Optimal Sizing of Battery Energy Storage Systems Self-consumption in Urban Micro-grids

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***Abstract*—With the increased adoption of distributed energy resources in the urban context, there is a growing potential for realization of grid-connected networked micro-grids that can facilitate collective utilization of local energy resources. The coordination of different flexibilities in the generation and demand side, complemented by energy storage systems is required for an efficient local energy management. This work discusses a study on sizing of battery energy storage system for optimizing the overall return on such investment in the local scale and the planning of its operation for such self-consumption and market participation use-cases. The simulation studies have been conducted based on historical wholesale electricity price data of the region.**

***Index Terms*—Energy market, Flexibility, Storage sizing, Urban micro-grids**

I. Introduction

There is an increasing motivation in Singapore for the adoption of distributed energy resources (DERs). Networked micro-grids are inevitable players for an organized integration of distributed resources in the urban context with the involvement of the distribution system operator. Networked micro-grids is seen as a viable option for the integration of local resources in Singapore that is with a very high urban demand with a relatively small rooftop PV potential. The local resources in this case may include both the energy and flexibility resources, where the local energy production is minimal. The flexibility resources may include on-site energy storage systems and the demand-side flexibility. Due to the high urban energy demand, the local energy production from DERs of a single micro-grid is very less in comparison to the energy requirements from the main grid. So, the objective of micro-grids in this case would be to minimise their cost incurred from procuring energy from the main grid by optimally supplementing the energy from their local DERs.

This study is being carried out for potential use-cases in the future campus of Singapore Institute of Technology (SIT) and JTC industrial developments in the Punggol Digital District (PDD) in the north-east of Singapore. The study area contains DERs such as solar photovoltaic (PV), waste-to-energy generation, and battery energy storage systems (BESS) and both controllable demand such as centralized cooling and electric vehicles, and non-controllable demand. The scope of this study is to size the storage flexibility optimally to maximize the benefit of such flexibility in these networked micro-grids.

There are several methods which have implemented to find the optimal BESS size, namely mixed-integer linear programming (MILP) [1]–[3], mixed-integer quadratic programming (MIQP) [4], iterative method [5], genetic algorithm (GA) [6], [7], and particle swarm optimization (PSO) [8]–[10]. In [4], a MIQP based optimization is proposed to size the BESS and perform energy management system (EMS) rule in shipboard power system which consists of diesel generators, PV, and BESS. Impact of discharge current, life cycle and initial investment cost on BESS size are investigated. In [1], an optimization method based on MILP to determine the optimal size of BESS, technology, depth-of-discharge (DOD), and replacement year by considering operation constraints, service life and capacity degradation was proposed. In [5], a two-layer optimization method consisting of optimal BESS sizing in the outer layer and economic dispatch in the inner layer was used. In [7], both GA and PSO were used to find the optimal siting and optimal BESS size by minimizing cost caused by voltage deviation, power loss, and peak demand in the distribution network. In [8], the authors utilized PSO to solve a multi-objective optimization problem for battery sizing in hybrid electric vessels considering DOD, lifespan and replacement.

This paper aims to present optimal sizing of BESS and their operation in the micro-grid based on historical whole-sale electricity price from the power system operator, i.e., Energy Market Authority (EMA), Singapore. Capital (CAPEX) and operational (OPEX) expenditures of various DERs, such as PV system and BESS, are considered in order to reduce overall cost to the prosumer. A MILP-based optimization has been applied to determine the size of the BESS and manage its operation to minimize total cost of the micro-grids.

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II. SYSTEM AND PRICE TRENDS

A. Micro-grid demand

The campus has various loads that contribute to the overall demand. Non-cooling loads such as operation of electrical equipment, cooling load for temperature control and electric vehicle (EV) chargers placed in carparks have been considered for this case study. Fig. 1 shows a typical demand profile of the SIT campus and JTC, which are the 2 micro-grids considered in this study.

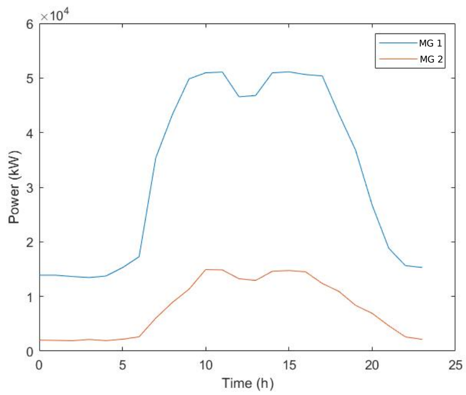

Fig. 1: Typical demand profile of the micro-grids considered in this study.

B. Distributed Energy Resources

1) Photovoltaic system: The PV system is installed atop rooftop buildings across the campus. It is estimated that micro-grid 1 may have a cumulative production potential and capacity of 1.4 GWh per year or 3.8 MWh per day with an installed capacity of 1.1 MWp. The industrial micro-grid 2 is estimated likewise to have a production potential anof 1.9 GWh per year or 5.2 MWh per day with a 1.82 MWp sikar system installation respectively. Fig. 2 shows the expected production from the PV system for 24 hours, generated using the total rooftop area and the typical meteorological year weather data (TMY) [11].

The CAPEX is estimated with the assumption of SGD 1200/kWp, amounting to a total of SGD 1.32 million. The OPEX is SGD 10 000/kWp [12]. The lifespan of PV is 20 years.

2) Battery energy storage system: The BESS participates in energy arbitrage by storing/charging energy from the grid and discharging its energy for micro-grid consumption under favourable conditions. The BESS is mainly used for cost-savings and also for local contingency plans. We consider the use of a lithium-ion BESS. The BESS energy capacity is capped at 600 kWh for the academic campus micro-grid 1 and 10 MWh for the industrial campus micro-grid 2. The battery efficiency is set to 87 % [13]. The reference life cycle and reference depth of discharge are 8000 cycles and 80 % respectively [14].

The cost per kWh energy and per kW power are estimated to be SGD 450/kWh and SGD 110/kW [15], respectively. The

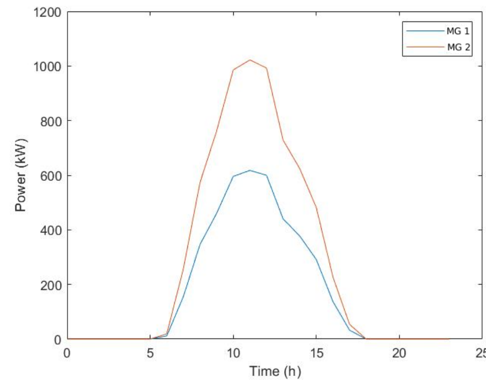

Fig. 2: Typical daily PV peak profile on SIT campus and JTC.

OPEX is assumed at 1 % of total CAPEX per year. The BESS parameters are listed in detail in Table I.

C. Market price trends

Consumers can participate in the wholesale electricity market where they are subject to price fluctuations. The Energy Market Company (EMC) operates the wholesale electricity market and has a historical record of wholesale prices [16]. The wholesale electricity price (WEP) is the prevailing price paid by the consumer and is updated every half hour.

Historical WEPs from May 2021 to Apr 2022 have been extracted. Fig. 3 shows the monthly WEP median prices over 24 h. Prior to Oct 2021, there was no significant monthly variation in WEP prices. However due to increase of energy prices in late 2021, the WEP also increased. By examining each figure individually, there are obvious local regions of maximum and minimum prices. These can be identified as ideal points of charging the BESS at lower WEP and discharging at higher WEP.

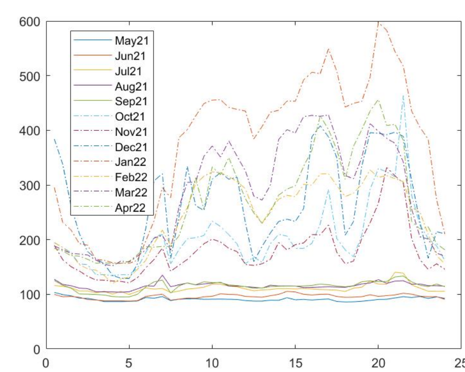

Fig. 3: Monthly median WEP from January 2022 to April 2022.

III. MILP-BASED OPTIMIZATION

In this section, a mathematical formulation of the sizing optimization is described as a MILP problem. The sources of

Name	Value	Remark
Battery energy cost	SGD 450/kWh	
Battery power cost	SGD 110/kW	
Service life	20 years	
Replacement	1	No. of replacements to meet service life
Efficiency	0.87	Round-trip eff. (BESS and power conversion) [13]
DOD	80 %	≤ 8000 cycles [14]
Number of cycles per day	2	$\frac{8000}{(1+n_{rep})*365}$
OPEX	1 %	Percentage of CAPEX
Interest	6 %	interest rate

TABLE I: Summary of CAPEX and OPEX associated with the DERs.

electricity are (1) the main grid, (2) discharging from BESS, and (3) operation of the PV system. Conversely, the loads are (1) aggregated load demand of the micro-grid (inclusive of cooling, non-cooling and EV loads) and (2) charging of BESS. The objective of the optimization is to minimize both micro-grid operation cost (cost incurred by purchasing electricity from the main grid) and BESS investment cost. The BESS investment cost consists of CAPEX, OPEX (e.g. maintenance cost), financing cost, and replacement cost. The optimal size of BESS depends on both rated energy (Wh) and rated power (W), which are calculated from the objective function (1) and constraints (2)–(9). The equality constraint in equation (2) ensures that the load demand in the micro-grid and supply power from both main grid and DERs are balanced at any time. The energy balance in the BESS is given by equality constraint (3). The BESS power is limited by equation (4) for charge and equation (5) for discharge. BESS power and maximum number of cycles per day constraint are given by equation (6) and (8). The maximum energy rating of the BESS is capped at 600 kWh for micro-grid 1 and 10 MWh for micro-grid 2. We assume that the total power output of the DERs will not exceed the load demand of the micro-grid as given in equation (9)). Hence, the electricity generated from the micro-grid shall not be sold to the main grid, but solely be utilised for demand within the micro-grid.

Nomenclature

- P_{grid} Power drawn from main grid
- $P_{b,dis}$ Power discharged from BESS
- $P_{b,ch}$ Power charged to BESS
- P_{pv} Power output from PV cells
- P_d Power load demand
- $P_{b,size}$ BESS power rating
- $P_{pv,size}$ PV power rating
- $E_{b,size}$ BESS energy rating
- $E_{b,max}$ BESS maximum energy rating
- E BESS energy
- $N_{cyc,day}$ Max. no. of BESS cycles per day
- DOD BESS depth-of-discharge
- C_{grid} Total cost incurred by the main grid
- $Cost_{b,kWh}$ Cost of BESS per kWh
- $Cost_{b,kW}$ Cost of BESS per kW
- $Cost_{pv,kW}$ Cost of PV per kW
- $OPEX_b$ BESS annual operating expenditure
- $OPEX_{pv}$ PV annual operating expenditure
- WEP Wholesale electricity price
- η_{batt} Battery efficiency
- CRF_b BESS Capital Recovery Factor
- CRF_{pv} PV Capital Recovery Factor
- i Interest rate
- N_b BESS lifespan in years
- N_{pv} PV lifespan in years
- z BESS mode
- Δt time step

$$Min(C_{grid}(k)) = Min[\sum_{k=1}^{24}[(P_{grid}(k) * WEP(k)] + (1+n_{rep}) * \frac{(CRF_b + OPEX_b)}{365} * (E_{b,size} * Cost_{b,kWh} + P_{b,size} * Cost_{b,kW}) + \frac{CRF_{pv}}{365} * (P_{pv,size} * Cost_{pv,kW}) + \frac{OPEX_{pv}}{365}] \quad (1)$$

$$P_{grid}(k) + P_{pv} + z(k) * P_{b,dis}(k) = P_d(k) + (1 - z(k)) * P_{b,ch}(k) \quad (2)$$

$$E(k+1) = E(k) + ((1 - z(k)) * \eta * P_{b,ch}(k) - z(k) * P_{b,dis}(k)) * \Delta t \quad (3)$$

$$0 \leq P_{b,ch}(k) \leq P_{b,size} \quad (4)$$

$$0 \leq P_{b,dis}(k) \leq P_{b,size} \quad (5)$$

$$0 \leq E(k) \leq DOD * E_{b,size} \quad (6)$$

$$E_{b,size} \leq E_{b,max} \quad (7)$$

$$\sum_{k=1}^{24}[|(E(k+1) - E(k))/(2 * E_{b,size})| \leq N_{cyc,day}] \quad (8)$$

$$P_{pv} + z(k) * P_{b,dis}(k) \leq P_d(k) \quad (9)$$

$$CRF_b = \frac{i * (1+i)^{N_b}}{((1+i)^{N_b} - 1)} \quad (10)$$

$$CRF_{pv} = \frac{i * (1+i)^{N_{pv}}}{((1+i)^{N_{pv}} - 1)} \quad (11)$$

To minimize the total cost, the MILP optimizer determines the BESS operation (e.g. charge or discharge mode) and BESS size to obtain the most of electricity cost savings based on the input given to the optimizer. Inputs to the MILP comprise time-dependent variables such as P_{pv} and WEP and constant parameters such as $Cost_{b,kWh}$, $Cost_{b,kW}$, $Cost_{pv,kW}$, $N_{cyc,day}$, n_{rep}, $E_{b,max}$, CRF_b, CRF_{pv}, $OPEX_b$, $OPEX_{pv}$, η and Δt. CRF in equations 10 and 11 determines equal annual payment of an asset over a period of time. The decision variables consist of E, $P_{b,ch}$, $P_{b,dis}$, P_{grid}, $E_{b,size}$, $P_{b,size}$, and z. Variable z is a binary variable which sets the BESS mode ($z = 0$ for charging, $z = 1$ for discharging).

IV. Scenarios, Results and Analyses

A. Scenarios

Three different scenarios are defined and investigated to perform a cost-benefit study as follows: Scenario 0: The reference scenario. All demands are fulfilled by the grid. Scenario 1: The micro-grid has only PV as DER. Scenario 2: The micro-grid has both PV and BESS as DERs. The BESS operation is managed by the MILP-based energy management strategy described before. In this sizing study, a median WEP from January 2022 to April 2022 in Fig. 4 was used as electricity price in equation (1).

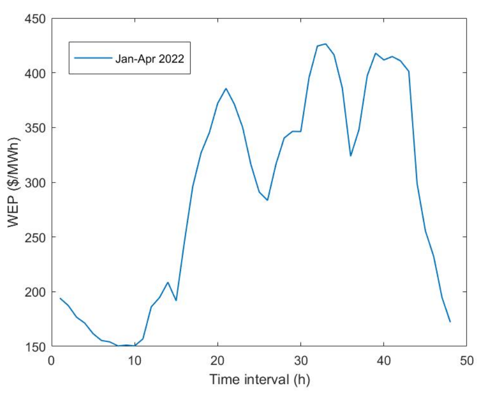

Fig. 4: Median WEP from January 2022 to April 2022 and monthly WEP.

B. Results and analyses

From Table II, the optimal size of the BESSs are 600 kWh, 82.75 kW and 10 MWh, 1.3 MW for micro-grid 1 and micro-grid 2, respectively. In scenario 0, average daily cost in micro-grid 1 and micro-grid 2 are SGD 78 371 and SGD 313 150. The cost in scenario 0 is solely based on electricity cost incurred from the main grid. The electricity cost is calculated based on the average of the daily electricity cost from January 2022 to April 2022. In scenario 1 and 2, the average daily cost consists of electricity cost and investment cost of the DERs. In Table II, the percentage of average daily savings in scenarios 1 and 2 in micro-grid 1 are 1.62 % and 1.66 % respectively. The percentage of average daily savings in scenarios 1 and 2 in micro-grid 2 are 0.67 % and 0.82 % respectively. Average daily savings are obtained by subtracting average daily cost in scenario 0 from average daily cost in scenario 1 or 2. The percentage of savings derived from the DERs are rather small in comparison to the total cost. The reason is the insignificant amount of power generation from the DERs in comparison to the load as shown in Fig.5 and Fig.6. Furthermore, with optimal BESS size and operation in scenario 2, the savings in scenario 1 can be increased further by 2 % in micro-grid 1 and 22 % in micro-grid 2. The substantial increase in micro-grid 2 is credited to the size of the BESS (10 MWh for microg-grid 2 vs. 600 kWh for micro-grid 1). To ensure that the BESS can meet the target of service life as stated in Table I, the optimizer limits the amount of energy throughput in the BESS to two cycles per day. The daily energy profiles of micro-grid 1 and 2 are given in Fig. 7 and Fig. 8.

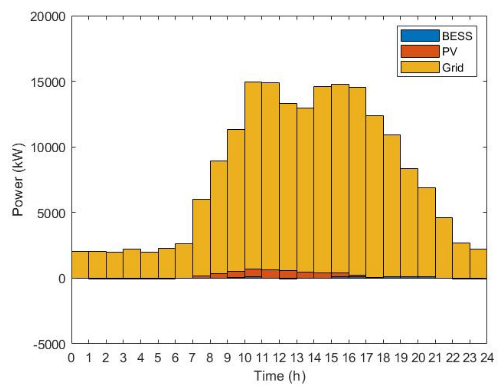

Fig. 5: Grid, BESS, and PV power profile in micro-grid 1.

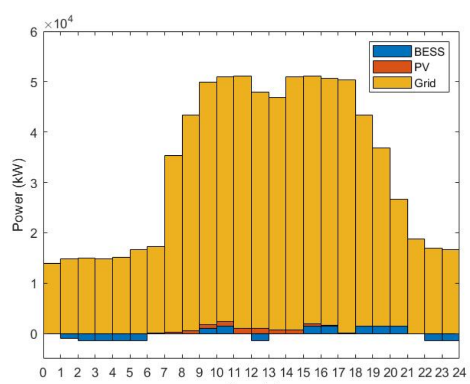

Fig. 6: Grid, BESS, and PV power profile in micro-grid 2.

TABLE II: Scenario comparison with varying inclusions of DERs and EMS.

	Academic campus			Industrial campus		
	0	1	2	0	1	2
DERs	–	PV	PV, BESS	–	PV	PV, BESS
EMS	No	No	Yes	No	No	Yes
BESS Energy	–	–	600 kWh	–	–	100 MWh
BESS Power	–	–	82.75 kW	–	–	1.38 MW
Avg. daily cost (SGD)	78 371	77 100	77 070	313 150	311 040	310 558
Avg. daily savings (SGD)	–	1271	1301	–	2110	2592
Avg. daily savings (%)	–	1.62	1.66	–	0.67	0.82

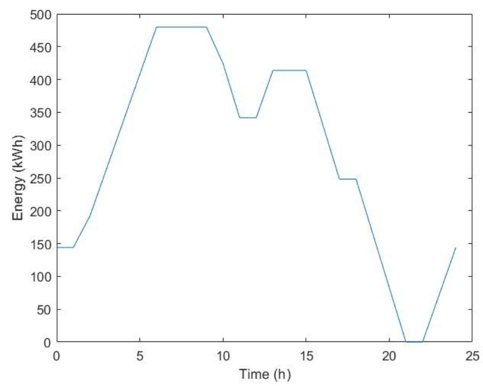

Fig. 7: BESS energy profile in micro-grid 1.

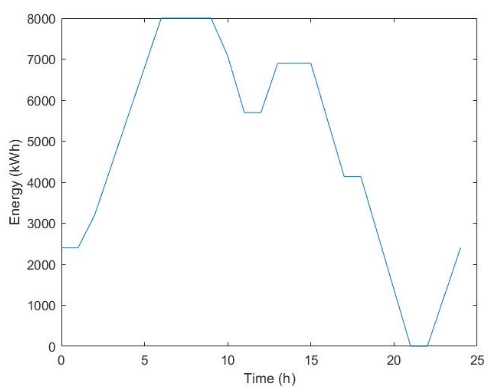

Fig. 8: BESS energy profile in micro-grid 2.

V. Conclusion

In this work, a MILP-based optimization for optimal BESS sizing in micro-grids has been presented. The optimizer determines the BESS size and its operation which minimizes the total cost including electricity cost, investment cost and replacement cost, and satisfies technical constraints. To validate the effectiveness of the optimizer, several scenarios were investigated. Using the optimizer, total cost can be reduced by 1.62 % and 0.82 % in the two micro-grids, respectively. Comparison with more complex control of BESS can be interesting to model in the future along with stacked revenue options such as grid service participation with BESS.

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