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Optimal planning and modelling of the solar roof-top PV system with different incentive policy schemes for residential prosumers: a real-time case study

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Abstract

Renewable Energy Sources (RES) are essential for establishing a new trend in the Indian energy sector and developing sustainable energy sources. To reduce its reliance on fossil fuels and dispute climate change, while India as a whole has been promoting renewable energy sources (RES), including solar, wind, and biomass, individual states within India may have their own specific programs and initiatives tailored to their local needs and resources. In this case, the Tamil Nadu government has taken steps to implement initiatives aimed at promoting rooftop solar PV energy systems and RES potential specifically within the residential sector in the state. An optimal on-grid roof top solar PV 2 kW and 3 kW for residential system is designed with various incentive schemes based on the real time 50 residential buildings data at selected location Hosur, Krishnagiri, Tamil Nadu. Additionally, considering scenarios of two incentive policies, such as 30% and 50%, this research undertakes multiple techno-economic analyses. Additionally, here HOMER software (Hybrid Optimization Model for Electric Renewables) is employed for the design and implementation of the proposed system. Moreover, the optimal system has motivated to reduce total investment cost of proposed system, reducing purchasing energy cost, increasing selling energy cost. Therefore, the consequence of these two incentive policies shows that the Net Present Cost of 50% incentive scheme is $ 1,126.735 and Operating and Maintenance cost (O&M) is $ 101.998 are the best effective than 30% incentive scheme. Thus, the performance of each scheme is examined in the selected capacity of solar energy production in 2 kW is 3257 (kWh/yr) and 3 kW is 4885 (kWh/yr) for the residential load of total energy consumption is 3248 (kWh/yr) with lowest cost of energy is $ 0.26. Therefore, the proposed system under various policy incentive scheme is economically feasible according to the selected capacity which render that the emission level of CO_2 (1,213 kg/yr), NO 1.66 kg/yr, and SO_2 3.01 kg/yr, respectively.

Keywords Solar PV system · Techno-economic analysis · HOMER software · Incentive policies · Emission analysis

1 Introduction

Energy sources that can be consumed and replenished naturally without getting out are referred to as renewable energy sources. Innovative software tools, including HOMER, are being developed to determine the appropriate size and design of a renewable energy system for a residence or commercial organization based on energy consumption, location, and resource accessibility. Depending on the reliability and penetration of renewable energy sources, demand–supply management (DSM) and particle swarm optimization (PSO) are combined to optimize the system and minimize total net present cost (TNPC) utilizing the multi-agent system concept. In 2022, with 1177 gigawatts already in place, the addition of 239 gigawatts in just one year highlights the accelerating pace of adoption. The growth in solar photovoltaic (PV) capacity indeed signifies a significant shift in global markets towards renewable and distributed energy technologies. China and the United States have been at the forefront of this movement, leading the global PV market with substantial cumulative solar PV capacities. It's noteworthy that by 2021, China had amassed 307 gigawatts, while the United States had 122 gigawatts of cumulative solar PV capacity [1]. Explored Palestine's renewable energy potential and highlighting significant PV power generation capacity

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and varying wind energy densities across regions. Utilizing SAM software for biomass energy and proposes integrating renewable sources with the grid to reduce costs, generate income, and combat global warming by decreasing reliance on fossil fuels [2].

The potential of solar and wind energy technologies in semi-arid and arid regions, using Libya's climatic conditions as a case study. Various factors such as solar radiation, wind speed, and climate variability are analyzed to assess the viability of these renewable energy sources in the region. The findings contribute to understanding the feasibility and challenges of implementing solar and wind energy projects in similar environmental contexts [3]. Introduced a novel Hybrid Renewable Energy System (HRES) utilizing Stirling engine-powered dish solar concentrators and biomass digesters to provide sustainable electricity, heating, and cooking gas while addressing waste management, exemplified in Brack City, Libya, with promising technical and economic viability [4].

This research investigated the economic feasibility of 2-kWp rooftop PV systems in Indonesian cities, rooftop PV systems in Jakarta, Denpasar, and Kupang are currently economically unviable but could become profitable with a combination of installation incentives and increased NEM rates, suggesting the need for location-based incentive schemes to promote widespread adoption in Indonesia [5]. It examined the sustainability challenges of solar panel production and the lack of clear recycling strategies. And proposed an optimization framework for reverse logistics in Delhi to enhance the collection and recycling of end-of-life solar PV modules, aiming to maximize operating profits for collection centres and provide insights for effective PV waste treatment regulations [6]. This paper presents a robust IoT-enabled Smart Energy Management Device (SEMD) designed for Distributed Energy Resources (DERs) equipped consumers, facilitating cost minimization through sequential software modules and real-time implementation, validated via experimental testing [7].

This paper examines the influence of post-pandemic policies on photovoltaic technology adoption in Italy and Portugal, emphasizing differences in self-consumption schemes and energy community configurations, highlighting varying national approaches and their impact on PV system profitability [8]. This work offers a comprehensive overview of Battery Energy Storage Systems (BESS) in hybrid installations, emphasizing their role in Distributed Energy Resources (DERs), Demand Side Management (DSM), and controllable Renewable Energy Sources (RES), while identifying key research trends and gaps for future exploration [9]. A model for optimizing an integrated PV/CHP/battery/gas boiler hybrid energy system, considering EV charging, demand response programs, and net energy metering, showcasing superior performance in cost reduction, emission mitigation,

and resiliency enhancement validated through a representative multi-residential complex case study [10].

Proposed a hybrid off-grid energy system (HES) design using PV, wind, and diesel generators optimized with HOMER-Pro to effectively and economically power a quarantine COVID-19 center in Gaza, demonstrating significant cost savings and environmental benefits compared to diesel-only systems [11]. Designed and optimized a hybrid wind/PV solar power system using HOMER to meet the energy needs of the Libyan Center for Solar Energy Research Center (LCSERS), assessing its technical and economic feasibility, with the best scenario featuring a 5% capacity shortage and comprising a 20 kW PV system, a 25 kW turbine, and 72 Hoppecke batteries [12]. Investigated the sensitivity and control strategies of a hybrid PV/Wind/Diesel/Battery microgrid system using Typhoon HIL simulation, aiming to enhance understanding of renewable energy resources and optimize technical and economic factors in microgrid design [13].

Focused on leveraging renewable energy resources in Jenin Governorate, Palestine, utilizing System Advisor Model (SAM) and Hybrid Optimization of Multiple Energy Resources (HOMER) to design an 80 MW PV solar field, 66 MW wind farm, and 50 MW biomass system, ensuring energy self-sufficiency and addressing the region's persistent energy crisis with a minimal LCOE of 0.313 $/kWh Nassar, Yasser F et al. (2022). Proposed a Real-Time Photovoltaic (RTPV) system for Assuit University, employing Particle Swarm Optimization (PSO) for optimal sizing and validating economic viability against industry-standard software, showcasing the effectiveness of PSO in achieving superior system sizing for meeting future load demands Nassar, Yasser F et al. (2022). Proposed an optimal sizing procedure for a hybrid PV/Wind power system integrated with Pumped Hydro Storage (PHS) to provide sustainable electricity supply to an urban community in Brack City, Libya, demonstrating cost competitiveness and reliability in harnessing renewable energy resources [14].

Assessed the solar energy potential in the Gaza Strip, proposing urgent and long-term scenarios leveraging photovoltaic systems to alleviate the electricity crisis, reduce reliance on imported energy, and foster socioeconomic development in Palestine [15]. The study evaluated how demand-side management impact the balance of supply and demand for energy utilizing HOMER software and particle swarm optimization. According to bibliometric data, most studies used supply-side management strategies when developing renewable energy systems [16]. HOMER optimized and modelled a biogas producer, wind turbines, and solar panels. Furthermore, it is a dependable and cost-effective method for long-term remote rural electrification. Detailed economic research takes into account the levelized cost of

energy, payback period, and other economic aspects. It pertains to grid expanding and the off-grid hybrid power system [17].

An energy source that is dependable is created by combining solar, wind, and a diesel generator, maximizing non-traditional generation systems while lowering system costs overall. Simulated and investigated are standalone hybrid renewable energy solutions for an average ATM machine in remote places. Ideal response to the world's energy problem [18]. A hybrid PV/biomass design that is optimized for producing electricity for an agricultural facility and a residential area. Using HOMER software, load data for residential and agricultural demands are collected and assessed. The techno-economic analysis was carried out employing solar irradiance data and the presence of biomass potential, which takes into account sensitivity factors such as biomass potential, biomass costs, solar irradiance, and load improvements. Based on net present value and energy cost, the method is technically and economically viable [19].

The assessment of four different situations and comparison of the results with HOMER software show that the Genetic algorithm approach can produce a system that is more reliable and economical than HOMER. By taking into account a tiny possibility of power supply loss (LPSP), a reduction in the original cost of capital, operational costs, and COE. It is preferable to be supplied with some electricity than none at all in off-grid or rural places [20]. The consequences of alternative dispatch mechanisms employing the two main battery technologies (Lead Acid—LA and Lithium-ion) are examined in terms of the Cost of Energy (COE) and the Net Present Cost (NPC). When compared to the load following (LF) and circular charging (CC) approaches, the combined dispatch (CD) strategy has a much lower energy cost. The renewable fraction in load following is higher than in combined dispatch and cyclic charging systems but at the expense of additional energy [21].

Maintaining and decreasing the amount and cost of energy are required to fulfil the needs of a specific application require optimizing the size of components and implementing an energy management strategy (EMS). The system's reliability can be improved by including some variety of renewable energy sources, in addition for back up energy sources and storage devices. EMS is essential for system reliability, operational effectiveness, cost reduction, and prolonging the lifespan of energy storage devices. It is recommended that an energy management system (EMS) be developed to regulate the flow of energy between hybrid systems and loads that are either directly connected to these sources or connected to the grid [22]. The efficiency, stability, and response time of various control techniques for bidirectional DC-DC converters, including PWM, SMC, and PI control, are contrasted. Also describes some microgrid applications for bidirectional DC-DC converters. Five alternative scenarios that depict potential results of integrating renewable energy in an unreliable power sector and one in which dependability is considered to have been secured utilized to gather information of consumers about willingness to the payment for renewable energy sources [23].

In order to account for unmet electric consumption and excess power, the analysis focuses on the energy output and cost of energy from both wind turbines and solar sources in the hybrid system. It is critical to size the system components effectively for a wind/solar hybrid system to produce power at an economical price while meeting all electrical demands [24]. This included an explanation of the entire PV system sizing model and the analysis of the system's life cycle costs was used to do an economic evaluation. Residential off-grid PV applications are both technically and financially feasible [25]. In a PV-diesel-battery hybrid system, taking into consideration various scenarios increase efficiency and make it possible for the system to handle higher load demands, which improves efficiency. The performance of two decentralized power generators is examined, and outcomes show that load demand may be accomplished at the lowest total net present cost and levelized energy cost [26]. Three solar tracking models for off-grid residential PV power systems have been examined. The NPV and GHG reduction cost values improve in response to rising fuel cost inflation and project life, whereas the two values fall in response to rising discount rates. The solar tracking model for an off-grid solar hybrid power system is heavily influenced by economic and environmental considerations [27].

As the two best ideal system configurations, the PV-diesel-battery and PV-wind-diesel-battery systems are compared to the characteristic stand-alone diesel generator system. It highlights the beneficial environmental impacts of using hybrid systems to provide electricity in remote areas. Results of the sensitivity analysis and ideal system configurations are given. For all system configurations, HOMER performs hourly time series simulations to assess operational features including power output and load supplied [28]. It is recommended to use an effective framework for choosing the best site and size for off-grid PV-diesel installations. Comparative to other heuristic techniques, the framework is more accurate. The difficulty of determining 3 out the placement as well as the capacity of solar-diesel systems is addressed. Using a hybrid optimization technique, the best capacity for handling the load while reducing costs is determined [29]. The best stand-alone hybrid energy system combines PV, wind, diesel generator, and battery components. Implementing standalone hybrid renewable energy systems can offer an affordable and environmentally friendly approach to gaining access to electricity. The optimized system has lower net present costs, energy costs, and CO_2 emissions than a system that uses simply diesel. Any sightseeing opportunities and scattered locations in SCSM, as well as anywhere else

with equivalent climate circumstances, may use the created and evaluated HRES model [30].

The essential criteria influencing an island potential to acquire an increasing proportion of renewable sources are the configuration of the existing energy infrastructure, the presence of a reliable energy storage system, and the profile of the electricity demand. Successful system design depends on accurate demand data, evaluation of nearby renewable resources, and sufficient storage solutions. Photovoltaic/Diesel/ Battery systems are a perfect configuration for rural villages [31]. The viability of deploying PV systems as an alternative to freestanding diesel systems is investigated using HOMER software. Low finance expenses are also preferred for the general implementation of hybrid PV/diesel with battery systems at conventional diesel costs. Due to the high cost of diesel and transportation, standalone diesel systems are unsustainable. In emphasises with equivalent solar radiation levels, the effects of interest rates, diesel costs, and load sizes can be evaluated [32].

The cost analysis and feasibility study show that the hybrid renewable energy system is a viable and cost-effective choice for supplying RHC. The usage of renewable energy sources improves healthcare delivery in remote locations while increasing hybrid system dependability. The potential for renewable energy's quality determines the best system configurations [33]. The proposed approach can deliver an efficient and sustainable power source while satisfying an isolated island's energy requirements. Additionally, it decreases the dependence of rural communities on fossil fuels. In remote areas, transferring from diesel to energy sources with a high renewable energy penetration is growing ever more frequent. Combining solar and wind energy with battery storage is an inexpensive option for the remote island [34].

Electrical demand and renewable energy resource potential indicate the lowest cost and highest reliability of energy supply. By taking into account varying degrees of capacity shortfall and the percentage of unmet power requirements, various scenarios are offered. For analysis, MATLAB and HOMER software use real household data and historical wind speed data. The ideal power supply system combination is established by taking into account the operational reserve and various levels of MACS [35]. The SHS initiative has aided in the economic development of rural areas and a reduction of poverty. The scheme's funding, procurement, installation, and maintenance procedures are all included in the data that is provided. The income and standard lifestyles of the rural lower classes are significantly raised by PV technology. Private business owners, IDCOL, governmental organizations, and NGOs are building organizations solar PV systems in rural locations to address energy needs [36].

Off-grid systems have higher energy costs than on-grid systems because of a result of the system architecture. In a profit analysis, battery storage is more profitable than

hydrogen. After considering two occupancy situations and two storage possibilities, six hybrid systems, and 24 simulations were performed using the HOMER program and the configurations for each storage option were established. Hybrid energy technology's ability to supply off-grid vacation occupies with the energy required [37]. Data analysis on sunlight irradiance and wind speed are examined at for four significant cities in TRNC using the RET-Screen tool. The potential energy production can be estimated using the proposed hybrid model with NiMH battery. Additionally, 6 kW PV-wind hybrid systems appear to be more affordable than conventional grid-based systems. The method helps maintain an environment free of carbon dioxide (CO_2) emissions. The hybrid model is applicable worldwide for locations with various meteorological factors [38].

Economic factors and PV derating factors are used in sensitivity analysis to ensure sure the proposed HES is reliable and affordable for commercial use. Grid-integrated systems are more economically feasible than off-grid, and the LCOE of off-grid systems is much lower than the current government tariff. On the basis of cost analysis an ideal off-grid and grid-integrated solutions are recommended for best solution. A hybrid system is effective for commercial use and can deliver electricity continuously per day [39]. The efficiency of PV systems is influenced by meteorological elements like solar energy, air temperature, and wind speed. PV systems higher initial investment costs when compared to alternative energy sources are a disadvantage. It examines PV system inverter size optimization techniques such as Artificial intelligence techniques like genetic algorithms and artificial neural networks are being utilized to enhance optimization processes [40].

In comparison to the grid tariff, the grid-connected HES with the sell-back energy possibility is most economical and provides significant cost advantages. The standalone hybrid PV/diesel/battery system has marginally lowest net present cost and cost of energy when compared to the other sites. It is researched like how different sell-back prices affect the national grid as well as the environmental benefits of HES. It addresses the difficulties and opportunities of carrying out such initiatives in an off-grid location [41]. Utilizing renewable energy for electrical purposes is essential for enhancing the existence of rural populations due to the decreasing expense of renewable energy technology and government assistance for embedded generation. The HOMER tool is used to compare various locations for the capacity and life cycle cost of energy production in rural areas. It makes a possible to evaluate the potential and economic benefits of off-grid solar electricity [42].

It examines the technological, economical, and environmental aspects of hybrid power supply systems, where a fuel cells viability as a substitute for traditional energy storage technology is examined. Further research is being conducted

into whether price fluctuations in diesel fuel influence economic competitiveness. Due to investment expenditures, the PV hydrogen system offers a high cost of energy production; nevertheless, if fuel prices increase, the price becomes comparable with that of traditional diesel systems. Compared to conventional systems, hybrid systems tend to be more economically competitive [43]. PVHMS delivers superior 5 electrical services at a lower cost. PVHMS is exposed to a number of risks that exist such as inadequate system sizing, difficulties integrating the community, equipment compatibility problems, inappropriate economic models, and the threat of geographical isolation. There are known mitigation strategies for these concerns and significant concerns also include geographic isolation and a lack of community and social interaction. Risks that are frequently mentioned include load uncertainty, a lack of acceptable business strategies, and power quality concerns [44].

In the system financial viability, the effect of annual demand increase and government energy policies is explored, including loans with low interest rates, a tax on greenhouse gases, and changes to grid electricity prices. Based on individual PV panel, inverter, and wind turbine capacities, the ideal grid-connected configuration with the lowest COE is identified. It is possible to make a sizable number of systems economically feasible by raising the price of grid electricity. The system cost of electricity (COE) and the amount of renewable energy shows that the generated energy depends on the size of the solar panels, wind turbines, and batteries which are used [45]. Current TE approaches and companies that have made use of the demand-side adaptability of home prosumers are evaluated. It is emphasized the necessity of the TE framework for active pricing and trading of demand-side flexibility in residential networks. Future power systems with complicated grid-edge DERs and RES build LV distribution networks that distribute electricity to capacity-constrained residential neighbourhoods [46].

The HOMER tool was used to maximize the efficiency of a hybrid PV-wind-diesel system and a PV-wind-battery system for industrial applications, taking cost and energy consumption studies into account. The lowest feasible PV/wind/diesel/- battery electricity cost. The average total net current cost of the optimized systems varied between 3.9 and 9.9 million US dollars. It is suggested that a hybrid system be employed in other locations with comparable environmental conditions [47]. A genetic algorithm is used to optimize the sizing of grid-connected hybrid systems under varied charging and discharging circumstances. To improve system performance and efficiency, real-time price signals are used. Raising the RESC limit also reduces the overall energy cost of a grid-connected renewable energy system. For improved operation, the comprehensive solution seeks to combine and coordinate different components. The analysis considers various renewable energy system contribution

minimum values as well as various PEV charge states [48]. In 2023, India's total energy consumption was approximately 34,193 petajoules. This reflects the country's growing energy demands, driven by industrialization, population growth, and urbanization. Furthermore, the agricultural sector, while not the largest consumer of energy, plays a significant role in the country's energy profile. In 2021–22, it accounted for about 3–4% of the total energy consumption, primarily through electricity and diesel for irrigation, machinery, and other agricultural processes from Ministry of Statistics and Programme Implementation (MOSPI) [49]. Moreover, agriculture also contributes notably to air emissions in India. The sector is a significant source of methane and nitrous oxide, potent greenhouse gases, due to livestock digestion and rice paddies. Additionally, the burning of crop residues contributes to particulate matter and other pollutants, exacerbating air quality issues (MOSPI). Highlighting the energy use and emissions from agriculture underscores the importance of research in improving efficiency and sustainability within this sector, which can have far-reaching benefits for both energy conservation and environmental health.

The significance of the study using PV solar energy in particular, as it considered the ideal partner for renewable or/and other traditional energies in hybrid energy systems, which are considered the most widespread around the world because they are the most reliable and stable in producing energy from individual systems, such as: PV/Grid, PV/Wind, PV/Diesel, PV/CSP, PV/Wind/Diesel, PV/Wind/Battery.

2 Research gap

Based on the several analyses of having literature gap, there is a significant number of studies focusing on different optimization techniques, feasibility analysis, control strategies, and economic analysis that consider factors such as payback period, return on investment, and other relevant economic metrics of single residential solar PV systems and there is a lack of literature discussing their real-time implementation. Furthermore, there is a shortage of research that especially examines the effects of different incentive policies to advance RES in the residential sectors. The objective is to address the electrification challenges faced by rural areas during power outages and blackouts. This study requires to develop the optimum on-grid solar PV system for multiple residential households to overcome these problems in real time considering two incentive policies with ON grid and OFF grid, specifically targeting the reduction of consumption costs associated with household appliances using HOMER software. Moreover, Literature reviews and preliminary market analyses indicated that these incentive levels are likely to provide meaningful insights into cost reductions and feasibility enhancements. Also, the selected incentive levels are realistic

and feasible for government implementation which provides a balance between being substantial enough to encourage adoption and practical enough to be considered for policy-making.

2.1 Contributions

- To utilize the real-time data from 50 residential buildings in Hosur and Krishnagiri, Tamil Nadu, ensuring the analysis is accurate and relevant by reflecting actual energy usage patterns and local conditions.
- To examine the proposed system using HOMER for simulation and optimization is a sophisticated approach that enhances the precision and efficiency of system design.
- To provide valuable insights into cost reduction and economic feasibility by conducting a thorough techno-economic analysis of RES-based on-grid solar PV system capacity (2 and 3 kW) with two distinct incentive policies (30% and 50%) towards the financial viability of solar PV systems.
- To assess the environmental impact by lowering emissions and emphasize the importance of net-metering facilities of solar PV system with and without battery system.

2.2 Novelty

- Utilizing a real-time data from 50 residential buildings in specific locations (Hosur, Krishnagiri, Tamil Nadu) to design an optimal rooftop solar PV residential system.
- Conducting a comprehensive techno-economic analysis by considering two incentive policies (30% and 50%) to evaluate their impact on the viability of the rooftop solar PV system.
- Employing advanced simulation and optimization capabilities offered by HOMER to enhance the accuracy and efficiency of system design.
- Evaluating the economic feasibility of the rooftop solar PV system of 2 kW and 3 kW and the environmental impact by quantifying the reduction in emissions associated with the adoption of renewable energy technologies.

3 Real-time case study location and its res nature

In the selected location, the community-based residential system offers limited facilities for solar energy. As a consequence, the current study and the upcoming process include a variety of areas, such as the representation of the region of choice, home load information, weather forecasting data
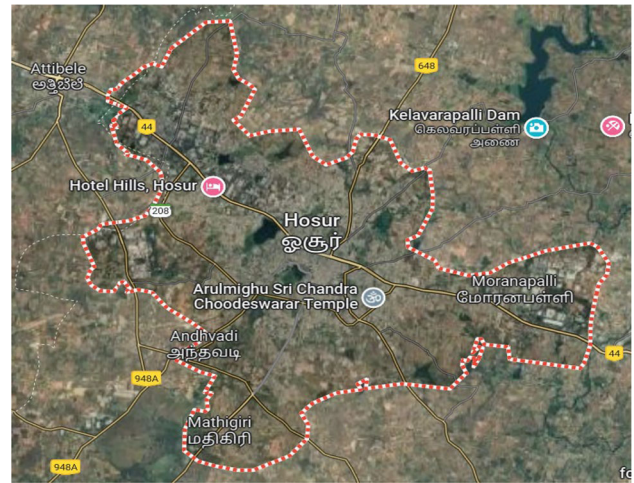
Fig. 1 Google map view for the chosen location

for solar and temperature, and electrical power consumption with daily and seasonal profiles.

3.1 Site location

The RES potential is taken out specifically using solar PV for the residential building in Hosur, situated at a Latitude of 12.735126^0N and a Longitude of 77.829338^0E, shown in Fig. 1. It possesses substantial solar potential due to its abundance of residential buildings by taking around 50 houses for a particular location in the selected site where some houses solar installation facilities, so which stimulate to make concern on the chosen location. The concept aims to establish solar photovoltaic systems as the primary energy source for residential use, particularly during periods when the grid is unavailable Fig. 1 shows the proposed system's layout for the specified location. The research carried out with the location selected indicates significant insolation power, global horizontal irradiance (GHI) and sunlight temperature have an instantaneous effect on the efficacy of solar PV panels. The location encompasses a variety of residential houses including single, double and triple bedroom hall kitchen (BHK) buildings are covered an almost 30 acres.

3.2 Solar GHI

Figure 2 depicts the proposed solar-based residence load systems of monthly Global Horizontal Irradiance (GHI) profile and clearness index. In order to design the system, the flat PV array panel output and the overall horizontal radiation are both determined by HOMER using solar GHI as an essential variable. The solar PV panels are designed to maximize solar energy within an annual average of 8.90 kWh/day and an annual insolation average of 5.61 kWh/m^2/day. Daily radiation and clearness index data, as well as the proportion of
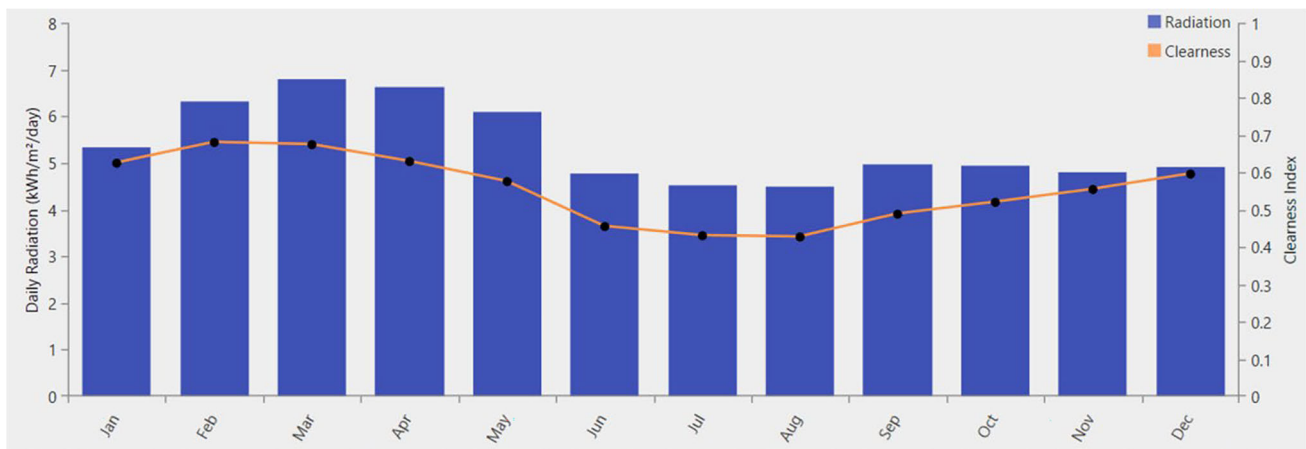
Fig. 2 The level of solar global horizontal irradiance for the selected site

solar energy that flows effectively through the atmosphere and on the outermost layer of the Earth, are gathered as confirmation of atmospheric clarity. Surface radiation reduced by extraterrestrial radiation produces the clearness index, a single-dimensional measurement with a range of 0 to 1. When the weather is clear and sunny, the clearness index has a higher value, whereas overcast conditions result in a lower value. This data confirms that the chosen location possesses a significant solar potential, enabling more efficient power generation. As a result, from June to January, when there is an absence of irradiance, a diesel generator (DG) is used as the primary source of energy generation.

3.3 Temperature

While consider about the temperature of monthly average range is obtained from the National Renewable Energy Laboratory (NREL) database and HOMER energy scheme, which is revealed about annual mean of 25.32 °C where the cell midpoint latitude is 9.75° and the cell midpoint longitude is 77.75°. According to the data is obtained from the HOMER software, the ambient temperature reaches about 30 °C in April and May whereas the PV cell temperature remains at 25 °C from June to March. Figure 3 illustrates the planned solar-based household load system daily variations in temperature.

3.4 Residential loads and analysis

Data regarding the real-time electrical loads of diverse residential, as well as consumer availability information, is collected from a specific location. The table provides an overview of various appliances considered in these studies, including their types, power ratings, durations (which can vary among consumers), and quantities. Among them, Electric heaters, washing machines, Induction stoves, geysers,

and Electric kettles are examples of high-power equipment that contribute to increased peak demand. To address these challenges, solar installations are being implemented to meet the load, mitigate power fluctuations, reduce gas emissions, and ensure uninterrupted power supply during outages and blackouts. Individual residence of daily energy usage is computed by partitioning the residential system according to their load requirements. The energy required for various types of units such as 1BHK units demands 14.72 kWh/day, 2BHK units require 17.137 kWh/day, and 3BHK units require 21.216 kWh/day. These statistics is established in accordance with the accessibility and usage trends. Also, Table 1 provides detailed information on the appliances considered, including their types, power requirements, duration, and varying quantities and these factors may vary from one consumer to another.

3.4.1 Electrical load consumption

Electrical load consumption in remote rural areas can vary greatly depending on the specific region, socio-economic factors, and access to energy resources such as grid connection or solar power. Residential building located of selected area often lack reliable electricity infrastructure, resulting in limited access to power supply. Due to challenges in extending power grids for such places required continuous power supply. Therefore, off-grid solutions like standalone solar systems or grids may be employed. Electrical load consumption may vary seasonally and the performance study is based on the solar radiation to ensure the reliability and security of the power supply. The HOMER software programme, which permits thorough examination and optimization of solar energy systems, can be used to achieve this. By analysing solar radiation data, the software aids in determining the feasibility and efficiency of solar power generation, facilitating reliable and sustainable energy solutions. In the process, the
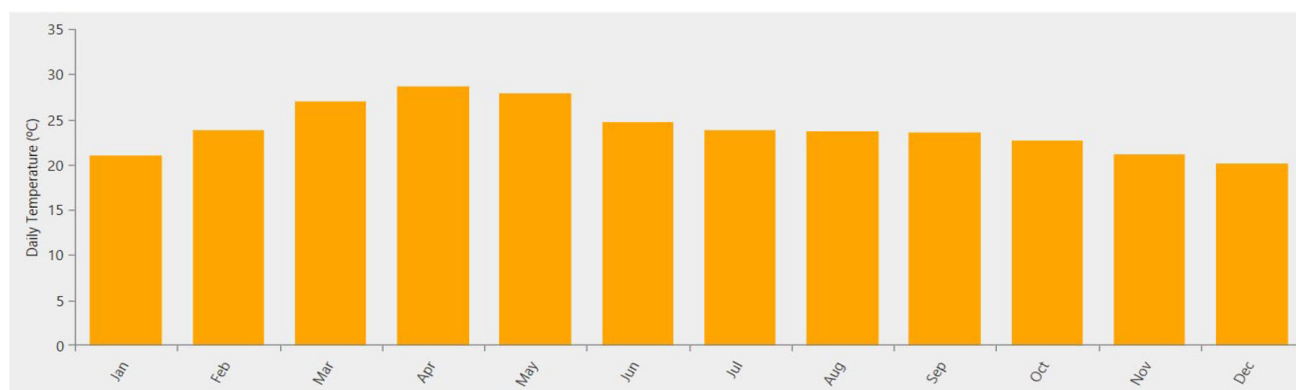
Fig. 3 The temperature level for the selected location

Table 1 Residential household load parameters

Categories of devices	Power (kWh)	Duration (Hour)	Quantity
Electric heaters	1.5	00.00–01.00	2
Air conditioners	1.95	00.00–05.00	2
Fans	0.031	00.00–14.00	5
lamps	0.42	00.00–11.00	2
Tube light	0.04	00.00–12.00	4
Induction stoves	2.00	00.00–03.00	1
Refrigerators	0.127	00.00–14.00	1
Washing machines	2.1	00.00–01.00	1
Dryers	1.8	00.00–01.00	1
Wet grinder	0.75	00.00–01.00	1
Television	0.1145	00.00–10.00	2
Geyser	2.0	00.00–03.00	2
Laptops	0.05	00.00–01.00	2
Mobile chargers	0.004	00.00–05.00	4
Electric kettles	2.0	00.00–01.00	1
Microwave oven	1.2	00.00–02.00	1
Water purifier	0.30	00.00–01.00	1
Mixie	0.75	00.00–01.00	1

HOMER tool estimates the overall load by comparing the default baseline with the optimized scaled average kilowatt per day.

3.4.1.1 Daily load profile A daily load profile of residential electricity consumption reflects the typical pattern of energy usage by households throughout the day. Furthermore, the peak demand typically occurs at 6 pm of 1.63 kW due to several factors. Additionally, during an evening hour, there is simultaneous enhancement in the usage of multiple electrical appliances and devices for residential areas which depicted in Fig. 4. As a result, a daily load profile for the residential system with a scaled annual average of 8.44 kWh/- day and an initial annual average of 16.56 kWh/day is established. During morning hours, there will be higher energy consumption for lighting, heating appliances and small kitchen appliances. Energy consumption is generally lower during the daytime as occupants are often away at work or school. Energy demand rises as residents return home, resulting in increased electricity usage. Depending on the season and climate, there may be a higher demand for cooling or heating appliances. Energy consumption gradually decreases during the night time, and usage of lighting, entertainment devices, and major appliances is typically reduced during sleeping hours.

3.4.1.2 Seasonal profile In terms of seasonal electricity consumption for residential loads, exhibits higher energy consumption for some particular months, while the remaining months demonstrate a moderate level of consumption. Figure 5 depicts the typical consumption of solar radiation for residence loads based on the monthly average in the mentioned city. The HOMER software is used to assess the whole load while comparing it to the standard compared with the optimum scaled average kilowatt per day. It shows how temperature and sunlight irradiation work together to support the load. During the summer, the quantity of energy necessary to meet the load from sunlight increases. The annual load is 2.32 kW, the daily minimum load is 16.56 kWh/day, the average load is 1.2 kW, and the load factor is 0.52. User-defined load profiles for weekdays and weekends have taken into account, and the software utilizes these inputs to forecast loads for an entire year.

4 Mathematical representation

In the present study, the following framework is adopted. The subsequent workflow encompasses a comprehensive system component modelling, specifications of the selected location,

Fig. 4 The daily load profile of electricity consumption for residential purposes
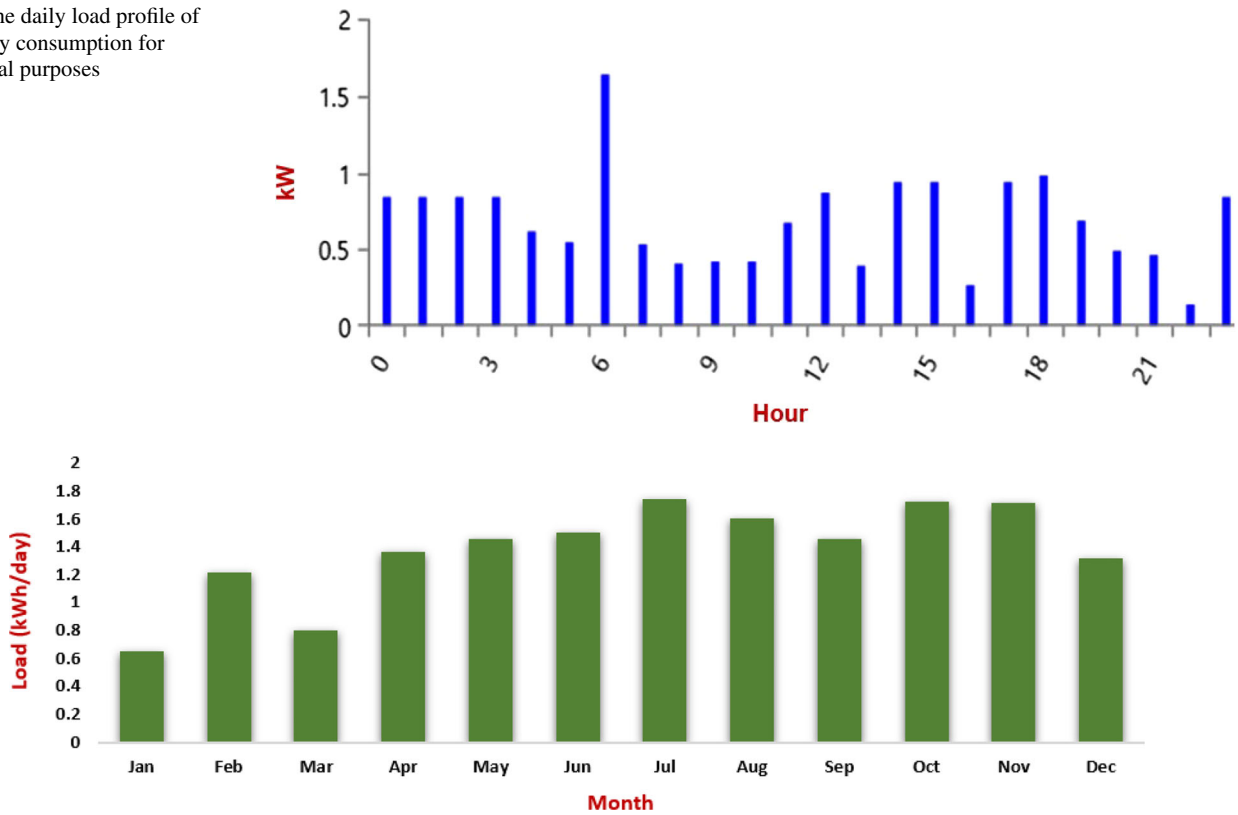

Fig. 5 The average load profile on a monthly basis

electrical load specifications, as well as meteorological data pertaining to solar irradiance and temperature.

4.1 System modelling

The parameters for various components, including Solar PV, Utility, Battery and Converter, are gathered from the residential solar-based optimal system. Additionally, each component for the proposed system is connected together for an on-grid and off-grid cases are shown in Fig. 6.

The installation cost of a 1 kW on and off-grid solar PV system in Tamil Nadu, India, is $ 950 when local costs are taken into consideration. To promote the consumption of solar energy, the government of India then provides a 40% subsidy. Therefore, this study carries 2 kW and 3 kW solar PV system is considered and entered into the HOMER software. HOMER software is implemented for analysing every aspect of the project in order to maximize both technical and economic advantages. Moreover, the initial cost of each component such as 1 kW of solar is $ 487.66, 1 kW converter is $ 231.64, and 1 quantity of battery is $ 170. Also, the initial cost, O&M cost for all component cost of technical specifications are outlined here in Table 2. Moreover, the capacity parameters of each component for the proposed system with
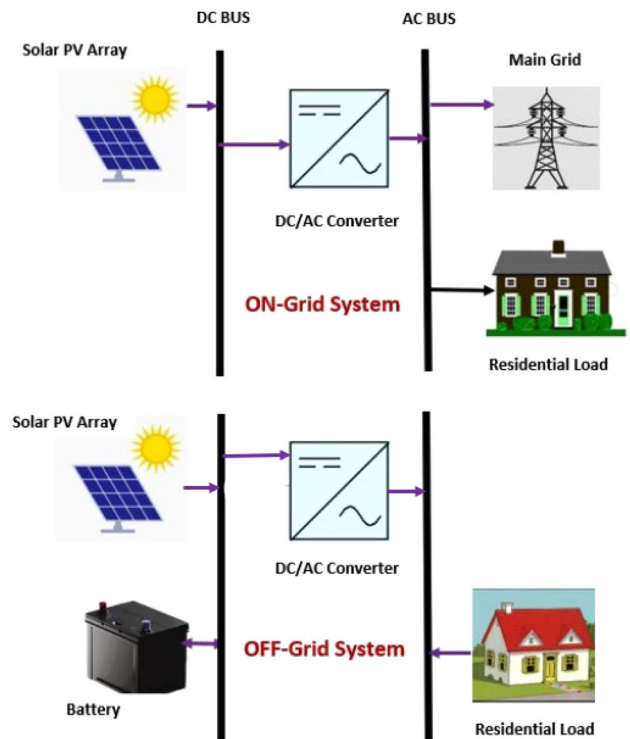

Fig. 6 The block diagram of the proposed system components

Table 2 Equipment cost parameters

Parameters		Components	
Capacity	Initial cost ($)	O & M ($/year)	Lifetime (years)
Solar PV- Canadian solar 320CS6U-320 M			
2 kW	$976.205	$709.870	25
3 kW	$1,464.308	$788.744	25
Converter			
2 kW	$463.697	$630.995	15
3 kW	$695.546	$709.870	15
Generic 1kWh lead acid			
Quantity (1)	$170.836	$236.623	10

following ratings are mentioned in the below Table 3. Moreover, prices are considered one of the sources of uncertainty in the results, as [1] indicated, there is a variation in the prices of solar energy equipment and devices amounting to about 360%.

4.1.1 Solar

When the grid decreases, the PV system continues functioning and generates electricity from sunlight based on the surrounding climate. The solar PV system has a 25-year expected lifespan with capacities of 2 kW and 3 kW. To supply the power needed, a battery along with a diesel generator is employed sequentially. The Canadian Solar 320CS6U-320 M system is high efficiency which ensures maximum energy production per unit area. Also, this is crucial for optimizing the output of the solar PV system particularly in areas with limited roof space with a capacity of 2 kW and 3 kW, has been set up. Moreover, this model offers a good balance between cost and performance which are the lower initial investment and operational costs help in achieving a better return on investment. Using high efficiency modules like the 320CS6U-320 M helps in reducing the carbon footprint and promoting the use of renewable energy. Thereby, its high efficiency and reliability make it suitable for meeting the load demands and achieving desired energy output. It consists of maximum power of 320 W with an efficiency of 13% and operating temperature of 44.20C. Furthermore, the name plate voltage is 45.60 V and the current is 9.13 A for throughout the year of 25 years with 85% derating factor. Additionally, Each Canadian Solar 320CS6U-320 M module typically has dimensions around 1.96 m in height and 0.992 m in width, with a thickness of around 40 mm. Before proceeding with the implementation process for the location, it is important to consider the specifications and preliminary steps. When attempting to do this, the quantity of required

Table 3 Technical specifications of the proposed system [50]

Component	Factors	Parameters
Solar PV	Rated capacity (kW)	3
	Rated power (W)	320
	Derating factor (%)	85
	Temperature coefficient (°C)	− 0.407
	Operation temperature (°C)	44.2
	Efficiency (%)	13
	Vmp (V)	37.4
	Imp (A)	8.57
	Voc (V)	45.8
	Ioc (A)	8.99
Battery	Nominal capacity (kWh)	1
	Nominal voltage (V)	12
	Maximum capacity (Ah)	83.4
	Round trip efficiency (%)	80
	Capacity ratio	0.403
	Maximum charge current (A)	16.7
	Maximum discharge current (A)	24.3
	Maximum charge rate (A/Ah)	1
	Rate constant (1/hr)	0.827
Converter	Relative capacity (%)	100
	Inverter efficiency (%)	95
	Rectifier efficiency (%)	95
Diesel generator	Rated power (kW)	40
	Running minimum hours (h)	9500
	Minimum load ratio (%)	25

output power must be determined based on aspects such as total area, panel area, and total number of panels.

Using entire inputs obtained from the solar resource page where HOMER utilizes Eq. (1) to calculate an output solar PV power.

$$P_{\text{PV}} = Y_{\text{pv}} f_{\text{pv}} \left(\frac{\overline{G_T}}{G_{T,\text{STC}}} \right) \left[1 + \alpha_P \left(T_c - T_{c,\text{STC}} \right) \right] \quad (1)$$

where, Ypv represents PV-rated capacity (kW). fpv represents PV derating factor (kW). GT represents PV array solar incident radiation (kW/m^2). GT,STC represents standard test conditions of incident radiation (1 kW/m2). αP represents temperature power coefficient (%/ °C). Tc represents cell temperature of PV (°C). TC, STC represents standard test conditions of PV temperature (25 °C).

PV modeling: The real power (P_{PV}) of the PV panel under real operation and climatic conditions is in Eq. (2)

$$P_{\text{PV}} = P_{\text{STC}} \left[1 + \beta_p (T_{\text{cell}} - T_{\text{STC}}) \right] \frac{H_t}{H_{\text{STC}}} \quad (2)$$

where: T_{STC} and T_{cell} are the celll's surface temperature at Standard Test Condition, β_p is the power temperature coefficient. The challenge that researchers will face is to find an empirical Eq. (3) to determine the cell surface temperature T_{cell}.

$$T_{cell} = T_\infty + 7.8 \times 10^{-2} H_t \tag{3}$$

4.1.1.1 Converter A generic system converter is an item of equipment that converts alternating current (AC) to direct current (DC) which selected in HOMER. The HOMER software can immediately model both solid-state and rotor converter. The inverter capacity of the converter, which specifies the largest amount of AC power it can produce from DC electricity, determines the converter's size. The relative capacity of the rectifier input is 100%, and the inverter's lifespan efficiency is 95% with the relative capacity of 100%. It also determines the maximum alternating current power that can be rectified to generate DC power. The continuous inverter and rectifier capabilities can sustain the load for however long is required. Other power sources and the converter may operate together in parallel. For converting electricity in HOMER, it needs the converter capacity rating of the proposed system. The capital cost, O&M cost, replacement costs, and expected lifespan in years are among the economic characteristics of the converter. The converter of the proposed system has a capacity of 2 kW, while CEC component provides 3 kW at a nominal voltage of 208 V. Also, an inverter-based source output power is calculated using this Eqs. (4) and (5)

The inverter-based source output power is calculated as follows:

$$P_t^{out\_inv} = P_t^{in\_inv} \times \eta^{Inverter} \tag{4}$$

$P_t^{out\_inv}$ represents output power of inverter (kW). $P_t^{in\_inv}$ represents input power of inverter (kW). $\eta^{Inverter}$ represents Inverter efficiency (%)

$$P_{inv}(t) = \frac{P_l^m(t)}{\eta_{inv}} \tag{5}$$

4.1.1.2 Battery While coming into the battery specifications which have multiple models in HOMER tool and each model battery as a device with a specific capacity and fixed energy efficiency. The batteries have limitations on charging, discharging rates, and total energy cycling before replacement. HOMER assumes consistent battery characteristics over time, unaffected by environmental factors. The anticipated life of the battery bank is based on electrical cycles, irrespective of cycle depth. In order to preserve more energy produced by the PV system, the estimated performance of the

solar system battery is examined. An appropriate battery storage capacity is required to limit power consumption during system blackouts and breakdowns, as well as to reduce solar heat absorption during the winter. A generic 1kWh lead acid battery kinetic battery model with a nominal voltage of 12 V and a nominal capacity of 1 kWh is used for this purpose. The battery maximum capacity is 83.4 Ah, the maximum charge power is 16.7 A, the maximum discharge power is 24.3 A and the maximum charge current is 16.7 A, and the maximum trip efficiency is 80% with maximum charge rate of 1 (A/Ah), rate constant is 0.827 (1/hr), and the capacity ratio of 0.403, Furthermore, the chosen battery 12 V capacity indicates that its initial state of charge (SOC) is 100% and that the minimum SOC is 40% in order to keep the power supply functioning for ten years. Excess solar energy is stored in a battery and used as necessary. Equation (6) is used in this study to solve the excess power produced by the PV panels that is stored in a battery. The computation takes both the contribution from primary actuators and the additional power from batteries into account. Excess solar energy is stored in a battery and used as necessary. Equation (7) is used in this study to solve the excess power produced by the PV panels that is stored in a battery. The computation takes both the contribution from primary actuators and the additional power from batteries into account.

$$Q_{Bat} = Q_{Bat,0} + \int_0^t V_{Bat} I_{Bat} \, dt \tag{6}$$

Q_{Bat} represents battery charge (kWh). $Q_{Bat,0}$ represents initial battery charge (kWh). V_{Bat} represents battery voltage (V). I_{Bat} represents battery current (A).

The battery state of charge (SOC) can be determined using the following formula:

$$SOC(\Delta t) = SOC(0) - \frac{\int_0^{\Delta t} \xi p(t) dt}{E_{ESS,\ rated}} \tag{7}$$

where, $\xi = \begin{cases} \xi c \, p(t) < 0 \\ \frac{1}{\xi d} \, p(t) > 0 \end{cases}$

The battery power which denoted as p(t) is exhibits negative values during the charging process and positive values during the discharging period. EESSrated, represents the nominal energy capacity, Δt signifies the charge and discharging time, ξc and ξd represents the efficiency of charging and of the battery. Therefore, the modelling of the battery for the energy storage in terms of SOC and its output is using Eqs. (8) and (9).

$$oC(t) = SoC(t-1).(1-\sigma)$$
$$+ \left((P_{PV}(t) + P_{WT}(t)) - \frac{P_L(t) + P_{EV_{Dem}}}{\eta_{inv}} \right) \times \eta_b \tag{8}$$

$$\text{SoC}(t) = \text{SoC}(t-1).(1-\sigma)$$
$$+ \left(\frac{P_L(t) + P_{\text{EV}_{\text{Dem}}}}{\eta_{\text{inv}}} - (P_{\text{PV}}(t) + P_{\text{WT}}(t)) \right) \times \eta_b$$
$$(9)$$

4.1.1.3 Utility A proposed method is connected to the grid in order to deal with limits such as cloudy weather and power fluctuations, as well as to enable the export of excess solar energy. A parameter analysis of a standalone solar PV system is used to establish the parameters of the overall load. The energy tariff for utilizing power from the utility in the chosen locations of the proposed system has two incentive policies such as 30% of 2 kW is \$ 0.055and 3 kW is \$ 0.11and 50% of 2 kW is \$ 0.055 and 3 kW is \$ 0.17. Additionally, there is a Grid power price of 4.500 per kilowatt hour and a Grid Net excess price of 4.500 per kilowatt hour.

4.2 Economic analysis modelling

Carbon emission calculations, electricity costs, net present costs, and cost minimization are all included in the HOMER economic analysis representations. These measures contribute to evaluating the long-term financial viability and profitability of renewable energy projects. It is feasible to examine the cost-effectiveness of alternative system configurations, maximise the financial benefits by maximizing the amount and mix of renewable energy technology, and reduce energy costs by using HOMER's economic analysis modelling. These renders are possible to develop and implement the renewable energy systems with informed decision-making.

4.2.1 Net present cost

It involves to calculate the present value of cost and benefit over a specified time frame. The NPC analysis considers factors such as initial investment, operational costs, revenue streams, salvage value, and discount rates. By comparing the cost present value that benefits, the NPC analysis determines if a project is economically viable. A positive or zero NPC value suggests financial feasibility, while a negative value indicates potential financial challenges. Equation (10) is utilized for converting single investments into annual costs with the objective to get the overall annual real discount rate in HOMER. The nominal discount rate and the average inflation rate represents as input which is given in Eq. (11).

$$r' - n \div 1 + n \tag{10}$$

"r" represents the real interest rate. "$r0$" represents the nominal discount rate. "n" represents the normal inflation rate.

Initial capital costs, replacement costs, operation & maintenance costs, and diesel demands belong to the list of economic costs in HOMER. Equation (12) gives these lists.

$$\text{NPC} = \text{CCF0} \div (1+r)0 + \ldots \ldots \text{CCF}n \div (1+r)n \tag{11}$$

"CCF" represents the Capital Cash Flow. "NPC" represents the Net present cost (USD). "n" denotes lifetime of the project or work. "r" represents discount rate.

4.2.2 Cost of electricity

The COE evaluates the financial viability for different electricity generation technologies and it considers factors such as capital costs, operational expenses, fuel prices, and expected energy output. By comparing the COE of various options of decision-makers can select cost-effective and sustainable energy sources. The modelling helps identify cost drivers and optimize project economics. It guides the transition to affordable and environmentally friendly energy systems. The average cost per kilowatt-hour (kWh) for the system has been referred as the COE. The method mentioned in Eq. (12) is used to determine the COE.

$$\text{COE} = \frac{C^{\text{Annual}}}{P^{\text{Demand}}} \tag{12}$$

C^{Annual} is total annual NPC that is represented by:

$$C^{\text{Annual}} = \text{CRF} \times \text{NPC} \tag{13}$$

The Capital Recovery Factor (CRF) in Eqs. (13) and (14) is designated as follows:

$$\text{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{14}$$

N represents project life time (year), i represents annual interest rate (%).

4.3 Objective functions and constraints

The principle behind a recommended solar PV system for the location selected states that the main function of the problem of the optimization of two different steps is to help minimize the present value and energy costs.

4.3.1 Objective function: minimizing TNPC

The goal is to identify strategies that minimize overall costs while maintaining desired performance levels. It involves using advanced techniques to assess and optimize various factors, such as investment costs, operational expenses, and

maintenance 18 costs. By analysing different scenarios and using optimization algorithms, decision makers can make informed decisions that lead to improved financial performance and competitiveness.

The sizing of the problem is to minimize the total net present cost (TNPC) and which is obtained from the optimization problem of using number of PVs, battery, grid, converter (NP V, NBat, NGrid, NConv) are the decision variables and Net present cost of PV, battery, grid and converter (NPC_{PV}, NPC_{Bat}, NPC_{Grid}, NPC_{Conv}). Therefore, the objective function is mentioned using below Eq. (16) respectively.

$$\text{Min. TNPC } \left(N_{PV}, N_{Bat,} N_{Grid}, N_{Conv}\right)$$
$$= NPC_{PV} + NPC_{Bat} + NPC_{Grid} + NPC_{Conv} \tag{15}$$

4.3.1.1 Constraints The following constraints for the related optimal system components towards the categories of maximum number of PV, battery, grid and converter (NPVmax, NBatmax, NGridmax, NConvmax) are explained here in Eqs. (15), (16), (17), (18), and (19).

$$0 \leq N_{PV} \leq N_{PV,\,max} \tag{16}$$

$$0 \leq N_{Bat} \leq N_{Bat,\,max} \tag{17}$$

$$0 \leq N_{Grid} \leq N_{Grid,\,max} \tag{18}$$

$$0 \leq N_{Conv} \leq N_{Conv,\,max} \tag{19}$$

5 Methodology

The proposed system is having the main concept of two scenarios under two different incentive policy to optimize the cost as well as energy level. Therefore, the following, limitations, assumptions and uncertainties, scenario related concepts, incentives policies details, two solar PV capacity cases are discussed below.

5.1 Limitations, assumptions, and uncertainties

While the study provides valuable insights into the techno-economic feasibility of on-grid rooftop solar PV systems under specific incentive schemes, it is essential to consider the limitations related to data specificity and technology constraints, assumptions about energy prices and load profiles, and uncertainties due to market dynamics, regulatory changes, environmental factors, and economic conditions. To simplify the analysis, the following points are considered:

5.1.1 Limitations

Data Specificity: The study's findings and conclusions from real-time data on 50 residential buildings in Hosur, Krishnagiri, Tamil Nadu, may not be directly applicable to regions with differing climatic, economic, or social conditions.

Technology Constraints: The analysis is specific to the Canadian Solar 320CS6U-320 M PV technology and HOMER software, and other technologies or software may produce different results.

Incentive Schemes: The study analysed only two incentive schemes (30% and 50%), and other potential incentives or combinations might yield different economic benefits and feasibility.

Grid Reliability: The study's assumption of stable grid availability means its results might differ significantly in regions with unreliable grid access.

5.1.2 Assumptions

A Fixed Energy Prices: The analysis assumes static energy purchase ($0.11/kWh) and selling prices ($0.17/kWh). Any future fluctuations in energy prices could impact the economic feasibility of the system.

Constant Load Profile: The load profile of the residential buildings is assumed to be constant over the analysis period. Changes in consumption patterns could affect the system's performance and economic outcomes.

Incentive Policy Implementation: It is assumed that the incentive policies will be implemented as described and will remain consistent throughout the system's operational period.

Technological Performance: The performance parameters for the solar PV, inverters, and batteries are assumed to be consistent with the manufacturer's specifications and remain stable over time.

5.1.3 Uncertainties

Market Dynamics: Future market conditions, including changes in technology costs, energy prices, and availability of incentives, are uncertain and could significantly impact the projected outcomes.

Regulatory Changes: Potential changes in government policies and regulations on renewable energy incentives and grid integration could impact the feasibility and attractiveness of the proposed systems.

Environmental Factors: Variability in weather conditions and environmental factors can affect solar PV performance and energy generation, introducing uncertainties in energy yield estimates.

Economic Factors: Economic factors such as inflation, interest rates, and currency exchange rates could affect the capital and operational costs, altering NPC and LCOE.

5.2 Scenario-based studies

While considering the optimal system of proposed work examines different incentive policies to enhance the penetration rate of Renewable Energy Source (RES)-based grid connected with battery storage system.

In several researches fails to consider NPC, COE and policies of incentives for developing countries. Therefore, the current study determines the problem to overcome through incentive policies as well as segregate different kilowatt solar PV system in the selected site Hosur because of highly utilization of renewable energy source. Therefore, the scenario-based incentive policies for two RES categories of with and without battery system are optimized used HOMER software as shown in Fig. 7. Moreover, the various policies and RES capacities with on-grid and off grid for with and without incentive scheme are discussed below.

5.2.1 Scenario 1: without incentive policy schemes

When comparing the amount of utilizing electrical power from the grid during the shortage of solar renewable energy and the present performance of the greatest purchasing cost for the load consumption benefits is revealed. Therefore, if there are no incentive policies, implementing solar PV on-grid system for residential building still can be economically feasible due to some following reasons below,

- Cost savings: As generating individual energy to prevent higher tariff slabs, then the solar energy may substitute a significant portion of the energy used from the grid which leads to the reduction of electricity costs.
- Net metering: The capacity of surplus energy from residence rooftop solar power plants back into the grid helps to minimize electricity costs and maximize Return on Investment (ROI).
- Increasing electricity prices: Due to enhancing electricity prices tends to invest solar PV system to protect future price hikes by fixed cost for their energy generation.
- Environmental benefits: By installing solar PV system, house owners can contribute to reduce carbon footprints and promote a more sustainable energy future.
- Self-consumption potential: Consumers can contribute to reducing carbon footprints and advance an environmentally friendly energy future by installing solar PV systems.

While specific incentive policies can provide additional financial support a make solar installation more affordable, an inherent economic benefits of solar PV system such as long-term savings, net metering, and protection against rising electricity prices, can still make them financially attractive for residential buildings in Tamil Nadu even in the absence of such policies. Therefore, the above reasons are induced to move towards some incentive categories for the concern of cost enhancement in the residential building which will be discussed below in the second scenario.

5.2.2 Scenario 2: with incentive policy schemes

Consider the consequence of RES penetration for the estimated system study has including three incentive policy criteria such as,

A. Reduce the investment cost for the proposed system component
B. Decrease the utility purchasing cost
C. Increase the utility selling price

Additionally, the investigation of these three incentive policies has different cases including selected on-grid solar PV system of 2 kW and 3 kW with and without battery system of each capacity. Moreover, having the concern of reducing the cost of entire system is the reason to move towards the two case of RES penetration such as (a) A 30% of RES penetration level and (b) A 50% of RES penetration level of 50%. Thereby, designing and implementing an optimal solar PV ON-grid system for residential buildings in Tamil Nadu can help reduce energy costs and avoid moving to higher tariff slabs and each unit consumers rate is shown in Table 4. Additionally, solar PV systems produce power from sunshine that can be employed to reduce the amount of grid energy that is consumed. This comprehensive description of each scenario will be addressed above. When meeting towards the load demand in the consideration of the proposed solar PV system for the residential building at the location of choice required an uninterrupted supply of electricity. Additionally, the concept of choosing incentive policies is investigated by the help of renewable energy solar capacities to reduce the power fluctuation during power blackouts and outages. Meanwhile, the incentive scheme for the RES penetration rate of 30% and 50% having the range of 2 kW and 3 kW solar PV capacity benefits of economic, environmental and emissions analysis are determined in the upcoming result outcomes.

6 Results and discussion

Though, the reasons of validating energy analysis and cost analysis to determine the best feasible solution of estimating the cost of all equipment, energy generation and production, emissions values. Moreover, the discussion will be based on
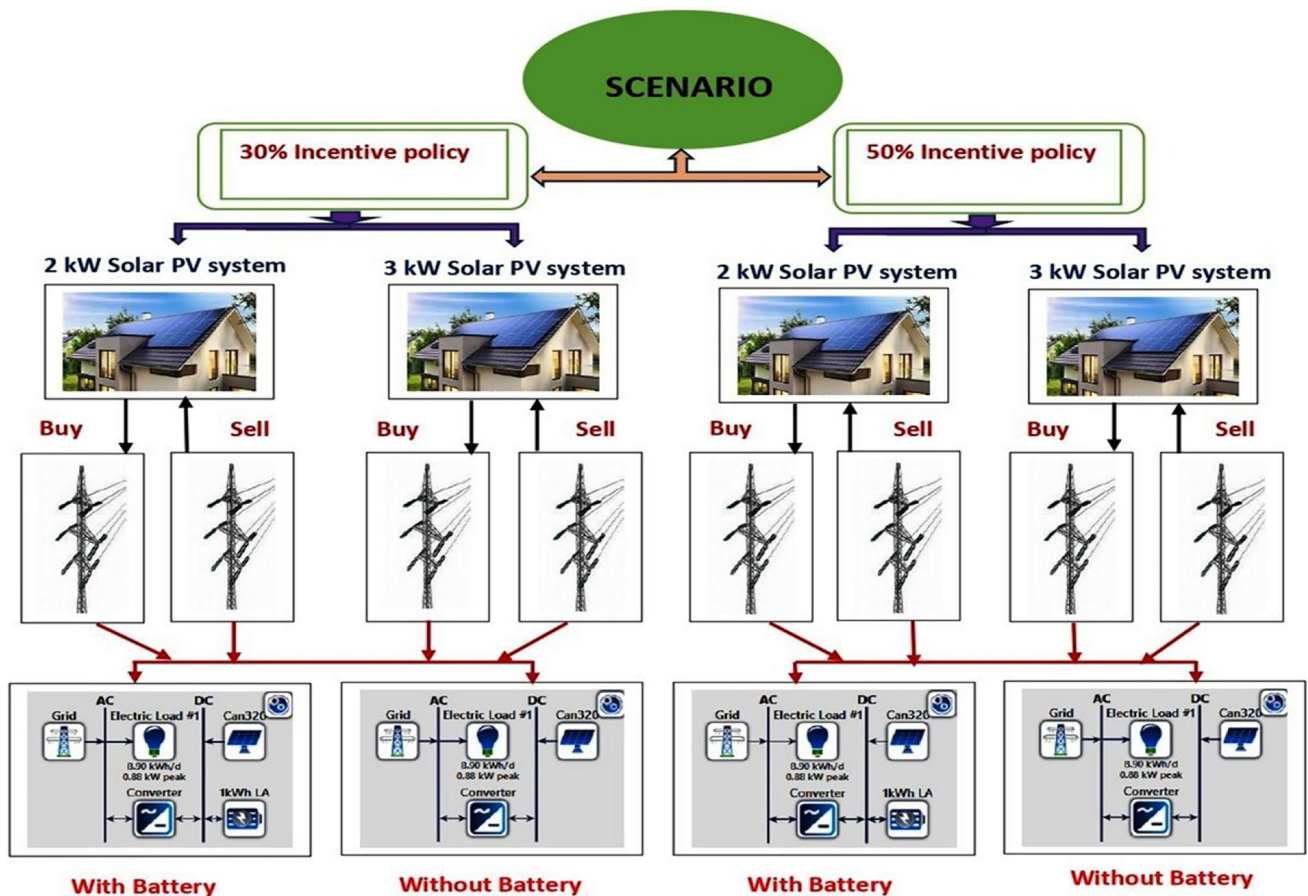
Fig. 7 Flow chart layout for the proposed system

Table 4 Slab rate tariff for residential building of TNEB

Slab	From unit	To unit	Rate ($)	Max unit
I	1	100	0	100
II	1	100	0	200
	101	200	0.00032	200
III	1	100	0	500
	101	200	0.00032	500
	201	500	0.00065	500
IV	1	100	0	9,999,999
	101	200	0.00065	9,999,999
	201	500	0.072	9,999,999
	501	Above	0.096	9,999,999

investment cost reduction, exporting energy benefits, importing energy process.

6.1 Reduce the investment cost for the proposed system component

In this case, the government offers a fixed percentage of the investment cost as an incentive to encourage investors to adopt RES-based solar PV residential system. Moreover, the specific percentage of 30% and 50% of 2 kW and 3 kW solar PV system can vary depending on government policies and targets.

Table 5 30% and 50% policy of grid purchasing energy price parameters for each capacity

Categories	With battery	Without battery
2 kW on-grid solar PV system		
Grid purchase (kWh/yr)	2181	1,823
Net energy purchased (kWh)	226	154
Energy charge ($)	12.221	8.346
3 kW on-grid solar PV system		
Grid purchase (kWh/yr)	2004	1,981
Net energy purchased (kWh)	252	176
Energy charge ($)	13.496	10.052

6.2 Reduce the price of purchasing energy

The combination of entire system component for the real-time solar PV installation of the proposed system denotes the reduction of purchasing energy cost for grid availability. Also, the both RES capacity case is investigated for variety of houses depends upon the high and medium load energy consumption. As a consequence, the simulation HOMER software is employed to calculate the 2 kW and 3 kW capacities, as well as the grid and energy level purchase costs and the availability of solar combined with grid and battery energy systems. Therefore, an incentive policy such as 30% and 50% of both cases are followed below in the basis of grid purchasing energy level.

6.2.1 The government pays investment cost of the proposed system for at least 30% and 50% of RES penetration

For maximum energy availability and the purpose of cost reduction is obtained by using the most effective on-grid and off-grid solar PV system for both selected capacities in this situation. It is additionally regarded as different when solar PV is used in combination with grid and battery storage systems. Moreover, the gird power cost of 2 kW and 3 kW of 0.054 $/kWh examined that with battery storage cost is much higher than on-grid without battery storage which details are shown in Table 5. While moving to the government subsidy of 30% and 50% for the consumers to move towards the net metering facilities to overcome grid vulnerability.

In this case, the cost electricity of the grid can be compared across different incentive regimes, exhibiting an appropriate solution. The energy consumption from 2 and 3 kW capacity of utilized power from the grid during the day with any excess power preserved in the battery to be employed at night. Consequently, the solar PV energy system is employed for both the performance of the residential building at the location selected. In addition, the maximum output is carried out using HOMER tool on the basis of solar energy production and load consumption with increasing RES penetration. Furthermore, a real-time on-grid and off-grid solar PV system implications are established to the selected building for this scenario and each case. Therefore, grid purchase, solar PV generation, total load served, RE penetration and battery SOC are shown in Fig. 8.

6.2.1.1 2 kW and 3 kW on-grid solar PV of 30% policy with and without battery system Taking into account the potential for renewable energy generated by 2 kW and 3 kW solar systems from primary solar and secondary grid sources. Additionally, the analysis of energy transfer to the load of each house is validated due to the real-time consideration of solar PV installation. Taking into account of these two capacities of solar ratings for the analysis of technical and economic benefits.

As a result, the HOMER software was used to analyse solar PV generation and load consumption with RES penetration. The efficient energy level is shown in Table 6 as a result of the analysis of solar PV generation and load consumption with RES penetration rate, maximum output for each capacity, and operating period of 4,377 h/yr.

6.3 Increase the price of selling energy

Considering about the RES penetration level for the selected system with on-grid and battery storage system with the level of 30% and 50%. In this case, solar PV generation, battery state of charge (SOC), converter conversion beyond the limits of load demand is obtained using HOMER tool. Furthermore, 2 kW and 3 kW solar photovoltaic (PV) systems for residential buildings are necessary to meet the load requirement for their purpose. Thereby, the energy production and consumption to the load is received from solar energy and grid with the help of battery storage to reduced carbon emissions and increased contribution of RES. Especially, the incentive policy of 30% and 50% is induced to having the concern of net-metering facility. The demand of energy for the residential building at the selected location is analysed and having the benefits of selling energy with higher cost to the mini-grid to overcome the government tariff slab rate. Thereby, the incentive policy of both capacities investigation is examined by validating the investment cost of each subsidy for the RES penetration rate is discussed below.

6.3.1 The government pays investment cost of the proposed system for 30% RES penetration rate

The 30% incentive policy of 2 kW and 3 kW will be considered for the investigation of greater quantities of selling energy provided back to the grid. Meanwhile, the grid purchasing cost of this case is 0.108 $/kWh for both capacities

Fig. 8 30% component-based purchasing energy level of each capacity solar PV

2 kW Purchasing Energy

Without Battery

With Battery

3 kW Purchasing Energy

Without Battery

With Battery

Canadian Solar 320CS6U-320M Power Output
Total Electrical Load Served
Grid Purchases
Renewable Penetration
Generic 1kWh Lead Acid State of Charge

Canadian Solar 320CS6U-320M Power Output
Total Electrical Load Served
Grid Purchases
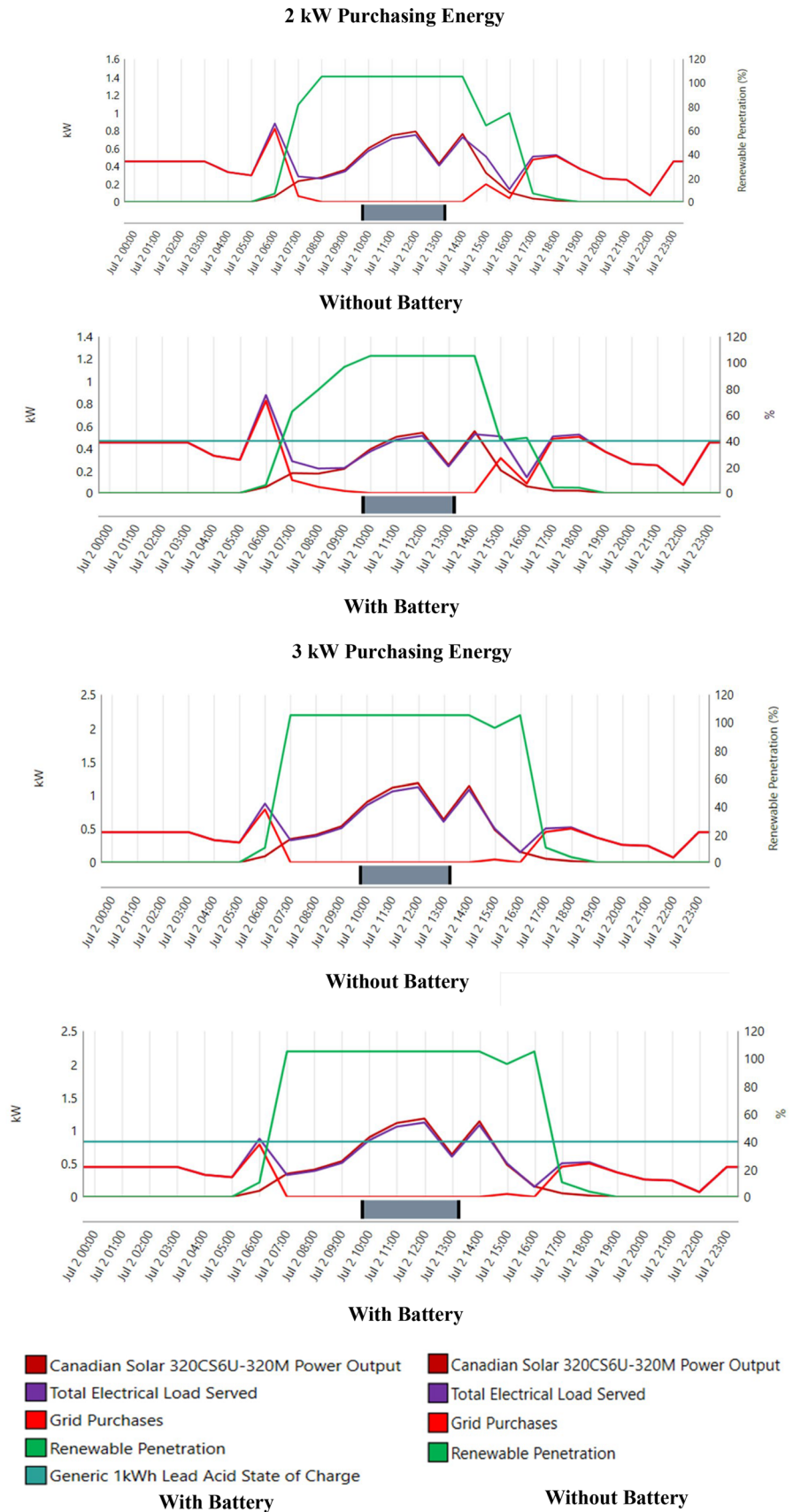Renewable Penetration

With Battery   **Without Battery**

Table 6 30% policy of RES potential of purchasing energy for 2 kW and 3 kW capacity

Categories	With battery	Without battery
2 kW on-grid solar PV system		
Solar production (kWh/yr)	3257	3257
AC load served (kWh/yr)	3248	3248
Solar battery excess (kWh/yr)	1256	–
Max. Ren. Penetration (%)	225	115
PV penetration (%)	100	100
Solar mean output (kWh/day)	0.372	0.372
Solar maximum output (kW)	1.82	1.82
3 kW on-grid solar PV system		
Solar production (kWh/yr)	4885	4885
AC load served (kWh/yr)	3248	3248
Solar battery excess (kWh/yr)	1983	–
Max. Ren. Penetration (%)	205	105
PV Penetration(%)	150	150
Solar mean output (kWh/day)	0.558	0.558
Solar maximum output (kW)	2.72	2.72

Table 8 30% policy of RES potential of selling energy for 2 kW and 3 kW capacity

Categories	With battery	Without battery
2 kW on-grid solar PV system		
Solar production (kWh/yr)	3257	3257
AC load served (kWh/yr)	3248	3248
Solar battery excess (kWh/yr)	41.2	–
Max. Ren. Penetration (%)	185	115
PV penetration (%)	100	100
Solar mean output (kWh/day)	8.92	8.92
Solar maximum output (kW)	1.82	1.82
3 kW on-grid solar PV system		
Solar production (kWh/yr)	4885	4885
AC Load Served (kWh/yr)	3248	3248
Solar Battery Excess (kWh/yr)	74.3	–
Max. Ren. Penetration (%)	225	145
PV penetration (%)	150	150
Solar mean output (kWh/day)	13.4	13.4
Solar maximum output (kW)	2.72	2.72

Table 7 30% policy of grid selling energy price parameters for each capacity

Categories	With battery	Without battery
2 kW on-grid solar PV system		
Energy sold (kWh)	1900	1526
Energy charge ($)	5.246	4.693
3 kW on-grid solar PV system		
Energy sold (kWh)	3372	3142
Energy charge ($)	5.874	4.486

and the Table 7 provides a comparison of energy selling and energy charge for 2 kW and 3 kW on-grid solar PV system under a 30% policy incentive with and without battery storage. For both the 2 kW and 3 kW on-grid solar PV systems, the configurations without battery storage sell more energy and incur a lower energy charge compared to those with battery storage under the 30% policy incentive. This suggests that while battery storage can provide benefits like energy independence and backup power, it may lead to higher energy charges and less energy being sold back to the grid. Similar to the 2 kW system, the 3 kW system without a battery sells lower energy (3,142 kWh) than the system with a battery (3,372 kWh). The energy charge is lower without the battery ($4.486) compared to with the battery ($5.874).

Additionally, the selected capacity of 2 kW and 3 kW of this 30% incentive scheme shows that the grid selling

energy level, solar production, battery SOC, RES penetration validated outcome is the best efficient power supply for the residential building for the selected location. Therefore, both capacity of renewable penetration of the month of July promotes that the 2 kW selling energy of without battery and with battery has much lower energy potential than 3 kW load served and grid sale level is shown in Fig. 9.

6.3.1.1 2 kW and 3 kW on-grid solar PV of 30% policy with and without battery system An account of, using HOMER tool the proposed system of solar PV system for 50% subsidy towards the focus of minimizing the cost from the increment of purchasing cost. Hence, the incentive policy of 50% is best effective when compared to the 30% of government subsidy. Moreover, the capacity of 2 kW and 3 kW solar production, load consumed energy, excess battery storage during night hours, RES penetration, solar output, solar maximum output is validated for the household appliances to satisfy the load shown in Table 8. Thus, the grid purchase of both 30% and 50% for the selected optimal system has similar like above section because an energy purchased from the grid is much smaller than a solar generation.

6.3.2 The government pays investment cost of the proposed system for 50% RES penetration rate

The incentive scheme of 50% investment cost of estimated residential system is taken to determine the best efficient energy potential compared to the 30% of incentive policy,

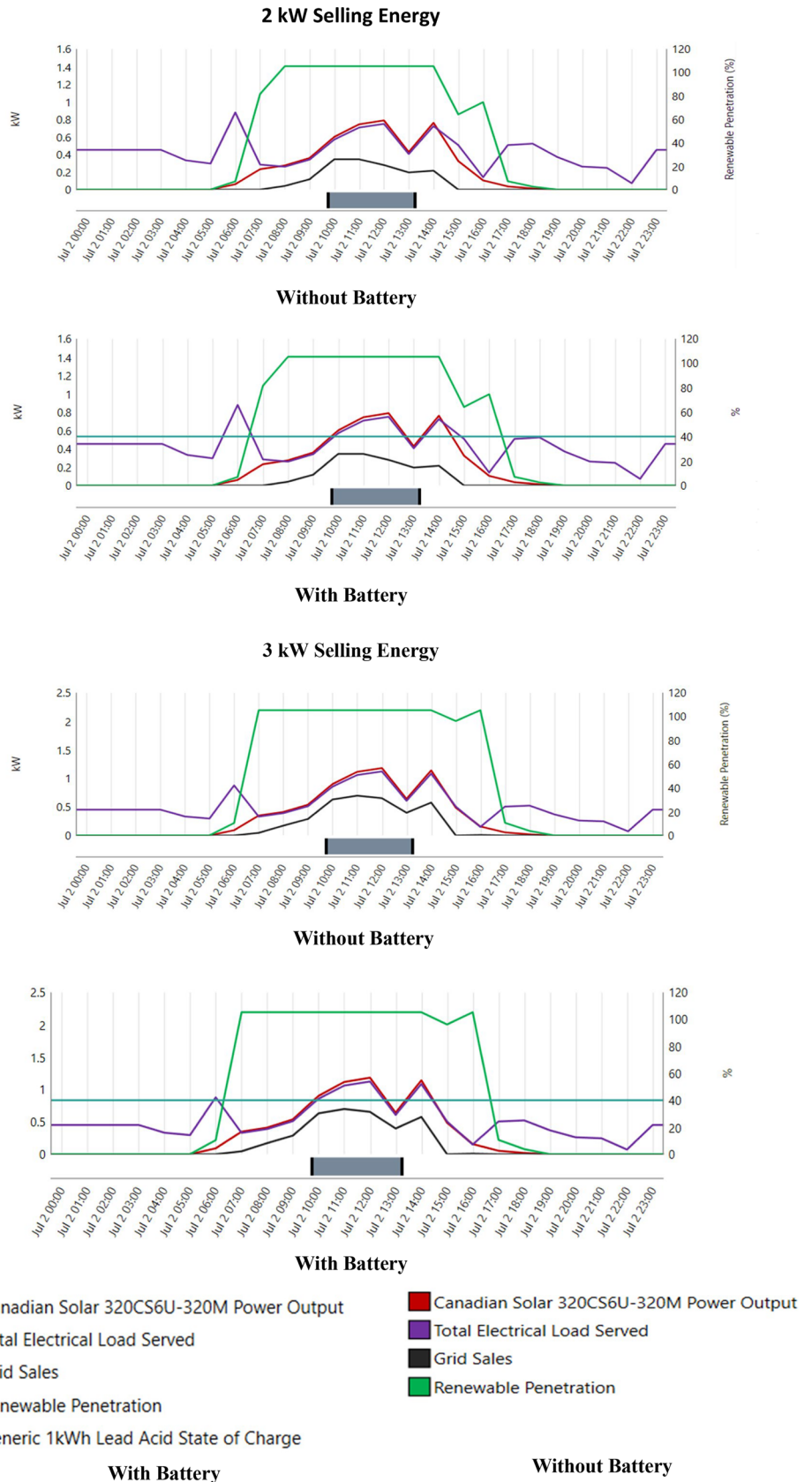**Fig. 9** 30% component-based selling energy level of each capacity solar PV

2 kW Selling Energy

Without Battery

With Battery

3 kW Selling Energy

Without Battery

With Battery

Legend (With Battery):
- Canadian Solar 320CS6U-320M Power Output
- Total Electrical Load Served
- Grid Sales
- Renewable Penetration
- Generic 1kWh Lead Acid State of Charge

Legend (Without Battery):
- Canadian Solar 320CS6U-320M Power Output
- Total Electrical Load Served
- Grid Sales
- Renewable Penetration

With Battery   **Without Battery**

Table 9 50% policy of grid selling energy price parameters for each capacity

Categories	With battery	Without battery
2 kW on-grid solar PV system		
Energy Sold (kWh)	1900	1861
Energy Charge ($)	4.389	2.668
3 kW on-grid solar PV system		
Energy Sold (kWh)	4654	3374
Energy Charge ($)	13.496	10.052

Table 10 50% policy of RES potential of selling energy for 2 kW and 3 kW capacity

Categories	With battery	Without battery
2 kW on-grid solar PV system		
Solar production (kWh/yr)	3257	3257
AC load served (kWh/yr)	3248	3248
Solar battery excess (kWh/yr)	61.8	–
Max. Ren. Penetration (%)	172	122
PV penetration (%)	100	100
Solar mean output (kWh/day)	8.92	8.92
Solar maximum output (kW)	1.82	1.82
3 kW on-grid solar PV system		
Solar production (kWh/yr)	4885	4885
AC load served (kWh/yr)	3248	3248
Solar battery excess (kWh/yr)	82.3	–
Max. Ren. Penetration (%)	205	115
PV penetration (%)	150	150
Solar mean output (kWh/day)	13.4	13.4
Solar maximum output (kW)	272	2.72

because the selling price of utility for both capacity is $ 0.168/kWh for the excess energy stored in battery which send back to the mini-grid for the economic benefits. Additionally, the net energy sold rate and annual energy charge of each case is scheduled using simulation tool by feeding real-time data for the technical and cost analysis. Therefore, an entire investigation for ratings of with and without battery storage of on-grid solar PV system is given in Table 9.

Furthermore, the strategies of selling energy focus towards the satisfaction of load demand using 2 kW and 3 kW capacities is simulated in that software. In addition, the with and without battery energy system for a selected kilowatts shows that the representation of grid sales, solar power generation, load consumed energy, RES penetration and battery SOC is shown in Fig. 10. Meanwhile, comparing these categories with the above selling level of 30% incentive investment to contribute effective system.

6.3.2.1 2 kW and 3 kW on-grid solar PV of 50% policy with and without battery system
Additionally, although an on-grid extension, the residential building's precise location received more energy from solar radiation and with the assistance When compared to exporting electricity to a mini-grid and the costs associated with the demand for grid purchases is significantly lower. An account, the RES penetration is almost low in 2 kW but can satisfy the load of some variety of houses. Additionally, due to a significant primary source of energy exploration, the maximum solar output power with a battery system is 3 kW. Therefore, the following categories covered during the validation of energetic benefits are given in Table 10.

6.4 Cost summary

Focus towards the contribution of maintaining an effective cost for the proposed selected system to the residential building is obtained using HOMER tool. The functioning of load demand energy consumption for all the household appliances is performed using solar PV system, gird energy completely during day hours. While this happens taking place during

an excess solar energy is being utilized to power a battery storage system to help with peak demand energy analysis. For the purpose of doing technical and economic analysis, the study examines how the component required for this estimated system is simulated in the program. Hence, the scenario-based incentive policy would exhibit for the two different solar PV capacities with the cases of selling and buying energy capability. Thereby, 2 kW and 3 kW solar PV system is considered as real-time future performance by with and without battery system via on-grid extension. An account is established utilizing economic criteria such as the net present cost, energy cost, and operation and maintenance costs for the scenario given above with the goal of reducing overall investment costs and achieving net metering facilities for every residence. Therefore, the cost analysis for both incentive policies is delivered in Table 11 after the calculation obtained in the software. According to the specifications of cost for each capacity, a 3 kW solar PV system's NPC (without battery) of selling energy is significantly lower than a 2-kW solar system, and the COE is also similar to NPC. Here, without-battery system is substantially more feasible than with-battery system when compared to the 2 kW purchasing energy and 3 kW buying energy approach since sending energy back to the grid has advantages.

In addition, the main objective for the both scenarios expose that 50% incentive policy adoption has more efficient than 30% investment cost reduction. Hence, the reason for the effective solution is that of selling energy price is much higher in 50% incentive than 30% due to the load availability

Fig. 10 50% component-based selling energy level of each capacity solar PV
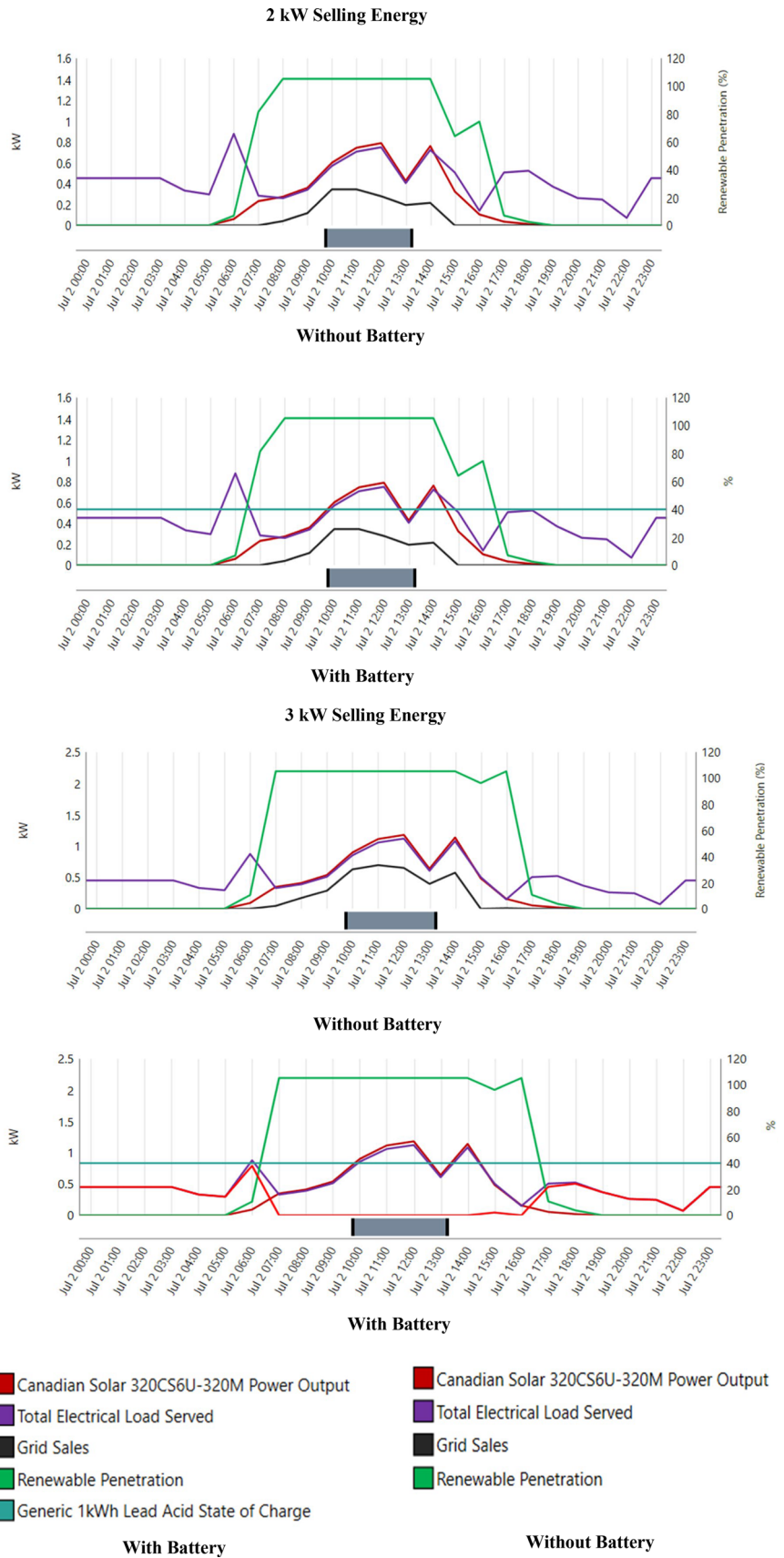
2 kW Selling Energy

Without Battery

With Battery

3 kW Selling Energy

Without Battery

With Battery

Canadian Solar 320CS6U-320M Power Output
Total Electrical Load Served
Grid Sales
Renewable Penetration
Generic 1kWh Lead Acid State of Charge

With Battery

Canadian Solar 320CS6U-320M Power Output
Total Electrical Load Served
Grid Sales
Renewable Penetration

Without Battery

Table 11 Economic analysis of 30% incentive scheme

Categories	Without battery Buying energy	With battery	Without battery Selling energy	With battery
30% incentive of 2 kW solar PV system				
NPC ($)	2,966.513	3,297.712	2,799.464	3,200.373
O&M ($)	110.490	132.392	106.865	124.862
COE ($)	0.043	0.050	0.042	0.048
30% incentive of 3 kW solar PV system				
NPC ($)	2,629.189	3,030.816	1,655.611	2,057.611
O&M ($)	38.849	92.953	80.946	114.441
COE ($)	0.031	0.035	0.019	0.024

Table 12 Economic analysis of 50% incentive scheme

Categories	Without battery Buying energy	With battery	Without battery Selling energy	With battery
50% incentive of 2 kW solar PV system				
NPC ($)	2,792.051	256,442.13	171,849	221,994
O&M ($)	134.508	15,236	9,084.04	13,055.61
COE ($)	0.045	4.34	2.60	3.94
50% incentive of 3 kW solar PV system				
NPC ($)	1,456.643	1,738.495	1,127.008	1,516.934
O&M ($)	127.800	160.133	102.032	156.190
COE ($)	0.035	0.047	0.015	0.035

and energy storage level in battery. Therefore, the Table 12 denotes that the total NPC, COE and O&M for both 2 kW and 3 kW for 50% incentive scheme. Although complete analysis explains the on-grid 3 kW solar PV system in the absence of battery storage is much higher benefit in economically than 30% incentive of both cases as well as 2 kW capacity in 50% also. Thus, the buying and selling energy of 50% incentive shows that the NPC and O&M of without battery system is efficient than with battery energy storage system because of the lowest level of COE.

6.5 Emission analysis

As per the investigation of having concern on real-time solar PV installation for the chosen site towards the grid, there are some energy fluctuations are obtained via transmission wire. Additionally, the present study having an aim for achieving the solar power supply to overcome some pollution such as greenhouse gas emissions such as carbon dioxide (CO_2), nitrogen oxide (NO), and sulphur dioxide (SO_2). Furthermore, HOMER software is employed to calculate the selected scenarios, in addition to a visual representation of each capacity for technical and economic analysis. Meanwhile, by giving the inputs to that software such as solar parameters, grid details, battery ratings for the investigation

of emissions free optimal system. Therefore, the following above gases calculation is analysed and given in Table 13. Furthermore, when comparing to the battery system and the grid expansion is determined to have the most significant emission level which indicates that the battery stand-alone system is the most effective in terms of emission analysis due to its losses. With the goal to create the winning system containing the lowest level of emissions, the system that is recommended for pollution level is taken from the base case system.

7 Conclusion

By reducing fossil fuels and decreasing greenhouse gas emissions, renewable energy sources (RES) contribute to the development of green energy technologies. This study emphasizes the real-time performance of solar PV installations to address the need for reasonable and efficient energy for residential development. The current research provides a techno-economic analysis of RES-based on-grid solar PV systems, considering real-time data from approximately 50 residential buildings in Hosur and Krishnagiri, Tamil Nadu. The goal is to optimize these PV panels and battery backup systems to manage the intermittent nature of RES.

Table 13 Emission interpretation analysis of both incentive policy

Categories	Selling energy	Buying energy	Selling energy	Buying energy
2 kW on and off-grid solar PV system			3 kW on and off-grid solar PV system	
30% incentive policy				
CO_2 (kg/yr)	1265	1298	1235	1252
SO (kg/yr)	4.23	5.63	5.12	5.43
NO (kg/yr)	2.02	2.75	2.25	2.65
50% incentive policy				
CO_2 (kg/yr)	1228	1247	1213	1228
SO (kg/yr)	3.23	4.63	3.01	4.33
NO (kg/yr)	2.02	2.36	1.66	1.82

The proposed system evaluates the potential for RES utilization in the selected locations and its efficiency in meeting the load requirements of household appliances. Additionally, the study aims to reduce the total investment cost of the system equipment. To achieve this, two incentive policy schemes offering subsidies of 30% and 50% are proposed. These policies are designed for solar PV systems with capacities of 2 kW and 3 kW. The aim is to reduce overall costs, minimize the cost of purchased energy ($0.11/kWh), and maximize the selling price of exported energy ($0.17/kWh). The study investigates the economic benefits of these incentive policies for on-grid solar PV systems with and without battery backup. It focuses on ensuring load satisfaction during both day and night by utilizing solar energy, which can provide up to 4,885 kWh/year for a 3 kW system with a 50% subsidy, supplemented by utility energy as needed.

Therefore, HOMER software is used for comprehensive performance analysis, both technical and economic. The simulation results indicate that a 50% incentive for systems without battery backup is more efficient than a 30% incentive, based on load usage. For example, the Net Present Cost (NPC) is $1,127.008 and the Operations and Maintenance (O&M) cost is $102.032 for these systems. Additionally, the on-grid system with a 50% incentive significantly reduces emissions (CO_2, NO, and SO_2) emissions are nearly 50% lower without a battery system, at 1,213 kg/year, 1.66 kg/year, and 3.01 kg/year, respectively. Mainly, future recommendations include decreasing grid purchasing costs and increasing energy costs to encourage consumers to adopt net metering for real-time solar PV performance with on-grid extensions and battery backups.

Author contributions J. Nishanthy contributed to conceptualization, methodology, software and writing-original draft, data curation and software Dr. S. Charles Raja helped in supervision, writing-review & editing, formal analysis D. Bharathy Priya helped in visualization, validation and investigation

Declarations

Conflict of interest The authors declare no competing interests.

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