed at applying economic and sensitivity analyses to solar energy generation as compared to the use of non-renewable energy sources in Saudi Arabia.

Economic and sensitivity analyses of data collected at King Abdullah City for Atomic and Renewable Energy showed that among the several forecasting models tested, it was found that the best method was Multiple Linear Regression with Sine and Cosine terms. Therefore, these models were developed for all 32 cities so that they can be used to forecast solar irradiation in the future.

In the course of this research, a model was also applied to find the power output of the solar generator P_{pv} . Inputs to this model include: A_m , the area of a single module used in the system in m^2 , G_t , the global irradiance incident on the tilted plane in W/m^2 , and N , the number of modules in the system. The result of that model was used to find the power generation output for all 32 cities. Riyadh City was found to have the largest amount of potential output. Hence, Riyadh City is the best candidate city for the construction of a solar farm.

Concentrating solar power technology utilizes focused sunlight. Concentrating solar power plants generate electric power by using mirrors to

concentrate the sun's energy and convert it into high-temperature heat. That heat is then channeled through a conventional generator. The plants consist of two parts: one that collects solar energy and converts it to heat, and another that converts the heat energy to electricity. Concentrating solar power technology utilizes three alternative technological approaches: trough systems, power tower systems, and dish/engine systems.

The solar panel system is capable of storing enough energy to produce power 6 hours after the Sun had set by using thermal storage. Solar panel plants can potentially operate for 65 percent of the year without the need for a backup fuel source. Also, the plant will have a capability with up to 6 hours' worth of storage. However, in aggregate, it is sensitive. On cloudy or rainy days, the plant should have a storage capacity to compensate for the inability to produce energy on those days and, if needed, be able to generate power using diesel and natural gas as a back-up.

This study focused on forecasting solar irradiation monthly over a period of 20 years, the potential output of solar power, and the total cost of generating and transmitting that power in Saudi Arabia. Below are several recommendations for further research:

- Include additional analysis to study the potential for maximizing renewable power generation to support the grid supply from Saudi Arabia to other nations.
- Enhance the predictive capability of the forecasting equations by using hourly data of solar irradiation in the selected cities.
- Develop prediction intervals on forecasts obtained from the seasonal model so that an upper and a lower limit on the expected costs associated with each option studied may be developed.

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