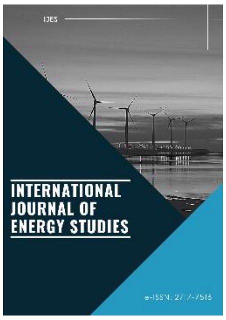
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Research Article

Int J Energy Studies 2026; 11(1): 207-254

DOI: 10.58559/ijes.1812948

Received : 29 Oct 2025
Revised : 06 Jan 2026
Accepted : 11 Jan 2026

Design and simulation of integrated solar-hydroelectric systems: Complementary renewable profiles and MATLAB/Simulink-based analysis

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Highlights

• This study focuses on the optimization of installed capacity in a hybrid energy system.
• An algorithm has been developed within the scope of this research, supported by MATLAB/Simulink.
• The results obtained demonstrate a high degree of precision and enhanced efficiency in terms of capacity and grid stability.

You can cite this article as: Saltuk MF. Design and simulation of integrated solar-hydroelectric systems: Complementary renewable profiles and MATLAB/Simulink-based analysis. Int J Energy Studies 2026; 11(1): 207-254.

ABSTRACT

The increasing penetration of renewable energy sources necessitates the development of hybrid energy systems capable of ensuring reliability, economic viability, and operational flexibility. This study investigates the optimal design and techno economic performance of a hybrid renewable energy system (HRES) integrating photovoltaic (PV) generation and hydropower for a selected case study in Türkiye. In this study, a Solar-Hydroelectric (SHE) hybrid system was designed and modeled using MATLAB/Simulink. The system is designed to supply an annual electrical load of approximately 10,500 MWh, while minimizing total system cost and improving energy reliability. A comprehensive optimization framework is employed to determine the optimal capacities of the SHE facility. The results indicate that the optimal configuration consists of 4.375 MW of PV capacity combined with an existing 3.065 MW of hydropower, enabling effective load coverage throughout the year. The total initial investment cost of the proposed system is estimated at 3.3 million USD, with an annual operating cost of 150,000 USD. The hybrid configuration achieves a levelized cost of energy (LCOE) of 0.02685 USD/kWh, which is lower than that of comparable single source hydroelectric power plant (HEPP) systems. The integration of solar PV significantly reduces hydropower dependency during dry seasons and enhances overall system flexibility. In addition, the hybrid system improves energy utilization and reduces curtailment while maintaining supply reliability. Also, an enhanced MATLAB/Simulink design is demonstrated in this study. The findings demonstrate that solar-hydropower hybridization represents a technically feasible and economically competitive solution for expanding renewable energy deployment in Türkiye. The proposed approach provides practical insights for policymakers and energy planners aiming to develop cost-effective and sustainable hybrid energy systems.

Keywords: Solar hydro energy, Hybrid energy, MATLAB/Simulink, Energy efficiency

1. INTRODUCTION

Renewable energy has emerged as the central pillar of sustainable energy transitions worldwide. Globally, hydropower accounts for more than 1,300 GW of installed capacity, making it the largest renewable energy source in operation. Its advantages lie not only in scale but also in dispatchability: reservoirs allow water to be stored and electricity to be generated on demand, providing flexibility that intermittent renewables cannot match. Türkiye mirrors this global trend. Hydroelectricity remains the country's single largest renewable contributor, with a substantial share of total electricity generation capacity. Large dam projects along the Euphrates, Tigris, and other major rivers have provided significant installed capacity. Among the available technologies, hydropower has historically dominated global renewable electricity generation due to its mature technology, large-scale deployment, and ability to provide both base-load and flexible capacity. In Türkiye as well, hydroelectric power plants (HEPPs) have long represented the largest share of installed renewable capacity, benefiting from the country's rich hydrological resources and extensive dam infrastructure. Overall hydropower installed capacity of 2024 is given in below Figure 1[1].

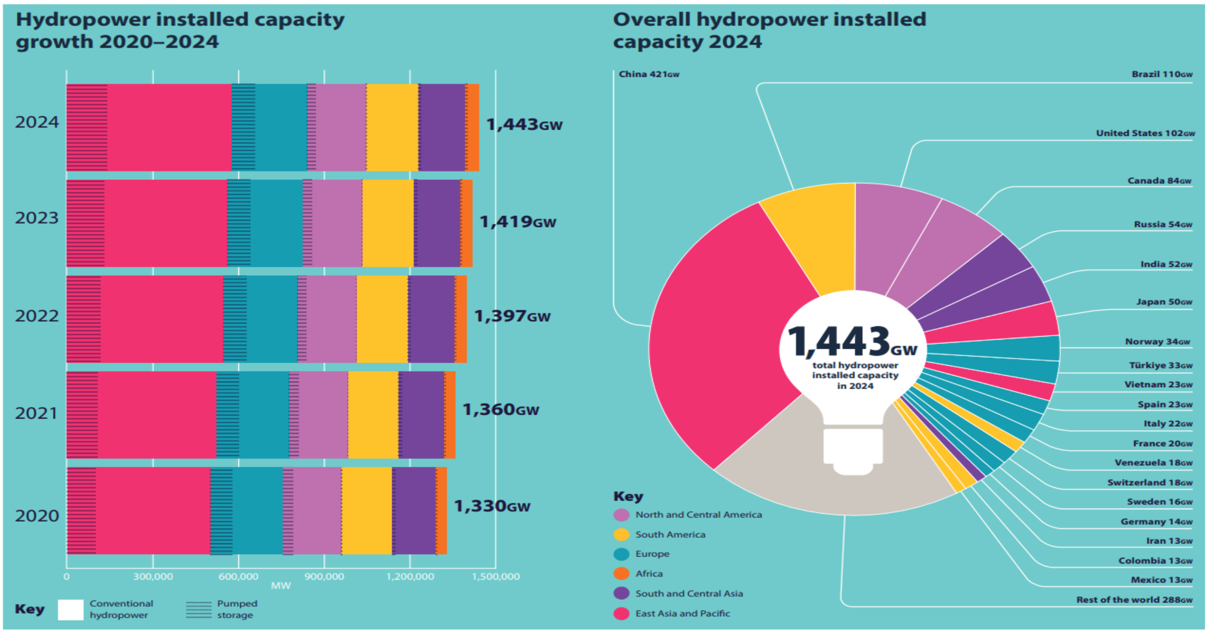

Figure 1. Overall hydropower installed capacity of 2024 [1]

While seasonal and annual variations in rainfall affect hydropower generation, its infrastructural dominance ensures its continued importance. However, reliance on hydrology alone exposes energy systems to climate-related vulnerabilities such as droughts and irregular precipitation patterns. Unlike hydro, solar energy has only recently emerged as a major component of global electricity supply. Over the past fifteen years, it has experienced unprecedented cost reductions. Between 2010 and 2020, the average cost of utility-scale PV projects fell by nearly 85%, according to the International Renewable Energy Agency (IRENA). This transformation is driven by economies of scale, improvements in module design, innovations in inverter technology, and advances in materials science. Rapid technological advancement, coupled with dramatic cost reductions, has enabled solar photovoltaics (PV) to become the fastest-growing renewable energy source globally. Module efficiency improvements, large-scale manufacturing, and competitive markets have driven solar's levelized cost of electricity (LCOE) down to levels that rival or even undercut fossil fuels. Consequently, while hydropower retains the largest share of cumulative installed capacity, the steepest growth in new installations is now driven by solar energy investments. Global weighted solar energy cost trend is given in below Figure 2 [2].

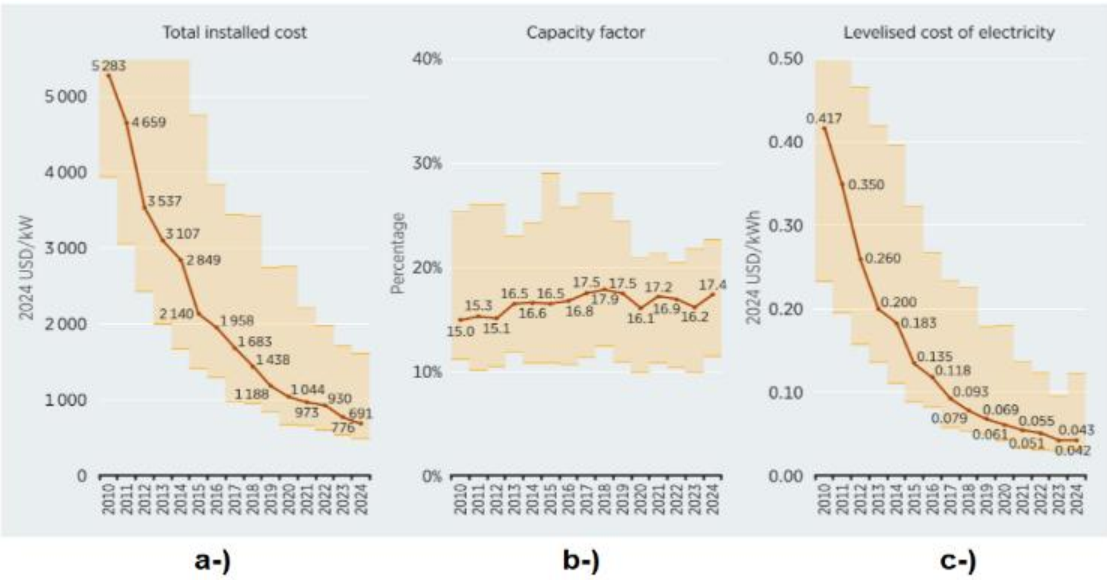

Figure 2. a-) Total installed cost; b-) Capacity factor; c-) Levelized cost of Energy (LCOE) for utility scale solar PV, 2010-2024 [2]

In Türkiye, the solar sector has rapidly expanded, particularly in regions with high solar potential such as Konya, Karaman, and Denizli. Although the country's solar installed capacity is still smaller than its hydro base, growth rates are significantly higher. Türkiye's strategic geographic position, spanning both Mediterranean and continental climates, provides excellent solar resources, positioning PV as a key driver of future renewable expansion. The interplay between hydro and solar is particularly important from a system perspective. Their generation profiles are naturally complementary. Hydropower output peaks during rainy seasons when solar irradiation is relatively low, whereas solar generation reaches its maximum during dry, sunny months when hydrological inflows decline. This inherent complementarity creates a synergy that strengthens the case for hybridization of these two resources. Hydropower and solar PV differ fundamentally in their production dynamics, yet their variations are complementary rather than conflicting. During rainy seasons (spring in Türkiye) hydroelectric output increases substantially as rivers and reservoirs fill, while solar generation tends to be lower due to reduced irradiation and cloud cover. Conversely, during dry and hot summer months, hydrological inflows decline, limiting hydropower output, but solar PV generation reaches its peak. This relationship means that a hybrid solar hydro system can provide a balanced and more predictable energy profile. Hydropower smooths out solar's intermittency by dispatching stored water during cloudy days or nighttime, while solar reduces hydropower's dependence on variable inflows. The two resources together therefore create a system that is both reliable and cost-effective. A typical graph of energy generation from a hydroelectric plant is given below (Rego et al. 2020). To illustrate differences in generation patterns, the PVGIS program was used to provide an SPP energy production profile at a location representing the average radiation amount in Türkiye and with an installed capacity of 40 MW. A simple energy generation profile comparison of hydro and solar is given in below Figure 3.

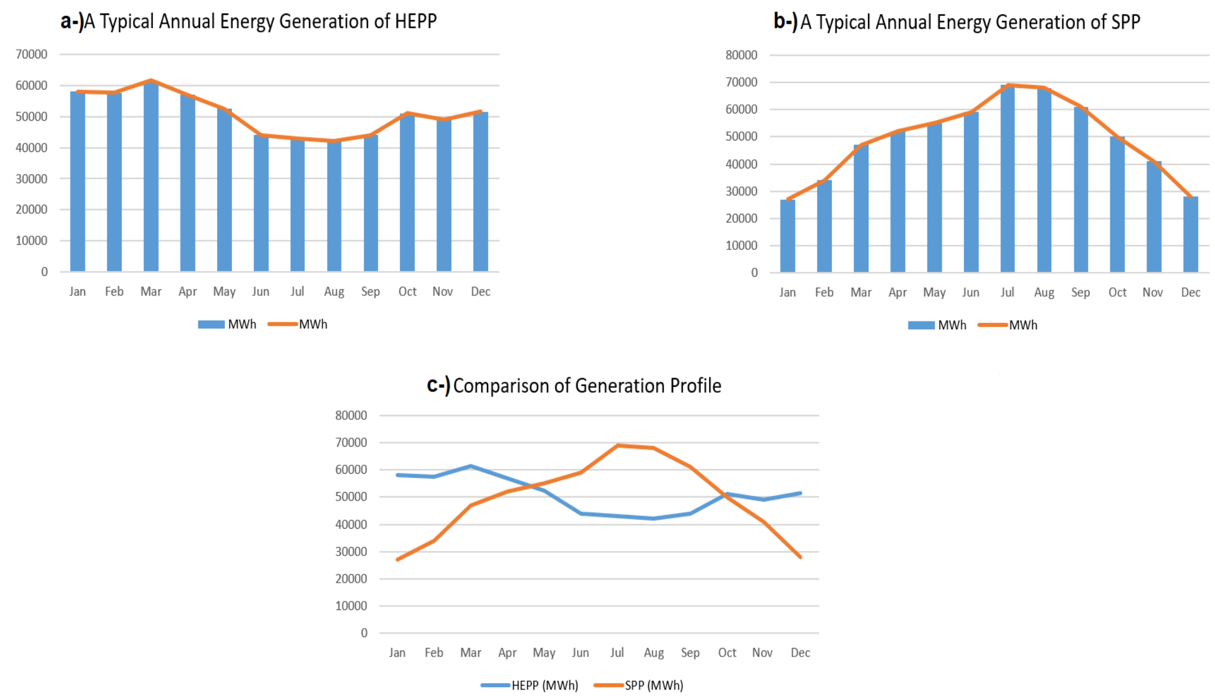

Figure 3. a-) A typical Energy generation of HEPP [3]; b-) A typical Energy generation of SPP; c-) Comparison of generation profile

Wu et al. developed a capacity optimization model for building energy storage, integrating flexibility via LSCR. Among PV-BES, PV-TES, and PV-HES systems, PV-HES proves most cost-efficient, with TOU tariff ratios significantly shaping economic performance and flexibility management [4]. Mojumder et al. optimized and validated hybrid renewable energy systems for remote electrification in Bangladesh using HOMER Pro and MATLAB/Simulink. Results show PV-Wind-Battery-Grid offers lowest LCOE and NPC, with sensitivity, SOC-based control, and LCA ensuring technical, economic, and environmental sustainability [5]. Malakar and Lal studied a 1 MW grid-connected phasor-type wind turbine in MATLAB/Simulink, employing BEM-optimized aerodynamics and superconducting generators. Results show effective 0.96 MW power delivery, with capacitor-supported reactive compensation, validated performance across variable wind speeds, and reliable grid integration efficiency [6]. Ramkumar et al. introduced a hybrid QI-NLS-G2O and GRZPNet-based energy management framework for Multi-Energy Microgrids. Implemented in MATLAB/Simulink, it optimizes micro-source scheduling under renewable uncertainty, enhancing dispatching accuracy by 15% and efficiency by 20%, demonstrating cost-effective, resilient, and sustainable solutions for industrial microgrid energy management [7]. Khosravi et al. proposed a hierarchical deep learning-based energy management strategy for a multi-source networked microgrid integrating PV, wind, biomass, BESS, and hydro storage. Validated in MATLAB/Simulink, the method optimizes distribution, enhances flexibility, and ensures robust performance across diverse operational scenarios [8].

Melamu et al. presented a PV–Microhydropower hybrid system for rural electrification, designed to meet 180 kW demand. Using synchronous generation, converters, and control strategies, results confirm stable supply under optimal irradiance and flow, though PV fluctuations necessitate load shedding to prevent blackout [9]. Nigam and Sharma analized a MATLAB/Simulink-based hybrid power system integrating solar PV, wind, and hydro sources. By addressing intermittency challenges, the study highlights hybrid configurations' potential to ensure continuous electricity supply and grid stability, offering a comparative evaluation of system performance [10]. Niringiyimana et al. stated that Rwanda remains one of the least developed countries, with electricity access limited to around 63%, leaving large rural populations unserved. Musanze district exemplifies this challenge, where 60% of inhabitants live in remote areas, making grid extension difficult. Although micro hydropower plants have been introduced, their capacity is insufficient, particularly during the dry season when river flow diminishes. To address this gap, this study investigates and optimizes a hybrid PV-hydropower system. A 200 kW Mutobo micro hydro station is combined with a 100 kW PV array, integrated through inverter-based parallel control strategies. The system employs a modified Perturb and Observe (P&O) MPPT algorithm, incorporating an additional ΔI condition to eliminate drift and improve maximum power tracking under fluctuating irradiance. Simulation in MATLAB/Simulink using local meteorological and hydropower data confirms that the PV-hydro hybrid enhances supply reliability, mitigates seasonal shortages, and outperforms alternatives in efficiency, cost-effectiveness, environmental sustainability, and operational resilience [11]. Singh et al. proposed a hybrid solar-hydro-battery system for Gorakhpur, India, addressing rising energy demand, fossil fuel depletion, and emissions. Leveraging solar's declining costs and microgrid integration, it highlights green energy's potential to ensure reliable, economical, and sustainable electrification [12]. Hadith et al. explored a solar–hydro hybrid system in Haditha, Iraq, where declining water levels have reduced hydro output from 660 MW to below 160 MW. A proposed 100 MW solar plant aims to complement hydropower, ensuring reliable energy supply [13]. Ali et al. proposed an innovative hybrid multi-stage renewable energy system to address voltage minimization and stability challenges in Egypt's real-world grids, particularly for communities along the Nile. The system integrates multi-stage hydro-matrix undershot water wheels with photovoltaic (PV) solar arrays through a common DC bus, ensuring reliable operation in both grid-connected and isolated modes. The hydro-matrix subsystem consists of three undershot water wheels driving induction generators, delivering approximately 20 kW, while the PV subsystem includes six multi-stage arrays totaling 28 kW. A controlled battery storage bank is incorporated to mitigate fluctuations from varying water speeds, solar irradiance, and PV temperature, ensuring stable voltage levels. The design also employs PID controllers, rectifiers, converters, and inverters to optimize energy conversion and integration. MATLAB/Simulink simulations confirm that the proposed system effectively maintains load voltage magnitude and frequency under dynamic conditions, highlighting its potential to enhance grid reliability, support rural electrification, and advance renewable energy utilization [14]. Kumar et al. presented a modified single P&O MPPT control algorithm for hybrid solar-wind energy systems, aiming to extract maximum power efficiently from both sources in standalone applications [15]. Chullai et al. introduced third-order field-oriented sliding mode control for BLDC drives in PV-integrated pump hydro storage. MATLAB/Simulink simulations and prototype validation confirm superior stability, efficient bidirectional power flow, and IEEE-compliant harmonic distortion, outperforming conventional PI-based control strategies [16]. Tereci and Atmaca explored the integration of renewable energy in recreational spaces, focusing on Adalet Park in Konya. This paper evaluated solar and wind energy applications to enhance sustainability and environmental impact [17]. Veramalla et al. presented a unit template control algorithm for off-grid asynchronous generators driven by hydro turbines and integrated with solar PV. Using fewer sensors, MATLAB/Simulink simulations confirm effective load balancing, harmonic mitigation, and stable voltage–frequency control via VFC with MPPT [18]. Somefunn et al. modelled a renewable integration at injection substations using MATLAB/Simulink. PV and energy storage significantly improve voltage stability (13.33% enhancement) and ensure feeder supply during grid outages, demonstrating the potential of renewable–storage coupling for reliable, sustainable power system operations [19]. Patel and Chilipi developed a CSF-MPCC-based control strategy for a micro-hydro-PV standalone microgrid with VSI integration. Using TOF filters and BESS management, MATLAB and hardware results confirm improved PCC voltage regulation, harmonic suppression, and reliable power quality under dynamic loading conditions [20].

Checklie et al. investigated the design, modeling, simulation, and techno-economic feasibility of a stand-alone hybrid renewable microgrid system integrating solar PV, mini-hydro, and battery storage for rural electrification in Ethiopia. Focusing on Gora Got and Dibkan villages, the system is sized to serve approximately 292 households and community institutions. The hybrid configuration comprises a 174.2 kW hydro plant, 48 kW PV array, and 226.3 kWh battery storage with two days of autonomy. Modeling and simulation are performed in MATLAB/Simulink, incorporating converters, rectifiers, inverters, and appropriate controllers to ensure voltage stability and battery protection. Economic feasibility is assessed using HOMER software, yielding a cost of \$0.08/kWh, competitive with grid tariffs. Annual energy production achieves a 100% renewable fraction, with hydropower contributing 96% and PV 4%. Results confirm system reliability, stability, and affordability. The study highlights the potential of hybrid microgrids in rural poverty alleviation and recommends system expansion with other renewable resources [21]. Ibekwe et al. designed a solar-pumped hydro storage system in MATLAB/Simulink using fuzzy logic control. The intelligent valve system regulates irradiance and water levels, ensuring continuous supply, achieving over 99.5% MPPT efficiency, and enhancing grid stability, resilience, and renewable integration [22]. Asare-Bediako et al. assessed Ghana's Bui hydro-solar hybrid plant using simulations. Results show benefits and challenges, including voltage fluctuations and power losses, mitigated by storage, smart grids, and FACTS devices. Findings provide insights for reliable renewable integration supporting regional sustainability goals [23]. Iweh et al. optimized a hydro–solar PV–battery hybrid system for rural Cameroon using HOMER

Pro and MATLAB-based genetic algorithms. Results show GA yields lower NPC ($86,991) and LCOE ($0.0344/kWh), demonstrating superior cost-effectiveness and reliability over deterministic HOMER optimization [24]. Neupane et al. designed a solar-microhydro hybrid microgrid in MATLAB/Simulink using synchronverter-based power angle control. Results demonstrate stable frequency, low harmonic distortion, and effective power sharing under irradiance variations and nonlinear loads, ensuring reliable operation and smooth synchronization in standalone systems [25]. Sakouvogui et al. analyzed solar–hydro hybrid systems for rural electrification in Tamagaly using HOMER-based sizing and simulation. Results show 71% PV and 29% hydro contributions, yielding 527,936 kWh annually, ensuring load coverage, reliability, and reduced greenhouse gas emissions in remote communities [26].

Twaróg evaluated Poland’s Porąbka-Żar pumped storage plant in MATLAB/Simulink, incorporating AI-based forecasting for demand and contingencies. With 500 MW generation and 542 MW pumping capacity, results highlight its regulatory role and potential hybrid integration for enhanced grid stability [27]. Gizaw and Bekele designed a hybrid FPV–pumped hydro–diesel system for Ethiopia’s Tulu Gudo Island. Using GIS, PVsyst, and HOMER optimization, results show $0.14/kWh COE, improved capacity factor, water savings, and W-E-F nexus integration, ensuring sustainable, reliable electrification for remote communities [28]. Kenfack et al. designed an optimized PV/T–hydro–diesel tri-hybrid system for rural Cameroon using MATLAB. Results show demand-side management reduces costs by 59% and emissions by 22%, highlighting DSM’s role and PV/T hybridization’s potential for efficiency and net-zero targets [29].

Konneh et al. evaluated Sierra Leone’s Bo-Kenema hybrid power network through techno-economic-environmental optimization. Among 13 scenarios, PV-hydro–diesel–battery proved most cost-effective ($0.211/kWh), though turbine efficiency significantly influenced results. Higher-efficiency turbines reduced costs but increased CO_2 emissions, highlighting trade-offs between sustainability, affordability, and policy preferences [30]. Agajie et al. optimized renewable energy scenarios for Gaita Selassie, Ethiopia, using MOGWO and MOGOA in MATLAB. Results show PV–Wind–PHES hybrid achieves lowest COE (€0.126/kWh) and TLCC, with superior reliability and sustainability, highlighting MOGWO’s effectiveness in rural energy planning [31]. Oladigbolu et al. evaluated off-grid PV–hydro–diesel–battery systems for Nigerian rural electrification using HOMER. Results show the optimized hybrid yields $0.112/kWh COE, lowest NPC, and 77.1% CO_2 reduction, ensuring technical reliability, economic viability, and environmental sustainability under varied sensitivity conditions [32]. Ma and Yuan optimized off-grid PV hybrid systems with battery and hydrogen storage using MATLAB-based particle swarm optimization. Results show PV/battery systems are more economical under higher interest rates and lower reliability, while PV/hydrogen requires larger PV capacity but enhances independence [33]. This paper presents a study in which a hybrid hydro-solar system was designed, modeled, and simulated using MATLAB/Simulink. Special attention was given to the operational characteristics of each technology, their integrated performance, and the evaluation of current-voltage (I-V) curves as part of photovoltaic system characterization.

Driven by growing concerns over climate change, global warming, and energy security, the renewable energy market has experienced unprecedented expansion in recent years. In 2024 alone, the global installed capacity of renewable energy increased by approximately 50%, highlighting a decisive shift in the global energy landscape toward low carbon and sustainable technologies. By the end of 2024, the total global installed renewable energy capacity, specially encompassing solar, wind, hydropower, geothermal, marine, and biogas resources, reached about 4,448.1 GW. Photovoltaic (PV) solar energy systems accounted for nearly 1,600 GW of this capacity, while global hydropower installations stood at approximately 1,450 GW. This rapid and sustained growth reflects not only technological advancements and cost reductions but also strengthened policy commitments and international efforts to mitigate greenhouse gas emissions and promote sustainable development. Such global trends underscore the increasing relevance of hybrid renewable energy systems as effective solutions for enhancing system reliability, optimizing resource utilization, and supporting the large scale integration of renewable energy into modern power systems [34].

Nassar et al. addressed Libya's persistent electricity deficit by proposing an optimally sized grid connected hybrid renewable energy system (HRES) integrating wind, solar photovoltaic, and pumped hydropower storage. Using multi criteria decision making, the system is optimized with respect to economic, technical, and environmental indicators, including LCOE, NPV, LPSP, payback period, and life cycle CO_2 emissions. Results demonstrate that locally available renewable resources can fully compensate for the national electricity shortfall while significantly reducing emissions and social carbon costs. Sensitivity analysis confirms the robustness of the design, highlighting its applicability to other developing countries facing similar energy challenges [35].

Salim et al. addressed the intermittency of renewable energy sources and variable demand by proposing an optimally sized photovoltaic (PV) system integrated with pumped hydroelectric storage (PHS) for sustainable urban electricity supply in Brack, Libya. A constrained optimization framework is employed to determine system sizing while accounting for operational constraints and renewable output uncertainty. Multiple operational scenarios are evaluated to identify the optimal configuration. Results indicate that a system comprising 500 MW of PV capacity and 5,770 MWh of storage can reliably meet an annual load of 590,019 MWh. The proposed solution reduces CO_2 emissions by 611 tons while achieving favorable economic performance in terms of LCOE and investment cost [36]. Nassar et al. investigated the optimal sizing of a pumped hydro storage (PHS), integrated hybrid photovoltaic and wind power system to ensure a reliable and sustainable electricity supply for an urban community in Brack, Libya. A constrained optimization framework is developed to account for renewable resource intermittency, load variability, and operational uncertainties. Using measured climatic and demand data, energy production is simulated via the System Advisor Model. Economic evaluation based on the levelized cost of energy identifies an optimal PV to wind capacity ratio of 1:5. Results demonstrate that PHS contributes 15% of annual demand, confirming the cost competitiveness and reliability of the proposed system [37].

El-Khozondar et al. investigated the feasibility and optimal design of off grid photovoltaic (PV) systems for street lighting at the Kuwaiti Roundabout in Gaza Strip, Palestine. Several solar powered lighting configurations are evaluated through mathematical modeling and validated using PVsyst software. The analysis emphasizes the transition from conventional centralized sodium lighting systems to autonomous LED based solar solutions with intelligent control mechanisms. Key design challenges, including energy consumption, spatial constraints, and grid load reduction, are addressed. Innovative components such as dual-voltage lamps and advanced charge controllers are proposed. The results demonstrate that well-designed PV LED systems offer efficient, reliable, and sustainable urban lighting solutions [38]. Khaleel et al. evaluated the role of green energy technologies, specifically photovoltaic systems, wind power, and hydrogen fuel cells, in advancing sustainable development and reducing greenhouse gas emissions. It reviews recent technological progress and empirical evidence demonstrating the effectiveness of renewable energy deployment in lowering carbon emissions and supporting global climate objectives. Comparative case studies from China, the European Union, the United States, India, and Japan highlight substantial emission reductions associated with increased renewable capacity. Despite differing cumulative CO_2

emissions between 2015 and 2023 across these regions, the findings consistently confirm that large-scale adoption of renewable energy technologies is a critical driver of decarbonization and long term Sustainability [39]. Elnaggar et al. evaluated the technical, economic, and environmental feasibility of wind energy deployment in Palestine's coastal region as a strategy to mitigate electricity shortages and enhance energy security. Ten commercial wind turbines with varying rated capacities are assessed using wind speed data at multiple hub heights. Performance indicators including capacity factor, annual energy yield, levelized electricity cost, benefit/cost ratio, and payback period are analyzed. Results show that while the Siemens SWT-2.3-93 achieves the highest annual energy output, the Lagerwey-LW58/750 turbine offers superior economic performance, with the highest capacity factor, lowest generation cost, and shortest payback period. The proposed wind deployment also enables substantial annual CO_2 emission reductions [40].

Abuhelwa et al. investigated public awareness of renewable energy (RE) in Palestine and its role in facilitating effective adoption amid rising energy demand and declining conventional resources. It examines how education level, community type, and building characteristics influence perceptions, attitudes, and willingness to acquire RE related knowledge. The analysis also reviews current practices, RE education status, and their implications for engineers and technical capacity building. Individual and institutional initiatives aimed at overcoming adoption barriers are highlighted, alongside recommendations for improved utilization of RE resources. Despite challenges such as infrastructural, financial, and political constraints, opportunities exist through international cooperation and modular, scalable RE grid solutions [41].

Nyasapoh et al. assessed Ghana's progress toward a sustainable energy transition by evaluating renewable energy integration using the IAEA MESSAGE modeling framework. It examines the feasibility of achieving the national target of 10% renewable energy penetration by 2030 and beyond. Results reveal a substantial gap between policy targets and actual deployment, with renewables contributing only 4.77% of the energy mix and installed capacities significantly below projections. Continued reliance on fossil based thermal generation raises sustainability and emissions concerns. The study highlights the need for targeted policies, investments in energy storage and smart grids, financial incentives, and the integration of renewables with low carbon baseload options to accelerate Ghana's energy transition [42].

El-Khozondar et al. evaluated the feasibility of supplying Gaza Strip's electricity demand through a grid connected hybrid renewable energy system amid persistent energy shortages. Using the HOMER optimization tool, multiple scenarios are assessed against economic, environmental, technical, and energy security criteria in alignment with UN SDG-7. The optimal configuration integrates photovoltaic, wind, hydropower, biomass, geothermal, and grid electricity, with renewables contributing the majority of generation. Results demonstrate substantial economic benefits, including low LCOE, reduced net present cost, and a short payback period, alongside a 52% reduction in CO_2 emissions. The findings confirm the strong potential of large-scale renewable integration for Gaza's urban energy supply [43]. Elmnifi et al. investigated the integration of pumped hydroelectric energy storage (PHES) with hydroelectric, solar, and wind power systems to enhance energy sustainability and flood mitigation in the city of Derna. The proposed hybrid system comprises 30 MW of hydropower, 25 MW of solar, and 40 MW of wind generation. Using MATLAB based simulations, the study evaluates the technical feasibility, economic performance, and environmental impacts of PHES integration. Results demonstrate that PHES provides a cost-effective, environmentally sustainable solution while enabling large-scale energy storage and efficient utilization of renewable resources. The findings offer valuable insights for policymakers and energy stakeholders in advancing integrated renewable energy systems [44].

Khaleel et al. focused on the modeling and stability analysis of a battery based hybrid energy storage system (HESS) integrated into a microgrid to enhance operational performance and power reliability. The proposed system combines photovoltaic, fuel cell, and battery units to support load demand under various operating conditions. Advanced phasor based modeling is employed for design evaluation, while intelligent control strategies using Adaptive Neuro Fuzzy Inference System and Genetic Algorithm techniques are applied for system optimization. Simulation results demonstrate significant improvements in fault mitigation, with ANFIS and GA achieving injection values of 99.6% and 98.9%, respectively, during single line-to-ground fault scenarios, effectively reducing voltage sag compared to conventional systems [45].

Mohammed et al. employed a GIS based approach to identify suitable locations for pumped hydropower energy storage (PHES) development in Libya by integrating geographic and climatic criteria within a multi layer decision making framework. The objective is to support Libya's long term energy strategy by mitigating grid deficits and increasing the share of renewable energy to over 50% by 2050, in line with national and international climate commitments. Results indicate that approximately 24.73% of Libya's land area is potentially suitable for PHES deployment, classified into high, medium, and low suitability zones. The identified sites exhibit significant elevation ranges and storage capacities, highlighting PHES as a viable solution for large-scale energy storage and grid stability [46].

2. MATERIALS AND METHODS

An optimization algorithm is developed for the design and performance assessment of a hybrid power system. The mathematical formulation of the algorithm and Equations (1-10) are expressed as follows [47]:

$$Ghyd = actual\ electricity\ generation\ of\ the\ HEPP \quad (1)$$

$$Gsol = calculated\ electricity\ generation\ of\ solar\ energy \quad (2)$$

$$G\ (x) = Ghyd + G\ sol\ (x) \quad (3)$$

$$Chyd = actual\ cost\ of\ HEPP \quad (4)$$

$$Csol = calculated\ cost\ of\ solar\ energy \quad (5)$$

$$C\ (x) = Chyd + Csol\ (x) \quad (6)$$

$$P = feed\ in\ tariff \quad (7)$$

$$B\ (x) = G\ (x)\ .\ P \quad (8)$$

$$Loop(x) = \frac{B(x)}{C(x)} \quad (9)$$

$$Foptimum\ (x) = max\ (Loop\ (x)) \quad (10)$$

Here, $Ghyd$ represents the realized hydropower generation, while $Gsol$ denotes the forecasted solar generation. $G\ (x)$ is the combined generation of the hybrid facility at iteration step. Similarly, $Chyd$ is the realized cost of hydropower and $Csol$ is the estimated investment cost of solar, with $C\ (x)$ being the total system cost. P denotes the feed-in tariff, $B\ (x)$ expresses the benefit of the hybrid configuration, and $\mathrm{Loop(x)}$ represents the benefit-to-cost ratio. The function $foptimum(x)$ identifies the maximum ratio, thereby determining the optimal installed capacity of the solar photovoltaic (SPP) component within the hybrid system.

The energy produced by PV and wind energy are estimated by these two equations directly as [48, 49]:

$$E_{PV} = P_{STC}\left[1 + \beta_p(T_{cell} - T_{STC})\right]\frac{H_t}{H_{STC}} \tag{11}$$

Where: T_{STC} and T_{cell} are the cell's surface temperature at Standard Test Condition and under real operation conditions (°C), $\beta_p$is the power temperature coefficient (%/°C), and H_{STC} and H_t are the STC and real global solar irradiance incidents on the PV module surface. The challenge that researchers will face is to find an empirical equation to determine the cell surface temperature T_{cell}.

$$P_{Storage} = \rho_w g \dot{Q} H \eta_{tur} \tag{12}$$

Where ρ_w refers to the water's density (1000 kg/m3), g is the gravity (9.81 m/s2), $\dot{Q}$ states for volumetric flow rate (m3/s), H is the head (m) and η_{tur} is the turbine's efficiency [50].

$$LCOE = \frac{\left(\frac{r(1+r)^n}{(1+r)^n-1}\right)\times C + C_{O\&M} - C_{CO2}}{E_t} \tag{13}$$

$$PBTM = \frac{C}{Income} \tag{14}$$

$LCOE$ is the levelized cost of electricity [51], r is the discount rate, n is the economic life. The cost of environmental damage (CCO_2) caused by CO_2 gas can be calculated by the following equation [52].

$$C_{CO2} = EF_{CO2} \times E_t \times \emptyset_{CO2} \tag{15}$$

where: EF_{CO2} represents the CO2 emission factor of the electric power generation system (kg CO2/kWh) [53], $\emptyset_{CO2}$ represents the carbon social cost ($/ton CO2), which may be considered as $ 70/ton CO_2 [54].

The flow of the proposed algorithm is illustrated schematically in Figure 4.

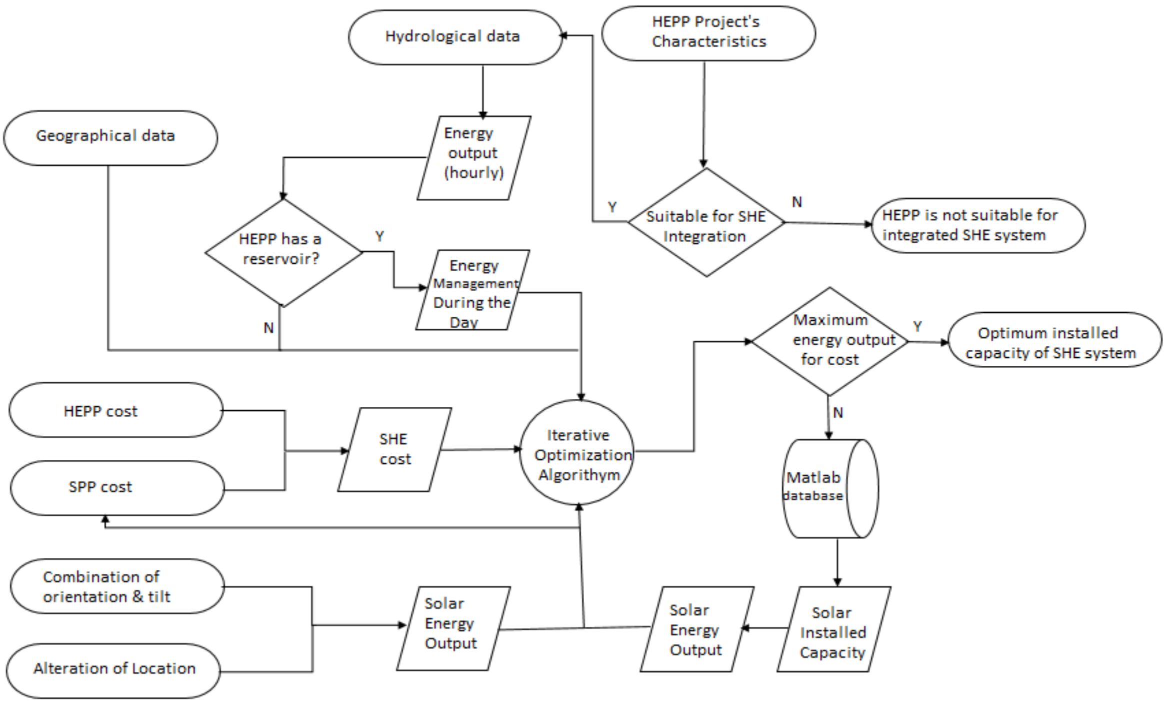

Figure 4. The designed algorithm for installed capacity optimization decision

The proposed algorithm for the development of an integrated Solar-Hydroelectric (SHE) system is structured into five major sections. Each section addresses a critical dimension of system design, optimization, and implementation. Collectively, these sections build a methodological foundation to ensure that integrated hybrid systems can be designed, evaluated, and deployed in a technically, economically, and environmentally efficient manner.

- Constraints: The first stage in designing an integrated SHE system involves identifying the principal constraints within which the system must operate. These constraints establish the operational and technical boundaries of the system, defining both opportunities and limitations. Among the most critical factors are transformer capacity and the availability of physical space for the installation of solar arrays. Regulatory constraints imposed by the system operator or relevant authorities must also be taken into account. Transformer capacity represents an immutable technical ceiling. Energy production that exceeds the capacity of the transformer risks destabilizing the grid and violating operational safety margins. Consequently, the maximum level of electricity that may be supplied to the grid is predetermined, and this allocation remains generally fixed. Integrated SHE systems, therefore, must be designed with explicit consideration of this grid injection limit. Physical space is another key constraint. The usable land or water surface area for photovoltaic (PV) installations is often limited. For hydropower plants, the length of diversion channels, the usable surface of reservoirs, or other water surfaces determine the maximum number of panels that can be deployed. Certain hydropower schemes, such as those relying on tunnels for conveyance, inherently lack suitable surfaces for PV deployment. Geographical and site-specific features further constrain feasibility, dictating whether hybrid integration is technically possible.

- Hydropower Component: Hydropower constitutes the backbone of any SHE system. Its suitability is determined not only by physical integration possibilities but also by hydrological stability. Dam-based hydropower projects, with their large reservoirs, are particularly well-suited for floating solar arrays, which can be deployed on the reservoir surface with relative ease. In contrast, run-of-river projects often present difficulties, as not all offer sufficient space for PV integration. Only those with suitable canals, headponds, or regulating basins can support hybridization. The essential step in evaluating hydropower suitability is the accurate estimation of water flow and its long-term variability. Data are drawn from streamflow observation stations (AGI), ideally with long-term, reliable measurements. When direct data are not available, hydrological drainage patterns and proxy stations within the same basin are used. In addition, ecological flow requirements, downstream water rights, reservoir volumes, and planned upstream or downstream facilities must be considered. Meteorological data, precipitation regimes, and long-term climate variability, including droughts and snowmelt patterns, further refine the hydrological dataset. Reservoir based hydropower plants provide an important advantage: storage capacity enables temporal shifting of electricity production. During daytime hours when solar production peaks, the hydropower plant can store water rather than generate electricity. At night or during cloudy periods, when solar output falls to zero, stored water can be released for generation. This complementary relationship enhances the overall reliability of the hybrid system, smoothing fluctuations caused by solar intermittency. For this reason, hydropower's ability to balance system variability makes it the decisive component in SHE integration. The hydropower model incorporated long-term hydrological averages, reflecting flow variability and reservoir characteristics. The plant was assumed to operate flexibly, storing water during periods of high solar output and releasing it during low solar availability. This approach maximizes system reliability and ensures continuity of supply.
- Solar Energy Component: Solar generation within SHE systems is evaluated with respect to both technical and geographic parameters. Key determinants include; the coordinates

and latitude of the installation site, local meteorological data, particularly solar radiation, temperature, wind, and humidity, geographical features such as slope, elevation, and surface orientation, the type and rated capacity of PV panels, inverter specifications and efficiency and loss factors including shading, soiling, and system inefficiencies.

- Electricity production from PV systems is modeled using established methodologies. These results are subsequently combined with hydropower output to assess total hybrid system generation. Notably, specialized software such as PVsyst is frequently employed to simulate PV performance under long-term meteorological conditions. PVsyst enables detailed modeling of solar irradiation, system losses, and uncertainty analysis, thereby providing accurate forecasts of solar output within the integrated framework. The solar subsystem was modeled based on irradiance and temperature data obtained from meteorological stations. PV panel characteristics, including maximum power point, efficiency coefficients, and temperature dependence, were incorporated using MATLAB's built-in libraries. The Incremental Conductance MPPT method with Integral Regulator was applied to maximize energy extraction from the PV arrays under varying conditions.
- Cost Assessment: Economic evaluation constitutes the fourth dimension of the algorithm. For solar components, costs are relatively standardized and predictable due to the modular nature of PV technology. Principal cost categories include; photovoltaic panels, inverters, mounting structures, civil works, site preparation, electrical infrastructure, including transmission lines, transformers, and SCADA systems. In contrast, hydropower costs are site-specific and heavily influenced by civil engineering requirements. Geological conditions, topography, and project characteristics play a decisive role in determining construction costs. Thus, while solar costs may be assessed on a per Watt basis, hydropower requires a detailed bill of quantities (BoQ) and site-specific estimates. Once costs are established, a cost-benefit analysis is performed. The system's installed capacity is optimized by balancing the maximum feasible energy yield from the water resource against the capital and operating costs. The aim is to identify the configuration that maximizes net benefit, thereby ensuring that the SHE system achieves economic viability as well as technical feasibility.
- Algorithmic Loop: The final stage of the algorithm is the iterative loop, implemented in MATLAB. Here, all components-constraints, hydropower output, solar output, and costs-are integrated within a dynamic optimization routine. The hydropower facility's data are input into MATLAB, including its long-term hydrological records. If storage is available,

the algorithm instructs the plant to reserve water during solar production peaks and generate electricity when solar output falls. This ensures continuity of supply and maximizes system reliability. Constraints are entered once and remain fixed throughout the process. The variable is the installed solar capacity, which is incrementally adjusted according to a predefined step size. For each iteration, total generation and economic performance are calculated. The optimal solution corresponds to the configuration that maximizes revenue relative to cost. This point represents the ideal installed capacity of the solar subsystem, which in turn defines the overall capacity of the SHE plant. Subsequent to the MATLAB-based loop, further validation is performed using PVsyst simulations. These enable detailed calculation of solar generation under real-world meteorological conditions, incorporating shading, uncertainty, and loss analyses. By comparing simulated results with real case studies and historical data, the reliability of the proposed algorithm is verified. Multiple scenarios are tested, including variations in hydrology, solar radiation, and cost structures, ensuring robustness across diverse conditions. The proposed five-part algorithm provides a comprehensive framework for designing integrated Solar-Hydroelectric systems. By systematically considering constraints, hydropower and solar characteristics, economic costs, and iterative optimization, it enables planners to identify the most effective hybrid configurations. The methodology ensures that integrated systems not only maximize energy production but also enhance grid stability, optimize resource utilization, and deliver economic value. The central conclusion is that hybrid SHE systems offer a viable pathway toward enhancing renewable energy portfolios, particularly in countries with substantial hydropower resources and rising solar potential, such as Türkiye. By leveraging the storage and balancing capabilities of hydropower alongside the growing affordability and scalability of solar, such systems can deliver reliable, flexible, and sustainable power. The algorithm, grounded in both theoretical rigor and practical validation, thus constitutes an important contribution to the advancement of hybrid renewable energy systems. Due to this algorithm, the optimum installed capacity of SPP is determined and the next step simulation is obtained by MATLAB/Simulink.

The core of this study involved the design and modeling of an integrated hydro-solar system using MATLAB/Simulink, a widely used platform for dynamic system simulation. The hybrid system was conceptualized such that solar PV arrays are integrated into the infrastructure of an existing hydropower facility-e.g., canal-top or reservoir-based floating PV-leveraging available surface areas while avoiding land-use conflicts. The most suitable installed capacity optimization of hybrid system decision can be determined by this MATLAB/Simulink loop. A Voltage Source Converter (VSC) was employed to regulate voltage levels and grid synchronization. The control system operated on a dual-loop architecture: one loop regulating DC link voltage, and the other controlling active and reactive current components. Harmonic mitigation was addressed through filtering strategies and capacitor banks. The entire system was simulated in discrete mode, compressing one year of operational data into a representative three-second simulation window. A critical element of PV system performance is the current–voltage (I-V) characteristic curve, which reveals how output varies with irradiance and temperature. In this study, MATLAB/Simulink was used to generate I-V and P-V (power–voltage) curves for the selected PV panels under dynamic conditions. The I-V curve illustrates the relationship between terminal voltage and output current, while the P-V curve identifies the maximum power point (MPP), at which the panel produces its highest possible output under given conditions. By comparing simulated curves with manufacturer datasheet values (STC and NOCT), the model was validated. The results demonstrated high correlation, confirming the reliability of the simulation environment for further hybrid system studies. Simulation outcomes confirmed the complementary nature of hydro and solar within the integrated framework. During daytime, solar output provided significant energy, allowing the hydropower facility to conserve water. At night or during cloudy intervals, hydropower generation ensured supply continuity. Seasonal shifts further reinforced complementarity: high inflows in spring coincided with lower solar output, while summer drought conditions coincided with peak solar generation. Moreover, the I-V characterization confirmed that the PV subsystem operated efficiently under varying irradiance and temperature profiles, with the MPPT control ensuring maximum energy extraction. Voltage Source Converter performance was stable across multiple power levels, though harmonic distortions became apparent under higher capacities-issues mitigated through line-length adjustments and filtering strategies. These findings underscore the practical viability of SHE systems as reliable, cost-effective solutions for renewable integration.

2.1. Assumptions, Limitations and Uncertainties

The HEPP is situated along an irrigation canal, with its loading reservoir located at the 7,500th meter of the channel. By utilizing the available head at this location, the facility generates electricity primarily outside the irrigation season (May-October), when surplus water is released. This operational dependency results in a relatively low-capacity utilization factor, as the plant is unable to exploit irrigation flows during the summer months. The main characteristic data of the HEPP is given in below Table 1.

Table 1. The existing HEPP's project characteristics

The Existing HEPP's Project Characteristics	Explanation
Province	Denizli
Installed Capacity of HEPP (MW)	3.065
Power Restriction of Transformer (MW)	3.065
The Flowrate of HEPP (m3/s)	11.11
The Lenght of Canal (m)	7,500
The Width of Canal (m)	10.2
The Height of HEPP (m)	23.62
The Estimated Energy Generation of HEPP	3,945,000
The Capacity Utilization Rate (%)	14.7
The Restriction of Hybrid Structure	*3.065 MW power restriction of HEPP *10 MW is the maximum applicable installed capacity size of hybrid SPP

The existing hydropower's long term electricity generation is approximately 5,600 MWh. This generation value states a 14.7% capacity utilization rate of the present hydropower plant. The integrated renewable hybrid SHE system is implemented to the current existing hydropower. During this study, two scenarios are compared. One in all them takes under consideration the long term flow value of the prevailing hydropower. The opposite scenario considers regulating the prevailing flow. These scenarios are compared as possible installed capacity, electricity generation, and capacity utilization rate. The most acceptances are given in below;

- The economic lifetime of facilities is accepted as 25 years
- Two scenarios are emphasized during this study
- The first scenario is predicated on irregular flows
- The second scenario relies on regulated/managed flows
- The existing hydropower's irrigation canals are accepted as suitable solar power installation areas
- Yingli Solar 250 Watt PV module data sheet is employed as solar energy parameters
- The meteorological data is obtained from the Turkish State Meteorological Service
- The daily based radiation is obtained from the NASA website.
- The hourly based radiation is obtained from the daily radiation by the empirical method

- The installed capacity is obtained from the algorithm
- The electricity generation is obtained from the algorithm
- The existing hydropower plant's implementation cost is accepted as realized expenditure, 4.6 million USD-
- The solar energy unit cost is accepted as approximately 750,000/MW
- 1000 steps last the iterative trigonometric function of the primary scenario
- 1500 steps last the iterative trigonometric function of the second scenario
- Unit step size is defined as 25 kW
- The total electricity generation is restricted to 3.065 MW by hourly
- The electricity sales price is accepted as 73 USD/MWh. The existing hydropower's long term irregular flow based electricity generation is created by the algorithm.
- 10 MW is the maximum applicable installed capacity size of hybrid SPP

This study is based on a set of technical, economic, and operational assumptions that provide a consistent framework for evaluating the integration of a solar photovoltaic (PV) system with an existing run of river hydropower plant. The economic lifetime of all facilities is assumed to be 25 years, during which system performance, costs, and revenues remain within predictable bounds. Capital costs for the hydropower plant are treated as sunk costs, based on realized expenditures of USD 4.6 million, while PV investment costs are adopted from contemporary market values and international benchmarks. Electricity sales revenues are calculated using a fixed feed in tariff of USD 73/MWh, assuming long term policy stability. Meteorological inputs, including solar irradiation and ambient temperature, are derived from NASA databases and national meteorological services, and are assumed to be representative of long term climatic conditions. Furthermore, ceteris paribus conditions are applied across scenarios, such that system configuration, loss factors, and component efficiencies remain constant, with storage availability and hydrological regulation treated as the primary variables.

Despite its comprehensive modeling framework, the study is subject to several limitations. The hydropower facility operates as a run of river system with minimal storage capacity, making electricity generation highly dependent on short-term hydrological conditions and irrigation practices. The irrigation canal storage volume of approximately 85,000 m³ allows only two hours of full capacity hydropower generation, which constrains operational flexibility and limits the potential benefits of hybridization. Additionally, the optimization algorithm employs discrete step sizes of 25 kW and finite iteration counts (1,000 steps), which may exclude marginally better solutions that fall between step intervals. The PV system performance is modeled using manufacturer datasheets and standard test conditions, which may not fully capture long term degradation, soiling, or extreme weather effects. Moreover, the analysis does not explicitly account for grid constraints beyond transformer capacity limits, nor does it incorporate potential curtailment risks or future changes in market regulations. Uncertainty remains an inherent aspect of hybrid renewable energy system assessments, particularly in systems dominated by natural resource variability. Hydrological uncertainty is a major factor, as precipitation patterns, river inflows, and irrigation demand may deviate from long term averages due to climate change or altered water management policies. Although long term streamflow records and average monthly flows were used to mitigate this risk, year to year variability can still result in significant deviations in energy output.

Similarly, solar PV generation is sensitive to uncertainties in irradiance and temperature projections, which were identified as the most influential parameters in sensitivity analyses. Economic uncertainties also persist, including future PV cost trajectories, inflation, exchange rates, and potential revisions to feed-in tariff mechanisms. While these assumptions, limitations, and uncertainties do not undermine the validity of the findings, they highlight the importance of cautious interpretation and adaptive planning. The results should be viewed as robust under average conditions rather than precise forecasts. Future studies could reduce uncertainty by incorporating stochastic hydrological modeling, climate change scenarios, dynamic pricing mechanisms, and real-time operational data. Nonetheless, within the defined assumptions, the study provides a reliable and replicable framework for assessing hybrid solar-hydropower systems in semi arid regions.

3. RESULTS AND DISCUSSION

As renewable penetration increases globally, Solar-Hydroelectric hybrid systems offer a promising pathway to achieving secure, low-cost, and sustainable energy systems. For Türkiye, with its abundant hydro capacity and high solar potential, such integration represents not only a technological opportunity but also a strategic necessity for long-term energy resilience. A case study is performed for detailing the integrated SHE system. The increasing global demand for reliable and sustainable energy has driven significant interest in hybrid renewable energy systems that integrate the complementary features of different sources. This study presents a detailed assessment of a run-of-river hydropower plant (HEPP) located in Denizli Province, Türkiye, and its prospective integration with a solar photovoltaic (PV) facility to establish a small-scale Solar-Hydropower Energy (SHE) hybrid system. The facility under consideration has an installed capacity of 3.065 MW and is positioned downstream of an irrigation regulator. The following sections examine the plant's technical characteristics, constraints, and the feasibility of solar integration based on both empirical and modeled data. The Google Earth image of the HEPP is given in below Figure 5.

Figure 5. The existing HEPP's Google Earth image

The hydrological inputs for this case study were derived from long term streamflow data. Average monthly flows were calculated to characterize inter seasonal variability, while electricity generation records from the plant provided empirical evidence of production patterns. Run of river HEPPs such as this are inherently dependent on precipitation and river hydrology, as they lack significant storage capacity. This dependency introduces substantial annual fluctuations in energy yield. To mitigate uncertainties, long term flow averages and regional precipitation-runoff relationships must be considered, particularly for facilities with limited operational histories. The irrigation regulator supplying the facility is operated by the General Directorate of State Hydraulic Works (DSİ) and the local irrigation union. During the irrigation season, water is stored and distributed for agricultural use, leaving the HEPP reliant only on surplus or flood discharges. Given the canal's storage volume-approximately 85,000 m^3-continuous generation at full capacity can only be maintained for about two hours. While modest, this storage potential remains critical for short-term energy management. To complement the hydropower output, a solar PV facility was modelled using SunPower modules. The modelling process incorporated monthly averages of solar irradiation and ambient temperature derived from NASA's meteorological databases for the year 2020. Hourly irradiation values were calculated from daily figures, enabling the application of detailed PV performance algorithms within MATLAB Simulink.

The PV system architecture included DC/DC converters and DC/AC inverters, transforming the generated electricity to AC mode before integration with the grid. Step-up transformers raised the output to 25 kV for transmission. The simulation also employed existing MATLAB embedded current voltage (I-V) and power curves, calibrated with manufacturer datasheets. For validation, real production data from a nearby grid connected solar facility in Denizli, utilizing Yingli Solar 250 W polycrystalline panels, were compared with model results. The correlation reached approximately 86%, demonstrating the robustness of the modelling approach. Sensitivity analyses accounted for standard test conditions (STC) and nominal operating cell temperature (NOCT), with irradiance and temperature emerging as the most influential factors on PV performance. The hydropower plant was constructed at a cost of approximately USD 4.6 million. For the solar facility, contemporary investment costs were adopted based on IRENA's report on renewable energy costs. Over the past decade, PV system costs have declined dramatically-from an average of USD 4.7 million/MW in 2010 to under USD 1 million/MW after 2019, with further reductions continuing. The financial evaluation considered levelized cost of electricity (LCOE), capacity factors, and feed-in tariff mechanisms under Türkiye's Renewable Energy Support Scheme (YEKDEM), which guarantees sales at USD 7.3 cents/kWh. This sizing balances available hydrological input, grid transformer limits, and economic return.

Two operational scenarios were further examined in algorithm. Results are given in Figure 6.

- generation without storage, directly utilizing inflows, Step 142 as the optimal PV size under immediate river flow. 3.550 MW installed capacity can be applicable for no storage case.
- and limited storage operation enabling two hours of full capacity hydropower output.

Benefit cost steps of hybrid model is illustrated in below. A systematic loop was designed to run over 1,000 increments, each representing 25 kW of installed panel capacity. Step 175 as the optimal PV size when two-hours of full-capacity storage (approximately 85,000 m^3) was available. 4.375 MW installed capacity can be applicable with hydro storage.

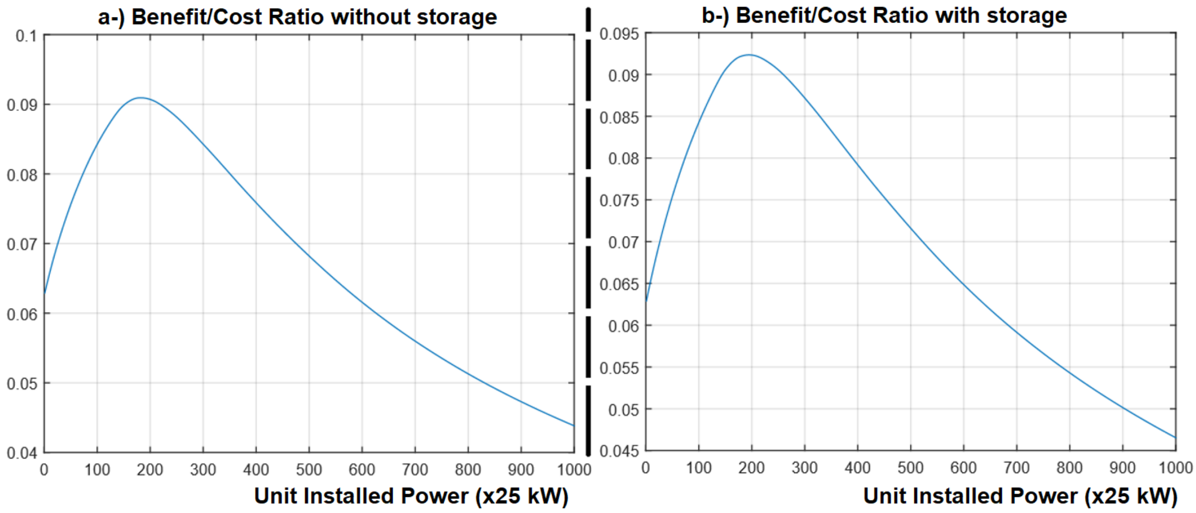

Figure 6. a-) Benefit/cost ratio without storage; b-) Benefit/cost ratio with storage for installation capacity of SPP

Hydropower production, lacking reservoir storage, is highly dependent on irregular precipitation patterns, leading to significant year-to-year output fluctuations. For long operational HEPP facilities, a long-term average annual production provides a stable planning baseline. In contrast, new or short-operational projects necessitate streamflow estimates derived from adjacent Automatic Gauging Station (AGS) records and hydrological modeling of drainage areas. Critical hydrological constraints-including environmental flow requirements, irrigation allocations, and minimum "life water" rights-were incorporated in energy estimations. Applying the ceteris paribus principle, all other simulation conditions-irradiance, temperature, system layout, and loss models, remained constant across scenarios; the only variable was the storage capability. This enabled a clear comparison of performance under varying climatic conditions. Although the plant's storage potential is modest, its integration into dispatch algorithms provides valuable operational flexibility. Such flexibility is increasingly relevant for systems with high shares of variable renewable generation.

The case study illustrates the technical and economic potential of integrating small scale run of river hydropower with solar PV systems. The hydropower facility, constrained by seasonal irrigation demands, operates with a low-capacity factor when considered independently. However, the addition of a PV facility-optimized at 4.375 MW, creates a hybrid system capable of leveraging complementary seasonal resource profiles, reducing output variability, and improving economic returns. The study underscores the necessity of using long term hydrological averages rather than extreme or short-term datasets to guide hybrid design, given the volatility of precipitation and flow regimes. Moreover, it demonstrates the value of rigorous modelling, combining empirical plant data, satellite-derived meteorological inputs, and simulation tools such as MATLAB Simulink. At a broader scale, the findings contribute to the growing body of literature on hybrid renewable energy systems in semi-arid regions. By aligning hydropower's wet-season strength with solar power's summer dominance, Hydro Solar Energy hybrids provide an adaptable pathway toward resilient, low carbon electricity generation. As costs of PV modules and inverters continue to fall, the financial viability of such hybrid structures strengthens further, offering a replicable model for small- to medium-scale facilities across Türkiye and beyond. An illustration summary is given below Figure 7 for no storage case.

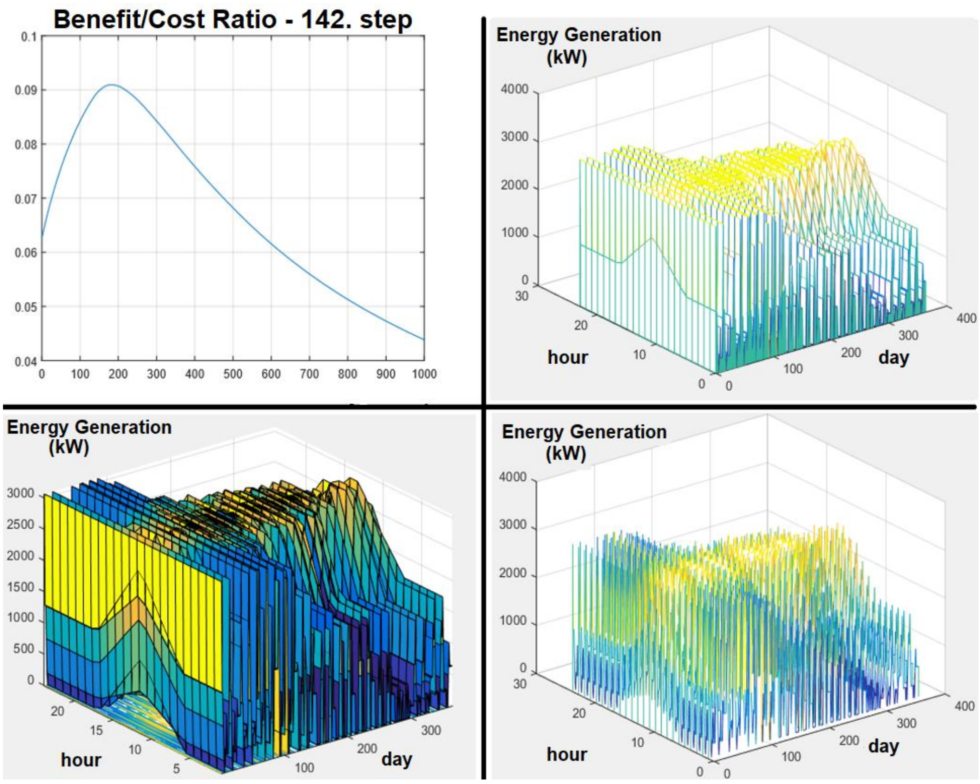

Figure 7. Results of no storage case

In the current context, there exists a substantial irrigation canal and associated storage capacity. The presence of such storage enables the solar energy component (SPP) of the hybrid system (SHE) to operate with enhanced flexibility, particularly by extending active generation into nighttime hours, periods typically reserved for hydropower (HEPP) output, thereby increasing total energy yield. When water availability is irregular (no-storage scenario), optimization through MATLAB reveals that installing a 3.55 MW PV array in parallel with the HES system offers the best trade-off between cost and energy production. This figure corresponds to the 175th step in the model's 25 kW per step, 1,000 iteration simulation loops, marking the most feasible configuration under such constraints. However, when regulated water flow and storage are introduced, optimization shifts, achieving a capacity of 4.375 MW PV, approximately 23% higher than the no storage case. This increment reflects the higher energy capture enabled by the additional flexibility of stored water, permitting generation in periods otherwise reliant on HEPP. This relatively small yet meaningful difference underscores that the HEPP facility may currently operate under low-capacity utilization, limiting incremental gains from hybrid installations unless accompanied by reliable storage. The optimization graph (benefit vs. cost) and simulation output from MATLAB highlight how regularized water flow elevates the hybrid system's energy profile. The benefit/cost curve peaks at these respective PV capacities, illustrating the ideal balance between additional capital and expected energy returns. The storage case results are given in below Figure 8.

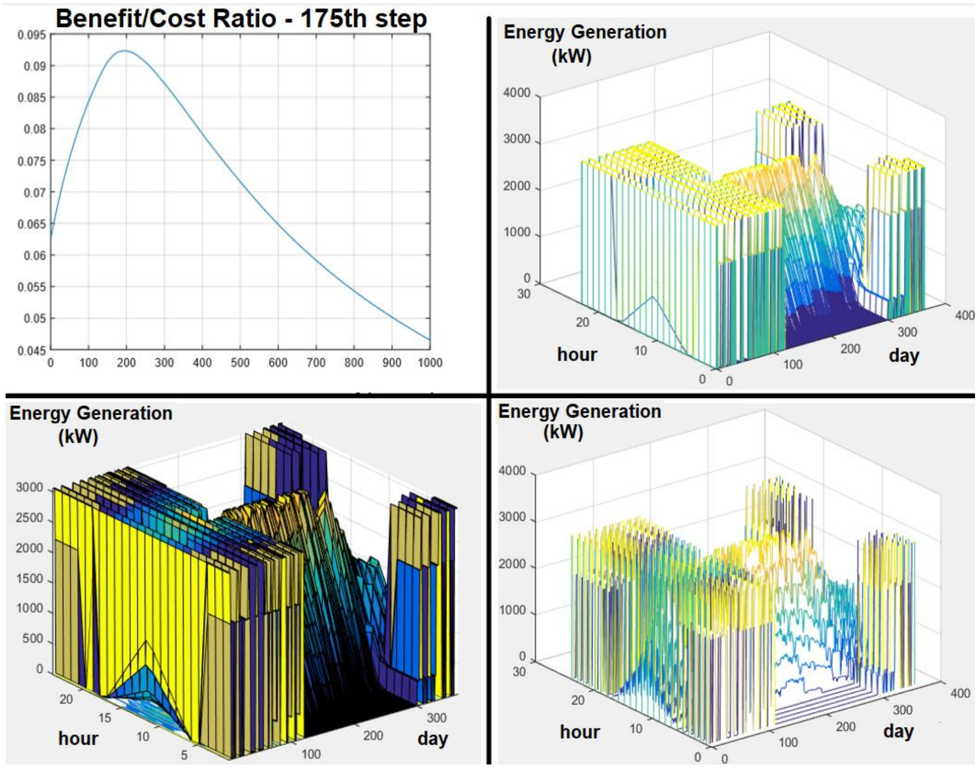

Figure 8. Results of storage case

The existing hydroelectric (HEPP) facility, when evaluated against long term operational data, functions with a capacity factor of approximately 14.7%, indicative of limited utilization relative to its rated capacity. In contrast, the modeled Solar Hydro Energy (SHE) hybrid system achieves an annual average capacity factor of approximately 34.5% for no storage case and 39.1% for storage case, demonstrating substantially higher efficiency by leveraging both generation sources.

The complementary patterns of solar and hydro (solar during daylight, hydro during non-solar hours) yield a more continuous and reliable energy profile. This is consistent with findings in hybrid renewable integration literature emphasizing reduced variability and improved performance. By combining dynamic generation sources, hybrid designs can lower system costs per unit output, optimize dispatchability, and reduce the need for large-scale storage. Cost-benefit and techno-economic optimization frameworks support such system sizing strategies, striking a balance between maximal energy capture and cost efficiency. This analysis highlights how the SHE hybrid approach not only amplifies energy yield but also streamlines utilization and system resilience. Incorporating real world generation patterns with modeled hybrids underscores the practical value of complementarity in renewable energy strategies. Daily energy generation of SHE system is given in below Figure 9 for storage case.

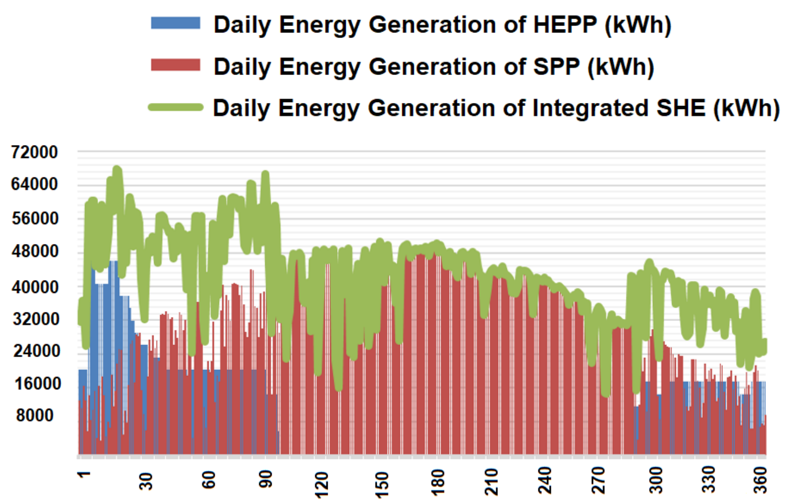

Figure 9. A comparison of Energy generation

The integration of hybrid renewable energy systems has become an increasingly prominent research field in recent years, largely motivated by the global imperative to accelerate the transition toward low-carbon electricity production. Within this context, the present study focuses on the design and evaluation of a Solar Photovoltaic Power Plant (SPP) that is conceived as a hybrid auxiliary source for an existing energy infrastructure. The research process has been structured around a systematic algorithmic optimization, followed by advanced simulation modeling using MATLAB. This dual approach ensures both the technical soundness of the proposed system and the credibility of its projected performance outcomes. The initial stage of the study was devoted to the optimization of the installed capacity of the SPP facility. This step was crucial because the sizing of photovoltaic resources directly determines both the feasibility and the efficiency of hybrid structures. Oversizing may lead to curtailment losses and underutilization of assets, while undersizing can compromise the reliability and resilience of the hybrid system. Through the algorithmic procedure, an optimal configuration was identified that balances investment cost, expected lifetime energy yield, and compatibility with the primary generation source. The output of this optimization process was not limited to a numerical capacity figure; rather, it provided a set of technical boundaries within which the system could operate with maximum efficiency and minimum operational risk. Once the optimal installed capacity was determined, the annual energy production of the proposed SPP installation was calculated. This computation incorporated solar resource availability, panel efficiency, and system losses under realistic operating conditions. By combining these inputs, the study produced a robust estimate of the plant's electricity output, thereby establishing a quantitative foundation for subsequent hybrid system modeling. These energy yield calculations serve as both a validation of the optimization results and as an indispensable dataset for the next phase of the research. The forthcoming stage of the investigation involves the utilization of MATLAB/Simulink for the modeling and simulation of the hybrid Solar Hybrid Energy (SHE) structure. The previously obtained energy production figures will be integrated into the simulation environment, ensuring that the modeled system reflects real-world operational expectations. Simulink offers a versatile platform for dynamic system analysis, enabling the study not only of steady-state performance but also of transient behaviors, load interactions, and potential system instabilities. Through this modeling framework, it will be possible to assess the response of the hybrid structure to varying operating conditions, such as fluctuations in solar irradiation, grid disturbances, or demand changes. By combining algorithmic optimization with simulation-based modeling, the research aims to achieve a comprehensive understanding of the operational potential and constraints of a hybrid SPP facility. This methodological sequence ensures that design decisions are both data-driven and validated against dynamic system behavior. Ultimately, the study provides valuable insights into how hybrid auxiliary sources can be systematically planned, dimensioned, and integrated into larger energy systems in a way that enhances both efficiency and reliability. In the first stage of MATLAB/Simulink, a simple conceptional model is designed for proposed SHE system. This illustration is given in below Figure 10.

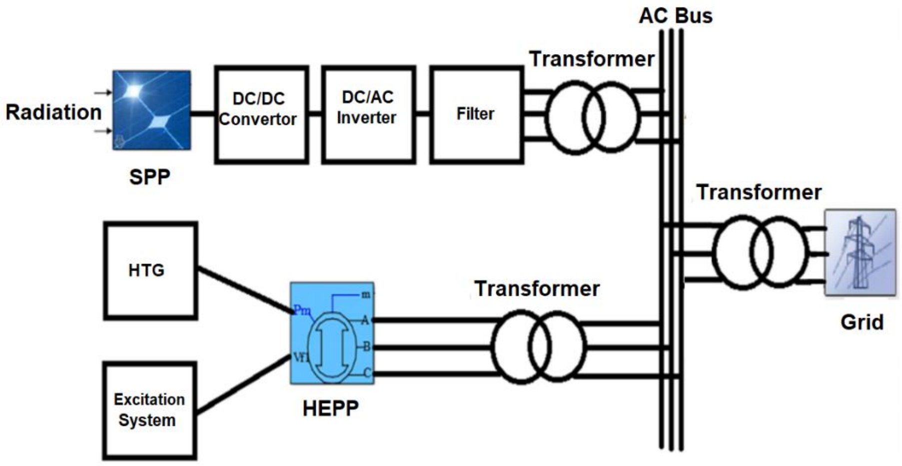

Figure 10. The conceptional model of the SHE system

In conclusion, the previously developed algorithm enables the optimization of a PV solar plant (SPP) to be integrated with an existing or planned hydropower facility (HEPP). Utilizing MATLAB loops, the algorithm executes the mathematical model and evaluates system scenarios iteratively. For a hydropower system with 3.065 MW capacity, the model reveals that integrating a 4.375 MW solar PV plant yields an optimal hybrid configuration, regarding maximum energy output while maintaining cost effectiveness. Upon reaching this result, the hybrid Solar–Hydro Energy (SHE) system was implemented in MATLAB/Simulink. The modeling process was meticulously structured, beginning with schematic layout followed by component modeling and hierarchical assembly. Simulink Model Architecture;

- Solar Irradiance & Temperature Inputs: Feeds meteorological data driving solar module behavior.
- PV Panel Model: Represents photovoltaic array dynamics based on datasheet parameters.
- MPPT Controller: Implements Maximum Power Point Tracking to maximize solar energy extraction.
- DC/AC Inverter: Converts DC output from PV array to AC compatible with grid and hydro systems.
- Hydropower Data Module: Simulates hydroelectric generation based on discharge profile.
- Grid Interface: Integrates combined power output into the external AC grid bus.

This topology merges HEPP and SPP via an AC bus, enabling seamless energy dispatch and system control. Such modular block design in Simulink mirrors best practices shown in hybrid modeling research. The detailed integrated SHE model is given in below Figure 11.

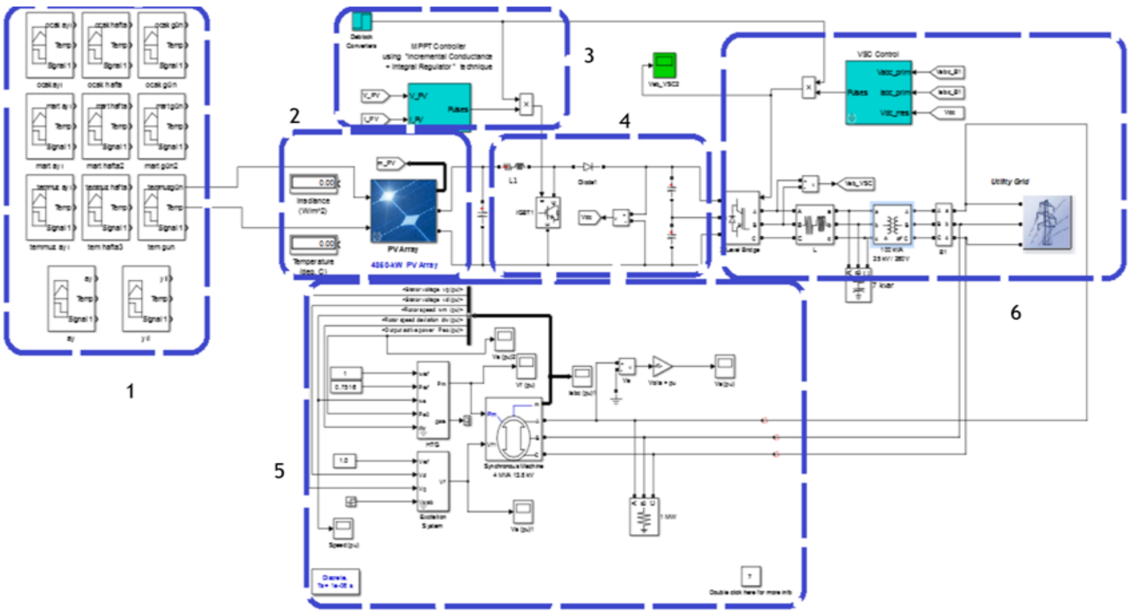

Figure 11. The detailed integrated SHE model

Using the previously developed algorithm and MATLAB database, the integrated Solar–Hydro Energy (SHE) system's optimal installed capacity is determined through iterative evaluation. Once the optimal PV (SPP) and hydro (HEPP) capacities are identified, the system is modeled in MATLAB/Simulink as an integrated hybrid configuration. Simulink's parameters of HEPP is given in below Table 2.

Table 2. The existing HEPP's project characteristics

Nominal Power (VA) / Voltage (V)	3.065 / 25,000
Reaktance [Xd Xd' Xd'' Xq Xq'' Xl] (pu)	[1,305 0,296 0,252 0,474 0,243 0,18]
Time Constant [Td' Tq'' Tqo'']	[1,01 0,053 0,1]
Stator Rezistance (pu)	2,8544e-3
Frequency (Hz)	50

The hydroelectric energy capture and generation module (HEPP) is structurally composed of two primary subsystems within MATLAB Simulink:

- Hydro Turbine-Generator (HTG): This subsystem faithfully replicates the mechanical-to-electrical conversion process using the built-in Hydraulic Turbine and Governor block. It integrates; a nonlinear hydraulic turbine model, responsive to water flow dynamics, a PID governor controller to regulate gate position or power output, a servomotor mechanism to actuate turbine gate movement. The HTG block's inputs typically include reference speed (wref), mechanical power reference (Pref), and machine electrical parameters (we, Pe0, dw). Outputs such as mechanical power (Pm) and gate position (gate) feed into subsequent generator models. Regulation parameters, like servo-motor dynamics, droop settings, and feedback gains, are customizable via Simulink's property inspector.

- Excitation System: The synchronous generator's field excitation is managed by Simulink's Excitation System block. This module comprises; a voltage regulator, enforcing terminal voltage setpoints, a DC exciter model, providing field voltage (Vf) in response to regulator output. Inputs include stator terminal voltage (vref, vd, vq) and optional stabilizer input (vstab) for oscillation damping. Standard parameters-such as regulator gain, filter time constants, output limits, and initial field voltage-are adjustable for dynamic performance tuning. The detailed design of HEPP model is given in below Figure 12.

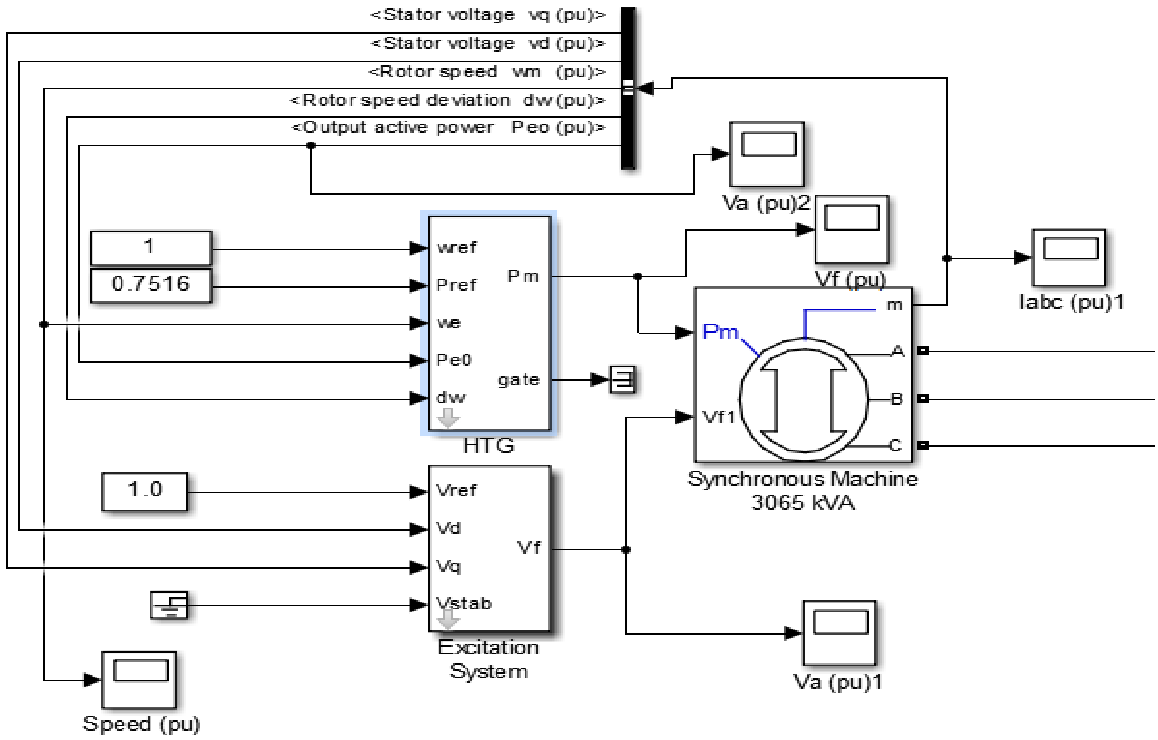

Figure 12. The detailed design of HEPP model

Within the Solar–Hydro Energy (SHE) hybrid integration, the PV plant data was derived from modules readily available in the MATLAB database. The module selected for modeling was

SunPower's SPR-305-WHT monocrystalline photovoltaic panel, chosen due to its favorable efficiency, thermal performance, and practical relevance. Key performance indicators for the SunPower SPR-305-WHT-U (used in the simulation) include in Table 3;

Table 3. MATLAB/Simulink SPP model's parameters

Brand Name	Sun Power	Current of Maximum Power Imp (A)	5,58
Model	SPR-305-	Temperature Coefficient of Voc	-0,177
Open Circuit Voltage Voc (V)	64,2	Temperature Coefficient of Isc	0,003516
Short Circuit Current Isc (A)	5,96	Temperature Coefficient of Vmp	-0,186
Voltage of Maximum Power Vmp	54,7	Temperature Coefficient of Imp	-0,00212

Within the MATLAB environment, the current–voltage (I–V) and power–voltage (P–V) characteristics of the SunPower SPR-305-WHT photovoltaic module are illustrated below. These curves provide a precise representation of the panel's electro-technical behavior under varying irradiance and temperature conditions. The I–V curve reflects the dynamic relationship between current output and terminal voltage, while the P–V curve demonstrates the power delivery profile and maximum power point (MPP) under standard operating conditions. Such graphical representations are essential for performance modeling, efficiency analysis, and system optimization in advanced PV simulation and hybrid energy studies. The module's I-V and P-V characteristic graphic is given in below Figure 13.

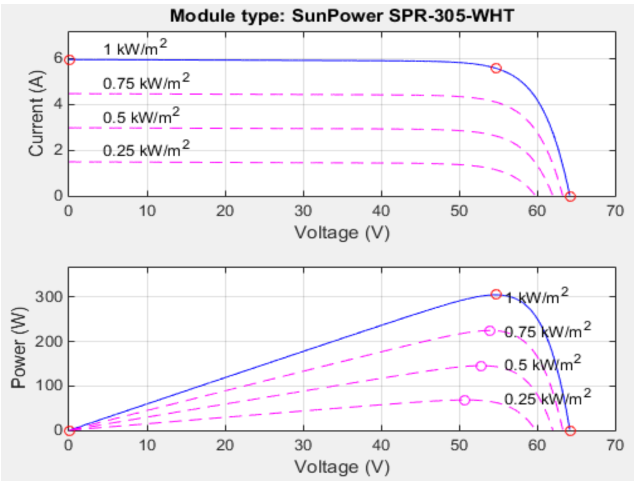

Figure 13. The module's I-V and P-V characteristic

In the MATLAB/Simulink environment, the photovoltaic (PV) facility has been represented through a sub-model provided as a packaged block. This modular structure encapsulates the key parameters outlined in the preceding table, including electrical, thermal, and operational characteristics of the selected PV technology. The packaged model enables direct simulation of current–voltage behavior, power output, and dynamic response under variable irradiance and temperature profiles. By integrating these parameters, the block offers a reliable framework for system-level analysis, hybrid energy optimization, and sensitivity studies, thereby ensuring consistency between theoretical design assumptions and practical performance outcomes. PV model of MATLAB/Simulink is given in below Figure 14.

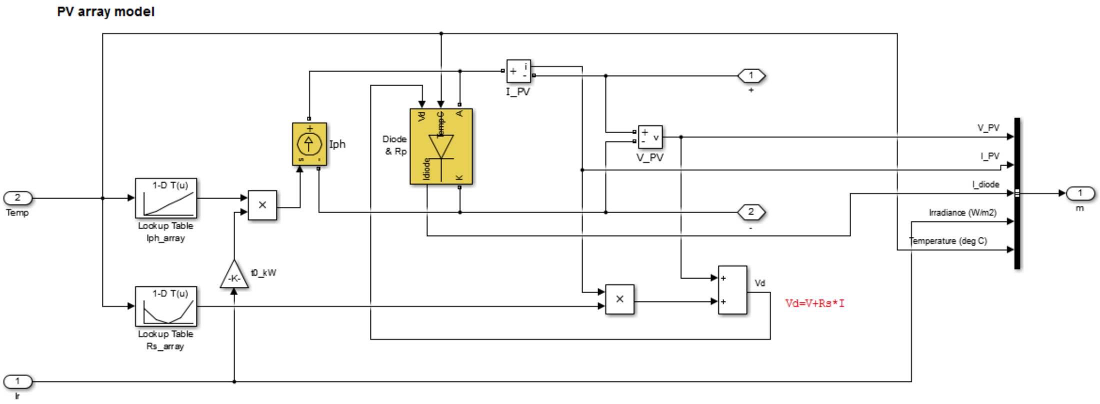

Figure 14. PV module of MATLAB/Simulink

In the MATLAB/Simulink sub-model illustrated above, the inputs labeled 1 and 2 correspond respectively to solar irradiance and ambient temperature data provided on an annual basis. The irradiance values were obtained through the previously described methodological framework, while the temperature data were sourced directly from the nearest meteorological station to ensure accuracy. These datasets serve as the primary dynamic inputs for the PV simulation model, enabling the reproduction of realistic operating conditions. The Figure 15 below presents the input profiles, illustrating seasonal variations in irradiation and temperature that govern the photovoltaic system's performance throughout the year.

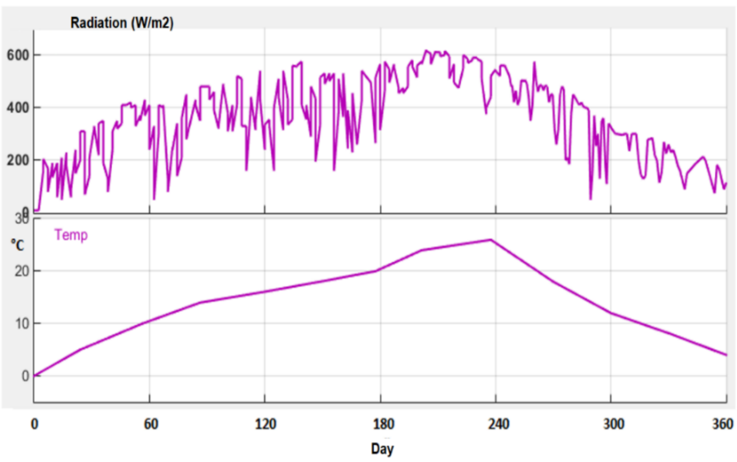

Figure 15. Seasonal variations in irradation and temperature

After executing the MATLAB/Simulink program, the resulting power output, voltage response, and corresponding input signals are illustrated in the MATLAB, generated plots are given in below Figure 16. Due to the substantial size and density of the dataset, a representative temporal compression was applied in the simulation, such that an entire year of operational data is modeled as if occurring within approximately three seconds. This approach facilitates the clear visualization of system dynamics while preserving the integrity of seasonal variability and transient behavior for discrete mode of MATLAB/Simulink. Consequently, the graphical outputs provide valuable insights into the photovoltaic system's annual performance under realistic irradiance and temperature conditions.

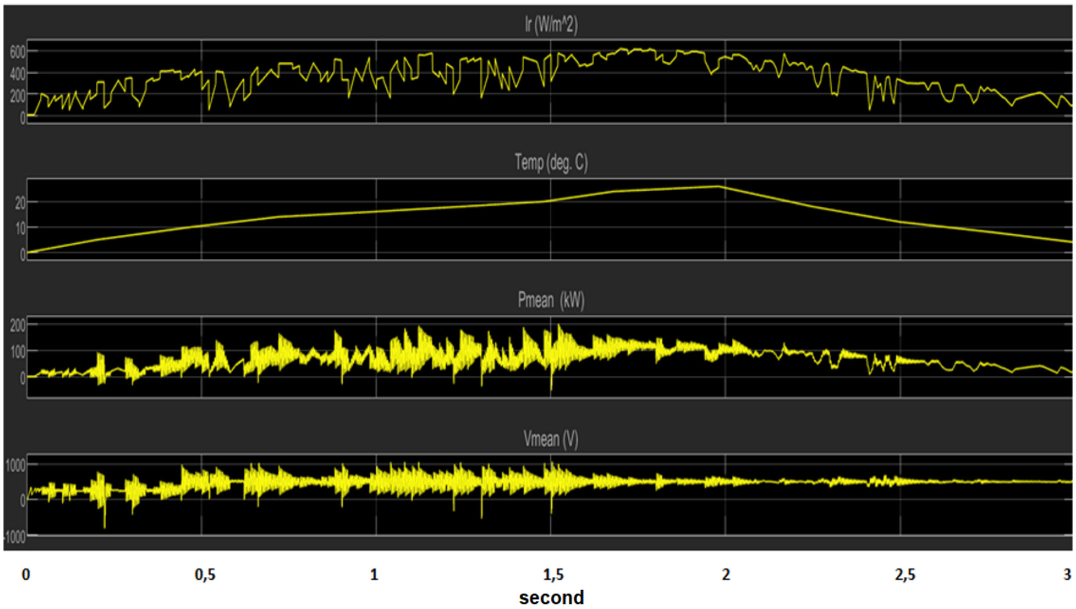

Figure 16. Data of discrete mode in MATLAB/Simulink

To optimize the output of the photovoltaic (PV) arrays, a Maximum Power Point Tracking (MPPT) strategy was employed. The selected technique is the Incremental Conductance with Integral Regulator, which is available within MATLAB/Simulink and is particularly suitable for dynamic irradiance and temperature variations. The system architecture incorporates an RL circuit (R = 0.005 Ω, L = 5000 H) and an Insulated Gate Bipolar Transistor (IGBT) switching device for efficient control. A Voltage Source Converter (VSC) is applied to perform voltage level conversions and is governed by a dual-loop control strategy. The first loop regulates the DC link voltage, maintaining it around ±250 V to ensure stability, while the second loop regulates the Id and Iq grid currents, where the reactive component (Iq) is fixed at zero to maintain unity power factor. Using Pulse Width Modulation (PWM), the system transforms voltages Vd and Vq into their respective reference values. The control system operates with a sampling interval of 100 microseconds, providing high temporal resolution. To mitigate harmonic distortions generated by the VSC, a capacitor bank has been integrated as a filter. Its sizing was determined in accordance with the grid's transmission line length, ensuring compatibility with both generation and load requirements. The Figure 17 below presents the detailed sub-model of the grid structure implemented in MATLAB/Simulink.

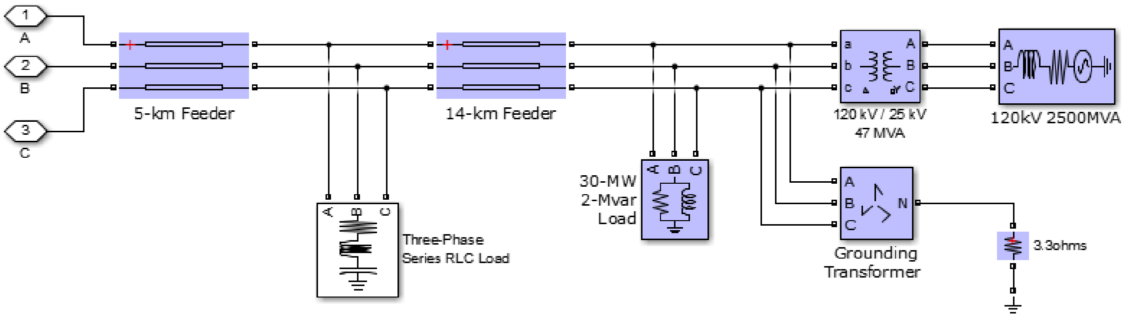

Figure 17. The detailed sub-model of grid structure in MATLAB/Simulink

In MATLAB/Simulink, the pre-defined grid structure was integrated with the proposed system to assess its dynamic performance. During simulations, noticeable distortions in the voltage waveform were observed, reflecting the interaction between the photovoltaic generation and grid components. Specifically, when operating under 15 MVA, 1500 MVA, and 15 MW conditions, the resulting current and voltage profiles exhibited deviations from the ideal sinusoidal form, particularly under transient states. These results emphasize the importance of system coordination and highlight the role of filtering and control strategies in mitigating harmonic effects. The corresponding current and voltage graphs are presented below Figure 18.

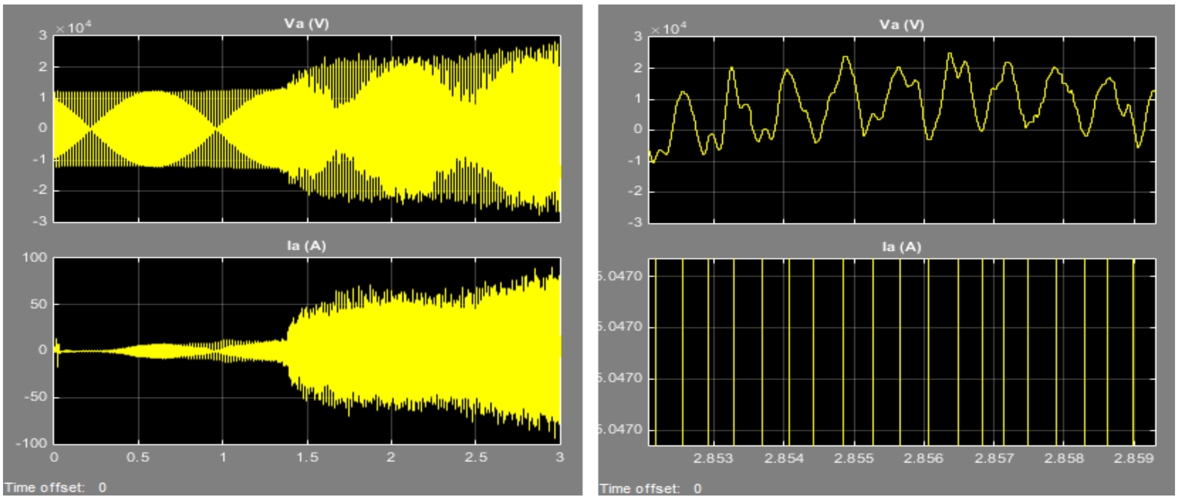

Figure 18. The corresponding current and voltage graphs

The simulation results reveal that harmonic distortions become particularly evident after 1.5 seconds, as illustrated in the figure. These distortions are primarily associated with the interaction between the photovoltaic system, the converter, and the transmission network, leading to waveform deviations that reduce overall power quality. To mitigate this effect, an initial corrective measure was applied by reducing the transmission line (ETL) and feeder connection lengths. When the line lengths were updated to 1 km and 2 km, respectively, the harmonic impact was significantly reduced, resulting in improved waveform quality. The revised current–voltage graphs, presented below, demonstrate a smoother profile with reduced oscillations, confirming the effectiveness of this modification. This adjustment highlights the importance of grid configuration parameters, particularly line length, in influencing harmonic behavior and ensuring the stability and efficiency of integrated renewable energy systems in Figure 19.

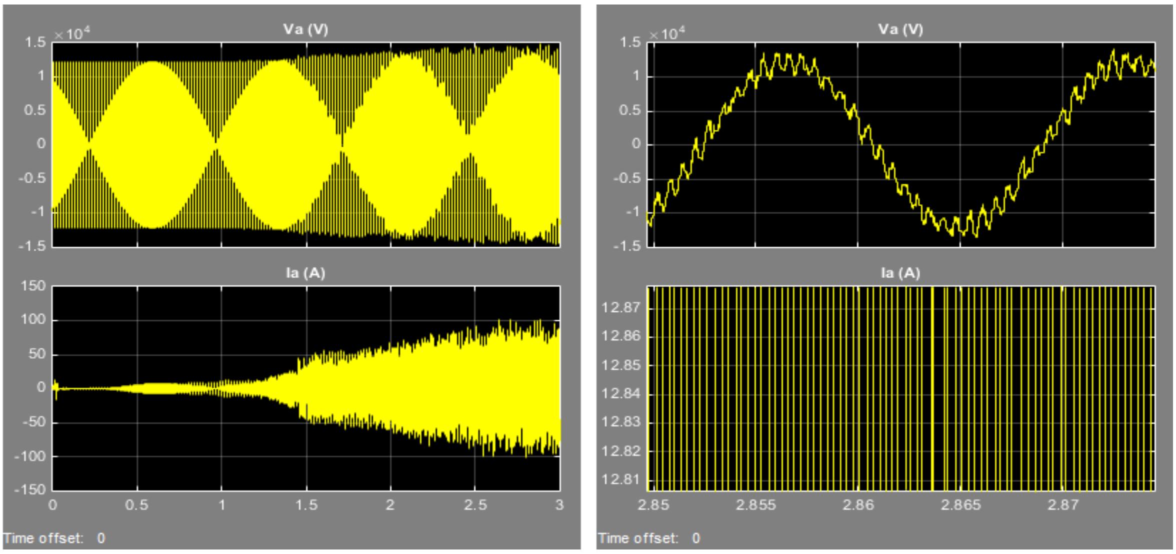

Figure 19. The updated corresponding current and voltage graphs

Under the proposed framework, the system was subjected to operating powers of 47 MVA, 30 MW, and 2500 MVA, and the corresponding simulation results are illustrated in the figure below. These values were selected to represent a range of realistic operational conditions, including both moderate and relatively high grid capacities, in order to evaluate the adaptability and robustness of the integrated photovoltaic–hydropower configuration. The results demonstrate that, although the system is capable of maintaining stability across all tested power levels, there are notable differences in current and voltage profiles. At 47 MVA, the system exhibits relatively smooth waveforms with minimal harmonic distortion, indicating efficient coordination between the Voltage Source Converter (VSC) and the grid. When operated at 30 MW, the influence of the converter becomes more visible, with slight waveform deviations that nonetheless remain within acceptable quality limits. At the higher capacity of 2500 MVA, transient oscillations and harmonic components are more pronounced, reflecting the sensitivity of the system to large-scale voltage and current flows. Overall, these findings confirm that the proposed design framework is adaptable across varying operational scales, but they also underline the need for robust harmonic mitigation and fine-tuned control strategies to ensure optimal power quality at higher grid capacities. The updated current and voltage graphs are given in Figure 20.

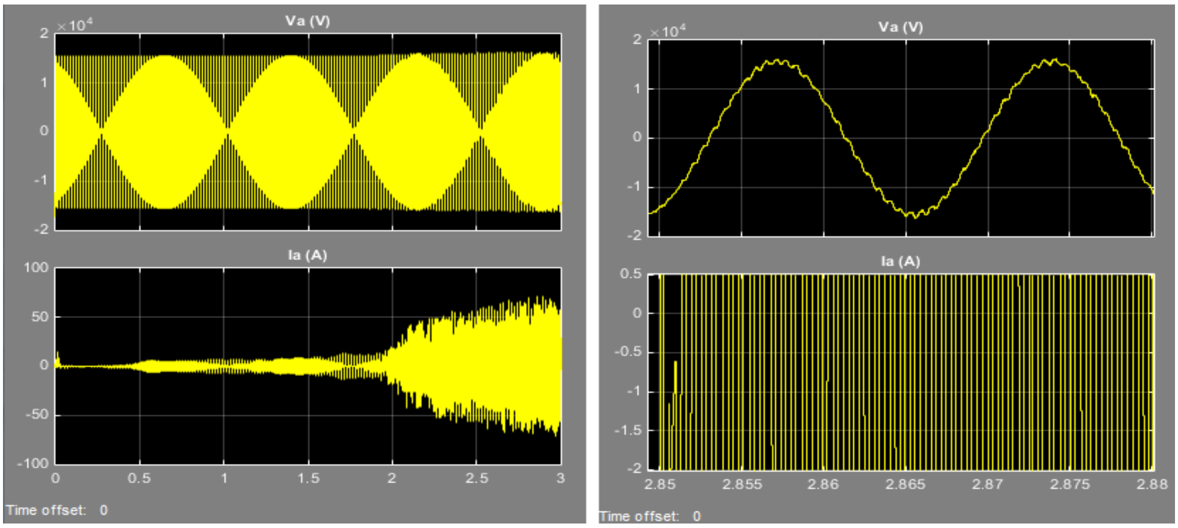

Figure 20. The updated corresponding current and voltage graphs

In the final stage of the study, the RLC filter was removed from the system configuration, and the resulting current–voltage profiles are presented in the figure below. Remarkably, the simulations indicate that it was possible to obtain a voltage waveform free from harmonic distortions, even in the absence of the filter. This outcome highlights the effectiveness of the adopted control strategies and system configuration, which together minimized harmonic contributions that would normally necessitate additional filtering. The MATLAB/Simulink simulations were performed in discrete mode, allowing for precise time-step calculations and improved representation of switching dynamics. To accommodate the extensive dataset while ensuring efficient computational performance, the simulation was structured such that one year of operational data was compressed into a three-second interval. This approach preserved the seasonal variability and dynamic transitions while enabling a clear evaluation of system stability and performance. The figures provided illustrate key parameters: solar irradiance levels as time-dependent inputs, the corresponding power output generated by the photovoltaic system, and the resulting voltage–

current (V–I) characteristics. Collectively, these outputs confirm the ability of the proposed model to replicate real-world conditions with high accuracy, ensuring that both transient behaviors and long-term operational trends are faithfully represented. The findings demonstrate that, with proper optimization and configuration, integrated renewable systems can achieve high-quality power delivery without relying extensively on external harmonic mitigation equipment. The final current and voltage graphs are given in Figure 21.

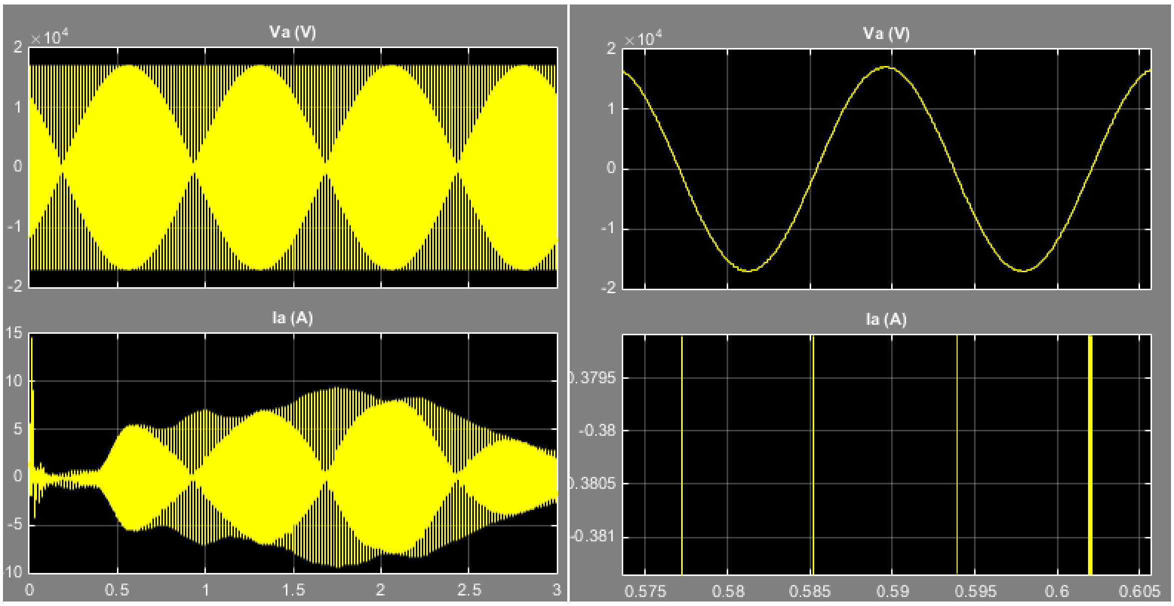

Figure 21. The final corresponding current and voltage graphs

The final grid configuration employed in the study is presented below. This structure reflects the optimized arrangement achieved after successive adjustments to line lengths, control strategies, and filtering components. By integrating the photovoltaic system with the hydropower framework under this configuration, stable operation with improved voltage and current waveforms was achieved. The finalized grid model demonstrates the capacity of the proposed approach to ensure reliable performance, reduced harmonic distortion, and effective power quality management. The Figure 22 illustrates the detailed layout of this ultimate network structure implemented in MATLAB/Simulink.

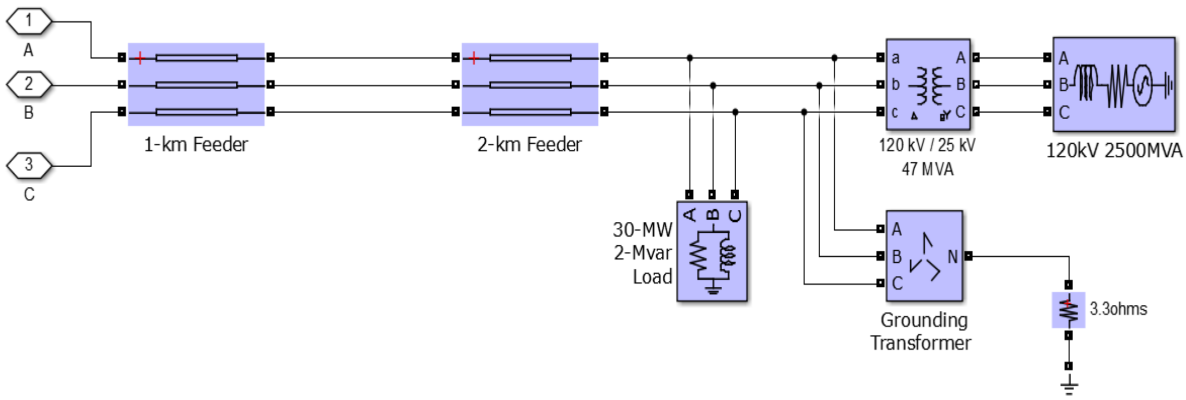

Figure 22. The final grid configuration of MATLAB/Simulink

4. CONCLUSION

The findings of this study highlight the central role of hydropower and solar energy in global and national renewable energy portfolios, as well as the advantages of their integration within a hybrid framework. Hydropower continues to represent the largest share of installed renewable capacity worldwide, including in Türkiye, where large dam and run of river projects dominate the renewable energy landscape. At the same time, solar energy has undergone a profound transformation over the past fifteen years. Thanks to rapid advances in PV technology, large-scale manufacturing, and competitive investment conditions, the cost of solar has declined drastically, falling from several million USD per megawatt in 2010 to less than one million USD per megawatt in recent years. This unprecedented reduction has made solar the fastest growing renewable technology in terms of installed capacity expansion. Beyond their individual trajectories, the two resources exhibit complementary generation profiles that make them natural partners for hybridization. Hydropower output typically peaks during spring and rainy seasons, when solar irradiation is relatively low due to cloud cover, while solar generation reaches its maximum in dry summer months, when hydrological inflows decline. This seasonal and diurnal complementarity provides a strong technical rationale for combining the two technologies to achieve greater supply stability, reduce variability, and optimize grid integration.

In this study, an integrated hydro-solar system was designed and modeled using MATLAB/Simulink. Hydropower inputs were based on long term hydrological averages, reservoir capacity, and project characteristics such as turbine type and storage volume. Solar energy production was simulated using irradiance and temperature data obtained from meteorological stations, with PV module characteristics incorporated from datasheets. To optimize energy extraction, the Incremental Conductance with Integral Regulator MPPT technique was applied, ensuring that the photovoltaic system consistently operated at or near its maximum power point under variable conditions. The hybrid model also incorporated a Voltage Source Converter (VSC) for voltage level transformation and synchronization with the grid. The VSC was controlled through a dual-loop system: the first loop regulating DC link voltage (±250 V), and the second managing active and reactive current components, with Iq fixed at zero to maintain unity power factor. Harmonic distortions were observed in certain configurations, particularly at higher power levels (e.g., 2500 MVA). These were mitigated through adjustments in transmission line lengths, filtering strategies, and capacitor banks, improving waveform quality. In the final configuration, even without an RLC filter, a stable voltage free from harmonics was achieved, demonstrating the robustness of the control architecture. A key focus of the solar subsystem was the I–V characterization of PV modules, modeled in MATLAB/Simulink and validated against real plant data from Denizli province. The results showed strong agreement, with approximately 86% correlation between simulated and actual energy outputs. This validation confirmed the reliability of the methodology and its applicability to other regions and facilities. Furthermore, scenario analysis revealed that long-term hydrological averages provide the most accurate foundation for system design, as relying on maximum capacity years or short-term records risks overestimating or underestimating hybrid potential. From an economic perspective, the integration of solar into hydropower facilities has become increasingly attractive.

Hydropower projects, while capital intensive, are already operational in many cases. Adding solar arrays-whether on canal tops, reservoirs, or adjacent lands-represents a comparatively low-cost extension that enhances output without requiring major new infrastructure. With PV panel prices having fallen by more than 80% and inverter technologies becoming both cheaper and more efficient, the hybrid model aligns well with the global downward cost trajectory documented by IRENA and similar institutions. Overall, the study demonstrates that integrated Solar-Hydroelectric (SHE) systems can achieve technical feasibility, economic viability, and environmental sustainability. By leveraging hydropower's storage and dispatchability alongside solar's cost-effective scalability, SHE systems deliver a balanced and optimized renewable energy solution. For Türkiye, with its abundant hydro base and strong solar potential, hybrid systems present a strategic pathway to enhance energy security, improve grid flexibility, and accelerate the green energy transition.

The integration of photovoltaic (PV) systems with existing hydroelectric power plants to form SHE facilities offers notable social and environmental benefits beyond purely technical and economic advantages. From an environmental perspective, the hybrid utilization of solar and hydropower significantly increases the share of renewable energy in the grid while reducing dependence on fossil fuel based generation, thereby lowering greenhouse gas emissions and air pollution. The use of existing hydropower infrastructure, such as canals, forebays, and transmission facilities, minimizes additional land use, civil works, and ecosystem disturbance, which are commonly associated with standalone renewable installations. This infrastructure sharing enhances overall energy efficiency while preserving local landscapes and water resources. Socially, SHE systems contribute to improved energy security and supply reliability by diversifying generation sources and smoothing seasonal and daily variability. Increased transformer utilization and grid stability support more resilient electricity networks, particularly in regions with growing demand. Moreover, the avoidance of extensive new construction reduces social disruption and project related environmental conflicts. The deployment of SHE projects can also generate local employment during installation and operation phases while fostering public acceptance of renewable energy through visible, cost-effective solutions. Overall, hybrid solar–hydroelectric systems represent a socially inclusive and environmentally sustainable pathway for accelerating renewable energy integration with minimal incremental costs.

DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

M. Fatih Saltuk: Contributed to the conceptualization and design of the study, carried out the analytical procedures, and undertook the comparative analysis.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] World hydropower outlook opportunities to advance net zero, IHA, International Hydropower Association, 2025.

[2] Renewable Power Generation Costs in 2024, IRENA, International Renewable Energy Agency, 2025.

[3] Rego EE, Costa OLV, Ribeiro C de O, Lima Filho RI da R, Takada H, Stern J. The trade-off between demand growth and renewables: A multiperiod electricity planning model under CO2 emission constraints. Energy 2020; 213 (118832).

[4] Wu Y, Liu Z, Li B, Liu H, Liu R, Zhang L. Optimal storage capacity for building photovoltaic-energy storage systems considering energy flexibility management. Energy and Buildings 2025; 338(115757).

[5] Mojumder MFH, Islam T, Rafi MMR, Asef IH, Hasan M, Chowdhury NUR. Enhanced hybrid energy generation solutions for sustainable rural electrifications in Bangladesh: A system optimization and performance evaluation approach using HOMER Pro and MATLAB/Simulink. Journal of Energy Storage 2025; 115 (115971).

[6] Malakar K, Lal S. Effect of wind speed and capacitive power on a grid connected 1 MW wind energy power plant using MATLAB/Simulink. International Journal of Science and Engineering Invention 2025; 11(02): 23-36.

[7] Ramkumar MS, Subramani J, Sivaramkrishnan M, et al., Optimal energy management for multi-energy microgrids using hybrid solutions to address renewable energy source uncertainty. Sci Rep 2025; 15 (7755).

[8] Khosravi N, Oubelaid A, Belkhier Y. Energy management in networked microgrids: A comparative study of hierarchical deep learning and predictive analytics techniques" Energy Conversion and Management: X 2025; 25 (100828).

[9] Melamu MT, Orumwense EF, Abo-Al-Ez KM. Simulation of a hybrid PV system and micro-hydropower using Matlab/Simulink. AIUE Proceedings of the 18th Industrial and Commercial Use of Energy Conference 2020.

[10] Nigam A, Sharma KK. Integration of hybrid energy model with solar PV, hydro & wind turbine by using MATLAB/Simulink. 2022 International Conference on Electronics and Renewable Systems (ICEARS) 2022; Tuticorin, India, 228-232.

[11] Niringiyimana E, WanQuan S, Dushimimana G. Feasibility Study of a Hybrid PV/Hydro System for Remote Area Electrification in Rwanda. Journal of Renewable Energy 2022; 2022: 1-11.

[12] Singh P, Yadav AK, Sood YR. Simulink modelling of a solar-hydro-battery integrated microgrid system for rural electrification in India. 2020 IEEE International Conference on

Computing, Power and Communication Technologies (GUCON), Greater Noida, India, 2020: 159-164.

[13] Hadith SS, Haque A, Bharath Kurukuru VS. Solar-hydro based hybrid power generation. 2021 IEEE Bombay Section Signature Conference (IBSSC), Gwalior, India, 2021: 1-6.

[14] Ali MEM, Ebeed M, Khamies M. Hybrid multi-stage hydro-matrix and PV solar cell in a real grid for minimizing electricity consumption and avoiding voltage issues" Sohag Engineering Journal (SEJ) 2025; 05(1): 48-58.

[15] Kumar K, Prabhu KR, Ramesh Babu N. Design and analysis of modified single P&O MPPT control algorithm for a standalone hybrid solar and wind energy conversion system. Gazi University Journal of Science 2017; 30(4): 296-312.

[16] Chullai ERJ, Nannam H, Roy P, Roy R, Banerjee A. Performance evaluation of a TOFOSMC-based pump hydro energy storage in the application of grid-connected photovoltaic system. Electrical Engineering 2025; 107: 11121-11142.

[17] Tereci A, Atmaca M. Integrating renewable energy systems into urban furniture for recreational spaces: A design proposal for Konya Adalet Park. Gazi University Journal of Science 2020; 33 (1): 1-12.

[18] Veramalla R, Gundeboina D, Bochu S, Salkuti SR. Unit template-based control algorithm for control of voltage and frequency in solar-hydro system. Artificial Intelligence for Integrated Smart Energy Systems in Electric Vehicles 2025; 1427: 675-691.

[19] Somefunn TE, Ayodeji OD, Mary LO. Power system operation enhancement modelling using MATLAB/Simulink. E3S Web of Conferences 2025; 601(00029).

[20] Patel AB, Chilipi R. Model predictive control for micro-hydro, solar photovoltaic-based standalone microgrid with power quality improvement. Australian Journal of Electrical and Electronics Engineering 2025; 2025: 1-15.

[21] Checklie GN, Tadiowose T, Ejigu NA. Design and modeling of hybrid solar PV/mini hydro micro-grid systems for rural electrification: A case of gilgel abay river, Ethiopia" Journal of Electrical Power & Energy Systems 2023; 7(1): 26-46.

[22] Ibekwe EC, Amadi HN, Horsfall DJ. Solar pumped hydro turbine storage system for efficient power supply" International Journal of Engineering and Modern Technology (IJEMT) 2024; 10(9): 94-106.

[23] Asare-Bediako F, Antwi EO, Diawuo FA, Dzikunu C. Assessing the performance of hydro-solar hybrid (HSH) grid integration: A case study of Bui Generating Station, Ghana. Solar Compass 2024; 10(100071).

[24] Iweh CD, Semassou GC, Ahouansou RH. Optimization of a hybrid off-grid solar PV-hydro power systems for rural electrification in Cameroon. Journal of Electrical and Computer Engineering 2024; 2024(4199455).

[25] Neupane D, Gurung S, Neupane S, Bhattarai N. Power sharing in solar PV: Microhydro hybrid system using power angle control strategy" Journal of Control, Automation and Electrical Systems 2022; 34(2).

[26] Sakouvogui A, Camara EO, Balde NA, Keita M. Sizing and simulation of a hybrid hydroelectricity and photovoltaic system with storage for supplying the Tamagaly district in Mamou, Guinea. Journal of Energy and Power Engineering 2023; 17: 69-77.

[27] Twaróg B. Modelling a pumped storage power plant on the example of the Porąbka Żar power plant. Technical Transactions 2023; 2023(1): 1-16.

[28] Gizaw M, Bekele G. Design of a solar island with a water-battery storage system for Lake Ziway islanders in Ethiopia. Cogent Engineering 2024; 11(1).

[29] Kenfack AZ, Nematchoua MK, Simo E, Ntegmi GJB, Chara-Dackou VS. Transition towards net zero emissions: Integration of a PV/T system with a hydroelectric generator and the impact of demand-side management. Heliyon 2024; 10(17).

[30] Konneh KV, Masrur H, Othman ML, Senjyu T. Performance assessment of a hybrid complementary power system for sustainable electrification: A case study. Sustainable Cities and Society 2022; 76(103412).

[31] Agajie EF, Agajie TF, Amoussou I. et al. Optimization of off-grid hybrid renewable energy systems for cost-effective and reliable power supply in Gaita Selassie Ethiopia. Sci Rep 2024; 14(10929).

[32] Oladigbolu JO, Ramli MAM, Al-Turki YA. Optimal design of a hybrid PV solar/micro-hydro/diesel/battery energy system for a remote rural village under tropical climate conditions. Electronics 2020; 9 (1491).

[33] Ma J, Yuan X. Techno-economic optimization of hybrid solar system with energy storage for increasing the energy independence in green buildings. Journal of Energy Storage 2023; 61(106642).

[34] Nassar Y, Irhouma M, Salem M, El-Khozondar H, Suliman S, Elmnifi M, Khaleel M, Rekik S. Towards Green Economy: : Case of Electricity Generation Sector in Libya. Solar Energy and Sustainable Development Journal 2025; 14(1): 334-360.
[35] Nassar YF, El-Khozondar HJ, Fakher MA. The role of hybrid renewable energy systems in covering power shortages in public electricity grid: An economic, environmental and technical optimization analysis. Journal of Energy Storage 2025; 108(115224).
[36] Salim E, Abubaker A, Ahmed B, Nassar Y. A Brief Overview of Hybrid Renewable Energy Systems and Analysis of Integration of Isolated Hybrid PV Solar System with Pumped Hydropower Storage for Brack city - Libya. Wadi Alshatti University Journal of Pure and Applied Sciences 2025; 3(1): 152-167.
[37] Nassar YF, Abdunnabi MJ, Sbeta MN, Hafez AA, Amer KA, Ahmed AY, Belgasim B. Dynamic analysis and sizing optimization of a pumped hydroelectric storage-integrated hybrid PV/Wind system: A case study. Energy Conversion and Management 2021; 229 (113744).
[38] El-Khozondar HJ, Asfour AA, Nassar YF, Shaheen SW, El-Zaety MF, El-Khozondar R. J., Khaleel, M. M., Ahmed, A. A., & Alsharif, A. H. Photovoltaic Solar Energy for Street Lighting: A Case Study at Kuwaiti Roundabout, Gaza Strip, Palestine. Power Eng. Eng Thermophys 2024; 3(2): 77-91.
[39] Khaleel M, Yusupov Z, Alderoubi N, Abduljabbar RL, Elmnifi M, Nassar Y, Majdi HS, Habeeb LJ, Abulifa S. Evolution of Emissions: The Role of Clean Energy in Sustainable Development. Chall. Sustain. 2024; 12(2): 122-135.
[40] Elnaggar M, El-Khozondar HJ, Salah WA, Nassar YF, Bashir MJK. Assessing the Techno-enviro-economic viability of wind farms to address electricity shortages and Foster sustainability in Palestine. Results in Engineering 2024; 24(103111).
[41] Abuhelwa M, Elnaggar M, Salah WA, Nassar YF, Bashir MJK. Exploring the Prevalence of Renewable Energy Practices and Awareness Levels in Palestine. Energy Science & Engineering 2025; 13: 1292-1305.
[42] Nyasapoh M, Gyamfi S, Debrah SK, Gabbar H, Derkyi N, Nassar YF, Djimasbe R, Gbinu J, Odoi-Yorke F, El-Khozondar HJ. Navigating Renewable Energy Transition Challenges for a Sustainable Energy Future in Ghana. Solar Energy and Sustainable Development Journal 2025; 14(1): 237–257.
[43] El-Khozondar HJ, El-Khozondar RJ, Nassar YF, El-Batta F. Technical-economical-environmental assessment of grid-connected hybrid renewable energy power system for Gaza Strip-palestine. Engineering Science and Technology, an International Journal 2025; 69 (102120).

[44] Elmnifi M. et al. Solar and Wind Energy Generation Systems with Pumped Hydro Energy Storage: City of Derna. In: Xu, H. (eds) Proceedings of the 7th International Symposium on Water Resource and Environmental Management. WREM 2024. Environmental Science and Engineering. Springer, Cham.

[45] Khaleel M, Yusupov Z, Yasser N, El-Khozondar HJ. Enhancing Microgrid Performance through Hybrid Energy Storage System Integration: ANFIS and GA Approaches. Int. J. Electr. Eng. And Sustain. 2023; 1(2): 38–48.

[46] Mohammed S, Yasser Y, Algassie H, Asma A, El-Khozondar H, Elmnifi M, Khaleel M, Sassi Rekik S, Salem M. Exploring Optimum Sites for Exploitation Hydropower Energy Storage Stations (PHES) Using the Geographic Information Systems (GIS) in Libya. Solar Energy and Sustainable Development Journal 2025; 14(1): 394–409.

[47] Chelli A, Brander L, Geneletti D. Cost-Benefit analysis of urban nature-based solutions: A systematic review of approaches and scales with a focus on benefit valuation. Ecosystem Services 2025; 71(101684).

[48] Nassar Y, Alsadi S, Amer K, Yousef A, Fakher M. Numerical Analysis and Optimization of Area Contribution of The PV Cells in the PV/T Flat-Plate Solar Air Heating Collector. Journal of Solar Energy Research Updates 2019; 6.

[49] Mohammed S, Yasser Y, Algassie H, Asma A, El-Khozondar H, Elmnifi M, Khaleel M, Sassi Rekik S, Salem M. Exploring Optimum Sites for Exploitation Hydropower Energy Storage Stations (PHES) Using the Geographic Information Systems (GIS) in Libya. Solar Energy and Sustainable Development Journal 2025; 14(1): 394-409.

[50] Mohammed S, Nassar Y, Algassie H, Mahammed A, El-Khozondar H, Alatrash A. Exploring Promised Sites for Establishing Hydropower Energy Storage (PHES) Stations in Libya by Using the Geographic Information Systems (GIS). Wadi Alshatti University Journal of Pure and Applied Sciences 2025; 3(1): 85-94.

[51] Mohammed SM, Nassar Y, El-Osta W, El-Khozondar HJ, Miskeen A, Basha A. Carbon and Energy Life Cycle Analysis of Wind Energy Industry in Libya. Solar Energy and Sustainable Development Journal 2023; 12(1): 50-69.

[52] Abodwair A, Guneser M, Khaleel M, Nassar Y, El-Khozondar H, Elbaz A. Feasibility Assessment of Hybrid Renewable Energy Based EV Charging Station in Libya. Solar Energy and Sustainable Development Journal 2024; 13(2): 311-349.

[53] Almhdi E, Miskeen G. Power and Carbon Footprint Evaluation and Optimization in Transitioning Data Centres. Wadi Alshatti University Journal of Pure and Applied Sciences 2025; 3(2): 221-229.
[54] El-Khozondar H, El-Khozondar R, Nassar Y, Asfour A, Albardawil M, El-Zesty M, Shaheen S, Elmnifi M, Khaleel M, Alkhazmi A, Ali A. Economic and Environmental Implications of Solar Energy Street Lighting in Urban Regions: A Case Study. Wadi Alshatti University Journal of Pure and Applied Sciences 2025; 3(1): 142-151.