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Original Research Article

Assessing the feasibility of off-grid photovoltaic systems for rural electrification

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ABSTRACT

In this investigation, the absence of an electricity grid in numerous locations, including military bases, tiny houses, and chalets, prompted the development of a model for providing electrical energy through an off-grid Photovoltaic (PV) system in Konya, Türkiye. The study delineates the daily energy consumption of a residential dwelling as 39,974 Wh/day, and the feasibility of satisfying this demand through the implementation of a 9.45 kWp PV system is scrutinized. The research encompasses the determination of optimal tilt and azimuth angles set at 35° and 0°, respectively. The maximum global effective irradiation intensity, recorded in August at 208.3 kWh/m², contrasts with the minimum intensity observed in December, registering at 106.2 kWh/m². Likewise, electricity production attained its zenith in August at 1,581.3 kWh, starkly contrasting its lowest level in December at 791 kWh. Modelling outcomes conclude that Solar Fraction (SF) values equate to unity during summer but fall below unity during winter. Furthermore, a surplus in electricity generation relative to demand is observed during the summer, resulting in the full charge of batteries. Evaluating the annual average SF, it is deduced that the modelled system fulfils 90.8% of the energy requirement. The Performance Ratio (PR), an additional pivotal parameter in PV systems, reaches its zenith at 0.865 in November and its nadir at 0.614 in August. This comprehensive study underscores the efficacy of the modelled off-grid PV system in meeting the energy demands of the selected residence, emphasizing the significance of seasonal variations and key performance metrics in assessing system performance.

Keywords: Energy consumption; Photovoltaic modelling; PVsyst; Off-grid PV system; Rural electrification

1. Introduction

In pursuing sustainable development and universal access to electricity, off-grid photovoltaic (PV) systems have emerged as a promising solution, particularly for rural areas where traditional grid infrastructure is often challenging and expensive to implement [1]. This article delves into assessing the feasibility of off-grid photovoltaic systems for rural electrification, exploring the benefits, challenges, and considerations associated with this renewable energy solution.

In the aftermath of the COVID-19 pandemic, there has been a notable surge in interest and inclination toward rural and countryside living. Simultaneously, an increasing number of individuals are opting to relocate from urban centres to reside in chalets. Furthermore, certain military bases and outposts are strategically established in locations considerably distant from city centres, where the absence or inadequacy of an electricity network poses a formidable challenge. In such circumstances, implementing off-grid systems, including but not limited to wind energy and generators, particularly solar energy, emerges as a viable solution [2]. It is imperative to acknowledge that conventional fossil fuel systems incur substantial maintenance costs and necessitate continuous refuelling. In stark contrast, despite their upfront installation expenses, renewable energy systems boast minimal annual

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maintenance costs. The economic crises and escalating oil prices have significantly influenced the inclination of individuals and nations to turn toward renewable energy sources as a judicious alternative. This paradigm shift underscores the imperative for exploring sustainable and self-sufficient energy solutions, with solar energy prominently positioned as a viable contender in addressing the energy needs of remote and energy-deprived locales.

In recent years, solar energy systems have emerged as a prominent facet within renewable energy sources [3]. Their multifaceted applications span a spectrum encompassing electricity generation, hot water supply, heating, cooling, drying, and distillation [4]. Notably, Photovoltaic (PV) systems, adept at harnessing electrical energy through the absorption of photons from the sun, have gained widespread popularity in contemporary energy discourse [5, 6]. The efficacy of PV systems is contingent upon numerous variables, including panel type, panel geometry, and the geographical location of system deployment [7]. In this context, Türkiye, and more specifically, the region of Konya, occupy favourable positions relative to numerous European and global counterparts to solar radiation intensity. This is underscored by annual average values of 1524.18 kWh/m² for Türkiye and 1608.74 kWh/m² for Konya, as illustrated in Figure 1. In addition to radiation intensity, the duration of sunshine also assumes a pivotal role in influencing the performance of PV systems. Türkiye, with a daily sunshine duration of 7.52 hours, and Konya, with 7.95 hours, stand out as exceptionally suitable locales for the effective implementation of PV systems [8, 9].

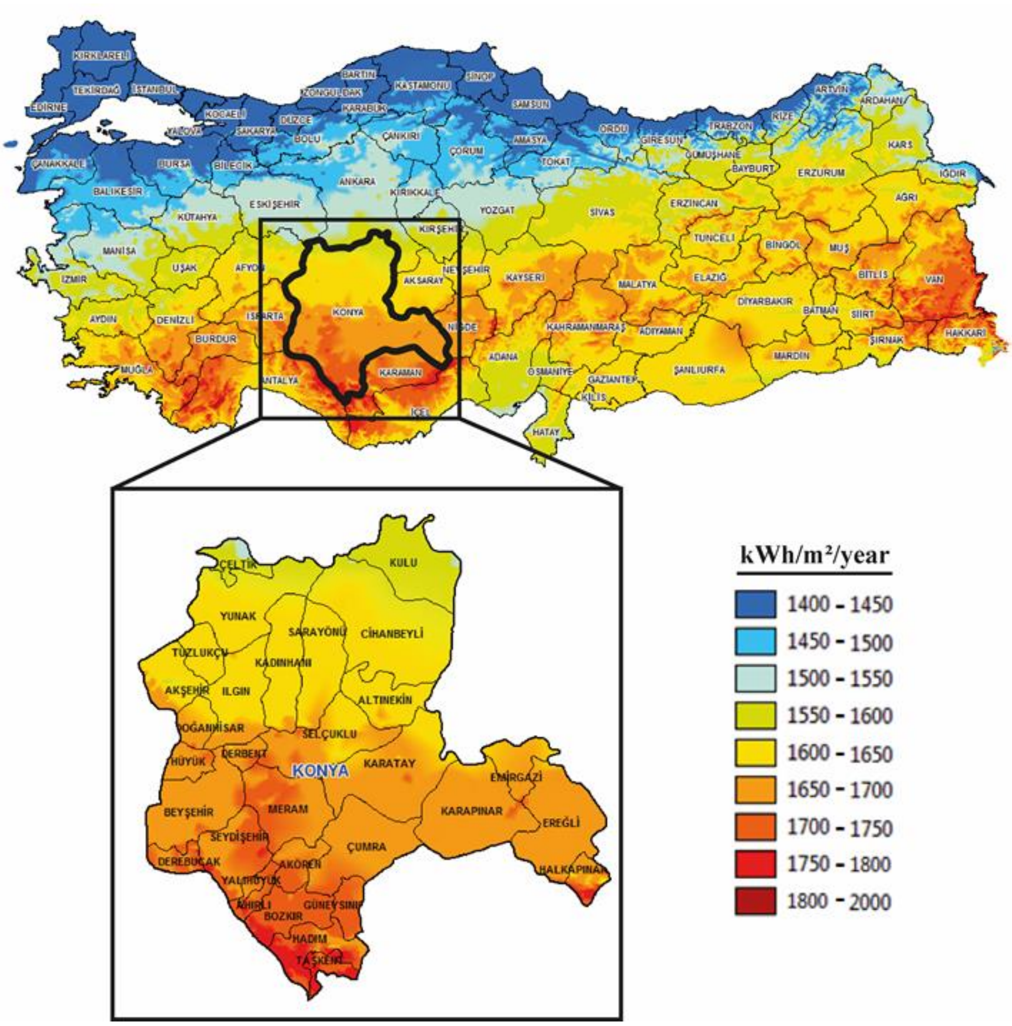

Fig. 1. Average annual solar radiation of Türkiye and Konya [10]

In contemporary discourse surrounding photovoltaic (PV) systems, a plethora of software solutions have been developed, including but not limited to RETScreen, HOMER, PV F-Chart, PVWatts, SolarPro, and PVsyst, as documented in numerous articles within the academic literature [11-14]. Notably, PVsyst distinguishes itself within this array of software due to its expansive selection of panel brands and models, comprehensive reporting features, an array of toolbars, and a dependable database, particularly in the domain of solar radiation [15, 16]. A salient advantage of

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PVsyst lies in its capacity to model both on-grid and off-grid systems [17], rendering it a preferred choice for various off-grid studies as evident in existing literature [18, 19].

Exemplifying the utilization of PVsyst, Kumar et al. [20] undertook a modelling endeavour for an office in Bikaner, India, necessitating a daily energy consumption of 2953 Wh. Their meticulous employment of PVsyst resulted in the annual satisfaction of 98.3% of the office's electricity requirements through a PV system boasting an installed power of 700 Wp. Similarly, Irwan et al. [21] conducted a PVsyst modelling exercise for a system demanding 2,016 kWh/day in Kangar, Perlis, Malaysia, achieving fulfilment through a 640 Wp PV system. This implementation allowed for the entirety of the energy demand to be met annually, generating 735.84 kWh of electricity, albeit with a 7.9% loss attributable to fully charged batteries. In a parallel study, Rekhashree et al. [22] modelled a daily electricity requirement of 9.3 kWh/day, striving to meet this demand with a PV system comprising ten modules, each with a unit power of 250 Wp. Their findings indicated that the system met 44.3% of the annual electricity requirement. Furthermore, Bhuvaneswari et al. [23] employed PVsyst to model a residential structure with an approximate daily electricity demand of 3 kWh, underscoring the software's versatility in accommodating diverse energy needs and system configurations.

2. Material and Methods

This investigation is dedicated to formulating a system to furnish electricity to an off-grid residence in Konya, Türkiye, utilizing the PVsyst software. The pertinent solar radiation data for the designated location were sourced from the Meteonorm database within the PVsyst framework, with geographic coordinates identified as 38.03 °N and 32.51 °E. The underlying assumption posits the system's uninterrupted operation at optimal yearly efficiency. Essential to the installation process is the prerequisite understanding of the unit electricity consumption and operational hours of the various household devices. The specific daily electricity requirements for the subject residence under consideration are delineated in Table 1, providing a comprehensive foundation for the subsequent modelling endeavours. It is considered to be working all lamps between 6 PM and 12 AM, TV and Laptop between 8 AM and 4 PM, Dish/Clothes washer between 12 PM and 2 PM, and Security System between 12 AM and 8 AM. Fridge and Heating/Cooling systems are assumed to operate 24 hours a day to prevent food spoilage and ensure air quality.

Table 1. Daily electricity needs of the modeled house

Appliance	Number	Unit Power	Usage Time	Energy
Lamps	6	15 W	6 h/day	540 Wh/day
TV/Laptop	1	200 W	8 h/day	1600 Wh/day
Heating/Cooling System	1	1150 W	24 h/day	27600 Wh/day
Fridge	1	62.5 W	24 h/day	1500 Wh/day
Dish/Clothes Washer	1	3150 W	2 h/day	6300 Wh/day
Security System	1	20 W	8 h/day	160 Wh/day
Hydrophore	1	750 W	3 h/day	2250 Wh/day
	Total			39974 Wh/day

It is assumed that the house has an area of 100 m² with floor dimensions of 10 m and 10 m. It was also assumed that the roof of the house was a triangular roof with a slope of 15° and one facade was towards the south. In this case, the floor area of the south-facing roof surface is 51.76 m². A tolerance of approximately 10% should be left in order to move easily between panels. In this case, the usable roof area corresponds to around 46.6 m². The investigation was executed through the utilization of PVsyst software. A fundamental consideration in off-grid systems lies in the requisite incorporation of batteries. The technical specifications for the PV panels and batteries employed in this study have been meticulously documented and presented comprehensively in Table 2.

Table 2. Technical characteristics of PV module and battery

PV Module		Battery	
Manufacturer	LG Electronics	**Manufacturer**	BAE Secura
Model	LG 450 N2W-E6	**Model**	BAE Secura Block Solar 12 V 3 PVS 210
Units power	450 Wp	**Technology**	Lead-acid, vented, tubular
Number of series	3	**Number of units**	13 in parallel × 8 in series
Number of strings	7	**Stored energy**	166.7 kWh
Number of units	21	**Voltage**	12 V
Nominal power	9.45 kWp	**Pack voltage**	96 V
Module area / Cell area	46.2 m² / 41.1 m²	**Capacity**	2171 Ah

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Tilt angle and azimuth angle significantly affect the efficiency of PV systems. Within the scope of the study, the optimum values for the location Konya were used, with the tilt angle of 35° and the azimuth angle of 0°. Shading losses due to panel row spacing are neglected due to roof application.

One of the paramount parameters indicative of the system's efficacy is the Performance Ratio (PR). This metric is derived by assessing the ratio of the electricity generated within a system relative to the unit installed power to the global horizontal irradiation incident upon the panel surface. It is defined mathematically as follows:

$$PR = \frac{E_G}{I_G \times P_{PV}} \tag{1}$$

Where, E_G is the amount of electrical energy produced, I_G is the global horizontal irradiation intensity and P_{PV} is the installed power of the system. Another important parameter in off-grid systems is Solar Fraction (SF) which is calculated as the ratio of generated electricity (E_G) to demanded electricity (E_D).

$$SF = \frac{E_G}{E_D} \tag{2}$$

3. Results and Discussion

The efficiency of PV systems depends on many angle values, especially azimuth and tilt angles. In addition, the location where the systems will be installed is critical. In the modelled system, the optimum angle values were selected as tilt and azimuth angles of 35° and 0°, respectively. The location is determined as Konya, Türkiye. Global effective irradiation (I_{GE}) values, which are directly proportional to the electrical energy obtained from the systems depending on the location, play a key role in PV systems. Monthly average I_{GE} values obtained at the specified location are given in Figure 2.

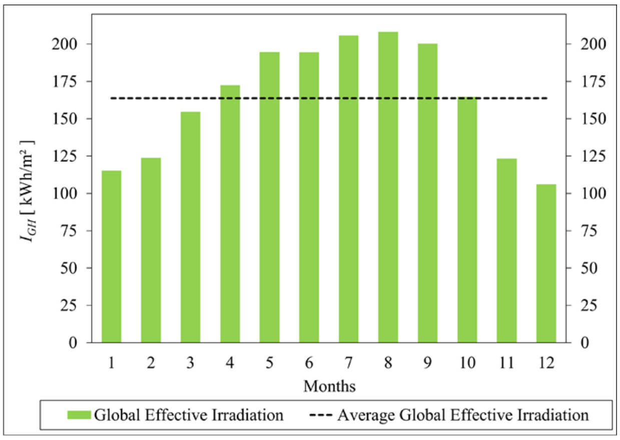

Fig. 2. Monthly average I_{GE} in Konya, Türkiye

Solar photons incident upon Konya, situated in the northern hemisphere, exhibit a varying angle of arrival, characterized by a more acute angle in winter and a broader angle in summer. Consequently, there is an observable augmentation in I_{GE} values reaching the panel surface during the summer months, juxtaposed with a decline during winter. August records the zenith in the maximum I_{GE} on the panel surfaces, registering at 208.3 kWh/m², while December attains the lowest with a 106.2 kWh/m² value. On an annual scale, the monthly average I_{GE} reaching the panel surfaces is computed as 163.66 kWh/m².

It is known that the I_{GE} values reaching the panel surfaces directly affect electricity production, and the irradiation intensity and the generated electricity value are directly proportional. Monthly average used electrical energy, excess electrical energy, and demanded electrical energy amounts are given in Figure 3.

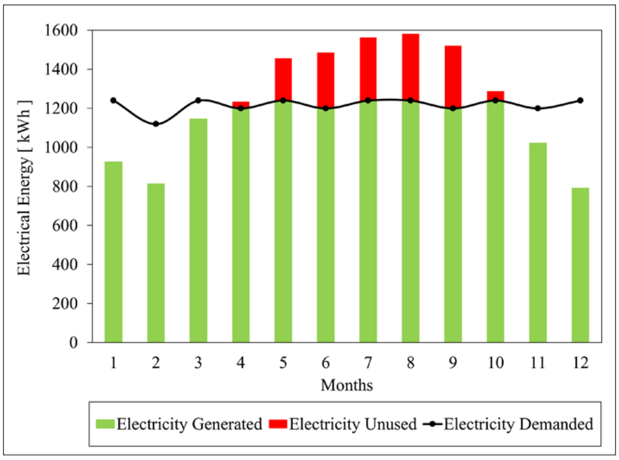

Fig. 3. Monthly average used, missed, and unused electrical energy

Due to less I_{GE} reaching the panel surfaces during winter, the demanded electrical energy levels could not be reached with the current system. The desired electricity levels were reached in the summer months. It was understood that the number of batteries was insufficient, especially in July and August. Due to the I_{GE} intensity on the panel surface, maximum electricity generation was obtained in July and August with 1563.4 kWh and 1581.3 kWh values, respectively. During these months, 324.4 kWh and 342.3 kWh of energy were unused respectively, and the battery capacities were full. The minimum electricity generation was achieved in December with a value of 791 kWh. When the minimum and maximum electricity production were compared, it was seen that there was a difference of 99.92%. It has been observed that the amount of energy produced varies seasonally.

It is known that PR and SF are parameters that show system performance in PV systems. Monthly average PR and SF values obtained using Eq. (1) and (2) are given in Figure 4.

It is established that an excess of electrical energy is generated during the summer months, resulting in SF values attaining unity during this period. Conversely, in winter, SF values diminish below unity due to the inadequacy of

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generated electrical energy and insufficient stored energy. Notably, the minimum SF value, indicative of the lowest electricity generation, is observed in December, registering at 0.638. When assessed annually, the cumulative SF value reaches 0.908, denoting that the current system satisfactorily meets the annual electricity requirements of the modeled residence at 90.8%.

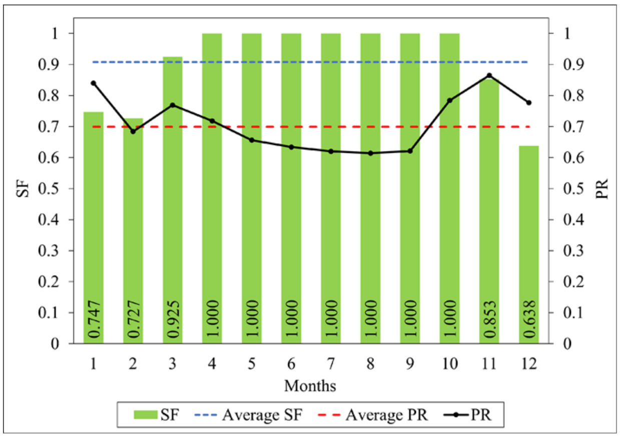

Fig. 4. Monthly average SF and PR values

The Performance Ratio (PR) is acknowledged to exhibit an inverse relationship with global horizontal irradiation incident upon the panel surface and a direct proportionality with the electrical energy produced. An intriguing observation is the decrease in PR values during the summer months, concomitant with an increase during the winter months, attributed to heightened losses with increased energy generation. August records the minimum PR value at 0.614, while the maximum is observed in November at 0.865. The annual average PR value is computed at 0.699. These trends underscore the dynamic nature of PR values in response to seasonal fluctuations and energy production.

4. Conclusion

In this study, a model was developed to fulfill the energy requirements of a house in Konya by implementing an off-grid Photovoltaic (PV) system utilizing PVsyst software. The optimal tilt and azimuth angles for the system were judiciously determined as 35° and 0°, respectively. The key findings derived from the study are succinctly summarized below:

- I_{GE} exhibits a discernible seasonal pattern, ascending during summer and descending during winter. The pinnacle of I_{GE}, recorded in August at 208.3 kWh/m², contrasts with the nadir observed in December, registering at 106.2 kWh/m². The annual average I_{GE} is computed at 163.66 kWh/m².
- As I_{GE} significantly influences electricity generation, the study reveals a concordant increase in electricity generation during summer and a corresponding decrease during winter. Consequently, the electricity demand is entirely met in the summer, while inadequacies in production are discerned during the winter.
- The maximum electricity production, recorded at 1563.4 kWh, transpires in August, whereas the minimum generation, documented at 791 kWh, occurs in December.
- Solar Fraction (SF) values, attaining unity in the summer months, contrast with a minimum SF value of 0.638 in December. The annual average SF value substantiates that the modeled PV system fulfills 90.8% of the stipulated energy requirements.
- The Performance Ratio (PR), inversely correlated with incoming radiation, manifests its maximum value in November at 0.865 and its minimum in August at 0.614. The annual average PR value is ascertained to be 0.699.

Upon analysis, it is established that the modelled PV system meets 90.8% of the prescribed energy requirements. Agricultural fields can be irrigated with the energy that cannot be used in the summer months. The energy need problem in winter months can be solved with a generator or heat pump.

Authorship contribution statement for Contributor Roles Taxonomy
Murat Ispir: Writing, Investigating, Visualization, Methodology
Muharrem Hilmi Aksoy: Writing, Investigating, Conceptualization, Supervision, Review and editing, Methodology

Conflict of interest
The author(s) declares that he has no conflict of interest.

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