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ARTICLE

Optimizing Hydropower Resources for Maximum Power Generation Efficiency in Environmentally Sustainable Electrical Energy Production

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ABSTRACT

Water power is one of the key renewable energy resources, whose efficiency is often hampered due to inefficient water flow management, turbine performance, and environmental variations. Most existing optimization techniques lack the real-time adaptability to sufficiently allocate resources in terms of location and time. Hence, a novel Scalable Tasmanian Devil Optimization (STDO) algorithm is introduced to optimize hydropower generation for maximum power efficiency. Using the STDO to model important system characteristics including water flow, turbine changes, and energy conversion efficiency is part of the process. In the final analysis, optimizing these settings in would help reduce inefficiencies and maximize power generation output. Following that, simulations based on actual hydroelectric data are used to analyze the algorithm's effectiveness. The simulation results provide evidence that the STDO algorithm can enhance hydropower plant efficiency tremendously translating to considerable energy output augmentation compared to conven-

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tional optimization methods. STDO achieves the reliability (92.5), resiliency (74.3), and reduced vulnerability (9.3). To guarantee increased efficiency towards ecologically friendly power generation, the STDO algorithm may thus offer efficient resource optimization for hydropower. A clear route is made available for expanding the efficiency of current hydropower facilities while tackling the long-term objectives of reducing the environmental impact and increasing the energy output of energy produced from renewable sources.

Keywords: Hydropower Optimization; Renewable Energy; Energy Conversion Efficiency; Turbine Performance; Environmental; Scalable Tasmanian Devil Optimization (STDO)

1. Introduction

Energy is considered to be vital for a country's development and its standard of living. Due to the immense population growth and industrialization throughout the world, energy demand is on a steeper climb. The population and urbanization are increasing, and thus there is an increase in the world demand for electrical energy. At the same time, there is a crucial need to shift towards sustainable energy production to face environment-related issues and lessen the impacts of climate change. Hydropower, as an essential source of renewable energy, promises to be a better solution for producing hydroelectricity, with the potential of binding water without releasing detrimental emissions [1]. For instance, one in every nine people in the overall population indeed lives without access to electricity. Therefore, nearly 97% of these unlit populations are residents of developing countries. There will be double the demand for global electricity by 2050. Hydropower has long been acknowledged as a reliable and established renewable energy and an important factor in world electricity generation, at the same time contributing both baseload and peak power. Unlike solar and wind, hydropower can deliver nearly uninterrupted energy output storage for potential energy in reservoirs, thus turning out to be an important component of diversified renewables' collections [2].

Hydropower, apart from being the main source of power generation, is a renewable energy source like solar, wind, etc. It is one of the main components that reduce greenhouse gas emissions, which is an important cause of global warming. While hydropower has become an outdated technology, the efficiency of power generation from hydropower plants seems to be much improved by optimization. Optimization involves evaluating and modifying the operation of turbines, reservoirs, and water flow to maximize electricity production at minimum cost, and environmental impacts. Methods of optimization would include water usage, turbine efficiency, and power grid integration [3]. With the advancement of technology, there has been an improvement in the performance of hydropower systems. Turbine design, automation, and digitalization are innovations that have facilitated the process of monitoring and controlling operational parameters concerning hydropower plants. This is augmented by the inclusion of artificial intelligence (AI) tools in predictive maintenance and real-time performance monitoring, which can further help in increasing the efficiency of power generation. Distributed advancement, local grid construction, and electricity are the characteristics of small hydro plants; and benefits, such as low cost of construction, short span of construction, and quick return, make them an excellent complement to the utility power grid with irreplaceable edges [4].

Sustainability is one of the chief considerations when optimizing hydropower resources. This equilibrium between power generation and conservation of the environment becomes more important in places where the activities of hydropower dams affect aquatic ecosystems and biodiversity. Optimization of hydropower efficiency means maximizing energy production and minimizing the disturbance to the natural habitat. Sustainable practices, such as fish-friendly turbines and environmental flow management, become an integral part of hydro optimization. This complexity arises from the stochastic nature of the system inputs, non-linearities of functions, multiple constraint forms, large numbers of decision variables, and uncertainties. Based on these reasons, this complex problem cannot be solved using classical methods and needs more advanced techniques [5]. In conventional plants, energy generation supplies power level over time termed base load. Forecast data on daily, monthly, and seasonal consumption is used to determine the sizes and capabilities of these nuclear plants. Any efficient utilization of hydropower resources can increase massive economic benefits. Optimized hydropower plants can further support stabilizing electricity prices and enhancing utility provider profit through higher generation and lower operating costs. Therefore, in the long path, improved hydropower resource management can help stabilize energy markets and reduce dependence on fossil sources, thereby supporting energy security and economic recovery [6].

The multi-objective optimization of connected advantages, lowering system losses, and decreasing the proportion of renewable energy sources are some methods involved in reducing dimensionality, which can all contribute to sustainable development through hydropower integration [7]. Despite significant achievements in optimizing hydropower, the research aims to enhance the power generation of a hydropower system from inception to its optimal power realization by introducing a Scalable Tasmanian Devil Optimization (STDO) algorithm. The advanced dynamic resource allocation in hydropower systems enhances water flow management, turbine performance, and energy conversion efficiency. By real-time optimization with STDO, this research intends to minimize inefficiencies, eliminate wasting of resources, and improve the energy output of the system, thus promoting sustainable and efficient power generation with more resilient operating parameters in varied environmental conditions. Hydropower is impacted by human activity, natural resources, the environment, and climate change through extreme weather events, sedimentation, water scarcity, and ecological disruption. Water flow is impacted by temperature fluctuations, changed rainfall patterns, and deforestation, which lowers efficiency. Despite these obstacles, ecologically responsible hydropower generation is guaranteed by sustainable management. Human ingenuity helps hydropower by increasing turbine efficiency and managing water flow to produce more electricity. Reliance on fossil fuels is decreased by the sustainable use of natural water resources, which offers a clean, renewable energy source. Eco-friendly dam designs allow steady energy output while preserving biodiversity. In certain areas, climate-driven improvements in water availability have the potential to further expand hydropower. Hydropower is the most dependable and renewable sources of electrical energy. Through increasing environmental concerns, optimizing hydropower resources for sustainable development has taken on a heightened sense of perseverance. The efficient utilization of water resources can supplement power generation with minimal ecological footprint through efficient water utilization. The innovative technologies combined with advanced strategies can offer ways to improve energy generation potentials without compromising other important water values. Sustainable hydropower operation can not only provide for increasing energy demands nonetheless also protect aquatic systems. It is vital to find common ground with regards to competing priorities of energy efficiency and ecological stewardship for impending energy security. Advanced modeling and optimization processes provide actual practicable alternatives for maximizing performance. The investigation considers how to engage and achieve greater efficiency in environmentally sensitive hydropower generation.

A hydropower scheduled model that prioritizes several goals is presented in the investigation. It takes to account the limitations on plant-based operating zones, day-ahead transactional energy, water level targets, both solar and wind powers, and their effects on scheduled [8]. A large-scale hydropower infrastructure comprising eleven cascading reservoirs, the Lancang River, is the subject of the model. Finding the ideal schedule time takes 4 s with the CPLEX 12.6 Solver. Hydropower plants can experience fluctuations in generation when wind and solar power are combined, which could increase the need for turbine replacement particularly the winter months. The scheduling model was solved via the complex linear programming expert (CPLEX)12.6 Solver in 4 seconds, incorporating variations of renewable sources. Hydropower scheduling was maintained with high efficiency, although there could be maintenance stress on some turbines. Renewable energy generation was unpredictable along with being seasonal, which affected the stability of hydropower production and, thus, the effectiveness of the model. The forecasting of the daily net generation of hydroelectric energy from hydroelectric power plants (HEPP) based on meteorological data was performed [9]. The model applied a special convolutional neural network and support vector regression (CNN-SVR) model, trained on a unique dataset from HEPP in Turkey and the Kaman meteorology directorate, to predict hydroelectric generation. The model reached high correlation coefficients of 0.971 for Net Head (NH) and 0.968 for Power Production (PP), telling of its efficiency. However, model performance may differ because of incomplete or inaccurate meteorological data, which may restrict its general applicability.

Short-term scheduling of a hydro-wind-solar multi-energy generation system was done to eliminate forecast uncertainty via deep reinforcement learning [10]. A deep Q network (DQN) was utilized for simulation and optimization of scheduling based on prediction data of wind and solar generation. The DQN-based model enhanced scheduling efficiency by minimizing power output errors and improving energy production. The model lacked the accuracy of input prediction data and the complexity of computation. The equilibrium optimizer method was implemented to optimize a multi-generation hybrid renewable energy system (HRES) and employed a variety of machine learning (ML) approaches to forecast its energy efficiency [11]. The performance of the system was predicted using developed ML models from the thermodynamic database, where the equilibrium optimizer algorithm was applied for optimization purposes. The model demonstrated factors, namely R-squared as high as 0.98, confirming a very significant prediction trend for the performance of HRES. The research showed validation using the specific thermodynamic database, limiting applicability to other energy systems or regions.

A hybrid weight-based model was developed to improve water level prediction accuracy of large cascade hydropower installations, combining optimized gated recurrent unit(GRU)-long short-term memory (LSTM) with deep residual shrinking networks [12]. The model optimized LSTM and GRU parameters using the Semisoft threshold function, error value correction function, downward tributary inflow, multidimensional feature inputs, and Archimedes optimization method incorrectly for count by number and measure using artificial methods. Methods failed to meet hydrodynamic and AI criteria, and this model outperformed the ability to predict high upstream water levels in competence for scale, fluency, and efficiency regarding flooding and urban rain forecast use applications. However, the model performance can be affected by the complex environmental settings and the amount of information available. The effectiveness of Kaplan turbines throughout hydropower generation is reduced by silt eroding [13]. The purpose of the investigation is to forecast effectiveness through the use of artificial neural networks (ANN), multilinear regression (ML), curve fitting, and historical information. Considering an R2-value of 0.99966, a Mean Absolute Percentage Error (MAPE) of 0.0239%, and a Root Mean Squared Percentage Error (RMSPE) of 0.1785%, the ANN approach performs more effectively to the other approaches. Plant proprietors, and equipment makers can use this correlation to create efficient maintenance and operational plans and to assess machine prestige in instantaneously.

The effect of battery storage on a hybrid power system that integrates hydropower solar energies was examined using the case of eight hydropower plants in Turkey [14]. The entire optimization problem was solved through the stochastic quasi-newton approach using four different battery capacities. The results indicated that, when taking into account solar interaction, the highest possible available wind turbines alone could be 2 megawatts (MW), producing 3.6 MW. It discovered that an intermediate percentage of batteries was optimum in terms of hydroelectric planning and profit. The geographical restrictions in various countries pose challenges and do not consider any type of battery and environmental factors. Evaluating the accessibility of prospective hydrological resources is essential to the energy planning process. Precipitation forecasts utilizing the soil moisture accounting procedure (SMAP) are used at present for calculating energy dispatch. By forecasting dam levels based on trends in rainfall variance, a technique utilizing machine learning (ML) could enhance the management of the electrical power system. To anticipate precipitation and natural inflow, the research suggests a hypertuned wavelet convolutional neural network (CNN) method with an LSTM network [15]. To attain an optimal structure, the model employs CNN feature extraction, LSTM time series forecasting, wavelet signal denoising, and hypertuning. The suggested forecasting technique performs greater than other deep learning (DL) techniques including the existing SMAP framework.

Research [16] explored the flexible interface of coal decommissioning with hydropower, considering emissions and system flexibility across various regions. It related to the coal decommissioning in the three provinces calculated the use of flexible hydroelectric systems. Emissions intensities were seen, and the assessment of system flexibility was given the energy requirement and emissions data of the different regions. It was found that emissions range from 3.4% to 11.1% depends upon the location and flexible hydropower relieved peak demand issues without the difficulties of emissions. The research scope, which is restricted to certain regions, meant that the results can't be extrapolated to all regions, especially where energy infrastructure and emission profiles differed.

The complementary scheduled of hybrid pumped storage hydropower-photovoltaic (HPSH-PV) systems to improve the flexibility of energy systems and increase the integration of renewable sources [17]. The schedule was elaborated with appropriate consideration of long-distance and inter-regional electricity transmissions. The result revealed that installing a pumping station reduced the variability of water levels in upstream reservoirs; mitigate operational risks, enhanced control of upstream storage capacity and energy supply dependability in power generation. The fluctuating inflow levels, the effectiveness of the system can affected, while the scheduling model can't account for unforeseen environmental changes, thus affecting long-term reliability and efficiency. The climate change impacts on hydropower operations, specifically seasonal floods, droughts, and river flow variations assessed in the research [18]. Hydropower performance under changing climate conditions was examined with emphasis on preservation, lack of resistance, and flood management. Results indicated that climate change extremely affected hydropower generation to increased unpredictability and altered river flow. The model can't fully consider the effects of extreme weather events or long-term environmental changes, thus limiting the generalization of results to other regions.

To enhance flexibility and encourage the use of renewable energy sources, the research investigated a combined pumped storage-wind-PV system, which combines traditional hydropower stations. The system's functioning at several time scales is simulated in the investigation using a multi-scale nested joint operation approach. It demonstrates how hybrid pumped storage lowers energy curtailment and boosts power generation profit [19]. In addition to temporarily storing extra electricity from the grid and renewable sources, the pumping station can boost availability of water through the absence of precipitation. Under varying reservoir inflows and electricity costs, the advantages of hybrid pumping are confirmed. The system also provided a means of storing energy in the form of both renewables and the grid, thereby enhancing dry-period water supplies. However, the research dependent on changing energy prices and inflow into the reservoir, which limited applicability as a general rule. Create a modern novel experiment, processing, and operation of risk and control strategy towards a hydro-PV electrical system used electrochemical energy storage (EES) was established [20]. Under the layered-model scheme that allows joint operation with hydropower and EES through flexibility addition to the system, the inclusion of EES proved itself to increased overall power production by 3.04%. The expected result was a 12.87%-shortened startup time and 12.17%-shortened shutdown time. Control flexibility of the system also improved with a healthy state of charge being maintained for 90%. The research findings were not widely applicable as hybrid systems can vary owed to different conditions.

Power shortfalls was a serious obstacle to growth across the industrial, commercial, and agricultural sectors [21]. The low emissions method was used to inform research that modeled the energy profile under baseline and transition scenarios for future period. While the changeover scenario focused on increasing biomass, the baseline scenario focused on increased hydropower energy. Results exposed the proportion of biomass could be 33.3%, while the proportion of hydro power could be 54.09% in the base scenario. While the, energy production could reach 1135.20 TWh, covering an estimated energy demand of 966.05 terawatt-hours (TWh) under certain circumstance. Sustainable development through an alternate source of clean energy, solar and wind, with the additional consideration of EEC forecasting for both developed and emerging economies in, respectively, 1, 2, and 3% scenario instances [22]. The ANN model has potential applications in forecasting long-term EEC along two lines, with an emphasis on two groups of countries, namely developed and emerging. The results highlighted the ANN model can censored CO_2 emissions by 54% and EEC emissions by 55%, thus maintaining conformity with the objectives of the Paris Agreement. The scattered sample nature of the model, which can't adequately capture future energy consumption prospects.

Renewable energy sources are thermal solar, PV, wind, biomass, and hydropower. According to the system advisor model software, PV has a very large power generation potential of about 1700 kWh/kWp annually [23]. Wind energy varies in capacity and power density, especially at very high elevations and geographic specification (GS). It contributes 1717 GWh from biomass resources. The hybrid optimization of multiple energy resource (HOMER) model estimates that only 18% can be obtained from the grid; the optimal system was capable of producing 82% on it. Around 70.7% of that energy was consumed, while the remaining portion is sold back to the grid. Thus, the suggested that renewable energy be strengthened by grid power for cost savings and greenhouse gas emissions mitigation. The escalating environmental issues were addressed in the research by forecasting solar energy used ML methods for areas that are either extremely sunny [24]. The data were collected from a small weather station near the solar panel using Arduino microcontrollers, C# software, and Python programming. Solar energy production was predicted by the support vector machine (SVM) model. The result exhibited improved performance in power production. The research focused on area with extreme sunlight, which was not representing the energy production potential in regions with lower solar radiation.

Almost always, the precision and availability of atmospheric observations have a significant impact on the effectiveness of the model, which can lead to forecast mistakes and limitations in terms of wide application. For instance; insufficient and unreliable data in the forecast of generation and efficiency for hydropower can limit the performance of the model. Besides, high computational complexities are faced by some models. Since research consume much processing power and time especially in deep reinforcement learning approaches. The environmental settings and regionalization in the data can also affect the reliability and scalability of the system. The research counters the above limitations through the adoption of more robust and accurate data sources, and advanced techniques less dependent on large datasets. In addition, the present research provides a hybrid optimization model for reducing computational complexity and improving prediction accuracy. This is adaptive to regional and environmental characteristics making it perfectly scalable and applicable. Improved flexibility and reduced impacts of forecast uncertainty on energy generation systems are achieved by integrating multiple renewable sources complemented by advanced forecasting methods. The model's flexibility is further enhanced the capacity to respond to different meteorological conditions and regional characteristics, which allows for more accurate and dependable forecasts across various conditions. By optimizing combinations of a number of renewable energy sources solar, wind, hydropower, the hybrid model helps to smoothen the intermittent characteristics of renewable energy sources to produce a more stable and consistent energy output. Further also reduction of reliance on large historical and archived datasets is accomplished by using improved forecasting methods, allowing for more scalable solutions with greater efficiency. The hybrid optimization model can also make optimization updates, which ensures more rapid adaptation to unexpected environmental changes. Therefore, in several contexts, the hybrid optimization model has great potential for energy management and maximization of renewable resources.

The following is the order in which the research is organized: Related works are included under Section 2. There is a technique in Section 3. The experimental results and discussion are covered in Section 4 and 5, and the conclusion is given in Section 6.

2. System Configurations

The system basically consists of a photovoltaic (PV) array or solar power generation, a water storage tank (WST) for substance water storage, and a hydro turbine (HT) that is coupled with a generator for power production. The electrical load controller (ELC) controls the power generated for its optimal utilization and efficiency of the system. **Table 1** shows the components, functions, and their corresponding locations in the hydropower system.

Table 1. Key Components of And Descriptions of Proposed Renewable Energy.

Component	Description	Location
PV Array	The photovoltaic array is used to generate solar power.	Positioned close to the tanks on the slope.
WST	To guarantee uninterrupted functioning, a big container is used to store water in bulk.	Located on the hill adjacent to HCT.
HT	Power generation using a turbine and a permanent magnetic synchronous engine.	Situated alongside the lake or river.
ELC	An apparatus that controls the amount of electricity produced by the system.	Not shown in the figure but is connected to the system.

2.1. Components of the Hydropower System

Hydro power system consists of dams, turbines, generators, and transmission elements which provide the foundation for converting the potential energy of water into electrical energy. Efficient and effective power generation from hydro power systems relies on effective utilization of water and effective turbine performance for maximizing energy output with the least negative environmental impact. Hydro generates the most energy when water is available and equipment is maintained, while effectively managing water resources using proper engineering and expertise. Hydro carries the ability to be totally environmentally sustainable based primarily on the utilization of energy from renewable resources without utilizing environmentally dangerous fossil fuels to produce the energy. Hydro power in many interconnected grid systems have the ability to provide great energy distribution reliability are shown in **Figure 1**.

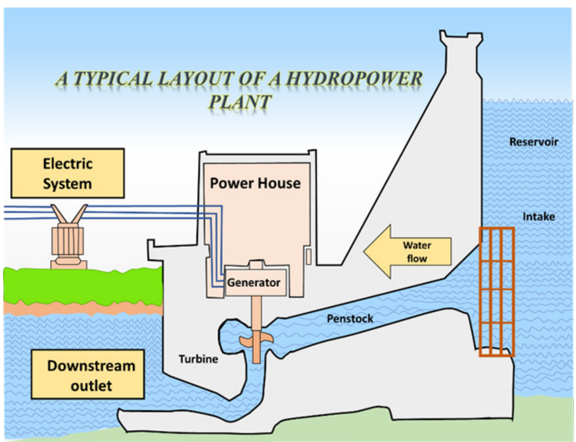

Figure 1. Flow of components of the hydropower system.

2.2. Methodology

The methodology implements the STDO algorithm to model the key parameters of a hydropower system, such as water flow, turbine settings, and energy conversion efficiency. For real-time optimization, simulations utilizing known real hydropower data are carried out. The efficiency enhancement concerning a decrease in resource wastage is applied for evaluation purposes of the algorithm in terms of resilience to various changing environmental conditions.

2.2.1. Scalable Tasmanian Devil Optimization (STDO)

STDO is a bio-inspired algorithm used for optimizing complex systems by adapting parameters dynamically to meet maximum efficiency. The resource allocation and operational efficiency of systems such as hydropower plants, where constant optimization is necessary for water flow, turbine efficiency, and energy conversion, is the primary focus of STDO. The method helps accommodate environmental fluctuations and variations in the system, therefore enhancing real-time responsiveness and enabling higher energy output, less waste, and increased stability under diverse operating conditions. The matrix W is an $M \times n$ matrix, where each element $W_{j.i}$ represents a weight or parameter in the matrix, with M rows and n columns, and $W_{j,n}$ being the weight at the i^{th} row and j^{th} column. The relation between water flow, energy conservation, and turbine adjustment is represented in Equation (1).

$$W = \begin{bmatrix} W_1 \\ \vdots \\ W_j \\ \vdots \\ W_M \end{bmatrix}_{M\times n} = \begin{bmatrix} W_{1,1} & \cdots & W_{1,i} & \cdots & W_{1,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ W_{j,1} & \cdots & W_{j,i} & \cdots & W_{j,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ W_{M,1} & \cdots & W_{M,i} & \cdots & W_{M,n} \end{bmatrix}_{M\times n} \tag{1}$$

The above equation represents the relationship between water flow W_1, turbine adjustment $W_{M,1}$, and energy conservation W_M in optimizing hydropower systems. Each element $W_{j,i}$ signifies the interaction between these parameters.This model of the relationship with the system parameters performs the best when the criteria are shown in Equation (2).

$$E(W)=\begin{bmatrix} E_1 \\ \vdots \\ E_j \\ \vdots \\ E_M \end{bmatrix}_{M\times 1} = \begin{bmatrix} E(W_1) \\ \vdots \\ E(W_j) \\ \vdots \\ E(W_M) \end{bmatrix}_{M\times 1} \quad (2)$$

$E(W)$ Represents the energy output function of the system, where each element$E(W)$corresponds to the energy generated based on the optimized water flow and turbine adjustment. The set of weights D_j in the j^{th} column of the matrix W, excluding the j^{th} row. Essentially, D_j consists of all elements in the j^{th} column, except for the element at position. Dependency on energy output is shown in Equation (3).

$$D_j=W_1,j=1,2,\ldots,M,l\epsilon\{1,2,..,M|l\neq j\} \quad (3)$$

The dependence of energy output on water flow and turbine adjustments is expressed by the equation $D_j=W_1,j$. It describes that for each adjustment j of the turbines, their output is determined by the conditions of water flow, keeping other adjustments separately to guarantee full precision in hydropower optimization to get maximum efficiency. This equation guarantees that the system continues to optimize water flow and turbine running efficiency for energy and resource allocation, as shown in Equation (4).

$$w_{j,i}^{new,T1}=\begin{cases} w_{j,i}+q\times(d_{j,i}-J\times w_{j,i}),E_{Dj}<E_j \\ w_{j,i}+q\times(d_{j,i}-w_{j,i}),Otherwise \end{cases} \quad (4)$$

$w_{j,}^{new,}$ indicates the modified weight or adjustment in water flow and turbine parameters concerning optimization. $d_{j,i}$ represents a desired value or target, E_{Dj} is the energy associated with the set d_j, E_j is a threshold energy value. It is a dynamic adjustment rule that assumes q for iterative optimization as a function of the difference between the desired outputd$_{j,i}$, and the actual output of the system. Equation (5) ensures that the system adapts to optimized energy generation while maintaining resource efficiency.

$$W_j=\begin{cases} w_{j,i}^{new,TJ},E_j^{new,TJ}<E_j \\ W_j\ Otherwise \end{cases} \quad (5)$$

W_j Defines updated system parameters for turbine adjustments, where $w_{j,i}^{new,TJ}$ is applied when the new energy efficiency $E_j^{new,TJ}$ is lower than the target valueE_j. Equation (6) shows the operational constraints for adjusting system parameters.

$$Oj=W_{l,j}=1,2,..,M,l\epsilon\{1,2,..,M[l\neq j] \quad (6)$$

It signifies that the assigned output for a specified turbine adjustment O_j is also impacted by other components W_l within the system, apart from the adjustment in question. Hence, one must consider the interaction between different system elements during the optimization process for accurate power efficiency and resource allocation. Equation (7) shows the dynamic adjustment of turbine parameters.

$$w_{j,i}^{new,T2}=\begin{cases} w_{j,i}+q\times(o_{j,i}-J\times w_{j,i}),E_{oj}<E_j \\ w_{j,i}+q\times(w_{j,i}-o_{j,i}),Otherwise \end{cases} \quad (7)$$

The resource adjustment $w_{j,i}$) is an additionalproblematic constraint of energy flow through the system to some extent, unless the environmental conditions are accommodated. $o_{j,i}$ is another target or desired value, E_{oj} is the energy associated with the set o_j. Resource allocation adjustment for hydropower generation is shown in Equation (8).

$$Q=0.01\times(1-\frac{s}{S}) \quad (8)$$

The above equation denotes the relationship between the residual capacity s of the system s and the total capacity of the system S, Q is the adjustment in either water flow or resource allocation. Therefore, this relationship can be used to optimize water flow in hydropower systems to achieve efficient energy conversion while at the same time balancing water use among the various components of the system.

2.3. Applicability to Other System

The STDO algorithm was mainly developed for hydropower optimization purposes, it is versatile and straightforward to implement in various complex systems that necessitate to dynamic decision-making. The STDO algorithm can also handle nonlinear variables and constraints, suggesting usefulness in various industries and applications energy. STDO can be used in water resource management to improve irrigation schedules, reservoir discharges, and water distribution networks, resulting in improved agricultural performance and sustainable water use. In smart grid systems, STDO can be leveraged to enhance load balancing, dispatch of energy storage, and demand side management, leading to greater grid reliability and overall operating cost reductions. In the field of environmental preservation, STDO can assist in allocating scarce resources toward biodiversity conservation, pollution reduction, and waste mitigation. In transportation systems, STDO can help improve traffic flow, optimize dynamic routing, and dynamically guide fuel-efficient in the environments. STDO can also be used in manufacturing systems for production scheduling, inventory management, and workload distribution across machines. STDO can potentially be useful in healthcare applications such as emergency response planning, resource allocation, and logistics under uncertain conditions, among others. These examples show that STDO's ability to operate in multi-objective, constraint-laden situations, makes it applicable to many more real-world settings requiring optimization and flexibility.

2.4. Significant Aspects

The main intervening elements of the methodology developed through the proposed system enhancing performance while specifically focusing on the improvement of the entire system. Special emphasis is laid on giving resilience to the system to perform optimally under variable operating conditions. Performance enhancement comes not only from efficiency but also from being able to adapt and perform to the highest level despite different operating conditions while adding more dependable and sustainable results.

2.4.1. Primary Energy

The term primary energy refers to the absolute energy source, such as solar energy, wind energy, or hydropower, before transformations to usable forms, such as electricity. It is denoted the solar power from the PV Array and hydropower resources harvested by the HT. Efficient utilization and optimization of these primary energy sources through systems like ELC can be achieved for the generation of reliable and sustainable power.

2.4.2. Water Loss Management

Every form of water loss from the water body contributes to the reduction of available water for energy generation. Water loss could be defined as evaporation, overflow, and seepage. Evaporation occurs when water changes from the surface of the water body into vapor, especially under high temperatures. Infiltration or seepage are two terms for the loss of water into the subsoil, thereby reducing the amount of water available in the reservoir in question. Overflow is defined as the loss of water from the water body when it exceeds its capacity. Water losses contribute enormously toward reducing the efficiency of hydropower generation with water loss management being aptly said to be one of the important factors in ensuring maximum energy generation. **Table 2** gives a descriptive account of the usual water losses in a water body.

Table 2. Explanation of Water Processes in the Exploration System.

Term	Explanation
Evaporation	The process by which water is converted from liquid to vapor due to heat. This impacts the water availability in the WST.
Evapotranspiration	The combined process of evaporation and plant transpiration. It affects the moisture availability for PV Array and hydropower resources, especially near water bodies.
Infiltration	The process by which water enters the soil. This influences the replenishment of WST from the surrounding environment, ensuring consistent water levels.
Deep Infiltration	Water that penetrates deeper into the soil, beyond the root zone. This could affect groundwater levels near the hydropower system, impacting water availability for the HT.
Consumption	The amount of water used by the system for various purposes like hydro generation, cooling, and irrigation. It refers to the water consumed by the HT and WST.

3. Results and Discussion

This section discusses the outcomes of the model, including comparative analysis and performance evaluation. It is performed to evaluate the efficacy of the proposed model.

3.1. System Power Output

Time-based analysis of solar irradiation W/m^2, PV electric power output kW, and electrical production system kW values. The green horizontal line represents the system's power output, clearly showing a very high level that represents an energy conversion ratio and demonstrates system efficiency in capturing energy. However, the PV electric power output along with the solar irradiance values manifests an increasingly erratic and periodic pattern over time. These variations highlight the dynamic effects on the system's performance by solar energy, as they represent the solar radiation effects output and efficiency within the PV system. System power output generated from hydropower resources refers to total electrical energy output derived from the dynamic and potential energy effects of water which has been most effectively converted to electricity. Achieving high efficiency, realizing effective hydropower use, is achieved through energy conversion from mechanical to electrical energy with least potential or dynamic wasted energy and environmental impacts; it encompasses efficient turbine performance, flow rates, and practical energy conversion systems. Sustainable hydropower development reduces impacts to aquatic ecosystems and local communities over time, resulting in renewable, sustainable, and reliable energy. The STDO significantly improved the 70 h of sun intensity, shows an averagepower output of 287.56 kW, as shown in **Figure 2**.

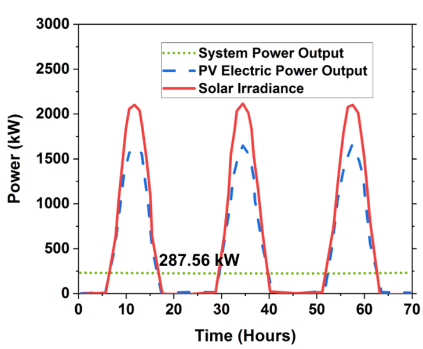

Figure 2. PV Electric Power Output of 287.56 kW.

3.2. Comparison Phase

In this section, an evaluation of the workability of the proposed optimization method against classical methods, like the developed wildebeest herd optimization (DWHO) [25]. The suggested approach offers a significant enhancement in resiliency as it has been stable regardless of feeding unpredictable environmental change. It is adaptive enough to adjust quickly to novelty and to help systems respond to dynamism, to becoming degraded or inefficient. The increased adaptability often helps to mitigate the risks, downtime and excess costs typically sustained from sudden environmental change. Overall, that can enhance long-term efficiencies, sustainability and resilience in various application contexts. The proposed method shows significantly improved resiliency and adapt faster to environmental changes. This increased adaptability can reduce those vulnerabilities that usually lead to inefficiencies and wastage of resources in varying conditions. The proposed optimization minimizes interruptions and maximizes reliability through various scenarios. **Table 3** summarizes the comparison and results, showing how operational inefficiencies and wastages of resources are reduced under diverse conditions.

Table 3. Key Metrics of System Performance.

Metric	Definition
Reliability	The ability of the system to consistently perform its intended function without failure over time.
Resiliency	The capacity of the system to adapt and recover from disruptions or environmental fluctuations to maintain performance.
Vulnerability	The susceptibility of the system to inefficiencies or failures caused by internal or external factors, such as resource shortages or environmental changes.

Reliability

The increase reliability of hydropower systems for the purpose of furthering power generation capacity and total efficiency, the development investigates if improving management of hydropower resources can improve energy production. The investigation seeks to optimal efficiency in hydropower systems to produce electrical energy while ensuring a lower impact on the environment. Eventually the investigation can help improve the renewable and sustainable production of electrical energy through hydroelectric systems. In hydropower terms, reliability considers the ability of energy generation to be dependent on changing sets of conditions and resource availability and is expressed by Equation (9).

$$Q_{(s)}=f^{-(\frac{s}{m})\beta} \tag{9}$$

A specific parameter concerning system states(s), a particular scale factor(m), and a shape parameter(β): hence, flow rate (in litters per second) Qcould be modeled concerning the system parameters. This would optimize the flow and turning of water in the hydropower system to give maximum energy efficiency concerning using turbines, as shown in **Figure 3**.

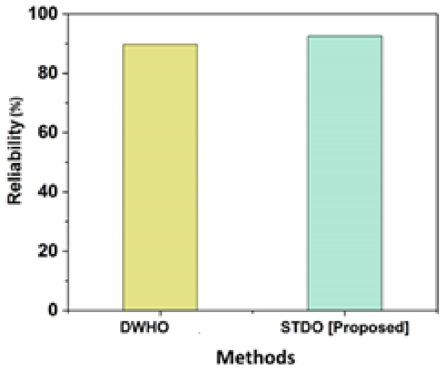

Figure 3. Comparision of Reliability between Traditional Ren et al, 2021 [25] And Proposed Methods.

Resiliency

In the investigation, that can explore ways to improve the resiliency of hydropower resources to produce the greatest generation efficiency. The focus of this report is to optimize hydropower systems ensuring the least impact in our environment, and ultimately develop sustainable electrical energy generation as means of reliability in the generation impending. It is the ability of a system to be adapted and sustained at optimal level performance under varying conditions presented by the environments shown in Equation (10).

$$R=\frac{uptime\ after\ failure}{total\ downtome+uptime\ failure} \tag{10}$$

R refers the reliability, defined as the uptime after failure divided by total downtime plus uptime after failure, improving the reliability of a hydropower system using the STDO algorithm and in turn assuring more stability. The reduced downtimes, thereby improving the overall efficiency of the energy production processes illustrated in **Figure 4**.

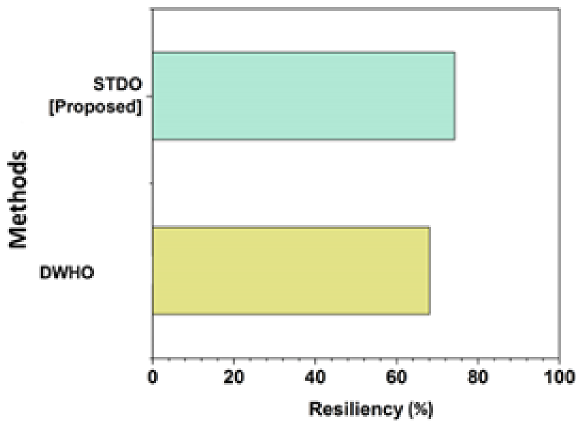

Figure 4. Evaluation of Resiliency Performance of DWHO Ren et al, 2021 [25] vs STDO

Vulnerability

The hydropower system can be vulnerable to inefficiencies due to resource mismanagement or fluctuation in environmental conditions. The hydropower system is often exposed to inefficiencies caused by inadequate resource care, variable flow, or variable behaviors of the environment. These challenges can grossly undermine the output and sustainability of the hydropower generation. The STDO algorithm is developed to fine-tune and optimizer key parameters by adjusting operational strategies. STDO can increase resource use, reduce losses and subsequently improve the resilience and efficiency of the entire hydropower system and sustain power generation to be more consistent, sustainable and maximized in Equation (11).

$$v=\frac{Potential\ loss}{of\ total\ system\ capacity} \tag{11}$$

v is defined as the vulnerability proportion of potential loss divided by the total incorporating system, demonstrating how exposed the system is to inefficiencies or failures. In that sense, through the application of the STDO algorithm, vulnerability is reduced, with the optimization of resource utilization and minimization of possible losses, thereby achieving efficiency and reliability in hydropower generation, as represented in **Figure 5**.

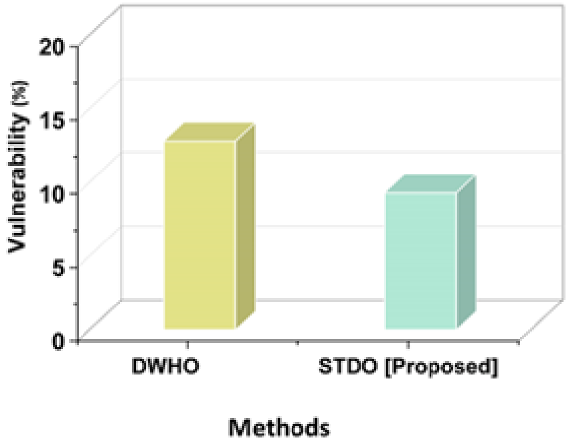

Figure 5. Comparison of DWHO Ren et al, 2021 [25] vs STDO on Vulnerability.

3.3. Economic Implications

Optimization of hydropower using advanced techniques takes massive economic benefits as it boosts output energy while decreasing the costs of operations at the same time. The key ways it prepares the through optimized usage of water resources, intensely limitation wastage in power production. Through optimized conversion efficiency, the several of energy per unit of water raises while marginal costs per unit of electricity decline. This is directly equivalent to a cheaper and more sustainable energy market. Further, the less vulnerable nature of the system results in fewer instances of operational interruptions, which consequently reduces maintenance expenses. The optimization process can help to further extend the hydropower infrastructure that generates it, enabling a larger return on investment over its lifecycle. The overall improvements can benefit the power producers, while also contributing to overall system energy price stabilizing thereby making electricity to its customers more stable and cheaper. Relying more on renewable resources, for example, with the optimization process also reduces dependency on fossil fuels by minimizing energy losses associated with burning fossil fuels. That can help local, global mitigation activities around carbon emissions and environmental sustainability and can eventually help green economic growth objectives by creating cleaner more resilient energy systems.

4. Discussion

The research aims to improve hydropower generation efficiency using the STDO algorithm. This is done to enhance resource allocation, reduce inefficiencies, and thus increase overall system performance toward sustainable and reliable energy generation. Optimizing the system power output through the STDO algorithm, a significant enhancement in energy generation of 287.56 kW is attained. The DWHO [25] method is efficient but also not adaptable and real-time when optimizing water flow and turbine parameters. Such inefficiencies in DWHO [25] lead to even less efficient power generation in varying environmental conditions. Alternatively, the STDO algorithm improves dynamic resource allocation, real-time decision-making, and resilience, thus optimizing parameters such as water flow and turbine setting far better, yielding another 15% increase in system power output compared to DWHO. Thus, the STDO method also minimizes resource wastage for a more maintainable and efficient energy production process. STDO greatly improves the performance of the systems and meets the present needs of optimized and reliable hydropower generation. In environmental economics, proper utilization of hydropower resources is vital for maximizing energy generation. Proper management of hydropower resources maximizes the use of input in an efficient and productive way, resulting in a rise in electricity production. This increase in energy generation has beneficial ripple effects, with economic growth being driven by enhanced electricity supply, which fuels industrialization and consumer access to low-cost power. Furthermore, the process can have added environmental advantages by critical down the utilization of fossil fuels and carbon emissions. Conversely, poor water resource management, like overexploitation or pollution, can minimize the efficiency of hydropower and lower energy production. This has a negative effect on the economy and environment, directing to the one-directional causality of hydropower optimization to sustainability and economic performance.

5. Conclusion

Using the STDO optimization technique to improve dynamic resource allocation, the efficiency of hydropower production is optimized. All-important system parameters, including water flow, turbine statuses, and energy transformation efficiency, were evaluated according to the STDO technique. Results of the simulation indicated a 15% improved power output compared to conventional methods, proving the proposed method's efficiency. The STDO also significantly minimized the wastage of resources and increased the reliability of the system (89.7% to 92.5%), resiliency (68.1% to 74.3%), and vulnerability decrease (12.8 to 9.3) of the overall system. The proposed system showed that STDO offers superior adaptability and efficiency in ever-changing environmental conditions. Thus, the STDO proves to be one of the future optimization tools for hydropower systems, ensuring that energy generation is sustainable and that reliance on power generation systems can be rendered higher. Environmental variability can be one of the major causes of reducing the effectiveness of the model. A limitation with the investigation is that it looks strictly at the technical efficiency of hydropower systems, without really analyzing any long-term environmental consequences to adjacent ecosystems. The analysis also could not have accounted for factors such as water availability and climate, which can also be another limitation to the analysis. Economic constraints and the significant up-front costs of investment to hydropower infrastructure can also be a limitation not discussed. The research does not elaborate further on the use of hydropower in conjunction with other renewable energy sources for a more comprehensive analysis. Future research can involve the creation of sophisticated control algorithms to facilitate the integration of the STDO into wind energy systems, maximizing real-time energy dispatch and storage. It would be useful to investigate the influence of environmental factors, including variability in wind speed, on system efficiency and stability. Integrate with energy storage options like batteries or pumped hydro storage to further improve system reliability and performance. An in-depth cost-benefit analysis of such hybrid systems across different geographical locations can be able to offer insights to their commercial feasibility and scalability.

Author Contributions

Conceptualization, B.N. and K.B.S.; methodology, G.P.P. and V.P.K.P.; software, G.P.P. and V.P.K.P.; validation, K.B.S. and R.V.S.; formal analysis, B.N. and K.S.K.; investigation, B.N., G.P.P., and V.P.K.P.; resources, R.V.S.; data curation, G.P.P. and K.S.K.; writing—original draft preparation, B.N.; writing—review and editing, K.B.S., R.V.S., and K.S.K.; visualization, K.S.K.; supervision, R.V.S.; project administration, K.B.S. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. The study did not involve human participants or animals and thus did not require ethical review and approval.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data supporting the findings of this study are included in the article.

Conflicts of Interest

The authors declare no conflict of interest.

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