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Low-Voltage Microgrid Planning Strategies for an Isolated Village – A Case Study in Cambodia

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Abstract— The purpose of this paper is to propose three different solutions to handle the issue of excess electricity to the MV grid from LV microgrid with PV. These scenarios are compared based on their TOTEX (total costs) calculated for 30 years. Firstly, the Mixed Integer Linear Programming (MILP) approach is used to allocate power to each household load across all three phases (phase A, B, C) of the system. Secondly, the network is built using the Shortest Path (SP) algorithm to establish radial topology by defining all line connections. Thirdly, a Genetic Algorithm (GA) is used to determine the size and location of the photovoltaic (PV) and decentralized battery energy storage (DeBES). After having simulated the LV microgrid for 30 years, the power at the slack bus is analyzed to identify the occurrence of excess electricity when the PV-generated power exceeds the load consumptions. To handle this issue, three different scenarios are proposed: selling the reversed energy back to the MV grid, MV grid with centralized battery energy storage (CeBES), and LV generator with CeBES. For the case study, a non-electrified Cambodian village with 73 households is selected. Based on the simulation results, in terms of the smallest TOTEX, scenario 3 (LV generator with CeBES) is the most interesting solution compared to the other two scenarios.

Keywords— *low-voltage microgrid, MILP, shortest path, Genetic Algorithm, PV and decentralized battery, centralized battery*

ABBREVIATIONS AND NOMENCLATURE

CAPEX	: Capital Expenditure [k\$]
CeBES	: Centralized Battery Energy System [kWh]
DeBES	: Decentralized Battery Energy System [kWh]
GA	: Genetic Algorithm
LV	: Low Voltage
LCOE	: Levelized Cost of Energy [\$/kWh]
MILP	: Mixed-Integer Linear Programming
MST	: Minimum Spanning Tree
MV	: Medium Voltage
Main.	: Maintenance Cost [k\$]
OPEX	: Operational Expenditure [k\$]
PV	: Photovoltage
SHS	: Solar Home System
SP	: Shortest Path
TOTEX	: Total Expenditure [k\$]
T	: Planning Period [year]
t	: Index Hour
CO ₂	: Emissions [kg/year]
$C'_{s/kWh}$: Cost of purchasing energy from the grid [\$/kWh]
r	: Discount rate [%]

$C'_{s/kWh}$: Cost of selling energy to households [\$/kWh]

i : Index Year

I. INTRODUCTION

Low voltage microgrids are gaining popularity due to their ability to provide a reliable power supply and improve the overall efficiency in both urban and rural areas [1]. A low voltage microgrid is a small-scale local power distribution system that can be either operated in isolated mode or operated in parallel with the active main grid [2]. Despite the potential benefits of low voltage microgrids, there remain several challenges that need to be addressed, such as power quality issues (including voltage fluctuations and harmonics), control and management difficulties, scalability limitations, structures and economic feasibility. Therefore, this research focuses on building a radial LV microgrid topology which integrates PV and batteries and proposes several solutions to handle the issue of excess electricity to the MV grid. In this section, several relevant research papers have been reviewed as follows.

In references [3] [4] [5], the authors have combined the MILP algorithm and Simulated Annealing to balance power into three-phase system. These approaches have improved the voltage drops and power losses in the distribution networks. Next, the planning of LV distribution grids using Minimum Spanning Tree (MST) and graph theory to optimize radial topology and minimize the length of conductors is presented in [6] and [7], respectively. In [8], The authors have addressed microgrid planning for 30 years by comparing its structure with and without PV and batteries, in order to minimize investment costs. The SP algorithm is implemented first to build a radial topology and then the MILP approach is used to balance the powers at each electrical pole into three-phase system. Next, the GA algorithm is used to define the sizes and locations of the PV module and DeBES. Based on the results, this network with PV and storage has lower investment costs. In [9], this paper proposed a method to find the optimal electrification scheme, i.e., full AC or hybrid AC/DC distribution integrated with PV and batteries. A case study was implemented to analyze the technical, economic, and environmental key performance indicators. To handle the excess energy issue, the authors have proposed decentralized battery energy system (DeBES) is clusters to charge the energy. The results demonstrate that the overall cost of a full AC microgrid is less than the hybrid AC/DC system. The reference paper [10] dealt with determining the size of PV-storage injections into the MV grid. The authors applied the

GA algorithm to define the maximum PV penetration and minimum decentralized battery capacity. Another research in reference [11], the authors designed a network using MST algorithm and integrated it with PV storages. A Centralized Battery Energy System (CeBES) is installed to charge the excess energy from the PV and provide it back when the LV grid requires energy. A cost comparison of on-grid and off-grid modes is provided, showing that the on-grid mode has a lower cost compared to the off-grid mode. However, when the LV microgrid is isolated or located far from the MV grid, building an MV grid for the on-grid mode are costly. Therefore, this research includes a case study that reveals the planning and cost analysis required for providing energy to an isolated area.

The primary goal of this paper is to present a methodology for LV microgrid planning for an isolated village, which involves topology building (based on MILP and SP algorithm) and defining the sizes and locations (defined by GA) of SHSs. Next, three different scenarios (on-grid and off-grid mode) are proposed to address the problem of excess energy from the LV network being fed back into the MV grid at the slack bus. The investment costs of the three scenarios are compared and evaluated for 30 years. The scenario with the lowest TOTEX would be selected for this study. The cost analysis of these three scenarios would be beneficial for distributors during the planning phase.

This paper is organized into several sections. Section II discusses the methodology and formulations used in the research. Section III provides the data from a case study for simulation. Section IV demonstrates the simulation results and corresponding discussion. Finally, section V draws conclusions.

II. METHODOLOGY

To achieve the research objectives, a methodology is proposed and presented in Fig. 1. The flowchart illustrates the following steps:

- **Step 1:** Input data for the simulation model, as detailed in the case study section.
- **Step 2:** To balance the powers of each load (household) into the three-phase (phase A, B, C) system using the MILP algorithm.
- **Step 3:** Define all connections from each load to the nearest electrical pole, using the SP algorithm, to build a radial topology.
Note: Steps 2 and 3 of the proposed methodology are detailed in reference [6], which describes the objective function and constraint equations used in the MILP algorithm. This reference also illustrates how the SP algorithm works.
- **Step 4:** After having built a radial topology using the SP algorithm, the GA algorithm is executed for all loads to determine the sizes and locations of the PV and DeBES.
- **Step 5:** The next step is to simulate the network with the PVs and DeBES for 30 years, taking into account a yearly load growth of 3% [8]. This simulation enables the analysis of the power at the slack bus over the course of the planning period.
- **Step 6:** During the day, the PV modules generate power that is delivered to the DeBES and loads. If the generated PV energy is higher than the load consumption, the

excess energy is injected into the MV grid via the slack bus at the transformer pole. To handle this situation, three scenarios are proposed:

- 1) **Scenario 1 (on-grid):** The exceeded PV energy is sold back to the MV grid through an energy meter (net-metering). However, it is noted that this solution is not yet available in Cambodia, but it should be considered as a future strategy.
 - 2) **Scenario 2 (on-grid):** A CeBES is installed at the slack bus. The CeBES is used to charge the excess energy and provide it back when the LV network requests energy. Additionally, the LV network is supplied by the MV grid when the CeBES is fully discharged.
 - 3) **Scenario 3 (off-grid):** The MV grid is replaced by a small-scale local LV generator. In this case, the energy provided to the LV network at the slack bus is provided by the LV generator while being integrated with the CeBES.
- **Step 7:** The last step is to calculate all costs for 30 years and compare the TOTEX.

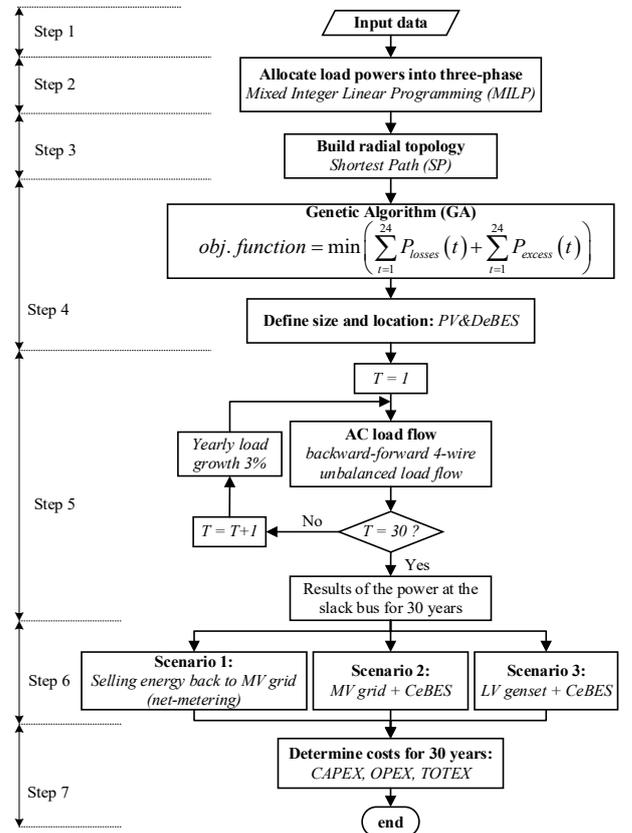


Fig. 1. Flowchart of the research methodology

A. Genetic Algorithm (GA)

In power distribution planning, the GA algorithm is commonly used to solve complex non-linear problems subject to non-linear constraints [11]. Therefore, this algorithm is proposed for this work to define sizes and locations of the PVs and DeBES. The algorithm is implemented using MATLAB. The individuals and iteration number are set to 50 and 200, respectively. To minimize simulation time, a 24-hour (one-day) simulation is considered to determine the size and

location of PVs and DeBES. This day is selected based on the highest difference between the annual PV curve and the first-year load curve. Based on the flowchart in Fig. 1, the size and location of PVs and DeBES are defined in the first year. After the simulation, the results are obtained and implemented into the network for 30 years without any changes in size or location of the PVs and batteries. Hence, the objective function and constraints provided are the following:

- Objective function:

$$\min \left(\sum_{t=1}^{24} P_{losses}(t) + \sum_{t=1}^{24} P_{excess}(t) \right) \quad (1)$$

- Constraints [12]:
- $$0.9 pu \leq V_{system} \leq 1.1 pu \quad (2)$$
- $$I_{main_feeder} \leq I_{max_main_feeder}$$
- $$I_{sub_feeder} \leq I_{max_sub_feeder}$$

These constraints are employed in the simulation to ensure the voltages and line currents of the network are in permitted range values after sizing the PVs and batteries.

B. Solar Home System (SHS)

Each SHS unit contains a PV module, a charge controller, an inverter, and a battery (DeBES). In this case, the size and location of the PV and DeBES refer to a solar home system (SHS) installed on a household/load (which is defined by GA). Therefore, all of these SHS units are identical in this research. Fig. 2 shows the model of SHSs integrated with the AC grid.

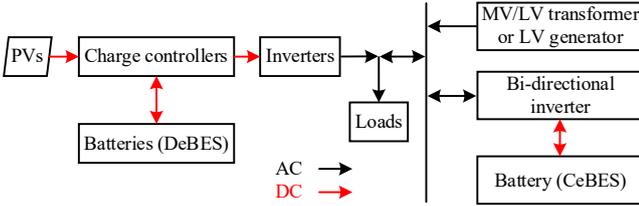


Fig. 2. The model of SHSs integrated with the AC grid

C. Costs Calculation

In this section, the total expenditure (TOTEX) is calculated. This contains the capital expenditure (CAPEX), which includes the costs of the equipment, as well as the operational expenditure (OPEX) which includes the costs of operation, power losses, and maintenance. Additionally, $OPEX_{income\ LV}$, $OPEX_{income\ MV}$, and salvage value are considered. Thus, the TOTEX formulation is given as:

$$TOTEX = CAPEX + OPEX - OPEX_{income\ LV} - OPEX_{income\ MV} - Salvage \quad (3)$$

$OPEX_{income\ LV}$ is the cost of selling energy to customers without considering energy losses. $OPEX_{income\ MV}$ is the cost of selling energy to the MV grid. Moreover, salvage value is the resale value of the PVs at the end of the study period. Based on the different scenarios at the slack bus, the CAPEX and OPEX equations can be written as the following:

1) Scenario 1: selling energy back to MV grid (on-grid)

$$CAPEX = CAPEX_{MV\ grid} + CAPEX_{MV/LV\ transformer} + CAPEX_{LV\ cable} + CAPEX_{PV\ \&\ DeBES} + CAPEX_{Inverter\ \&\ ch\ arg.} + CAPEX_{protective} + CAPEX_{equipment\ replacement} \quad (4)$$

$$OPEX = \sum_{i=1}^T \left(\frac{\sum_{t=1}^{8760} [P_{slack_positive}(t,i) \times C_{S/kWh}] + Main.}{(1+r)^i} \right) \quad (5)$$

$$OPEX_{income\ MV} = \sum_{i=1}^T \left(\frac{\sum_{t=1}^{8760} [P_{slack_negative}(t,i) \times C_{S/kWh}]}{(1+r)^i} \right) \quad (6)$$

$$OPEX_{income\ LV} = \sum_{i=1}^T \left(\frac{\sum_{t=1}^{8760} [P_{slack_positive}(t,i) \times C'_{S/kWh}]}{(1+r)^i} \right) \quad (7)$$

2) Scenario 2: MV grid + CeBES (on-grid)

$$CAPEX = CAPEX_{MV\ grid} + CAPEX_{MV/LV\ transformer} + CAPEX_{LV\ cable} + CAPEX_{PV\ \&\ DeBES} + CAPEX_{CeBES} + CAPEX_{Inverter\ \&\ ch\ arg.} + CAPEX_{protective} + CAPEX_{equipment\ replacement} \quad (8)$$

$$OPEX = \sum_{i=1}^T \left(\frac{\sum_{t=1}^{8760} [P_{slack_new}(t,i) \times C_{S/kWh}] + Main.}{(1+r)^i} \right) \quad (9)$$

3) Scenario 3: LV generator + CeBES (off-grid)

$$CAPEX = CAPEX_{LV\ cable} + CAPEX_{PV\ \&\ DeBES} + CAPEX_{CeBES} + CAPEX_{Inverter\ \&\ ch\ arg.} + CAPEX_{Generator} + CAPEX_{equipment\ replacement} \quad (10)$$

$$OPEX = \sum_{i=1}^T \left(\frac{\sum_{t=1}^{8760} [P_{slack_new}(t,i) \times C_{S/kWh}] + Main.}{(1+r)^i} \right) \quad (11)$$

The value of P_{slack_new} is obtained by subtracting $P_{slack_negative}$ from $P_{slack_positive}$. The equations for levelized cost of energy (LCOE) and CO2 emissions are presented in reference [9].

III. CASE STUDY

The case study is a non-electrified village [10°42'39.6"N 103°18'36.8"E] located on Koh Rong Island in Cambodia, situated 20 km away from the mainland of Preah Sihanouk province [9]. This village comprises of 73 households/loads, or 29.5 kW of total powers with a power factor of 0.95 in the initial year. The detailed power and coordinates of each household are provided in reference [9]. Fig. 3 shows the location of this village which was captured from Google Maps. It is proposed that 12 electrical poles are installed in this village.

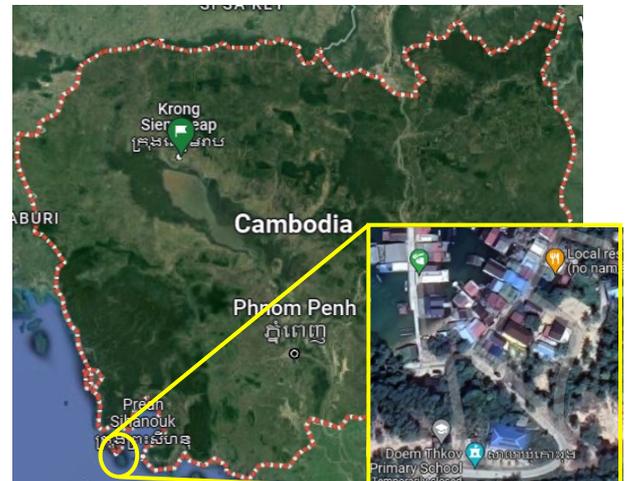


Fig. 3. The site location captured from Google Maps

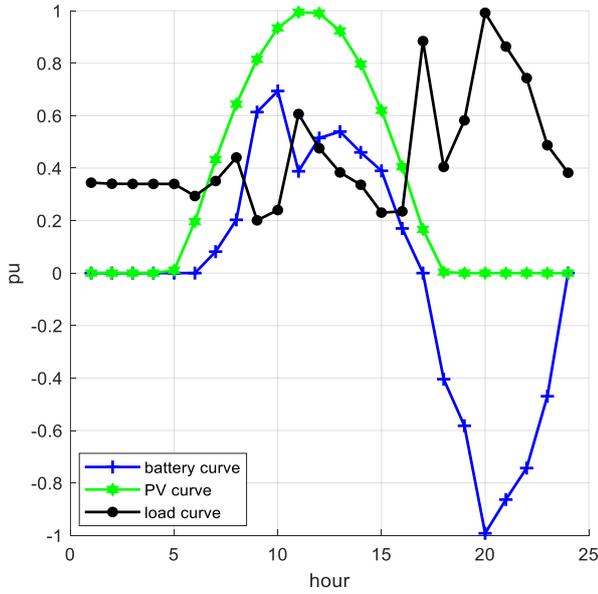


Fig. 4. The load, PV, and DeBES curve in pu

Fig. 4 illustrates the daily load curve (based on a survey, i.e., the times of use of load consumption), PV curve (this 24-hour curve is selected from the annual PV curve), and battery curve (DeBES). It is important to note that these curves are used to define the sizes and locations of PV and DeBES in the initial year. Cambodia experiences two seasons (rainy and dry season), with load consumption in the rainy season considered to be 3% lower than in the dry season. To simplify this work, four assumptions have been taken into account. First, there are no new loads connected to the network. Second, the daily load curve shape remains the same for 30 years, but the yearly load growth is 3% for the entire load curve shape. However, the PV curve shape changes based on the weather in the different seasons. The annual PV curve is provided in reference [13]. Lastly, the daily charged energy of the DeBES is equal to the discharged energy at the end of a day. The input data for simulation and economic analysis is provided in TABLE I.

TABLE I. INPUT PARAMETERS

Items	Values
Total load power at the initial year (73 loads)	29.5 kW
Total load power at the 30 th year (73 loads)	71.6 kW
Cable costs [13]	4 mm ² (1 core) 0.3 k\$/km
	50 mm ² (1 core) 0.8 k\$/km
Cost of purchased energy from MV grid [12]	0.000121 k\$/kWh
Cost of selling energy to households [12]	0.000152 k\$/kWh
PV price [14]	0.6 k\$/kWp
Lithium battery price (DeBES or CeBES) [14]	0.105 k\$/kWh
PV DC/AC inverter [13]	0.72 k\$/kW
DC charge controller [15]	0.13 k\$/piece
Bi-directional AC/DC inverter [14]	1.115 k\$/kW
Minimum state of charge (SoC) [13]	20%
Maintenance cost (PV+BES+Inverter) [16]	0.0115 k\$/kW/year
Generator cost [14]	0.5 k\$/kW
Fuel cost [14]	0.000495 k\$/kWh
Mean cost of building MV lines [9]	100 k\$/km
DC Charge controller or inverter efficiency [14]	95%
Degradation (DC Charge controller, inverter, PV, battery)	0.5%/year
Battery efficiency	95%
PV lifespan	25 years
DC charger or inverter lifespan [14]	15 years
Battery lifespan [14]	5 years
Generator lifespan [14]	15 years

IV. RESULTS OF SIMULATION AND DISCUSSION

Fig. 5 presents the results of simulations of the radial topology with SHSs. It also illustrates each scenario at the slack bus. There are a total of 58 SHS units. Additionally, a PV module with a capacity of 550W and a DeBES with a capacity of 4.8kWh have been obtained.

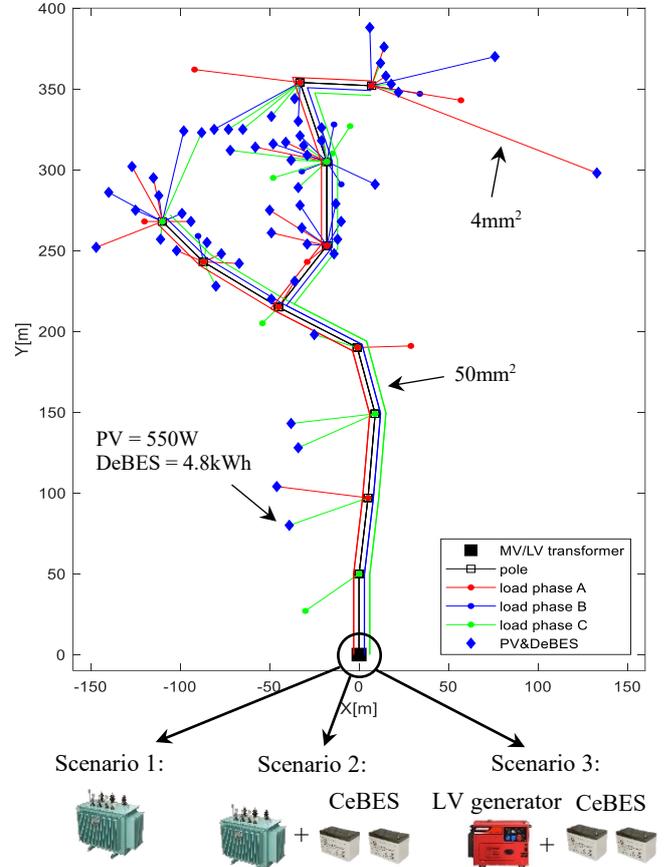


Fig. 5. The radial topology integrated with PV and DeBES (with three different scenarios at the slack bus)

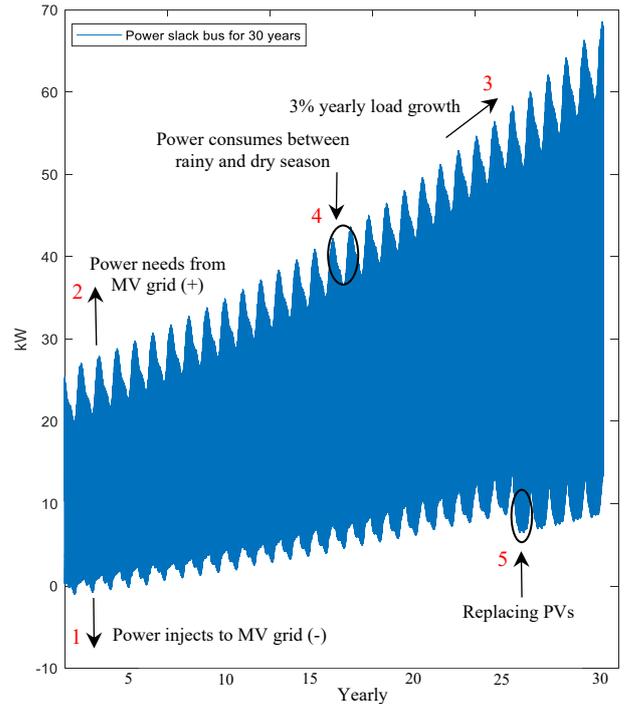


Fig. 6. Power at the slack bus for 30 years

After integrating with SHSs, the power at the slack bus for 30 years is shown in Fig. 6. The numbers indicated on the graph can be explained as follows. (1) the reversed powers (negative values) represent the power injected into the MV grid when the PV modules produce more power than required by the loads. (2) the powers (positive values) represent the power required from the MV grid, generator, or CeBES. (3) this power curve slightly increases year by year due to the yearly load growth of 3%. (4) it represents the difference in power consumption between the rainy and dry seasons. (5) at the end of the 25th year, the PV modules need to be replaced. Thus, this reflects the impact of replacing new PV modules in the entire network. The peak power value at the 30th year is 68.5 kW, while the total load power is 71.6 kW. This peak value is quite high, even when the network is integrated with SHSs. It can be explained that it occurs at 17h00 (as shown in Fig. 4) when there is less sunlight (resulting in less power from PVs) and the DeBES has not yet released any energy back into the system during that time.

The cost analysis for each scenario for 30 years is shown in TABLE II. Based on the results, the difference in TOTEX between scenario 1 and scenario 2 is small, around 0.24%. Both scenarios have large CAPEX values, which led to an increase in the value of LCOE, primarily due to the cost of building the MV line to supply power. In Fig. 6, there is a small amount of reversed power to the MV grid that occurs only for the first four years. Therefore, in scenario 1, the $OPEX_{income\ MV}$ value has no significant impact on $OPEX_{purchase}$ and $OPEX_{income\ LV}$ when compared to scenario 2. Note: $OPEX_{purchase}$ is the cost of purchasing energy from MV grid/generator (exclude the maintenance costs). Nevertheless, scenario 3 has a lower TOTEX, with a difference of less than 66% when compared to scenarios 1 and 2. However, the $OPEX_{purchase}$ has a high value due to the fuel cost required for the LV generator. By taking into account the environmental impact of CO₂ emissions, it is evident that scenario 2 is preferable to scenarios 1 and 3. In short, considering the smallest TOTEX value, scenario 3 (LV generator + CeBES) is the most suitable solution in this research.

TABLE II. RESULTS OF SIMULATION FOR 30 YEARS

Items		Values		
Cables used [m]	50mm ² [3p+1n]	2066		
	4mm ² [1p+1n]	4109		
Voltages [pu]	V _{max}	1.0		
	V _{min}	0.91		
Power losses [kW]		6.35		
Total maximum DeBES power [kW]		29		
		Phase A	Phase B	Phase C
PV power / phase [kW]		10.45	10.45	11
DeBES [kWh]		91.2	91.2	96
		Scenario 1	Scenario 2	Scenario 3
CeBES [kWh]		-	4.8	4.8
LCOE [\$/kWh]		0.9	0.9	0.21
CO ₂ emissions [kg/year]		115210	115200	154030
CAPEX [k\$]		2076.4	2080.4	230
OPEX _{purchase} [k\$]		181.2	182.1	669.9
OPEX _{income\ MV} [k\$]		0.025	-	-
OPEX _{income\ LV} [k\$]		198.26	198.22	198.22
Salvage [k\$]		0.84	0.84	0.84
TOTEX [k\$]		2058.4	2063.4	700.8

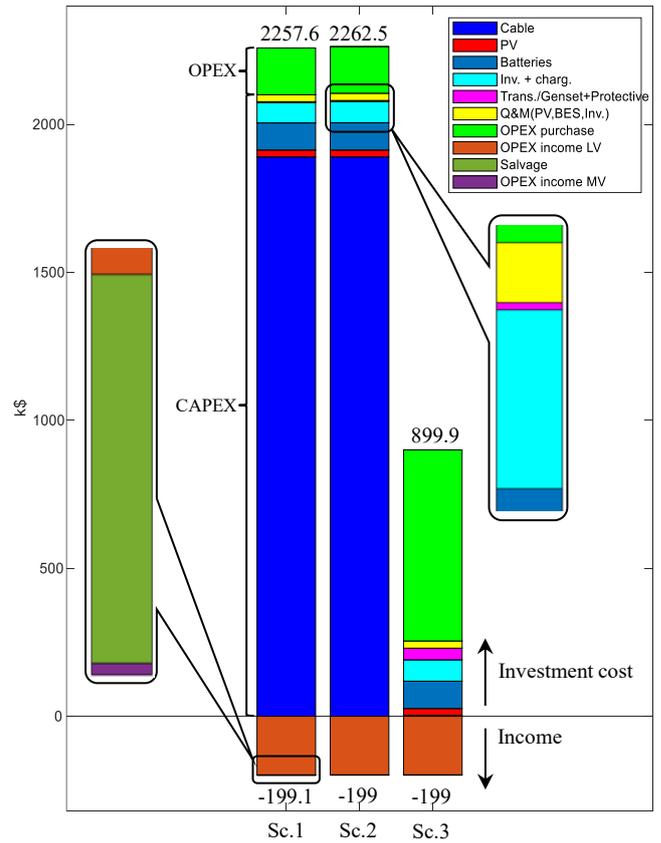


Fig. 7. TOTEX, CAPEX, OPEX (purchase and income), and Salvage for each scenario for 30 years

Fig. 7 provides a detailed cost analysis. These three bar charts represent the costs for scenarios 1, 2, and 3, respectively. The positive values represent investment costs, while the negative values represent the income. Therefore, the percentage cost of each item is demonstrated in TABLE III.

TABLE III. COSTS OF EACH ITEM IN PERCENTAGES

Investment cost			
	Scenario 1	Scenario 2	Scenario 3
Cable [%]	84.76	83.55	0.32
PV [%]	1.03	1.03	2.59
Batteries [%]	4.06	4.07	10.25
Inv.+charg. [%]	3.04	3.18	8.01
Trans./Gen.+ Protec. [%]	0.13	0.13	4.37
Q&M [%]	1.03	1.07	2.07
OPEX _{purchase} [%]	6.98	6.97	72.39
Total [%]	100	100	100
Income			
	Scenario 1	Scenario 2	Scenario 3
OPEX _{income\ MV} [%]	0.012	-	-
OPEX _{income\ LV} [%]	99.56	99.58	99.58
Salvage [%]	0.42	0.42	0.42
Total [%]	100	100	100

Fig. 8 depicts the influence of replacement costs on investment costs as the equipment reaches their respective lifespans in each scenario. As mentioned, scenario 1 and scenario 2 have a significant CAPEX value (compared to scenario 3) due to the cost of the MV grid. The graphs indicate that the batteries need to be replaced every 5 years, resulting in a slight increase in cost values. Next, the inverters and charge controllers are replaced for all scenarios after 15

years. Moreover, the replacement cost of the LV generator is also included for scenario 3. Finally, at the end of 25 years, the PVs are replaced with new modules thus, the replacement cost of the PVs is considered.

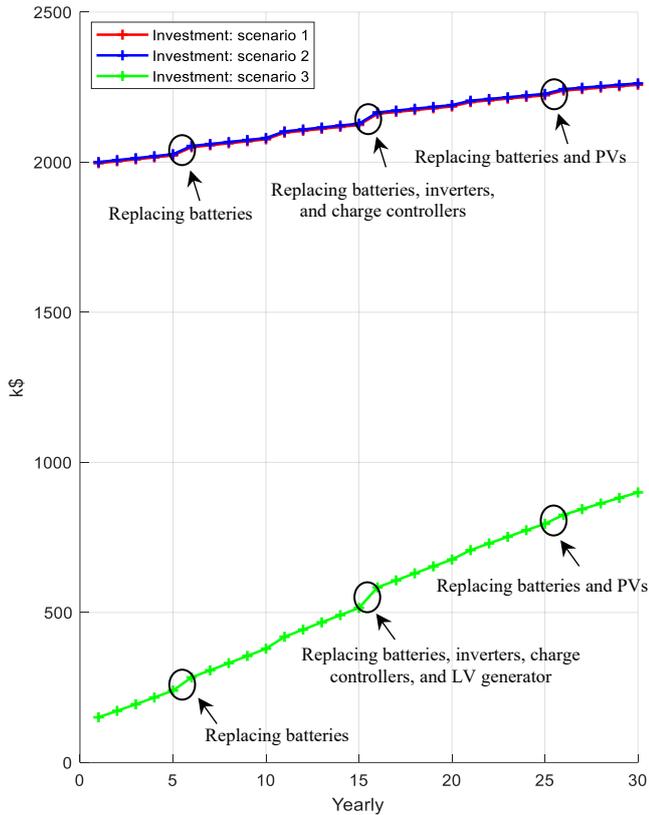


Fig. 8. The investment cost for each scenario for each year

V. CONCLUSION

This paper proposed three different scenarios at the slack bus to address the issue of excess energy in microgrid. Firstly, the MILP technique is used to balance the load powers into a three-phase system, while the SP algorithm is used to define a radial topology. Next, the sizes and locations of PV modules and DeBES are identified using a GA algorithm. Finally, the costs of the three different scenarios are calculated and compared for 30 years. Based on the results, it is found that the network containing the LV generator and CeBES (scenario 3) has the smallest TOTEX value compared to two other scenarios. Next, the sensitivity analysis of load profiles will be considered in the future research.

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