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Transmission Network Expansion Planning with High-Penetration Solar Energy Using Particle Swarm Optimization in Lao PDR toward 2030

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Abstract: The complexity and uncertainty of power sources connected to transmission networks need to be considered. Planners need information on the sustainability and economics of transmission network expansion planning (TNEP). This work presents a newly proposed method for TNEP that considers high-penetration solar energy by using the particle swarm optimization (PSO) algorithm. The power sources, thermal and hydropower plants, and conditions of load were set in the account, including an uncertain power source and solar energy (PV). The optimal sizing and locating of the PV to be connected to the network were determined by the PSO. The PV grid code was set in the account. The new line's investment cost and equipment was analyzed. The PV cost was considered based on the power loss, and the system's reliability was improved. The IEEE 118 bus test system and Lao PDR's system were requested to test the proposed practice. The results demonstrate that the proposed TNEP method is robust and feasible. The simulation results will be applied to guide the power system planning of Lao PDR.

Keywords: transmission network expansion planning; solar energy; renewable power generation; optimization; reliability

1. Introduction

The power system is a key element that can help to boost economic growth and the development of countries. It is confronted with significant challenges with regard to stability and economic energy supply [1,2]. The transmission network is the most significant factor for electrical power as it connects the power sources to consumers [3]. Power sources are mostly in land far away from the city. Power connection systems from power sources to the load centers need to involve more reliable transmission networks [4,5]. Renewable resources have been investigated, developed, and examined as the first choices to replace fossil energy [6,7]. They will be the main power sources in the future [8–10]. Renewable resources are increasingly used and encouraged worldwide, and the price of these technologies is slowly coming down. These sources have lower operating costs and are environmentally friendly [11,12]. However, connecting renewable generation, such as solar PV, into the power system is more complicated, and it is more difficult for transmission system planners and operators to maintain up-to-the-mark reliability and security levels for the supply [13,14]. The major problems with solar energy integration to the network are as follows: firstly, we have to determine how to connect solar energy, which is highly vulnerable, to the load demand; and secondly, we need to determine how to build a transmission network that is sufficient to transmit uncertainty sources from solar sources, which are usually located in remote areas [15]. Therefore, the system planners need to consider several factors to reach the requirements: the system power loss and reliability need to be improved, and the new lines to be expanded need to be considered [16]. Particularly, the system planning needs to be coordinated with the size and placement of solar generation and flexible sources [16,17].

Previous works associated with transmission system expansion planning considering uncertain sources and load have been presented in international journals of the power sector. The approaches of these papers usually involved determinacy, uncertainty, and probability. The system costs, such as investment costs, operation costs, and unreliability costs, were considered [17]. The reliability and security parameters were classified as contingencies in N-1, expected energy not supply (EENS), and loss of load expectation (LLOE) [18,19]. The recently considered power systems involve risk, the new changes in the grid, environmental matters, a power market, and a computational burden. The methods were considered in a re-competition manner. The mathematical, heuristic metaheuristic, multiobjective algorithm, and AC and DC models were applied to assess the transmission networks to determine the power flow optimization model [20]. In the abovementioned studies, the DC optimal power flow model and the mathematical model were usually considered. Renewable generation was investigated in many of the papers. Low-predictability characteristics of intermittent renewable energy sources can be apprehended by approaches such as uncertainty and probabilistic models [18,21]. The advanced multistage TNEP technique, constructed on the deep Q-network (DQN) algorithm, has been used to solve the TNEP problem, and the economy, reliability, and flexibility of the TNEP have been evaluated through application in the IEEE 24 bus system [22]. Using a technique of coordinated expansion planning for renewable generation and transmission expansion planning (CNEP) that minimizes the total cost and pliability benefit, the generation planning interrelated transmission planning problem was solved by the energy storage system to improve the pliability of the grid. Moreover, in the CNEP problem, the AC power model was applied to determine the reactive power. The technique has been examined on the IEEE 6 bus and 24 bus test systems applying GAME software [16]. However, very few works that mention TNEP have considered the optimal sizing and locating of uncertain sources which apply PSO to solve the TNEP based on the load conditions related to the season. The PSO is applied to solve the TNEP problem in this work because it is easier to use and flexible to integrate with another optimizations [23]. PSO is metaheuristic and is more suitable to apply to complicated and big systems as well as the EDL grid, which has more data and the network is connected to neighbor countries.

Therefore, the major benefits presented in this work are as follows: (i) The TNEP considers the high penetration of solar energy, uncertainty sources, and the conditions of load. (ii) The investment cost of the new lines and equipment is minimized by the PSO based on the optimal size and capacity of solar energy. The power loss across the whole system and the system reliability are improved, and also, the solar grid code is considered. (iii) The research approach is verified with the IEEE 118 bus test system and Lao PDR's network.

There are four sections in this paper, as follows: Section 2 presents uncertainty models for load generation. Section 3 presents the implementation of the TNEP PSO, the network data for EDL, and the IEEE 118 bus test system. Section 4 presents the results and discussion for the TNEP based on the EDL network and the IEEE 118 bus test system. Finally, Section 5 presents the conclusions and recommendations.

2. Uncertain Power Sources and Load Modeling

2.1. Solar Energy Modeling

The production of solar energy involves the conversion of sunlight into direct current and alternating current, which can be integrated into the power grid as photovoltaic energy.

In solar cells, photovoltaic energy conversion involves two necessary steps. Firstly, the light absorption generates an electron hole pair. Secondly, the electron and the hole are divided by the device structure. Here, electrons move to the negative terminal and holes move to the positive terminal, consequently generating electrical power [24]. The monthly solar radiation data in Lao PDR are applied in the model shown in Figure 1 [25].

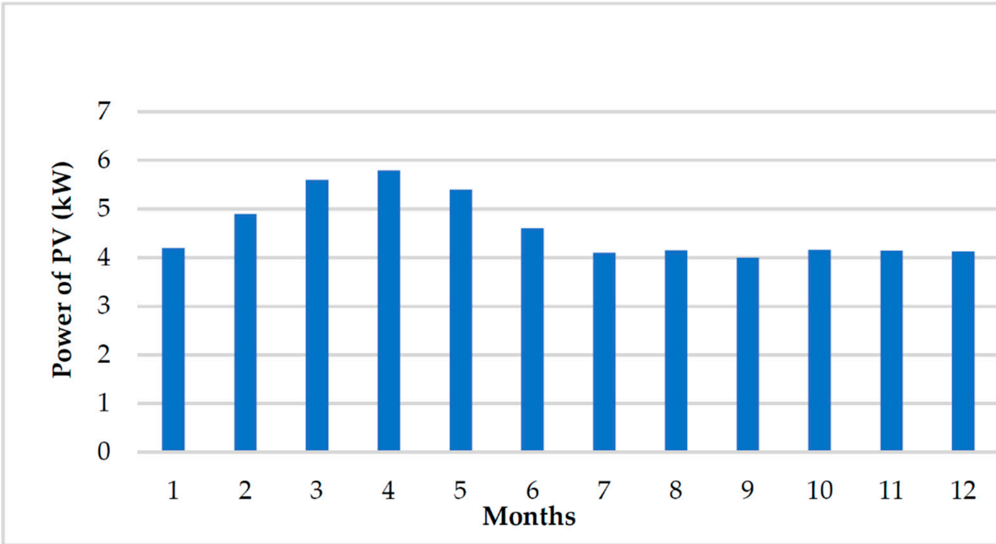

Figure 1. Monthly solar generation data in Lao PDR [25].

An uncontrollable power source and solar energy are applied in the model based on the solar radiation that is used to produce power daily. The daily output power lasts for 4.2 h. The plant factor of the solar farm is set to approximately 18% of the installed capacity [25]. Solar energy strongly impacts transmission network planning because of its uncertain power source. However, having the right location and capacity for this power source can reduce the new line's investment cost. Additionally, the power loss in the system will be improved and the reliability of the whole network will be reduced.

Generally, the intercontinental method is used for the evaluation of the power generated in the output of a photovoltaic system through Equation (1)

$$P_{PV} = r\,A\,H_{PV}\,P_R \tag{1}$$

where

P_{PV} is the photovoltaic power (W);
A is the total photovoltaic cells' area (m^2);
H_{PV} is the annual average solar radiation on tilted panels (W/m^2);
P_R is the performance ratio, which is a coefficient for losses with a range between 0.5 and 0.9, and a default value of 0.75;
r is the yield of the photovoltaic cells, given by the ratio of energy (kWh) from one photovoltaic cell to the area of one panel.

2.2. Hydropower Generation Modeling

The fundamental purposes of a hydropower plant are the hydraulic fluid storage and water; the transformation of the fluid hydraulic power into mechanical power in a hydraulic turbine; and the transformation of mechanical power into electrical power in an electrical generator.

The hydropower plant arrangement is divided into three main types, which are assigned according to the type of hydraulic flow control at the location:

1. Run-of-river power plants: these plants have no reservoir and a small amount of water storage, and consequently, a lack control of the flow through the plant;

2. Reservoir power plants: this type has a reservoir with the ability to store water, and hence, the ability to control the flow through the plant on a seasonal basis or routine;
3. Pumped-storage power plants: In this type of plant, the direction of rotation of the turbine is reversed during the off-peak times. The water is pumped from a low area up to a reservoir, generating "storage energy" for later; the power will be generated during peak hours.

The uncertainty of a hydropower plant is applied in the model according to the type of hydropower plant designed and the geographical location. There are two main types of power sources. The first one is hydropower plants with a reservoir that is dispatchable, and the second is the run-of-river hydropower plant, which is not able to dispatch and the power output can only be generated in the rainy season. Both of these hydroplants are located in remote areas, and the transmission lines implemented to transfer energy from these power sources must be reliable and economical. According to National Power Development Planning (NPDP), generation planning is applied in the uncertainties model. The power generated is based on typical hydropower plants and seasonal planning is considered [1,2].

The fundamental properties of a hydropower plant that generates power are the head function and the water discharge flow rate through the hydraulic turbine, as shown in Equation (2). The generation profile for 2022 is shown in Figure 2.

$$P = 9.8\eta\ Q\ H \tag{2}$$

where

P is hydroelectric power (W);
η is the efficiency of the plant;
Q is the water discharge flow rate (m^3/s);
H is the head of dam (m).

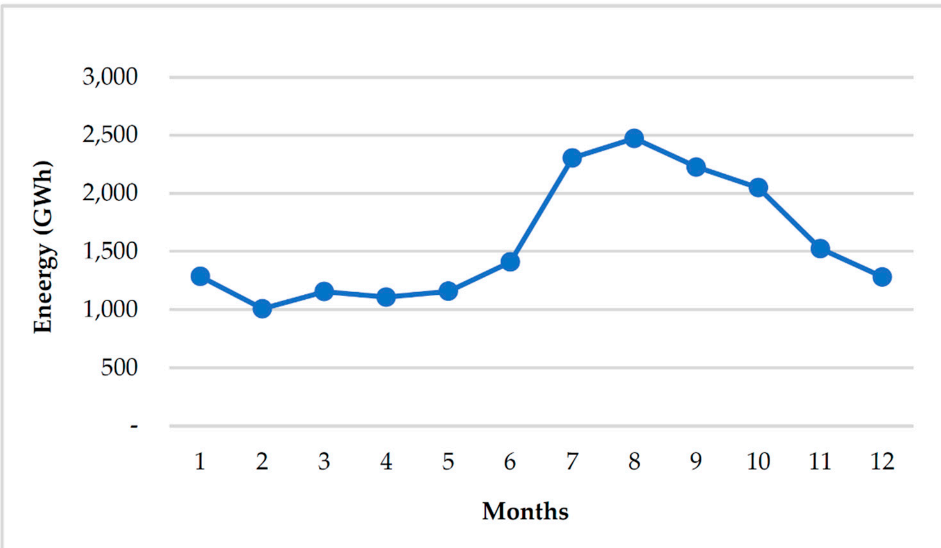

Figure 2. Generation profile of the EDL in 2022 [24].

2.3. Load and Demand Modeling

The load growth is presented in relation to the economy of the country's growth rate, which is the external factor considered during power system planning. The estimation of the load forecast is more complicated and complex. The load model presents the expected load growth for each year. The conditions and growth rate of the load are considered. The yearly load growth rate is approximately 10%. The existing load profile for the national grid is given in Figure 3. The load and demand modeling are described nonlinearly. The load model is presented in Equation (3).

$$L_n = \sum_{n=1}^{n} (L_1 + 0.1L_1(n-1)) \tag{3}$$

where

L_n is the load of n year (MW);
L_1 is the load of the first year (MW);
n is the number of year planning.

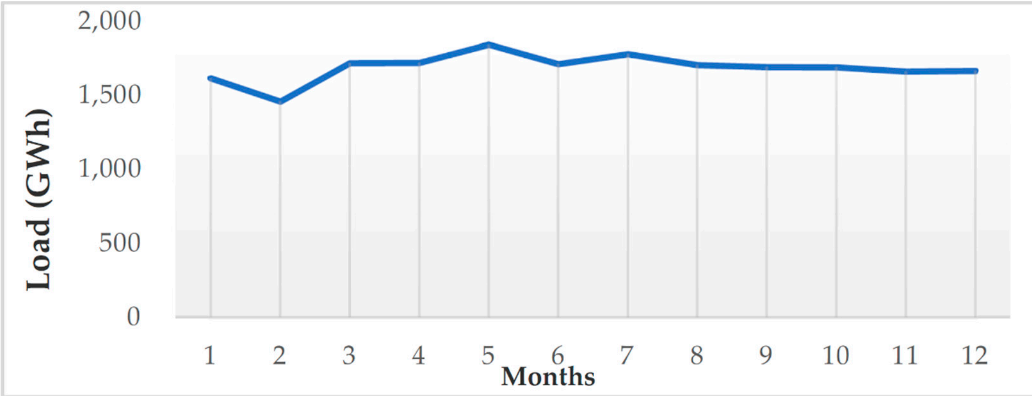

Figure 3. The existing load profile of the national grid [24].

3. Objective Function of the TNEP Formulation

The proposed method considers the objective function to reduce the total investment cost for the whole network. The generation of the PV that will be installed in the network requires the installation of an additional transmission line to allow power flow through the line that exceeds 80%. This will increase the cost of the investment. Therefore, the proposed approaches were designed to optimize the sizing and locating of the newly generated PV with less new line installation required. The power loss and system reliability are the main criteria used to select the size and location of the PV installed for the whole system. The objective function comprises two parts: to minimize a new line's investment cost and to maximize the benefit of the PV connected to the grid based on the optimized size and location of the PV. The system power loss and reliability are the main criteria which improve the PV connected to the network. The main objective function of this work is given in Equation (4).

$$\text{Objective function} = \text{Max } B_{PVtot} + \text{Min } C_{\text{invt}} \tag{4}$$

where

Max B_{PVtot} is the maximum of the PV connected to the grid (USD);
Min C_{invt} is the minimum of the investment cost of new lines (USD).

3.1. Maximum Benefit for PV Connection

The function of the total PV benefit criterion for the TNEP model was considered. There are three main functions of the total PV benefit when it is connected to the system. The benefit of power loss in the system is determined before and after the PV generators are connected. The PV energy sold to customers and exported to neighboring countries is obtained, and the reliability benefit is improved before and after the PV generators are connected to the grid. This is presented in Equation (5):

$$B_{PVtot} = B_{\Delta Ploss} + B_{P.sale} + B_{P.Rel} \tag{5}$$

where

B_{PVtot} is the total benefit from the PV connected to the grid (USD);
$B_{\Delta Ploss}$ is the benefit in terms of power loss, before and after the PV is connected (USD);
$B_{P.sale}$ is the benefit in relation to selling power produced from the PV connection (USD);
$B_{P.Rel}$ is the benefit obtained from the system reliability improvement due to the PV connection (USD).

3.1.1. Power Loss Difference in the System ($P_{\Delta Ploss}$)

The difference in power loss before and after the PV generators are connected to the network were compared. This benefit is the total power loss in the system when PV generation is not considered minus the new power loss after the PV generators are connected, as shown in Equation (6)

$$P_{\Delta Ploss} = P_{loss\_old} - P_{loss\_new} \tag{6}$$

where

$P_{\Delta Ploss}$ is the power loss difference in the system before and after the PV generators are connected (MW);
P_{loss_old} is the power loss before the PV generators are connected (MW);
P_{loss_new} is the power loss after the PV generators are connected (MW).

3.1.2. The Benefit of Power Increase with PV Connection ($B_{P.sale}$)

The increase in power following the connection of the PV generators to the grid was taken into account. The benefit was calculated as the capacity of the PV generators multiplied by the day of the year and the hours of power produced by the PV that are transferred to the grid, as shown in Equation (7):

$$B_{P.sale} = \sum_{p=1}^{np} PV_p N(365)(\mathrm{PF}) + B_{\Delta Ploss}(365)(\mathrm{PF}) \tag{7}$$

where

PV_p is the PV generated (USD);
N is the number of PV generators;
PF is a power factor (4.2 h per day).

The penalty function indicates that the PV generators cannot inject more than 70 MW of power into the grid for exportation to neighboring countries. This is shown in Equation (8):

$$\begin{gathered} P_{pen} = P_{exNet} - P_{exNetold} \\ P_{pen} \leq 70 \text{ MW} \end{gathered} \tag{8}$$

where

P_{pen} indicates that the amount of power injected to the grid by the PV generators for exportation to neighboring counties cannot exceed 70 MW (MW);
P_{exNet} is the power exported after the PV is connected to the grid (MW);
$P_{exNetold}$ is the power exported before the PV is connected to the grid (MW).

3.1.3. The Reliability Benefit (B_{Rel})

The reliability benefit is considered and compared for each year of planning through PSO. The reliability benefit is calculated as the total grid reliability before the PV generators are connected minus the total grid reliability after the PV generators have been connected to the system. These values are selected by PSO. This is shown in Equation (9):

$$B_{Rel} = B_{rel.old} - B_{rel.new} \tag{9}$$

where

B_{Rel} is the reliability benefit (USD);
$B_{rel.old}$ is the total reliability benefit before the PV generators are connected (USD);
$B_{rel.new}$ is the total reliability benefit after the PV generators are connected (USD).

3.2. Minimization of the New Lines' Investment Cost (C_{invt})

The investment required is increased with the need for new lines, new equipment, and the extension of substation bays in the system. The objective function is based on the load flow calculation, in which the lines are able to transfer power to customers. If the power flow in the line is over 80% of the line's capacity, it will be selected for extension. The calculation of the investment cost for the new line is shown in Equation (10) [26].

$$\text{Min}C_{invt} = \sum_{eq=1}^{neq} \sum_{p=1}^{np} n_p C_{ep.p} \tag{10}$$

where

C_{invt} is the investment cost of new lines (USD);
n_p is the number of lines to be extended;
$C_{ep.p}$ is the cost of new lines and equipment to be extended (USD).

4. Implementation of the TNEP

The TNEP is powerfully controlled by the input data, such as the yearly remand growth rate, the equipment forced-outage rates (FOR), the profile of the generated matrix, and the schedule for the newly commissioned network, substations, power sources, etc. [17,27]. Nevertheless, these data are able to be acquired from an engagement that may carry some level of unpredictability. Additionally, renewable generation, as wind and solar energies, is irregular and incalculable [28]. Renewable energies can also be integrated into distribution networks together with electric cars, storage devices, and smart grids, where they are able to replace the regular generation–transmission–load pattern of the big network used by the grid planner [29]. Although customary deterministic TEP models are easier to determine, they cannot represent the real stochastic manner of the power system, and in several circumstances, they may underestimate investment and produce unrealistic network plans [30–32]. TEP models determine forecasts to identify important variants, such as demand, supply, and power market practices that do not match the actual characteristics of the power system [33,34]. Nonetheless, these models have a high priority in the complementary literature, because they allow other significant aspects of planning to be addressed (with less estimation effort).

4.1. PSO Methodology

Optimization algorithms and approaches have been used in the literature in many areas to handle various concerns with experience [35]. In view of modern computing systems, optimization approaches are predicted to become increasingly significant and well-known for use in dissimilar engineering functions [36,37]. The purpose of this research is to present some existing improvements in the field of optimization literature, approaches, and functions in engineering [38]. The purpose of optimization could be to minimize the cost of production or the efficiency of production increase. An optimization algorithm is conducted by iteratively calculating and comparing various methods until an optimal or satisfactory method is found [39]. Following the appearance of computers, optimization became a computer-aided determination activity. Optimization algorithms are generally divided into two distinct types that are applied worldwide [35–39].

The PSO algorithm is a heuristic metaheuristic optimization method inspired by the natural activity of bird flocks and fish education cleverness. This optimization algorithm technique was first presented by Ebert and Kennedy in 1995 to picturesquely simulate the tasteful and unforeseeable composition of a swarm. To find the best solutions, the main object of the PSO algorithm is to use an assumed number of particles contained in the explored space. The emotional design of the particles is determined by social interactions between individuals from the population for the best solutions [35–39].

Particles are applied for the mathematical delineation of the flock, and the particles are presented as vectors in a multi-aspect found space. Optimization starts from the random generation of the population and the particles' velocities. To appoint the ascertained performance, the particles are estimated using the function of an objective. In these manners, the personal best attribute of each particle and the global best attributes of the entire population are defined. For this guidance, the velocity of an individual is calculated, allowing for its last velocity, global best (*gbest*), and personal best (*pbest*). Then, the new positions of the individuals are considered by computing the velocities to the actual positions using the equation shown below [40]:

$$\omega_i^{k+1} = W\omega_i^k + C_1 Rand(pbest_i - \theta_i^k) + C_2 Rand(gbest_i - \theta_i^k) \tag{11}$$

where

ω_i^{k+1} is the ith particle velocity at iteration $k + 1$;
ω_i^k is the ith particle velocity at iteration k;
W is the inertia coefficient;
C_1 and C_2 are weighting coefficients;
$pbest_i$ is the personal best of the ith particle;
$gbest_i$ is the global best of the population;
θ_i^k is the ith particle position at iteration k.

$$\theta_i^{k+1} = \theta_i^k + \omega_i^{k+1} \tag{12}$$

where

θ_i^{k+1} is the ith particle position at iteration $k + 1$.

The search process is carried out until a relative positional constant is encountered or computational limits are surpassed. The significance of the particle swarm optimization algorithm is the ratios of the three foundations. This affects the ability of the particle velocity in the optimization step to be adjusted. As a result, the performance of the particles to achieve the optimal solution can be improved by managing the weighting coefficients [35–40].

4.2. PSO Implementation of TNEP

The algorithm flowchart implemented for solving the TNEP problem is shown in Figure 4. The algorithm starts with a load flow analysis where the load conditions and power sources are set in the account. The lines that carry over 80% of the total power capacity of each line are selected to calculate the investment cost of the whole system. The flowchart used to add a line is shown in Figure 5.

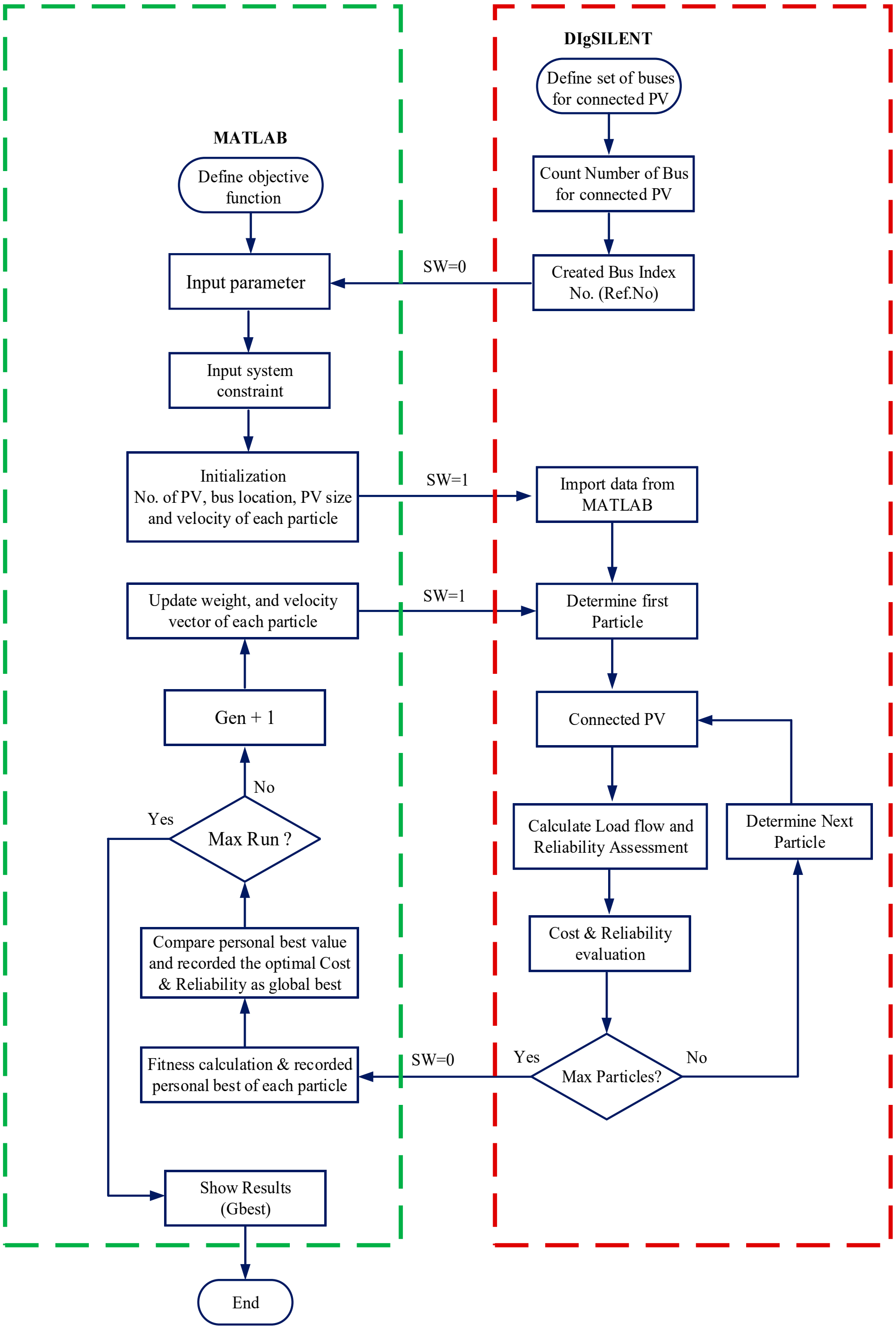

Figure 4. Flowchart of the implemented TNEP Optimization with MATLAB and DIgSILENT as shown as the green and red boxes, respectively.

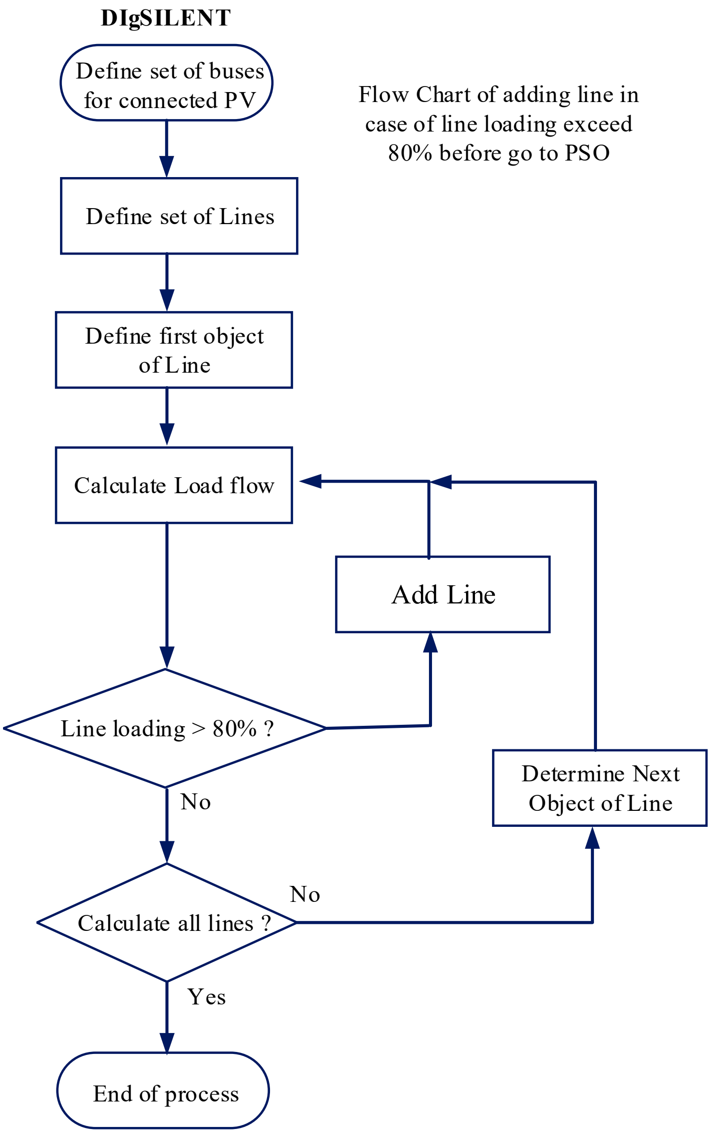

Figure 5. Flowchart used for auditing and adding a new line.

PSO begins with the definition of an objective function, the definition of the connected PV, and the setting of the number of buses for the connected PV. A bus index is created, and an input system constraint is added. The system initialization data, the number of buses, and the location, PV size, and velocity of the particles are set in the account. The first particle is determined, and after that, the PV is connected to the bus. The load flow and system reliability are evaluated. In addition, the investment cost and unreliability cost, including the power imported to the grid, are determined. The algorithm determines whether the maximal number of particles has been found and then moves to the next step; however, if the particle number is not maximal, the algorithm goes back to the PV connection. The fitness calculation and recorded personal best of each particle are verified, and then we move to the next step for the comparison of the personal best value. The optimal cost and reliability are recorded as the global best. The algorithm ends when the maximum run has been found and the results are shown (Gbest). This is the end of the TNEP planning optimization procedure. If the maximum run is not found, the algorithm will update the weight and velocity vector of each particle and determine the first new particle.

5. TNEP Implementation

5.1. IEEE 118 Bus Test System

For this work, the IEEE 118 bus test system is presented with the Illinois Institute of Technology 2003 version [41]. This version is related to the TNEP literature worldwide. The data applied for the IEEE 118 bus test system were considered for TNEP from 2022 to 2030, as shown in Table 1. Figure 6 shows a diagram for a single line of the IEEE 118 bus test system.

Table 1. Planning parameters for the IEEE 118 bus test system [40].

Parameter	Value
Transmission lines	186 lines with 118 buses
Generation	4794 MW with an increase of 8% per year
Demand	1.382 MW with 91 points and an increase of 8% per year
Transmission lines' cost	230,000 USD/km/circuit (230 kV transmission line)
Planning horizon	8 years
PV power purchasing costs	0.053 USD/kWh
PV power selling costs	0.072 USD/kWh

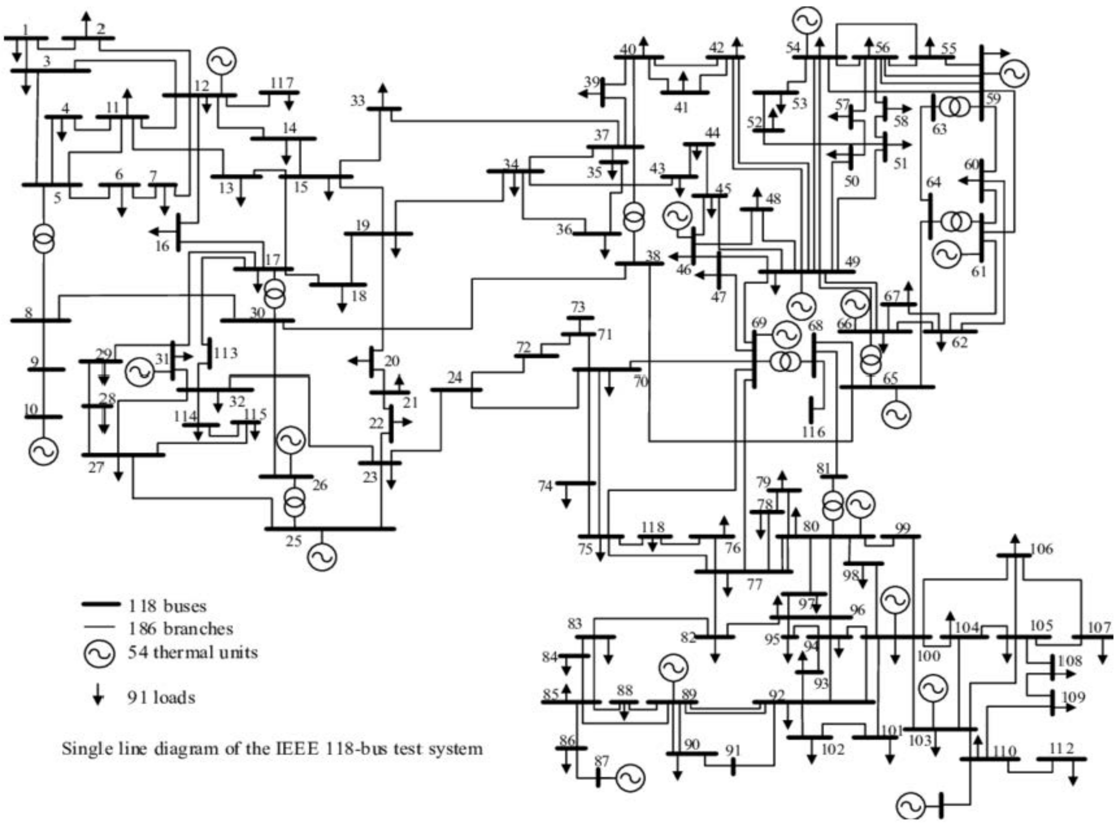

Figure 6. Single-line diagram for the IEEE 118 bus test system [41].

5.1.1. IEEE 118 Bus Test System Data

The data from the IEEE 118 bus test system that were verified in this research included the rated current for extra-high-voltage transmission lines that meets the standard for power flow analysis [42,43]. The control system in the original IEEE was removed and replaced by a terminal busbar in the power system. The loading of the lines that represents over 80% of the capacity was selected as the line candidate and was added to the new lines. The grid code for PV generation that will be connected to the bus was set in the account. In addition, the reliability conditions for buses and lines were set by following the standard. The planning parameters are given in Table 1 [43–46].

5.1.2. IEEE 118 Bus Test System Results

The IEEE 118 bus test system simulation results are shown in Table 2. The location and size of the PV selected by the PSO for yearly planning are given. The capacity is shown to increase slightly; however, the number of PV generators differs. The addition of new lines to extend the lines that carry the load is needed to meet the requirements only four times: in 2023, 2025, 2027, and 2029. The total that the new lines cost in each year of planning as a whole is approximately USD 172.9 million. The total cost for adding PV generators is increasing. The power loss in the system is reduced when the PV is connected to the grid; however, it does not have a significant impact on the grid because of its small capacity. The system's reliability is improved. The PSO process used for solving TNEP's IEEE 118 bus test system in 2025 is given in Figure 7. The power loss in the system with the PV and without the PV is given in Figure 8, and the reliability of the grid with the PV and without the PV is given in Figure 9.

Table 2. PSO of the TNEP for the IEEE 118 bus test system.

Description		Planning Horizontal Year 2022–2030								
		2022	2023	2024	2025	2026	2027	2028	2029	2030
Added lines/ equipment			Lines 77–78, lines 82–83, lines 85–89, lines 89–90, and lines 100–103 (USD 55.2 million)		Lines 61–62 (USD 8.5 million)		Lines 61–62 and lines 77–80 (USD 9.7 million)		Lines 37–39, lines 70–71, lines 77–82, lines 77–82, lines 82–83, lines 83–85, lines 94–100, and lines 110–111 (USD 81.8 million)	
Added PV	No. buses	none	34 buses	16 buses	29 buses	40 buses	39 buses	35 buses	47 buses	45 buses
	Capacity (MW)		391 MW	256 MW	323 MW	259 MW	443 MW	453 MW	555 MW	450 MW
Total active power gen. (MW)		3708.33	3976.86	4265.15	4549.14	4840.60	5123.45	5385.16	5676.70	6244.37
Total reactive power gen. (MW)		1084.85	1099.43	1291.40	1426.35	1601.58	1687.438	1639.39	1625.17	1787.68
Total load in the system (MW)		1381	3821	4101	4381	4660	4940	5223	5514	6066
Total benefit for adding PV (USD millions)		31.98	19.68	31.32	37.31	46.15	51.34	48.79	52.74	55.3

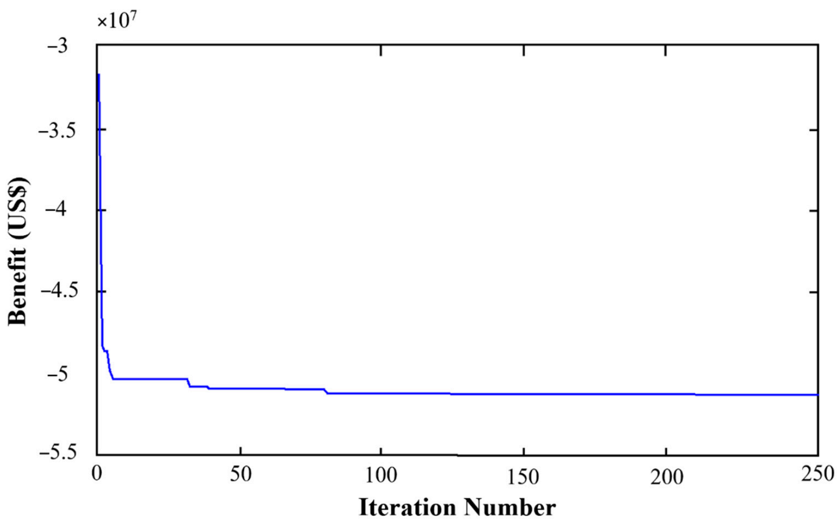

Figure 7. PSO process for the TNEP of the IEEE 118 bus test system in 2025 using 10 particles and 250 iterations.

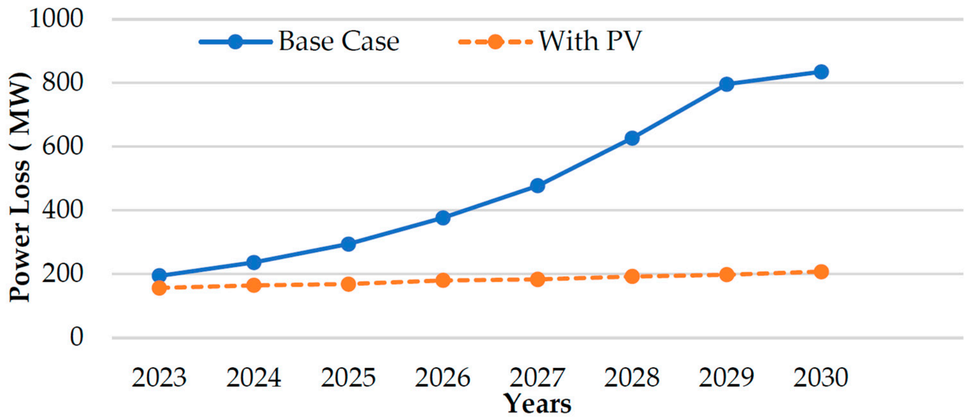

Figure 8. Comparison of the power loss in the base case and with PV for the IEEE 118 bus test system.

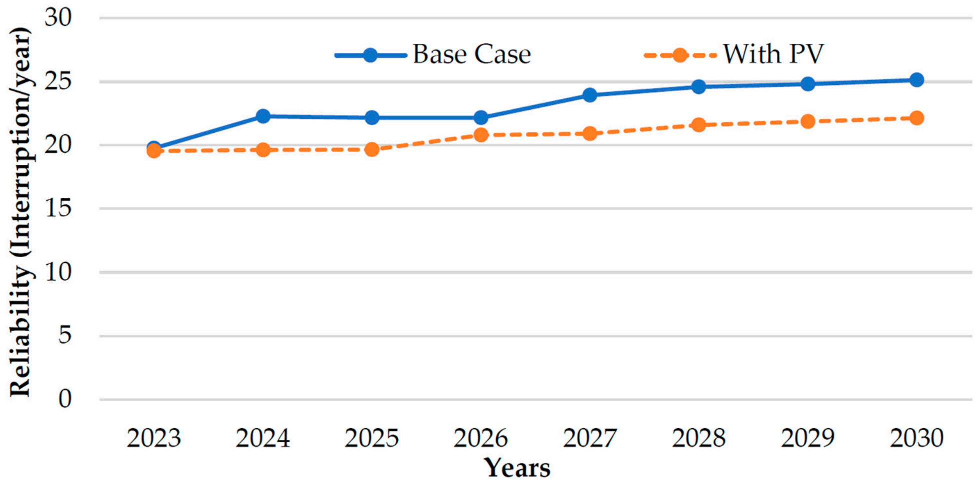

Figure 9. Reliability of the base case and with PV for the IEEE 118 bus test system.

5.2. Lao PDR Network

5.2.1. Lao PDR Network Data

The Lao PDR has harnessed its geographical resources, such as its potential for hydraulic power, for economic growth. The power system of Lao PDR, Electricite Du Laos (EDL), is divided into two main parts: transmission networks that are directly connected to the electric power systems of neighboring countries from dedicated power plants and those from the domestic supply. The power transmission network of the EDL is connected from north to south by transmission lines of 115 kV, 230 kV, and 500 kV, which are connected to power sources across the whole country to supply power domestically. There are five interconnections with Indochina grids. The power systems are interconnected with neighboring countries via 500 kV, 230 kV, and 115 kV transmission lines with power systems in China, Thailand, Cambodia, and Myanmar, respectively. The 35 kV distribution lines are connected to Vietnam systems, and in the future, they will be connected by extra-high voltages in the northern and southern parts. The Lao PDR aims to develop the national grid or backbone, which will connect the power sources nationwide through an extra-high-voltage 500 kV system. This will be connected to the neighboring grid (system to system scheme) for power trading with the Indochina grid and to enhance electric power exportation. The network data and planning parameters are given in Table 3 [24]. The power development plan of the Lao PDR is shown in Figure 10 [24].

Table 3. Planning parameters for the EDL grid [20].

Parameter	Value
Transmission lines	874 lines with 149 buses
Generation	1754 MW with an increase up to the National Power Development Plan (NPDP)
Demand	1415 MW with an increase of 10% per year
Transmission line cost	430,000 USD/km/circuit (500 kV), 230,000 USD/km/circuit (230 kV), and 120,000 USD/km/circuit (115 kV)
Planning horizon	8 years
PV power purchasing cost	0.053 USD/kWh
PV power selling cost	0.072 USD/kWh

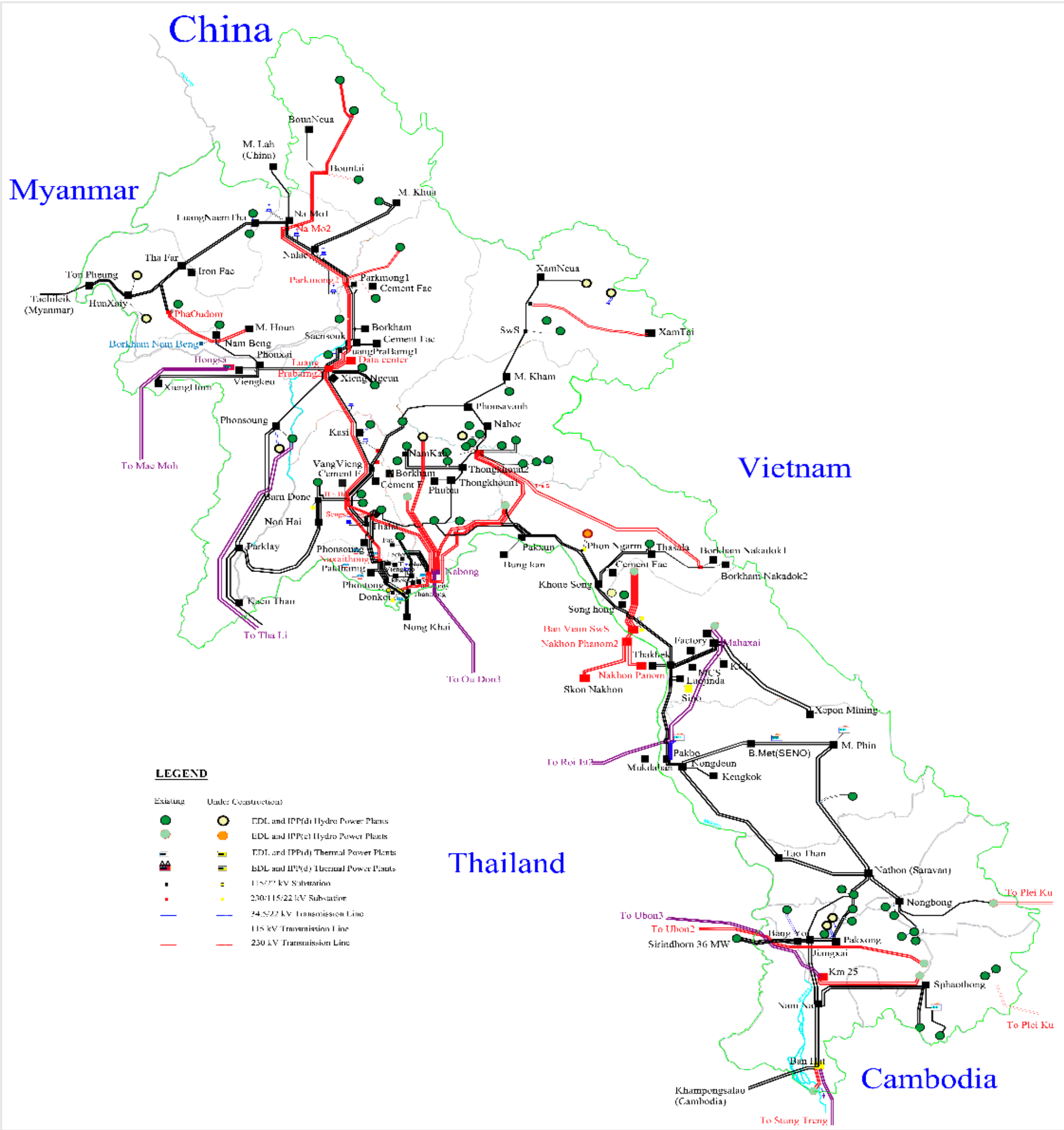

Figure 10. Single-line diagram of the existing grid of the Lao PDR [23].

5.2.2. TNEP for the EDL Grid Results

The TNEP for the EDL grid simulation results is shown in Table 4. The locations of the PV in each year of optimal planning differ. The capacity of the PV generators is optimal at approximately 10–15% of the capacity of total generation, which is the best result. The generation and load data for planning years are linked to national generation planning and demand growth. The number of generations of PSO must be above 140 to achieve the best results. In addition, particle numbers from 10 to 20 can be used to achieve the best results. The transmission network used for EDL was determined to meet demands, so grid extension is not required during the planning year. It is only transformers and other equipment that need to be extended. New lines constructed to transfer power from new sources only need to be generated in the years 2023, 2025, and 2027. The total cost of new lines in the total planning year is approximately USD 377.9 million. The total cost for adding PV generators is increasing. The power loss in the system is reduced when PV is connected to the grid; however, it does not have a big impact on the grid because of its small capacity. The system's reliability is improved. The PSO process for solving TNEP's EDL in 2028 is given in Figure 11. The power loss of the system is similar with PV vs. without PV, because the PV selected to connect the grid has a small capacity when compared with the total power generated. On the other hand, the EDL's grid not only supplies power to the domestic grid but also to neighboring countries. Therefore, the power loss in the system with PV vs. without PV does not differ significantly. This is shown in Figure 12. The reliability is shown in a summary grid for systems with PV and without PV in Figure 13.

Table 4. PSO of the TNEP results for the Lao DPR Grid.

Description		Planning Horizontal Year 2022–2030								
		2022	2023	2024	2025	2026	2027	2028	2029	2030
Added lines/equipment		None	103.6 million	None	263.9 million	None	10.4 million	None	None	None
Added PV	No. Buses	None	21 buses	33 buses	25 buses	35 buses	21 buses	29 buses	31 buses	57 buses
	Capacity (MW)		175 MW	153 MW	155 MW	159 MW	123 MW	136 MW	167 MW	256 MW
Total active power gen. (MW)		1753.58	1753.58	1829.89	2295.61	2445.91	2504.41	2602.09	2763.81	2860.21
Total reactive power		45.46	65.2	87.4	199.124	229.185	469.934	482.603	514.533	525.2
Total load in the system (MW)		1414.97	1642.70	1844.88	1942.93	2020.28	2238.45	2373.73	2473.16	2592.55
Total benefit from adding PV (USD millions)		3.7	3	2.6	2.6	2.7	8.9	11.22	7.3	8.5

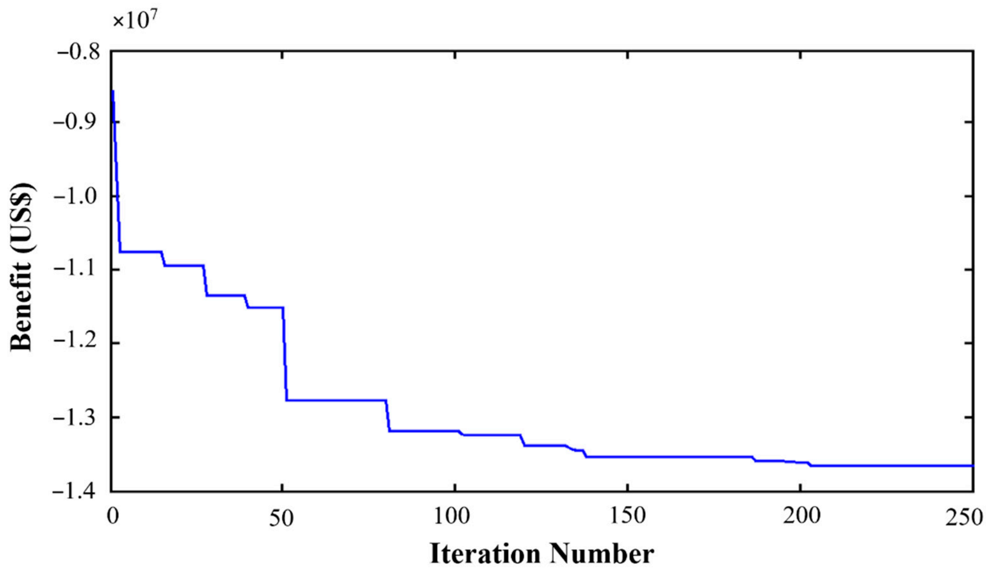

Figure 11. PSO process for the TNEP of the EDL grid in 2028 using 10 Particles and 250 Iterations.

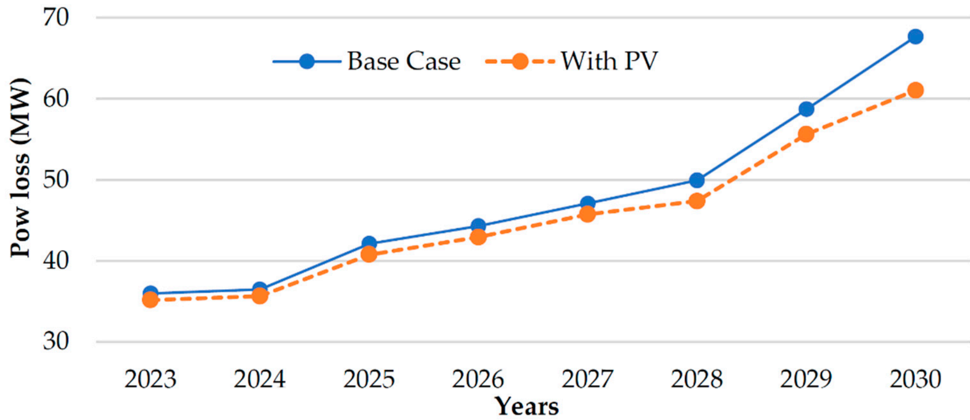

Figure 12. Comparison of the power loss in the base case and with PV for the EDL network.

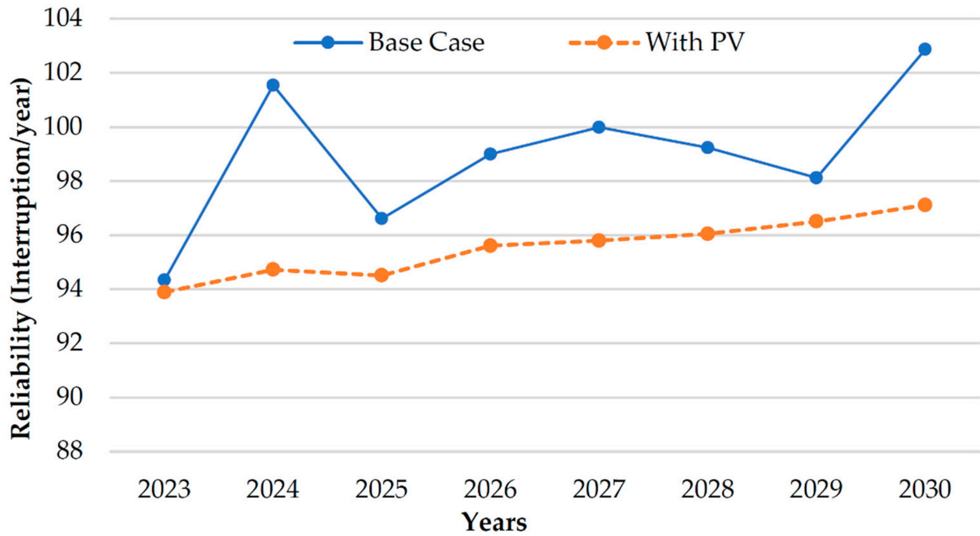

Figure 13. Reliability of the base case and with PV for the EDL network.

6. Conclusions

The high penetration of uncontrollable power sources makes power expansion planning more complicated. In this study, we used PSO to select the best location and size for solar PV based on the system reliability and power loss of the whole system. This paper presented a new way to solve the TNEP problem with high penetration, in which PSO was employed to select the best location and size for the PV. This was then connected to the yearly network planning. The system's reliability and total power loss were the main criteria used for considering the PV and solving the TNEP problem. The generation and uncertainty of power sources, such as thermal, hydropower, and solar energy, were set in the account. The conditions of the demand were considered based on the seasons of the year. A large network, the IEEE 118 bus test system, and EDL's network were applied to test the method. The new lines and equipment cost that will be extended were investigated. The benefit of solar energy was compared before and after connecting the network. The new approach of this work is represented by the condition of load and uncertainty power sources and the power loss and reliability conditions, including huge grid data that are connected to neighbor grids being applied by combining the metaheuristic technique with the systematic TNEP.

The results demonstrate that the high penetration of solar energy makes the system more complicated in terms of its operation and energy production. However, the location and size of solar energy are the most important factors when solving the TNEP problem by PSO. The investment cost and power loss of the whole system decrease with the best location and size for the PV connected to the grid. However, the system's reliability in terms of both the IEEE 118 bus and the EDL network do not differ significantly when the system is connected with and without PV. It is noted that the approach presented in this research can be used to solve the TNEP problem as PSO selects the best capacity and size for the PV that will be connected to the network, and this produces improvements in terms of power loss and reliability.

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Nomenclature

A	Total photovoltaic cells area (m^2)
B_{PVtot}	Total benefit from PV connected to the grid (USD)
$B_{\Delta Ploss}$	Benefit in terms of power loss, before and after the PV is connected (USD)
$B_{P.sale}$	Benefit in relation to selling power produced from the PV connection (USD)
$B_{P.Rel}$	Benefit obtained from the system reliability improvement due to the PV connection (USD)
B_{Rel}	Reliability benefit (USD)
$B_{rel.old}$	Total reliability benefit before PV generators are connected (USD)
$B_{rel.new}$	Total reliability benefit after PV generators are connected (USD)
C_{invt}	Investment cost of new lines (USD)
$C_{ep.p}$	Cost of new lines and equipment to be extended (USD)
C_1, C_2	Weighting coefficients
$gbest_i$	Global best of the population
H	Head of dam (m)
H_{PV}	Annual average solar radiation on tilted panels (W/m^2)
L_n	Load of n year (MW)
L_1	Load of first year (MW)
Min C_{invt}	Minimum of the investment cost of new lines (USD)
Max B_{PVtot}	Maximum of the PV connected to the grid (USD)
N	Number of PV generators
n	Number of year planning
n_p	Number of lines that will be extended
P_R	Performance ratio, coefficient for losses
P_{PV}	Photovoltaic power (W)
P	Hydroelectric power (W)
$P_{\Delta Ploss}$	Power loss difference in the system before and after PV generators are connected (MW)
P_{loss_old}	Power loss before the PV generators are connected (MW)
P_{loss_new}	Power loss after the PV generators are connected (MW)

$pbest_i$	Personal best of the ith particle
PV_p	PV generators (USD)
PF	Power factor (4.2 h per day)
P_{pen}	PV generators are not allowed to inject more than 70 MW of power to the grid for exportation to neighboring counties (MW)
P_{exNet}	Power exported after PV is connected to the grid (MW)
$P_{exNetold}$	Power exported before PV is connected to the grid (MW)
Q	Water discharge flow rate (m^3/s)
r	Yield of the photovoltaic cells, given by the ratio of energy (kWh) from one photovoltaic cell to the area of one panel
W	Inertia coefficient
η	The efficiency of plants
ω_i^{k+1}	The ith particle velocity at iteration $k + 1$
ω_i^k	The ith particle velocity at iteration k
θ_i^{k+1}	The ith particle position at iteration $k + 1$
θ_i^k	The ith particle position at iteration k

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