Forecasting solar irradiance for the strategic integration of hybrid hydro and solar photovoltaic systems in rural Indian regions

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ABSTRACT

Conversion of the conventional electrical grid into a smart and sustainable grid involves several considerations. The primary factors, however, are renewable energy penetration, associated storage systems, and energy generation costs. This research endeavors to conduct a thorough survey and analysis of the solar irradiance on various hydropower locations in India, including Run-of-River (RoR), Run-of-River with Pondage (RoRP), Reservoir Storage (S), Multi-Purpose Storage (MP) and Pumped Storage Systems (PSS). The hydroelectric projects in rural Indian regions have been the subject of the proposed case study. As a preliminary study, the probabilistic variables like minimum, maximum, and mean solar irradiance are calculated for 252 High-Scale Hydropower Plant locations (HSHPs) using the past 40 years day ahead solar radiation data to identify the high-irradiance hydropower plant location in each state of India. This study concludes that the maximum mean solar irradiance location in each state as these sites are well suited for hybrid PV-hydro systems. The identified high-irradiance locations 40 years day ahead data sets are analyzed employing 8 machine learning models and 2 deep learning models. This analysis aims to forecast solar irradiance, serving as a crucial foundation for the initial phase of the implementation of hybrid PV-hydro.

KEYWORDS

Hydropower; solar power; probabilistic analysis; forecast; high-scale hydro plant; grid integration

1. Introduction

India stands as an untapped reservoir of renewable energy potential nestled in the southern reaches of the Globe [1]. This region's energy resources are underutilized and offer enticing prospects for investment and exploration [2]. India, home to the world's one-sixth population, holds third in the world in terms of both energy consumption and carbon dioxide emission. As a result, the Indian economy depends on imports to satisfy its needs for chemical fertilizers, gas, petroleum, and coal. However, India has a significant potential to harness renewable energy sources such as hydro, wind, solar, geothermal, ocean, biomass, and fuel cell technology to address its energy shortages [3,4]. Solar energy [5], widely recognized as an abundant and infinite source of energy on earth, is particularly abundant in many rural regions of India. However, the large-scale deployment of photovoltaic (PV) plants faces challenges as significant land resources are required. Also, conventional ground-based PV systems have significant environmental impacts such as bird mortality, deforestation, runoff, and microclimate change. The limited land availability and the associated costs pose significant challenges for the construction of solar plants, particularly in densely populated countries. Floating Solar PV (FPV) presents an innovative solution wherein solar cells are installed over water bodies. This approach will enhance plant efficiency by harnessing the negative temperature coefficient of solar modules [6]. The highlighted advantages of the FPV imply that water bodies may emerge as focal points for solar site development [7]. Optimal sites for FPV installation include areas with abundant water bodies like the sea, reservoirs, dams, canals, lakes, and ponds, complemented by a suitable climate [8]. However, the accumulation of sea salt on PV systems poses a challenge, resulting in reduced electricity production and degraded performance. The reliable energy-generating potential of integrating floating solar plants into existing hydropower infrastructure is often frequently suggested by researchers, emphasizing the flexibility of operating such hybrid plants [9]. Moreover, the hybridization of solar radiation with various hydropower plants holds promising prospects in the search for sustainable energy solutions [10].

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In India, several states possess considerable basin regions that contribute to hydropower generation, comprising 1269 Small-scale hydroelectric projects (SSHPs) with less than 25 MW [11] and 252 High-scale hydroelectric projects (HSHPs) above 25 MW capacity. Since our research focuses particularly on high-scale hydropower systems, the study completely depends on HSHP. The 252 hydro plants include 211 operational hydroelectric projects with an installed capacity of 46,850 MW, and 41 under-construction hydroelectric projects totaling a capacity of 17,803.5 MW. The primary high-scale hydro-project types encompass Run-of-River, Run-of-River with Pondage, Storage, Multi-Purpose, and Pumped Storage plants. A Run-of-River power plant produces electricity directly from the river flow, avoiding significant impoundment [12]. The hydropower generation system adapts to the river's varying flow profile influenced by precipitation, groundwater, and runoff [13]. There are 28 RoR projects without any ponds. To compensate for fluctuations in electricity demand, a Run-of-River system includes short-term storage (pond systems) known as Run-of-River with Pondage. There are 82 RoRP hydro systems in India with small reservoirs. RoR projects are vulnerable to river changes like droughts or floods without substantial storage capacity. Therefore, RoR projects are ideally suitable for rivers with minimal flow fluctuations and require less construction work, offering economic and environmental benefits. RoR power plants can be either in-river or cross-river detour systems, optimizing power generation by increasing the head or volume of the river. In contrast, Storage (big reservoir) power plants utilize a large reservoir behind a dam to store water for future electricity generation. This reservoir enables flow regulation, providing greater power reliability than Run-of-River projects. These power plants can be situated either at the dam or further downstream and interconnected through tunnels or pipelines. Multiple Run-of-River plants can be installed downstream in cascade, leveraging the regulated flow for consistent hydropower generation. Storage hydropower plants are ideal for rivers with fluctuating water levels and benefit from topographical features such as gorges, and canyons to ensure high performance and efficiency. In India, there are 43 Storage power plants above 25 MW. The advantage lies in storing energy as potential energy in the dammed water, offering flexibility for both base and peaking load electricity generation. Furthermore, these projects enhance the reliability of power generation downstream by regulating river flow. Multi-purpose hydropower reservoirs are constructed not only for electricity generation but also to fulfill various functions such as water supply, irrigation, navigation, fisheries, flood and drought management, environmental protection, and recreation. While the objectives of renewable power, water management, economic growth, ecosystem services, and local livelihoods may occasionally conflict, they are often complementary. Nearly 51 Multi-Purpose hydro projects are present in India. Remarkably, only a quarter of the world's large dams have hydropower as one of their designated purposes.

Pumped Storage power plants [14] utilize the difference in altitude between two bodies of water to store energy. While electricity demand is high, it generates electricity by the water flowing downhill and driving a turbine [15]. In times of low demand, the excess electricity is used to pump the water uphill for later use. There are 8 PSS hydro plants in India. Pumped Storage does incur energy losses in the pumping process, but it offers extensive energy storage with flexibility at low operating costs. However, the high capital cost compared to other hydropower systems is an issue, and the technology is inherently site-specific, thriving primarily in mountainous areas with favorable topography for potential energy storage. Despite these considerations, pumped storage proves invaluable in managing peak power demands and ensuring efficient electricity production governance. The technology maintains nearly constant output, facilitating a smooth governing process for hydropower plants with Pumped Storage [16]. The integration of solar or wind energy makes it necessary to improve the efficiency and reliability of these hydro systems [17].

Predicting solar irradiance is also critical to optimizing the integration of solar energy into the present hydropower electricity grid and ensuring grid stability and reliability by balancing supply and demand. It helps maximize energy production efficiency, reduce operational costs, and lower greenhouse gas emissions. Accurate forecasting supports the growth of renewable energy infrastructure and enhances overall energy market operations. Traditional solar forecasting methodologies include persistence models, statistical methods like ARIMA, and physical models such as Numerical Weather Prediction (NWP). Satellite-based models also play a crucial role by using real-time imagery to estimate solar irradiance. In recent years, machine learning and deep learning have become transformative technologies across industries. Machine learning, a subset of artificial intelligence, involves creating algorithms that enable computers to learn from data and make predictions or decisions without explicit programming. This ability allows machines to recognize patterns, classify information, and make informed decisions based on past experiences. Popular algorithms include Linear Regression, Decision Trees, Random Forest, and Gradient Boost.

Deep learning, a specialized field within artificial intelligence, is inspired by the structure and function of the human brain's neural networks. These algorithms consist of multiple layers of interconnected nodes that process information hierarchically. By leveraging large datasets and computational power, these models can extract complex patterns and features from data, leading to exceptional performance in solar irradiance forecasting tasks. Recurrent Neural Networks (RNN), Convolutional Neural Networks (CNN), Long Short-Term Memory (LSTM) and Gate Recurrent Unit (GRU) are mostly used in deep learning algorithms.

This research focuses on the solar irradiance on Run-of-River power plants, Run-of-River power plants with Ponds, Storage, Multi-Purpose, and Pumped Storage hydropower plants. It contributes to the broader debate on renewable energy development and supports informed decision-making for India's energy goals with minimal environmental impact. Key features of the study include mapping the current number and capacities of hydropower plants in India, predicting optimal locations for a hybrid PV-hydropower system based on solar irradiation data and hydropower system types, and conducting statistical analysis along with data visualization and prediction of solar irradiation in optimal locations in different Indian states.

2. Related literature

The current global demand for electricity is steadily increasing due to population growth, urbanization, and industrial development. Non-renewable energy sources, like fossil fuels, pose significant environmental risks, including air and water pollution, habitat destruction, and greenhouse gas emissions, contributing to climate change. Raghuwanshi et al. [18] highlight the pressing issue of escalating electrical energy demand, leading to environmental concerns stemming from the widespread use of fossil fuels. Additionally, fossil fuels' finite nature leads to resource depletion and energy insecurity, driving the need for sustainable alternatives. Renewable energy is crucial for mitigating climate change, enhancing energy security, and fostering economic growth while minimizing environmental impacts. Subhashish et al. [19] emphasize the role of renewable energy technology as a direct substitute for existing methods, contributing to energy conservation and environmental improvement by reducing reliance on fossil fuels. Several earlier research studies have highlighted the individual solar energy potential in various Indian states, while some others have looked at the individual hydropower potential of each state. Ramachandra et al. [20] discuss the significance of solar hotspots, areas with exceptional solar power potential suitable for decentralized commercial energy exploitation. Harinarayana et al. [21] provide valuable insights for the strategic planning and deployment of solar energy projects in India. Sharma et al. [22] emphasize the critical role of hydropower as the backbone of India's development. Kaunda et al. [23] highlight the significance of hydropower as a renewable energy source globally while acknowledging the environmental and social challenges associated with its development. Vikas et al. [24] underscore the significance of assessing hydro-energy potential as a crucial aspect of sustainable energy planning, particularly in Indian regions characterized by abundant rainfall and diverse geographical features.

Some researchers also discuss the hydro potential based on water infrastructures and storage options to harness hydropotential effectively. Charalampos et al. [25] highlight the intricate relationship between large-scale hydraulic projects, water infrastructures, and their surrounding social and ecological landscapes. The study underscores the importance of multi-purpose hydroelectric plants in providing socioeconomic and environmental benefits alongside power generation. Tsuanyo et al. [26] emphasize the Run-of-River hydropower plants as efficient and reliable renewable energy systems for electricity generation. Parinaz et al. [27] present research on Pumped hydro-energy storage optimizations for better hydropower generations. Jurasz et al. [28] focus on the Run-of-River power plants with Pondage, and Storage power plants, stabilizing electricity generation from photovoltaics while maintaining hydropower capacity and enhancing water retention. In addition, some works have examined India's renewable energy potential, often dividing into North, South, East, West, and Northeast regions for analysis. Deepak Kumar [29] comprehensively analyzes solar energy resources, particularly in the southern states of India. Pankaj et al. [30] underscores the substantial potential for solar energy utilization in India, particularly in the North-Eastern (NE) region. Das [31] provides an insightful overview of the hydro-power potential in the North-Eastern region of India.

Most of the literature focuses on the solar irradiance potential prediction, particularly on the single dam or hydro powerhouse, using real-time data to calculate the feasibility of installing PV power plants on the site. Researchers use metrics such as energy cost to assess economic viability and quantify the potential savings in fuel, carbon emissions, and other pollutant emissions in each plant. F. Ise et al. [32] comprehensively compared the levelized cost of electricity (LCOE) among various renewable energy technologies and conventional power plants for electricity generation. Additionally, the research investigates the projected future cost ratio between different power generation technologies for 2030 and 2040.

However, little attention is towards exploring the synergies among various renewable energy sources. Jurasz et al. [28] address the growing environmental, societal, and economic pressures to enhance the contribution of renewable energy sources in meeting energy demands. The integration of photovoltaic and wind generation, the two primary renewable sources, into the power grid presents challenges due to their stochastic and non-dispatchable nature. Evgeny et al. [33] highlight the key advantages and limitations of floating solar PV (FPV) in hybrid operations. Notably, hybrid configurations integrating solar input with hydro energy emerge as promising methods for efficient power generation. The insights in this research offer valuable perspectives for fostering sustainable hybrid floating installations and fostering socio-economic growth while minimizing environmental impact. The reviews of the discussed literature are summarized in Table 1.

Remarkably, until 2024, no research has focused exclusively on assessing the photovoltaic (PV) potential of dams for hybrid PV-hydro systems, probably due to the significant number of hydropower plants in India, estimated to be around 1400 to 1500. The novelty of our study is that we determine the solar potential of hydropower plants, particularly on large plants (hydro plant rating greater than 25 MW) in India.

3. Proposed work and data analytics

The study begins with the objective of identifying optimal locations for hybrid PV-hydropower plants by utilizing data sets from various agencies in the United States and India. The HSHP locations are mapped accurately and the data from these locations is then carefully organized in a structured sequence to ensure seamless alignment of features between datasets from NASA's renewable energy database. In the next phase, statistical analyses are performed for 252 sites, including hydropower plant rating, and mean, minimum, and maximum solar radiation values on each location in almost every state of India except Goa, Tripura, Haryana, and Bihar. These states do not have high-scale hydropower houses in the state. The subsequent phase identifies the 25 HSHP locations with the highest solar irradiance, one from each Indian state or union territory, resulting from the statistical data analysis. Finally, the analysis extends to evaluating these selected 25 and 8 Pumped Storage sites using 8 machine learning models and 2 deep learning models to predict future outcomes. The study workflow is visually depicted in Figure 1 with a five-stage process.

Data analytics includes steps such as data collection, exploratory analysis, statistical modeling, data processing, and feature selection [38]. It involves using various tools to identify patterns and relationships within a data set to arrive at business, scientific, or social outcomes.

3.1. Data acquisition

Essential information is required from two sources to select the optimal locations for hybrid PV-hydropower plants: Hydropower data from India's Ministry of Power and renewable energy data from NASA's energy database.

3.1.1. Hydropower data

Data is accessible from India's Ministry of Power's official website [39], revealing the operation of 252 hydropower plants with a capacity exceeding 25 MW. Among them, 211 hydroelectric projects are operational, totaling 46,850 MW, and 41 hydroelectric projects are under construction, with a combined capacity of 17,803.5 MW. Additionally, there are 1,167 Small – scale Hydro Electric Projects with a capacity of less than 25 MW totaling 4,935.65 MW in operation, and 102 SSHPs with an installed capacity of 556.05 MW are under development nationwide.

3.1.2. Location data

The latitude and longitude locations are obtained with the help of the Global Energy Monitor wiki. by searching the plant and dam details. These locations are plotted in Figures 2–6. The locations of under-construction hydropower projects are represented by small alphabets and operational plants by numbers. Some plants are close to each other with the same dam in common, so these are represented by the same number adding additional small alphabets to it.

3.1.3. Solar radiation data

Solar radiation data is easily obtainable from databases like India's ISRO (NSRDB) or NASA's power database. Specifically, NASA's database provides a 43-year daily dataset for individual locations comprising 17 features initially and 32 features after two downloads for each hydropower plant on a daily radiation basis.

Table 1. Evaluation of recent review papers for hybrid pv-hydro systems.

Author	Data used	Contribution	Conclusion
Ramachandra et al. [20]	Insolation data derived from high-resolution satellites by NASA	To recognize and evaluate solar energy source potential with variability in India.	The work estimates an approximately 58% of the country's geographical area is a solar hotspot, with an average annual sun radiation of above 5 kWh/m^2/day in India.
Christoph Kost et al. [32]	Energy market data and publicly available data	To transparently analyze the current and future costs of renewable power generation technologies.	The study includes economic modeling of technology-specific Levelized Cost of Electricity (LCOE) for various installations, economic assessments of photovoltaic and battery storage systems, sensitivity analyses of technology, and financial parameters.
Ameesh Kumar et al. [22]	No data available	To analyze the hydropower potential in the western Himalayan region.	The study focuses on the untapped potential of small hydro projects in this region, aiming to identify factors affecting their development and proposing solutions for enhanced utilization.
Deepak Kumar [29]	Annual solar insolation (METEOSAT) data from the National Renewable Energy Laboratory's open-source database.	To analyze solar resource variability in southern states of India.	The work quantifies regional solar energy potential, developing a framework for localized resource assessment. It introduces a simplified method for solar insolation measurement, facilitating detailed modeling for real-time regional and national energy requirements.
Das [31]	Central Electricity Authority of India and NHPC websites.	To assess the hydro-energy potential in the North-Eastern states of India.	The research highlights the untapped hydropower potential of the North-East region and suggests that the region has the potential to become the 'Powerhouse of India.'
Kalita et al. [30]	Multiple online sources, the NASA weather database, and the National Energy Institutes.	To assess the solar energy potential in the North-eastern states of India.	The paper extensively reviews climatic data from diverse sources in Northeast India. It outlines the design of the PV plant, considering various losses, and influencing factors using theoretical methods.
Anjali et al. [34]	Geospatial and meteorological data from the Geographic Information System.	To quantify solar and wind potential by techno-economic analysis.	The research enhances power system planning and grid integration by correlating wind and solar energy to identify suitable locations for hybrid plants.
Koritarov et al. [35]	Publicly available literature, Company websites, Industry conferences and workshops, and other publicly available sources.	To analyze PSS hydropower technologies based on predefined evaluation criteria.	The research evaluates innovative solutions for reducing the cost and construction time for new PSS hydro projects. It also performs a landscape analysis of current trends in PSH innovations, considering the potential advantages and disadvantages of proposed concepts and technologies.
Chiyembekezo et al. [23]	Data from reports, conference papers, journals, and selected documents.	To discuss different technologies and advancements in hydropower plants.	The work discusses issues such as resource availability, technology, environment, and climate change, highlighting the sensitivity of hydropower to environmental conditions.
Vikas Khare et al. [24]	Rainfall data from the Meteorological, and Hydropower data from the Central Authority of India.	To assess hydropower potential based on rainfall patterns in India.	This approach provides insights for efficient hydro energy planning and management. It also addresses various statistical techniques to assess hydropower potential based on rainfall patterns.
Subhashish et al. [19]	National Portal of India	To underscore the renewable energy in sustainable development.	The research examines the relationship between a country's development level, measured by GDP per capita, and the evolution of its energy integration.
Charalampos et al. [25]	The meteorological data was acquired through 20 stations in both Bulgaria and Greece.	To analyze the Socio-Economic, and Environmental characteristics of hydropower plants.	The paper presents a sequential approach to water resources modeling, developed for assessing the economic viability and sustainable operation of large dam projects and renewable energy generation from water.
Solomin et al. [33]	Data not available	To outline the hybrid floating solar system to obtain reliable renewable energy.	The work discusses FPV + hydro, FPV + solar tree, FPV + wave energy converter, FPV + tracking, FPV + conventional power, and FPV + hydrogen systems.
Raghuwanshi et al. [18]	Government Reports by various energy departments.	To explain the renewable energy source potential with installed capacities in different regions of India.	The analysis leads the Indian southern region in solar, the western region in wind, and the northern region in hydropower plant capacities. However, East and Northeast India have barriers as financial, technical, and production issues hindering its development.
Jakub et al. [28]	Flow rate data from http://www.imgw.pl/, and solar data from http://www.soda-pro.com/.	To conduct a comprehensive analysis through simulation and optimization models.	The study highlights the impact on hydropower capacity factors and recommends the installation of multiple hydro turbines for more flexibility and efficient use of water resources.
Jyoti Parikh [36]	Public domain	To describe the need and significance of grid-connected renewable energy systems.	The study suggests planning more PHES projects and strengthening transmission systems are essential for maximizing hydro project capabilities for grid integration of Renewable energy.
David Tsuanyo et al. [26]	Statistical information on currently operated projects.	To analyze the techno-economic design of RoR hydro plants.	The report is a valuable resource for the planning and simulation of RoR power plants. It also helps to assess the economic feasibility of projects.
Harinarayana et al. [21]	Monthly irradiance meteonorm (NASA-SSE) data for 1200 stations spanning 20 years (1981–2000).	To evaluate the solar potential within the states of India.	The analysis provides valuable insights for solar developers as it highlights the influence of parameters such as ambient temperature, altitude, and wind speed on energy production beyond solar radiation alone.
Parinaz Toufani et al. [27]	Web of Science database journals.	To understand the growing importance of Solar PHES hybrid systems.	The review advocates for multi-objective models considering economic and environmental impacts and addresses specific challenges in Solar-PHES systems.
Dolf Gielen [37]	Data from trade journals, industries, auctions, tenders, and IRENA member countries.	To review the design and economics of renewable power installations.	The study discusses the operating and maintenance costs for onshore wind, biomass, photovoltaic, concentrating solar, and hydropower plants by region, market maturity, labor, and manufacturing costs.

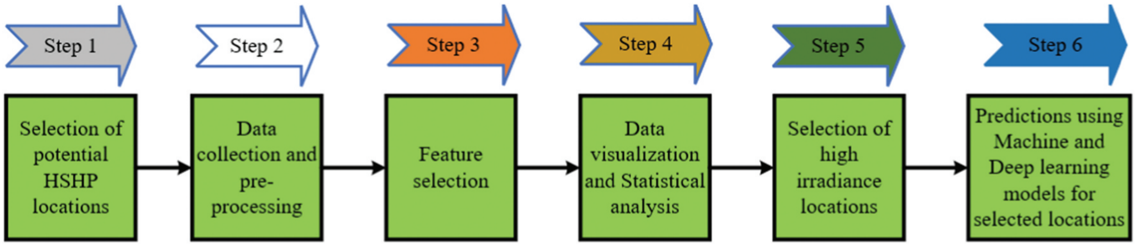

Figure 1. Proposed workflow to identify optimal locations for hybrid PV-hydro powerhouses.

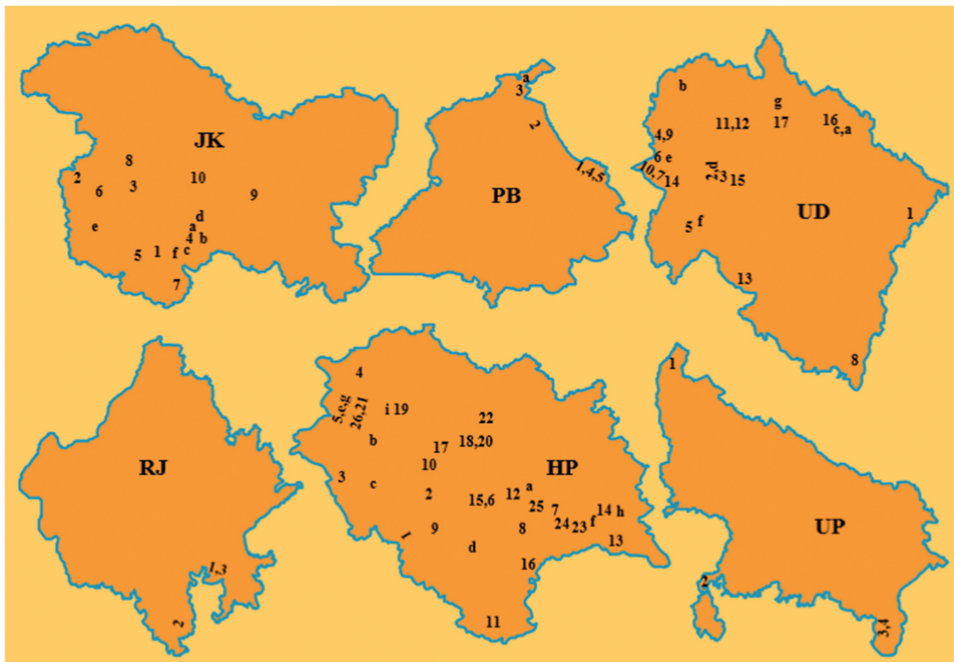

Figure 2. HSHP locations in the northern part of India.

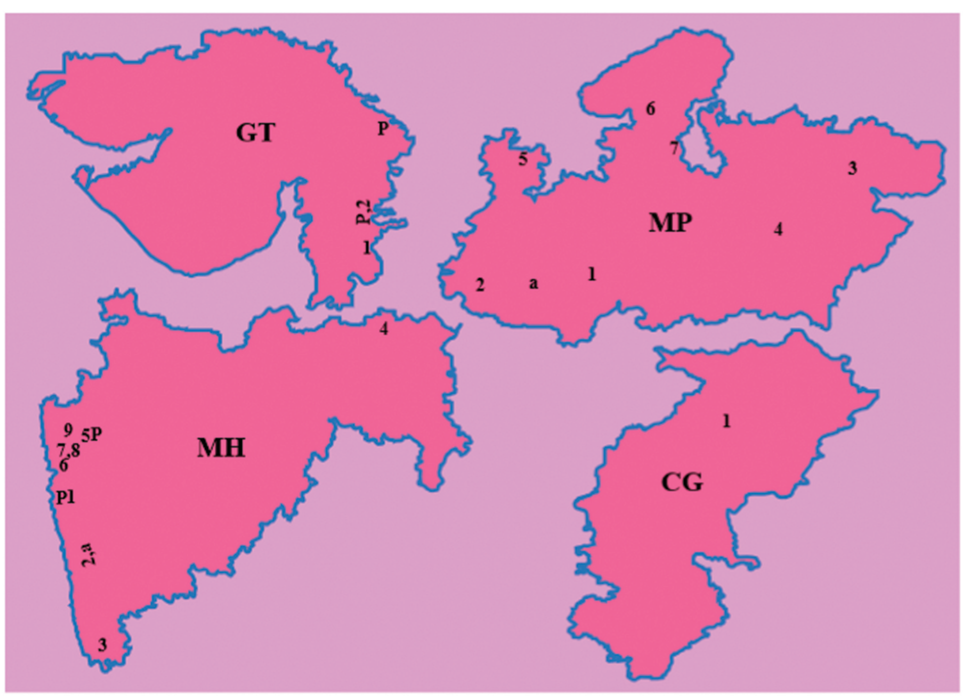

Figure 3. HSHP locations in the Western part of India.

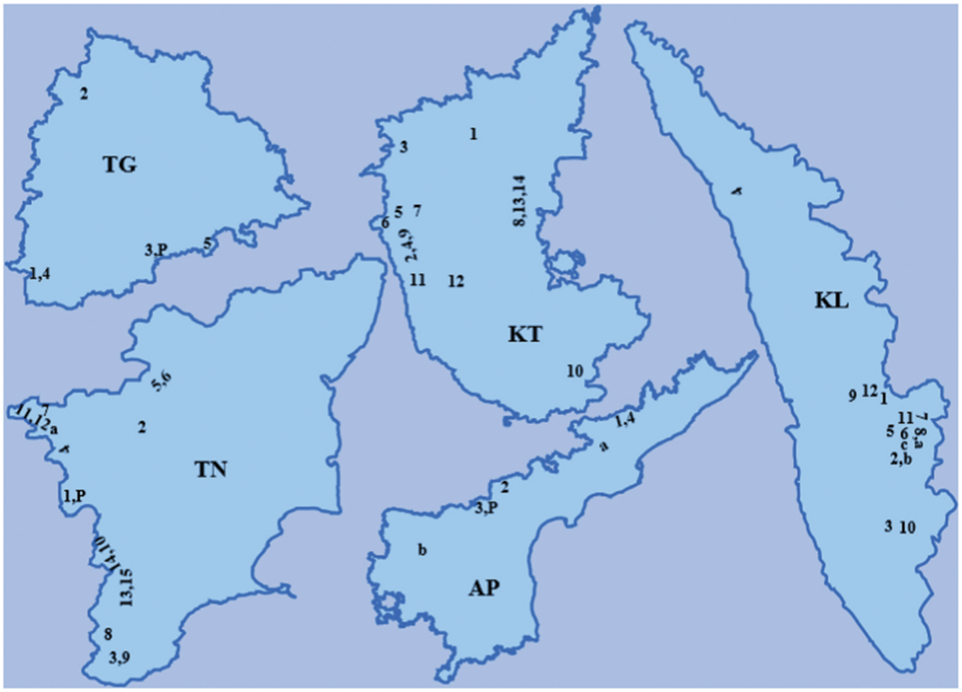

Figure 4. HSHP locations in the Southern part of India.

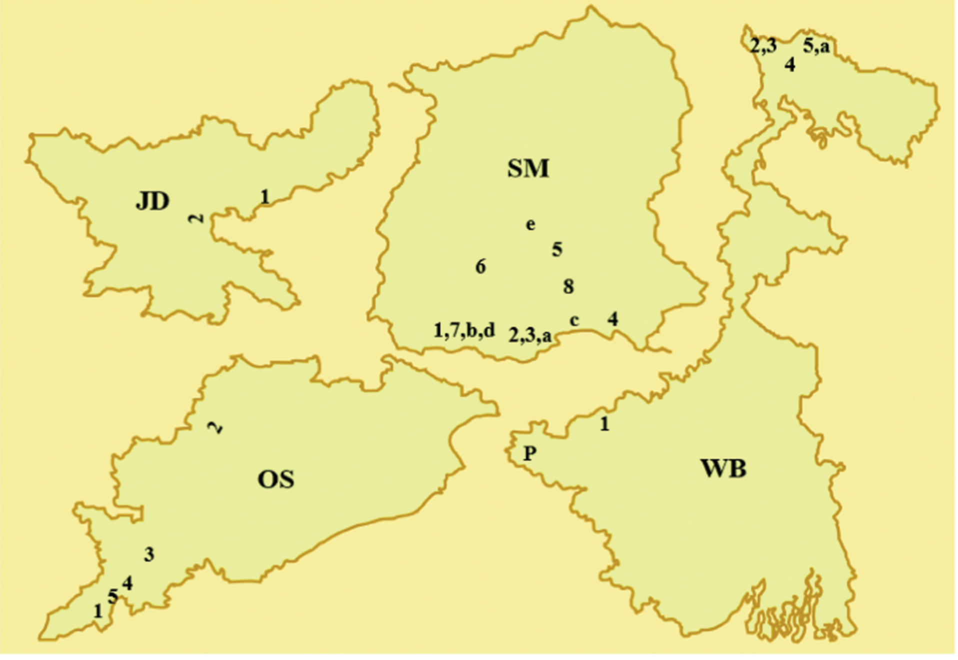

Figure 5. HSHP locations in the Eastern part of India.

3.2. Data processing

The downloaded data are processed through Python libraries NumPy and Pandas and probabilistic data is calculated that includes mean, minimum, standard deviation, and maximum solar irradiance. The analysis focuses on a 40-year dataset from 1984 to November 2023, considering the average mean solar irradiance in each state and the maximum mean solar irradiance at each hydro-plant location. The preference for daily data over hourly data is based on the need for long-term insights into solar power plants [40], as the official data websites also lack 40 years of

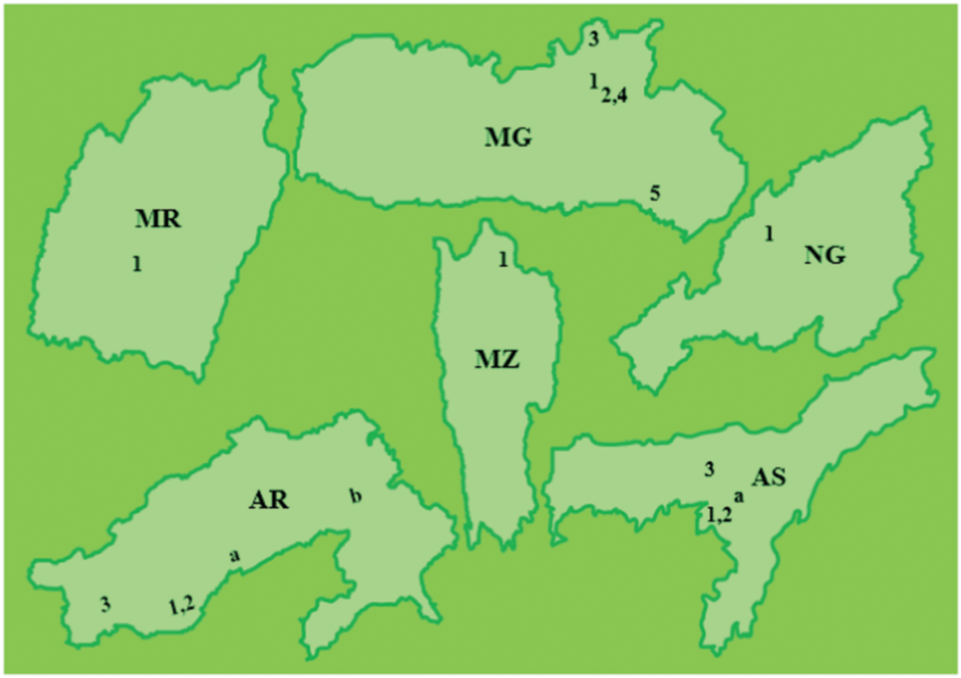

Figure 6. HSHP locations in the Northeastern part of India.

hourly data. Weekly, monthly, and annual data samples are also considered insufficient for predictions. Additionally, this dataset holds the potential for a more detailed prediction analysis through machine learning, deep learning, and various hybrid AI models [41]. For easy analysis, each HSHP's location is represented by the (Location's short name, Serial No on the Map, Type of hydropower plant). Additionally, the operational plants other than PSS in the work are represented with 'numbers', PSS plants are represented by 'P', and under-construction plants are represented by 'small alphabets.

3.3. Feature selection

Feature selection is fundamental in building effective machine and deep learning models to increase the model performance by reducing overfit and improving interpretability. This comprehensive data covers 252 locations and includes only highly co-related features like clearness index, wet bulb temperature, surface pressure, solar irradiance, earth skin temperature, specific humidity, relative humidity, precipitation corrected, temperature, dew point, wind speed, and wind direction at 2 m/s and 10 m/s, etc. The data is further divided into 70 percent as training and the remaining 30 percent as test data.

4. Solar – hydro mapping and potential analysis in India

Combining floating or ground-mounted solar panels with hydropower plants in hybrid projects holds significant technological potential for generating a substantial portion of global annual electricity. Especially beneficial for countries with numerous hydropower plants featuring dams, the Hybrid Floating Photovoltaic (HFPV) approach leverages existing power infrastructure, such as transmission lines near hydropower plants [23]. This synergy offsets the inherent instability of hydropower generation, with the floating solar system compensating for short-term fluctuations and the photovoltaic systems filling the gaps in hydropower generation in the medium to long term. Hence, this research performs an analysis to survey solar irradiance on HSHPs in India to hybridize the system with PV hydro systems. The analysis comprises five surveys conducted in different hydropower regions of India. The first survey focuses on northern India, followed by the second on western India, the third on the southern region, the fourth on eastern India, and the fifth on the north-eastern part of India. For easy analysis, hydropower houses are pointed on regions through various maps, and each HSHP's location is represented by the (Location's short name, Serial No on the Map, Type of hydropower plant) and the mappings are shown in Figures 2–6. In these maps, integers (1, 2, . . .) indicate the already constructed hydro powerhouses, small case alphabets (a, b, . . .) indicate under construction hydro powerhouses, and small case alphabet beside integer

(AP1a, AP1b, . . .) in theory presents multiple hydro-plant constructions near the same dam and is indicated by simple integer or alphabet (1a, 1b, ... represented by 1) in Andhra Pradesh map.

4.1. Solar – hydro mapping in North Zone

The Northern part of India, encompassing Himachal Pradesh (HP), Uttarakhand (UD), Punjab (PB), Uttar Pradesh (UP), Haryana (H), Rajasthan (RJ), and the union territories of Ladakh and Jammu Kashmir (JK), boasts significant potential for renewable energy sources, particularly hydropower [42].

4.1.1. Jammu & Kashmir and Ladakh

Jammu & Kashmir and Ladakh union territories alone have an estimated hydropower potential exceeding 20,000 megawatts. Baglihar I and II (JK1a (RoRP), JK1b (RoRP)), Lower Jhelum (JK2 (RoRP)), Upper Sindh II (JK3 (RoRP)), Dulhasti (JK4 (RoRP)), Salal I and II (JK5 (RoR)), Uri I and II (JK6a (RoR), JK6b (RoR)), Sewa II (JK7 (RoRP)), Kishanganga (JK8 (RoRP)), Chutak (JK9 (RoR)) and Nimoo Bazgo (JK10 (RoRP)) are HSHPs operational currently in the state. Other ongoing HSHP projects include Pakul Dul (JKa), Kiru (JKb), Ratle (JKc), Kwar (JKd), Parnai (JKe) and Lower Kalnai (JKf). Several hydropower plants discussed face extended closures in winter due to freezing temperatures, causing complete river and stream freeze-ups and necessitating plant shutdowns [43]. The other existing hydropower plants and diesel generators provide insufficient and unreliable power, compounded by environmental concerns related to conventional fuels like coal and lignite [44]. In light of these challenges, solar energy emerges as an appealing alternative [45].

4.1.2. Himachal Pradesh

Himachal Pradesh relies on hydropower as its primary electricity source, contributing about 25% of India's hydropower capacity, exceeding 10,000 MW. Harnessing its rivers like the Sutlej, Beas, Ravi, and Chenab, the state has developed numerous hydroelectric plants, both small- and large-scale. Notable projects include Bhakra Left (HP1a (MP)), Bhakra Right (HP1b (MP)), Dehar (HP2 (RoRP)), Pong (HP3 (MP)), BairaSiul (HP4 (RoRP)), Chamera I, II and III (HP5a (S), HP5b (RoRP), HP5c (RoRP)), Parbati III (HP6 (RoRP)), Nathpa Jhakri (HP7 (RoRP)), Rampur (HP8 (RoR)), Koldam (HP9 (S)), Bassi (HP10 (RoRP)), Giri Bata (HP11 (RoRP)), Larji (HP12 (RoRP)), Sanjay (HP13 (RoRP)), Integrated Kashang (HP14 (RoRP)), Sainj (HP15 (RoRP)), Sawra Kuddu (HP16 (RoR)), Shanan (HP17 (RoRP)), Malana I and II (HP18 (RoRP), HP20 (RoRP)), Budhil (HP19 (RoRP)), Chanju I (HP21 (RoRP)), Allain Duhangan (HP22 (RoRP)), Baspa (HP23 (RoRP)), Karcham Wangtoo (HP24 (RoRP)), Sorang (HP25 (RoR)), and Bajoli Holi (HP26 (RoR)) are operational. Water scarcity hampers power generation in winter, prompting the state to purchase electricity from other regions. Therefore, leveraging solar energy availability becomes crucial for addressing these issues [46]. Under-construction projects like Parbati St. II (HPa), Luhri (HPb), Dhaulasidh (HPc), Sunni (HPd), Uh I, II, and III (HPe), Shongtong Karcham (HPf), Chanju III (HPg), Tidong I (HPh), Kutehr (HPi) and Tangnu Romai (HPj) also benefit from high solar irradiance, emphasizing the state's commitment to sustainable energy.

4.1.3. Punjab and uttarakhand

Moving south of the northern regions of India, Punjab primarily relies on coal and hydropower plants, while Uttarakhand contributes approximately 8% of India's total hydropower capacity, with 3000 MW of installed capacity [47,48]. Many hydroelectric projects including Anandpur Sahib I and II (PB1a & PB1b (RoR)), Mukerian I, II, III, and IV (PB2a, PB2b, PB2c & PB2d (RoR)), Ranjit Sagar (PB3 (S)), Ganguwal (PB4 (RoR)), Kotla (PB5 (RoR)), Dhauli Ganga (UD1 (RoRP)), Tehri St I (UD2 (MP)), Koteshwar (UD3 (RoRP)), Chibro (UD4 (RoRP)), Chilla (UD5 (RoR)), Dhakrani (UD6 (RoR)), Dhalipur (UD7 (RoR)), Khatima (UD8 (RoR)), Khodri (UD9 (RoRP)), Kulhal (UD10 (RoR)), Maneri Bhali I and II (UD11 &12 (RoRP)), Ramganga (UD13 (MP)), Vyasi (UD14 (RoRP)), Shrinagar (UD15 (RoRP)), Vishnu Prayag (UD16 (RoR)), Singoli Bhatwari (UD17 (RoR)) have been built on rivers in the state, including the Bhagirathi, the Alaknanda, the Mandakini, and others. The construction of the Shahpurkandi hydropower house (PBa), Vishnugad Pipalkoti (UDa), Naitwar Mpori (UDb), Tapovan Vishnugad (UDc), Tehri PSS (UDd), Lakhwar (Ude), Lata Tapovan (UDf), Phata Byung (UDg) is currently underway. In addition, the state governments made initiatives to encourage the usage of hybrid hydropower projects by providing different incentives to private investors [49].

4.1.4. Uttar Pradesh and Rajasthan

The highly populated state of Uttar Pradesh, covering 75 districts, heavily depends on coal for power generation [50]. The state depends on various reservoirs to fulfill its water requirements, providing essential support for drinking and irrigation needs. Khara (UP1 (RoRP)), Matatila (UP2 (MP)), Obra (UP3 (MP)), and Rihand (UP4 (MP)) stand as prominent hydro plants in the region. Rajasthan, on the other hand, India's largest area state, faces challenges in conventional power generation but utilizes its two perennial rivers for hydropower potential. Due to the scarcity of large rivers, notable hydropower projects like Jawahar Sagar (RJ1 (RoRP)), Mahi Bajaj I and II (RJ2a (MP), RJ2b (RoRP)), and RP Sagar (RJ3 (MP)) are limited, and the substantial transportation cost of coal, a major energy source, constitutes 50% of production costs. Leveraging the region's high solar radiation [51], installing solar panels on these dams can not only conserve water through reduced evaporation, but also enhance renewable energy production within a hybrid PV-hydro system in these two states [52].

In summary, the Northern region of India, with its diverse states and territories in Figure 2, presents a comprehensive canvas for renewable energy integration. The synergistic utilization of hydropower and solar energy showcases a sustainable approach to meet the growing energy demand, offering opportunities for integrated systems and contributing to India's pursuit of a greener and more resilient energy landscape.

4.2. Solar – hydro mapping in West Zone

West India comprises four states: Madhya Pradesh (MP), Maharashtra (MH), Chhattisgarh (CD), and Gujarat (GT). These states, with high solar irradiation and expansive arid lands receiving abundant sunlight for 250–300 days annually, must prioritize solar energy for sustainable and efficient energy production [53]. These states are also endowed with abundant water resources, including major rivers such as Narmada, Tapi, Sabarmati, Krishna, and Godavari.

4.2.1. Madhya Pradesh

Madhya Pradesh, the second-largest state, exhibits considerable hydropower potential, housing large projects like Indira Sagar (MP1 (MP)), Omkareshwar (MP2 (MP)), Bansagar I, II and III (MP3a (MP), MP3b (RoRP), MP3c (RoR)), Bargi (MP4 (MP)), Gandhi Sagar (MP5 (MP)), Madhikhera (MP6 (MP)), Rajghat (MP7 (MP)) and the under-construction Maheswar project (MPa). The state is also a promising location for small and micro-hydropower plants and benefits from high solar irradiation.

4.2.2. Maharashtra

Maharashtra, the third-largest state, with a significant population, has a high electricity demand and contributes 13.91% to India's total installed power generation capacity. With an installed renewable energy capacity of 11.8 GW, Maharashtra relies on rivers like Godavari and Krishna for consistent water flow, making it a valuable energy source [54]. The state also has prominent hydroelectric power facilities like Bhira tail race (MH1 (RoRP)), Koyna I & II, III, IV, and DPH (MH2a (S), MH2b (S), MH2c (RoRP), MH2d (S)), Tillari (MH3 (RoRP)), Vaitarna (MH4 (S)), Pench (MH5 (MP)), Bhandardhara St. II (MH6 (RoRP)), Bhira (MH7 (S)), Bhivpuri (MH8 (S)), Khopoli (MH9 (S)), and Koyna left bank (MHa), currently under construction. Additionally, the integration of solar energy, with its abundant availability, holds immense importance, especially in densely populated and economically significant regions like Mumbai.

4.2.3. Chhattisgarh

Chhattisgarh, known for its thick forests and abundant rainfall, harnesses around 2500 MW of hydropower capacity in its northern and eastern regions, with the Hasdeo Bango hydro project (CG1 (MP)) being a major contributor [55]. The state's ideal geographical structure for solar photovoltaic power generation makes it essential to integrate renewable energy for sustainable power production.

4.2.4. Gujarat

Gujarat, with 185 river basins, focuses on hydropower production through major projects like Ukai (GT1 (MP)), Sardar Sarovar CHPH (GT2 (RoRP), and Kadana (PSS). Despite having significant water resources, Gujarat's solar potential is also recognized, with bright sunlight for over 250–300 days annually [56]. The state is exploring hybrid PV-hydropower plants to save water resources and meet future energy demands efficiently.

In conclusion, the western states of India exhibit rich potential for renewable energy integration, particularly in hydropower resources in Figure 3. Integrating solar power into the hybrid energy systems is a strategic and vital move for these states, addressing land constraints and optimizing renewable resources.

4.3. Solar – hydro mapping in South Zone

Indian South comprises five states: Andhra Pradesh (AP), Telangana (TG), Tamil Nadu (TN), Karnataka (KT) and Kerala (KL) and are well known for high solar and hydropower potentials.

4.3.1. Andhra Pradesh

Andhra Pradesh, with its diverse topography, benefits from abundant water resources for hydropower generation, particularly in the delta regions formed by the Godavari, Krishna, and Penna rivers [57,58]. Notable hydropower projects in the state, such as

Lower Sileru (AP1 (S)), Nagarjuna Sagar RBC & Ext (AP2a (S)), Nagarjuna Sagar TPD (AP2b (RoRP)), Srisailam (AP3 (MP)) and Upper Sileru (AP4 (MP)) contribute significantly to its hydroelectric capabilities. The state also demonstrates an annual fluctuation in solar irradiance, ranging from 5.14 kWh/m^2 to 6.03 kWh/m^2. Ongoing projects such as Polavaram (APa) and Pinnapuram (APb) can also be effectively utilized for renewable energy generation and integration.

4.3.2. Telangana

Telangana's semi-arid climate showcases a significant potential for solar power generation, complementing its robust hydropower infrastructure [59]. The region has notable hydropower plants, including Priyadarshini Jurala (TG1 (RoRP)), Pochampad (TG2 (MP)), Nagarjuna Sagar, and LBC (TG3a (MP), TG3b (RoR)), Lower Jurala (TG4 (RoRP)), and Pulichinthala (TG5 (RoRP)), contributing to its hydro potential. However, reduced solar energy generation during July and August is observed, aligning with trends in other states.

4.3.3. Tamil Nadu

Tamil Nadu [60], known for its diverse topography, features of hills, coastal plains, and arid central areas. The state relies on hydropower plants like Aliyar (TN1 (MP)), BhavaniKattalai Barrage I, II, and III (TN2a (RoRP), TN2b (RoRP), TN2c (RoRP)), Kodaya I and II (TN3a (MP), TN3b (MP)), Kundah I, II, III, IV, and V (TN4a (S), TN4b (S), TN4c (S), TN4d (S), TN4e (S)), Mettur I, II, III, IV, Dam, and Tunnel (TN5a (RoRP), TN5b (RoRP), TN5c (RoRP), TN5d (RoRP), TN6a (MP), TN6b (MP)), Moyar (TN7 (S)), Papanasam (TN8 (MP)), Parson's valley (TN9 (S)), Periyar (TN10 (MP)), Pykara and Pykara ultimate (TN11 (S) & TN12 (S)), Sarakarpathy (TN13 (RoRP)), Sholayar I (TN14 (S)), Suruliyar (TN15 (S)) and under construction Kundah Pumped Storage (TNa) plant. It [61,62] experiences an annual fluctuation in solar irradiance ranging from 4.82 kWh/m^2 to 6.05 kWh/m^2.

4.3.4. Karnataka

Karnataka, situated in the southwestern part of India, boasts three main geographical zones, and utilizes significant river basins like Krishna, Cauvery, and Tungabhadra for hydroelectric power generation [63]. The state has a high number of operational hydropower plants [64], such as Almatti (KT1 (MP)), Gerusoppa (KT2 (RoRP)), Ghat Prabha (KT3 (MP)), Gandhi (KT4 (S)), Kadra (KT5 (S)), Kalinadi Nagjhari and Supa (KT6a (S) and KT6b (S)), Kodasali (KT7 (S)), Munirabad (KT8 (MP)), Sharavathi (KT9 (S)), Siva samundrum (KT10 (RoRP)), Varahi (KT11 (RoRP)), Bhadra (KT12 (MP)), Tungabhadra Dam (KT13 (MP)), and Hampi (KT14 (MP)), with an annual fluctuation in solar irradiance ranging from 5.08 kWh/m^2 to 6.02 kWh/m^2.

4.3.5. Kerala

Kerala, located between the Western Ghats and the Lakshadweep Sea, relies on its extensive river network for hydropower generation. With strategically constructed dams, the state harnesses the abundant monsoon rainfall [65] for electricity generation. Well-known hydroelectric projects in Kerala include Idamalayar (KL1 (MP)), Idukki (KL2 (MP)), Kakkad (KL3 (RoRP)), Kuttiyadi I, II, and III (KL4a (MP), KL4b (MP), KL4c (MP)), Lower Periyar (KL5 (RoRP)), Nariamangalam (KL6 (S)), Pallivasal (KL7 (S)), Panniar (KL8 (S)), Poringalkuttu (KL9 (S)), Sabirigiri (KL10 (S)), Sengulam (KL11 (S)), and Solayar (KL12 (S)) with an annual variation in solar irradiance [66] from 4.82 kWh/m^2 to 5.93 kWh/m^2. Additional projects such as the Pallivasal extension (KLa), Thottiyar (KLb), and Mankulam (KLc) are currently under construction to meet future power demands [67].

In summary, the southern states exhibit rich potential for renewable energy integration, particularly in hydropower houses in Figure 4 [68]. As these southern states continue to develop and expand their hybrid renewable energy capacities, they play a crucial role in India's journey towards a greener and more sustainable energy future.

4.4. Solar – hydro mapping in East Zone

Indian East zone comprises four states: Sikkim (SM), Odisha (OS), Jharkhand (JD), and West Bengal (WB) which are full of small reservoirs and dams.

4.4.1. Sikkim

Sikkim, covering an area of about 7096 km2, is a landlocked state bordered by Tibet, Nepal, Bhutan, and the Himalayan district of Darjeeling in West Bengal, India [69]. Abundantly endowed with tributaries of the Teesta River [70], the state boasts a hydropower peak potential of 8000 megawatts (MW), with hydro plants like Rangit (SM1 (RoRP)), Teesta III and V (SM2 (RoRP), SM3 (RoRP)), Chujachen (SM4 (RoRP)), Dikchu (SM5 (RoRP)), Tashiding (SM6 (RoRP)), Jorethang loop (SM7 (RoRP)), Rongnichu (SM8 (RoR)), Teesta VI (SMa), Rangit II and IV (SMb), Bhasmey (SMc), and Panan (SMd). Solar PV emerges as a viable alternative [71], benefiting from approximately 300 clear sunny days annually and a daily average solar radiation of 5.5 kWh/m^2.

4.4.2. Odisha

Odisha, located south of the Tropic of Cancer, heavily relies on coal (74.7%) and hydropower (24%) for its energy resources. The state covers a total area of 3478.7825 km2 of wetlands and features notable hydroelectric facilities like Balimela (OS1 (MP)), Hirakud Burla, Chiplima (OS2a (MP), OS2b (RoRP)), Upper Indravati (OS3 (MP)), Upper Kolab (OS4 (MP)), and Machkund (OS5 (S)).

4.4.3. Jharkhand

Jharkhand [72], with a potential of 18.2 GW for solar power generation, presents a hydro potential of 209 MW and relies on small hydropower plants along with large power plants like Panchet (JD1 (MP)) and Subernrekha I and II (JD2a (MP), JD2b (RoRP)). The state has abundant resources, including solar, biomass, and small hydro [73].

4.4.4. West Bengal

West Bengal, known for its diverse topography, faces challenges in maximizing its renewable energy potential [74]. The state has identified a hydropower potential of 6,300 MW, with prominent hydroelectric power stations like Maithon (WB1 (MP)), Teesta Low Dam III and IV (WB2 (RoRP) & WB3 (RoRP)), Jaldhaka (WB4 (RoRP)), and Rammam (WB5 (RoR)).

Due to the presence of rivers and reservoirs in Figure 5, large-scale solar power plant installation requires significant capital investment and skilled labor, posing challenges in suitable locations in the Eastern States of India.

4.5. Solar – hydro mapping in North–East Zone

Geographically, the Northeast region of the country comprising Assam, Arunachal Pradesh, Meghalaya, Mizoram, Nagaland, Manipur, and Tripura consists of a diverse mosaic of ethnic groups with different social, cultural, and economic identities living in hilly terrains and valleys. Hydro and gas/diesel are the primary sources of electricity in this region, with small hydro emerging as a significant renewable energy source, particularly suited for decentralized power generation in the hilly landscape. The northeastern states of India, have hydropower potential in the country due to their mountainous terrain and perennial watercourses [75]. Collectively, these states contribute nearly 40% of India's total hydropower potential. This hydroelectric potential is crucial for accelerating the overall regional development of Northeast India.

4.5.1. Arunachal Pradesh, Meghalaya, and Nagaland

Arunachal Pradesh, with its abundant rainfall and steep terrain, possesses vast hydropower potential, evident in projects like Ranganadi (AR1 (RoRP)), Pare (AR2 (RoRP)), Kameng (AR3 (RoRP)), Lower Subansiri (AR5) and Dibang (ARa). Meghalaya's hydropower plants, such as Kyrdemkulai (MG1 (RoRP)), Umiam St. I and IV (MG2 (S), MG5 (RoRP)), New Umtru (MG3 (RoRP)), and Myntdu St. I (MG4 (RoRP)), play a significant role, while Nagaland's rugged topography and abundant water resources contribute to substantial hydro-energy potential. Small and medium-sized hydropower plants, like the Doyang Hydropower Plant (NG1 (S)), thrive in Nagaland.

4.5.2. Assam, Manipur and Mizoram

Assam, with hydropower plants like Kopili (AS1 (S)), Khandong (AS2 (S)), and Karbi Langpi (AS3 (RoRP)), is expanding its infrastructure with projects like the Lower Kopili extension (ASa) [76]. Loktak (MR1 (MP)), a significant hydro project in Manipur, generates over 25 MW of electricity to meet the needs of the residents. The final state of Mizoram's primary hydro powerhouse is the Tuirial (MZ1 (S)) hydropower plant.

Despite the vast hydro potential in Figure 6, the NE region faces power shortages, with per capita energy consumption (300W) significantly lower than the national average (900W) [77]. Challenges like inadequate infrastructure, harsh weather conditions, and poor connectivity contribute to this disparity. While solar energy remains underutilized, with less than 5% of the region's potential tapped, the tropical climate and proximity to the Tropic of Cancer offer opportunities for solar energy projects [78], including floating PV plants, and hybrid PV-hydropower plants to address the current load and future energy needs.

If effectively utilized, HSHP's solar integration can adequately meet the future energy demand in North, South, East, West, and North – Eastern regions of India arising from industrial activities and tourism

5. Data visualization

For each HSHP in each state, the mean, maximum, and mean solar radiance is calculated and plotted in Figure 7 with hydro plants on the X-axis, solar irradiance on the primary Y-axis, and capacity of the plant on the secondary Y-axis. These graphs show the potential of solar irradiance along with hydro potential. Thereby, it is easy to choose the optimal location for a hybrid PV-hydro system.

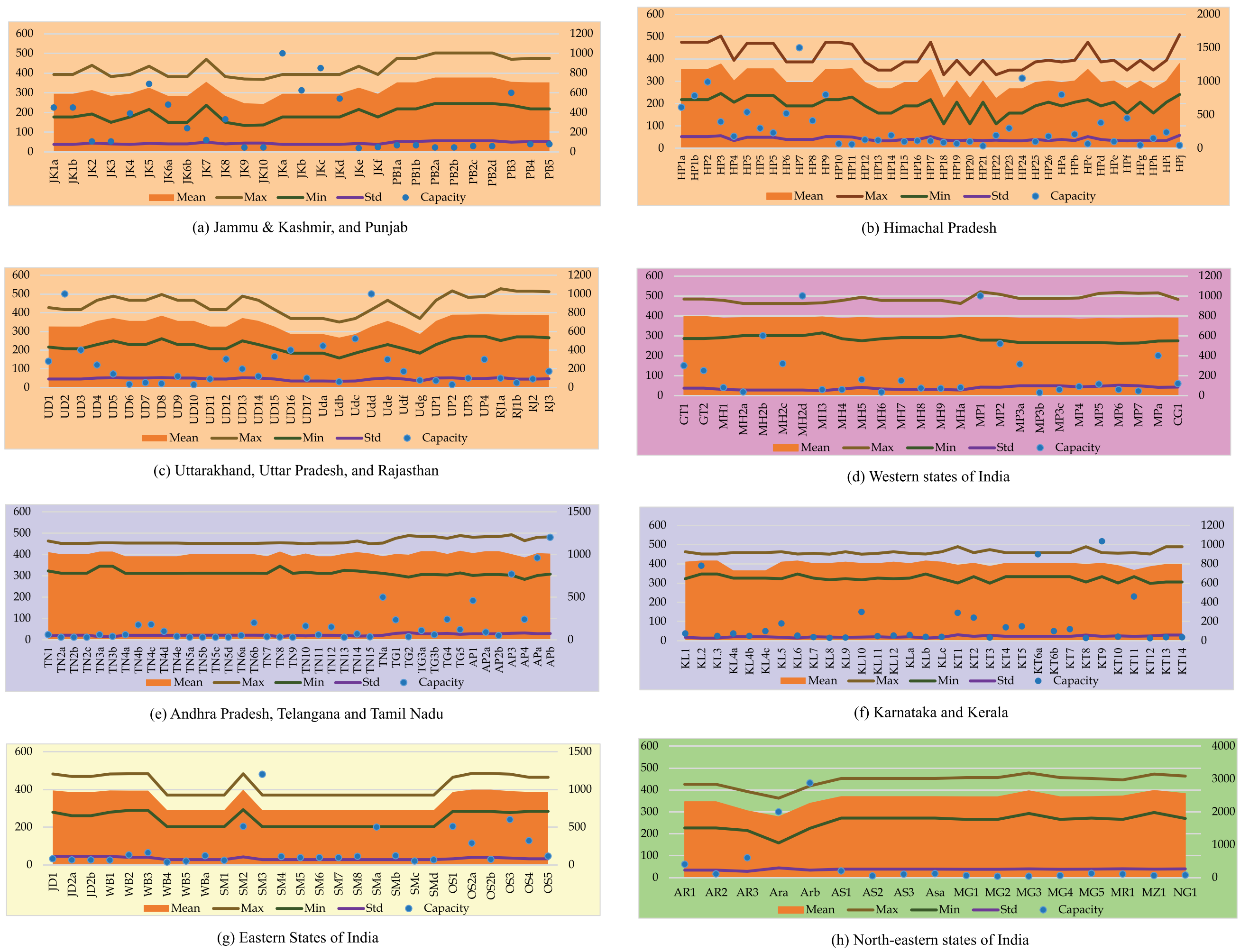

Figure 7. Statistical analysis of solar irradiance on HSHPs in India.

6. Results and discussions

The results are interpreted from these graphs with concluding maximum average solar potential locations in each state in Figure 8. The advantages of PSS are high compared to other hydro plants. So, the probabilistic analysis is performed for these plants separately and presented in Figure 9.

Finally, the study identified 42 hydro plants located across 33 sites, with classifications including 11 Multi-Purpose, 10 Run-of-River with Pondage, 6 Storage, 8 Pumped Storage, and 5 Run-of-River plants. Furthermore, it noted the ongoing construction of two hydro plants during the research period. It also noticed among 28 RoR hydropower plants, Nagarjuna Sagar LBC and Bansagar Tons-III plants display elevated solar irradiance. Similarly, Kakkad and Nagarjuna Sagar TPD in 82 RoRP plants, and Nagarjuna Sagar in 8 PSS plants also exhibit high solar irradiance. Additionally, Nariamangalam and Nagarjuna Sagar stand out in solar irradiance among 43 Storage plants, while Idukki and Nagarjuna Sagar notably showcase high solar irradiance among 51 Multi-purpose hydro projects. Therefore, these locations' day-ahead data is passed into the machine and deep learning models for further analysis for predictions. Notably. Forecasting of 25 state locations and 8 PSS locations is enough as each type of plant lies in these hydro powerhouses.

The day ahead dataset of 40 years from the final 25 locations and 8 Pumped storage systems from Table 2 is pre-processed by dividing samples in a 7:3 train/test ratio. Thereby, the samples are passed into various regression models including Ridge, Elastic Net, Poly Linear, Extra Trees, Random Forest, Gradient Boost, Extra Gradient, Light Gradient, LSTM, and GRU models [79]. The Linear regression model is taken as the benchmark reference model for this study.

The RMSE results are compared for 10 models including machine and deep learning in Figures 10 and 3 best models are selected. The prediction performance for the three best discussed models is shown in Tables 3–5. By comparing the RMSE values

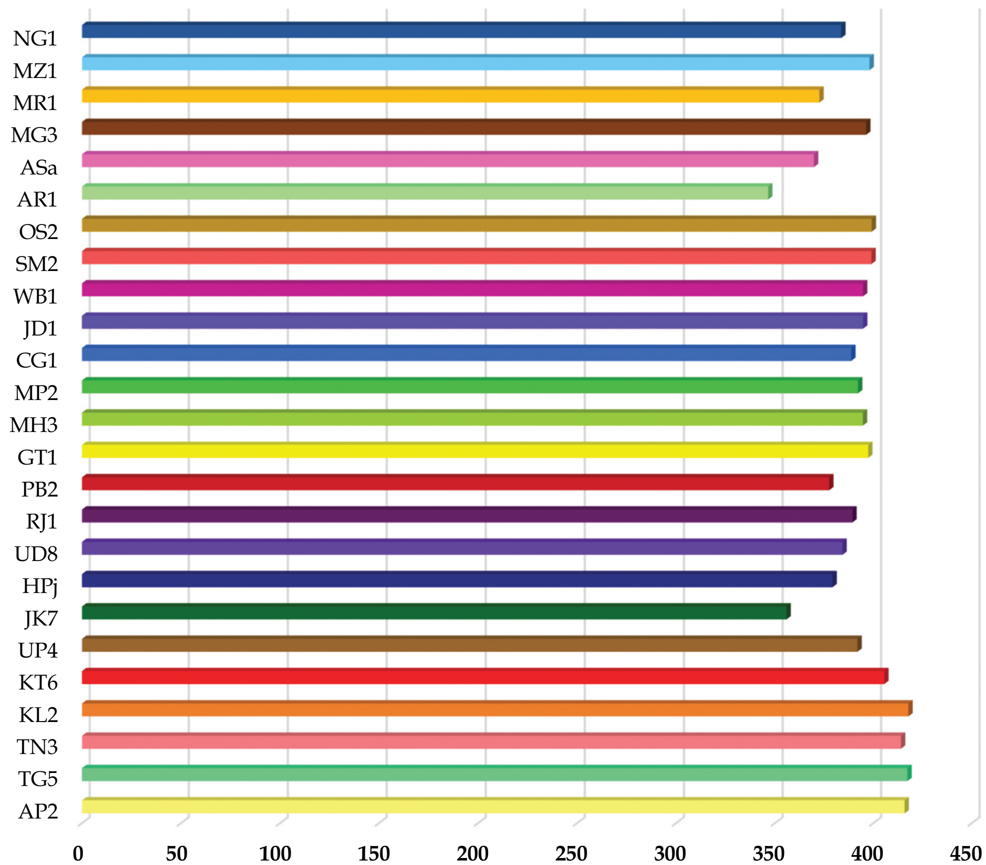

Figure 8. Maximum mean solar irradiance in different states and union territories in India.

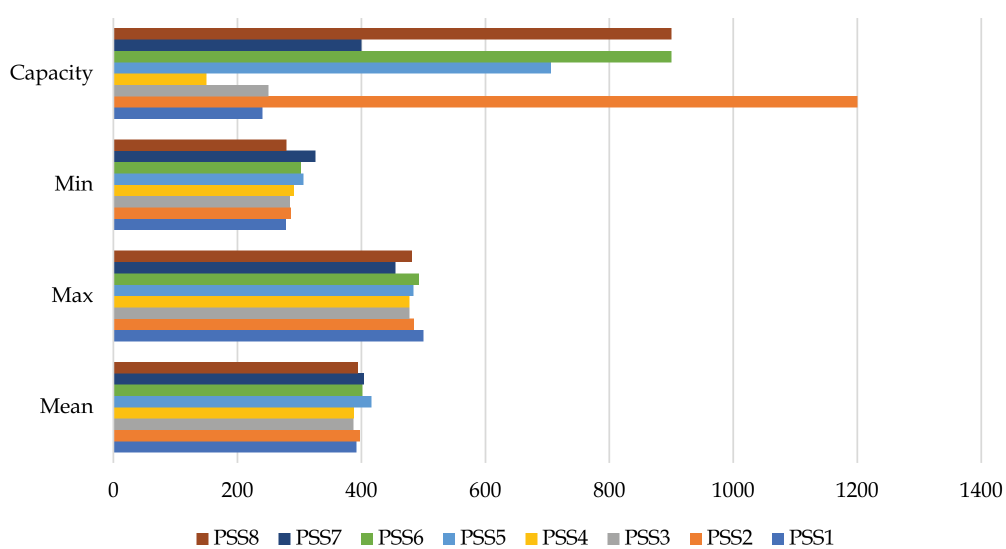

Figure 9. Solar irradiance on pumped storage systems in India.

of all the models, the GRU provided the best results. The other models like Random forest and Extra gradient followed next. The LSTM performed quite well for some datasets and the results of other datasets are not impressive. The GRU and LSTM models are run for 100 epochs with batch size 64 and optimized neuron numbers and learning rate are considered. The LSTM, Random forest, and Extra

Table 2. Solar irradiance on selected 33 (25 sites + 8 PSS) locations in India.

Name of the HSHP	Mean Solar Irradiance (W/m^2)	Name of the HSHP	Mean Solar Irradiance (W/m^2)	Name of the HSHP	Mean Solar Irradiance (W/m^2)
1. Nagarjuna Sagar (AP2)	415.80539	12. Ukai (GT1)	397.28818	23. Loktak (MR1)	372.44573
2. Pulichinthala (TG5)	417.25421	13. Tillari (MH3)	394.58691	24. Tuirial (MZ1)	397.98344
3. Kodaya (TN3)	413.95633	14. Omkareshwar (MP2)	392.14762	25. Doyang (NG1)	383.59695
4. Idukki (KL2)	417.7276	15. Hasdeo Bango (CG1)	388.6654	26. Kadana (PSS1)	391.976
5. Kalinadi (KT6)	405.43905	16. Panchet (JD1)	394.63794	27. Sardar Sarovar=RBPH (PSS2)	397.288
6. Rihand (UP4)	391.8257	17. Maithon (WB1)	394.63794	28. Ghatgarh (PSS3)	386.871
7. Sewa (JK7)	355.79087	18. Teesta (SM2)	398.93535	29. Bhira (PSS4)	388.218
8. Tangnu Romai (HPj)	379.12531	19. Hirakud (OS2)	399.05101	30. N J Sagar (PSS5)	415.805
9. Khatima (UD8)	384.21292	20. Ranganadi (AR1)	346.49186	31. Srisailam LBPH (PSS6)	402.001
10. Jawahar Sagar (RJ1)	389.27655	21. Kopili (ASa)	369.73014	32. Kadamparai (PSS7)	403.677
11. Mukerian (PB2)	377.47006	22. New Umtru (MG3)	396.26761	33. Purulia (PSS8)	394.638

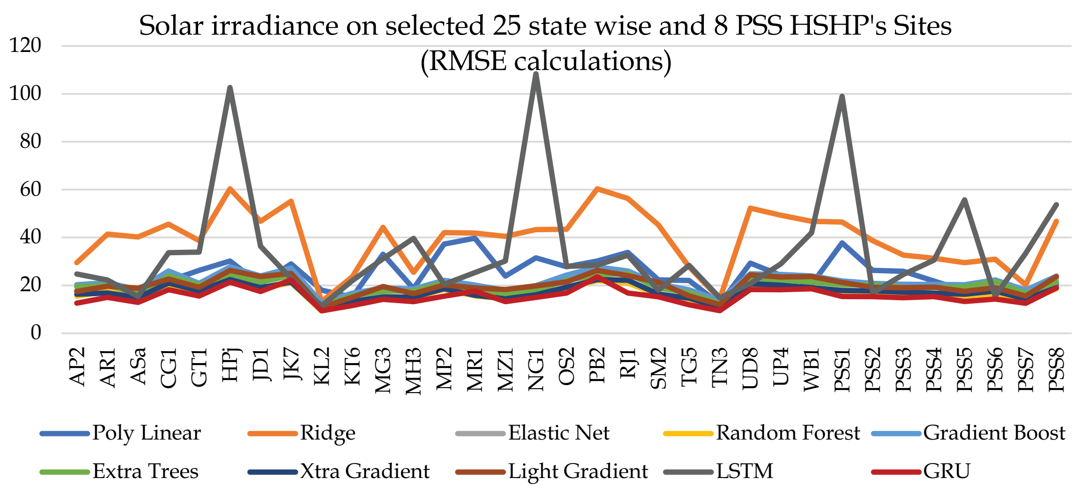

Figure 10. Comparison of RMSE values for machine and deep learning models.

Table 3. RMSE value comparison for north and Southern Indian locations.

Location	AP2	TG5	TN3	KL2	KT6	UP4	JK7	HPj	UD8	RJ1	PB2
GRU (W/m^2)	12.6	11.9	9.5	9.4	11.6	18.2	22.3	21.4	18.3	16.8	23.6
Random Forest (W/m^2)	15.5	14.3	10.5	9.33	13.1	19.3	21.1	22	19.8	21	21.99
Extra Gradient (W/m^2)	16.4	14.7	10.8	9.65	13.4	20.1	21.5	22.5	20.7	22.2	22.47
Linear Regression (W/m^2)	27.5	25.2	14.2	13.8	21.3	47.4	46.8	54.0	49.3	51.5	54.1

Table 4. RMSE value comparison for west, East, and north–Eastern Indian locations.

Location	GT1	MH3	MP2	CG1	JD1	WB1	SM2	OS2	AR1	ASa	MG3	MR1	MZ1	NG1
GRU (W/m^2)	15.6	13.2	15.5	18.2	17.5	18.6	15.2	16.8	15	12.9	14	17.6	13.2	15
Random Forest (W/m^2)	16.9	15	18.3	20.1	18.6	18.6	16	19	17.5	14.8	14.8	15.6	14.43	16.31
Extra Gradient (W/m^2)	17.7	15.1	18.6	21	19	19	16.4	19.3	16.8	14.9	15.2	15.9	14.47	16.05
Linear Regression (W/m^2)	36.3	23.6	41.2	41.9	43.6	42.7	39.7	37.9	34.9	36.4	36.2	38.2	36.3	36.8

Table 5. RMSE value comparison for pumped storage Indian locations.

Location	PSS1	PSS2	PSS3	PSS4	PSS5	PSS6	PSS7	PSS8
GRU (W/m^2)	15.38	15.33	14.85	15.29	13.24	14.32	12.53	18.98
Random Forest (W/m^2)	17.5	16.9	16.9	16.5	15.51	16.47	13.46	18.63
Extra Gradient (W/m^2)	17.9	17.7	17.16	16.78	16.37	17.68	14.26	19.02
Linear Regression (W/m^2)	43.8	36.3	32.9	29.8	27.5	30.0	18.9	43.6

gradient model results are validated with the benchmark Linear regression machine learning model depicted in Table 5. The results of GRU, Extra Gradient, and Random forest are enhanced in every location and show better RMSE performance with GRU ranging from 146% to 282%, Random forest ranging from 135% to 251%, and Extra gradient ranging from 131% to 251% improvement over Linear regression model with change in locations.

7. Conclusion

This research has delved into the accurate coordinates mapping and statistical analysis of 40 years of solar radiation data for 252 existing & upcoming hydropower projects in India. Notable states like Himachal Pradesh, Uttarakhand, Sikkim, Madhya Pradesh, Maharashtra, Kerala, Karnataka, and Tamil Nadu are leading the way with higher concentrations of HSHP plants, highlighting their pivotal role in renewable energy initiatives. This study extended its impact by providing crucial data on the maximum, mean, and minimum solar irradiance for each high-scale powerhouse, categorized regionally into north, west, south, east, and northeast. Based on the maximum mean solar radiance high potential, 25 HSHP locations from each state are identified. The analysis also highlights states like Andhra Pradesh, Telangana, Kerala, Tamil Nadu, Gujarat, Rajasthan, Maharashtra, and Madhya Pradesh, where HSHPs stand out for their significant solar irradiation potential and create conditions for the effective utilization of solar energy in hybrid PV-hydro systems. The study forecasted solar irradiance potential for identified 25 locations and 8 Pumped storage systems by 8 machine learning and 2 deep learning models. The deep learning model GRU outperformed other machine and deep learning models, with root mean square error values ranging from 9.4 to 18.98 W/m^2 in predicting the day solar irradiance on data of concluded sites. The potential of a hybrid or ensemble combination of GRU deep learning models emerges as a promising avenue, offering superior predictive capabilities compared to alternative deep learning models. Finally, this analysis provides a path for a sustainable future through the harmonious integration of hydropower and solar energy, paving the way for reliable renewable energy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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