

Design and Development of Solar Powered E-Rickshaw for Sustainable Transport

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Abstract - Sustainable transportation and efficient waste management are key components of green campus initiatives. This paper presents the design and development of a solar photovoltaic (PV) powered electric cargo E-rickshaw intended for biomass waste transportation within a university campus. The proposed system integrates a 1.5 kWp solar PV array with a 48 V battery storage system using an MPPT charge controller. The vehicle uses a 900 W BLDC motor and four 12 V; 100 Ah batteries connected in series. PV system performance was analyzed using PVsyst simulation software. Results show annual solar energy production of approximately 1427 kWh with a solar fraction of 97%. The system significantly reduces dependency on grid electricity while improving campus waste management and reducing manual labor. The proposed model can serve as a replicable sustainable mobility solution for educational institutions and rural campuses.

Key Words: E-rickshaw, Battery Energy Storage System, Solar photovoltaic, Green campus mobility, Renewable energy integration

1.INTRODUCTION

The rapid increase in energy demand and environmental concerns has driven significant interest in sustainable transportation systems. Electric vehicles (EVs) are widely recognized as an effective solution to reduce greenhouse gas emissions and dependence on fossil fuels. In recent years, solar-powered EVs have emerged as a promising advancement, as they utilize renewable energy through photovoltaic (PV) systems to enhance efficiency and minimize environmental impact. Typically, such systems incorporate PV arrays, battery storage, and Maximum Power Point Tracking (MPPT) techniques to optimize energy extraction and improve overall performance [1].

To further strengthen energy reliability, hybrid renewable energy systems have been explored. A solar-wind integrated system has been proposed to support both residential loads and EV charging under varying grid conditions, ensuring improved stability and energy availability [2]. In addition, continuous advancements in battery technologies and energy management systems have significantly enhanced EV performance, lifespan, and operational efficiency. However, the expansion of charging infrastructure and implementation of supportive policies remain critical factors for large-scale adoption [3].

The integration of renewable energy-based charging infrastructure plays a crucial role in reducing carbon emissions. Techno-economic studies have demonstrated that hybrid systems combining solar PV, wind energy, and battery storage can achieve sustainable and cost-effective operation compared to conventional grid-based systems [4]. Similarly, hybrid energy configurations have proven beneficial in off-grid and rural applications. For instance, a solar PV-diesel generator system has been developed to provide uninterrupted power supply to remote agro-processing units. The incorporation of intelligent control strategies enables effective load management while reducing fuel consumption and operational costs [5].

With the growing penetration of EVs, existing power grids are experiencing increased stress due to higher charging demands. To address this issue, grid-connected solar-based EV charging stations have been introduced, allowing excess energy to be fed back into the grid. Optimization techniques applied to these systems indicate improvements in efficiency and economic feasibility [6]. In EV propulsion systems, Brushless DC (BLDC) motors are widely utilized due to their high efficiency and reliability. However, maintaining stable performance under transient and steady-state conditions remains a challenge. To overcome this, advanced MPPT methods such as Harris Hawks Optimization (HHO) have been implemented, ensuring faster convergence and better energy utilization. Additionally, PID controllers are

employed for precise speed control under varying environmental conditions like shading and irradiance fluctuations [7].

The performance of PV systems is highly dependent on environmental factors such as temperature and solar irradiance. Therefore, efficient MPPT techniques, including modified perturb and observe (MP&O), are adopted along with power electronic converters to maximize power extraction. These systems integrate PV modules, DC–DC converters, and battery management systems to ensure reliable operation under dynamic conditions [8–9].

Recent developments in electric mobility emphasize the use of advanced control strategies and energy management techniques to improve system efficiency and reliability. Despite these advancements, many existing solar-assisted e-rickshaw systems utilize limited PV capacity, which restricts energy generation. To address this limitation, improved configurations with multiple PV modules and optimized mounting strategies have been proposed. The implementation of partial power processing schemes further enhances efficiency while reducing converter stress. These approaches have been validated through MATLAB/Simulink simulations for both vehicle and DC microgrid applications [10–11].

Another important approach toward sustainable mobility is the retrofitting of conventional auto-rickshaws into electric vehicles. This method allows the reuse of existing vehicle structures, reducing overall costs while maintaining performance. Studies have shown that retrofitted e-rickshaws can serve as an efficient and environmentally friendly alternative to traditional fuel-based vehicles [12].

Furthermore, modelling and performance evaluation of solar-powered e-rickshaws have been carried out under different operating conditions. These systems integrate key components such as battery storage, motor drives, onboard solar charging, and grid support. Simulation results indicate reliable system performance and improved operational efficiency [13]. Since e-rickshaws are widely used for last-mile connectivity, the design of efficient charging infrastructure must consider user behavior, energy demand, and operational patterns to ensure optimal performance [14].

Solar-powered e-rickshaws offer significant advantages, including reduced dependence on grid charging, improved range, and enhanced sustainability. However, gaps in awareness, communication, and system optimization still limit their widespread adoption. Detailed modelling and simulation studies, including battery management systems (BMS), drivetrain analysis,

and drive cycle evaluation, have demonstrated the potential of these systems under varying load and speed conditions [15–18].

In summary, the integration of solar PV systems with EV charging infrastructure presents a viable pathway toward sustainable transportation. Although considerable progress has been made, challenges related to system optimization, cost, and large-scale implementation continue to exist. Therefore, further research and development are required to improve the efficiency, reliability, and economic feasibility of solar-powered EV technologies [19].

2. Propose System Design and Analysis

2.1 Architecture

The proposed system presents an integrated solar-powered electric rickshaw architecture in which photovoltaic (PV) modules serve as the primary energy source. The inherently variable PV output is interfaced with a DC–DC converter operating under Maximum Power Point Tracking (MPPT) control to ensure optimal energy extraction under changing irradiance and temperature conditions. The regulated DC output is supplied to the battery pack through a charging interface, while a changeover switch enables selective connection between solar charging and an auxiliary source if required. A Battery Management System (BMS) supervises the battery operation by continuously estimating the state of charge (SOC) and monitoring voltage, current, and thermal limits. Based on these parameters, the BMS controls the ON/OFF switching stage to prevent overcharging, deep discharge, and unsafe operating conditions, thereby enhancing battery lifespan and system reliability.

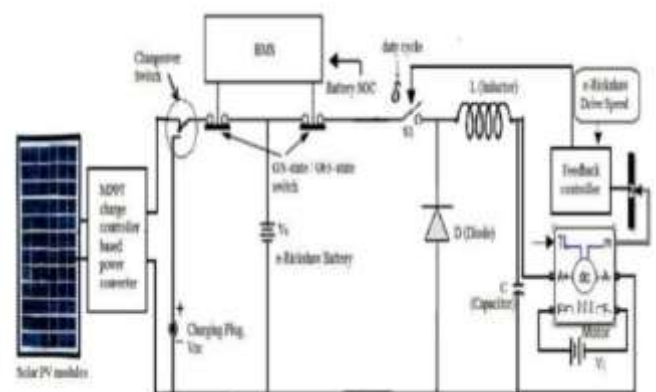


Fig.1 Circuit diagram for Solar Powered E-Rickshaw

The propulsion stage employs a DC–DC power conversion topology consisting of a controlled switch

(S1), inductor (L), diode (D), and capacitor (C), forming a step-down (buck-type) converter that regulates the motor input. The switching action is governed by a pulse-width modulation (PWM) signal with duty cycle (δ), which directly controls the average output voltage supplied to the motor. During the ON state, energy is stored in the inductor, and during the OFF state, it is transferred to the load through the diode, while the capacitor filters voltage ripples to maintain a stable DC output. The motor, typically a DC or BLDC type, converts the electrical input into mechanical torque for vehicle propulsion. A closed-loop feedback controller monitors the drive speed and compares it with a reference value, dynamically adjusting the duty cycle to achieve precise speed regulation and improved transient response. This coordinated control strategy ensures efficient energy utilization, reduced losses, and stable operation under varying load and driving conditions.

2.2 Specifications

The key specifications of the proposed solar PV-powered e-rickshaw include its dimensions, motor, battery, charging system, range per charge, maximum speed, suspension, controller, wheels, brakes, total weight, and load capacity. These parameters determine the vehicle's overall performance, efficiency, and usability, and are summarized in Table 1.

Parameter	Value
Dimensions	2800x1000x1800 mm
Motor	48V, 900W, BLDC Motor
Battery	100 AH x 4 (12v)
Battery Charge	EV Battery Charger (23v to 48v)
Distance Covered After Each Charging	90-110 km
Maximum Speed	25km / hr
Front Suspension	Telescopic
Controller	DC Brushless Controller
Wheel size	12"
Brake	Mechanical drum
Total Weight	380 kg
Load Capacity	520 kg

Table.1 Specifications of E-Rickshaw

2.3 Battery Energy Storage System

The Battery Energy Storage System (BESS) plays a critical role in ensuring the reliable operation of the solar PV-powered e-rickshaw by storing energy generated from the solar panels for use during periods of low or no sunlight. The system employs either lithium-ion or lead-acid batteries, selected based on factors such as energy density, lifecycle, charging efficiency, and cost. In the proposed design, four 12 V batteries are connected in series to provide a total supply voltage of 48 V, with a combined capacity sufficient to cover the daily travel requirements of the vehicle.

The BESS is managed by the charge controller, which regulates the charging and discharging cycles to maintain optimal state-of-charge (SoC) and prolong battery life. Additionally, the system ensures protection against overcharging, deep discharging, and short circuits, thereby enhancing safety and reliability. The performance of the BESS directly influences the overall range, efficiency, and operational feasibility of the e-

rickshaw, making it a key component in the sustainable design of the vehicle.

3. Cost Benefit Analysis

The solar PV-powered electric rickshaw is recognized as a sustainable alternative to conventional petrol or diesel rickshaws due to its economic and environmental advantages. A higher initial investment is required for the electric system, mainly attributed to components such as the solar PV modules, battery bank, BLDC motor, and control electronics. Typically, a 1 kW solar array combined with a 48 V, 100 Ah battery contributes to a major portion of the upfront cost. In contrast, conventional rickshaws are available at a lower purchase price; however, continuous expenses related to fuel consumption, lubrication, routine servicing, and engine component replacement are incurred during operation. Over the vehicle's lifecycle, it is observed that the cumulative fuel expenditure of a conventional rickshaw often surpasses the initial cost of an electric rickshaw system, thereby improving its economic feasibility over time.

Higher operational efficiency is achieved in electric rickshaws due to the use of BLDC motors, which typically operate with efficiencies exceeding 85%, along with solar energy integration that minimizes electricity costs. Recurring fuel expenses are eliminated, and maintenance requirements are reduced because of fewer mechanical components. Significant environmental benefits are also offered, as harmful emissions such as CO₂, NO_x, and particulate matter are not produced during operation, unlike in internal combustion engine-based rickshaws. Additionally, lower noise levels are experienced due to the quiet functioning of electric motors. Reliable performance is ensured by the battery energy storage system (BESS), which maintains a stable power supply during low solar irradiance or peak demand conditions. When total cost of ownership (TCO) is evaluated, including savings in fuel and maintenance, the solar-powered e-rickshaw is found to be more economical, with a typical payback period of 2–4 years in regions with high solar availability. Thus, despite the higher initial cost, the system proves to be a cost-effective, energy-efficient, and environmentally sustainable solution for modern urban transportation.

4. Simulation Results and Discussion

4.1 Daily solar input-outputs

The variation in the performance of the PV system throughout the year is represented by the daily solar input–output characteristics. In this analysis, the energy generated by the plant is plotted against the solar irradiation incident on the collector plane, as illustrated in Fig. 3. Each data point corresponds to the electrical energy output of the PV system for a given value of global incident solar energy. This representation provides a clear understanding of how the system responds to varying irradiation levels over different days.

It is observed that a significant concentration of data points lies within the range of 4–5 kWh/day, indicating that the system consistently generates energy within this range for most days of the year. Under favourable environmental conditions, the maximum energy output reaches approximately 8–8.5 kWh/day. As the average energy demand of the system falls within this operating range, the PV system is capable of meeting the load requirements under typical weather conditions. Consequently, reliance on grid electricity and conventional fossil fuel-based energy sources is substantially reduced, enhancing the overall sustainability of the system.

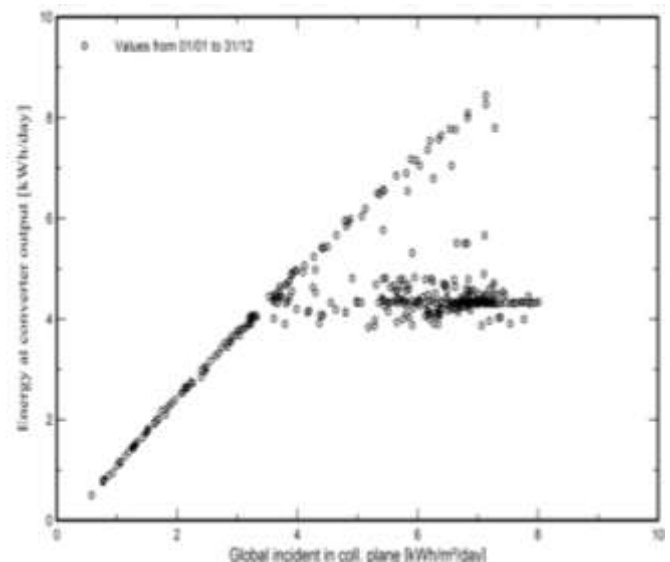


Fig.3 Daily solar input/ outputs of the PV system

4.2 Normalized Productions

Normalized energy production parameters are used as key performance indicators to evaluate PV system efficiency by accounting for different losses and energy outputs. These parameters are expressed with respect to the nominal installed capacity of the PV array under Standard Test Conditions (STC), typically in kWp, as specified by manufacturers. As a result, they remain independent of

system size, while being influenced by factors such as geographical location, solar irradiance, and array orientation. The normalized production metrics of the PV plant, illustrated in Fig. 4, provide insight into system performance under real operating conditions.

The PV array loss (L_c) represents the reduction in energy at the array level due to factors such as temperature rise, low irradiance conditions, partial shading, dust accumulation, DC wiring losses, and module mismatch. For the proposed system with fixed tilt configuration, the array capture loss is estimated to be around 1.01 kWh/kWp/day, reflecting environmental and operational impacts. The system loss (L_s), also referred to as inverter loss, accounts for losses during power conversion and transmission, including AC wiring losses and inverter inefficiencies, and is observed to be approximately 0.36 kWh/kWp/day. The final yield (FY) indicates the net usable AC energy output per unit installed capacity and is calculated by normalizing the daily delivered energy with respect to the rated array power under STC conditions. For the proposed hybrid system, the final yield is found to be about 2.61 kWh/kWp/day, which represents the effective energy available to the end user and serves as a reliable metric for performance comparison across similar PV installations.

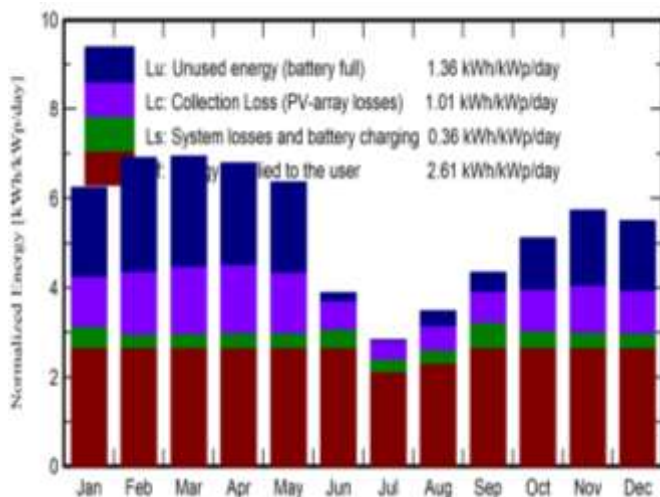


Fig.4 Normalized productions of the PV system

4.3 Performance Ratio

The performance ratio (PR) is expressed as a percentage and represents the ratio between the actual energy output and the theoretical energy generation of a solar PV system. It serves as an important indicator of how effectively the installed system converts available solar energy into usable electrical power. For the proposed PV plant, the PR attains its peak value in the range of approximately 75–78% during the months of June to September, while lower values of about 38–42% are

observed from February to May, as illustrated in Fig. 5. The average annual performance ratio is calculated to be around 48.88%, reflecting the overall efficiency of the system across varying environmental conditions.

The variation in PR throughout the year is primarily influenced by factors such as temperature fluctuations, irradiation levels, and inherent system losses. Despite these variations, the system demonstrates stable and acceptable performance over the entire operating period. Additionally, the Solar Fraction (SF) of the system is estimated to be 97.18%, which indicates that a major portion of the total energy demand is fulfilled by the solar PV system. This highlights the effectiveness of the proposed design in minimizing dependence on conventional energy sources and enhancing the sustainability of the system.

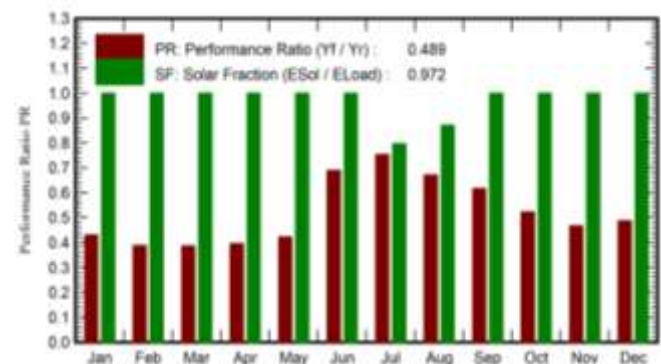


Fig.5 Performance ratio of the PV system

4.4 Loss and energy flow

Energy losses in a solar photovoltaic (PV) system occur at multiple stages, as depicted in Fig. 6. These losses arise primarily due to array capture inefficiencies, system-level losses, temperature variations in PV cells, and environmental factors such as soiling and module degradation. Collectively, these parameters have a significant impact on the overall system performance and energy output.

Under Standard Test Conditions (STC), the PV array operates with a conversion efficiency of 15.92% for a fixed tilt configuration, resulting in a nominal energy generation of 19.92 MWh. However, this theoretical value is reduced due to environmental and operational losses. Consequently, the effective energy available at the array level is evaluated at the Maximum Power Point (MPP), where the virtual array energy is estimated to be 16.91 MWh.

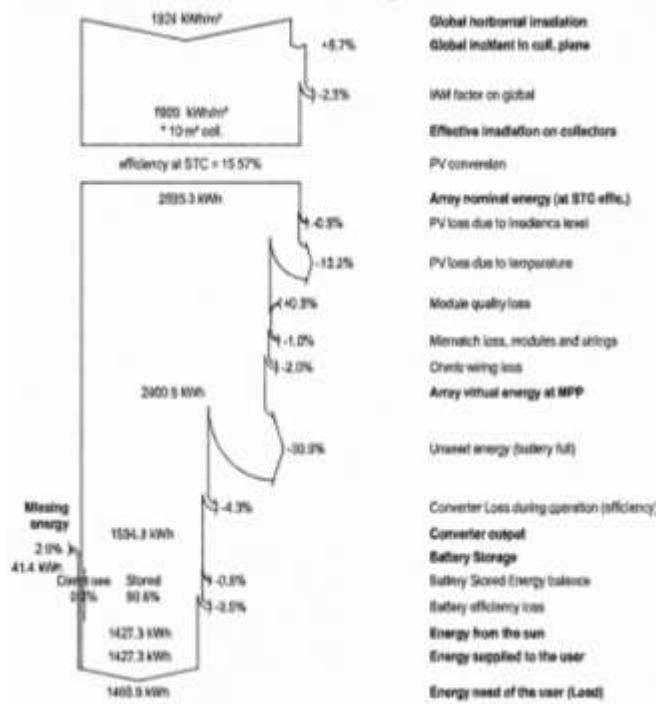


Fig.6 Loss and energy flow diagram of the PV system

Further reduction in energy occurs during the power conversion stage due to inverter losses. After conversion, the net energy available at the inverter output is found to be 16.50 MWh. This generated energy is then divided between local consumption and grid export. It is observed that 6.44 MWh of energy is utilized for local loads, while the remaining 10.06 MWh is delivered to the grid.

During periods of low solar irradiance or when solar energy is unavailable, the system depends on grid support to meet load requirements. In such conditions, approximately 9.69 MWh of energy is imported from the grid, ensuring continuity and reliability of power supply. This emphasizes the importance of grid integration in solar PV systems.

4.5 Balances and main results

The energy balance and key performance results of the PV system are summarized in Table I. The total available solar energy (E_{Avail}) for the proposed system is estimated to be 2296.8 kWh/year. Out of this, 1427.3 kWh/year (E_{User}) is effectively supplied to the end user. The unused energy (E_{Unused}), amounting to 742.5 kWh/year, occurs when the battery reaches its fully charged state and excess energy cannot be stored.

A small portion of energy, defined as missing energy (E_{Miss}), is calculated to be 41.4 kWh/year. This deficit arises due to insufficient solar irradiance during certain periods of operation. Seasonal variations significantly

influence system performance, with peak energy generation observed between March and May, while minimum output occurs during July and August due to reduced solar radiation.

The total annual energy demand (E_{Load}) of the user is 1468.8 kWh/year, and it is largely satisfied by the solar PV system. The system demonstrates a high solar fraction (SF) of 97.18%, indicating that the majority of the load demand is met through solar energy. Additionally, the performance ratio (PR) is determined to be 48.88%, which reflects the overall efficiency and effectiveness of the PV system under real operating conditions.

4.6 Global System Configuration

The proposed solar PV system is designed for TSSM BSCOER, Pune, (MH) India. The latitude of the site location is 18.52° N, whereas the longitude is 73.86° E, with an altitude of 545 m.

Monthly meteorological parameters such as global horizontal irradiation, diffused irradiation, ambient temperature, and wind velocity for the proposed site are considered for system analysis.

Fig. 7 shows the Sun Path diagram of the proposed site, which is used to determine the position of the sun at different times of the day and throughout the year. The diagram represents the variation of solar altitude and azimuth angles, which helps in selecting the optimal tilt angle (~20°) and orientation of the PV panels for maximum solar energy capture.

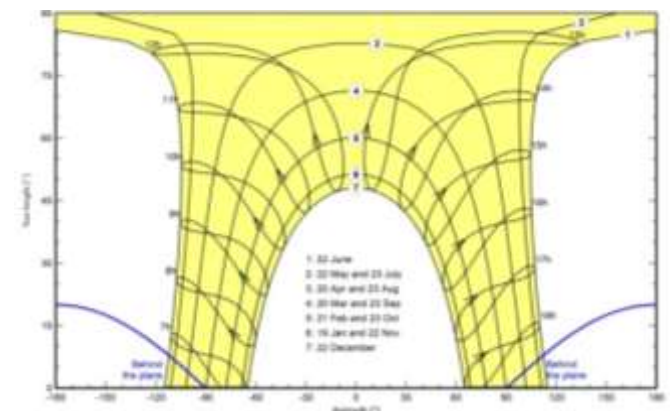


Fig.7 Sun Path Diagram of Campus

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5.CONCLUSION

The standalone solar photovoltaic (PV) system with a capacity of 1.5 kWp integrated with battery storage is successfully designed to meet the energy requirements of a solar-powered e-rickshaw for green campus mobility. The system delivers an annual useful energy of 1427.3 kWh, with a specific generation of 952 kWh/kWp/year, indicating satisfactory performance under given climatic conditions. A high solar fraction of 97.18% confirms that most of the load demand is met through solar energy. However, an energy deficit of 41.4 kWh/year occurs during low irradiance periods, while 742.5 kWh/year remains unutilized due to battery storage limitations. The overall performance ratio of 48.88% reflects the impact of temperature, battery, and conversion losses. Despite these losses, the system demonstrates reliable and efficient operation for real-world implementation. The proposed system provides a sustainable and eco-friendly solution for e-rickshaw operation by reducing dependence on conventional energy sources, lowering carbon emissions, and supporting clean transportation. It also offers economic benefits through reduced operational costs and energy savings. The modular design

enables scalability for larger applications such as fleet-based systems. Future work may focus on improving performance through advanced battery technologies, smart energy management systems, IoT-based monitoring, and optimized PV configuration.

NOMENCLATURE

e_avail	available solar energy	kwh
e_user	energy supplied to user	kwh
e_load	energy demand of the user (load)	kwh
e_unused	unused energy (battery full condition)	kwh
e_miss	missing energy (energy deficit)	kwh
e_solar	energy from the sun	kwh
glob hor	global horizontal irradiation	kwh/m ²
globeff	effective global irradiation	kwh/m ²
	(after corrections)	
t_amb	ambient temperature	°c
windvel	wind velocity	m/s
pr	performance ratio	%
sf	solar fraction	%.

	GlobHor	GlobEff	E_Avail	E_Unused	E_Miss	E_User	E_Load	SolFrac
	kWh/m ²	kWh/m ²	kWh	kWh	kWh	kWh	kWh	ratio
January	156.9	188.7	231.9	90.7	0.00	124.7	124.7	1.000
February	166.7	189.6	226.0	105.6	0.00	112.7	112.7	1.000
March	200.6	210.4	247.0	113.1	0.00	124.7	124.7	1.000
April	204.5	198.9	231.4	100.9	0.00	120.7	120.7	1.000
May	208.7	191.8	226.6	92.2	0.00	124.7	124.7	1.000
June	125.7	113.0	139.7	7.5	0.00	120.7	120.7	1.000
July	92.8	84.8	105.6	0.0	25.38	99.4	124.7	0.797
August	111.9	104.8	130.2	14.8	16.06	108.7	124.7	0.871
September	128.5	126.8	158.2	18.3	0.00	120.7	120.7	1.000
October	145.1	154.8	189.1	52.8	0.00	124.7	124.7	1.000
November	144.7	168.3	205.5	74.8	0.00	120.7	120.7	1.000
December	138.4	166.7	205.9	71.6	0.00	124.7	124.7	1.000
Year	1823.9	1898.6	2296.8	742.5	41.43	1427.3	1468.8	0.972

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