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Optimal sizing of an isolated DC microgrid using multi-objective optimization with linear programming

Fadi AGHA KASSAB, Berk CELIK, Fabrice LOCMONT, Manuela SECHILARIU

AVENUES, Centre Pierre Guillaumat, Université de Technologie de Compiègne, CS 60 319, 60203 Compiègne
fadi.gha-kassab@utc.fr, berk.celik@utc.fr, fabrice.locmont@utc.fr, manuela.sechilariu@utc.fr

ABSTRACT –A microgrid design is crucial to minimize components costs within the system by ensuring neither undersized nor oversized system components. This paper presents a sizing algorithm that determines the optimal capacity of photovoltaics (PV) system with battery energy storage system (BESS) in a DC microgrid. A multi-objective problem is formulated using linear programming that minimizes the cost of PV and BESS installation for the project lifetime (30 years). The multi-objective optimization problem is solved using CPLEX using one-year consumption, ambient temperature and solar irradiance data within one-hour time resolution (8760 hours). The simulation results show that the presented algorithm determines the annual cost by obtaining optimal PV and BESS capacities for a tertiary building.

KEYWORDS – Optimal sizing, DC microgrid, isolated mode, linear programming, multi-objective optimization

1. Introduction

Climate change is a major issue in the 21st century that is mainly caused due to utilization of fossil-based energy sources that has high CO₂ emissions. One of the objectives of Paris agreement is to keep the global average temperature below 2 °C above preindustrial level by reducing dependency on fossil-based electricity production resources [1]. To achieve this goal, renewable energy resources (RES) is one of the solutions due to their zero-carbon feature during the energy generation.

In this context, microgrids can be considered as a key component that facilitates the integration of RES in terms of deployment and control in the distribution level which aims to increase local renewable energy consumption. There are two operation modes of microgrids: (i) either grid-connected mode, which consists of a physical connection with the public grid, (ii) or stand-alone mode where microgrid operates autonomously without public grid connection. However, during the designing process, microgrids need to be properly sized to have efficient cost of the system with minimal capacities of microgrid components such as photovoltaics (PV) panels, batteries, wind turbines, etc. There are three types of microgrid; (i) AC microgrid, which consists of connecting all sources and the load to an AC bus, (ii) DC microgrid where components of the system are connected to a DC bus, (iii) hybrid AC/DC microgrid where an AC and a DC buses exist within the system. Regarding microgrids composed of PV system and battery energy storage system (BESS), a DC bus leads to the reduction of number of converters and therefore less losses in the system [2].

Microgrid cost is highly dependent on its design (size). Several studies are conducted in the context of optimal sizing of microgrids numerically and experimentally. A combined genetic algorithm (GA) with linear programming (LP) is utilized in [3] for a grid-connected microgrid to obtain the optimal size and location of distributed storage. A multi-objective optimization problem is conducted in [4] to minimize the BESS and the RES for a multiple railway substations without considering the economic aspects of the resources. In [5], the objective functions provide three minimums: greenhouse gas (GHG) emissions, life cycle cost (LCC), and the non-renewable energy quantity consumed during life cycle of microgrid equipment using GA by minimizing area of PV panels and wind turbines, and storage capacity. In [6], the study aims to minimize the cost of energy and the life cycle emissions by determining optimal BESS and PV capacities using GA. The study in [7] proposes an uncertainty analysis to determine the LCC of the BESS without using optimization algorithm to minimize its capacity. An improved gray wolf optimization algorithm is proposed to optimally size and place a BESS system in microgrids in isolated operation in [8].

In this paper, a multi-objective optimization algorithm is presented using LP to determine the optimal capacities of energy resources (PV and BESS) and the minimal annual cost of the system for a project life of 30 years in an isolated DC microgrid. LP is the most widely used technique of decision-making in wide area of application that improves the quality

of decision by determining global minimum/maximum of the optimization problem [9]. The optimization problem is formulated and solved using CPLEX library by programming in Python (docplex).

The reminder of the paper is organized as follows: Section 2 describes the studied model of the DC microgrid structure with components, the formulation of the multi-objective problem is explained in Section 3, the simulation setup and optimization results are exhibited in Section 4, Section 5 focuses on the discussion and analysis, the conclusion and the future work are given in Section 6.

2. System modelling

An isolated DC microgrid, which consists of PV panels, BESS, and a DC load, is considered in this study. The surplus power produced by the PV system is stored in BESS, thus the load can be supplied by BESS during the absence of solar irradiance. If the battery is fully charged or the surplus power produced by the PV system surpass the power limits of BESS than the surplus power is curtailed. PV system and BESS are connected to a common DC bus with the DC load. BESS losses are considered during the charging/discharging process of battery units. The simulation is performed using consumption and environmental data in one-hour time resolution (time step Δt : 60 minutes) for one-year (8760 hours). Figure 1 presents the studied DC microgrid structure.

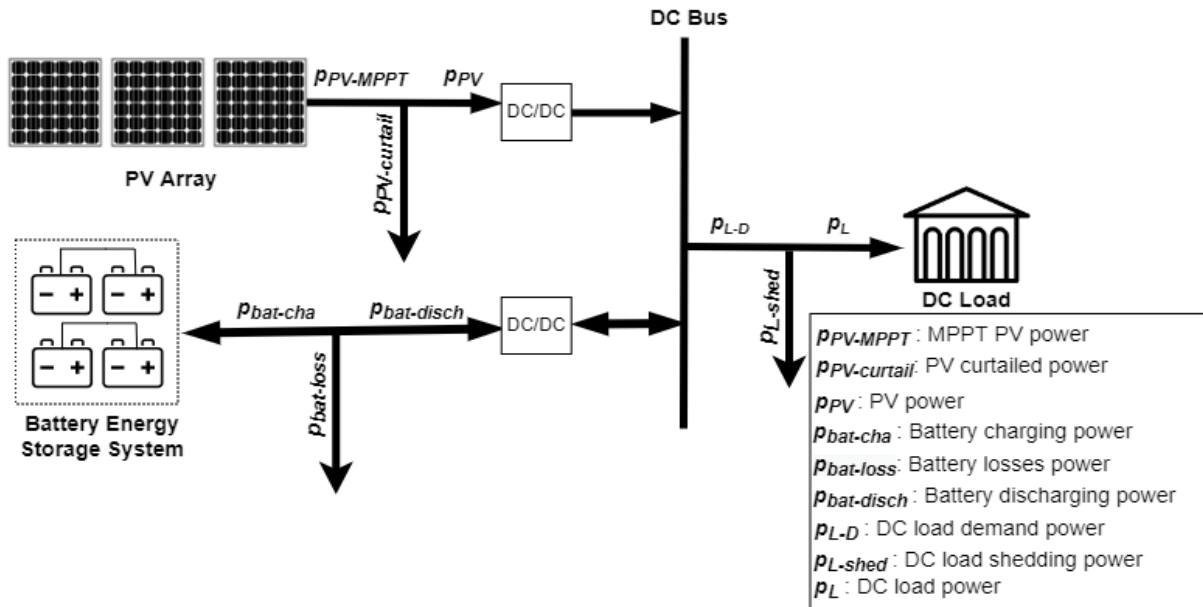


Figure 1: System structure

2.1 PV sources

Weather data is taken from *Météo France* provides the hourly solar irradiance g and ambient temperature t_{amb} for the location of Université de Technologie de Compiègne (UTC), Compiègne, France [10]. PV power production is calculated in Maximum Power Point Tracking (MPPT) mode ($p_{PV-MPPT}$) with gathered solar irradiance and ambient temperature data as follows [11]:

$$p_{PV-MPPT}(t_i) = P_{PV-STC} \cdot \frac{g(t_i)}{g_{STC}} \cdot (1 + \gamma \cdot (t_{PV}(t_i) - T_{STC})) \cdot N_{PV}, \quad (1)$$

$$\text{with } t_i = \{t_0, t_0 + \Delta t, t_0 + 2\Delta t, \dots, t_f\},$$

$$t_{PV}(t_i) = t_{amb}(t_i) + g(t_i) \cdot \frac{(NOCT - T_{air-test})}{g_{test}}, \quad (2)$$

where, P_{PV-STC} (135 Wp) is the module rated power at standard test conditions (STC); g is the solar irradiance and g_{STC} is the solar irradiance at STC (1000 W/m^2). γ is the power temperature coefficient ($-0.29\%/^{\circ}\text{C}$); t_{PV} is the PV cell

temperature; T_{STC} is the PV cell temperature at STC (25 °C); N_{PV} is the number of PV panels; $t_i, t_0, \Delta t$ and t_f are the continuous time, initial time, time step, and time length simulation respectively. t_{amb} is the ambient temperature; $NOCT$ is the nominal operating cell temperature (41 °C); $T_{air-test}$ is the fixed air temperature for testing (20 °C); g_{test} is the fixed solar irradiation for testing (800 W/m^2).

2.2 Battery Energy Storage System

After satisfying the load from the PV power production, the surplus power is stored in BESS, so that the BESS can feed the load in the absence of solar irradiance (during night hours). The battery state of charge (soc_{bat}) is defined by:

$$soc_{bat}(t_i) = soc_{bat}(t_i - 1) + (p_{bat-cha}(t_i) + p_{bat-disch}(t_i)) \cdot \Delta t / E_{bat} \quad (3)$$

where, E_{bat} is the battery energy capacity in kWh which equals to total battery number (N_{bat}) multiplied by single battery energy capacity ($E_{bat(1)}$); $p_{bat-cha}$ is the battery charging power and $p_{bat-disch}$ is the battery discharging power. The objective of BESS utilization in isolated microgrid system is when the load power is greater than PV power, BESS will be in discharging mode only if battery state of charge (SOC) is greater than the minimum battery SOC. Otherwise, BESS will be in charging mode only if the battery is less than the maximum battery SOC. The amount of charge/discharge power depends on the difference between load power and PV power with battery power and SOC constraints.

2.3 DC load

In the studied microgrid system, the DC load demand power P_{L-D} is considered similar as the profile curves recorded by the utility company for a tertiary building in UTC, Compiègne, France.

3. Problem formulation

Several approaches are defined to solve multi-objective optimization problems such as: weighted-sum, trade off or ϵ -constraint, hierarchical, goal programming and global criterion methods [13]. The preference-based multi-objective optimization approach is considered to solve multi-objective optimization problem by transforming multi-objective problems to mono-objective one. The weighted sum approach (in preference-based method) is used in this study as a higher-level information. The multi-objective problem is transformed to a mono-objective one, and then, an optimization technique, which is LP in this study, can be used to get an optimal solution. Figure 2 shows the preference-based multi-objective optimization approach.

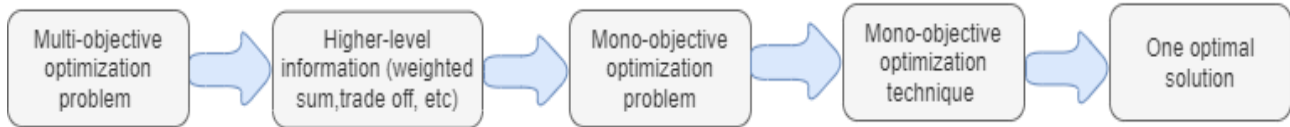


Figure 2: Preference-based multi-objective optimization approach

3.1 Constraints

Safe battery integration in the microgrid is important to extend battery lifetime. Therefore, constraints on the maximum charging/discharging power $P_{bat-max}$, maximum battery energy $E_{bat-max}$, and minimum battery energy $E_{bat-min}$ are given as follows:

$$0 \leq p_{bat-cha}(t_i) \leq P_{bat-max}, \quad (4)$$

$$-P_{bat-max} \leq p_{bat-disch}(t_i) \leq 0, \quad (5)$$

$$E_{bat-min} \leq e_{bat}(t_i) \leq E_{bat-max}, \quad (6)$$

where $e_{bat}(t_i)$ is the energy of the battery at each instant t_i , $E_{bat-min}$ and $E_{bat-max}$ are the minimum and maximum battery energy limits. In the soc_{bat} calculation given in Equation (3), three decision variables which are the of battery

charge/discharge power ($p_{bat-cha}$, $p_{bat-disch}$) and E_{bat} are divided on each other to determine soc_{bat} , which can convert linear problem to nonlinear one. Therefore, the constraints are defined based on the battery energy $e_{bat}(t_i)$ in the optimization problem, and then the battery SOC is calculated afterwards for presenting the simulation results.

Lastly, the stored battery energy in the end of the year is assumed to be equal or higher to the initial battery energy in the beginning of the year. This constraint will enable to store enough energy for the first day in the next year without fully discharging the battery. The final battery energy constraint is given as below:

$$e_{bat}(t_f) \geq e_{bat}(t_0). \quad (7)$$

In order to determine available charging/discharging power values for BESS, load shedding p_{L-shed} and PV curtailment $p_{PV-curtail}$ powers are required to be calculated by subtracting load demand power from MPPT PV power. The positive part of the subtraction represents load shedding power and negative part represents PV curtailment power. These are the consumption/generation power that will be shedded/curtailed in the absence of enough battery; therefore, they are referred as “load shedding power” and “PV curtailment power” in this paper. However, in order to determine both values separately in two different variables (p_{L-shed} and $p_{PV-curtail}$) in LP, the absolute value of the subtraction ($|p_{L-D} - p_{PV-MPPT}|$) should be determined using two constraints as follows:

$$p_{L-shed}(t_i) - (p_{L-D}(t_i) - p_{PV-MPPT}(t_i)) \geq 0, \quad (8)$$

$$p_{PV-curtail}(t_i) - (p_{PV-MPPT}(t_i) - p_{L-D}(t_i)) \geq 0, \quad (9)$$

The algorithm will determine $p_{L-shed} = p_{L-D}(t_i) - p_{PV-MPPT}(t_i)$ when $p_{L-D}(t_i) - p_{PV-MPPT}(t_i) \geq 0$ and $p_{L-shed} = 0$ at other times; and $p_{PV-curtail} = p_{PV-MPPT}(t_i) - p_{L-D}(t_i)$ when $p_{L-D}(t_i) - p_{PV-MPPT}(t_i) < 0$ and $p_{PV-curtail} = 0$ at other times. Accordingly, both load shedding and PV curtailment powers will be determined positive in the algorithm.

The objectives of these calculations are: (i) to limit BESS charge/discharge power between excess consumption and generation powers, and (ii) to calculate accurately BESS loss power in Equation (12) for charging/discharging conditions separately. The limits of BESS charging/discharging power are given as follows:

$$p_{bat-disch}(t_i) \geq -p_{L-shed}(t_i) / \eta_d, \quad (10)$$

$$p_{bat-cha}(t_i) \leq p_{PV-curtail}(t_i) \cdot \eta_c. \quad (11)$$

Where, η_d and η_c are the charging and discharging efficiency, respectively. The losses of the battery are calculated after determining the charging and discharging power of the battery as given below:

$$p_{bat-loss}(t_i) = -p_{bat-cha}(t_i) \cdot \left(1 - \frac{1}{\eta_c}\right) - p_{bat-disch}(t_i) \cdot (1 - \eta_d). \quad (12)$$

The net power p_{net} accumulated on the DC bus should be less or equal to zero, which means that load demand power should be satisfied for all time instants t_i :

$$p_{net}(t_i) = p_{L-D}(t_i) - p_{PV-MPPT}(t_i) + p_{bat-cha}(t_i) + p_{bat-disch}(t_i) + p_{bat-loss}(t_i), \quad (13)$$

$$p_{net}(t_i) \leq 0. \quad (14)$$

Constraint (14) means that the load shedding is not allowed, while PV curtailment is not limited in order to avoid oversizing BESS units. Lastly, the number of PV N_{PV} and battery N_{bat} units should be higher than zero, which is imposed by following inequality constraints below:

$$N_{PV} > 0, \quad (15)$$

$$N_{bat} > 0. \quad (16)$$

3.2 Objective functions

The optimization problem is a multi-objective optimization one. The first objective function F_0 and the constraints (8) and (9) aim to calculate the absolute value of ($|p_{L-D} - p_{PV-MPPT}|$) in LP. The calculation of the absolute value is necessary to calculate the value of $p_{bat-cha}$ and $p_{bat-disch}$ at each time step (either charging or discharging), hence F_0

is defined as an objective function to minimize the load shedding power p_{L-shed} and the PV curtailment power $p_{PV-curtail}$. In other words, F_0 is an objective function to control the battery power.

The second objective function F_1 aims to minimize the BESS and PV capacities using economical aspects such as initial investment, maintenance, and replacement costs [6]. The following multi-objective optimization problem is solved by determining the following decision variables: PV curtailment power ($p_{PV-curtail}$), the load shedding power (P_{L-shed}), the battery number (N_{bat}), PV panel number (N_{PV}), and battery discharge/charge power ($p_{bat-cha}$, $p_{bat-disch}$).

$$\min \{ F_0 = p_{L-shed}(t_i) + p_{PV-curtail}(t_i) \}, \quad (17)$$

$$\min \{ F_1 = C_{system-annual} \}, \quad (18)$$

$$C_{system-annual} = TPV \times CRF, \quad (19)$$

where, TPV is the total present value, which is the project life time costs for 30 years and CRF is the capital recovery factor. The importance of this factor is to transform the project cost for 30 years to an annual cost. CRF and TPV are calculated by [6]:

$$CRF = \frac{d(1+d)^N}{(1+d)^N - 1}, \quad (20)$$

$$TPV = ICC + OMC + RPC - PSV, \quad (21)$$

where d is the discount rate and N is the project lifetime; ICC is the total initial capital cost, which is the initial investments of the project, OMC is the operation and maintenance cost; RPC is the replacement cost and PSV is the present salvage value at the end of the project lifetime. The following equations define these parameters.

$$ICC = C_{bat} \cdot N_{bat} + C_{PV} \cdot N_{PV} + C_{I,EC,TRES}. \quad (22)$$

where, N_{bat} and N_{PV} are the numbers of batteries and PV panels; C_{bat} is the battery cost (per unit); C_{PV} is the PV panel cost (per unit) and $C_{I,EC,TRES}$ is the installation, electrical connections, and testing of the RES components costs. OMC is calculated as [14]:

$$OMC = OMC_k \times \sum_{j=1}^N \left(\frac{1+\varepsilon}{1+d} \right)^j. \quad (23)$$

where, OMC_k is the operation and maintenance cost of the k th component and ε as the escalation rate. RPC calculated as [15]:

$$RPC = RPC_k \times \sum_{j=1}^{NR} \left(\frac{1+\varepsilon}{1+d} \right)^j. \quad (24)$$

where, RPC_k is the replacement cost of system components of k th component and NR is the number of replacements during the project life.

The higher-level information used in this study is the weighted sum approach to transform the multi-objective function into a mono-objective optimization as follows:

$$\min \{ F_2 = w_1 \cdot F_0 + w_2 \cdot F_1 \}, \quad (25)$$

Where $w_1 = 10^{-4}$ and $w_2 = 1 - 10^{-4}$. The choice of these weights is justified by the fact that the optimization problem aim to minimize the annual cost of the installation to size optimally PV and BESS capacities in DC microgrid, hence w_2 should have the bigger weight for objective function F_1 . The objective function F_0 is defined to calculate only the absolute value of ($|p_{L-D} - p_{PV-MPPT}|$) by minimizing p_{L-shed} and $p_{PV-curtail}$ therefore smaller weight is assigned to w_1 for objective function F_0 .

4. Simulation results

In this section, the system setup, which includes solar irradiance, ambient temperature and electrical load data for one year, simulation parameters and numerical results of the simulation are presented.

4.1 System setup

The one-year solar irradiance, ambient temperature and load data for UTC, Compiègne, France over 8760 hours is presented in Figure 3. One unit battery capacity ($E_{bat(1)}$) is chosen 2.4 kWh (12 V, 200 Ah) in this study [16]. The rest of the simulation parameters are presented in Table 1. PV panel cost is taken from [12]. The PV lifetime is chosen 30 years in this study.

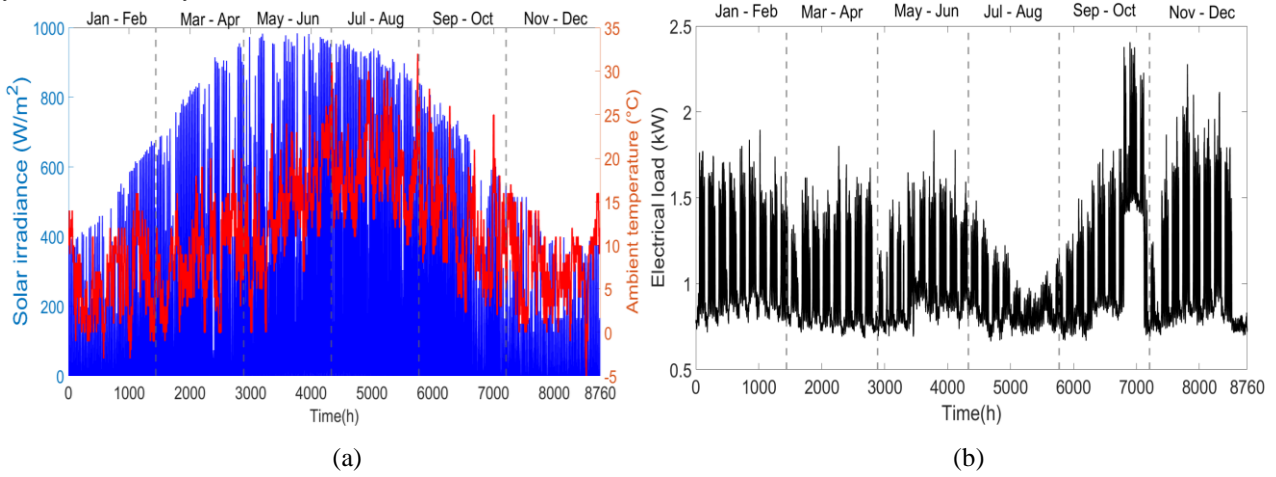


Figure 3: Annual (a) solar irradiance, ambient temperature and (b) load data (over 8760 hours)

Table 1. Simulation parameters

Parameter	Value	Parameter	Value
Project lifetime	30 years	Battery cost	450 \$
Discount rate (d)	10%	Installation, electrical connection cost	30% of C_{PV}
Escalation rate (ε)	2%	OMC_{PV}	2% of C_{PV}
PV lifetime	30 years	OMC_{bat}	5% of C_{bat}
Battery lifetime	10 years	Present salvage value	10% of N_{PV} and 10% of N_{bat}
PV module cost	310 \$	$P_{bat-max}$	3 kW
Battery charging efficiency	0.90	Battery discharging efficiency	0.90
$E_{bat}(t_0)$	$0.5 \cdot E_{bat}$	$E_{bat-min} / E_{bat-max}$	$(0.2/0.8) \cdot E_{bat}$

4.2 Numerical results

The optimum capacity of the PV system is 58 kWp and the optimum battery capacity equals to 82 kWh which is equivalent to 428 PV panels with a nominal power of 135 Wp and 34 batteries with a capacity of 2.4 kWh each (12V, 200 Ah). The annual cost equals to 28256 \$ for a simulation time of 180s.

Figure 4 shows the annual optimization results for the considered isolated microgrid system. PV power (p_{PV}) is presented after subtracting the MPPT PV power from PV curtailed power ($p_{PV}(t_i) = p_{PV-MPPT}(t_i) - p_{PV-curtailed}(t_i)$). The total produced energy by the PV system in MPPT mode is 91.5 MWh, the battery charge and discharge around 5

MWh with respect to its limit ($P_{bat-max}$). Battery losses are equal to 1.08 MWh. The net power P_{net} is determined always lower than zero, hence the unused energy is calculated around 81.5 MWh. The battery SOC given in Figure 4 (b) indicates that BESS makes 105 cycles over the year.

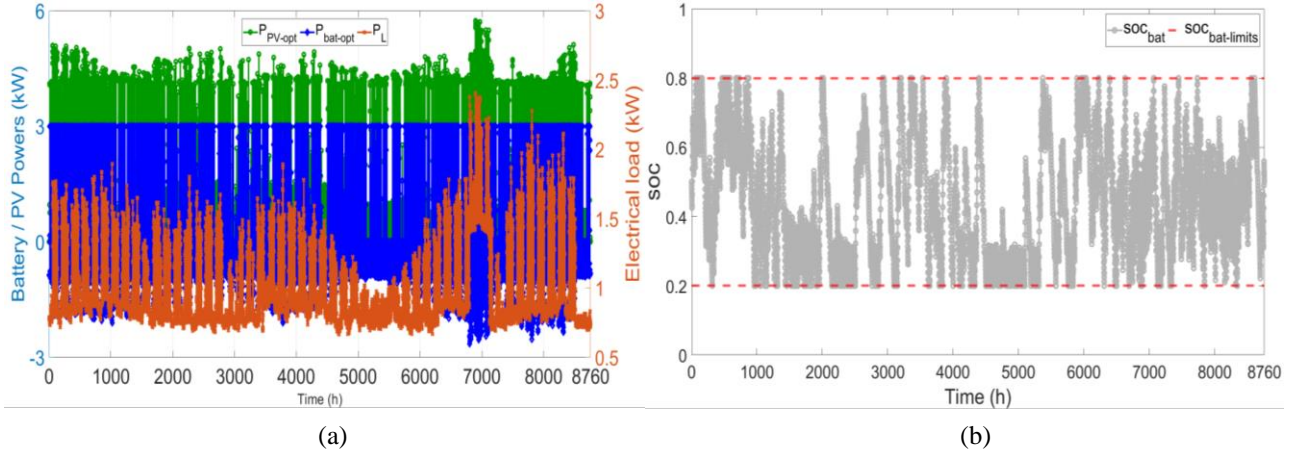


Figure 4: Annual optimization results ($\Delta t = 60$ min): (a) P_L , P_{PV} and P_{bat} optimal power results (b) soc_{bat} optimal results

The optimization results for 100 hours of the simulation is presented in Figure 5. When solar irradiance is not available, the BESS recovers the deficit by discharging the stored energy for the load. Otherwise, BESS is in charging mode in order to store the excess energy produced by PV system after satisfying the load as shown in Figure 5 (a). The SOC of BESS is charged/discharged according to generation-consumption balance within SOC limits as shown in Figure 5 (b) in order to extend battery lifetime.

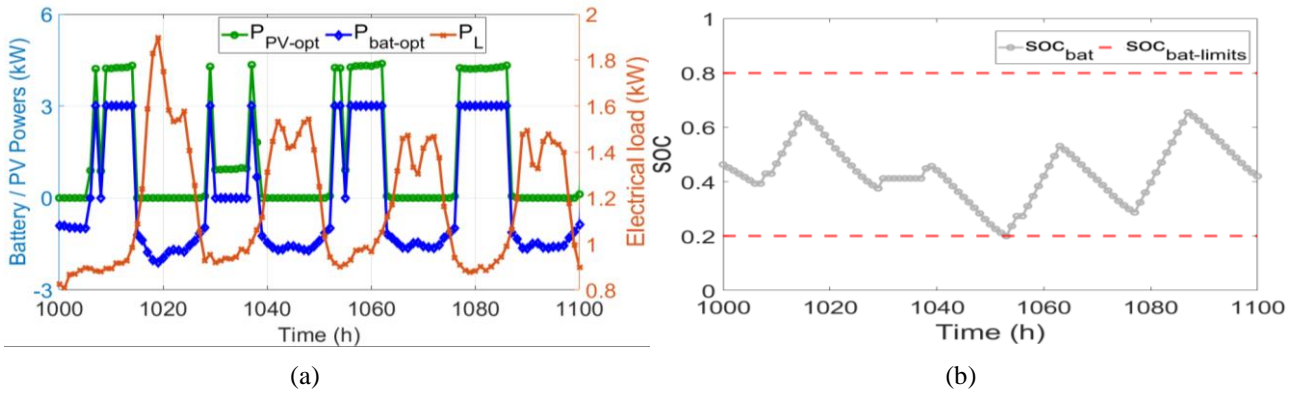


Figure 5: Optimization results: (a) P_L , P_{PV} and P_{bat} optimal power results (b) soc_{bat} optimal results

5. Discussion and analysis

The utilized PV energy is around 11% of the total produced energy in the microgrid, and the rest of the unused energy is curtailed, so the energy efficiency is quite low. However, the economic efficiency is high because of the low battery capacity determined by the algorithm. There are two reasons that explains the situation: (i) net power (P_{net}) is equal or lower than zero in the constraint expressed in Equation (14), and (ii) low PV investment cost are required. Firstly, according to Equation (14), curtailment of PV power is not limited in the microgrid in order to not oversize the BESS. The reason is that when PV curtailment is limited, the algorithm determines higher BESS capacity that can lead to obtain more expensive annual cost. Otherwise, when the load shedding is minimized (as in the presented algorithm), then the algorithm tends to increase PV capacity because of the solar irradiance fluctuations to satisfy the load so a lot of energy is curtailed when there is enough solar radiation. Secondly, PV cost is significantly lower than BESS cost, therefore, the algorithm determines the most economical solution as the optimal result even though there is high unused PV energy in the microgrid. Accordingly, the unused energy can be transferred to another microgrid to be consumed, or injected into the main grid for providing grid support services via demand response and/or ancillary services.

In addition, the battery makes 105 cycles during the one-year simulation, which can impact its performance and its life time. The limitation of the presented algorithm is the efficiency from an energetic point of view as a lot of PV power produced is being curtailed, in addition there is a disadvantage in terms of performance and lifetime of the battery.

6. Conclusion

This study presents a sizing algorithm for an isolated microgrid, which provides its required total energy from PV system with the help of BESS without load shedding. The optimization problem is formulated as multi-objective optimization where the first objective function is introduced to limit the battery charging/discharging power in LP, while the second objective function determines the economic aspects of PV and BESS installations in DC microgrid. The weighted-sum approach is used as a higher level of information to turn the problem into a mono-objective optimization one. The problem is formulated using LP in Python and solved by CPLEX. The simulation are performed using one-year of irradiance, ambient temperature and load data to determine the optimal PV and BESS capacities that provides the minimal cost for the project lifetime. The presented algorithm can be utilized as a tool for isolated microgrids to obtain the optimal configuration between the size of component and the minimum annual cost of the project.

The future work is to integrate battery aging model while considering minimization of GHG emissions as an additional objective function in parallel to economic objectives.

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