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Design and Techno-Economic Analysis of an On-Grid Solar System for a House in Lahore, Pakistan

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***Abstract*—** Pakistan's geographical location - characterized by abundant sunlight throughout the year - presents a unique opportunity to harness solar energy, offering a viable alternative to traditional fossil fuel-based power generation at lower costs and improvement in gender-related energy access. This investigation examines the feasibility of installing a solar photovoltaic (PV) system in a house in Lahore, Pakistan, focusing on reducing utility bills, energy security and affordability. It presents the house annual energy data and detailed Homer Pro, SAM, and REopt analysis. Additionally, it provides an analysis of solar systems with and without battery storage. The obtained results unveil that the installed system can produce 13% extra energy by adding battery backup to the inverter while serving the house load. This research also provides risk mitigation strategies to address risks associated with large-scale solar PV installations in developing nations. The obtained findings underscore the financial attractiveness of investing in `renewable energy solutions with energy storage capabilities.

***Keywords*—** Solar energy; Renewable energy; Homer Pro; Hybrid power systems; PV system design; On-grid solar system.

1. INTRODUCTION

Pakistan's geographical location, characterized by abundant sunlight throughout the year, presents a unique opportunity to harness solar energy, transforming it into a sustainable and cost-effective solution for households across the country [1, 2]. With the ever-increasing demand for electricity coupled with the challenges of energy security and affordability, solar energy emerges as a beacon of hope, offering a viable alternative to traditional fossil fuel-based power generation [3, 4]. By embracing solar power, Pakistani households can generate electricity, reducing their reliance on the often unreliable grid and mitigating the impact of frequent power outages [5].

The adoption of rooftop solar photovoltaic (PV) systems in Pakistan has gained significant traction, particularly following the introduction of a green metering system by utility companies [6–8]. This approach allows homeowners to generate clean and uninterrupted electricity and sell excess generated energy back to the grid, eliminating the need for battery storage. This mutually beneficial arrangement reduces household electricity bills and contributes to a more sustainable and resilient energy infrastructure [9–11].

Several studies have explored the viability and long-term impact on environmental, economic, and social aspects of PV systems in Pakistan. For instance, the study [12] explores optimal component planning for a grid-connected microgrid in Pakistan. The objective is to

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reduce the cost of energy, increase the renewable share, cut greenhouse gas emissions, enhance power supply reliability, and make electricity generation sustainable. Results show a 92.47% reduction in the cost of energy for residential applications and a 48.52% reduction for commercial applications.

This study [13] assesses the socio-technical aspects of implementing solar power in Tharparkar, Pakistan, focusing on equitable energy access. It discusses the potential for solar power to replace current energy sources at lower costs and improve gender-related energy access. The analysis emphasizes long-term planning for the lowest prices, emissions reduction, and equitable outcomes. This study [14] evaluates a solar-biomass on-grid hybrid system for the Hattar Industrial Estate in Pakistan. The study aims to provide cost-effective and uninterrupted power supply by considering available resources. The optimal system combines solar PV and biogas generation, reducing energy costs, achieving a payback period of 4.6 years, and significantly cutting carbon emissions. This paper [15] examines the barriers and potential for solar energy development in Pakistan. It highlights the need for cleaner energy sources and identifies solar energy as a promising option. The study proposes policy recommendations to overcome barriers and promote solar energy use. This research [16] evaluates the techno-economic effectiveness of grid-connected and standalone integrated hybrid energy systems for remote electricity supply. The study considers factors like net present cost, cost of energy, and payback time, concluding that grid-connected hybrid systems are best for reliable energy supply in remote areas. This work [17] proposes a hybrid energy model for fulfilling Pakistan's educational institute's power requirements. It considers various stand-alone and grid-connected energy systems and shows that PV, wind, and fuel cells are cost-effective for energy production and storage. This study [18] conducts a life cycle assessment of multi-Si PV systems in Pakistan. It evaluates environmental impacts and energy payback time, concluding that these systems have an EPBT of 2.5 to 3.5 years, making them a viable option for energy production. This research [19] employs the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) to understand the acceptance of solar technology in Pakistan's southern region. Environmental beliefs, social influence, and price value influence consumers' intention to use solar technology. This study [20] evaluates a 150.7 kW grid-connected PV system in a public university in Pakistan. It analyzes energy generation, performance ratios, and annual energy yields, concluding that the system is efficient and has a performance ratio of 79.64%. This study [21] focuses on integrating solar photovoltaic (PV) energy into the residential sector. It uses a decision tree and design parameters optimization to assess sustainability and electrification requirements. The research quantifies synergies and trade-offs between design parameters, evaluates the impact of solar PV systems on energy sustainability, and analyzes the competitiveness of various solar PV integrated energy systems. The findings suggest that combining solar PV systems with grid power has a greater impact, while combining them with battery energy storage systems is more competitive, providing valuable insights for encouraging renewable solar integration. This paper [22] investigates the challenges hindering the adoption of distributed solar photovoltaics (PV) in Pakistan. It finds resistance from incumbent actors due to misaligned institutional logics, focusing on difficulties in acquiring finance and insufficient incentives for distribution companies to facilitate distributed generation. This misalignment leads to user preferences for fossil-fuel backup energy systems, under-facilitation of distributed generation, restricted lending behavior, and limited coordination between system actors. The findings have generalizable implications for regions facing similar challenges. This study [23] explores the economic viability and feasibility of installing photovoltaic (PV) solar energy systems in Pakistan, specifically in Faisalabad. It highlights Pakistan's favorable solar radiation characteristics and assesses the cost-benefit analysis of installing PV systems in households. The research shows that the true financial cost of a PV module decreases significantly when energy cost savings are considered in generating conventional electricity, emphasizing the potential for solar energy in Pakistan. This work [24] focuses on the risk assessment and mitigation strategies for large-scale solar PV systems in Pakistan. It collects data on complaints related to PV systems from reputable companies and presents insights into potential risks and their severity. The study also provides risk mitigation strategies to address these complaints, aiming to reduce risks associated with large-scale solar PV installations in developing countries.

The paper is structured as follows: Section 2 presents the methodology; section 3 presents and discusses the results obtained from the simulation software and section 4 concludes the study.

2. SITE DATA AND SYSTEM ANALYSIS

In this section, we present site details and the software used to simulate the PV setup on a house in Lahore, Pakistan.

2.1. Site Description

The site selected for this research is a house in Lahore. Lahore is considered the second densely populated city and most populated division of Pakistan with a total population of around 22 million [25]. The exact location of this site is long 31.5481, Lat 74.3916 and google map in Fig. 1 shows the image of solar panels installed on the roof of this house. House is in Askari X housing society, Lahore and the total rooftop area of this house is 1680 ft2. This house is made of bricks with a flat rooftop.

Fig. 1. Site location on Google maps (Latitude: 31.5481, Longitude: 74.3916).

Structure of the house, size of the house, number of family members living in a house and their lifestyle play a very important role in the energy demand of a household. Seven family members are living in this house including three kids and four adults. Fig. 2 shows monthly energy consumption of the house before the installation of the Solar PV system. This data is collected through old utility bills. High energy consumption in summer months is mainly due to the use of window type air conditioner.

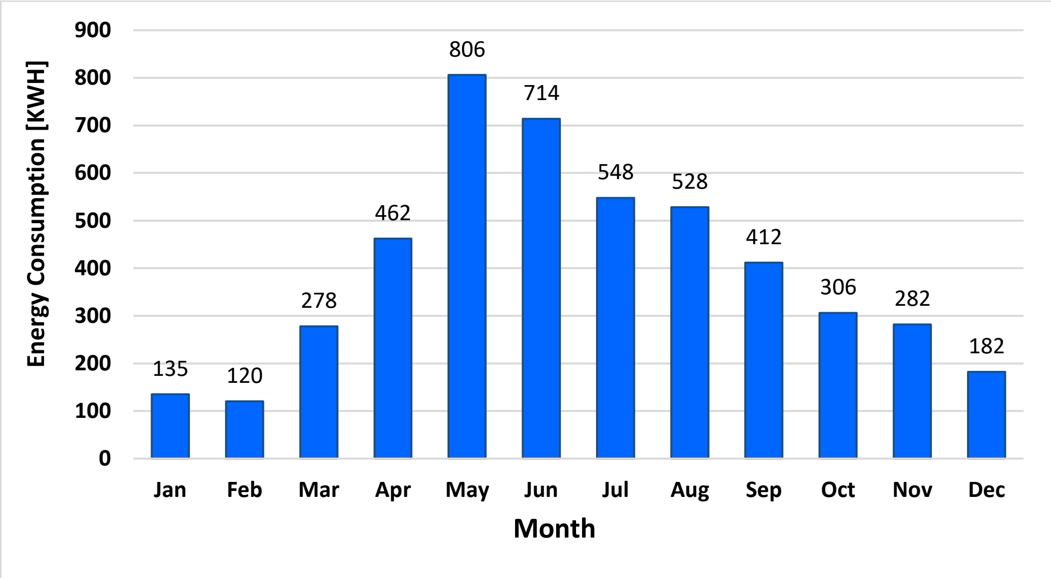

Fig. 2. Electric energy consumption of the house in 2022.

Table 1 shows major electric appliances installed in this house and their load. Temperature rises to 45°C during summers in Pakistan, so air conditioning units are used to maintain indoor temperature. Historical energy trend of the house shows that average monthly energy consumption of this house is around 400 kWh with peak consumption in summer. Total in Table 1 shows that the full load of this house is around 5.1 kW. All the appliances in this house are rated at 220 VAC. Air conditioners are used only for a few hours a day.

Table 1. Installed electric load in the house.

Appliance	Load [W]	Quantity	Total load [W])
Ceiling fan	60	7	420 W
LED light	10	16	160 W
Refrigerator	400	1	400 W
LED TV	350	1	350 W
Air Conditioner	1250	2	2,500 W
Microwave	1200	1	1,200 W
Laptop	100	1	100 W
Modem	20	1	20 W
Total			5,150 W

2.2. Details of the Installed Solar PV System

Local utility supply company in Lahore is offering net metering options to the residential users to promote the domestic clients to install rooftop solar PV units. The selected house is equipped with a grid-tied Solar PV unit which supplies electric power to the house and feeds extra energy back to the grid during daytime. Inverter and Solar PV panels are two major parts of a Grid-tied system. This Solar PV unit is equipped with an 8.2 kW hybrid inverter and 14 solar panels of 545 watts each. The following are some details of installed components.

2.2.1. *The Solar Panel*

A total of 14 Monocrystalline solar panels manufactured by JA Solar are being used in this project. The model number of the solar panel is JAM72S30, and the total rated power of each solar panel is 545 watts. JA Solar used half-cut configuration of the modules which offers advantages of higher power output, better temperature-dependent performance, reduced shading effect on the energy generation, lower risk of hot spot, as well as enhanced tolerance for mechanical loading. The company offers 12 years of product warranty and 25 years of linear power output warranty with 0.55% annual degradation over 25 years as illustrated in Fig. 3.

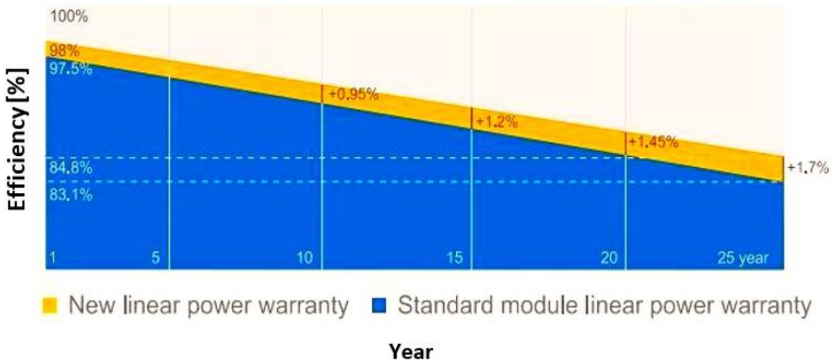

Fig. 3. Projected efficiency of the solar panel for 25 years [3].

This solar panel has 2,279 mm Length and 1134 mm width with a net weight of 28.6 kg each as shown in Fig. 4. 14 solar panels and their mounting frames will put 700 kg load on the roof of the house, which will not be any problem with roof structure type of this house. 14 panels will produce total 7630W as per following formula:

$$\text{Power of single Panel} = 545 \text{ W}$$
$$\text{Total Solar Panels} = 14$$
$$\text{Total DC Capacity of System} = 545 \times 14 = 7{,}630\ W$$

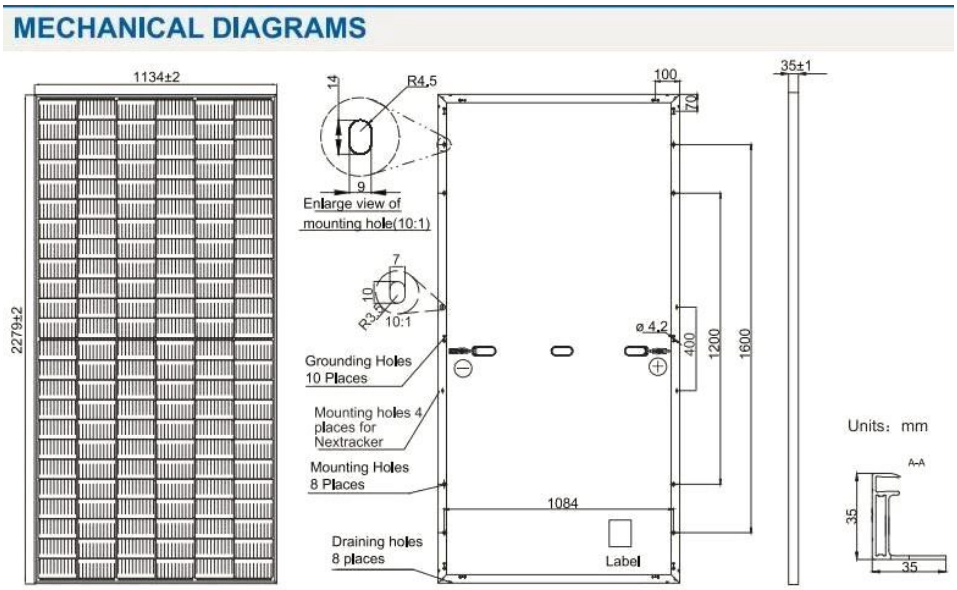

Fig. 4. Physical dimensions of the solar panel.

Table 2 shows electrical parameters of the solar panel. This panel is rated for 1500V DC maximum system voltage and operating temperature range is -40C to 85C. The maximum series fuse rating of this solar panel is 25A [3].

Table 2. Electrical specification of the solar panel.

Type	Rating
Maximum power (Pmax)	545 W
Open circuit voltage (Voc)	49.75 V_{DC}
Maximum power voltage (Vmp)	41.80 V_{DC}
Short circuit current (Isc)	13.93 A
Maximum power current (Imp)	13.04 A
Module efficiency	21.10%
Power tolerance	0 – 5W
Temperature coefficient of Isc (α_Isc)	-0.045% °C
Temperature coefficient of Voc (β_Isc)	-0.275% °C
Temperature coefficient of Pmax (γ_Isc)	-0.350% °C

2.2.2. The Inverter

Crown Nova PV-12000 8.2 kW pure sine wave hybrid inverter is used in this system. This inverter is rated for 230 VAC and 50Hz systems as per the local demand of the utility supply company. The maximum efficiency of this inverter is 93% and users can synchronize up to 6 units in parallel. Nova 8.2 kw comes with two solar MPPT with maximum PV input current capacity of 27A each. MPPT voltage range is 90Vdc to 450VDC.

This inverter offers three different operating modes. This can be used as a stand-alone inverter by adding battery backup and removing utility supply, grid-tied by only connecting solar panels and utility and hybrid inverter by connecting battery backup and utility supply at the same time. Inverter also offers dual output for smart load management, which means one of the outputs can be programmed as noncritical load to turn off a certain level of battery backup during nighttime. Table 3 shows major technical specifications of the inverter as an online datasheet [4].

Table 3. Technical specifications of the inverter.

Type	Rating
Rated output power	8200VA/8200W
Rated voltage	230 V_{AC}
Frequency range	50Hz/60Hz Auto sense
Surge power	16 kVA
Peak efficiency	93%
Maximum PV array power	12 kW (6 kW X 2)
MPPT range	90 - 450 V_{DC}
Maximum PV array Voc	500 V_{DC}
Maximum solar charging current	150A
Operating temperature	10 °C – 50 °C

2.2.3. Layout of the System

The inverter used in this system has 2 MPPT charge controllers and 2 strings of 7 panels are arranged to connect to each charge controller. Both strings have their own isolation switches and circuit breakers in the PV combiner box as shown in Fig. 5.

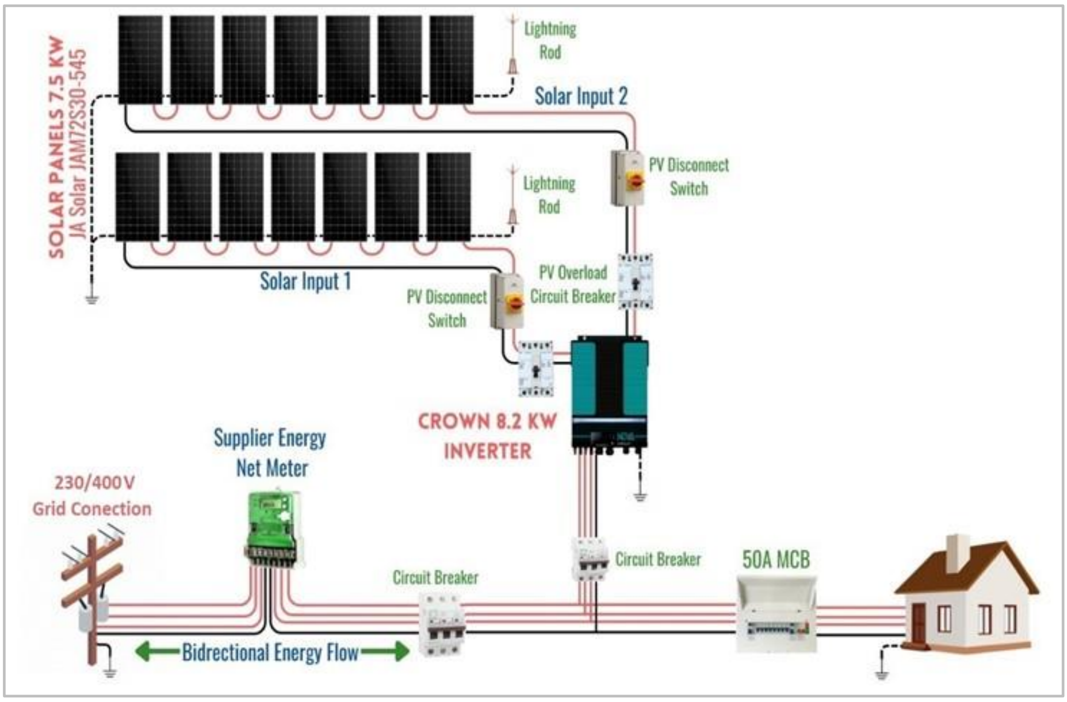

Fig. 5. System layout.

Table 4 shows the rating of each string in this solar PV system. The voltage of a string is 7 times the voltage of a single panel due to series connection.

Table 4. Technical specifications of the PV setup.

Parameter	Rating
Open circuit voltage (Voc)	348.25 V_{DC}
Maximum power voltage (Vmp)	292.6 V_{DC}
Short circuit current (Isc)	13.93 A
Maximum power current (Imp)	13.04 A

House is running totally on solar energy during daytime and extra energy is sold to the grid. House consumes electric energy from the grid during nighttime and cloudy days. Solar inverter is logging the total energy delivered by a solar PV unit. This house is equipped with a green energy meter and sells extra energy back to the grid.

PV Inverter counts the electric units fed to and from the grid and the utility company charges the client for net electric units. Solar PV system installed at this house is generating more than the consumption of the house and the user is always getting credit from the electric supply company. System was installed in August 2022, but net metering of the grid was approved in December 2022.

Solar PV inverter counted energy production by this PV system and shows 9,173 kWh from Sep-2022 to Aug-2023. Fig. 6 shows monthly production logs of PV inverter. The result shows that the Solar PV system produces maximum output during the summer season.

This result also proves that solar PV systems are the best solution as per the energy consumption trend of Pakistani homeowners. Residential consumers use more energy during summer for cooling and Solar PV systems will also be producing extra energy due to prolonged summer daylight.

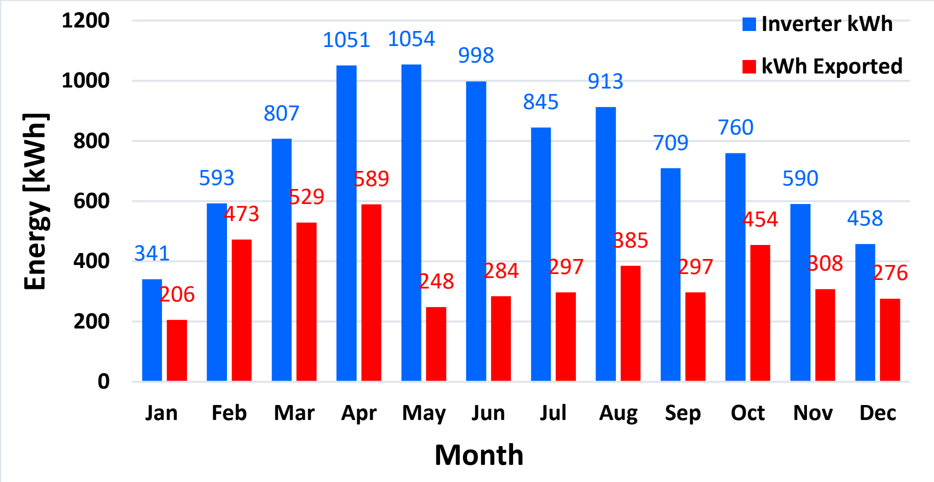

Fig. 6. Monthly energy production log of inverter.

2.3. Performance Analysis in System Advisor Model

System Advisor Model (SAM) is software that is used for performance and financial analysis of any Solar PV system. This software collects online weather data and performs a simulation on the designed system. Simulation results of SAM can provide the estimation of return on investment by projecting system's out for the next 25 years. Sam can model many types of solar energy systems including rooftop PV systems, battery storage systems, concentrating solar power systems for electric power generation and solar water heating systems. SAM requires all system details before running the simulation. Analysis and results are presented in the next section.

2.4. Financial Analysis of the Selected System in ROpt

The REopt is a platform used by NREL researchers for the optimization of energy systems for buildings, institutions, communities, micro grids, and more. REopt provides techno-economic analysis of selected systems. REopt proposes the ideal combination of renewable energy, grid generation, and energy storage technologies to meet cost savings, resilience, emissions reductions, and energy efficiency goals. REopt is a web tool that helps to evaluate the economic viability of distributed PV, wind, battery backup storage, combined heat, and power (CHP), and thermal energy storage. This tool can also identify system sizes and dispatch strategies to reduce energy costs. Users can also estimate the capability of a system to sustain critical load during a grid outage. REopt offers system selection at the beginning of every simulation design. User must select the proper site, Energy goals, and technology to get the desired results. Fig. 7 shows an overview of these selections.

Site selection offers a choice between a single site and portfolio analysis. Users can analyze more than one site by selecting Portfolio analysis. Single site selection will provide financial analysis of one site. Users can select between cost saving, resilience, and clean energy as their energy goals. As this software is used for financial analysis of selected systems, only cost saving is selected as energy goals of this simulation. Step 3 for data input is technology selection. The selected system is a grid-tied PV system so only PV and grid are selected for step 3. REopt requires data for site location, local electric rates, load profile, system costing, electric grid emission factor and PV sizing limits. REopt will be able to get solar irradiance and electricity charges by local grid after the location selection of proper site.

Solar irradiance data helps to determine annual energy yield of solar PV systems. REopt can determine the minimum size of the system by load profile. REopt will make sure to run load defined in load profile 100% on renewable energy if selected by the user. Analysis and results are presented in the next section.

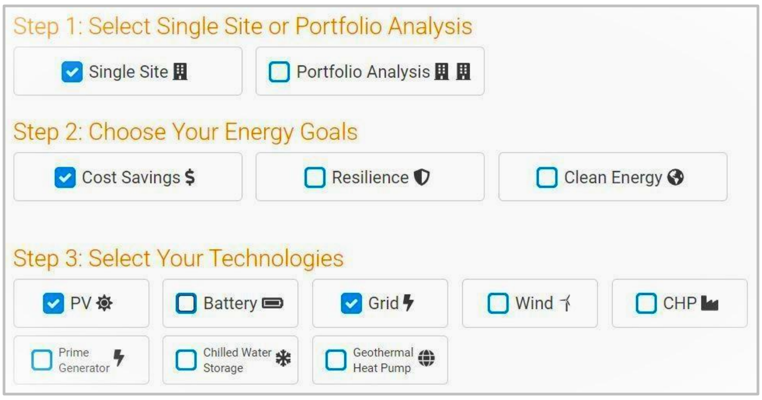

Fig. 7. REopt simulation category selection.

2.5. System Modeling in HOMER Pro

HOMER Pro is a software tool developed by HOMER Energy that is widely used for energy system analysis, optimization, and planning. This versatile software is particularly valuable for professionals and researchers in the fields of renewable energy integration, microgrid design, and the overall sustainability of energy systems. HOMER Pro is equipped with a user-friendly interface and a range of powerful features, making it an essential resource for designing and evaluating energy solutions. Users can model and simulate various energy systems, from small-scale residential setups to complex industrial microgrids. These models can account for factors like energy sources, load profiles, costs, and environmental considerations.

One of the key strengths of HOMER Pro is its ability to perform optimization, helping users find the most cost-effective and environmentally friendly solutions for their energy needs. It can suggest combinations of energy sources, storage options, and grid interconnections to achieve desired objectives, whether they involve cost reduction, reduced environmental impact, or ensuring power reliability.

In summary, HOMER Pro plays a vital role in the energy industry by enabling professionals and researchers to design and analyze energy systems that are not only economically efficient but also sustainable and environmentally friendly. It provides a comprehensive platform for making informed decisions in the complex and evolving landscape of energy system design and management.

Homer pro has access to an online solar irradiance database and uses it to simulate efficient results for selected projects. Homer Pro calculates annual energy production of the designed system by using online solar GHI and temperature database. Selected grid-tied solar PV system is designed in Homer Pro after selection of location. Fig. 8 shows the designed system structure in Homer pro.

This diagram shows 7.63 kW solar panels connected to a DC busbar and 8.2 kW PV inverter connecting the system to household and power grid. Household load is also designed as per annual energy consumption data of the house collected through electric bills.

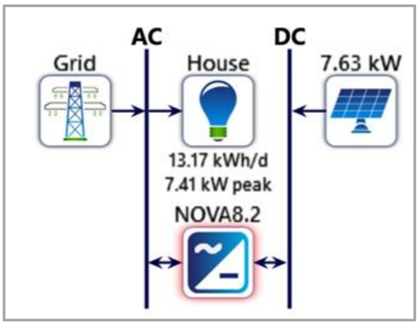

Fig. 8. System structure in Homer Pro.

3. RESULTS AND DISCUSSION

3.1. Simulation Results by SAM

SAM needs basic parameters to simulate projected energy and ROI of the desired system. SAM requires the location parameters to extract online solar irradiance data. Weather data was downloaded for selected location and added in the weather library of the software. SAM has many brands in solar panels and inverter libraries, but users can also define a new product if parts are not available in the list.

Fig. 9 shows monthly global irradiance of the site. This data is being downloaded from the online Solar Resource Library by providing the exact location of the site. As per this data, May and June are the best energy yield months for solar PV systems installed at selected location. Most of the time, solar irradiance data is calculated through weather records of the previous year. Solar Irradiance data indicates that winter is not a good season for solar power systems at selected locations. It does not affect the efficacy of the system because load trend shows that energy consumption is also low during these months. Data in this graph indicates kWh/m2/day for selected site. As described in Table 2, maximum efficiency of selected solar panels is 21.1 % and only 21.1 % of this available solar resource will be converted to electrical energy by using these panels.

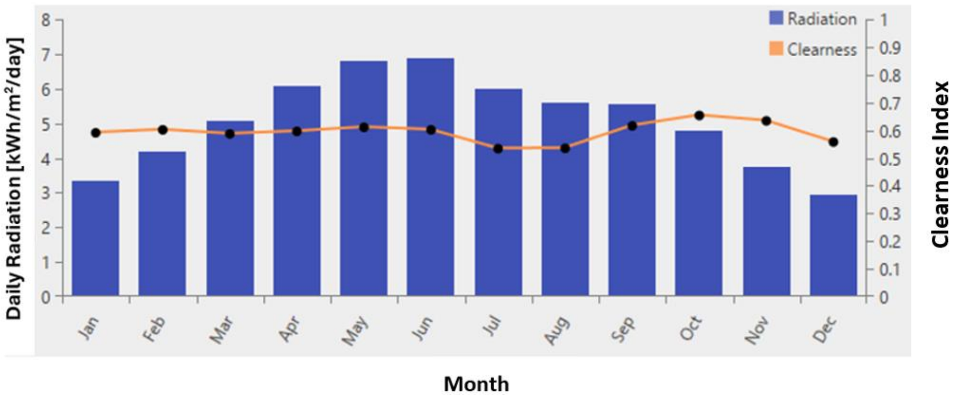

Fig. 9. Monthly global irradiance and clearness index at the site.

The second most important parameter to calculate annual energy output of a solar PV system is the temperature graph of the selected location. Fig. 10 shows the dry bulb temperature of the selected location for one year. This graph shows that temperature reaches up to 46 °C during summer season, which is way higher than standard test condition (STC) temperature. This rise in temperature will affect the energy output from solar panels. Installed solar panels will lose energy with respect to temperature coefficients of solar panels described in Table 2.

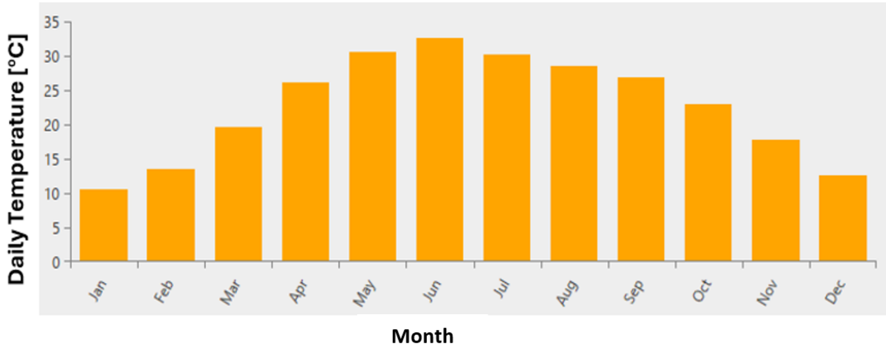

Fig. 10. Dry bulb temperature of site.

Solar Irradiance reaches to peak during April and May, but temperature still shows it below 35 °C. This indicates that solar PV system installed at this site will experience comparatively less temperature losses during these months of summer. Fig. 11 shows monthly energy production of installed solar PV system.

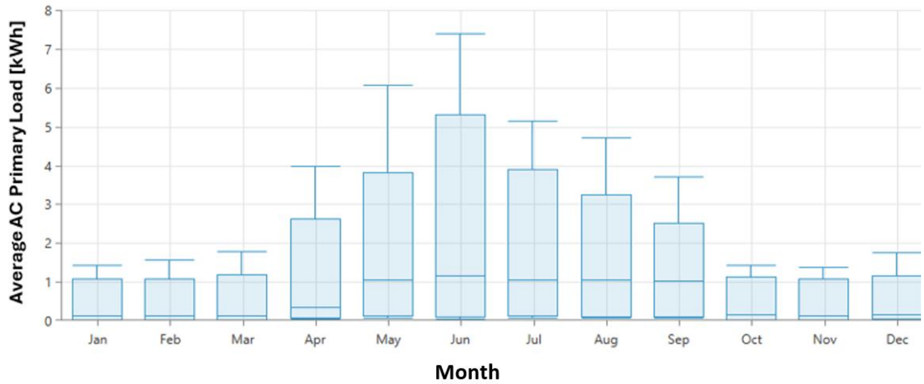

Fig. 11. Monthly energy production of installed solar PV system.

This data correlates with the GHI graph downloaded in SAM. Result also shows that May is at top in terms of energy production. Energy production in June is quite low as compared to May because June is a very hot month in Lahore and the rise of temperature directly affects the performance of Solar PV systems.

This result shows that the energy production capacity of this system is way more than the electric energy consumption of the house.

Fig. 12 shows the heat graph of annual AC energy production by the system. This results in performance losses of inverter and solar panels. The top axis of this graph represents the number of days in the year and the left axis is the total hours of the day.

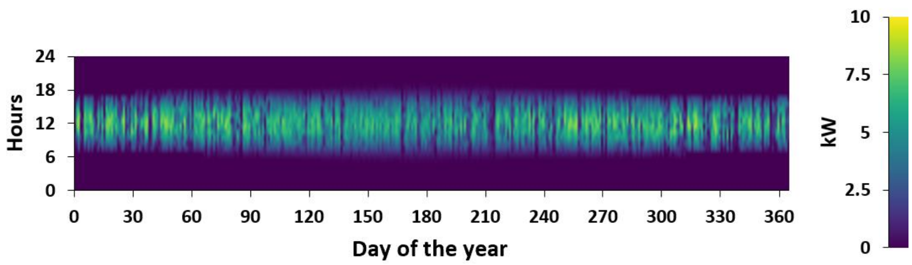

Fig. 12. Annual AC energy production.

Fig. 13 demonstrates all the losses that SAM considered during the simulation. These are shading loss, Soiling loss, DC wire loss, DC mismatch loss, reflection loss, diodes and connection loss, AC wire loss, Dc module deviation from STC, inverter power consumption loss, and AC inverter efficiency loss. Most of the losses reported by the software are DC module deviations from STC. Solar Panels are tested under standard test conditions (STC) which is 25'C and solar panel will not be providing same output at higher temperatures.

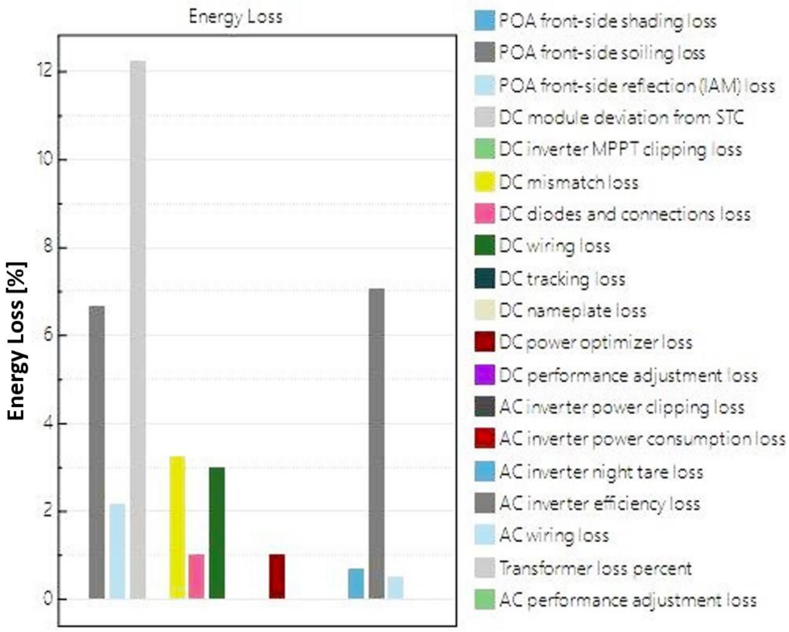

Fig. 13. Energy losses of the system.

Table 5 illustrates the summary of the system over 1 year. The table shows that this system can produce 10,620 kWh annually and the internal rate of return (IRR) calculated for 10 years is 18.41%. Total capital cost for installed system is 4,696 Canadian Dollar (CAD).

Table 5. System summary metric over one year.

Metric	Value
Annual AC Energy in year 1	10,620 kWh
DC Capacity factor in Year 1	15.9 %
Energy yield in Year 1	1,392 kWh/kW
Performance ratio in year 1	0.73
PPA price in Year 1	9.00 ¢/kWh
PPA price escalation	0.50 %/kWh
levelized PPA price (LLPA), nominal	9.49 ¢/kWh
levelized PPA price (LLPA), real	7.04 ¢/kWh
levelized cost of energy (LCOE), nominal	3.78 ¢/kWh
levelized cost of energy (LCOE), real	2.81 ¢/kWh
Net present value (NPV)	$ 10,574
Internal rate of return (IRR)	18.41 %
Year IRR is achieved	10
IRR at end of project	21.95 %
Net capital cost	$ 4,752
Equity	$ 4,752
Size of debt	$0.00
Minimum DSCR	inf

Local utility supply company is purchasing energy generated from residential solar PV systems at a rate of 18 PKR (0.09 CAD).

Fig. 14 Shows the projected energy of the system for the next 25 years. SAM also factored in annual degradation of solar panels to generate these results. This graph calculates 0.55% annual solar panel efficiency loss for the next 25 years. Results show that this system will still be producing 9,300 kWh after 25 years of operation.

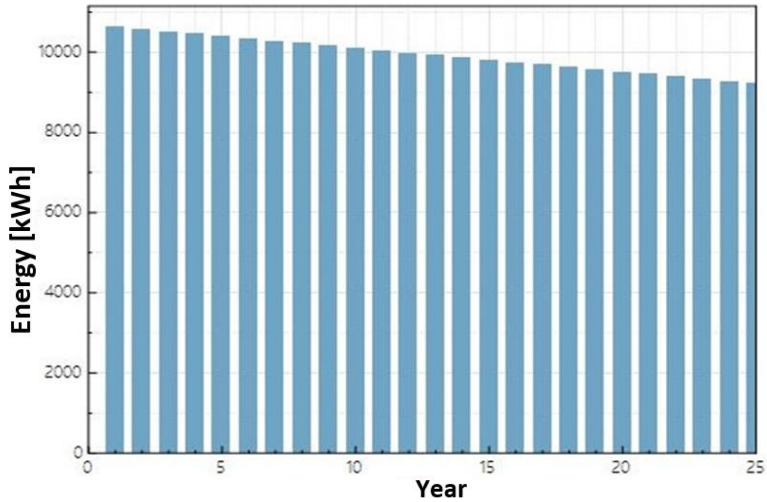

Fig. 14. Projected energy of the system for 25 years.

3.1.1. Comparative Analysis of SAM Results with Inverter Data

SAM collects online available solar irradiance data for a selected location and simulates expected energy generation for the next 25 years. Solar Irradiance data in SAM for this simulation is downloaded for year of 2017 for selected location. In Fig. 15, SAM shows results after factoring all losses, but any type of system failure or maintenance downtown will not be calculated by this software. As Solar irradiance data is not from the same year, there is a minor difference between SAM results and inverter data. Data collected from the inverter as shown in Fig. 16 describes that installed system generated 9,119 kWh energy from Aug-2022 to Aug-2023.

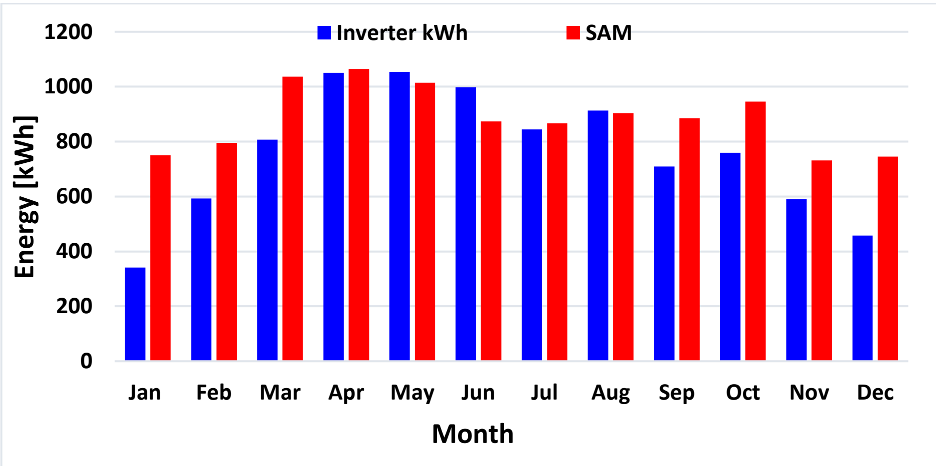

Fig. 15. Comparison chart of inverter output and SAM results.

There are some mismatches between energy output for winter months because solar irradiance is not the same every year. SAM results show the annual output of this system should be 10,620 kWh and solar inverter logged 9,119 kWh for 1 year. Error between SAM simulation results and real time data can be calculated by using the following formula:

$$\text{SAM Projected Annual Energy} = 10{,}620 \text{ kWh}$$
$$\text{Inverter real time annual energy} = 9{,}119 \text{ kWh}$$
$$\text{SAM Results Accuracy} = \frac{9119}{10620} = 0.87$$

Calculation shows that SAM results are 87 % close to the real time solar generation data. Realtime output is less than SAM results because the installed system will only generate maximum energy in the presence of grid connection. The load of this site is very low during winter and in case of any grid outage, grid-tied solar PV system will not be able to feedback extra generation to the grid. Pakistan is facing energy shortages, and this leads to around 6-10 hours of power outage in major cities. Energy lost during the power outage of grid can be stored in battery backup system but presently, there is no battery bank installed at this site. SAM results show that the installed system can produce 13% extra energy by adding battery backup to the inverter. Energy lost due to grid outage would have been exported to the grid at a rate of 18 PKR (0.09 CAD) per unit. The following calculation shows annual loss due to absence of battery backup.

$$\text{Annual Energy Loss} = 10{,}620 - 9{,}119 = 1{,}501 \text{ kWh}$$
$$\text{Energy Sale Rate} = 0.09 \text{ CAD}$$
$$\text{Total Loss per year} = 1{,}501 \times 0.09 = 135 \text{ CAD}$$

The above calculation shows that users of this system can save around 135 CAD annually by adding battery backup to the system and get a power backup during nighttime power outage.

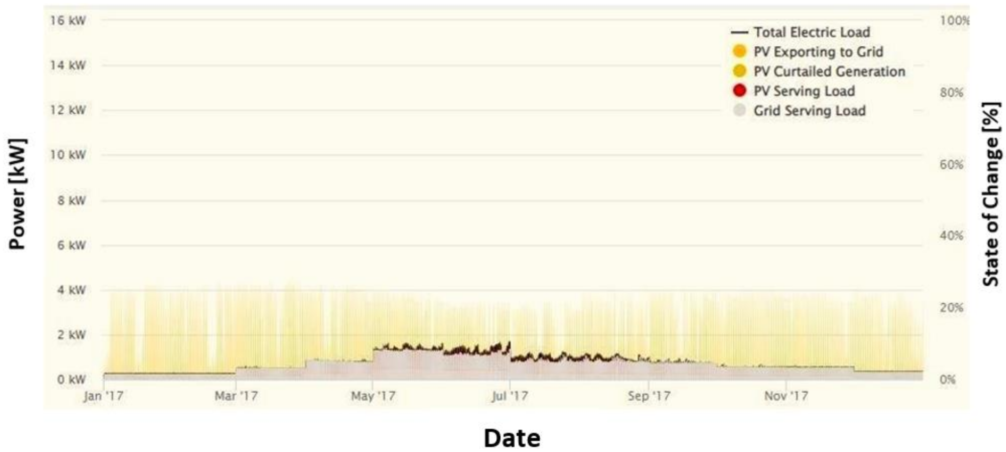

Fig. 16. System performance for one year.

3.2. REopt Simulated Results

As the system is already installed and running, minimum and maximum selection in PV sizing parameters is adjusted to get system recommendation near the installed unit. Fig. 17 shows that REopt recommended a 7kW solar PV unit after providing all basic site parameters. This system size is recommended by REopt to minimize the life cycle cost of energy at selected sites. This system will meet the energy requirements of the local site and feed extra generated energy back to the grid. The size recommended by REopt is near to the PV system size for selected size. It shows the designed system's performance for one year. This performance is calculated by REopt after collecting solar irradiance data of site location. REopt provides daily energy yield of the system, and this graph is being zoomed out to show data for the whole year.

The yellow marking in this graph represents energy exported to the grid. PV energy consumed by load is marked red in this graph. RED color is more visible from May to Sep because the site consumes more energy during these months. Gray color defines the energy imported from the local grid. This system imports energy from the local grid during nighttime and during cloudy weather.

It is a zoomed view of the previous power analysis graph and shows daily power analysis of the site. This graph clearly indicates the full site load runs on grid supply during nighttime. Most of the energy generated during daytime is exported to the grid as the yellow color represents in this graph.

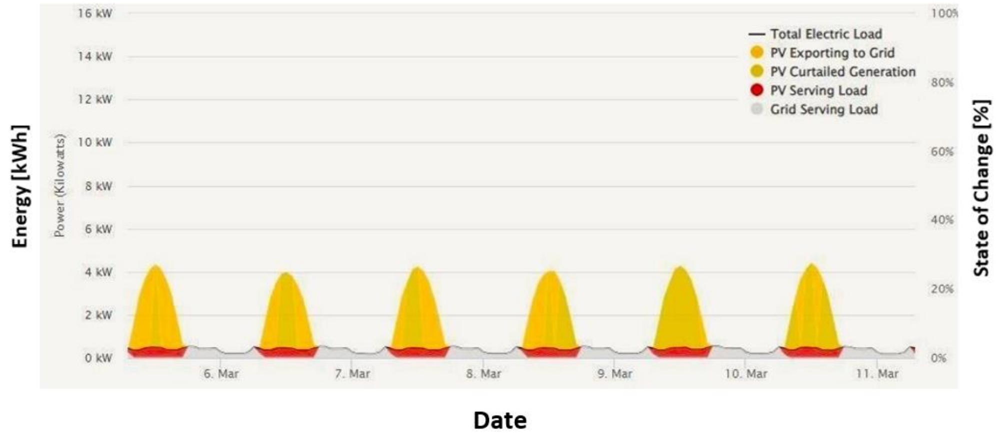

Fig. 17. Daily power analysis.

Fig. 18 shows net load duration of the site. This interactive graph shows the reduction in peak load that occurred after the installation of the Solar PV system on this site. Users can also zoom in on the date range and check the system's impact for a particular day. Gray color represents energy demand before installation of Solar PV system and blue color represents energy demand after implementation of solar PV solution.

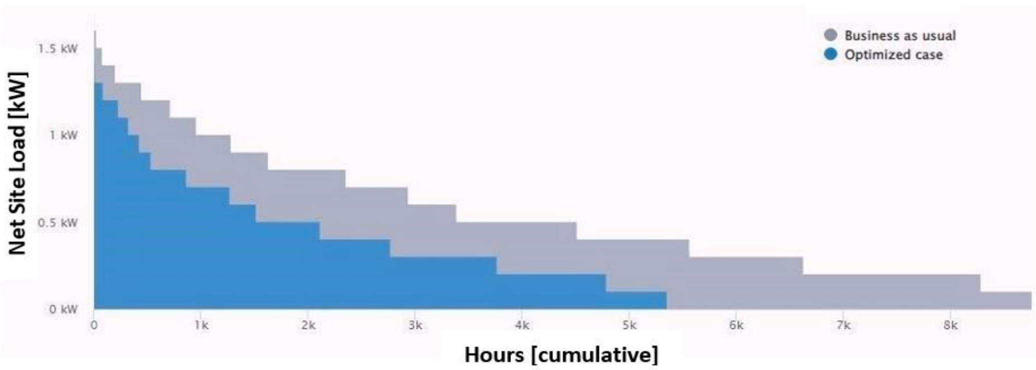

Fig. 18. Net load duration.

REopt calculated that a 7kW solar PV system for selected sites will save 21,208 CAD within the next 25 years. This saving is calculated after considering 0.1 CAD per kWh rate of Solar PV reverse feeding at selected site. The self-load of this site is 4,770 CAD per year and this load is fully powered on solar PV units throughout the year. Extra units consumed from the grid at night are returned during daytime. Local electric supply company is currently charging 0.25 CAD per kWh average (including taxes). REopt is charging every imported electric unit at a rate of 0.25 kWh but as per the power purchase agreement of electric supply company, customer will not be charged for any imported energy if the solar PV system is feeding back more than consumption of the site and net units at the end of the month is negative. Table 6 shows financial analysis of the system including the comparison of electric energy cost before and after the installation of Solar PV system. This comparison shows that the selected site will import 2,410 kWh annually from the local grid and REopt calculated this as a utility electricity cost. As a result, electric energy consumed from the grid will cost 31,395 CAD within 25 years of operation. This cost also includes the 7,400-capital cost of the project. Results demonstrate that the 7kW system at this site will produce 8,813 kWh annually which is way more than self-consumption of the site.

Table 6. Financial analysis of the system.

Metric	Business As Usual	Financial	Difference
PV size	0 kW	7 kW	7 kW
Annual average PV energy production	0 kW	8,813 kW	8,813 kW
Average annual energy supplied from grid	4,770 kW	2,410 kW	-2,2360 kW
Annual renewable electricity (% of electricity consumption)	0%	100%	100%
Year 1 utility energy cost – before tax	$1,192	$982	-$210
Year 1 utility demand cost – before tax	$20	$19	-$1
Total year 1 utility cost – before tax	$1,213	$1,001	-$211
Life cycle (capital costs + replacements, after incentives)	N/A	$7,400	$7,400
Life cycle (O&M costs)	$0	$1,850	$1,850
Total utility electricity cost	$38,026	$31,395	-$6,632

3.2.1. Analysis of REopt Results

REopt calculated 38,026 CAD cost of electric energy for next 25 years without any solar PV system. This value is calculated after factoring in the 2% annual electric energy price increase for the next 25 years. REopt projected 8,813 kWh annually by a 7kW PV system at this site which is almost the same as calculated in SAM and inverter after factoring it as 7.5kW. The REopt considered 31,395 CAD electric cost for this system for the next 25 years but as per the contract, the electric supply company will not be able to charge any bill to the customer because net units at end of each month would be in negative. As per the local tariff, the energy export rate for this site is 0.1 CAD/kWh and energy import rate for this site is 0.25 CAD/kWh (including all taxes). The following calculation gives an estimated idea of indirect savings for 25 years of life span.

Let's assume self-consumption of the site is denoted by A, electric unit cost by utility company by B, total annual electric cost for self-energy consumption by C, and electric cost for 25 years by D, then:

$$A = 4{,}770 \text{ kWh}$$
$$B = 0.25 \text{ CAD/kWh}$$
$$C = A \times B = 1{,}192 \text{ CAD/Year}$$
$$D = 1{,}192 \times 25 = 29{,}875 \text{ CAD}$$

Above calculations show that consumers will save 29,875 CAD within 25 years by switching their load to the Solar PV system. Furthermore, annual energy production of the system by E, energy exported to grid by U, local PV energy export rate by R, annual revenue by energy export by L, revenue for 25 years by M, and total savings for 25 years by S. Then, revenue due to reverse feeding to the grid can be calculated as follows:

$$E = 9{,}173 \text{ kWh}$$
$$U = E - A = 4{,}403 \text{ kWh}$$
$$R = 0.1 \text{ CAD/kWh}$$
$$L = U \times R = 440.3 \text{ CAD}$$
$$M = L \times 25 = 11{,}007 \text{ CAD}$$
$$S = M + D = 40{,}882 \text{ CAD}$$

3.3. HOMER Pro Results

The calculation done using HOMER Pro shows that user will save around 40,882 CAD within 25 years of operation. 11,007 is the revenue through reverse feeding to the grid and 29,875 CAD would have been the electric bill for this site. All the costing calculations are carried out in CAD and energy sale rate of 0.09 CAD is used for the simulation. The cost summary of Homer pro shows (see Fig. 19) that designed solar PV system will sale 20,702 CAD value of electric power back to the grid within next 25 years. The total cost of the system used for this calculation is 4,780 CAD which is equal to 970,000 PKR as per local currency of the system location.

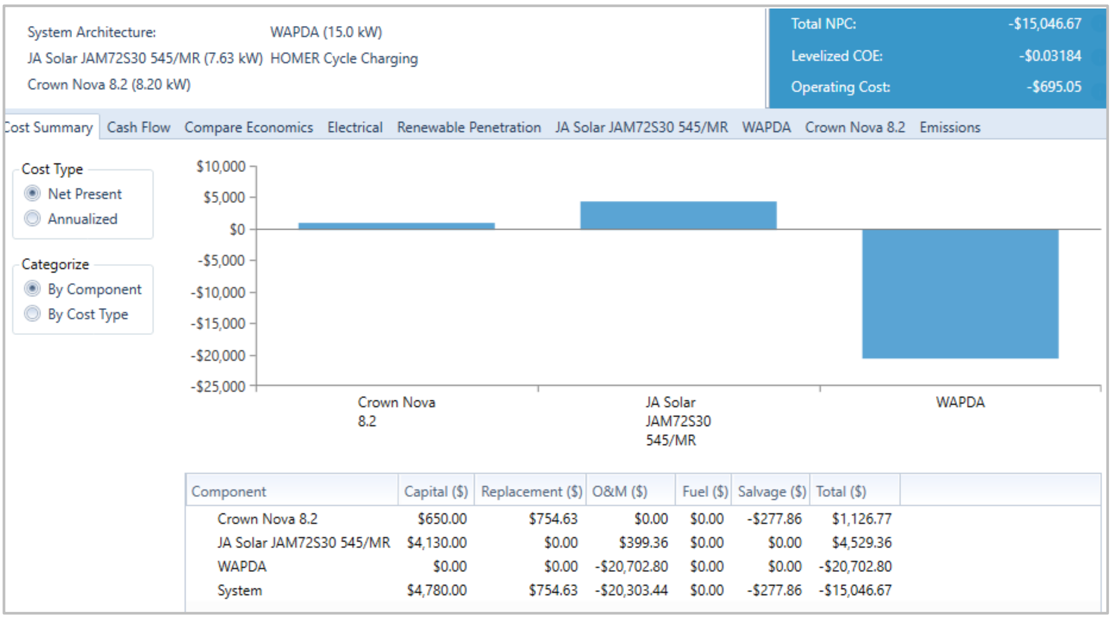

Fig. 19. Cost summary of the selected system.

Fig. 20 shows cash flow of the system for 25 years of time spam. The first year shows an initial investment and the next 14 years show revenue from utility company after selling extra generated energy. 15th year in this result shows replacement cost for inverter because projected life of PV inverter is approximately 15 years. The internal return rate (IRR) of this system calculated by homer pro is 23.7% with a return on investment (ROI) of 19.6% annually. This sums up a payback time of 4.2 years, which makes it an ideal project from an investment point of view. This Solar PV unit generates a revenue of 711 CAD annually with an initial investment of 4,780 CAD.

Global solar monthly average is shown in Fig. 21, which is an important parameter for the calculation of annual energy production of selected system. The average solar irradiance value cannot exceed the defined solar constant value of 1,367 W/m2 which is defined as the amount of solar light reaching to earth surface. Solar irradiance data shows that selected locations are enriched with natural solar light throughout the year.

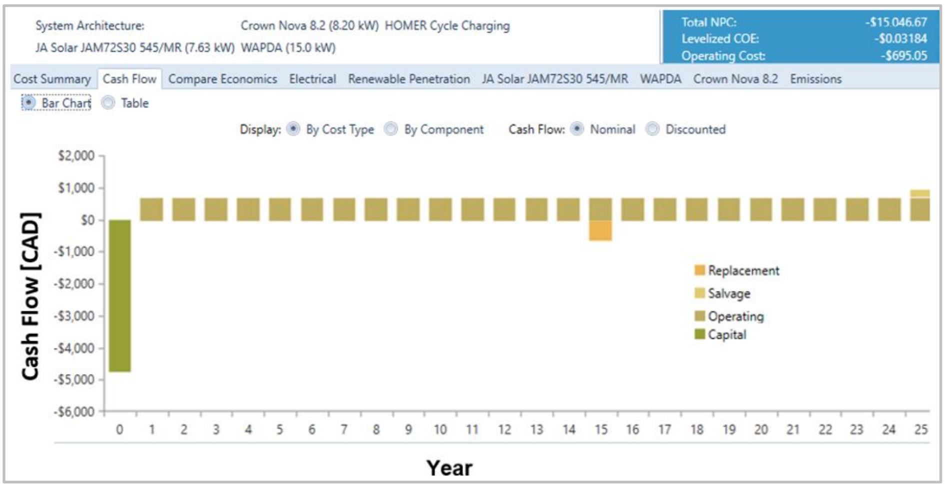

Fig. 20. Projected cash flow for 25 years.

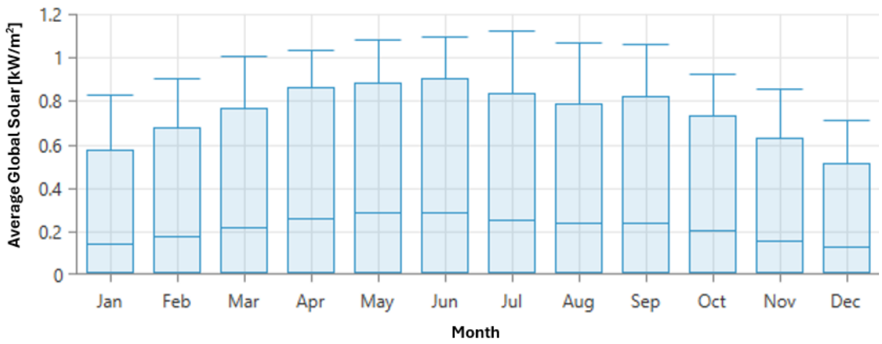

Fig. 21. Monthly average of global solar radiation.

Fig. 22 shows the annual energy graph of the system. Orange color indicates the energy imported from grid and green generation of solar PV unit.

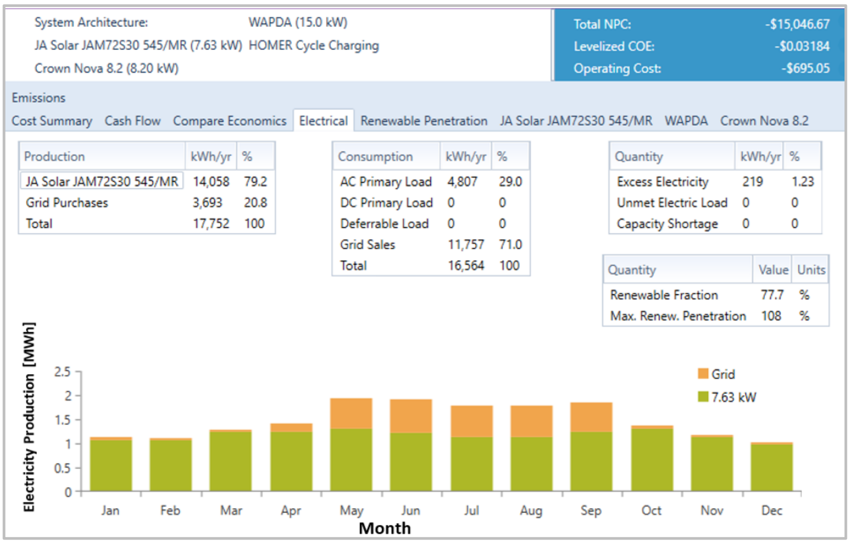

Fig. 22. Monthly electric production.

These results show that Solar PV system will generate 14,058 kWh annually which is way more that annual production results of SAM. Self-consumption of the house is 4,807 kWh annually which projects the true power consumption of the house. Fig. 23 shows energy purchase from grid and energy sold to grid throughout the year. Energy purchased from grid is more intense in summer because power consumption of the house is more during summer nights. Energy sold to the grid is intense in winter due to the same reason. House consumes less energy during winter and sales more to the grid.

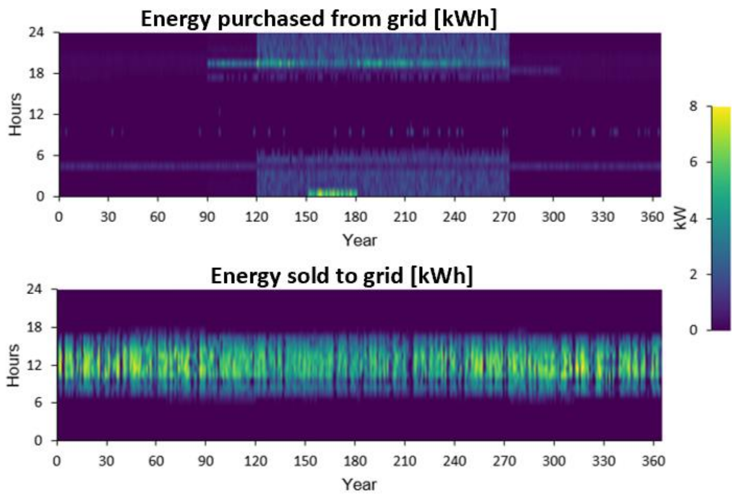

Fig. 23. Power grid import and export graphs.

Fig. 24 shows PV annual power output results of homer simulation. Total operational hours of this system are 4,385 hours/year with a capacity factor of 21 %. This sums up 14,058 kWh annually with a mean output of 38.5 kWh/day. PV penetration of this system in 292% with respect to self-load trend of the site. All these results make solar PV energy unit a reliable energy source for selected location.

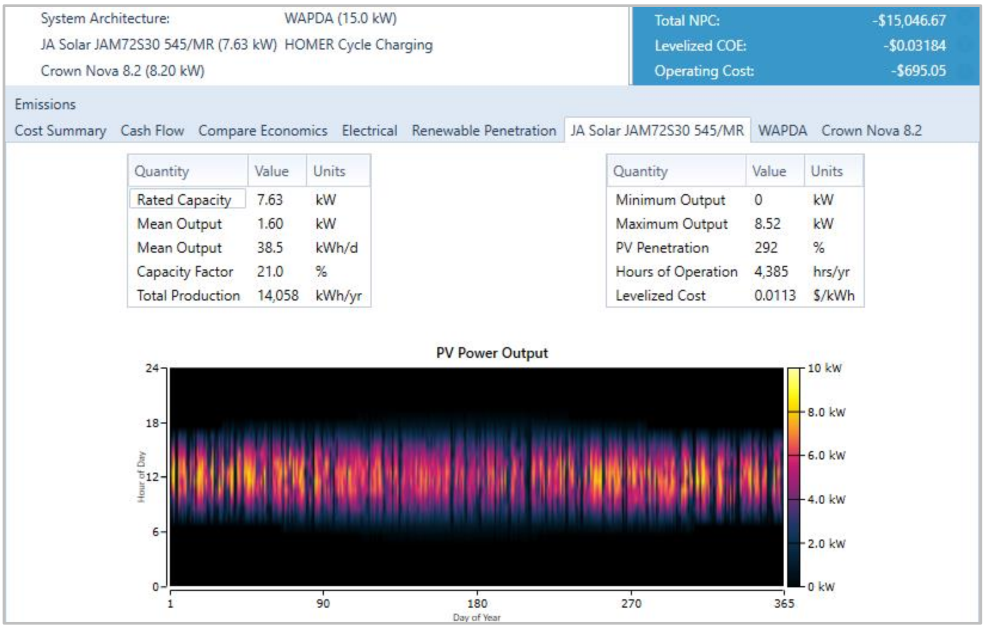

Fig. 24. Annual PV electric production.

3.4. Comparison of the Analysis Done by the Three Softwares

The decision to utilize multiple software tools, including Homer Pro, SAM, and REopt, in our study was driven by the need for a comprehensive and multifaceted analysis of the proposed solar PV system with battery backup. Each software brings unique capabilities to the table, allowing us to address different aspects of system design, performance assessment, and economic analysis. Homer Pro, renowned for its versatility, offers a robust platform for simulating hybrid renewable energy systems, facilitating rapid prototyping and scenario analysis. SAM, developed by the National Renewable Energy Laboratory (NREL), specializes in solar energy system modeling, providing detailed insights into energy production and financial viability. Lastly, REopt, also developed by NREL, focuses on optimizing renewable energy systems with energy storage, enabling us to identify cost-effective system configurations and operational strategies.

The inclusion of Homer Pro, SAM, and REopt in our study enhances the reliability and comprehensiveness of our analysis by leveraging the unique strengths of each software tool. By employing a multi-tool approach, we mitigate the risk of software-specific biases or limitations, ensuring robustness and consistency in our findings. Moreover, the use of multiple software platforms enables us to validate results across different simulation environments, enhancing the credibility and trustworthiness of our study outcomes. This approach also provides stakeholders with a more holistic understanding of the proposed solar PV system's performance, resilience, and economic feasibility.

Homer Pro: The annual production predicted by Homer simulation is 14,058 kWh for the 7.63 kW grid-tied solar PV system. This indicates the highest annual energy production among the three software tools used in the study. Homer Pro is known for its robust simulation capabilities and comprehensive modeling of hybrid renewable energy systems. Its ability to accurately predict energy production aligns with the observed high output in this case.

SAM (System Advisor Model): SAM results show an annual production of 10,620 kWh per year for the same system. While this is lower than the output projected by Homer Pro, SAM is widely recognized for its accurate modeling of solar photovoltaic systems and financial analysis tools. Despite a slightly lower energy production estimate compared to Homer Pro, SAM still provides valuable insights into system performance and economic viability.

REopt: The REopt analysis for the 7-kW system calculated an annual production of 8,813 kWh per year. REopt specializes in optimization algorithms for renewable energy and storage systems, aiming to identify optimal system configurations based on user-defined objectives. While the energy production estimate from REopt is lower than both Homer Pro and SAM, it offers unique optimization capabilities that contribute to a more thorough analysis of system design and operation.

4. CONCLUSIONS

The annual energy production estimates vary among the software tools, with Homer Pro predicting the highest output at 14,058 kWh per year, followed by SAM at 10,620 kWh per year, and REopt at 8,813 kWh per year. These variations highlight the importance of considering different simulation and optimization approaches to obtain a comprehensive understanding of system performance. SAM's energy production estimate aligns closely with the observed data from the PV inverter, indicating its ability to accurately model solar PV systems and factor in various losses. This underscores SAM's reliability in predicting energy production and assessing the financial viability of the system. Despite yielding a lower energy production estimate compared to Homer Pro and SAM, REopt offers valuable optimization capabilities for identifying optimal system configurations. By leveraging REopt's optimization algorithms, further enhancements in system design and performance can be achieved, contributing to long-term operational efficiency and cost-effectiveness. The discrepancies in energy production estimates emphasize the importance of thorough system modeling and analysis to ensure accurate sizing and performance evaluation. Integrating battery backup solutions, as suggested by the study, proves to be a viable approach for addressing grid outage issues and enhancing energy resilience. The proposed solar PV system with battery backup demonstrates promising economic returns, with a projected capital cost recovery within 5 years and significant cost savings of 40,882 CAD over the next 25 years of operation. These findings underscore the financial attractiveness of investing in `renewable energy solutions with energy storage capabilities.

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