Optimal Sizing of a Centralized Hybrid Photovoltaic System for Efficient Operation of Street Lights

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ABSTRACT

The photovoltaic energy generation system is one of the most promising technology to meet our future electricity demand as well as mitigate climate change. This study aims to design, simulate and evaluate the performance of hybrid photovoltaic (PV) system using PVsyst software to supply electricity for energy efficient streetlights in educational institute. Meteonorm database of daily and monthly irradiation, temperatures, precipitation and sunlight hours are utilized while performing the analysis. The photovoltaic system consists of 56 bifacial-polycrystalline 360-watt PV modules having 17.9% efficiency. The photovoltaic modules were installed at 0° azimuth angle and 15° tilt angle. Two hybrid inverters with rated capacity of 10 kW are used. The energy storage system consists of 16 batteries (2 in series x 8 in parallel) with a nominal capacity of 1600 ampere-hours and discharging minimum SOC is 20 %. A total of 100 streetlight poles with 8 working-hours/day are installed to cover both sides of the road, with monthly energy consumption of 672 kilowatt-hours. The average annual ambient temperature is 23.66°C, and the annual GH irradiation is 1693 kilowatt-hour/m^2. The annual production of the hybrid PV system is 25.96 MWh/year, the specific energy production of the system is 1288 kWh/kWp/year with 70.38% performance ratio. By means of proposed photovoltaic system for energy efficient street lightning structure, 157.9t CO_2 is reduced. The project can save 0.004737 million tonnes of CO_2 emissions over its lifetime of 30 years. The proposed system is a viable solution for public lighting with the right selection of system components.

Keywords: Photovoltaic system; Energy losses, Performance ratio, Street light; Storage system; PVsyst software; System Simulation

INTRODUCTION

The primary challenges facing the world today are environmental security, energy resource protection, and sustainable energy production. Because of population growth and industrialization, the demand for energy continues to grow (Al-Ghussain et al., 2020 & Abdin et al., 2019). Furthermore, traditional energy sources such as fossil fuels (i.e. coal, and natural gas) are diminishing with time. As a result, experts around the world are working to develop alternative energy resources that will meet the world's energy needs while also being environmentally acceptable (Dahiru et al. 2020).

Renewable energy sources (RES) are clean and green energy resources that are beneficial to the environment. The share of RES such as solar, wind, and hydro in world energy generation is constantly increasing (REN21, 2017). Photovoltaic energy generation technology is growing at a significantly higher rate than other renewable energy sources (RES). The basic and important reason for photovoltaic energy generation technology's success is the constant decrease in PV modules production costs and the increasing efficiency of solar cells (Fraunhofer, 2021). Renewable energy sources (RES) such as solar (PV) energy systems have been found to be the finest and optimum alternatives to conventional energy generation resources. As of the end of 2019, the total installed capacities of renewable energy in the world have reached 2500.0 gigawatt, of which the total installed capacity of photovoltaic energy generation system is 634.0 gigawatt, and it is still increasing (Sonnichsen, 2020).

Solar energy is thought to be the most feasible and viable source of renewable energy generation. In nature, solar energy is distributed uniformly, with an average of about 1400 $J=m^2s$ of energy radiated from the sun to the earth, and its power generation potential exceeds the total consumption of the earth (Abdelhafez et al., 2021). Harvesting solar energy through photovoltaic technologies are the most efficient form of renewable energy that does not require significant operating costs and has a minimal environmental impact (Solangi et al., 2011 & Hassan et al., 2017).

The industrial sector is very important to the economic development of any nation. Currently, Pakistan facing a huge energy crisis and these crises affects economic development. In many commercial and industrial applications, diesel generators are used as reliable backup energy supply sources during load shedding times. The use of diesel engines increased environmental emissions and energy costs per kWh (Ahmed et al., 2021). Pakistan's present energy situation indicates that it is experiencing critical energy shortages, estimated to be 4.0 GW to 6.0 GW in recent years (Javid et al., 2020). The demand for energy in Pakistan is growing at a rate of 8.0% annually (Shakeel et al., 2016). Pakistan primarily relies on imported fossil fuels (oil, LPG) for power production, but the cost is very high and not the best option due to environmental hazards (Shabbir et al., 2020).

Annually, Pakistan receives approximately $15x10^{14}$ kilowatt-hour of solar energy, with an average daily sunshine duration of eight to ten hours (Tamoor et al., 2020). PV energy generation technologies are developing as one of the most competitive solutions to Pakistan's current energy challenges (Muhammad et al., 2021). PV integrated distributed power generation system contributes to the sustainable development of energy. Optimizing the integration of photovoltaic systems can not only meet the energy demands of our existing systems but also inject some excessive energy into the national utility grid (Memon et al., 2021 & Tamoor M. et al., 2021). The cost of electricity (per kWh) generated by the PV energy generation system is lower than the cost of electricity (per kWh) delivered by the national utility grid (Kumar et al., 2021).

The efficiency of a photovoltaic system depends on PV modules orientation and geographic location (Chandrika et al., 2021). When designing and installing a large-scale photovoltaic energy generation system, it is important to consider the optimum number of photovoltaic panels, their tilt angle and orientation, and spacing between PV rows. The tilt angle and interrow spacing are used to evaluate the performance of PV systems and to assist in the maximum utilization of the available space, which is critical for investment in PV energy generation systems. The PV systems installed at an optimal tilt angle with optimum interrow spacing have maximum total collector irradiance and annual energy production (Tamoor et al., 2022).

The quality of life in the community is greatly improved when the streets are illuminated at night (Gutierrez-Escolar et al., 2015 & Kiwan et al., 2018). Traditionally, street lights have been powered by energy from the national utility grid. But, irregular power supplies and frequent power outages often result in loss of life and property due to the constant darkness on city highways and community streets. Recent advancements in technologies have shown that renewable energy sources (RES) such as photovoltaic energy generation systems can be used to operate streetlights (Kumar et al., 2016). A large number of grid-connected or standalone photovoltaic systems have been installed for public street lighting. The photovoltaic street lighting system (PSLS) is one of the most practical and feasible street lighting systems (Lagorse et al., 2009). The PV-powered energy-efficient street lighting system is a viable and realistic solution for public lighting with the right combination of system components (Tamoor et al., 2021).

Usually, the PV-powered streetlight (single-pole complete sets) have become popular. In this type of lightning system, PV modules, battery charging units, batteries, and light bulbs are installed on each pole of a streetlight. The major drawback of these systems is that each pole has their own costly components like PV modules, battery charging unit, batteries, and the additional power produced by the system did not feed into the grid and wasted. In recent years, it is observed that single-pole complete set streetlights located in cities are often damaged or vandalized. In most cases, PV modules, battery charging units and batteries were stolen by vandals. In view of this setback, the energy system planner and researcher find an alternative solution for street lighting systems and consider the use of centralized photovoltaic energy generation systems as an alternative option.

A centralized photovoltaic system consists of PV modules, inverters, and energy storage systems. Electric cables are used to distribute the electricity generated by the PV system, which is used to power streetlights located on the road or street in the city and surrounding areas. The rate of vandalism or damage to solar streetlights will be minimized with a centralized PV system, and the additional generated electricity will be fed into the national utility grid via the net metering procedure. Therefore, in this research study, the simulation study and designing of an On-grid photovoltaic (PV) hybrid energy generation system for energy efficient streetlights installed on the one-way road in Government College University, Faisalabad is conducted using PVsyst simulation software.

MATERIALS AND METHODS

Proposed Site Location and Climate Conditions

The proposed PV powered energy efficient street lightning system (PVEESL) is designed for the one-way road in Government College University, Faisalabad, which is located at latitude 31.388541 and longitude 73.027953 in Punjab Province, Pakistan, as shown in Figure 1. Using Google Maps, the length of the road for the installation of PV powered energy efficient streetlights were calculated. A one-way road is 2004 meters long (1002 m on each side). There are various professional tools available to gather meteorological data from satellites. This study made use of the Meteonorm database and software. For assessment of photovoltaic energy output, daily and monthly irradiation data, average, minimum and maximum temperatures, precipitation and sunlight hours were all relevant characteristics to examine. The radiation level is maximum during the summer season, especially in the months of June and July. At the proposed site, the average annual global horizontal irradiation (GHI) is 1693.0 kilowatt-hour/m^2 and the horizontal diffuse irradiation is 862.3 kilowatt-hour/m^2.

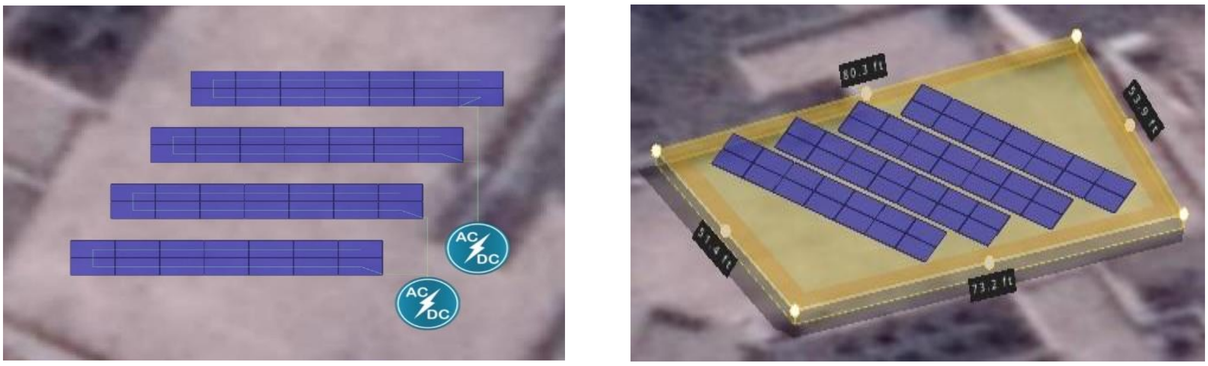
The temperature of the proposed site increased in summer and decreased in winter. The average monthly temperature is 23.66 °C. This information suggests that a photovoltaic energy generation system can harness a significant amount of solar energy. Precipitation is usually higher in all months of the summer season and lowers in the winter season. The monsoon season occurs from the month of May to September and the monsoon season is at its peak in the month of July/August, with approximately 60.0-75.0% of annual rainfall. The duration of sunshine hours is critical in determining how much irradiation is necessary to provide the desired output energy. The average annual sunny day is 7 to 9 hours.

Figure 1. Proposed Site Location for PVEESL

Experimental System

The spacing between adjacent poles of streetlights is 20m, an energy efficient streetlights (EESL) with a rated capacity of 28.0 watts are installed. A total of 100 streetlight poles are required to cover both sides of the road, with a total daily energy consumption of 22.40 kilowatt-hour and monthly energy consumption of 672.0 kilowatt-hours. The PV-powered energy efficient street lightning (PVEESL) system is designed to work for 8 hours every day. To ensure that photovoltaic (PV) modules can generate adequate electricity throughout the year, the hybrid photovoltaic (PV) energy generation system is designed with a minimum average monthly peak sunshine hours. The proper design of a PV-powered energy efficient street lightning system (PVEESL) required accurate size of all components of the system. The following are the fundamental components of a PV-powered energy efficient street lightning system: PV modules, energy storage system, Hybrid inverter, and energy lights.

Then, the PVsyst software is used to select the PV modules, hybrid inverter, and batteries for energy storage. We chose a 360 Watt Bifacial Si-poly Canadian solar (CS3U-360PB-AG 1500V HE), a 10 KW hybrid inverter Huawei (SUN2000-10k TL), and a battery bank that includes Narada (AcmeG 12V 200) batteries from the PVsyst database based on system capacity. The specification of PV modules includes Vmp: 39.6 V, Voc: 47 V, Imp: 9.1 A, Isc: 9.67 A, and 17.9% module efficiency. The photovoltaic modules were installed at 0° azimuth angle and 15° tilt angle, and there is no shading effects on the PV modules. The hybrid photovoltaic energy generation system has 4 parallel strings, and each string has 14 photovoltaic modules connected in series. The specification of hybrid inverter includes operating voltage: 200.0-950.0 V, Unit Nom. Power: 11.0 kWac, and Pnom ratio: 0.92. The energy storage system consists of 16 batteries (2 in series x 8 in parallel) with a nominal capacity of 1600.0 ampere-hours (C10) and discharging minimum SOC is 20.0 %. The complete layout of hybrid PV system are shown in figure 2(a) and PV layout in 3D is shown in figure 2(b). Summary of the installed system are shown in table 1.



(a) (b)

Figure 2. Layout of hybrid PV system (a) complete (b) 3D

Table 1. System summary

Number of PV modules	56
PV Module area	112 m²
Cell area	99.1 m²
Nominal PV Power (STC)	20.16 kWp
Number of Inverters	2
Unit Nominal Power	11.0 kWac
Title Angle	15°
Azimuth angle	0°

RESULTS

Balances and Main Simulation Results

The results are based on monthly and annually ambient temperature (°C), horizontal global irradiation (kWh/m²), DHI (kWh/m²), global incident in collector plane (kWh/m²), and effective global corrected irradiance of solar (kWh/m²), which are essential for the PV energy generation system simulation. These values are significant as they will assist in determining the renewable energy potential at the desired location. The average annual ambient temperature of 23.66℃., and maximum temperature is measured in the month of June (32.17°C), and minimum temperature is measured in the month of January (11.27°C). The annual GH irradiation at the proposed location is 1693.0 kilowatt-hour/m^2, DHI is 862.3 kilowatt-hour/m^2, and the global incident in the collector plane (kWh/m²) is 1830.3 3 kilowatt-hour/m^2 as shown in figure 3.

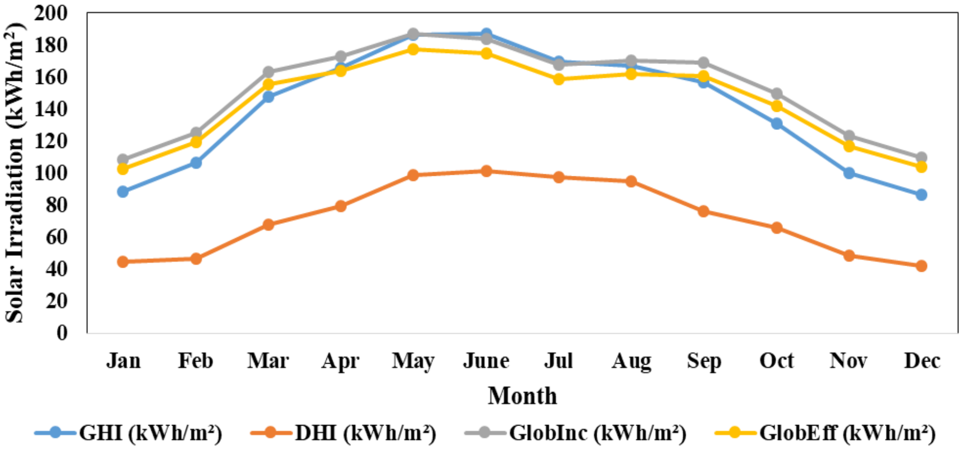


Figure 3. Meteorological data of the proposed site

The main simulation results from figure 4 show that the annual production of the hybrid photovoltaic system for EESL is 25.96 MWh/year, and the specific energy production of the hybrid PV system is 1288.0 kWh/kWp/year. The performance ratio (PR) of the hybrid PV system is 70.38 % and solar fraction is 14.82 %. The battery cycle state of wear is 100.0% and the static state of wear is 91.7%.

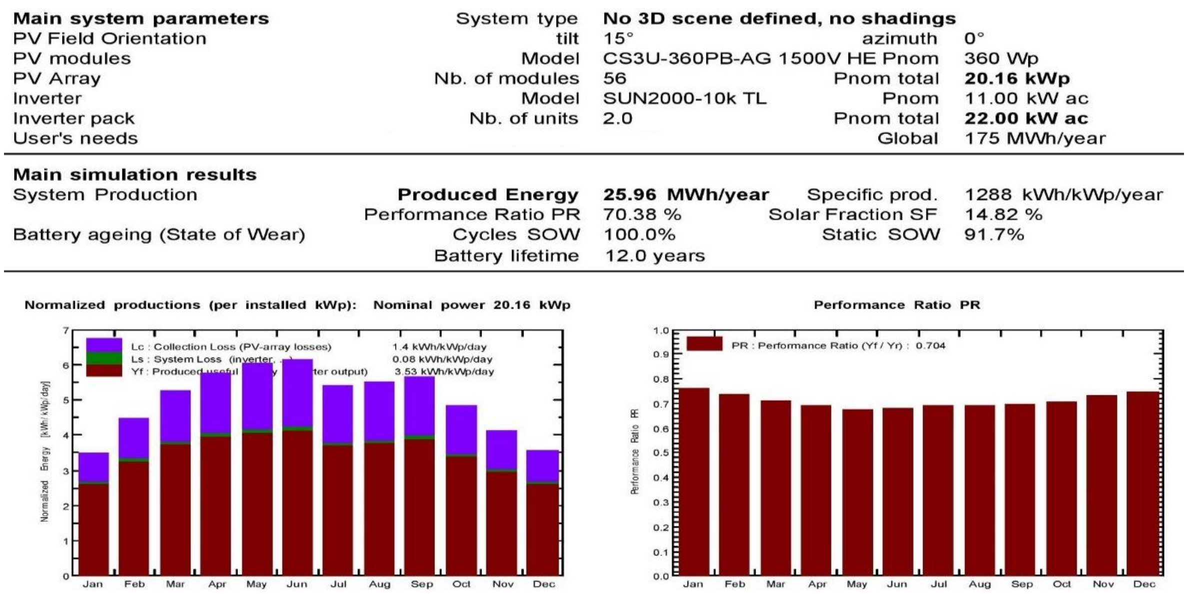


Figure 4. Main Simulation results

At the output of the photovoltaic array, the effective energy is 27.296 MWh/year, the energy consumed by streetlights is 7.88 MWh/year, and the produced energy injected into the public grid is 17.080 MWh/year. The PV system produces enough energy to operate streetlights, just in the month of January takes 0.001 MWh of energy from the grid. In the month of June, the photovoltaic system generated and injected maximum energy into the national grid i.e. 1.814 MWh. In the month of January, the photovoltaic system generated and injected minimum energy into the national grid i.e. 0.848 MWh. Figure 5 shows the details about the energy generation, consummation, and injection into the grid.

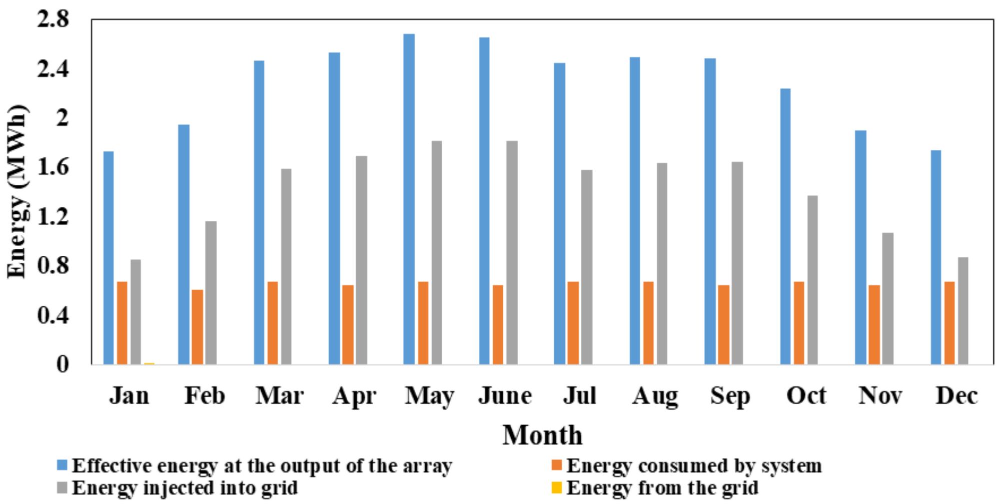


Figure 5. Comparison of energy generation, consummation, and injection into the grid.

The expected energy outputs at the photovoltaic array have decreased over several months (usually in January, February, November, and December), because weather influence the performance of the system, particularly PV module temperatures. Apart from this, several other factors, like PV module quality, mismatch, degradation, ohmic losses, have an impact on PV array efficiency. Available solar energy (kilowatt-hour/day) versus global incident in collector plane (kWh/m².day) is shown in figure 6.

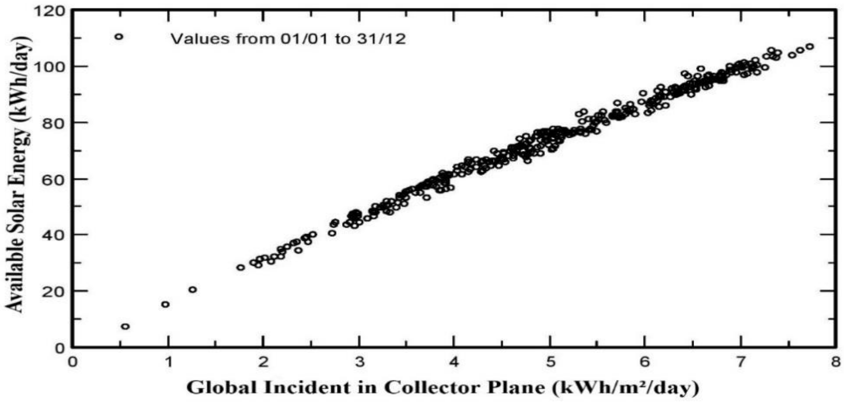


Figure 6. Daily input energy versus daily energy production

Every dot on the curve represents the energy production of one day. From the figure it is shown that solar irradiance increased on the collector plane, the energy output (kWh) of Photovoltaic modules increased. The system output power distribution is shown in figure 7.

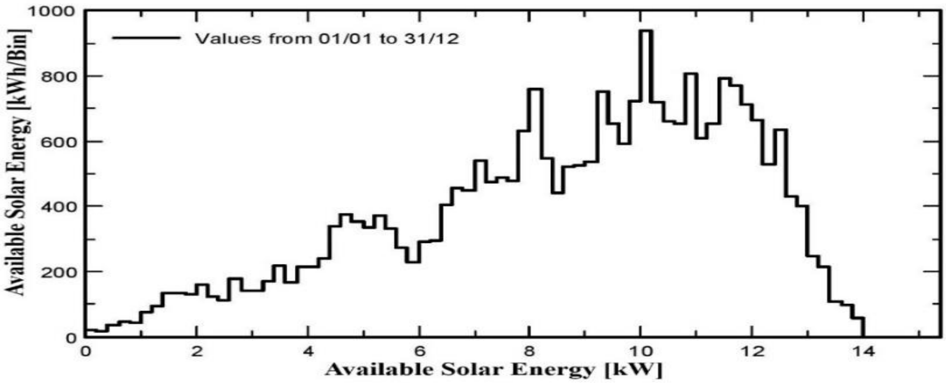


Figure 7. System output power distribution

Energy System Losses

From simulation result, it is determined that the global radiation on the horizontal plane is 1693 kWh/m². However, the effective radiation on the collector is 1737 kWh/m². Electrical energy is produced when this effective radiation strikes on PV module surface. At standard testing conditions (STC), the array nominal energy after PV conversion is 35.07 MWh and the photovoltaic array has a 19.42% efficiency. At MPP, the annual virtual array energy is 26.58 MWh. The several losses that occur at this stage such as 9.68% temperature loss, 9.80% PV module degradation loss, 5.41% PV module array mismatch loss and 0.97% ohm wiring loss, and 0.35% PV module quality loss. On an annual basis, available energy at the inverter output is 25.96 MWh 26.68 MWh. In the end, the streetlights consumed 7.88 MWh of energy, while 17.08 MWh of energy was injected into the electrical grid. During this stage, different losses occur, including 2.31% inverter losses during operation and 0.03% losses due to night-time consumption.

Reduction in CO_2 Emissions

The simulation of carbon dioxide (CO2) emissions during the next 30 years is shown in figure 30, and we determine that the annual savings in CO_2 emissions from installing a photovoltaic system for energy efficient street lightning system is 157.9 tCO2, and the PV system has a lifetime of 30 years as shown in figure 8. The project can save 0.004737 million tonnes of CO_2 emissions over its lifetime of 30 years. This demonstrates the system's viability and the benefits of having a PV-powered energy efficient streetlights, which will save natural resources and improve air quality, and the ecosystem.

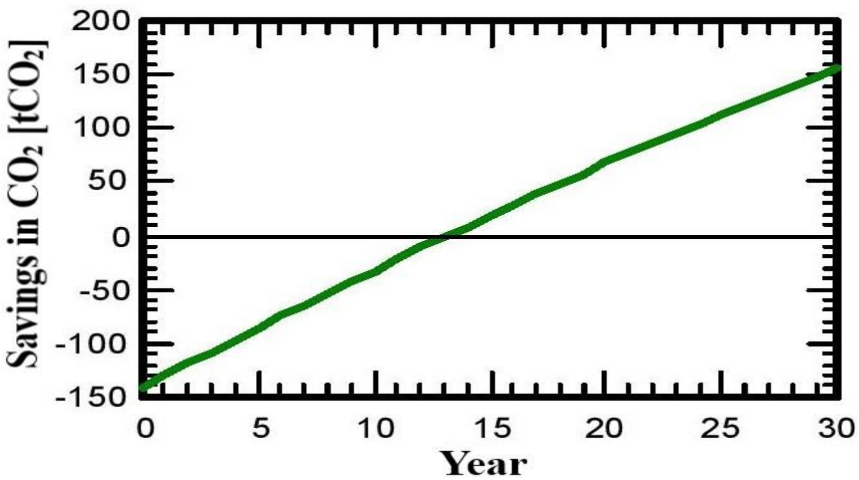


Figure 8. CO_2 Emission Balance

CONCLUSION

This research presents a comprehensive methodology for designing and simulating a PV energy generation system using to operate energy efficient streetlights using PVsyst simulation software. More accurate findings are obtained by using the measured global solar irradiance data for the Faisalabad district. A total of 100 streetlight poles are installed to cover both sides of the road, with a total daily energy consumption of 22.40 kilowatt-hour and monthly energy consumption of 672.0 kilowatt-hours. The annual production of the hybrid PV system for EESL is 25.96 MWh/year and in the month of June, the photovoltaic system generated and injected maximum energy into the national grid i.e. 1.814 MWh. The performance ratio (PR) of the hybrid PV system is 70.38 %, the solar fraction is 14.82 %. The battery cycle state of wear is 84.8% and the static state of wear is 91.7%. The several losses that occur such as 9.68% temperature loss, 9.80% PV module degradation loss, 5.41% PV module array mismatch loss and 0.97% ohm wiring loss, 0.35% PV module quality loss, 2.31% inverter losses during operation and 0.03% losses due to night-time consumption.

By using a photovoltaic system for energy efficient street lightning system, 157.9t CO_2 is reduced. The project can save 0.004737 million tonnes of CO_2 emissions over its lifetime of 30 years. A centralized grid-connected hybrid PV-powered energy efficient street lighting system is a viable solution for public lighting with the right selection of system components. This approach minimizes vandalism and damage to PVEESL components that can occur with single-unit installations.

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