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# Decentralized Battery Energy Storage Integration into an Optimal Grid-Connected PV System with Zero Power Injection Considerations

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**Abstract:** *Distributed photovoltaic (PV) and battery energy storage (BES) generating systems are interesting to power utilities owing to their benefits in terms of technology, business, and the environment. However, improper distributed generation (DG) sizes and locations might have an impact on the technological distribution network. The aim of this study is to improve the production of grid-connected PV on the electrical three-phase poles of a low-voltage distribution system for a period of 25 years. This improvement will be explored both without and with the inclusion of decentralized BES (DeBES). The purpose of this comparison is to assess the absence of power injection into the LV and MV grids by PV over a 25-year period of planning studies. This assessment will focus on evaluating energy loss and voltage profiles, utilizing DeBES in the radial unbalanced LVAC distribution system. The first step involves identifying the radial topology and phase connections within the target area. This includes assessing the performance using an unbalanced load flow analysis, which is based on the forward-backward sweep technique. Next, the water cycle algorithm (WCA) is implemented to determine the optimal locations and sizes of PV generation at the electrical poles of the system. Next, the DeBES is used to store the residual energy from the PV integration to supply power back into the grid when PV production is not available. A study site was located in a rural village area in Cambodia. Finally, the simulation results of system performances with the proposed method are discussed and analyzed in the planning procedure. The implementation demonstrated that the installed DeBES system with distributed PV can be further enhanced in both scenarios. This can be achieved by attaining zero integration into the LV and MV grids, achieving the highest reduction in energy loss, and maintaining voltage within the operational topology limit. However, a techno-economic analysis was conducted to calculate the total expenditure (TOTEX) in the case with PV. This analysis aimed to determine the optimal approach, considering environmental factors.*

**Keywords:** Low-Voltage Alternative Current Distribution System, Water Cycle Algorithm, Capital Expenditure, Operating Expenditure, and Net Present Cost.

## 1. INTRODUCTION

Population growth and the difficult economic environment in developing countries are the two main causes of the yearly increase in energy consumption, particularly in rural areas [1]. PVs are a significant component of the electrical sector and a growing low-carbon technology. Proper PV penetration levels have significant technological integration for grid operation in terms of energy loss, voltage deviation, and feeder usage capacity, especially in low voltage (LV) networks [2]. It would be interesting to compare the traditional networks with the renewable energy sources integration-based modern distribution networks throughout the development process to minimize the expense of electricity [3]. Providing two zero injections into the LV and MV grid conditional scenarios to avoid the impact of power flowing back to the MV/LV transformer in the radial unbalanced LVAC distribution grid is considered for renewable energy sources utilization.

In the literature review, the authors have proposed the methods to improve the system quality and economics in the used areas. The shortest path algorithm (SPA) is simulated to reduce the length of the conductor [3,4,5,6]. The repeated-phase sequence (RPABC) is implemented to allocate the phases on the electrical poles for pole balancing [5]. The first fit bin packing

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(FFBP) is included to enhance load balancing in the radial system [5]. However, the authors have done the mixed-integer quadratic programming (MIQP) algorithm to obtain the minimization of the conductor line and phase balancing improvements [1,5]. Also, to balance the three-phase system, the Mixed Integer Linear Programming (MILP) algorithm has been assessed [3].

An IEEE 13-node unbalanced distribution feeder is used for a number of factors, such as static voltage stability, power loss, short-circuit, and voltage imbalance research [7]. The DIgSILENT PowerFactory simulation software is employed in this case. In this study, solar photovoltaic (PV) units and synchronous generators are introduced as distributed generators (DGs). A DG unit raises the short-circuit current at all feeder nodes, improving the voltage stability and power loss of the system [7,8]. A major disruption for energy utilities is the integrated distributed generation (DG) units. Reverse power flows due to low consumption during peak DG generation might affect network stability, increase voltages, and result in overloading [2]. Distribution energy storage systems (DESSs) may be set up appropriately to efficiently support the active distribution network's need for voltage control. The effect of energy storage operation characteristics on the system voltage, although the distribution network is mostly three-phase unbalanced. Therefore, the distribution performance as evaluated in technical injections may be improved by using the optimum DESSs [9]. A single-phase inverter is the source of the unbalanced voltage [10]. To prevent unequal reactive power absorption, the three-phase inverter needs to inject power into the LV distribution system. The reference point for the balancing algorithm is a point that is connected to the PV inverter [10]. By injecting reactive power when the voltage drops and absorbing reactive power when the voltage level exceeds the rated value, the voltage level is kept within the allowable values [10].

Important optimization issues, such as addressing the rising demand for electricity, involve determining the size and location of distributed generation. These issues can be tackled using methods like the genetic algorithm (GA), particle swarm optimization (PSO), and water cycle algorithm (WCA) [11]. To reduce the effects of under-voltage and current limitations caused by load consumption, a genetic algorithm (GA) has been used to find the appropriate location, PV size, and decentralized battery [3,4,6,12]. Considering various static load models, including constant power, constant current, constant impedance, residential, commercial, industrial, and mixed load models, particle swarm optimization (PSO) has been used for the best placement and sizing of distributed generation to minimize power loss in distribution networks [11,13,14]. PSO technique integrates power loss reduction and regulating voltage magnitudes in a manner similar to the GA. PSO has been shown to be more accurate and converge faster than the GA method [15]. The water cycle algorithm (WCA) technique is commonly used because, in comparison to other optimized algorithms (GA and PSO), it can more quickly optimize DG size, locations with more accuracy [16]. The multi-objective water cycle algorithm (MOWCA) decides where and how many distributed energy resources (DERs) to use after considering many load models. It is investigated that renewable energy sources (RES), such as solar and wind power, may affect load model uncertainty. Increased technical, financial, and environmental benefits while fewer objective functions, such as total emissions, DG cost, dissipated power, and voltage fluctuation, are the study's main objectives [17]. Using those methods, the authors have tried to overcome the issue of operating an appropriate distribution system with lower capital and operating expenditure investments.

Moreover, an optimal design of a low-voltage distribution network would have a photovoltaic solar and battery connection. The centralized BES (CeBES) sizing approach is designed to avoid reverse power flows into the medium-voltage (MV) grid [6]. The research is intended to supply the PV size and BES in the LV distribution network to the customers by simulating GA. The results of this work demonstrate the validity of a novel algorithm for the optimal grid sizing and appropriate sizing of PV and BES capacity [12]. In this comparative planning, the authors have aimed to compare the LVAC microgrid topology with deployed and undeployed PV and battery storage in a case study area. This work is integrated into a GA implementation to determine the PV penetrations and their locations to have a minimum cost of investment in the planning procedure and prove better performance for the system [3]. The lowest-cost solution is provided by distributed generators (DGs). This benefit requires the investigation of optimum efficiency and reliability by placing the DG penetration in the system with time-varying loads [18]. The PV hosting capacity is prepared for the strategy to inject in the IEEE 123-node system nodes to support the reactive power from PV generation and the control of load tap changers (LTCs). MATLAB software is chosen for PV injection nodes. This case study is arranged in multi-scenarios with one, two, five, and ten PV injection nodes and investigates maximum voltage deviations when increasing PV penetration 1. The methods are selected to design the PV sizing and BES capacity for the techno-economic consideration [17].

The goal of this study is to identify new innovation strategies for analyzing technical PV penetration and battery energy storage integrations over the next 25 years. The radial design of the distribution network is completed with load balancing. The WCA is used to define the locations and size of decentralized PV (DePV) with decentralized BES (DeBES) on three-phase electrical poles. Based on this, this paper is interested in studying two scenarios for zero integration into the LV and MV grids. In each scenario, there are two comparison cases: case 1 (with PV), and case 2 (with PV and BES). Provide two objectives to investigate the impact of DG injection and analyze the techno-economics to find which cases should be interesting, such as topology improvement and the highest profit income to be invested in the planning, which was not done by previous authors in this research.

The following is explained: Section 2 presents a proposed method. Section 3 discusses the case study and simulation results. The final Section 4 provides a conclusion.

## 2. METHODOLOGY

### *2.1 Research work*

The algorithms randomly determined all those PV locations and sizes in the three-phase LVAC system pole. The flowchart of the algorithms was used to analyze the technical impact of PV injection and then combined with BES to study the techno-economics to investigate which cases should be invested to have profitability. There were two scenarios: zero injection into the LV and MV grids. Each scenario was separated into two comparative cases: case 1 (with PV), and case 2 (with PV and BES). Fig. 1 provided a step-by-step explanation of this overall flowchart for studying the works as previously described;

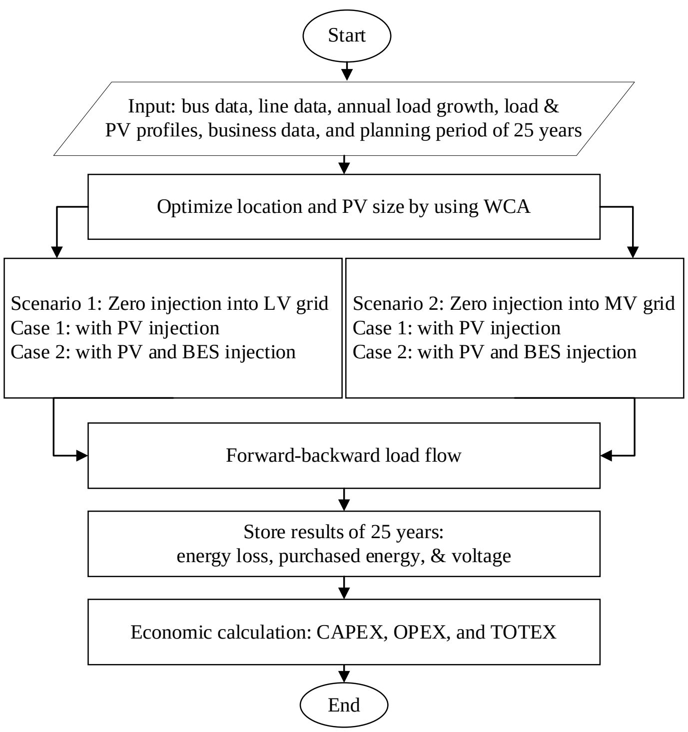


Fig. 1. The overall flowchart of the proposed method

- Step 1: Input bus data, line data, annual load growth, load and PV profiles, business data, and a planning period of 25 years that has 3% for load growth and study 24 hours per day per year until 25 years.
- Step 2: The WCA algorithm is used to optimize pole locations and their PV power sizes based on an objective function of energy loss minimization and a constraint of voltages so that the total size of the PV is less than 50% of the transformer size (i.e., the existing PV hosting regulation in Cambodia).
- Step 3: Focus on two scenarios: zero injection into the LV grid and zero injection into the MV grid. Each scenario provides two case studies: case 1 (with PV) and case 2 (with PV and BES).
- Step 4: Zero injection into the LV grid means that DG (PV or BES) power can only inject power to the buses on their PV pole each hour without any power to another pole, as studied in PV and PV with BES.
- Step 5: Zero injection into the MV grid means that the total DG (PV or BES) power can inject power to meet the total load demand in the LV grid system without any power flowing back to the MV/LV transformer at each hour.
- Step 6: The load flow is implemented to store results for all the case studies (such as power loss, voltage, etc.) at each hour to explore energy loss and voltages over 25 years.
- Step 7: Calculate the economics for the capital expenditure (CAPEX), operating expenditure (OPEX), and total expenditure (TOTEX) over the planning period of 25 years.

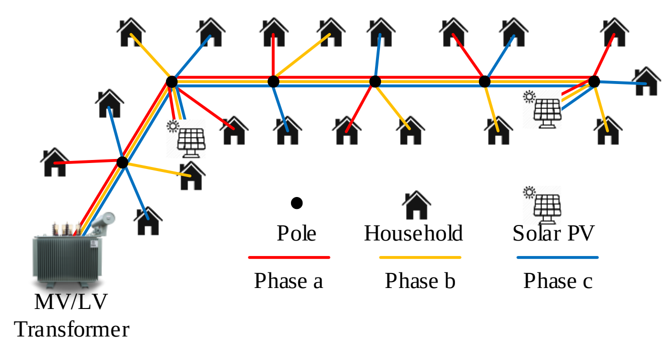


Fig. 2. Radial topology in case 1 with PV integration

Fig. 2 shows the radial topology in case 1 by integrating PV generation with the LV grid. The solar photovoltaic is connected in three-phase form to the electrical poles. The PV power is generated at the network poles to support only households without any reversed power flowing back to the transformer.

Fig. 3 demonstrates PV and battery storage generation with the LV grid to represent the radial topology in case 2 with PV and BES. On the electrical poles, the BES and solar PV systems are linked in a three-phase system. When power is produced by PV and exceeds the load requirement, residual PV power is present. The power loss of household lines connected to their PV pole is subtracted by the residual PV power to charge battery storage and discharged to the LV grid when the PV is not available and loads are being consumed. There is no power returning to the transformer because the DG power is generated at the network poles only for households.

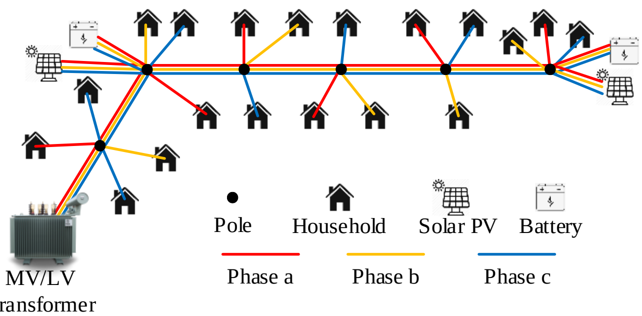


Fig. 3. Radial topology in case 2 (with PV and BES).

*2.2 Objective function and constraints*

In this work, the objective function focused on the minimum energy loss and subjected to the voltage constraints in the above-mentioned case studies [3];

- Objective function: $\min\left(\sum_{t=1}^{24} Ploss(t)\right)$ (Eq. 1)

- Constraints:

$$0.9 \le Voltage \le 1.1 \quad \text{(Eq. 2)}$$

$$Total\ PV\ size \le 50\%\ of\ transformer\ size \quad \text{(Eq. 3)}$$

*2.3 Design of equipment capacity*

❖ Solar photovoltaic design formulation

Solar panel size and solar irradiation both affect how much power the solar system would generate and the temperature of the selected location [17].

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right)[1+\alpha P(T_c - T_{c,STC})] \quad \text{( Eq. 4)}$$

$P_{PV}$ is the PV output power from the array [kW]. $Y_{PV}$ is the rated PV array capacity [kW]. $f_{PV}$ is the derating factor [%]. $\alpha P$ is the temperature coefficient of power [%]. $G_T$ is the actual solar inradiance [kW/m$^2$]. $G_{T,STC}$ is the standard test condition for solar inradiance [kW/m$^2$]. $T_c$ is the actual cell temperature [℃], and $T_{c,STC}$ is the standard test condition of cell temperature [℃].

❖ Battery capacity design method

The peak power needed by the system during a specific time period, the depth of discharge (DOD), and the roundtrip efficiency were taken into account while calculating the battery energy storage capacity of the system [17]. This was achieved by using the below equation;

$$BES\ capacity = \frac{Power\ requird \times Period\ requird}{DOD \times BES\ efficiency} \quad \text{( Eq. 5)}$$

Where $BES\ capacity$ is the battery energy storage capacity [kWh], $Power\ requird$ is the peak power demand for load consumptions [kW], $Period\ requird$ is the time requirement to be used [hour], $DOD$ is the battery's depth of discharge [%], $BES\ efficiency$ is the battery's efficiency [%].

*2.4 Economic computation*

❖ *CAPEX, OPEX, and TOTEX formulations*

In this approach, the economic analysis was necessary to provide a discount cost that takes into account both capital expenditures (CAPEX) and operating expenditures (OPEX). The CAPEX consisted of the costs of PV panels, PV inverters (charge controllers built-in), batteries, and cables. If a piece of equipment reached the end of its lifetime, the replacement cost was also included (i.e., the replacement cost of the inverter and battery) [3]. The OPEX included the sold energy and the purchased energy costs from the grid, as well as the operational and maintenance costs. The total expenditure (TOTEX) was calculated by including the OPEX with the CAPEX [3,20].

$$CAPEX = C_{PV} + C_{Inv} + C_{BES} + C_{Cable} + C_{Replacement} \quad \text{( Eq. 6)}$$

$$OPEX = \sum_{i=1}^{Y} \frac{C_{En\_purchased}(i) - C_{En\_sold}(i) + C_{O\&M}(i)}{(1+r)^i} \quad \text{( Eq. 7)}$$

$$TOTEX = OPEX + CAPEX \quad \text{(Eq. 8)}$$

$C_{PV}$, $C_{Inv}$, $C_{BES}$, and $C_{Replacment}$ are the PV, inverter, battery, and replacement costs in k\$. $C_{Cable}$ is the cable cost that is calculated for the inverter connected each PV pole [k\$]. $C_{En\_sold}$ is the cost of selling energy to customers [k\$]. $C_{En\_purchased}$ is the purchasing energy from the grid [k\$]. $C_{O\&M}$ is the operation and maintenance cost for the PV, inverter, and battery [k\$]. $Y$ is the planning year. $r$ is the real discount rate [%]. $i$ is the index of the year. Calculating all case studies' cash flow during the planning of the study required TOTEX to be considered in the two scenarios. In addition, even in cases 1 with PV and 2 with PV and BES, the TOTEX is required to be used to compute all case studies and compare them to find which case has the lowest total expenditure.

❖ *Real discount rate*

The real discount rate was a percentage that illustrated the present value of future cash flows after taking inflation into account, taken from Hybrid Optimization of Multiple Energy Resources (HOMER) software [20]. The real discount rate equation was given following;

$$r = \frac{r' - f}{1 + f} \qquad \text{( Eq. 9)}$$

Where $f$ is the expected inflation rate [%] and $r'$ is supposed to be the nominal discount rate [%].

*2.5 Studied load and PV profile curves*

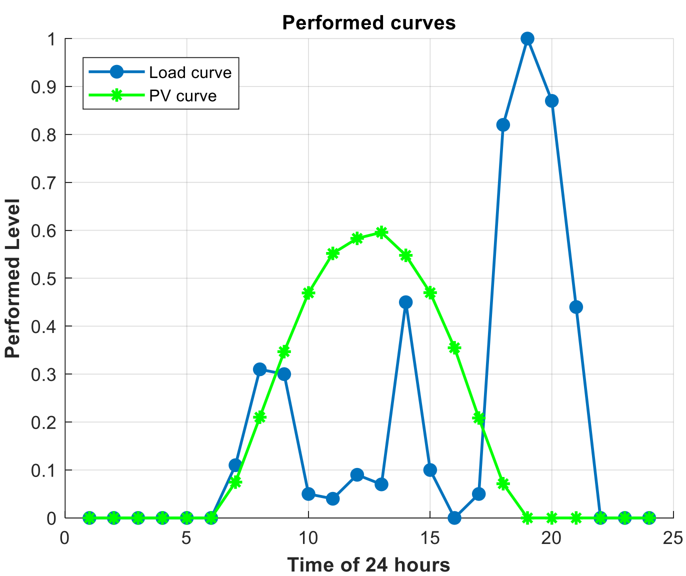


Fig. 4. Load, and PV curves [3].

In Fig. 4, load and PV profiles were plotted as two curves. The PV curve was simulated using the HOMER Pro software and studied in the testing system to provide the daily energy used by households (buses) and the PV power generation over 24 hours per day for the year. The peak PV curve is not set to 1 because it was examined by NASA in order to simulate the solar irradiance data of the target area. This simulation was carried out for each day over a period of 365 days per year, aiming to create a single average curve that remains constant throughout the 24 hours of the day in HOMER Pro. As a result, the PV curve cannot have a value of 1 pu due to the presence of different solar irradiations across the 24-hour period. Moreover, the load was also utilized as a constant curve over 24 hours per day for the year [3].

## 3. RESULTS AND DISCUSSION

In this paper, it is needed to specify the different costs of the equipment and the energy that is sold and purchased. All expenditures, including CAPEX, OPEX, and TOTEX, are calculated with those expenses included.

Table 1. Input data for business calculation [3,21].

| Item | Value |
|---|---|
| Project time period [Year] | 25 |
| Discount rate [%] | 8.7 |
| Load growth [%/year] | 3 |
| PV price [k$/kW] | 0.3069 |
| Hybrid inverter [k$/kW] | 0.456 |
| Bi-directional inverter [k$/kW] | 1.155 |
| Lead-Acid Battery [k$/kWh] | 0.105 |
| Mounting structure [k$/kW] | 0.300 |
| AC cable 4mm$^2$×3 [k$/m] | 0.0006 |
| PV+BES+inverter maintenance [k$/kW] | 0.0115 |
| PV installation service [k$/panel] | 0.0127 |
| Inverter installation service [k$/kW] | 0.0072 |
| Battery installation cost [k$/kWh] | 0.0009671 |
| PV lifetime [Year] | 25 |
| Inverter lifetime [Year] | 15 |
| Inverter efficiency [%] | 95 |
| Bi-directional inverter [Year] | 15 |
| Battery lifetime [Year] | 5 |
| Battery efficiency [%] | 70 |
| Battery's depth of discharge [%] | 70 |

Table 1 gives the item data required to operate those expenditures to study the economic investigation to define the expenditure and income by reference in [3,21].

Table 2. Electricity costs for customers per month

| Energy consumption [kWh/month] | [$/kWh] |
|---|---|
| $0 \leq$ Consumed energy $\leq$ 10 kWh | 0.0927 |
| $11 \leq$ Consumed energy $\leq$ 50 kWh | 0.1171 |
| $51 \leq$ Consumed energy $\leq$ 200 kWh | 0.1488 |
| $201 \leq$ Consumed energy $\leq$ 2000 kWh | 0.178 |

Table 2 expresses the different kinds of energy consumed by the rural customer's household per month based on the electricity authority of Cambodia's providing for tariff costs via the types of electric consumption [20]. Additionally, the exchange has 1 dollar, which is equal to 4100 rials.

Table 3. Type of electricity tariff purchased from the LV grid.

| Description | Value |
|---|---|
| General tariff [$/kWh] | 0.121 |
| PV customer tariff [$/kWh] | 0.118 |
| PV capacity charged tariff [$/kW/month] | 3.1 |

Table 3 illustrates the different kinds of electricity tariffs purchased from the LV grid based on the electricity authority of Cambodia for general and PV distribution system operators (DSO) with the capacity-charged tariff [20].

*3.1 Case study area*

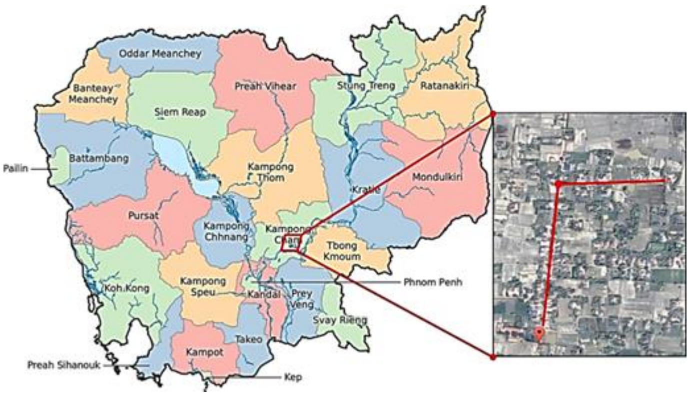


Fig. 5. Batheay testing system area in Cambodia.

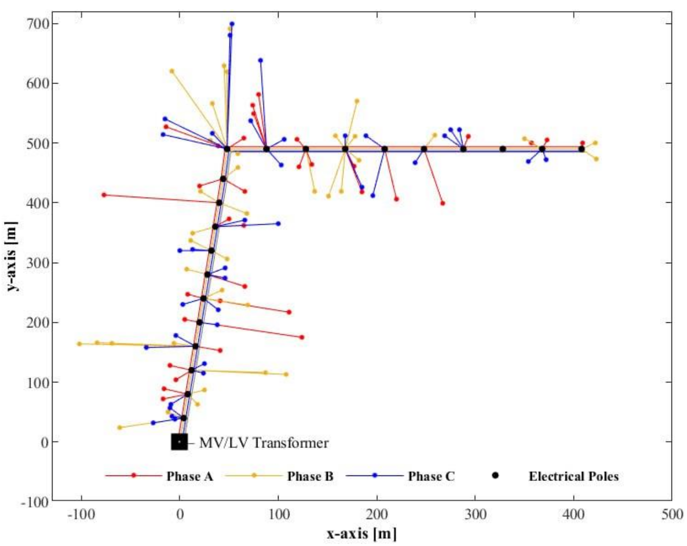


Fig. 6. Radial topology in Batheay district area

Fig. 5 expresses the study case as a rural community in Cambodia's Sandek commune, Bantheay district, and Kampong Cham province, at 12°08' 36.8" N and 104°57' 30.7" E. There are 107 houses, 22 electrical poles, a total power of 43 kW for the 1st year and 90.033 kW for the 25th year with 0.95 PF, and the MV/LV transformer is 160 kVA [22]. The mainline and secondary lines use conductor diameters of 70 mm2 and 4 mm2, respectively. Those kinds of conductors are fixed due to their tested impedance between the 1st year and the 25th year that be used and illustrate voltages in the operational limitations of the distribution network.

Fig. 6 depicts the final architecture with the distributed PV [3]. The radial topology grid in the load-balancing form that connected the MV/LV transformer, dividing into different three phases, such as phases A, B, and C of loads on the electrical poles, was built in a simulation to be Fig. 6.

*3.2 Scenario 1: Zero injection into the LV grid*

Table 4. Results in zero injection into the LV grid.

| Items | Case 1 | Case 2 |
|---|---|---|
| Peak demand for 25th year [kW] | 90.033 | 90.033 |
| Number of PV sites on poles | 12 | 12 |
| Total PV capacity [kWp] | 27.127 | 27.127 |
| BES size in years 1-5 [kWh] | - | 195.327 |
| BES size in years 6-10 [kWh] | - | 183.578 |
| BES size in years 11-15 [kWh] | - | 172.250 |
| BES size in years 16-20 [kWh] | - | 162.244 |
| BES size in years 21-25 [kWh] | - | 153.376 |
| Vmax [pu] | 1.03125 | 1.03592 |
| Vmin [pu] | 0.903618 | 0.93173 |
| Total sold energy over 25-year [MWh] | 2772.054 | 2772.054 |
| Total energy loss over 25-year [MWh] | 124.6048 | 63.68936 |
| Total purchased energy over 25-year [MWh] | 2619.811 | 1801.248 |
| CAPEX [k$] | 33.7051 | 108.652 |
| OPEX [k$] | -21.9076 | -60.2027 |
| TOTEX [k$] | 11.7975 | 48.4493 |

Table 4 describes the different kinds of capacity equipment installations using the conditions to calculate the economics in scenario 1. However, the BES capacity was changed every five years because it was charged from PV, which would annually decrease energy output through PV degradation. By observing the technical results obtained by providing acceptable voltages for all cases and the lowest energy loss in case 2 with PV and BES, However, focusing on economic calculations, case 1 with PV is better than case 2 with PV and BES in scenario 1 due to it giving the lowest expenditure by comparing the values of the TOTEX among case studies. Thus, zero injection into the LV grid was found in case 1 as the greatest topology for the research planning period.

In scenario 1's case 1 with PV was determined to be the best case when compared to case 2 with PV and BES, based on two comparative cases. The cash flow was presented by illustrating CAPEX, OPEX, and TOTEX values from the 1st year to the 25th year. The positive columns represented expenses in the corresponding year index, while the negative columns indicated the profitability in the respective year index as given in Fig. 7. Additionally, the CAPEX was present in the 15th year because it was the replacement cost for the inverter that reached the end of its lifetime.

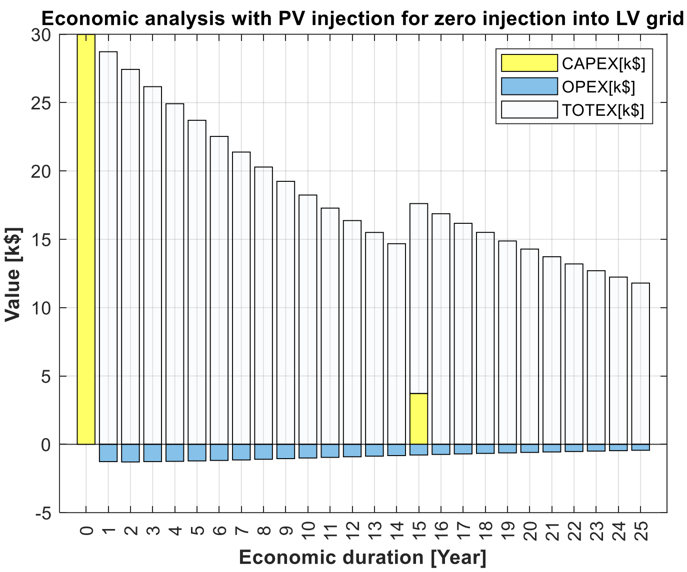


Fig. 7. Cash flow of scenario 1's case 1 with PV

*3.3 Scenario 2: Zero injection into the MV grid*

Positive and negative values mean expense and profitability, respectively, to be clarified in the two tables for zero integrations below;

Table 5. Results in zero injection into the MV grid.

| Items | Case 1 | Case 2 |
|---|---|---|
| Demand for 25th year [kW] | 90.033 | 90.033 |
| Number of PV sites on poles | 12.000 | 12.000 |
| Total PV capacity [kWp] | 27.127 | 27.127 |
| BES size in years 1-5 [kWh] | - | 145.7808 |
| BES size in years 6-10 [kWh] | - | 136.302 |
| BES size in years 11-15 [kWh] | - | 126.5053 |
| BES size in years 16-20 [kWh] | - | 116.1748 |
| BES size in years 21-25 [kWh] | - | 105.5294 |
| Vmax [pu] | 1.0312 | 1.0312 |
| Vmin [pu] | 0.9036 | 0.9317 |
| Total sold energy over 25-year [MWh] | 2772.054 | 2772.054 |
| Total energy loss over 25-year [MWh] | 123.1163 | 73.00019 |
| Total purchased energy over 25-year [MWh] | 2370.605 | 1774.753 |
| CAPEX [k$] | 33.7051 | 95.3219 |
| OPEX [k$] | -33.3911 | -61.5720 |
| TOTEX [k$] | 0.3140 | 33.7499 |

The different capacity equipment installations were shown in Table 5 using the same components that were utilized to calculate the economics in scenario 2. With operational constraints, the realistic voltages were approved, with scenario 2's case 2 (with PV and BES) still resulting in the lowest energy loss. But the TOTEX was the smallest expenditure value in case 1 (with PV) by analyzing two cases in the same scenario. As a result, during the research planning phase, it was demonstrated that in case 1, zero injection into the MV grid was the best topology.

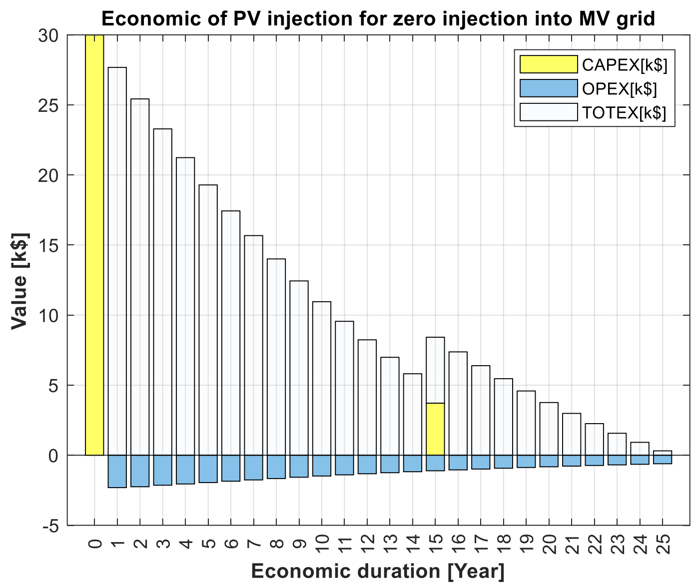


Fig. 8. Cash flow of scenario 2's case 1 with PV

In scenario 2, when comparing case 1 with PV and case 2 with PV and BES, the optimal case was chosen based on the cash flow of the lowest TOTEX expense at the 25th year (Fig. 8).

*3.4 Discussion*

According on what Table 4 and Table 5 demonstrated, the distribution system's voltages had the same reliability in the two comparative scenarios discussed above. In case 1 (with PV), there is a possibility that scenario 2 can consume more power than scenario 1 for PV generation. This is because the conditions of scenario 2 allow the total PV power to meet the total load demand that caused Scenario 2 would compute lower energy loss and energy purchased than scenario 1 in case 2 (with PV). Table 4 stated that the battery capacity of scenario 1 was greater than scenario 2 in Table 5 to discharge into the LV grid for supporting loads and that the size of BES was changed every five years due to annual PV degradation. Due to the different BES capacity integration between the two scenarios, scenario 1 showed less energy loss than scenario 2 in case 2 (with PV and BES). However, in case 2, scenario 2 still purchased less energy than scenario 1 because scenario 2's PV power generation was larger than scenario 1 for the LV grid integration to support load demand.

Based on the techno-economic analysis and the TOTEX computations, two comparative case studies were determined to specify that case 1 (with PV) was the best option in each scenario. In the two comparative scenarios, scenario 2’s case 1 (with PV) was found to be the greatest case over 25 years.

## 4. CONCLUSIONS

In the planning of radial unbalanced LVAC topologies in a rural region, all scenarios were discussed in cases 1 and 2 to find which case was interested in investing among the two scenarios. With the proposed methods, a testing system was simulated with an objective function to decrease energy loss and the constraints of voltage operating limits. Load balancing was well applied to do the simulation to improve the unbalanced network. The electrical poles and their PV power size were determined using the water cycle algorithm (WCA), with a total PV size not exceeding 50% of the MV/LV power transformer. Depending on the results, case 1 (with PV) was approved with voltage performances, and the total expenditure (TOTEX) was given the lowest expense by taking into account computations for capital expense (CAPEX) and operating expenditure (OPEX) in scenario 2 of zero integration into the MV grid. Therefore, the planning research was chosen for scenario 2's case 1 (with PV) for investing for over 25 years. Centralized solar PV (CePV) and centralized BES (CeBES) will be employed in another distribution system in future work.

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