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Assessment of Small Scale Solar PV Electricity Generation Potential using a Novel Technique

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ABSTRACT: Estimation of sustainable renewable electricity generation potential with substantive evidence derived from meteorological datasets has the potential of providing to the authorities and individuals, clear and reasonable information in designing policies for the penetration of renewable energy sources in electricity generation. This research made efforts to evaluate the solar PV electricity potential in Kasaragod district of Kerala, India using a novel approach. PVGIS5 solar irradiation data and the global benchmark model for solar PV electricity estimation are used in evaluating the potential of solar PV in electricity generation. Although the lack of literature for comparison with the previous studies was among the major challenges, this study can serve as a roadmap towards understanding the potential of solar PV across the district at large. The findings of the research demonstrate that 520Wp solar PV system with Battery Energy Storage System can deliver the electricity demand of typical household with 1.23 kW excess power that can be exported to the national grid. Thus, the findings of the study concluded that solar power is the realistic alternative in reducing the energy poverty across the district, especially in the rural areas where grid extension through difficult terrain and the thick forest is not economical.

Keywords: Photovoltaic Cells, PVGIS, Typical Household Electricity Consumption, Global Solar Radiation; Kasaragod, India.

I. INTRODUCTION

Electricity has been the backbone of development of any society because is the most versatile and easily controlled form of energy for human development. Unfortunately, electricity has already contributed 37.5% of the total global CO_2 emission in the globe, releasing 7700 million tons of CO_2 annually [1-3]. This huge emission shows that a serious transition is required for the reduction of electricity-related CO_2 emission in the energy sector. Considering the amount of CO_2 from the electricity sector, it is clear that, a sustainable electricity supply is the major challenge of the developed, developing and underdeveloped countries across the globe. Fortunately, several methods of decarbonising electricity generation are already identified in the global energy sector among which includes, the used of efficient fossil fuels electricity systems (CHP), conventional fossil fuel electricity generation technologies with carbon capture systems and the use of renewable energy technologies for small, medium and large scale electricity generation [4, 5, 1].

Developing countries like India has been witnessing chronic energy poverty with a significant percentage of the population living without access to electricity. This is the reason behind the lower per capita electricity consumption in comparison to developed countries across the globe. Surprisingly, most of the population living without access to electricity in India are local villagers in the remote regions with considerably higher renewable energy potential. Although the central and state governments in India has taken several initiatives and designed policies, for harnessing renewable energy sources in electricity generation, the Indian government has a long way to go in shifting from fossil fuel-based energy system to sustainable technologies in electricity generation. As shown in Fig. 1, until 30-December-2018 about 64.3% of the Indian total installed electricity capacity is from fossil fuel. This status quo is of special interest in consideration of the abundant renewable energy potential especially solar resources in the country. Due to the clean nature, practicability as well as been the most promising renewable energy resource, solar energy can be the key technological option in realizing the shift in decarbonizing the Indian energy sector because it is fairly, and consistently distributed across all the regions of the country [7-9].

Various studies of the performance analysis of the solar PV system for electricity generation in the literature are still modest and does not go beyond some recommendations. Dondariya *et al.*, [10] carried out a modelling and feasibility study of a grid-connected solar PV system at a proposed location at Ujjain, India using PVGIS software. The findings of the study revealed that the grid-tied solar PV systems are technically viable electricity solutions even in the urban areas of India. Singh & Banerjee [11] performs a study to estimate the solar PV potential for the Indian city of Mumbai using satellite datasets. By comparison with the daily electricity demand for different months, the findings of the study revealed that solar rooftop system alone could provide 12.8-20% of the daily electricity demand of the city with the median efficient solar PV systems available in Indian markets.

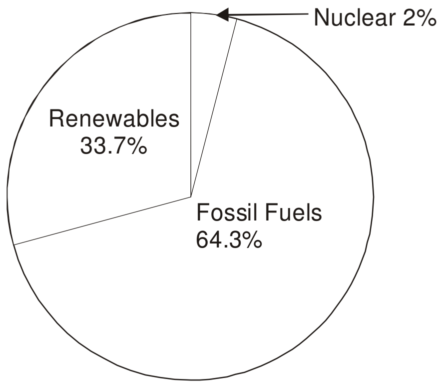


Fig. 1. All Indian installed electricity by the source as of 30-December-2018 [6].

Sharma and Goel (2017) [12] investigated the performance of the installed rooftop solar PV system in Eastern part of India across the seasons of the year summer, winter and rainy season. The findings of the study revealed that the annual performance ratio of the installed solar PV system is higher than that of many studies conducted in many countries across the globe.

The major drawbacks observed in the previous research studies conducted on the feasibility, viability and performance of solar PV systems in electricity generation is the absence of in-depth analysis of the solar resources at diurnal level, and adequate reference to particular electricity demand is missing in most of the studies.

This paper intends to fill the gap in solar PV potential studies by proving a comprehensive, detailed and novel approach for the assessment of solar PV electricity generation potential in Kasaragod city of Kerala, India. The motive behind the conduct of the research is to assess the solar resource potential and to investigate the performance of solar PV technology in delivering the electricity demand of typical household in the poorest energy district of Kerala, India. Certainly, the proposed approach will be a step forward toward a better understanding of the solar PV potential of the district at large.

The importance of the present study lies in the necessity of identifying sustainable energy solution to the endemic electricity shortage in the Kasaragod district. Thereby, there is no doubt, that a comprehensive renewable energy potential study must be conducted to obtain results that could be leads to a roadmap for the investment of solar PV across the government institutions and the citizens of the district at large.

II. OVERVIEW OF SOLAR POWER IN INDIA

Electrification of rural India has been the top agenda of almost all governments since independence as a key to national development. India, a tropical solar rich country is the second populous country in the world. The country is having an average of 300 sunny days in a year. This is equivalent to solar electricity potential of 4-7 kWh per square metre per day in most parts of the country. Starting with these values is very clear that, India is having higher solar irradiance in comparison to many countries of the globe. The Jawaharlal Nehru National Solar Mission, an Indian government initiative with the aim of generating 20GW solar power by the year 2022 is the most successful solar mission ever set by the GoI (Government of India) [13]. Due to this initiative, the Indian installed solar power has already reached 20 GW in February 2018, initially which was targeted for the year 2022. This tremendous achievement has already availed solar power to be among the competitive electricity sources, with average solar electricity price dropping 18% below the average coal-fired plant's electricity price.

Generally, besides the availability of suitable insolation for solar PV electricity generation, usually political instability and land availability are among the major obstacles that can limit investment into solar PV electricity generation across the globe. Fortunately, no obstacles are issues of concern in India. Because of the government enabling policies for the penetration of solar PV in the mix of electricity generation technologies, the Indian rooftop solar system is the cheapest around the world as shown in Fig. 2.

Kerala the “God’s Own Country” is one of the small states in India, ranked 12th by population and the first state to be declared fully electrified [16]. However, despite this achievement, one can question about the houses within the forested and hilly areas in the remote locations where grid electricity installation is very difficult due to the nature of the terrain.

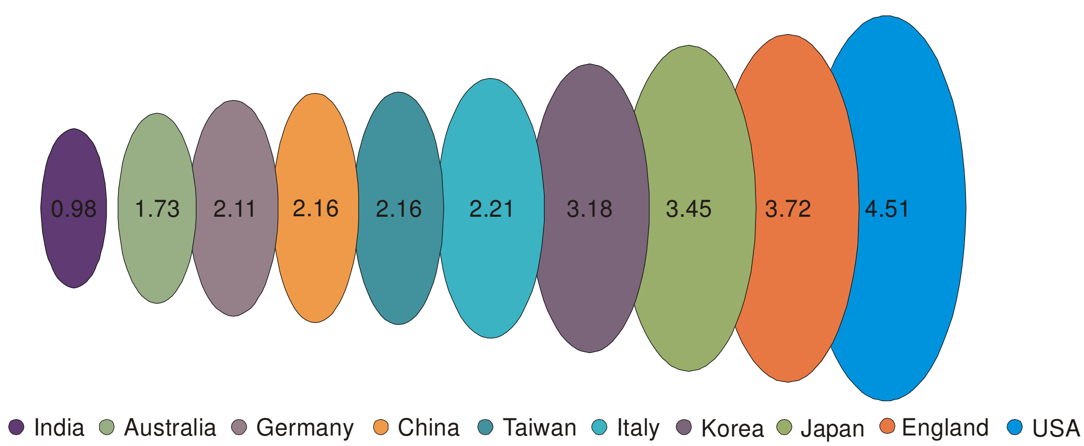


Fig. 2. Rooftop solar PV system prices around the world ($/Wp) [15].

The abundant renewable energy sources in Kerala is capable of supplying the total electricity demands of the state in a clean, green and sustainable way [16]. Kerala state has already achieved much in solar power, because of numerous initiatives such as floating solar power plants, 10,000 rooftop and 25,000 rooftop solar plants programme across the state, which are unique initiatives in comparison to Indian states.

Malabar region of Kerala, especially Kasaragod Fig. 3, is facing an acute shortage of electricity, which makes the region far backwards in terms of industrialization. Virtually, all the areas in Kasaragod district suffer very low voltage and erratic electricity supply during the hours of the day [17].

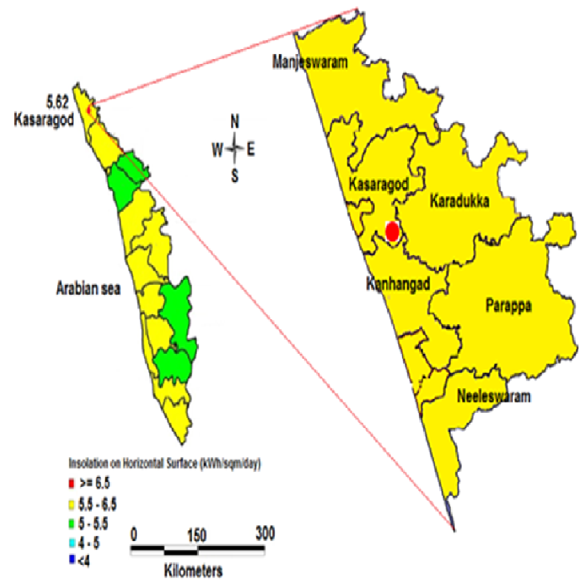


Fig. 3. Average annual solar insolation in kWh/m^2/day at the study site.

Although some solar energy projects are initiated by the Kerala state government in the district, one can say that the success is not appreciable because of the rejection by the immediate dwellers, due to lack of awareness about the potential of the projects in eradicating the ever-increasing power crisis in the district.

III. MATERIALS AND METHODS

A. Insolation Data

To predict the performance of the solar PV system the study employed the PVGIS5 hourly meteorological datasets (2006-2016). The PVGIS is among the accurate solar irradiation data source for solar electricity generation potential studies [18-21]. The validation and any information related to the data utilized in this study is available from Amillo *et al.,* (2014) [22].

Because of the absence of any responsible agency for weather monitoring and forecasting at the study site, this study adopted satellite irradiation data. However, even with ground-level solar radiation measurement, satellite data sources are often preferred in solar PV potential studies. Ground-level solar radiation measurement is prone to several limitations and errors, which can propagate inaccuracies in solar PV potential decisions. Among the major overarching problem of the ground level solar irradiation, is the failure of the measuring device itself, covering of the sensor by snow, dirt, frost and shadow by the buildings and trees around the measuring device [23-25].

B. Solar PV Generating Components

This study adopted 520 Wp solar PV system delivered by Tata power 260 Wp multi-crystalline solar photovoltaic module, in modelling the 1kW typical household electricity consumption profile. Table 1 provides the specifications of the selected solar PV system at Standard Test Condition (STC).

Tilt angle and azimuth angle are among the major parameters in ensuring maximum efficiency from the solar PV electrical system. The position of the study site falls in the region of Northern hemisphere, which requires an optimal angle of 0° (azimuth 0°) and according to models calculations, the best tilt angle for the study site was found to be 25° (i.e. 25° azimuths 0°) for the solar panel to receive maximum solar radiation to ensure maximum PV system output.

Table 1: Technical parameters of the PV system at STC (Standard Test Conditions) [26].

Parameter	Value
Nominal power (P_{max})	260
Panel area (m^2)	1.67
Open Circuit Voltage V_{OC} (V)	37.9
Short-circuit current I_{SC} (A)	8.80
Voltage at maximum power V_{MPP} (V)	30.6
Maximum power current I_{MPP} (A)	8.49
Module efficiency (%)	15.60
Power tolerance (W)	0 ~+5
Operating temperature range (°C)	-40 -+ 85

C. Solar PV Potential Estimation

In recent years, solar PV electricity generation is growing and becoming more competitive with other electricity generation technologies [24, 27]. Due to recent discoveries and advances, solar PV technology is now competitive to all other electricity generation technologies efficiency wise. Recently, researchers from the Fraunhofer Institute for Solar Energy Systems have developed a solar PV cell with 44.7% efficiency. This discovery is eventually showing the signs of reaching the 50% efficiency, which is similar to most of the global thermal power plants [28].

This study adopted the global benchmark model (Eqn. 1) for estimating the solar PV electricity output. The Performance Ratio (PR) is the parameter assigned to take account of all the system loses [22, 23, 24, 29, 30]. To improve the accuracy of the model, this study selected 0.75 optimal value in the calculations.

$$E = Ar\, G_i PR \qquad (1)$$

where,

E = Energy Output (W), A = Total solar panel Area (m^2), r = solar panel yield (%) GHI = Global Horizontal Irradiance, PR = Performance Ratio

The module operating temperature T_{mod} calculated using Eqn. 2 for comparison with the Nominal Operating Cell Temperature (NOCT) of the selected PV system. The model requires the ambient temperature T_{amb} and Global Horizontal Irradiance G_i as inputs.

$$T_{mod} = T_{amb} + 0.035 \cdot G_i \qquad (2)$$

It is important to points out that, the model is not taking account of the PV modules cooling due to the wind passing below the PV system which can increase the efficiency of the PV system up to the range of 0.7% [31-33].

For generating a typical household electricity demand profile,numerous methods based on estimates such as Interpolation method, ANN (Artificial Neural Networks), non-linear and multiple regression methods, etc. exist in the literature as reported in Gado *et al.,* [34] and Ramírez-Mendiola *et al*., [35].

This study proposed a typical household electricity demand approach based on the consumption of all the electrical appliances connected to a load of a typical household, during the total hours of the day. This method is similar to the method adopted by Pillai & Naser, [19], Gado *et al*., (2018) [24], and Ghazvini *et al*., [37].

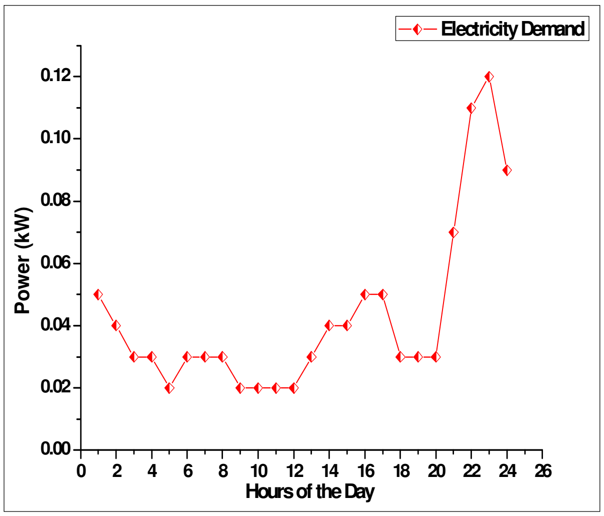


Fig. 4. Typical household electricity demand profile.

IV. RESULTS AND DISCUSSION

This section presents the results of the solar resources modelling at all level (monthly, seasonal and diurnal) for a clear understanding of the solar PV system in electricity generation overall potential.

A. Monthly Solar Resources and Energy Generation

As it is explicitly evident from Fig 5, the monthly insolation varies between 351.75 W/m^2 to 582.55 W/m^2 and the highest value of monthly irradiation are observed in the month of March and the corresponding lowest value in the month of June.

Additionally, the highest monthly temperature value of 29.72℃ is evident in the month of April, and the lowest value of 26.28℃ in the month of September. The advantage of low temperature below the selected PV module operating temperature will surely help in maximizing the solar PV system output throughout the year.

The simulation of the monthly average electricity generation depicted in Fig. 6 shows the highest power output in the month of March, and the lowest insolation as well as the lowest power output in the month of June. Preview Fig. 5, it is clear that the monthly simulations of the solar resources and the solar PV system at the site revealed the huge potential of the system for electricity generation at the site.

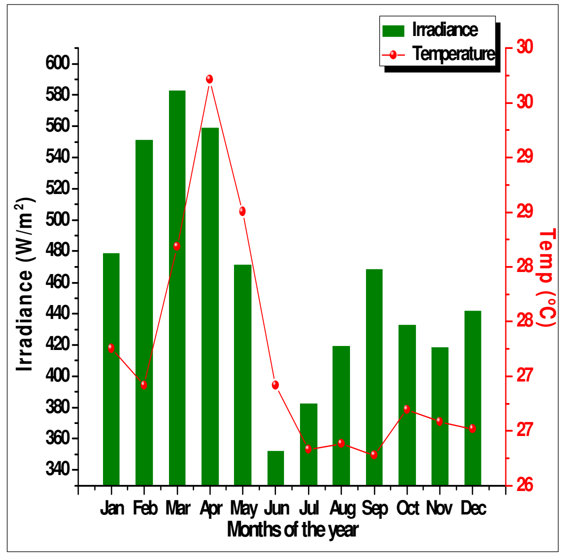


Fig. 5. Global Horizontal Irradiation and air temperature.

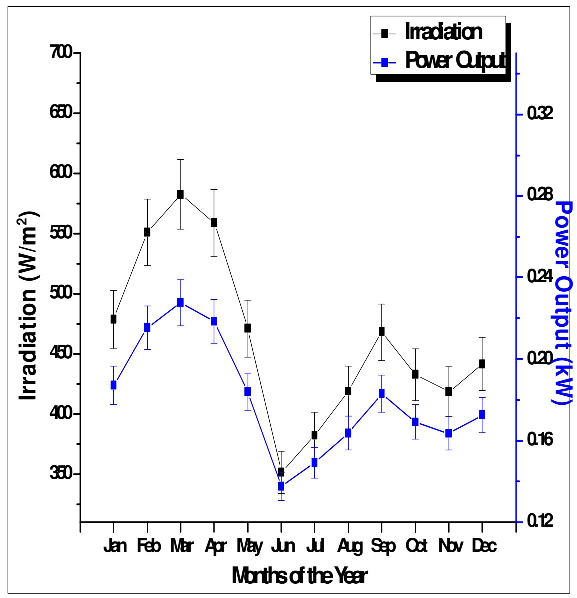
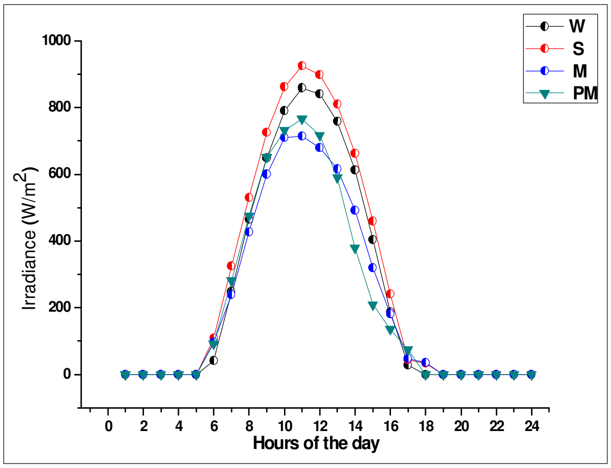


Fig. 6. Mean monthly insolation and solar PV performance.

B. Seasonal Variability and PV Potential

Considering the seasonal variability of solar resources in solar is very essential in the planning of any solar PV electricity system. The irradiation of a typical day across the seasons of the year at the site shown in Fig. 7 clearly revealed that the irradiation across the site shows a clear pattern of high values during the peak sunshine hours.

Fig. 8 (a-d) presented the simulation results of the solar PV system performance across the seasons of the year. The results show that the highest power output generated by the solar PV system is 2.59 kW in the summer season, 2.3kW in winter, 2.02kW, and 1.99kW in post-monsoon and monsoon respectively.

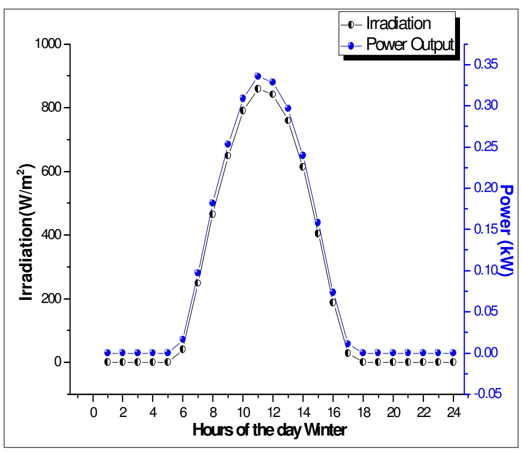


Summer: Mar, Apr, May   Winter: Dec, Feb, May

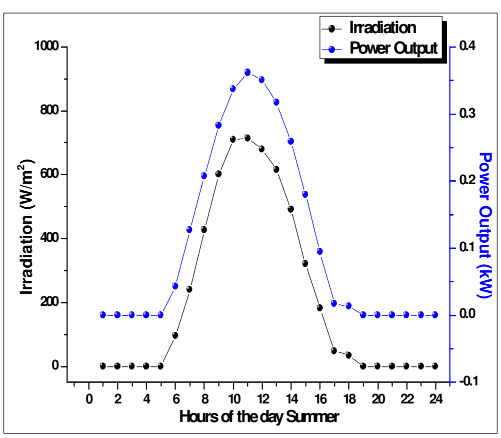
Monsoon: Jun, Jul, Aug, Sep   Post Monsoon: Oct, Nov

Fig. 7. Diurnal insolation across the seasons of the year.

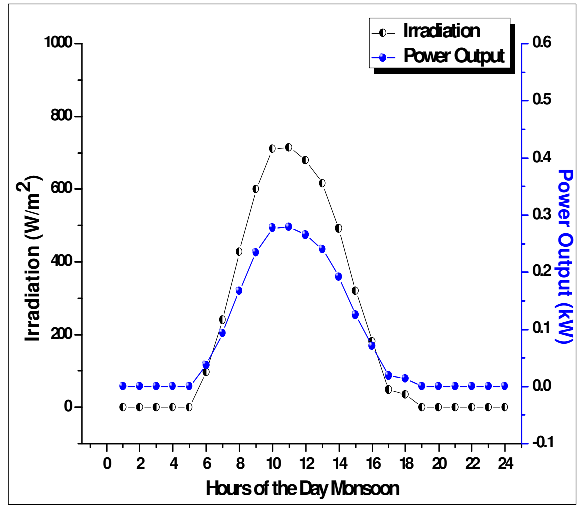
The figures demonstrate that the system performance across all the seasons during the sunshine hours is promising and can give high return in investment. The depletion of GHI as a result cloud cover in the monsoon equivalent season is responsible for the lower power output observed despite having the highest number of months based on the Köppen climate classification.



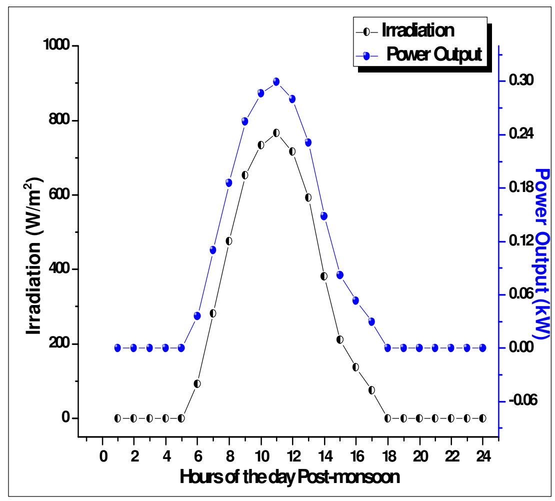
(a)



(b)



(c)



(d)

Fig. 8. Seasonal insolation and solar PV output simulation results (a) winter (b) summer (c) monsoon (d) post- monsoon.

The effects of other meteorological parameters such as wind speed and ambient temperature play a very vital role in the simulation of the solar PV systems.

Although the highest ambient temperature of 28.8°C exists in the summer equivalent season, which is having the highest insolation, as well as the highest solar PV, performance across the seasons of the year, it corresponds to 48°C module operating temperature using Eqn. 2. This value falls within the range of NOCT (Nominal Operating Cell Temperature) of the selected solar PV system. It is worth noting that, the NOCT calculations for solar PV systems are usually at a wind speed of 1m/s. However, the analysis of the wind speed data of the study site revealed 3m/s at 10m height. Hence, by putting into consideration the cooling advantage of wind passing below the solar PV system, this will surely reduce the module operating temperature, which will help in increasing the performance of the PV system to a substantial level.

C. Diurnal Solar PV System Simulation and Demand Dynamics

Fig. 9 presents the diurnal insolation and corresponding air temperature at the site. It clearly observed that there is sufficient insolation to support solar PV electricity generation at the site. As highlighted, temperature and other meteorological parameters such as wind speed and relative humidity can affect the efficiency of a solar PV system. The diurnal distribution of temperature of the study site revealed a higher temperature during the morning hours. This is not surprising because generally, there are diurnal temperature variations in humid areas compared to desert regions mainly because of large water bodies, soil type, cloud cover and moisture of the ground.

The insolation and corresponding estimated power output of a typical day shown in Fig. 10, gives an idea of how much energy is available from the solar PV system across all the seasons of the year. The diurnal analysis will improve the estimation accuracy by giving a realistic potential output for the sizing of the solar PV system. Without a proper diurnal analysis, the results of any renewable energy potential studies could sensibly compromise the performance of the solar PV system in real-time situations.

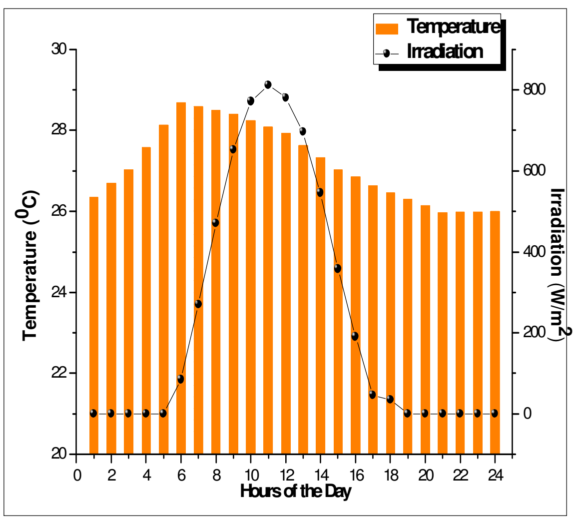


Fig. 9. Diurnal solar radiation and corresponding air temperature.

The information about the diurnal insolation and corresponding power output presented in Fig. 10, gives an idea about the energy available from the solar PV system at any hour of the day across all the seasons of the year. The diurnal analysis will improve the estimation accuracy by giving a realistic potential output that is required in sizing the solar PV system based on the electricity demand of the end-user. It is worth noting that without a proper diurnal analysis, the results of any solar PV potential studies could sensibly compromise the performance of the solar PV system in real-time situations.

This is among the novelty of this study in addressing this gap in the solar PV potential studies by presenting a novel demand dynamics.

Starting from the simulation results of the diurnal power output, Fig. 11 summarised the performance of the solar PV system against the typical household electricity consumption profile. By analyzing this figure, it is clear that there is a huge gap between the electricity demand and power output from the solar PV system during the sunshine hours.

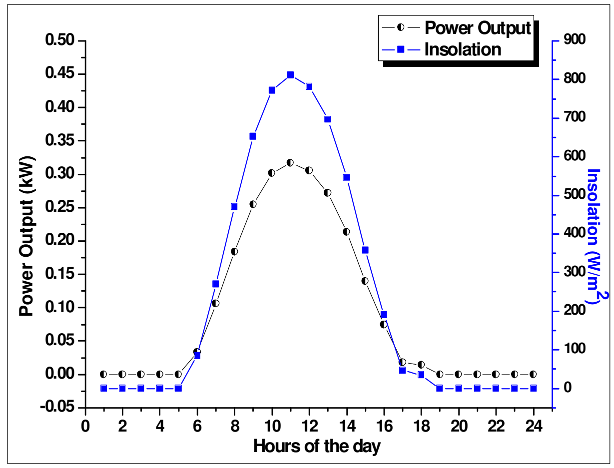


Fig. 10. Insolation and corresponding simulated power output.

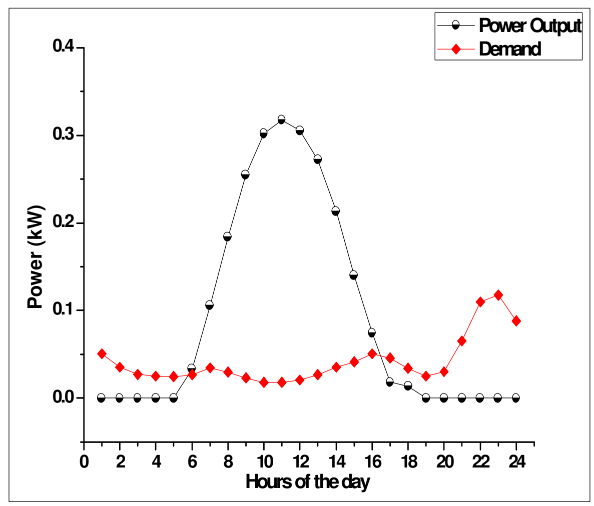


Fig. 11. Simulated solar PV output against the typical household electricity demand.

It is explicitly evident from Fig. 11, during the generation hours (sunshine hours) the generation exceeds the electricity demand greatly, which is justifying the need for storage system in the system design. In order to rigorously evaluate the potential, further analysis of the simulation results shows that with the storage option the total electricity demand of a typical household can be delivered by the solar PV system with additional 1.23kW excess power that can be exported to the grid.

V. CONCLUSION

Estimation of renewable electricity generation potential with substantive evidence derived from meteorological datasets has the prospect of providing to the authorities and individuals, clear and reasonable information in designing policies for the penetration of renewable energy sources in electricity generation. This paper proposed a novel approach in the assessment and analysis of solar PV electricity system for typical household electricity application. The monthly and diurnal solar PV potential of the site modelled using the global benchmark model for solar PV power output calculation revealed that the month of March has the highest insolation, and the lowest insolation is observed in the month of June. The overall diurnal analysis of the system revealed that with the aid of Battery Energy Storage System (BESS), the 520Wp solar PV system could deliver smoother and uninterrupted power to the typical household with 1.23 kW excess power to the national grid. Although the validation studies of the simulation results are per amount in establishing the potential studies, it is concluded beyond any doubt that solar PV electricity generation has greater potential that can be utilized for electricity generation at the study site.

VI. FUTURE SCOPE

Based on the obtained results, solar PV in Kasaragod can reduce the ever-increasing energy poverty, which is endemic to the district. Although we need to further the scientific investigations based on the findings of this study. This study is part of the series of studies to by the authors in identifying and validating the potential of renewable energy sources in electricity generation across the Kasaragod district of Kerala, India. It could be interesting to consider the validation studies of these potential studies in the near future. Additionally, the authors will consider designing a scenario based on different renewable energy sources in the form of hybrid.

Conflict of Interest. The authors declare that they have no conflict of interest

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