RESEARCH ARTICLE

10 kW Grid-Connected PV System Cost and Environmental Analysis for Government Offices: Darbandikhan Technical Institute as a Case Study

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Received: 27-10-2019 **Accepted:** 13-06-2020 **Available online:** 31-12-2020

A B S T R A C T

The Iraqi Kurdistan region has significant potential for implementing solar energy with an average annual rate of 5.245 kWh/m^2. However, most of its energy supply currently comes from nonrenewable energy sources. With the continually increasing demand for energy, an alternative energy-generation technique is required. Among the various renewable energy resources, generating electricity directly from sunlight is the best option because it can be applied by the average household and is environmentally friendly. In this study, a cost and environmental analysis for a 10 kW grid-connected photovoltaic system is presented for a government building with the aim of reducing the load demand on the grid during weekdays and also to inject the generated power into the power grid during weekends. A simulation of the proposed PV system was generated by using Photovoltaic Geographic Information System software to estimate the system's production performance. The software showed that the highest energy production was 1,660 kWh, which occurred in August; the total electricity production was 16,184 kWh over a 1-year period. The study also showed that the geographical location of Darbandikhan City is quite sufficient for generating electric power from solar energy. It further showed that it can reduce CO_2 emissions by 356.60 tons during its lifetime when compared with a gasoline generator and by 131.38 tons when compared with that of a natural gas generator. The proposed system could serve as a good revenue source for the government by exporting the generated electricity to the grid while at the same time serving as motivation for households in the region; furthermore, this system can also be applied to other governmental offices in Kurdistan to generate some or all of its energy needs.

Keywords: Electricity generation, Grid connected PV system, Darbandikhan, Environment, Economic, Solar energy, PVGIS

1. INTRODUCTION

In recent years, the demand for national electricity in the Kurdistan region has has significantly risen because of the increase in population and industrialization (Abbas, 2013).

Access this article online

DOI: 10.25079/ukhjse.v4n2y2020.pp157-165 | E-ISSN: 2520-7792

Based on official data, the total power demand for the region in 2009 was 2,096 MW, whereas power production was 809 MW (Diler, 2018).

According to the Kurdistan region's electricity region's electricity minister, the demand for electricity increased to 6,500 MW in late 2019, whereas the power production in the region was 3,800 MW (NRT, 2019). This illustrates that the request for power in the region has increased almost 3-fold during a decade. Government data show that a mere 60% of the total power demand was provided by the Kurdistan Regional Government (KRG) in 2019, which led to most households in the region experiencing electricity cutoffs that lasted for 8 hours or more during a day. However, the unexpected cutoffs varied according to the seasons, demands, and the remaining hours provided by private generators. Currently, the region has 9 power stations. Seven of these run on natural gas and gasoline, and the other 2 operate on hydropower. More than 80% of the electricity in the region is generated from fossil fuels, and only 15% to 20% of the energy is generated by hydropower plants (Abdullah & Abdulrahman, 2015; Diler, 2018).

Apart from a fossil fuel-driven generator's drawback of creating environmental pollution, greenhouse gas emissions over the long term are costlier compared with those of the photovoltaic (PV) system (Johnson and Ogunseye, 2017). Based on the International Renewable Energy Agency (IRENA) database released in May 2019, the global weighted average cost of electricity generated by solar PV has fallen into the fossil fuel cost range since 2014 (IRENA, 2019). According to the newest data, renewable energies represent 25% of the global electricity generation. It is expected that 65% of energy use could be supplied by renewable sources by 2050 (IRENA, 2017).

Over the last few decades, in many developed and developing countries, renewable energy has become the main source for the production of electrical energy. Many countries, e.g., New Zealand, Norway, Sweden, Brazil, Canada, and Iceland generate more than half of their power from renewable energy sources (Muhy Al-Din et al., 2017).

The PV system, as a type of renewable energy, has recently gained increasing attention. Several studies have evaluated the potential of PV systems to generate electricity in terms of cost analysis, annual income, and carbon footprints for particular regions (Thotakura et al., 2019). When comparing the operational performance of a 1 MW grid-connected PV system with the operational performance generated by the simulation software tools, the results show that the differences between the operational data, recorded for 12 months, and the, estimated energy determined by the Photovoltaic Geographic Information System (PVGIS) software, the actual PV watts, and the PV system software were 5.33%, 12.33%, and 30.64%, respectively. Hussein et al., (2013) introduced photovoltaic system design software (PVSD) that is compatible with the Iraqi climate conditions by using Visual Basic. A project, designed using this program, has been implemented by the Ministry of Science and Technology. This program determines the results for a system based on the data from existing systems that were measured over a year. Aziz et al. (2019) presented a performance analysis for a 5-kW rooftop solar PV microgrid system in Iraq. A household in Baghdad was selected for the case study. Furthermore, Dihrab and Sopian (2010) proposed hybrid PV–wind systems for power generation in 3 cities in Iraq. The results showed that it is possible to use solar and wind energy to generate enough power for some villages in the rural area.

Diler (2018) analyzed the potential and social awareness of the use and implementation of renewable energy sources in Kurdistan; furthermore, the study used a qualitative and quantitative methodology. Based on the qualitative review it was found that the region has the ability to utilize renewable energy resources, whereas the quantitative results indicated that the majority of participants think the public sector should take the first step toward renewable energy production; furthermore, about 63% of the participants were willing to pay extra to obtain this technology. In the study by Bamisile et al. (2019), RETScreen software was used to simulate and analyze the data for a 10 MW PV plant based on economic factors for 3 different locations in Kurdistan. Abdullah and Abdulrahman (2015) proposed a 200 kW PV system for Koya City. The study showed that building PV systems in the area can significantly reduce the CO_2 emission in the air. Mohammed and Mahdi (2018) used a fuzzy system to predict the solar radiation for solar energy production in Duhok City. Majeed et al. (2019) conducted a technoeconomic analysis of a 2 MW on-grid solar power plant system in Chavy Land located in Sulaymaniyah City. The simulation results, as determined by system advisor model software, showed that the system contributed significantly to power the area and reduce demand on the national grid.

The objective of this study was to propose a grid-connected PV system to the local government offices in the Kurdistan region. To conduct this study, the solar horizontal radiation values for Darbandikhan City were obtained from meteorological data from 2010 to 2019. Based on that, this study analyzed the performance of the grid-connected PV system and also analyzed the costs and environmental impact of the system. Furthermore, the results of this study indicated that the solar irradiation rate of the city would be sufficient for the installation of a PV system in the area.

2. METHODOLOGY

The grid-connected PV system is strongly affected by geographic and topographic factors such as climate, altitude, longitude, and terrain conditions. Geographically, the elevation of Darbandikhan Technical Institute is 522 m above sea level and located in Darbandikhan City, Al Sulaymaneyah, Iraq. The city is located at a latitude of 35° 11' 53.052" north and longitude of 45° 68' 29.264" east, with the sun shining about 7 hours in winter and up to 14 hours in summer on average (Weather Atlas, 2020). The solar irradiation rate and temperature in the city for a period of over 9 years (January 2010 to September 2019) were measured using a weather station (provided by Darbandikhan Dam Directorate). Based on that, this study analyzed the suitable grid-connected PV system for the Darbandikhan Technical Institute building. The total roof area of the building is 1,175 m^2 and the chosen area for the estimated plant capacity is estimated to be 135 m^2 on the building's concrete rooftop. The roof is horizontally flat, which offers the advantage of choosing the desired tilt angle for generating maximum solar energy.

The simulation was conducted by using PVGIS software to analyze and evaluate the irradiation rate and the average obtained electrical energy during the year. The PVGIS software has been proven to be a useful tool for estimating the regional potential energy generating capacity and to support the decision making in energy planning (Qianna et al., 2014).

3. SOLAR PHOTOVOLTAIC MODULES

PV modules are made up of silicon semiconductor cells. Solar cells can produce electricity when exposed to sunlight. The output power generated by each single PV cell is very low. A large number of PV cells are connected in series and parallel, ensuring that the PV module produces the desired power. Several modules are then connected in series-parallel to make a PV array as shown in Figure 1 (Rashid, 2001).

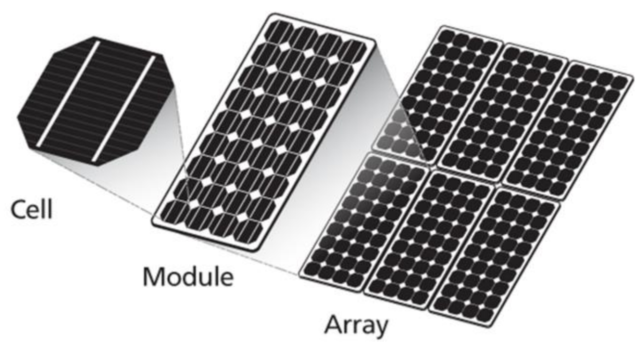

Figure 1. PV generator terms

A PV system is a good choice for generating electrical power. It can be situated in a residential area, typically on the rooftops of domestic, commercial, and government buildings. It can also be mounted on the ground. The rooftop PV technology can reduce the peak summer load, and the power generated by this technology can supply the residential demand for things such as lighting, cooling, televisions, fans, and other domestic needs. Whenever the load demand is greater than the power generated from the PV solar panels, the required power is drawn from the grid. The main advantages of PV technology are that it can be applied by households, it is environmentally friendly, has a long lifespan (>20 years) with a low maintenance cost (Rashad, 2014), and does not require a highly skilled person for its maintenance. In contrast, the cost of PV technology is continuously decreasing as demand and production increase. According to the IRENA, solar PV module prices have fallen by around 90% since the end of 2009 (Rashid, 2001; IRENA, 2019). The major drawbacks of this technology are the high manufacturing cost and low efficiency (15%–20%).

4. MATHEMATICAL MODELLING

4.1. GRID-connected PV system

The main components of a grid-connected PV system are shown in Figure 2 (Apricus). The system consists of the following 3 essential components: PV arrays, which are responsible for the direct conversion of sunlight to electrical energy; an inverter, which is necessary to convert direct current (DC) power to alternating current (AC) power and also to generate the sinusoidal power that is utilized by the local loads and/or for injecting the generated power into the grid; and a bi-directional meter, which is used to record the electricity flow from or to the power grid.

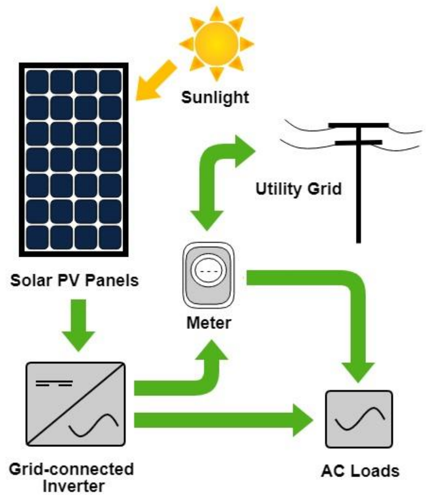

Figure 2. Main components of grid-connected PV system

In In the Kurdistan region, the standard single-phase AC voltage is 240 V. This voltage will determine the DC voltage needed from the PV module strings. As mentioned in Johnson and Ogunseye (2017), the DC voltage can be calculated as follows:

$$V_{DC} = \sqrt{2} \times V_{ac} \Rightarrow V_{DC} = \sqrt{2} \times 240 = 339.412\ V \quad (1)$$

where 10% is added to account for the measurement uncertainty in the design as follows:

$$V_{DC} = \sqrt{2} \times V_{ac} + 10\% = 373.35\ V \quad (2)$$

The open-circuit voltage of the module is 39.8 V. Thus, the total number of modules required in a string is calculated as follows:

$$V_{DC} \div V_{OC} = \frac{373.35}{45.2} = 8.26\ \text{modules} = 8.5\ \text{modules} \quad (3)$$

The maximum power point voltage (V_{MP}) of the string of 8.5 modules at the standard test condition (STC) is calculated as follows:

$$8.5 \times V_{MP} = 8.5 \times 36 = 306\ V \quad (4)$$

The aim of connecting PV panels in series is to obtain a higher voltage. Thus, the open-circuit voltage of the string of the 8.5 modules at an STC is equal to

$$8.5 \times V_{oc} = 8.5 \times 45.2 = 384.2\ V \quad (5)$$

The actual DC voltage required is 373.35 V. The surfeit voltage will take care of the voltage variation from the PV system caused by temperature increases above 25°C, cable losses, and other environmental condition variations (irradiation). Temperature has a significant effect on the PV cell performance. With increasing temperature, the voltage and output power of PV modules will decrease (Fesharaki et al., 2011).

The short circuit current remains the same because the modules are connected in series. To obtain a higher current, a parallel connection of the string is required. Four strings connected in parallel produce 384.2 V and 35.44 A at an STC or 306 V and 33.48 A at the maximum power point as calculated below:

$$4 \times Isc = 4 \times 8.86 = 35.44\ A \quad (6)$$

$$4 \times Imp = 4 \times 8.37 = 33.48 \text{ A} \quad (7)$$

The PV panels are connected to a grid through an inverter without battery storage. Based on the power generating capacity of the PV system, a 10 kW inverter is required. The grid's interactive inverter must produce a pure sine wave output, must be synchronized with the grid in terms of voltage and frequency, and must extract the maximum power from the solar cells with the help of a maximum-power point tracker. The inverter input stage modifies the input voltage until the maximum power point on the I-V curve is found. The characteristics of the PV panels, inverter, and the system parameters used in this paper are shown in Table 1, Table 2, and Table 3, respectively.

Table 1: Specifications of the PV Modules

Cell type	**Monocrystalline**
Number of cells	72 cells
Rated power	300 Wp
Voltage at maximum power	36 V
Current at maximum power	8.37 A
Open circuit voltage	45.2 V
Short circuit current	8.86 A
Module efficiencies at STC	16.6%
Dimensions (L×W×H)	1950×992×45 mm
Weight	25.5 kg

Table 2: Inverter Specifications

Output voltage	220 VAC /230 VAC
Rated AC power	10 kW
Frequency range	50Hz/60Hz
Wave form	Pure sine wave
Efficiency (DC to AC)	93%

Table 3: System Parameter Calculation

No. of PV panels required	34
Required area	135 m2
Output voltage	384.2 V
Output current	35.44 A
Inclination of PV panels	35.1º

4.2. Cost estimation

The PV panel cost is normally between one-half and one-third of the capital cost of the PV system depending on the size of the project and the PV module type (IRENA, 2012). A monocrystalline PV module is used in this study because it offers the highest efficiency among all the PV module types. The cost of this solar module per watt in local market price in the Kurdistan region is US$0.3 and the maximum power of the modules is 300 W. Thus, the total cost of this module could be estimated as follows:

$$PV\ panels\ estimated\ cost\ = maximum\ power\ in\ watt \times cost\ of\ solar\ model\ per\ watt \times total\ number\ of\ modules = 300 \times 0.3 \times 34 = US\$\ 3060 \quad (8)$$

The PV system output power is 10 kW. Inverters with ratings of 0.5 kW, 1 kW, 5 kW, and 10 kW are available in the markets. Installation charges for a chosen inverter amounts to US$1,000.

The management and maintenance costs are about 15% of total estimated cost of the PV system (Azabany et al., 2014). Therefore, the estimated management and maintenance costs are calculated as follows:

$$Extra\ cost = 4060 \times 0.15 = US\$\ 609 \quad (9)$$

The capital cost of the system could be estimated as follows:

$$Capital\ cost = PV\ panels\ cost + Invertor\ cost + extra\ cost = US\$\ 4669 \quad (10)$$

Apart from the calculated costs stipulated above, a grid-connected PV system requires no additional costs for resources. However, for a fossil fuel-driven generator (gasoline and natural gas), daily consumable resources are required. Abdullah and Abdulrahman (2015) noted that 1 L of gasoline can generate 3.66 kWh energy. Therefore, to produce 16,184 kWh/year, 4,421.85 L of gasoline is required. Based on a cost of US$0.5 for 1 L of gasoline, the total estimated cost to operate a 16,184 kWh gasoline generator for 1 year is around US$2,210.92. At the same time, to generate 1 kWh energy, 0.2838 m^3 of natural gas is required (Abdullah and Abdulrahman, 2015). Therefore, to generate 16,184kWh/year, 4,593 m^3 of natural gas is required. The cost of 1 m^3 of natural gas is US$2.5. Therefore, the total cost of natural gas to generate 16,184KWh energy over a 1-year period will be US$11,482.54. Table 4 presents the resource cost for fossil fuel-driven generators, whereas PV modules are operated without additional resources.

Table 4: Resource costs for fossil fuel generators

Resources	Resource required to generate 1 kWh	Resource fost for generating 1 kWh	Total cost of generating 16,184 kWh/year
Gasoline	0.2732 L	$ 0.136	$ 2210.95
Natural Gas	0.2838 m^3	$ 0.7095	$ 11,482.54

4.3. CO2 emission

The The generation of electricity and industry are responsible for 65% of the global greenhouse gas emissions today (IRENA, 2017). For every kilowatt hour of electricity generated, a coal power plant will emit 950 g of CO_2, whereas natural gas power plants will emit 350 g. For renewable power plants, the only CO_2 emissions produced are related to their construction. Accordingly, for every kilowatt hour of electricity generated, a solar PV system emits between 60 and 150 g of CO_2 (Planète, 2016). It is clear that most of the energy supplies in the Kurdistan region come from nonrenewable energy sources (gasoline and natural gas), which has a greater impact on the environment. The most important benefit of this technology is that it is environmentally friendly and does not require extra costs because renewable energy sources, e.g., sunlight, are freely available in nature. Therefore, the proposed 10 kW rooftop grid-connected PV system can reduce the CO_2 emissions by 14,264.25 kg/year when compared with gasoline and by 5,255.25kg/year when compared with natural gas in the atmosphere.

5. RESULTS AND DISCUSSION

Based on the data recorded by Darbandikhan Dam Directorate (Darbandikhan Dam, 2019), the average monthly solar irradiation for the city varies from 2.549 to 8.872 kWh/m^2 throughout the year. Under these conditions, solar PV power plants can play a crucial role in supplying a significant portion of the city's electricity demand. According to the same source, the highest average monthly temperature recorded in the city was 44ºC in August 2018. Table 5 shows the city's solar radiation rate in Wh/m^2 for 9 years (Darbandikhan weather station).

Table 5: Darbandikhan soloar irradiation rate (Wh/m^2)

Month / Year	January	February	March	April	May	June	July	August	September	October	November	December	Annual Solar Irradiation
2010	2852	2576	4619	6150	7254	8700	8959	7998	5850	4712	3840	2759	5252.2
2011	2449	2996	5363	5370	6975	8280	8587	8060	6510	4774	3270	3100	5211.2
2012	2573	2968	4743	6480	6913	8460	8277	7688	6120	5270	2760	2418	5129.4
2013	3038	2576	4774	5940	6882	8820	8835	7874	5610	5208	2640	2325	5118.1
2014	2263	2632	4464	6060	6820	8640	9083	7719	5250	4836	3060	3038	5067.6
2015	2728	3360	4805	6840	7564	8670	8866	8308	6030	3999	3180	2604	5305.3
2016	2449	3444	4712	6540	7378	8130	9765	7874	6240	4805	3480	2263	5315.1
2017	2976	3500	4433	5940	8029	9120	8866	8122	6450	4805	2760	2728	5365.1
2018	2666	2688	4867	6000	7130	8490	8618	7967	6360	4774	2580	1705	5066.4
2019	2542	3360	4216	4890	7595	8640	8866	7688	6420				5623.6
Average	2654	3010	4700	6021	7254	8595	8872	7930	6084	4798	3063	2549	5245.4

The solar potential energy was estimated based on the climate data (irradiation and temperature) of the defined location, the well-known PVGIS software simulation that was used to provide the expected amount of average daily electricity production (Ed), average monthly electricity production (Em), average daily sum of global irradiation (Hd), and average monthly sum of global irradiation (Hm) received by the proposed modules as shown in Table 6. The table also shows that the average daily electricity production from the proposed 10 kW PV system is 44.2 kWh, and that the average monthly production from the same system is 1,348.67 kWh. Moreover, the annual electricity production is 16,184 kWh.

Table 6: Monthly energy output from a fixed-angle pv system

Month	Ed	Em	Hd	Hm
January	32.1	995	3.81	118
February	38.3	1070	4.67	131
March	42.9	1330	5.42	168
April	46.5	1400	6.08	182
May	47.4	1470	6.35	197
June	51.7	1580	7.32	219
July	51.7	1600	7.45	231
August	53.6	1660	7.49	232
September	52.1	1560	7.05	212
October	44.9	1390	5.85	181
November	38.7	1160	4.73	142
December	31.3	969	3.7	116
Average	44.2667	1348.67	5.82667	177.417
Total	531.2	16184	69.92	2129

The monthly energy production of the proposed PV system is shown in Figure 3. It is clear that the maximum PV output power is generated during the months with the highest solar radiation and lowest production will be in the months with the lowest solar radiation over a period of 1 year. This is because of the fact that Darbandikhan is located in the northern part of Iraq, and hence is exposed to and enriched with solar radiation that is direct between April and September.

Figure 3: Monthly average power generated by the PV system in kWh

Based on the financial metrics of the system that was presented in section 4, the capital cost of the system has been calculated using United States Dollar as the currency. The annual average energy production from the proposed PV system is 16,184 kWh, and the charge for 1 kWh in the region is around US $0.015. Therefore, the system can generate an annual income of around US$242.76. It thus implies that it will take 19 years to pay back the system's initial cost. Assuming that the average lifetime of a PV system is around 25 years, the 10 kW grid connected system gives a net profit of around US $1,456.56 during that time**.**

6. CONCLUSION

This study investigated the national electrical power status of the KRG. Demand for electricity in this region is increasing continuously, and power generation is created by fossil fuel products. In this study, a 10 kW on-grid PV rooftop system was designed based on climate data for a government building in Darbandikhan City. It has been shown that the city has a sufficient amount of solar irradiation throughout the year for installing a PV system. The solar potential energy in the location was estimated with the help of PVGIS software. The results show that the city has the highest energy production potential during summer, which is 1,660 kWh in August, and has the least production potential during winter. Although the proposed grid-connected PV system is costly, no additional resources are required after installation, and it can pay back the system's initial cost in 19 years. However, for a fossil fuel-driven generator, daily consumable resources are required. In addition, a PV system has lower CO_2 emissions compared with those of fossil fuel. The proposed system can reduce the CO_2 emissions in the city by 356.60 tons during its lifetime when compared with gasoline and by 131.38 tons when compared with natural gas. It is thus plausible to conclude that by installing multiple solar panels throughout all government offices, significant impacts on CO_2 emissions and load demand in the city can be achieved, which consequently leads to a decrease in the power cutoffs, especially during the months with the highest solar radiation.

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