Hybrid Solar-Hydropower Systems for Green Energy Production: A Comprehensive Analysis

R J Anandhi[1*], Navdeep Singh[2], *Deepthi* Palakurthy[3], *Dinesh* Kumar Yadav[4], *Ali* Albawi[5], *Ashish* Kumar Parashar[6], *P* Jithendar[7]

[1]Department of Information Science Engineering, New Horizon College of Engineering, Bangalore, India.
[2]Lovely Professional University, Phagwara, India.
[3]Department of AI&ML, GRIET, Bachupally, Hyderabad, Telangana, India.
[4]Lloyd Institute of Engineering & Technology, Knowledge Park II, Greater Noida, Uttar Pradesh, India.
[5]Radiology Techniques Department, College of Medical Technology, The Islamic University, Najaf, Iraq
[6]Lloyd Institute of Management and Technology, Greater Noida, Uttar Pradesh, India-201306
[7]Department of Electrical and Electronics Engineering, MLR Institute of Technology, Hyderabad, Telangana, India-500077

Abstract. This paper presents a detailed analysis of hybrid energy systems combining solar photovoltaic (PV) panels and hydropower technologies. Focusing on the increasing popularity of Archimedes screw generators for low head sites, we examine the efficiency and environmental benefits of such systems, particularly in reducing greenhouse gas emissions as part of global efforts like the Paris Agreement. We explore the integration of solar and hydropower systems in the context of Brazil's renewable energy hybridization and discuss the challenges of their stochastic nature on power grid integration. The paper delves into the theoretical foundation, mathematical simulations, and optimization models that enable these hybrid systems to maintain energy and irrigation balance. The paper also investigates the use of photovoltaic-battery energy storage systems in building power supply and the potential of micro-grids featuring an array of renewable energy technologies. Ultimately, we present a novel approach to off-grid hybrid system deployment contributing to sustainable development goals.

Keyword-: Power generation, solar power, hydro power, hybrid energy systems, green energy.

1 Introduction

One important kind of energy is renewable energy, which includes solar and hydropower. While solar energy collects radiant heat and light from the sun, hydro energy uses the force of moving water. These energy sources are combined to provide power in hybrid energy

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[*] Corresponding author: *rjanandhi@hotmail.com*

systems as shown in Fig.1, which increases their economy and environmental friendliness. Because of their great efficiency and minimal impact on the environment, Archimedes screw generators, or ASGs, are getting more and more common in low head sites. [1] As the head gets closer, these technologies can continue to operate at high efficiency levels. GHG emissions account for 65% of worldwide emissions, making climate change a critical issue for the global energy sector. By lowering GHG emissions, the Paris Agreement seeks to restrict the rise in global temperatures. Growing the use of renewable energy can aid in a 35% reduction in GHG emissions. Brazil is a promising country with a varied energy mix, with 85% of its installed capacity coming from energy sources that are renewable. There has been an obvious spike in solar and wind power [2].

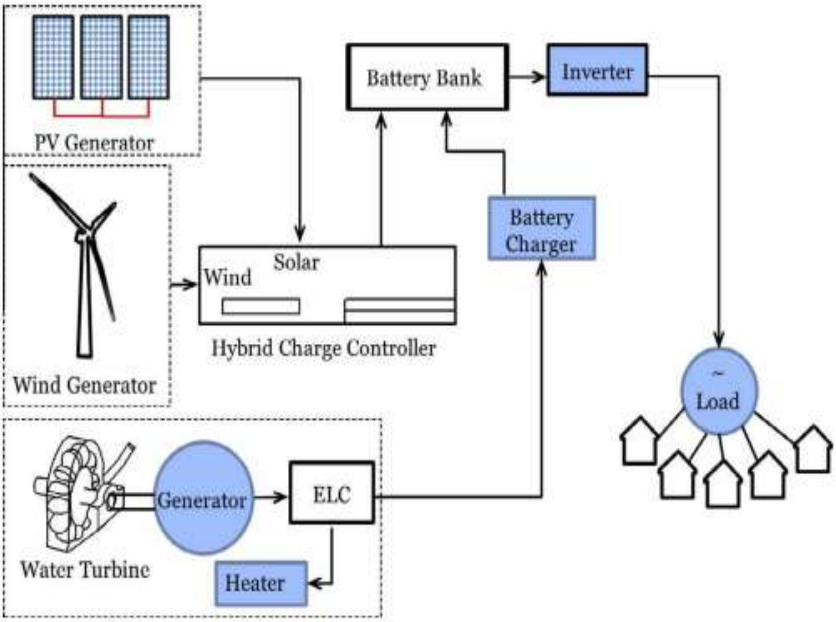

Fig. 1: Hybrid renewable energy system

There Despite social, cultural, and financial constraints, and wind power are not dispatch able and are stochastic, which makes it difficult to integrate them into the power grid. For the purpose of balancing electrical power and irrigation, the run-of-river power plant with pondage may efficiently generate energy from solar energy while maintaining the capacity for hydropower and improving water retention. The theoretical foundation, mathematical simulation and optimization model, and results analysis are included [3]. The effects on the hydroelectric capacity factor and the possible installation of many turbines are examined. According to the example study, a 176-kW water turbine with pondage capacity may effectively produce 687-kW of PV power while adhering to reliability and efficiency requirements. Natural resources deplete reserves, harming the ecosystem, such as coal and nuclear power. Because of erratic weather patterns, renewable energy sources can provide an endless supply of environmentally benign electricity, but their output is erratic. By reducing output variations and improving the integration of sources of clean energy into the traditional grid, purified hydroelectricity batteries (PHES) can assist stabilize the production of these sources of energy. The study in [4] examines hybrid pumped storage systems and proposes a new way to boost the effectiveness of these ecologically and financially viable solar-wind-pumped hydro storage systems for energy. Pumped hydroelectric energy storage devices boost the production of renewable energy sources and regulate it inside traditional power networks. Using computational modeling, manufacturing rules, and linear programming, the study examines and regulates the ideal power consumption of a renewable energy system in the Pamir area of Tajikistan while taking into account the possibility of a power shortage on the customers [5]. The project intends to optimize financial gains from electricity distribution and exporting while reducing costs relating to individual energy usage. Hydroelectric, wind, solar, and energy storage power generating ratios are ideal for wintertime use. At the micro- and mini-grid levels, each producing consumer may individually reduce power use and maximise profit from sharing energy with other customers, showing the use of carbon-free energy. In particular, photovoltaic applications for building power supply in urban areas encourage solar energy worldwide as an affordable and environmentally benign substitute for fossil fuels. In order to balance sun solar electricity production with structure request, hybrid pv-electrical batteries are discussed in this study along with its importance. Photovoltaic-battery energy storage is popular in leading economies; its technical, economic, and ecological sustainability is analyzed. The study in [6] looks at the worldwide installation capacity of hybrid photovoltaic-electrical energy storage systems in emerging areas. Hybrid photovoltaic-electric energy storage systems for buildings are a promising field of research, with flywheel, supercapacitor, and lithium-ion battery materials showing promise. Because renewable resources are intermittent, storage systems are essential to freestanding mixed energy sources. They must be designed with the best possible balance of dependability, cost-effectiveness, and power quality. In [7], a freestanding wind-photovoltaic system with hydroelectric storage of energy (PHS) is integrated, and a computational model and optimal scaling technique are described.

Using a unique technique, the study in [8] optimizes a hybrid photovoltaic-hydroelectric energy source for coastal locations in Iran, taking into account the possibility of energy interruption and expenditures on investments. A broad variety of design variables are taken into account in the suggested technique, which ensures optimal design for varying power demand. The study examines the best system configurations and performance for Iran's 32.4 kW annual average demand. It finds that there is a 26.1%/17.6% reduction in investment costs and a 13.8%/11.1% improvement in LPSP. Hydropower may improve long-distance transmission power's economic viability when paired with solar PV, and solar PV is projected to become less expensive owing to price reductions. This work proposes a quantification model based on installed capacity ratio of hydro-solar hybrid power, takes into account reservoir regulating capacity, solar generating features, and the expense of hydro and solar PV with long-distance transmission. According to [9], the ideal hydro-solar installed power ratio for hydro power plants with high generation factors and regulating capacities is 1:1; for those with daily regulating capacity reservoirs, the ratio is 1:0.3. Fossil resources are scarce and emit pollutants when used to generate electricity. Although it's more affordable and efficient, renewable energy still presents a superior option. In order to address the deployment of hybrid renewable energy resources, [10] concentrates on solar photovoltaic and wind systems, emphasizing their financial viability, scaling tactics, future potential, and organization. In [11], a micro-grid featuring a photovoltaic array, microturbine set, and supercapacitor module—all of which are controlled by conventional controllers—is shown. The PV array is prioritized to meet demand. While the SC module acts as energy storage during periods of surplus power or request, the MT synchronizes itself for a 24-hour power flow. The study in [12] recommends two workable, affordable hybridization techniques for tiny off-grid systems that use wind, micro-hydro, and photovoltaic, or PV, energy sources. For such systems to be implemented, precise resource evaluation and long-term information collecting are essential [13-16]. In an effort to fulfill the Millennium Development Goals, particularly Goal 7: Ensuring sustainable development, a unique method of linking clean energy sources to a utility mini-grid has been explored in an experimental capacity. The study offers a novel approach to off-grid hybrid system deployment for Nepalese village electricity, encompassing a hybridized system using both water and wind power sources [17].

2 Methodology

The primary goal of this research is to evaluate the effectiveness and practicality of a hybrid energy system that combines solar photovoltaic (PV) panels with hydropower generation for the production of sustainable green energy. The selection of the study region is probably contingent upon regions that provide both adequate sunlight exposure and sufficient water flow [18-22]. The location might be selected based totally on an preliminary geographical and meteorological evaluation to ensure it meets the crucial requirements for each solar and hydroelectric energy production. Additionally the float chart of the system is provided in Fig. 2.

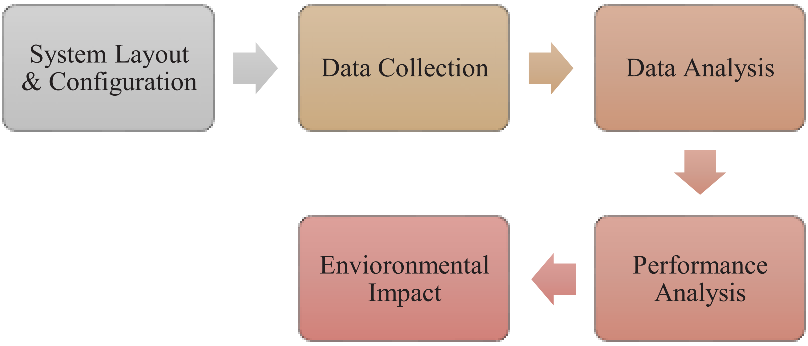

Fig. 2: Flowchart of proposed methodology

Resource Assessment: Initializing the process through assessing the solar and hydro sources available at the selected area. This involves studying the solar irradiance degrees and the hydrological conditions which include water flow rates, elevation drops, and available water volume in the region [23].
Site Selection: Determine a suitable location where each solar and hydro resources are considerable and complementary [24]. Preferably, the location should have access to enough sunlight for solar panels and a water source with enough flow and elevation drop for hydroelectric technology.
System Design: Design the hybrid energy plant layout considering the integration of solar panels and hydro turbines. Identify the potential of every component depending on the available resources and energy demand requirements. Factors which include land availability, topography, and environmental effect must additionally be considered at some stage in the design phase [25-27].
Solar Power Generation: Deployment solar photovoltaic (PV) panels within the location with maximum sunlight exposure. Use solar trackers to optimize the orientation of panels for optimum energy seize during the day. Connect the solar panels to inverters to convert the DC power generated by means of the panels into usable AC power [28].
Hydroelectric Power Generation: Assemble a small-scale hydroelectric plant utilizing the available water source. This involve constructing a dam or diverting a portion of the water flow to a turbine [29]. Choose the kind of turbine (e.g., Francis, Pelton, or Kaplan) primarily

based at the water flow rate and head (elevation drop). Deployment generators connected to the turbines to convert mechanical energy into electrical energy.
Integration and control: Integrate the solar and hydroelectric components into a unified power production system. Setup control systems and inverters to control the flow of electricity from both resources and ensure grid compatibility. Incorporating monitoring and control systems to optimize energy manufacturing and maintain system stability [30].
Storage and Backup: Consider incorporating power storage solutions consisting of batteries to store excess electricity generated at some stage in durations of high solar or hydro availability. This stored power may be utilized during intervals of low renewable energy generation or high demand.
Grid Connection and power Distribution: Connect the hybrid power plant to the electrical grid to distribute the generated strength to customers [31-33]. Make certain compliance with grid connection regulations and standards. Employing suitable energy distribution infrastructure together with transformers and transmission lines to deliver electricity to quit-users.
Monitoring and protection: Set up a comprehensive monitoring and protection program to ensure the efficient operation of the hybrid energy plant. Frequently check out and maintain solar panels, hydro generators, inverters, and other components to maximize performance and durability. Implement remote monitoring systems to come across and deal with any issues directly [34-36].

3 Numerical Calculations

The foundational equation for calculating the nominal electric power (P_{pv}) of a photovoltaic (PV) generator, expressed in watts (W), establishes the relationship between the outputted hydraulic energy and the energy received from solar radiation. The mathematical expression is presented in Eq. (1) given below:

$$P_{pv} = \frac{1000}{f_{lm}[1-\alpha_c(T_{pv}-T_0)]\eta_{mp}} . \frac{H_E}{S_E} \quad (1)$$

From the above equation, it is stated that H_E and S_E stands for output hydraulic energy and input solar energy of photovoltaic generator system. Load matching factor, according to characteristics of generator is denoted by f_{lm}. Standard temperature of generator is denoted by T_0 i.e; 25°C and T_{pv} is denoted for generator. Coefficient of cell temperature is denoted by α_c, motor–pump unit efficiency is denoted by η_{mp}.

Hence, the nominal electric power of the PV generator is determined by considering the monthly average daily demand for hydraulic energy (H_E), the available monthly average daily solar irradiation (S_E) during critical time periods, and the efficiency of the motor-pump unit (η_{mp}). Additionally, the impact of outside temperature on the PV generator's efficiency is taken into consideration. It's worth noting that shorter time intervals may also be utilized as per specific calculation requirements.

Hydraulic energy can be calculated as

$$H_E = \frac{2.72 V_{pv} H_{te}}{1000} \quad (2)$$

V_{pv} represents the average daily volume of water, measured in cubic meters per day (m^3/day), that is pumped from the lower to the upper reservoir. Meanwhile, H_{te} denotes the average manometric height, which is the difference in water levels between the upper and lower reservoirs, adjusted for hydrodynamic losses within the pumping system, measured in meters (m).

Putting value of Eq.2 in eq.1

$$P_{pv} = \frac{2.72\, V_{pv} H_{te}}{f_{lm}[1-\alpha_c(T_{pv}-T_0)]\eta_{mp}} \cdot \frac{H_E}{S_E} \qquad (3)$$

The PV power plant, with a nominal power of P_{pv}, consists of a stationary array of PV collectors connected both serially and in parallel to achieve the necessary voltage and current levels. Inverters are necessary to convert the generated DC power into alternating current (AC) for distribution.

4 Result and Discussion

Additional crucial information for the dimensioning of the PV power plant pertains to climate-related factors. Graphical representation includes average monthly figures for various climatological parameters: solar energy irradiance S_E, expressed in kilowatt-hours per square meter per day (kWh/m²/day), average monthly air temperatures Ta, noted in degrees Celsius per day (°C/day), along with monthly precipitation R (in millimeters per day, mm/day) and total monthly evaporation (in millimeters per month, mm/month).

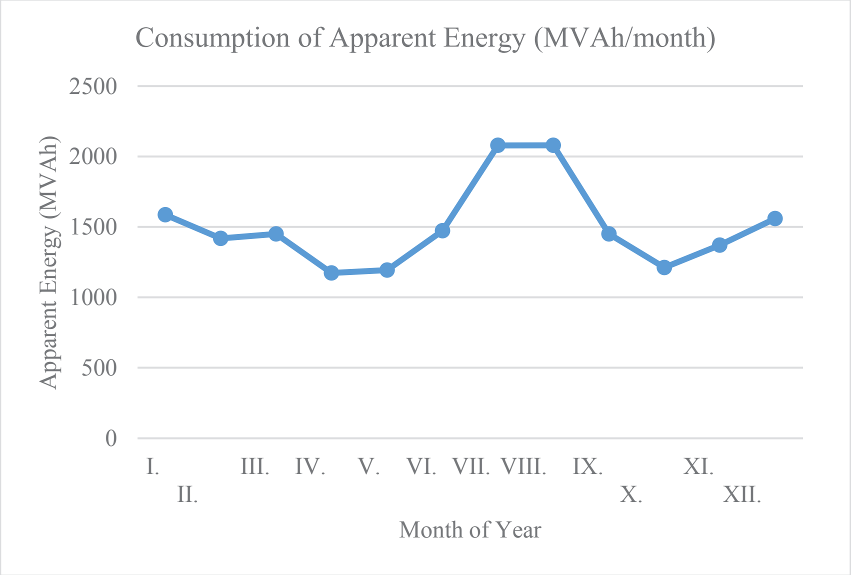

Fig. 3: Consumption of Apparent Energy

The graph in Fig. 3 presents data on the monthly consumption of apparent energy, given in mega-volt-ampere hours per month (MVAh/month). The consumption is highest during July and August, each with over 2078 MVAh/month, which could be associated with increased cooling demands or other seasonal factors. The lowest consumption occurs in April, with 1173.53 MVAh/month, potentially reflecting a period of reduced energy demand. This information is indicative of fluctuating energy requirements throughout the year and can be vital for energy management and planning purposes.

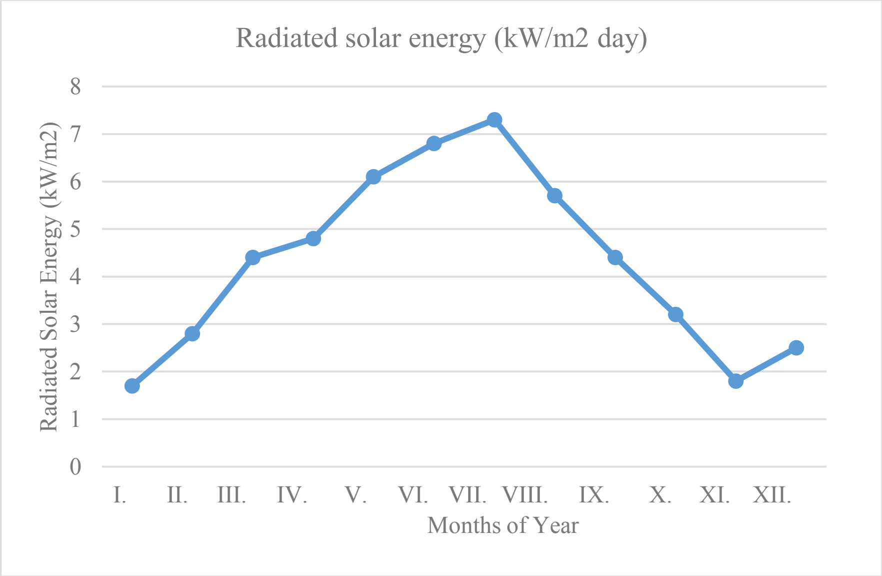

Fig. 4: Radiated solar energy

As shown in Fig. 4 kilowatt-per-square-meter-per-day (kW/m2/day) plot shows the average radiated solar energy over a month. The solar irradiance has a clear seasonal pattern, with 7.3 kW/m2/day reaching its peak in July, indicative of summertime peak conditions. November, on the other hand, has the lowest solar energy reception at just 1.8 kW/m2/day in response to the shorter days and lower sun intensity during the late autumn months. There is a significant difference between solar energy availability during the warmer and colder months, according to the data.

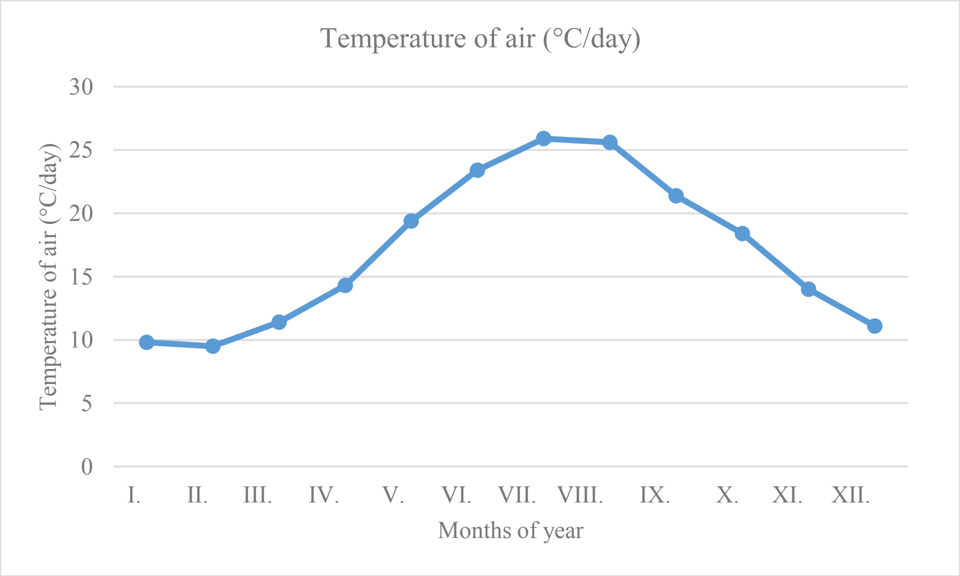

Fig. 5: Temperature of air

The average temperature for each month of the year is shown in Fig. 5, showing a typical temperate climate pattern. January and February are the coolest months with temperatures just below 10°C. The warmest months are July and August, both exceeding 25°C, suggesting the height of summer. There's a gradual increase in temperature from spring to summer and a decrease from autumn to winter, illustrating the seasonal temperature fluctuations.

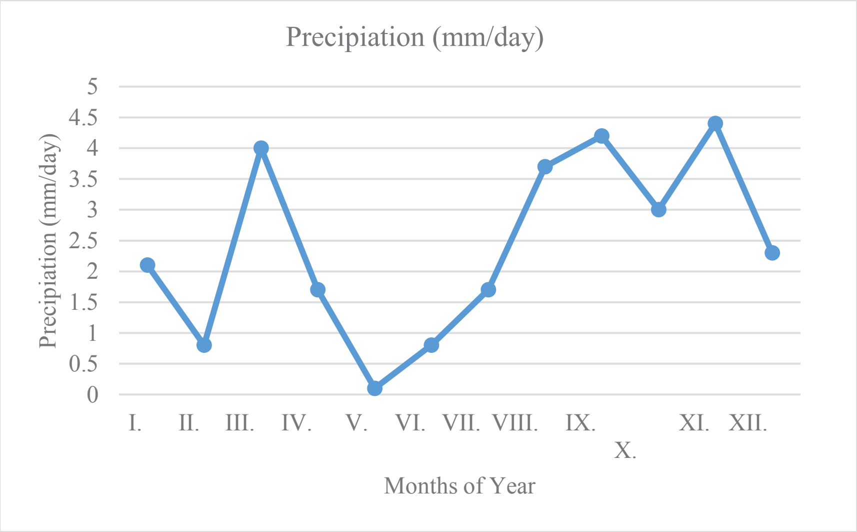

Fig. 6: Precipiation

The graph presented in Fig.6 shows the average daily precipitation measured in millimeters per day for each month. The data suggest that November has the highest average daily rainfall at 4.4 mm, while May experiences the least precipitation with only 0.1 mm. The pattern reflects a trend with drier conditions around May and wetter conditions in the autumn months, particularly November.

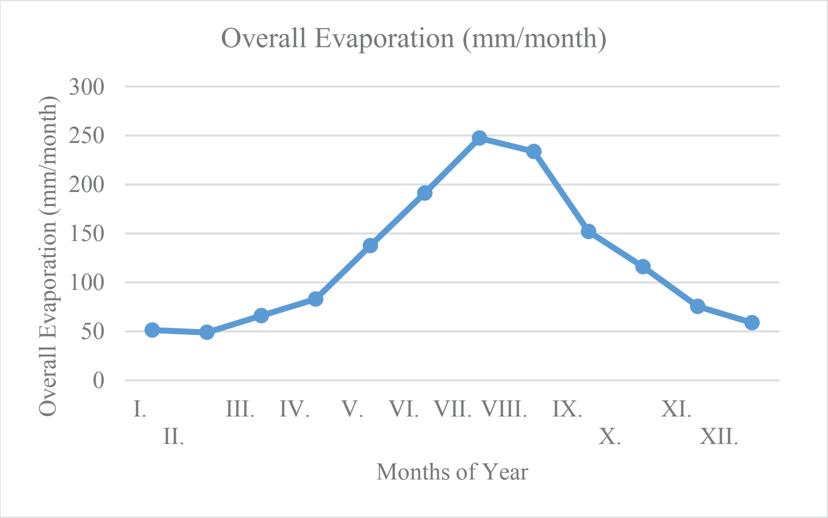

Fig. 7: Overall Evaporation

Fig.7 presents monthly evaporation data, measured in millimeters per month, for a specific location. The data indicate seasonal variation, with the lowest evaporation rates in the early part of the year (48.9 mm in February) and the highest rates during the summer months, peaking in July with 247.3 mm. This pattern suggests higher evaporation during warmer months and lower rates during cooler months.

5 Conclusion

The investigation into hybrid solar-hydropower systems confirms their potential to serve as robust and sustainable energy solutions. Our study reveals:

- Hybrid systems can effectively balance energy production and consumption, reducing reliance on traditional power grids and minimizing environmental impact.
- Technological advancements, particularly in storage and control systems, are crucial for stabilizing the inherently variable output from renewable sources.
- The economic analysis indicates that these hybrid systems are becoming increasingly cost-effective, with the potential for substantial reductions in investment and operational costs.
- Our findings advocate for the expanded adoption of such systems, especially in regions with abundant solar and hydro resources, to meet energy demands while supporting global sustainability goals.

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