

Feasibility and Estimation of Technical Potential and Calculation of Payback Period of Roof-Top Solar PV System in the City of Majmaah, Province of Riyadh, K.S.A

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Abstract: Depletion of fossil fuels in near future and accumulation of their emissions in the environment have attracted the world's attention to utilize renewable resources of energy. Oil and gas are the two main sources of power generation in Kingdom of Saudi Arabia. The problem of energy security, the aspect of environmental pollution and depletion of the known fuel reserves in future have created a scope for utilization of renewable resources. In this paper, the most feasible method of rooftop solar PV power generation will be evaluated. A techno-economic feasibility of rooftop PV solar power generation for the city of Al-Majmaah province of Riyadh, KSA is performed.

Keywords: Renewable Energy, Solar Energy, Greenhouse Gases, PV, Solar PV

1. Introduction

Depletion of fossil fuels in near future and accumulation of their emissions in the environment have attracted the world's attention to utilize renewable resources of energy. It is realized that a continuous reliance on fossil fuels will have catastrophic results because excessive carbon dioxide emission has dramatic global warming effects. Our earth could heat up by several degrees in future if we do not stop using non-renewable energy resources. Environmental pollution is supposed to be a serious threat to life on the planet. Therefore use of green energy sources is spreading day by day throughout the world. Fossil fuel burning results in emission of hazardous gases. Accumulation of these gases in the environment is a serious threat [1]. Scientific confirmation that CO₂ emissions associated with fossil fuel energy combustion represent the largest source of greenhouse gas emissions from human activity [2, 3]. It is becoming increasingly evident that the level of CO₂ emissions associated with fossil fuel combustion is so voluminous that an effective technical fix to the problem is inevitable [4-7]. Concerning oil, the Japanese government which oversees an oil dependent economy estimates that commercially recoverable reserves of oil will be exhausted in

40 years [8]. In terms of natural gas, the global reserves-to-production ratio of natural gas has been estimated at 63–66 years [9]. In other words, many young people alive today might actually witness the depletion of these vital resources.

These concerns with fossil fuels have attracted the world's attention to utilize renewable resources of energy because of their environmental friendly features [10] and abundant availability. Renewable energy sources are inexhaustible, contrary to fossil fuels, and more widely spread over the Earth's surface [11, 12]. The Sun being exceptional energy source, produces plentiful energy for the world. Energy produced by the Sun is in the form of electromagnetic radiation. Solar energy reaching the earth's surface averages to 1353 W/m² [13].

Commercial and residential buildings in Saudi Arabia consume about 50% of the total electrical energy consumed [14, 18]. Increasing demand of electrical energy is one of the main problems being faced by the power companies in KSA. In order to meet this increasing demand of electricity in the country, it is desirable to explore every possible option of generating electric power. Saudi Arabia has enormous oil resources. At the same time, the Kingdom is blessed with other resources, notably solar energy that may be the future electric supply in the Kingdom. Green energy presents many

potential advantages to KSA. Firstly, due to its abundant resources, the Kingdom has a viable option for domestic consumption that would save a large amount of oil for export. Secondly, the green energy reduces atmospheric pollution and greenhouse gases emissions. The monthly average daily solar radiation of KSA varies from 3.03-7.51 kwh/m², which is one of the highest in the world [15]. Most of the countries around the globe are interested to penetrate the RE in their power sectors to obtain economic and environmental benefits.

Research is being conducted throughout the world for the development of sustainable, renewable and new energy efficient systems. The increase in population and the development of the Industrial sector in the Kingdom of Saudi Arabia have resulted in an alarming increase in the use of fossil fuels. Though KSA is an oil rich country and the cost of fossil fuel is very low but the costs associated with emissions (in the result of fossil fuels) may affect the economy of the country. Fossil fuels, although produce useful energy, are responsible for production of harmful emissions like CO₂, SO_x, NO_x etc. The obvious choice available is to use renewable energy.

2. Global Solar Generation

The global share of renewable energy in the power sector was 20.3% at the end of year 2011 [16]. The hydroelectric generation being the oldest and most mature form of bulk power generation has a share of 15.3% whereas only 5% was contributed by other renewable generations [17].

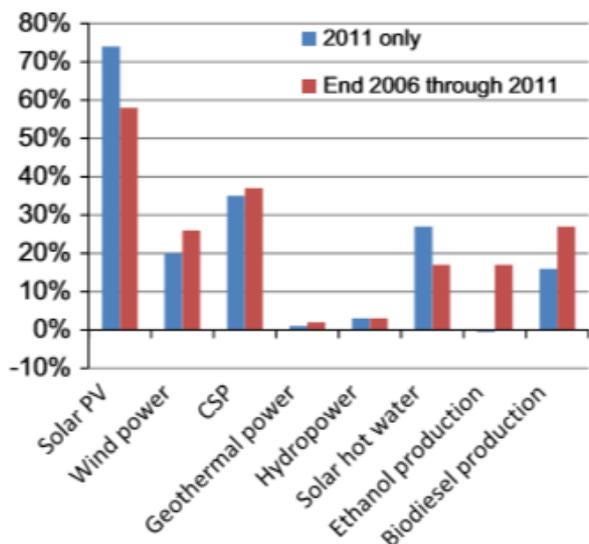


Fig. 1. Comparison of growth rates of renewable power generation.

The main methods of harnessing solar energy for power generation are solar thermal generation and Solar PV generation. Solar PV capacity has increased more rapidly during the last few years. The global installed capacity has increased from 2.2 GW in 2002 to 70GW up to the end of year 2011 [16]. The growth rates of different renewable energy technologies between 2006 and 2011 are shown in the Fig. 1 [17] It is evident from Fig. 1 that Solar PV has the

largest growth rate of 74% followed by CSP (35%), solar water heating (27%), wind power (20%), biodiesel (16%), hydropower (3%), geothermal power (1%) and ethanol production (-0.5%).

There are various methods to harness the power of the Sun and generate electricity. Fig. 2 shows the different Solar Power Generation options. Fixed PV system has the least operation and maintenance (O&M) costs. The tracking panel PV has intermediate output and O&M costs. In this study the fixed flat panel PV option has been taken into account because of its simplest design and lowest cost.

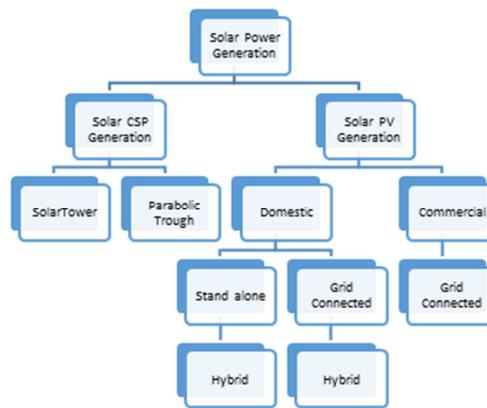


Fig. 2. Methods of Solar Power Generatins.

3. Methodology Adopted to Evaluate the Most Feasible Method of Solar Power Generation

The only viable method to evaluate the benefits of solar energy is the calculation and comparison of per unit cost of solar power generation. The crystalline silicon type are more efficient than the thin film type solar cells. Similarly the fixed flat panel PV has the lowest capital and maintenance costs. The tracking flat PV panel and concentrating PV(CPV) have more O&M costs and are technologically less matured in comparison. It has been proved that output of fixed plate system is maximum when inclined at an angle equivalent to latitude of the location. Therefore the PV panel system under study is fixed tilt poly crystalline PV system. The per unit installation cost of solar power generation is given by the following equation:

$$Cost = \frac{\text{Total Cost during life span in US \$}}{\text{Size of the installed system in KWp}}$$

The most feasible method assessed by studying a 1 KW_p system which produces comparable results for other larger sizes of roof top PV systems and thus satisfy the objective of this research. The cost of system components was found through survey of the local market. The solar industry is progressing very fast and todays solar systems may become obsolete in 10 years, therefore the manufacturers are cautious when guarantees are concerned. The systems which have 25 years life time working warranties are German and Japanese.

Therefore the cost of solar PV system has been taken from distributors of German and Japanese manufacturers because they provide around 25 years of warranties on the solar system components. Such PV systems have efficiencies of around 15% and are warranted that the output will decline by no more than 80% of the rated output in 25 years. The calculation of the solar PV system components and their costs are discussed in the following sections.

4. Size and Cost Calculations of PV Systems

Some solar projects are over 40 years of age and are still providing power. But solar projects are generally designed for an estimated life span of around 25 years. The Total Life Cycle Cost (TLCC) is given by:

$$TLCC = \text{Fixed charges} + \text{variable charges}$$

$$\text{Fixed charges} = \text{Upfront cost}$$

The upfront cost is the aggregate costs of system components required to initiate the project.

$$Cost_{upfront} = Cost_{panels} + Cost_{inverter} + Cost_{batteries}$$

Variable charges include operation and maintenance (O&M) costs and cost of replacement of batteries, inverters, charge controllers etc. during the life cycle. For a fixed tilt system the O&M charges are negligible, and battery and other components replacement charges are given by:

$$\text{Variable charges} = \text{Cost of system component replacements during life period}$$

4.1. Size of PV panels

Peak power delivered by PV panels is:

$$P_{peak,panels} = \text{No. of Panels} \times \text{Power per Panel}$$

It is not necessary for $P_{peak, usage}$ to be equal to $P_{peak, panels}$ since both the output and requirements change throughout the year. But in order to maximize the benefits, the energy produced by solar panels should be equal to energy utilized. i.e $E_{panels} = E_{used}$

$$\text{Peak power produced by panels} = P_{peak,panels} = \frac{E_{used}}{T_{sun}}$$

$$T_{sun} = \text{No. of hours of Sun shine}$$

$$\begin{aligned} \text{Cost of pannels} &= Cost_{panels} \\ &= \text{No. of Panels} \times SC_{panels} \end{aligned}$$

$$SC_{panels} = \text{panel specific cost in US dollars}$$

A more specific way to ensure solar power availability is to calculate the minimum solar power generation and then design a solar PV system that can support the required load even during the minimum generation period. The solar PV is tested to produce rated output under Standard Testing Conditions (STC): 1000W/m² solar irradiance, 1.5 Air Mass and cell temperature of 25°C. From Table-I, it can be easily seen that the solar generation is minimum in June and can be upto 603.05 Watt/m²/hr. There are many varieties of solar PV available in the market from 30W to 250W. After survey of market, Poly-crystalline PV with 250W, 12V ratings and dimensions of 1650 x 100 mm (1.65 m²) has been selected. Now the number of PV panels required for 1 KW_p load can be calculated as in Table-II. Table-II depicts that surplus power will be available that could be used locally, stored or fed to utility for utilization during the months with irradiance higher than 603.05W/m². Selection of smaller PV size than required will result in decrease of battery life and shut down of PV system by the inverter when voltage reach cut-off value; with no backup for cloudy days.

Table 1. Detail of Solar power irradiance collected in Riyadh/Majmaah.

Month	G _r Hor KWh/m ²	Days	Sun Hours	KWh/m ² /day	KW/m ² /hr	W/m ² /day	W/m ² /hr
Jan	174.3	31	7.2	5.62	0.78	5622.58	780.55
Feb	177.3	28	8.0	6.33	0.79	6332.14	791.25
Mar	209.4	31	7.0	6.75	0.96	6754.84	964.28
Apr	186.6	30	8.2	6.22	0.76	6220.00	758.53
May	201.1	31	9.03	6.49	0.72	6487.09	721.11
Jun	201.9	30	11.16	6.73	0.60	6730.00	603.05
Jul	211.2	31	11.13	6.81	0.61	6812.90	611.85
Aug	217.0	31	10.16	7.00	0.69	7000.00	688.97
Sep	219.0	31	8.55	7.31	0.85	7064.52	854.97
Oct	222.2	30	10.33	7.16	0.69	7406.66	693.12
Nov	179.6	31	8.53	5.99	0.70	5793.55	702.23
Dec	168.6	30	7.03	5.43	0.77	5620.00	772.40
Total/Average	2368.2	365	8.86	6.49	0.74	6487.02	745.19

Table 2. Size Calculassions of PV panels.

Area of One PV Panel	= 1.65 m ²
Solar irradiance under STC to produce rated output of 250W	= 1650 W
Thus the efficiency of the solar panel	=15.15%
Min.solar irradiance expected in June	= 603.05 W/m ²
Min. solar irradiance expected in June for panel with 1.65 m ² area	= 603.05 x 1.65 = 995.03 W
Min. generation of each solar panel during June	= 995.03 x 15.15% = 151 W
No. of PV panels required to meet load demand of 1 KWp	= 1000/151 = 7 No.
Similarly the max. solar irradiance expected in the month of March	= 964.28 W/m ²
Max. solar irradiance expected in March for panel with 1.65 m ² area	= 964.28 x 1.65 = 1591.06 W
The max. generation of solar panels during March	= 1591.06 x 15.15% = 241 W
Max generation from 07 No. Solar PV panels in March	= 241 x 7 = 1687 W

4.2. Size of Charge Controller

The output of the PV panels vary due to change in weather conditions. The charge controller controls and maintains the current from the panels to the batteries. It is rated in amperes and is designed in accordance with the output voltage of the panels. They convert the dc output of the panel to ac and then back again to dc to feed regulated supply to the batteries. They are around 95%-97% efficient. The charge controllers protect the batteries from being overcharged. They also protect the PV panels from the back flow of charge from the batteries. For both Off-grid and on On-grid systems, the size of the controller depends on the short circuit current ratings (I_{sc}) of the panels, which is 8.5A for the selected panels. The controllers must have spare capacity since it is not a good idea to use them at full capacity. During cool sunny days, the output of the panels can increase the rated output by 25%. Since the panels are connected in parallel, therefore the size of charge controller can be calculated by:

$$\begin{aligned} \text{Size of charge controller} &= I_{sc} \times \text{No of panels} \times 1.25 \\ &= 8.5 \times 7 \times 1.25 \\ &= 74 \text{ A or } 100 \text{ A approx} \end{aligned}$$

I_{sc} = Short circuit current of panel

4.3. Size of Batteries

To keep the upfront cost to minimum, we are designing the PV system for a backup of one day only. The life of a battery is a function of amount of battery discharge in percentage. This is also known as depth of discharge (Dod). For instance, a battery allowed to discharge 20% only will have more life as compared to that allowed to discharge 40%. The dry batteries can be discharged upto 70% with the output voltage and temperature of the cells in permissible limits. The batteries themselves are around 85% efficient. First the voltage and size of batteries in ampere hours (Ah) is selected. For systems with longer cables and high load, 24V or 48 V system may be adopted to minimize the losses. But for

smaller systems, the 12V system provides a simple solution. Therefore dry batteries of 200 Ah, 12V that could be discharged upto 70% without decline in their rated output voltage have been selected for the study. The number of batteries required can be calculated from the following formula:

$$N_{B\text{-req}} = \frac{Wh \text{ load}}{(V_b \times \eta_b \times Dod \times Ah_b)} \times \text{No. of days}$$

For a load of 1 KW the energy required at 40% load factor = 1000 x 24 x 40% = 9600 Wh/day

No of batteries required for an off-grid system with one day backup (incase of cloudy horizon) = $\frac{9600 \text{ Wh}}{(12 \text{ V} \times 0.85 \times 0.7 \times 200)} \times 1 = 6.7 = 7 \text{ batteries}$

Similarly, for an on-grid system the backup required to cope with an occasional electricity cut of 4 hours = $\frac{9600 \text{ Wh}}{(12 \text{ V} \times 0.85 \times 0.7 \times 200)} \times 0.167 = 2 \text{ batteries}$

This concludes that for an off-grid PV system of 1 KW_p, around 7 batteries of 200 A will supply one day backup (in case of cloudy wheather), whereas 2 batteries are required to provide 4hours of continuous backup in an on-grid solar PV system. In an off grid system the batteries will be replaced after every five years. Whereas in an on-grid system, the battery sets will be replaced after every six years owing to increase in life due to less frequency of charging and discharging.

4.4. Size of Inverter

In an Off-gird solar PV system, the peak power delivered by the inverter should be equal to peak power usage i.e.

$$P_{peak, inverter} = P_{peak, usage}$$

Considering a load factor of 40%, the load is 400W for a 1KW system.

$$\text{size of invert} = \text{load}(W) \times 1.3 = 400 \times 1.3 = 520W$$

In view of available solar power and possibility of future extension in load a 1 KW inverter is recommended for Off-

grid system. In an On-Grid system, the inverters not only have to confront the above load but also has to redirect the additional solar generation to the grid. The charge controllers are around 97% efficient at the most, the batteries can produce 85% of their input and the inverters themselves are around 90% efficient. If 2% drop in the cables is taken into account, the efficiency of the system (excluding efficiency of the panels) calculates to around 0.727 % as follows:

$$\eta_{sys} = 0.98 \times 0.97 \times 0.85 \times 0.9 = 0.727 \%$$

The max. power (P_{max}) supplied by the solar system is therefore:

$$P_{max} = 250 W \times 7 \text{ (no. of panels)} \times 0.727 = 1272.25 \text{ Watts}$$

Considering spare capacity for motive loads, the size of the inverter to be selected is around 2000 W.

Cost Comparison of Solar PV Systems

Saudi Arabia can save oil by generating electricity using Solar PV and as a result, can export more oil in international market. Saudi Arabia is an oil rich country and domestic oil prices are very low. Power generation in the country mainly comes from oil and gas power plants. A cost comparison is presented in this section to see the effectiveness of solar PV generation. According to U.S. DOE's EIA, 1.8barrels of oil is required to generate 1MWh of electricity [18]. The domestic price of oil charges to Saudi Electricity company is \$0.73/mmBTU or \$4.1/barrel [18]. Therefore, cost of electricity for an oil based power plant in Saudi Arabia is \$7.8 per MWh. There is some additional O&M cost which is assumed to be \$5.39 per MWh. These figure are very difficult to beat but use of rooftop solar PV is still a very good alternative. Around 50% of the generated electricity in KSA is being used by residential consumer. Therefore use of rooftop solar PV will save huge amount of oil which could be exported in international market and in this way Kingdom

can earn revenue and sustain as a leading oil export country for longer time. A cost of crude oil in international market is \$61.0/barrel as of today. For each MWh of electricity, the country can save 1.8barrel of oil which is equivalent to \$110 in international market. According to these international rates the cost of electricity production is:

$$\begin{aligned} \text{Cost per MWh} &= 61.0 \times 1.8 + \text{O\&M cost} \\ &= 110 + 5.39 = \$115.19 \\ \text{Cost per KWh} &= \$0.115 \end{aligned}$$

For the cost comparison, the existing solar solution provider companies were surveyed in this matter and the cost of equipment with extended warranties during the entire term of the project was found. The component wise cost of a 1 KW_p system is detailed in Table-III. The only difference between the off-grid and on-grid system is the net metering cost and hence increase in labor installation. Addition of batteries further increase the labor cost. The output of solar PV system in converted into energy value in US dollars according to oil prices in the international market. It had been observed that oil prices are showing an annual rise of 3%-8% per year in the last two decades. We assumed the minimum rise of 3% in our calculations over the life span of the project. Table IV indicates the energy value per year and the accumulative returns or payback. The payback period of each method is as under:

- Payback period of Off-grid rooftop solar PV system without batteries is 12 years
- Payback period of On-grid rooftop solar PV system without batteries is 13 years
- Payback period of On-grid rooftop solar PV system with batteries is 17 years
- Payback period of Off-grid rooftop solar PV system with batteries is 25 years

Table 3. Cost of Solar PV Power System.

Cost Type	System Components / Equipment	Quantity required for 1 KW _p roof-top solar PV system	Cost of Solar System in US\$				
			Per Unit Estimated Cost (US \$)	1KWp Off-grid without batteries (US \$)	1KWp Off-grid with batteries (US \$)	1KWp On-grid without batteries (US \$)	1KWp On-grid with batteries (US \$)
Installation Cost / Upfront Cost or Fixed Cost	Solar Panel	07 No (250 W _p PV panels)	2.13/W	3733	3733	3733	3733
	Charge controller	01 No	2.7/Amp	-	270	-	270
	Invertor	01 No (1 KW for Off-Grid) (2 KW for On-Grid)	0.135/W	135	135	270	270
	Batteries	07 No Off-Grid 02 No On-Grid	0.93/Ah	-	1302	-	375
	BOS (Cost of frames, cables, installation cost, transport cost, net metering cost etc.)	Once	500 to 800	500	600	700	800
Variable Cost	Batteries	one set after every 5 years	0.93/Ah	-	1302x4 = 5208	-	375x4 = 1500
Total cost	-	-	-	4,338	11,248	4,703	6,948

The cheapest solution for roof-top solar power generation at domestic level is Off-grid without batteries. But there is no other backup than solar power and the reliability of this system is least. To create a back-up source, batteries are required in an off-grid system for use in the evening and night and backup for cloudy days. But this makes the Off-grid system with batteries, the most expensive solar PV system. Similarly when the solar power generation is more than demand or someone has the capability to install a solar

system of higher capacity than his load requirements, the surplus generation will go waste. Therefore to maximize the benefits of solar power generation, the most feasible solar power method for solar power generation would be On-Grid without batteries. The per unit installation costs are comparable but the benefits expected with On-Grid solar PV system without batteries are far more. The payback period of this system is 13 years.

Table 4. Payback period of Solar PV system.

Year	Solar Irradiation on tilted plane (KWh/m ²)	Total area of solar cells (m ²)	Efficiency of Solar module	Efficiency of Solar system	Solar Output (KWh)	Expected Utility KWH Rate (US \$)	Energy Value (US \$)	Cumulative Returns (US \$)
Year 1	2368.2	11.55	15.15%	72.7%	3013	0.115	346	346
Year 2	2368.2	11.55	15.03%	72.7%	2989	0.118	353	699
Year 3	2368.2	11.55	14.91%	72.7%	2965	0.122	362	1061
Year 4	2368.2	11.55	14.79%	72.7%	2941	0.126	371	1432
Year 5	2368.2	11.55	14.67%	72.7%	2917	0.130	379	1811
Year 6	2368.2	11.55	14.55%	72.7%	2893	0.134	388	2199
Year 7	2368.2	11.55	14.43%	72.7%	2870	0.138	396	2595
Year 8	2368.2	11.55	14.31%	72.7%	2846	0.142	404	2999
Year 9	2368.2	11.55	14.20%	72.7%	2824	0.146	412	3411
Year 10	2368.2	11.55	14.09%	72.7%	2802	0.150	420	3831
Year 11	2368.2	11.55	13.96%	72.7%	2776	0.154	427	4258
Year 12	2368.2	11.55	13.85%	72.7%	2754	0.159	438	4696
Year 13	2368.2	11.55	13.74%	72.7%	2732	0.164	448	5144
Year 14	2368.2	11.55	13.63%	72.7%	2710	0.169	458	5602
Year 15	2368.2	11.55	13.52%	72.7%	2688	0.174	468	6070
Year 16	2368.2	11.55	13.40%	72.7%	2665	0.179	477	6547
Year 17	2368.2	11.55	13.29%	72.7%	2643	0.184	486	7033
Year 18	2368.2	11.55	13.18%	72.7%	2621	0.189	495	7528
Year 19	2368.2	11.55	13.07%	72.7%	2599	0.195	507	8035
Year 20	2368.2	11.55	12.97%	72.7%	2579	0.200	516	8551
Year 21	2368.2	11.55	12.87%	72.7%	2559	0.206	527	9078
Year 22	2368.2	11.55	12.76%	72.7%	2537	0.212	538	9616
Year 23	2368.2	11.55	12.65%	72.7%	2516	0.218	548	10164
Year 24	2368.2	11.55	12.55%	72.7%	2496	0.224	559	10723
Year 25	2368.2	11.55	12.45%	72.7%	2476	0.231	572	11295
Total	-	-	-	-	68,411	-	11,295	-

5. Conclusion

The purpose of this research is to optimize the power generation cost while reducing hazardous emissions. Feasibility of rooftop solar PV system in Riyadh region in Kingdom of Saudi Arabia is evaluated in this paper and the most feasible method of rooftop solar PV power generation is evaluated. A comparison of various solar PV generation options is conducted by studying their design in detail and finally the payback periods is calculated in light of costs and benefits of each project. It is found that On-grid rooftop solar PV system without batteries is the most feasible system from both reliability and economical point of view.

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