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Techno-economic design of a grid-tied Photovoltaic system for a residential building

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Abstract. Increasing cost of electricity due to rising price of fuel is one of the local community's main issues. In this research, switching of grid dependent system to the grid-tied Photovoltaic (PV) system with net metering for a residential building is proposed. The system is designed by considering the maximum energy demand of the building. The designed system is analyzed using RETScreen on technical, economic and environmental grounds. It is found that the system is able to produce 12,000 kWh/year. The system is capable to fulfill the electricity demand of the building during day time and is also capable to sell the energy to the local grid causing the electric meter to run in reverse direction. During night time, electricity will be purchased from grid, and electric meter will run in the forward direction. The system is economically justified with a payback period of only 3 years with net present value of PKR. 4,758,132. Also, the system is able to reduce 7.2 tons of CO_2 not produced in the entire life of the project.

Keywords: economic analysis; grid-tied PV system; residential building; RETScreen

1. Introduction

Energy is considered to be one of the basic human needs. A tremendous amount of energy is used by all nations to perform daily routine jobs and progress in all aspects. There is an energy crisis in our country Pakistan and the shortfall in the last five years is around 5000 MW (Latif *et al*. 2020). In this scenario, the people of Pakistan are focusing on different renewable energy systems like solar, wind, biomass, and small hydro to overcome the energy demand. Among all the renewable sources, photovoltaic systems or simply PV are widely accepted among the Pakistani Community. PV systems can be off-grid systems or on-grid systems (Masters 2004). Basaran *et al*. (2017) presented both off-grid and on-grid PV-wind hybrid systems and get around 2500 kWh/year average energy, and by utilizing net metering, positive impacts of the system can be noticed. Putra *et al*. (2017) analyzed the hybrid off-grid power system, which comprises a PV system and generator for backup. The analysis was done using PVSyst and HOMER Pro and concluded that the hybrid PV Generator

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system is technically and economically feasible. Mohammad *et al*. (2017) has examined and modeled PV modules with cooling systems for meeting power demands in Jordan Valley and found that the cell temperature influences the efficiency of the PV module. Ghafoor and Munir (2015) have designed the off-grid PV system for residential house electrification and determined the size and power rating of the PV system components. Kumar *et al*. (2019) analyzed the feasibility of a 1 MW PV plant for two different universities in Malaysia and concluded that the system can produce 1390 MWh of energy per year and can also reduce the 818.7 tons of carbon dioxide per year. Bartolini *et al*. (2014) performed the technical and economic modeling of a grid PV system with batteries as energy storage devices and found a cost reduction of around 24.5%. Fathi *et al*. (2014) have described the 7.2 kW PV-based power plant and found that the performance ratio is varied from 33% to 70.2%. Shahzad *et al*. (2017) analyzed hybrid PV biomass plant and found the optimized design with good economic benefits. Demoulias and Charis (2010) presented the analytical method for determining the inverter size for on-grid PV systems for any location and formed the mathematical expression that can be solved using the inverter manufacturer's data. Barua *et al*. (2017) designed and conducted the feasibility analyses of a 30-kW rooftop PV system using PVsyst and found that the system can produce 590 MWh of energy per year and can save 42 tons of carbon dioxide. Sreenath *et al*. (2020) performed the technical analysis of a PV plant for a Malaysian airport using SolarGis software and found that the studied site has a solar potential of 20 MW, and the proposed plant can generate the energy of 26304 MWh per year with maximum energy generation in March. Mansoor *et al*. (2020) experimentally compared the performance of PV systems with mirror mounting with conventional PV systems and found that for a 5 MW plant, the energy could rise to 30% with discounted payback and internal rate of return of 5.68 years and 13.45 % respectively. Khatri and Rahul (2016) performed the economic assessment of a PV plant for the girls' hostel of Jaipur University and found that the plant has a discounted payback of 13.4 years if inflation is considered. Mayer *et al*. (2021) presented the methodology for calculating environmental footprints and the levelized electricity cost of an on-grid PV plant and found that LCOE for medium and high irradiation regions are 57 and 77 €/MWh, respectively. Louie *et al*. (2016) has performed the investigation about the error in the estimation of daily load for off-grid system and found that the error can affect the reliability and cost of the system. Sharma *et al*. (2016) performed the mathematical of off-grid PV system for technical and economic analysis and found that the discussed system has a payback period of 10 years and is responsible for reducing 4490 tons of carbon dioxide in the air.

PV system along with net metering is considered to be the best possible solution to not only reduce the electricity bill of a residential building but also causes the reduction in greenhouse gas emissions. PV grid tied system with net metering has studied by different researchers (Dufo-López and Bernal-Agustín 2015, Andreas *et al*. 2013, Darghouth *et al*. 2011). Qamar *et al*. (2016) has determined the solar potential for a city of Mardan, Pakistan and proposal of net metering was made but failed to show the technical, economic and environmental advantages of net metering for Pakistan. Rehman *et al*. (2017) has showed that net metering policy results in annual savings in Pakistan but one cannot adapt net metering without considering the payback period and net present value of the project. Zahir *et al*. (2018) has suggested the feasibility analysis for grid tied system with energy storage system in Pakistan and found that system is technically as well as economically feasible but failed to show the net present value for the system, also, failed to show the environmental impacts of the system.

Keeping in view the above literature, one can conclude that different researchers have worked on grid-tied PV systems along with net metering but no one has considered the economic as well as

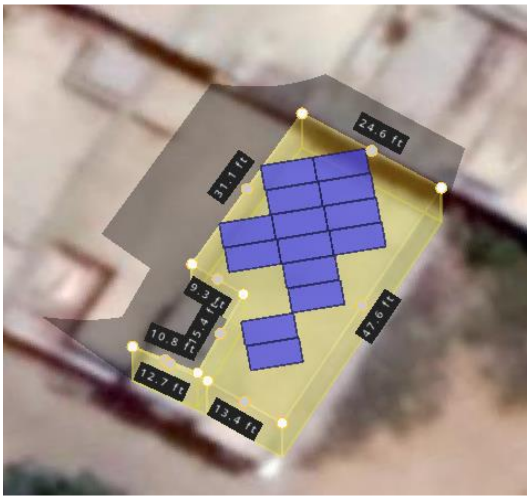

Fig. 1 Proposed system site for installation of PV system

the environmental effects of grid-tied PV systems. Without considering economics, one cannot adopt any alternative. In this paper, the grid- tied PV system for a residential building located in Karachi is designed and analyzed. The economic analysis of the design is conducted using RETScreen to check the system's financial feasibility and confirm that the system is very favorable to the local community. The emission analysis has also been performed by using RETScreen to know the impact of using a grid tied PV system instead of using entire grid electricity.

2. Methodology

The site selected for installing PV panels is located in Karachi (24.962019° N, 67.169593° E). Climatical conditions of Karachi are considered for the study. The climate of Karachi is mostly hot and humid, with an average ambient temperature of 30°C (Weather-atlas). May and June are scorching with an average high temperature is around 36°C (Weather-atlas).

The residential building has an effective area of 91 m^2 with an average energy demand of 7427 kWh/year. Fig. 1 shows the proposed site of PV installation. Helioscope is used to determine the maximum number of panels installed on the rooftop of the proposed site.

2.1 Load analysis

The existing load of the residential house is presented in Table 1. It is clear that the majority of electricity is consumed by a ceiling fan which is around 39% of the total energy consumed in a whole day. The average daily electric demand for every month is presented in Fig. 2. From where, it is clear that average daily energy of around 20 kWh/day is required in May and June because of the summer season. Most of the time, electrical appliances such as air conditioners and fans are running continuously while minimum energy of around 10 kWh/day is required in January due to winters. The winter season is not much harsh, so there is no requirement for heating.

Table 2 shows the specification of the PV module for study. These parameters are taken from

Table 1 Average electric load of residential house for the month of May

Appliances	Power Rating (W)	Quantity	Number of hours working	Energy Consumed (kWh)	Percentage consumptions
LED Bulb	10	20	9	1.8	8.85
Air Conditioner	900	1	4	3.6	17.69
Refrigerator	90	2	24	4.32	21.23
Laptop	40	2	1	0.08	0.39
Electric iron	1000	1	0.75	0.75	3.69
Ceiling fan	80	11	9	7.92	38.92
Washing Machine	900	1	1	0.9	4.42
Microwave oven	1200	1	0.5	0.6	2.95
Water Pump	750	1	0.5	0.375	1.84
Total energy				20.35	

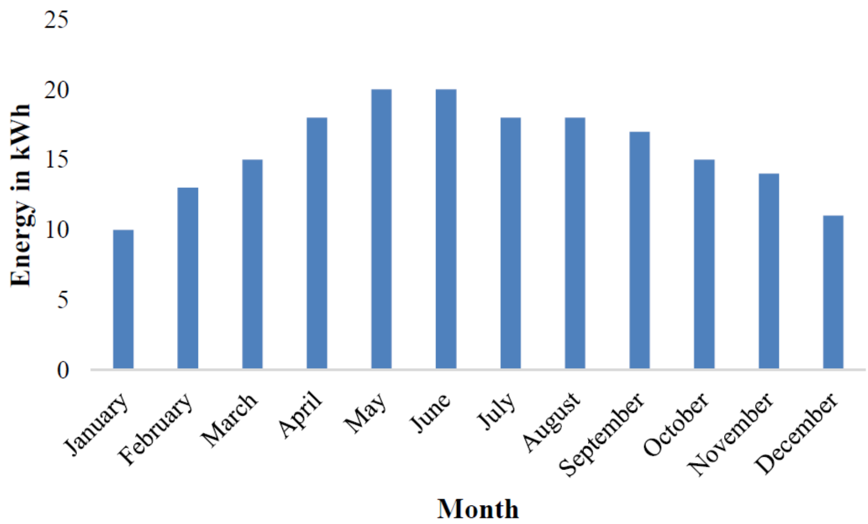

Fig. 2 Energy consumption in a day of each month

Table 2 Specification sheet of Canadian solar PV panel (Canadian Solar 2001)

PV Panel Specification Sheet	
Maximum power	590 W
Optimum operating voltage	44.3 V
Optimum operating current	13.23 A
Open circuit voltage	53.6 V
Short circuit current	13.97 A
Module efficiency	21.3%
NOCT	45°C

the website of Canadian solar because of readily available in the market. The parameters will be used to determine the temperature-adjusted DC power and the area required to fulfill the required load and will be used to determine the total number of panels needed. The specifications of the

Table 3 Specification of the inverter (Inverex Inverter 2020)

Inverter Specifications	
Power Rating	10 kW
Input DC voltage	200 V
Output AC voltage	280 V
Efficiency	97%

inverter are presented in Table 3. The NitroX inverter is selected for the study for readily available in the market. Specifications of the inverter are taken from the website of homage inverters.

The AC power requirement of the house in entire month that PV panels can fulfill is

$$P_{AC} = \frac{E}{h_{peak\ sun} \times no.days\ in\ month} \quad \text{(Masters 2004)} \tag{1}$$

The DC power of the PV modules is

$$P_{DC,STC} = P_{AC} \times \eta_{conv} \quad \text{(Masters 2004)} \tag{2}$$

The required area of the PV module for capturing the required DC power is

$$A = \frac{P_{DC,STC}}{1\ sun\ insolation \times \eta_m} \quad \text{(Masters 2004)} \tag{3}$$

The cell temperature of the PV module can be estimated as

$$T_{cell} = T_a + \frac{(NOCT-20)}{0.8} \quad \text{(Masters 2004)} \tag{4}$$

The temperature adjusted DC power can be predicted as

$$P_{T,DC} = P_{DC,STC}\left(1 - C_T(T_{cell} - 25)\right) \quad \text{(Masters 2004)} \tag{5}$$

Total energy produced in a year can be predicted by

$$Energy = P_{DC,STC} \times \eta_{conv} \times h_{peak\ sun} \times 365 \tag{6}$$

2.2 Economic analysis

The installation of an on-grid system for the proposed site will be justified only if it has positive economic impacts. The installation will require a considerable investment. The significant investment will be justified only if the outcome is positive; otherwise, the decision will be very wake. The entire system will be purchased from the local market. The investment cost consists of equipment cost, labor cost, spare parts cost, operating and maintenance cost, and miscellaneous cost. The input parameters for RETScreen are presented in Table 4. The daily solar radiation data for Karachi is available in RETScreen. Table 5 shows each cost in detail. The life of the PV modules system is taken to be 25 years (De Wild-Scholten 2013). Spare parts include inverter and supporting structures, which need to be changed after 12 years. Miscellaneous costs involve the process fees for implementation of net metering setup.

The economic justification of the project will be made on the basis of Net present value which is considered to be the best economic parameter to make the project economically acceptable and feasible.

Table 4 RETScreen input parameters for residential house

Location Data	
Location:	Karachi
Latitude:	24.962019º N
Longitude:	67.169593º E
Daily solar Radiation on Horizontal from RETScreen	
Annual Average:	5.34 kWh/m²/day
Maximum:	6.52 kWh/m²/day (May)
Minimum:	4.01 kWh/m²/day (December)
Grid Electricity Data	
Unit Cost:	18 PKR/kWh @ 24-hour
Electricity Selling Cost:	10 PKR/kWh
Solar Photovoltaic Data	
Size of Power system	8.3 kW
Grid Type	Grid Tied
PV Type	Mono-crystalline module
Manufacturer	Canadian Solar
Number of Units	14 Units of 590 W each
PV Orientation	Fixed
Inverter Capacity	10 kW
Capital Investment	PKR 1,000,000/-
Annual Costs (Operations)	PKR 20,000/-
Inflation rate	10.5 % [30]
Project Life	25 years
Debt Ratio	0

Table 5 Break up of system costs

Equipment Name	Cost in PKR
PV panels	298,000
Inverters	240,000
Wires	17,000
Structures	35,000
Labour	60,000
Spare Parts	300,000
Miscellaneous	30,000

The net present value can be calculated by

$$NPV = Annual\ savings \left(\frac{(1+r)^n - 1}{r(1+r)^n}\right) \text{ (Sullivan, William 2018)} \quad (7)$$

3. Results and discussions

Helioscope has been used to determine the maximum number of panels installed on the rooftop

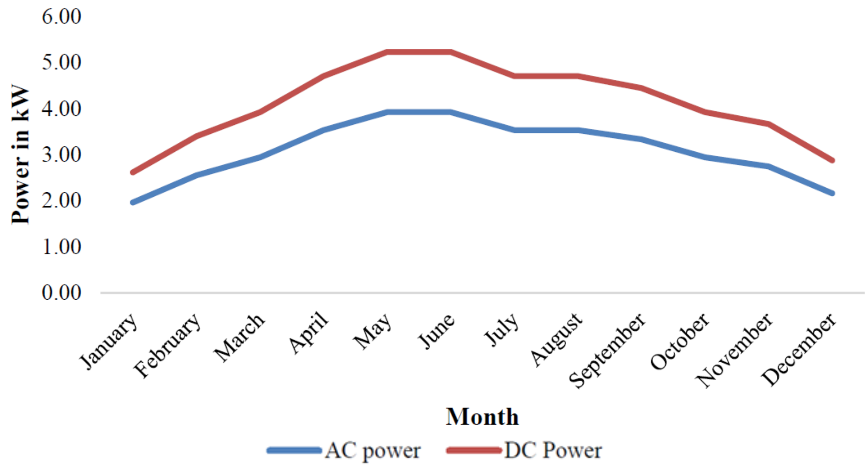

Fig. 3 Power requirement on daily basis for each month

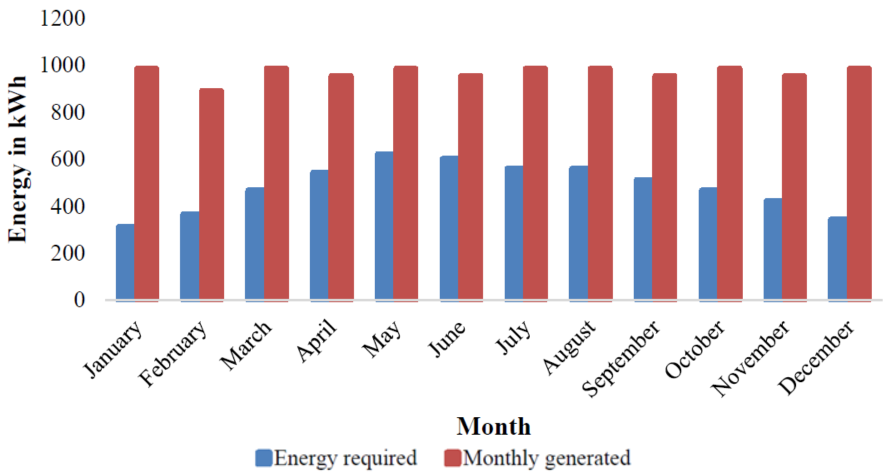

Fig. 4 Comparison of energy generated and energy requirement on monthly basis at day time

of the residential building. From helioscope, the maximum number of panels that can be installed on the rooftop is 14. Each panel will be of 590 W and oriented at a tilt of 25° and azimuth of 0°. Since this is the optimized number of PV panels mounted at the rooftop, a maximum of 8.3 kW setup can be installed.

The load was analyzed for Karachi by taking 5.4 hours at the 1-sun condition (Naqvi *et al*. 2022), and conversion efficiency was considered to be 0.75 (Masters 2004). The conversion efficiency includes mismatch losses, dirt losses, inverter efficiency, and temperature derating. The load was analyzed by Eq. (1) and Eq. (2). The average daily power requirement in every month is presented in Fig. 3. From where we can deduce that the AC power requirement is maximum in May and June and is around 3.92 kW with a maximum DC power of about 5.3 kW. The reason behind it is the weather is scorching in May and June and most of the time air-conditioners and fans are continuously running. The minimum AC power requirement in January is around 2 kW while the DC power requirement is 2.61 kW because, in January, Karachi experiences a winter season, and the winter

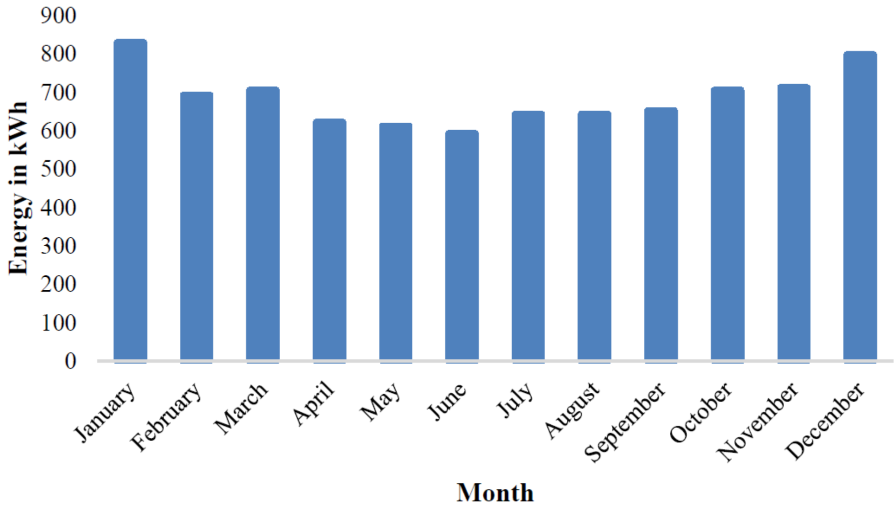

Fig. 5 Energy sell during day time

season is not so harsh, so there is no requirement of heating equipment which causes the low energy demand in the winter season. The decision for the size of the system will be made on the basis of the energy requirement of May and June, in which maximum energy is required. Hence, a minimum of 5.3 kW DC power plant setup is required to utilize the PV system effectively.

The maximum power generated through the rooftop area of the selected building was calculated from Eq. (3). From, 91 m^2 area available, the maximum DC power that can be generated from the PV panel is 13.65 kW. This power is different from helioscope because there is no effect of tilt, azimuth, and other keep outs in Eq. (3) which affect the utilization of area and play a part in maintaining the system while helioscope takes these parameters into consideration. For Karachi, the maximum setup of net metering is 1.5 times the sanctioned load (KE net metering 2015). The actual load requirement for the building is 5.3 kW, so it means that the maximum of 8.3 kW setup can be installed on the rooftop of the building, which is not only able to fulfill the power requirement of the residential building but can also feed electricity to the grid during the day time. The total number of 590 W panels required for meeting the energy demand of the building is 14. The total energy produced from the designed system is determined from equation 6 and is found that the system is able to produce around 12,000 kWh/year which is enough to fulfill the energy requirement of the building and is also able to sell the electricity to the grid.

The comparison of energy requirement and energy generation from an 8.3 kW PV system is presented in Fig. 4. The comparison is only for daytime because energy will be generated by the PV system only during the daytime as long as the sun is available. Fig. 4 clearly presents that the energy generated during day time is more than the energy requirement. The maximum energy requirement is in May and June. The part of the electricity will fulfill the house requirement while the rest of the electricity will be sold to the grid at the cost of PKR. 10/kWh as local practice. Fig. 5 shows the amount of electricity sell to the grid. It is clear that the maximum amount of energy available for sale is around 800 kWh in January, while the minimum is available around 600 kWh in June because in June the most of the energy that the system has generated is self-utilized to fulfill the demand of the building.

Fig. 6 shows the amount of electricity required from the grid. The electricity will be purchased

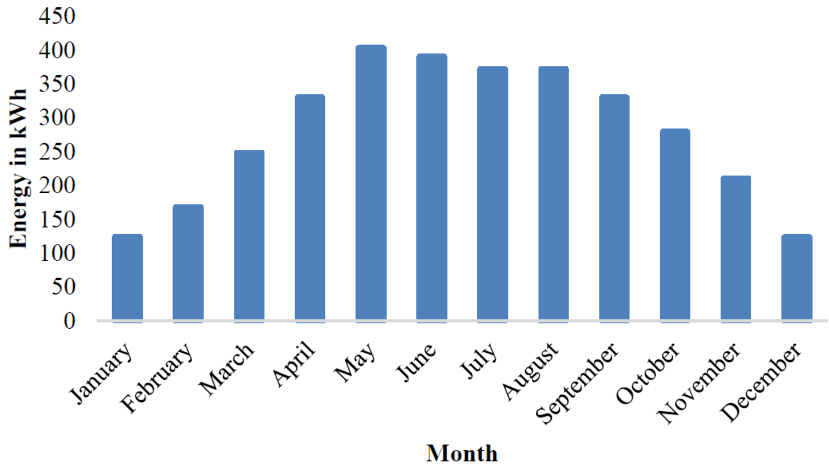

Fig. 6 Electricity requirement during night

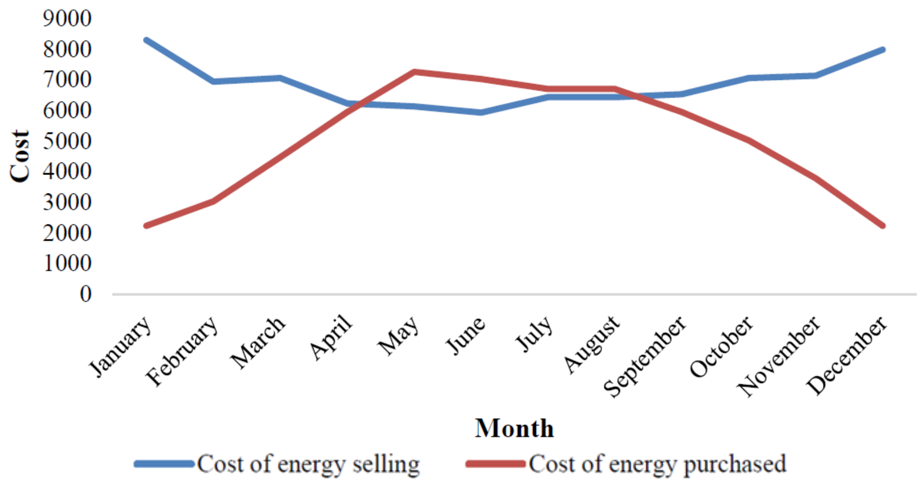

Fig. 7 Electricity sell and purchase cost

from the grid at a rate of PKR. 18/kWh for single phase system where there is no effect of peak hours. The maximum amount of energy will be required in May, while the minimum is required in December. The cost of energy during night time will be bear by the consumer but will result in a more significant economic advantage. Fig. 7 shows the cost comparison of electricity sell to the grid and electricity purchased from the grid. The electricity will be sold to the grid at a rate of PKR. 10/kWh as per local practice, while electricity will be purchased at a rate of PKR. 18/kWh. It is evident from Fig. 8 that the energy requirement in May, June, July, and August is more significant than the energy generated, so more energy in these months will be purchased from the grid than that of sell to the grid so in these months the consumer has to pay the amount to the utility company while in remaining 8 months, the energy requirement is less than the amount of energy generated, so more energy is available for sell than energy consumption. It will cause the meter to run in the reverse direction. The electricity is sold to the grid so that the overall bill will be negative, or the grid will pay for this energy.

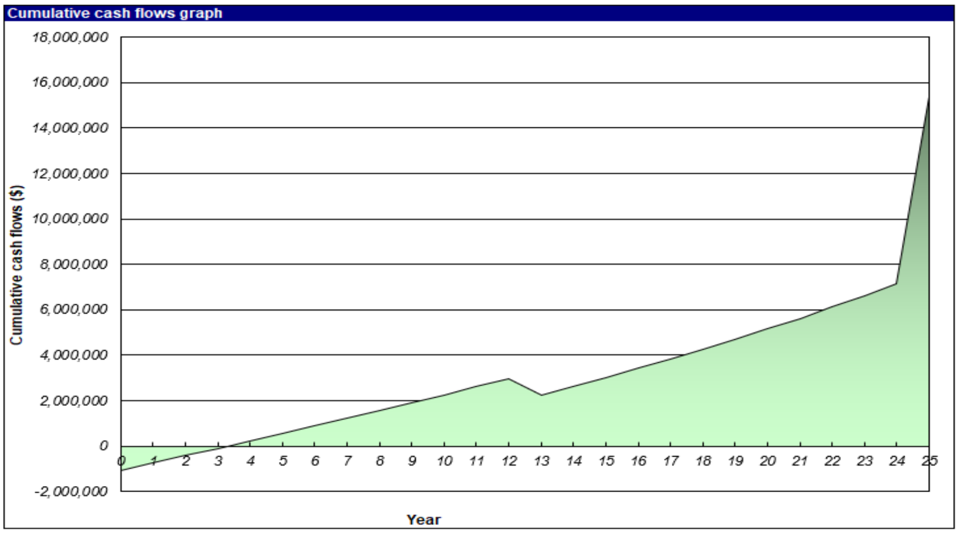

Fig. 8 Cumulative cash flow diagram of the system

From the above discussion, one can conclude that the grid-tied system is technically feasible, but its installation will be made only if it is economically viable. RETScreen conducted the economic analysis by taking the inflation rate of 10.5% and the discount rate of 6.20% for Pakistan. No loan will be taken from any bank, so the debt ratio, incentives, and grants will be zero. Fig. 7 shows the cumulative cash flow diagram of the system. From cash flow analysis, it has been found that the system has a positive economic impact. The payback of the project is around 3 years. It means that the investment will be return in just 3 years after the commissioning of the project. In the 13th year, the inverter and charge controller need to be replaced, requiring investment, but it will create no negative impact on overall economic life. Payback is not the only tool to check the economic feasibility of the setup, the net present value of the system has also been determined by Eq. (6) to check economic feasibility and from Eq. (6), the net present value of the system comes out to be PKR. 4,758,132/- which makes the system to be economically beneficial and adaptable.

Pakistan is located in a region that is greatly affected by global warming and environmental pollution so, RETScreen has also done the emission analysis of the project to check the impacts of the system on the environment, and it was found that the proposed setup will result in the reduction of 7.2 tons CO_2 not produced during the entire life cycle, which is equal to 3,094 litres of gasoline and 16.7 barrels of crude oil not consumed.

4. Conclusions

A detailed technical, economic, and emission analysis of a grid-tied system for a residential building was done. The technical analysis was done by considering the maximum electrical energy requirement. It was found that maximum electrical energy was required in May and June while the minimum is required in January. Due to environmental constraints, a grid-tied system was proposed for the house. It was found that in May, June, July, and August, the energy generation from PV system is low as compared to the energy purchase from the grid, causing the customer to pay to utility while in the remaining months, the energy generation is more than that of energy purchase from the grid causing the bill to move in reverse direction So, during these months the utility company will pay to the customer. RETScreen was used to conduct the economic analysis, and it was found that the project can payback in just 3 years by creating the overall positive impacts on economic life. During the 13th year of the project life, the inverter will need to be replaced, but it will not disturb the economic life's positive impact. NPV of the proposed system was found to be PKR. 4,758,132/- which do not only make the system economically feasible but also recommends to be adapted. The course will result in 7.2 tons of CO_2 produced during the entire life of the project which corresponds to the 3,094 liters of gasoline and 16.7 barrels of crude oil not consumed. This will create a positive impact on the environment. This research will make the community adapt to net metering more economically. Further research is required by considering a single axis and double axis tracking to capture more energy from the solar system in an economical manner. Also, due to the effect of temperature on PV performance, grid tied Photovoltaic thermal modules can be utilized to capture both electrical and thermal energy from a single system.

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