Renewable energy usage for home energy management and its adverse impact due to the increasing trend of electric load addition in homes in the State of Kerala, India

Thomas George, A. Immanuel Selvakumar
Department of Electrical and Electronics Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India

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ABSTRACT

Nowadays renewable energy generation techniques and their application for home energy management are becoming very common topics of discussion all across the globe. The increased user comfort, bill reduction, and government subsidy schemes make more consumers interested in installing these sustainable sources in their homes. Also, the utility company will be able to level its peak load and reduce its carbon footprint. Does installing renewable energy sources in homes with a conventional billing scheme help in reducing the carbon footprint of the utility company? Also, are there chances for an increased trend of electric load addition in homes installed with renewable energy plants having net metering schemes to lead to peak load management burden? This paper is an attempt to underline the benefits of using renewable energy sources at home but at the same time what are the precautions to be taken while using the same in the state of Kerala, India. The paper also proposes an economical portable solar-powered light tower that helps in leveling peak loads in homes with on-grid power plants which are billed under a conventional block rate pricing scheme through net metering.

Corresponding Author:

Thomas George
Department of Electrical and Electronics Engineering, Karunya Institute of Technology and Sciences
Karunya Nagar, Coimbatore 641114, India
Email: ktghcl@gmail.com

1. INTRODUCTION

Nowadays power generation from renewable energy sources is very common in many countries. There are a wide variety of methods that are being implemented to harvest renewable energy. The most common energy sources used are wind and sun [1]. Most of the developed countries of the world spend a lot on the research and development of sophisticated techniques for harvesting maximum energy from renewable sources. As more and more countries are trying to reduce their carbon footprint, the usage of renewable energy helps in attaining their intended goal at a much faster rate. Many homes in the world are installing renewable energy production techniques and thus their dependency on power utility companies can be reduced and thus the carbon footprint of thermal power plants can be reduced [2]. As more and more smart appliances are getting introduced in the market, consumers are in a stage of partially or fully automating their homes by purchasing and installing the same. Also, many cutting-edge researches are progressing in the battery sector, the electric vehicles (EV) industries can introduce their cars at a much affordable rate, and hence more people are switching to EVs. Also, a few countries are amending their tax laws for consumers who are willing to purchase an EV. Also, few nations have introduced restrictions for internal combustion engine-based cars from entering major towns [3]. For some consumers their objective of moving to EV is the reduction of carbon footprint, for some it is a step taken to reduce their fuel expense, and for a few, it is the sheer pleasure of driving an EV [4].

In the state of Kerala, India the major source for power generation is thermal power and hydropower [5]. During summer seasons, the state electricity board needs to purchase additional power from the central grid due to the high-power demand. It should be noted that most of the power generation plants in India are based on fossil fuels. Also, the major source of renewable energy in India is solar and wind [6]. Nowadays the state and central government have introduced a lot of subsidy schemes for consumers who are willing to install renewable energy-based power plants in their homes [7]. Utilizing this opportunity more and more consumers are installing solar power plants on their rooftops. Harvesting renewable energy tremendously reduces the dependency on thermal power plants, especially during peak loads [8]. But are the consumers seriously interested in leveling the peak load of the utility company? On the contrary, the consumers want to reduce their bill amount and also wish to increase their user comfort [9]. Installation of renewable energy power plants in homes helps reduce the bill amount and gives a decent return in the long run by selling the excess energy produced. On the other side as the utility bill reduces consumers tend to improve their user comfort by introducing more and more electric loads like smart appliances, EVs, and other automated equipment. The Kerala State Electricity Board is following an inclining block rate (IBR) billing scheme for homes located in Kerala [10] which only accounts for the number of units consumed and not the time of consumption. For homes installed with solar power plants, the energy generation is during day time only [10] and the additional loads installed in the home consume energy from the power utility company which therefore creates an additional burden when trying for peak load management or load leveling. This paper is an attempt to enlighten the side effects caused by to introduction of renewable energy-based power plants in homes through a case study. This paper also proposes an economical battery-based portable light tower that the utility company can install in places with high residential home intensity which helps to reduce outdoor lighting loads in homes and thus reduces peak lighting load demand during night. From the detailed literature survey, the following research gaps are identified and provided in Table 1.

Table 1. Research gaps identified

Area	Gaps	Impacts
Scalability of home energy management systems	Current HEMS systems are often not scalable to handle the increasing variety of electrical loads, particularly with the growing adoption of electric vehicles (EVs), smart appliances, and home automation systems.	This lack of scalability can lead to inefficiencies in energy management, with renewable energy sources being underutilized or overburdened, leading to grid instability and higher costs for homeowners.
Integration of renewable energy with HEMS	Many existing HEMS lack effective integration with renewable energy sources like solar panels and small wind turbines. The systems may not be optimized for the variability in renewable energy generation.	Poor integration can result in energy wastage, higher reliance on the grid during peak loads, and suboptimal use of renewable energy, thus reducing potential savings and environmental benefits.
Load forecasting and demand response mechanisms	There is a significant gap in accurately forecasting household energy demand, especially with the dynamic addition of new loads. Existing demand response mechanisms may not be adaptive enough to react to these changes.	Inaccurate load forecasting can lead to either overuse or underuse of renewable energy, causing stress on the energy storage systems and potentially leading to increased reliance on non-renewable backup power sources.
Energy storage solutions	The mismatch between renewable energy generation and consumption times creates a need for efficient energy storage solutions. However, current storage technologies are not always adequate to handle the increasing loads or to store surplus renewable energy efficiently.	Insufficient storage capacity can lead to energy loss and reduced effectiveness of renewable energy systems, forcing homes to revert to grid electricity during high-demand periods.
Grid interaction and stability	As homes increasingly generate and store their own energy, the interaction with the grid becomes more complex. Current grid infrastructures are not always designed to handle the bidirectional flow of energy from multiple homes.	This can cause grid instability, particularly when large amounts of renewable energy are fed back into the grid during low-demand periods, potentially leading to voltage fluctuations and even blackouts.
User behavior and awareness	There is a gap in understanding how user behavior impacts the efficiency of home energy management systems. Lack of user awareness and engagement with renewable energy technologies can lead to suboptimal usage and decreased effectiveness.	Without proper user engagement, even the most advanced HEMS might fail to achieve their potential, resulting in higher energy consumption, increased costs, and lower sustainability outcomes.
Policy and regulatory challenges	Existing policies and regulations may not fully support the integration of increasing electric loads and renewable energy sources at the household level. There is a need for updated frameworks that incentivize efficient energy management and support the development of smarter grids.	Regulatory barriers can slow down the adoption of renewable energy technologies and advanced HEMS, hindering progress toward sustainable home energy management.
Cybersecurity and privacy concerns	The increasing digitization of home energy management systems and the interconnectivity with the grid raises significant cybersecurity and privacy concerns. Current solutions may not be fully equipped to handle these challenges.	Vulnerabilities in HEMS can lead to data breaches, unauthorized control of energy systems, and potential disruptions in energy supply, undermining trust in renewable energy systems.

2. CASE STUDY: ON-GRID SOLAR POWER PLANT IN HOME AND THE TREND OF ADDITIONAL ELECTRIC LOAD PURCHASES

Nowadays, solar energy is one of the most harvested renewable energies for the generation of electric power in the homes of Kerala. Solar energy can be converted into electrical power with the help of PV cells, and mainly there are three types of PV connection patterns for electric power generation using solar power in homes, and they are the on-grid type, off-grid, and hybrid type [11]. The state and central government authorities of India have introduced a variety of beneficial schemes to promote renewable energy utilization in homes [12]. Figure 1 shows the energy generation (kWh) pattern for three consecutive months in the year 2022 of three different homes geographically located inside a 5 km radius circle in the state of Kerala, India, that has installed a 5 kW on-grid solar power plant.

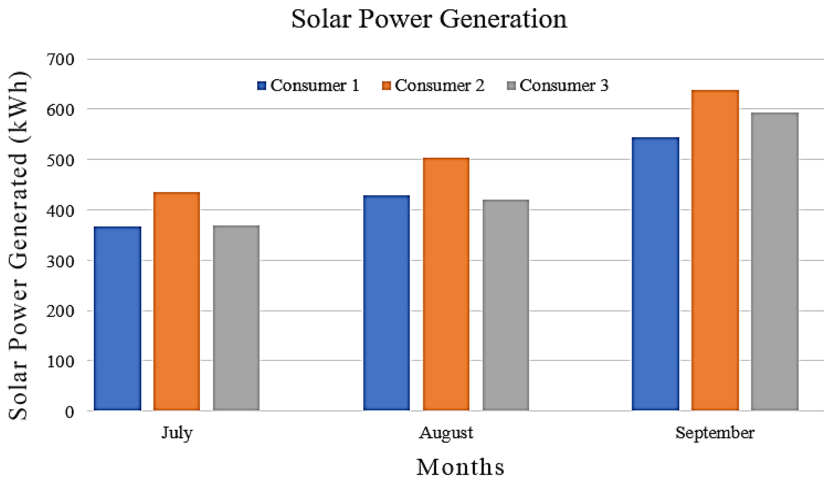

Figure 1. Solar power generation pattern of consumers located inside a 5 km radius geographical location in the state of Kerala, India

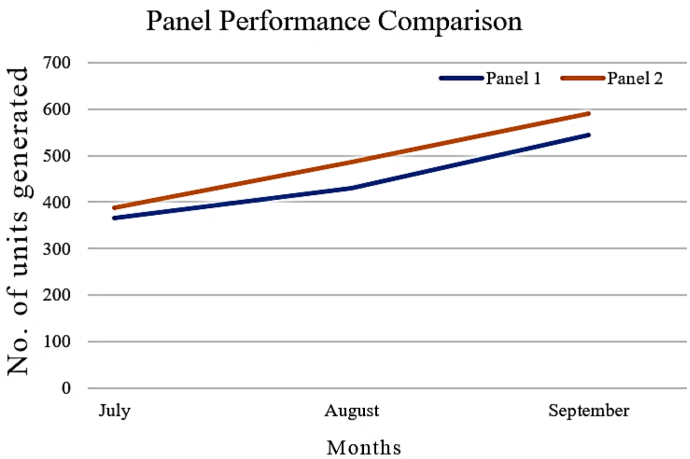

Figure 2. Solar panel performance concerning units generated

The reason for selecting these months is due to the cloudy weather, and hence receives most of its rainfall during this period [13]. Therefore, the generation can be scaled to the least possible value of annual production. Due to the tree plantations and complex agro forests, most of the homes in Kerala are under tree shadow [14], and hence 100 percent efficient generation of electric power is also not possible from PV panels installed in homes. Another reason that can affect the annual generation is the type and brand of PV panel that is being used for energy generation. Figure 2, shows the performance of two mono perc PV panel brands, one is an Indian brand (Panel 1) and the other is a foreign brand (Panel 2).

Due to technology differences and silicon purity level, Panel 2 makes more output power when compared to Panel 1 (shown in Table 2), but on the other hand, the cost of Panel 2 is higher when compared to Panel 1. India is a developing country, the consumers mostly tend to prefer items with low cost, even though the annual generation is getting reduced. Hence, dependency on utility companies for power can only be considerably reduced to a great extent during day time and not completely reduced. Apparently, on the other side, the consumer will be able to reduce their bill amount, but will indirectly tend to add additional loads that may in turn burden the utility during peak hours. Table 3 shows the change in monthly energy consumption pattern in a home during three consecutive months of the year 2021 and 2022. It should be noted that the billing cycle was bi-monthly before PV panel installation and hence the monthly unit consumption is taken as half of bi-monthly consumption. From Table 3, it is understood that the average energy consumption of the consumer has increased after the installation of renewable energy in the home. Since the power utility company of the state of Kerala, India is still following the conventional inclining block rate (IBR) tariff for billing the low tension (LT) consumers (10), the additional loads installed after solar PV installation in homes create an additional burden on power utility company during low solar energy production periods including night time.

Table 4 depicts the amount of energy supplied and taken from the grid by the home with a 5 KW on-grid solar power plant installed on the rooftop. It is understood that the use of renewable energy helps in supplying energy to the grid, but at the same time, the customer has a tendency to incorporate additional loads in their home due to reduced energy usage bills. This indirectly burdens the power utility company during peak hours and thus, the objective of carbon footprint reduction will not be met because of poor load leveling during peak loads in Kerala, India.

Table 2. Cost comparison of an Indian PV panel (Panel 1) with a foreign brand (Panel 2)

Panel brand	Price per cell ($)	Tax per cell	Cell price ($)	Number of cells per panel	Total price per panel ($)
Panel 1	.475	12%	.532	144	76.608
Panel 2	.55	12%	.616	144	88.704

Table 3. Energy consumption trend in a home before and after PV panel installation

Month	Monthly energy consumption (KWh)	
	Before the PV panel installation Year: 2021	After the PV panel installation Year: 2022
July	244.5	261.53
August	244.5	236.72
September	227.5	304.87

Table 4. Load on utility by home with conventional pricing scheme through additional electric load addition

Month	Generation through renewable energy source (KWh)	Export to utility from renewable energy source (KWh)	Import from Utility (KWh)	Import from renewable energy sources (KWh)
July	366.53	267	162	99.53
August	429.72	364	171	65.72
September	543.87	407	168	136.87

3. HEMS MODEL FOR OUTDOOR LIGHTING

3.1. The current trend in methods adopted for Outdoor lighting in residential consumer compounds and street lighting

Kerala, India is a land with high population density, most homes are closely located in sub-urban areas. Most of the roads and housing colonies depend on street lighting and outdoor lighting during the night. Nowadays the conventional bulbs used for street lighting are being replaced by LED lights [15]. To reduce the electricity consumption of outdoor lighting units, many researchers introduced different models that use multiple optimization strategies in the field of street lighting and home outdoor lighting, which are listed below. Most of the street lighting models presented here find application in home outdoor lighting.

Concerning vehicle traffic an optimization strategy using ZigBee was implemented to design street lights in [16]. A smart street light system that incorporated a vehicle detection system introduced in [17] helped to save energy by controlling the ON and OFF time of the light. Also, an Arduino-based smart street light with a motion sensor is introduced [18] which saves energy by around 70% when compared to a high-pressure sodium lamp. A lithium-ion battery-based street light system that had protection from overcharging and deep discharging problems was introduced [19]. The result in [20], a smart solar-powered street light system is proposed which has anti-theft features and employs an infrared (IR) sensor and light-dependent resistor (LDR) to improve the functionality. A considerable amount of energy can be saved by controlling the outdoor lighting [21] during night time which not only reduces the usage cost, it also helps to level the load curve during peak hours. Also, including photoluminescent material for outdoor lighting will help in reducing the carbon footprint [22].

3.2. Design of an economical portable solar light tower for outdoor lighting in residential homes

Most of the portable outdoor units available in the market run on fossil fuel and its usage leads to considerable pollution and usage cost. Also, homes with installed on-grid power plants tend to increase outdoor lighting loads since the billing scheme in the state of Kerala, India follows an Inclining block rate scheme for LT consumers [23] and does not take into account the time of use pricing scheme and thus indirectly burden the power utility company during peak loads [24]. On account of peak load shaving and the convenience of portability, a low-cost portable solar-powered outdoor light tower is designed which helps in the outdoor lighting of a residential home with an on-grid solar power plant and also a housing colony in rural areas [25]. The block diagram and the design layout of the model are shown in Figures 3 and 4 respectively.

The design parameters taken into account for modeling the portable light tower are detailed below:

- Total load = 200 watt (4 IP65 LED light, each 50 watts)
- Expected hours of working = 8 hours
- Energy required for 8-hour working = 200 × 8 = 1600 watt-hour
- Inverter efficiency = 95%
- Hence, the energy required = [1600 ÷ .95] = 1684 watt-hour
- Considering a 12 V battery, the battery capacity required will be [1684 ÷ 12] = 140 Ah.
- Hence, a 12 V, 150 Ah lead-acid battery is selected.

Let the battery efficiency be 85%, and therefore, the energy required to charge the battery will be [1684 ÷ .85] = 1981 watt-hour. Restricting the charge controller efficiency to 90%, the energy required at the controller side will be [1981 ÷ .90] = 2201 watt-hour. Considering a sun availability of 8.5 hours in a day and with a solar panel efficiency of 80%, 330 watts (2 panels with 165 watts each) is selected.

The height adjustment unit of this system consists of two square pipes (galvanized iron). A chain is attached to the first pipe, and the gear and sprocket setup is welded to the second pipe. With the help of a lever, the sprocket (Figure 5) can be rotated, which in turn moves the chain and thus the height of the light tower can be adjusted. The consolidated electrical specification of the portable solar-powered light tower is mentioned in Table 5. The consolidated mechanical specification of the solar-powered light tower is listed in Table 6.

The pole height can be reduced from 3.6 m to 2.4 m, and this will, in turn, help in the transportation of the light tower from one location to another via road. Along with this, the wheel mechanism, direction control lever, and braking system help in easy control while pulling this light tower inside a residential area. The hardware photograph of the portable solar-powered light tower is shown in Figure 6.

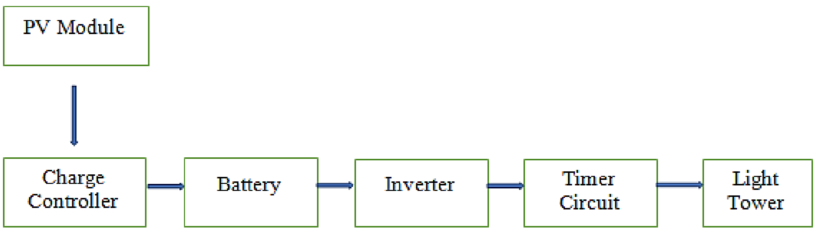

Figure 3. Block diagram of portable solar-powered light tower

Figure 4. Design layout of portable solar-powered light tower

Figure 5. Sprocket assembly of portable solar light tower

Figure 6. Portable solar-powered light tower

Table 7 depicts a comparative analysis concerning the total investment cost between an ordinary outdoor lighting system and a portable solar-powered light tower system. By utilizing this system, the consumption cost can be reduced and most importantly this kind of system helps to level the load curve and thus in turn helps the utility company to reduce carbon emissions during peak hours. This kind of system is most appropriate in places where the outdoor area is more like a residential colony or houses in Kerala, India with large courtyards where installation of small solar lighting loads would be difficult due to shadowing issues caused by big trees. In Table 7, considering the battery replacement cost for the portable solar-powered light tower, the overall usage cost of both types falls around the same figure, still peak load shaving achieved due to solar-powered light tower helps the utility company to level of demand factor and thereby achieving carbon footprint reduction. Table 8 provides the practical impacts of renewable energy usage for home energy management and the adverse effects due to the increasing trend of electric load addition.

Table 5. Electrical specification of the portable solar-powered light tower used for peak load shaving

S. No.	Item	Specification	Quantity
1	LED light	50 W	4
2	Inverter	500 W, 220 V AC, 50 Hz, sine wave	1
3	Battery	150 Ah, 12 V, lead-acid	1
4	Charge controller	12 V, 20 A	1
5	Solar PV module	165 wp	2

Table 6. Mechanical specification of the portable solar-powered light tower used for peak load shaving

S. No.	Item	Dimension
1	Base plate structure for housing electrical components	Length = 1.5 m Breadth = 1.5 m
2	Total pole height (fixed unit (outer pole) and movable unit (inner pole))	3.635 m
3	Gear ratio	1.5
4	Weight	200 kg

Table 7. Comparative analysis of return on investment between an ordinary outdoor lighting scheme and a portable solar-powered light tower in a home

Type of Lighting	Total light load in watts (W)	Total purchase cost of light ($)	Wiring Cost ($)	Making cost ($)	Capital cost ($)	Units (KWh) consumed in a year with a daily operating period of 8 hours	Total expenses in 10 years (per unit cost is $0.095)
Existing lighting load	300	39.58	525	0	564.58	864	820.8
Portable solar-powered light tower	200	45 (IP 65 type)	6.25	743.75	795	576	795

Table 8. Practical impacts of renewable energy usage for home energy management

Area	Impacts
Grid stability and reliability	The Indian grid is already under significant stress due to the increasing demand for electricity. The addition of electric loads in homes, such as air conditioners, electric vehicles (EVs), and smart appliances, can exacerbate this issue. When renewable energy sources like solar power are integrated into home energy management systems (HEMS) without adequate storage or grid interaction mechanisms, it can lead to grid instability, particularly during peak demand periods.
Economic implications for households	The adoption of renewable energy systems, such as rooftop solar, can reduce electricity bills for Indian households, especially with government incentives and subsidies. However, the benefits can be offset by the increasing electric loads, which drive up overall energy consumption. Additionally, the initial investment costs for renewable energy systems and HEMS may be prohibitive for lower-income households, limiting their access to these technologies.
Environmental impact	While renewable energy usage reduces greenhouse gas emissions and helps combat climate change, the overall environmental benefits can be diminished if the increasing electric load in homes is not managed efficiently. For instance, the rapid adoption of air conditioners and electric vehicles can lead to higher overall energy consumption, which may still rely on non-renewable energy sources during peak periods, especially if storage solutions are inadequate.
Strain on infrastructure	India's energy infrastructure, including distribution networks and substations, may struggle to cope with the combined impact of rising electric loads and the integration of decentralized renewable energy systems. This can lead to power quality issues, such as voltage fluctuations, and increase the need for infrastructure upgrades, which require significant investment.
Integration challenges	Integrating renewable energy with HEMS in Indian homes faces several challenges, including the variability of renewable energy generation (e.g., solar power being available only during the day), the lack of widespread energy storage solutions, and limited smart grid infrastructure. These challenges can result in inefficient energy use, with renewable energy being underutilized and homes relying more on grid power during peak load periods.

4. CONCLUSION

It is undoubtedly clear that harvesting and using renewable energy in the home helps to reduce the usage cost and improves user comfort. Moreover, it helps the utility company to reduce its carbon footprint during load leveling. However, utilizing renewable energy with a conventional billing scheme through net metering will burden the utility company, and thus, the real purpose of home energy management and sustainability would not be served. The consumer in an attempt to increase user comfort, will get a chance to add more loads because of the block rate billing scheme. Hence, a better pricing scheme, like a dynamic billing scheme and or gross metering, has to be followed for a responsible use of renewable energy resources in Kerala, India. Also, installing portable solar-powered light towers for outdoor lighting in areas with high home density helps the utility company to level their peak load demand. The consumers residing in homes surrounded by tree plantations can also utilize the same. Future research can focus on designing and developing HEMS that are scalable and adaptable to the increasing variety of electric loads in Indian homes. These systems should efficiently manage energy generated from renewable sources like solar power, especially under varying conditions of load demand.

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Thomas George	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	
A. Immanuel Selvakumar		✓				✓		✓		✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that supports the findings of this study are available from the corresponding author [TG], upon reasonable request.

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BIOGRAPHIES OF AUTHORS

Thomas George received the B.Tech. degree in Electrical and Electronics Engineering from Mahatma Gandhi University, Kerala, India and M.E. in Applied Electronics from Anna University, Chennai, India. He is a Chartered Engineer (India) and is a member of Institution of Engineers (India). He is currently pursuing his Ph.D. in Karunya Institute of Technology and Sciences, Coimbatore, India. His areas of interest are smart grid, embedded systems, and sustainable energy engineering. He can be contacted at email: ktghcl@gmail.com.

A. Immanuel Selvakumar received the B.E. degree in Electrical and Electronics Engineering from Madurai Kamaraj University, M.E. in Power Systems from Madurai Kamaraj University, and Ph.D. degree in Electrical Engineering from Anna University, Chennai, India. He is currently working as a Professor and Head of the Department of Electrical and Electronics Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India. He is working in the field of smart grid, electric vehicles, data analytics, and machine learning. He can be contacted at email: iselvakumar@yahoo.co.in.