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Optimal sizing and dispatch schedule of battery storage in grid-connected microgrid

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***Abstract*—Battery storage can provide considerable benefits in renewable energy transitions. However, high capital and maintenance costs become the main barriers to its implementation. To overcome the challenges, using the battery storage in multiple applications and incorporating optimization method are proven to be able to increase its economic benefits. Accordingly, the underlying question of this thesis is whether the economic benefits from using the battery to accommodate energy arbitrage and manage demand charge while also implementing optimization method can hurdle its high costs.**

During the optimization process, battery usage cost which sometimes being neglected in prior studies is deliberated, and its impact on the total cost of the battery is analyzed. The dispatch schedule optimization is built using mixed-integer programming algorithm with the objective function to minimize lifecycle costs of the battery storage. The optimization is simulated for 8-days time horizon.

Sustainable floating residentials, a microgrid project in Amsterdam, is used as a study case. The microgrid component consists of solar photovoltaic, load, and battery. Vanadium-redox battery technology is investigated using the optimization method. Day-ahead based rate is used as the electricity pricing scheme.

The results demonstrate that utilizing the battery for multiple applications might increase its economic benefits and overcome its high initial and operating costs. Another notable result is that the battery usage cost tends to have a significant impact on the total costs of the battery. Considering battery usage cost in the optimization method could reduce the total costs.

***Index Terms*—battery, optimization, microgrid, dispatch schedule, sizing**

I. INTRODUCTION

By coordinating and optimizing the operation of various energy sources and loads, microgrid technology offers an opportunity to improve the energy consumption in systems. Microgrid could be also a pinpoint of sustainable and reliable future model of prosumer since it might able to provide power, store energy, and reduce demand as needed. It incorporates generators, load, storage, and control devices to operate either connected to or isolated from centralized grid. Generators integrated in microgrid usually are renewable sources such as photovoltaic (PV), wind turbine, or fuel cell. These renewable sources are known to be challenging due to the intermittency and volatility characteristics. One of potential solutions to these challenges is energy storage.

Besides solving the intermittency and volatility challenges, energy storage could also provide economic benefits for the microgrid owner. It can store energy during low electricity prices periods and use the stored energy at times of high prices. Hence, it can help reducing energy cost and demand charge. Furthermore, energy storage might also be utilized for load following, voltage and frequency regulation, deferral of upgrade investment, and carbon emission reduction [1].

Finding optimal size should be performed when considering energy storage in a microgrid. Small energy storage might not provide economic benefits or desired flexibility as aimed in advance, while large energy storage system requires higher investment and maintenance cost to the microgrid. Consequently, an optimal size of the energy storage system should be determined where the reduction cost in operating the system is larger than the additional cost required to install it.

Scheduling and sizing the energy storage for various applications has become an actively pursued research topic. Especially for arbitrage accommodation and demand charge management applications. For instance, authors of [2] propose a method to optimize schedule for virtual power plant in order to accommodate the arbitrage using battery storage. Scheduling and sizing of energy storage to assist the arbitrage is also proposed to be determined in [3] by incorporating wind power, solar PV, microturbines and fuel cells, and battery storage in microgrid. In [4], the authors propose a method to scheduling and sizing energy storage for arbitrage accommodation and demand charge management applications. For these multiple applications, lead-acid battery is utilized. The optimization algorithm used in the article is mixed-integer programming (MIP). To the best of found knowledge, only this article discusses scheduling and sizing for these multiple applications.

In order to determine the optimal sizing, not only economic but also technical aspects should be considered. In [5], the authors criticize many papers which neglect technical aspects of battery storage, i.e. depth of discharge (DoD), operating temperature, lifetime, etc., to model. A study includes battery usage in a model, but simplify it as fixed cost [4]. As a consequence, the model cannot capture the effect of different DoD in battery usage cost which might lead to an expensive discharge cycle in reality. Another cost which most papers neglects is demand charge since it is extremely rare in residential case. Though, in industries and commercial customers, demand charge might reach half of the electricity bill [6]. Thus, demand charge might be an attractive option for future residential [7].

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In this study, an optimization method for dispatch schedule and sizing is proposed to obtain maximum economic benefits from battery which is used for energy cost and demand charge applications in a grid-connected microgrid system. Incorporating the battery storage system to the microgrid increases capital cost. Consequently, the objective of this study would be to minimize the summation of the capital cost and operating cost.

In order to obtain more realistic model, this study includes more comprehensive operating cost compared to previous studies, including electricity cost, battery usage cost, battery losses cost, and demand charge. The proposed method comprised of two stages: (1) optimizing the dispatch schedule and (2) optimizing the size. The dispatch schedule optimization is implemented using MIP, while the sizing optimization is performed using heuristic search.

TABLE II
PARAMETERS IN LIFECYCLE COST OF BATTERY STORAGE

Lifecycle costs elements	Cost element
Battery capital cost (C_{cap})	Battery banks
PCS (C_{PCS})	Power interconnection (converter, rectifier) Cabling and piping
BOP (C_{BOP})	Battery isolation and protection devices (switches, fuses) Monitoring and control systems (voltage and frequency control) Shipment and installation cost
Fixed O&M ($C_{OM,fixed}$)	Maintenance Taxes Administrative expenses
Variable O&M (C_1)	Electricity cost (C_{energy}) Battery usage cost (C_{usage}) Battery losses cost (C_{losses}) Demand charge (C_{demand})

II. METHODS

A. Optimization methods

The goal of this study is to build a method to determine the optimal size of the battery based on user input. The input and output of this method are listed in Table 1.

TABLE I
LIST OF INPUT FOR OPTIMIZATION

Battery data	Energy capacity costs Round trip efficiency Lifetime Power conversion system (PCS) costs Balance-of-plant (BOP) costs O&M costs Initial battery capacity Battery current rate (C-rate) Number of cycles as a function of DoD
Distributed generation (DG) data	Size Fuel consumption curve coefficients Carbon emission factor Oxides of nitrogen emission factor Sulphur dioxides emission factor
Solar PV generation profile	
Load profile	
Electricity price	
Economic parameter	Discount rate

B. Problem formulation

1) Objective function: The goal of this proposed method is to minimize lifecycle costs of the battery storage. Objective function which represents the lifecycle costs comprises of 9 different cost components as depicted in I. The objective function is divided into two phases of optimization. The first phase is to minimize variable O&M cost C_1 and the second phase is to minimize total cost of microgrid C_2.

The first phase of the optimization, which is formulated in Equation 1, can be solved using MIP algorithm.

$$C = min[\sum_{i=1}^{T_a}(C_{energy}(i) + C_{losses}(i) + C_{usage}(i) + C_{fuel}(i)) + \sum_{j=1}^{m} C_{demand}(j)] \quad (1)$$

The second phase of the optimization as depicted in Equation 2 is solved using heuristic search.

$$C_2 = min[C_1 + C_{cap} + C_{PCS} + C_{BOP} + C_{OM,fuel}] \quad (2)$$

As mentioned, the objective of the method is to determine the optimum solution subjected to system costs and constraints.

a) Energy charge: Energy charge is a cost of buying electricity from the main grid. In this study, the electricity price used is day-ahead based which is a real-time pricing.

$$C_{energy}(i) = P_{GridDrawn}(i) \cdot \cos t_{energy}(i) \quad (3)$$

b) Battery losses cost: A battery possesses conversion losses during charging and discharging depending on its roundtrip efficiency as written in Equation 4. The losses occur on the battery stored energy. In this study, the losses are assumed to be compensated by electricity from the main grid, thus, the power losses are multiplied by the energy tariff.

$$P_{Losses}(i) = (P_B(i) - P_B(i-1))(1 - \eta_B) \quad (4)$$

$$C_{Losses}(i) = P_{Losses}(i) \cdot \cos t_{energy}(i) \quad (5)$$

c) Demand charge: Demand charge is a cost which needs to be paid based on the microgrids maximum peak demand during the whole month. The peak demand is measured over a peak period of 60 minutes [7]. The microgrids owner is charged based on the average demand over that peak period.

$$C_{demand}(j) = \max_{1 \le i \le Tm} P_{GridDrawn}(i) \cdot \cos t_{demand} \quad (6)$$

d) Battery usage cost: Battery usage cost is a monetized parameter for battery capacity degradation. The irreversible effect of degradation process is occurred when the battery is active (cyclic aging) and inactive (calendric aging). Cyclic loss is a proportion of performed cycles from the total life cycles for a certain DoD [8]. Cost of cyclic loss, thus, is a product of cyclic loss and battery investment cost as written in Equation 9. Meanwhile, calendric loss depends on the battery operating temperature and idle time [9] which its cost is formulated in Equation 10. Total battery usage cost is a sum of cyclic and calendric aging cost as in Equation 11.

$$DoD(i)P_{BMax} + P_B(i) = P_{BMax} \tag{7}$$

$$N_{DoD}(i) = f(DoD(i)) \tag{8}$$

$$C_{cyclic}(i) = \frac{1}{2}C_{cap}\left(\frac{1}{N_{DoD(i)}} - \frac{1}{N_{DoD(i-1)}}\right) \tag{9}$$

$$C_{calendric}(i) = \frac{1}{2}C_{cap}\left(1.544 \cdot 10^5 \cdot e^{\frac{-40498}{8.31437T}} \cdot \frac{1}{720}\right) \tag{10}$$

$$C_{usage}(i) = C_{cyclic}(i) + C_{calendric}(i) \tag{11}$$

e) Battery system capital cost: Battery system capital cost can be calculated on yearly basis by multiplying it with capital recovery factor (CRF) as formulated in Equation 13.

$$C_{cap,a} = C_{cap} \cdot CRF = C_{cap}\frac{d}{1-(1+d)^{-n}} \tag{12}$$

C. Constraints

To prevent deep discharge of battery, the battery capacity at time step i should be higher than the minimum battery capacity and lower than the total battery capacity as formulated in Equation 13. Equation 14 reveals the charge and discharge rate of battery should be limited. Fast charging and discharging rate might lead to accelerated capacity reduction. While Equation 15 ensures the power balance of the microgrid system at every time step i. Equation 16 helps to set bound for grid capacity at each time step i.

$$P_{BMin} \leq P_B(i) \leq P_{BMax} \tag{13}$$

$$P_{MaxDischarge} \leq P_B(i) - P_B(i-1) \leq P_{MaxCharge} \tag{14}$$

$$P_{Grid}(i) = P_B(i) - P_B(i-1) + P_L(i) - P_{PV}(i) - P_{DG}(i) \tag{15}$$

$$P_{GridMin} \leq P_{Grid}(i) \leq P_{GridMax} \tag{16}$$

TABLE III
INPUT PARAMETERS FOR VANADIUM-REDOX BATTERY

Stochastic input parameters	
Roundtrip efficiency (%)	75
Energy capacity costs (€/kWh)	110
Lifetime (years)	12.5
Deterministic input parameters	
O&M costs (€/kW per year)	43
BOP costs (€/kW)	63
PCS costs (€/kW)	271
Initial battery capacity (%)	60
C-Rate	5C
LCOE input parameters	
Battery energy capacity (kWh)	250
Power rating (kW)	100

III. CASE STUDY

A. Simulation environment

The considered time horizon is 192 hours which represents typical days for different seasons (winter, spring, summer, and autumn). Solar PV array and battery generate DC power which is inverted to AC by bidirectional inverters. These bidirectional inverters and other power electronics such as DC-DC converters and battery management system (BMS) are assumed to be lossless. Vanadium-redox which has high power, long life, low maintenance requirements, and no self-discharge is a battery technology involved in this study. Parameters for this battery technology are shown in Table III.

Solar PV generation profile based on historical data in Amsterdam is shown in Figure 1. This profile is obtained from solar PV array with a nameplate capacity of 150 kWp. Figure 2 presents the load profile from sustainable floating residential in Amsterdam, which is used for the case study. Figure 3 shows the electricity price in the Netherlands, which is a day-ahead based price. Demand charge of 8.805 kW/month is also applied in this study [9] [7], [10]. An annual discount rate of 4% is used for simulation [11].

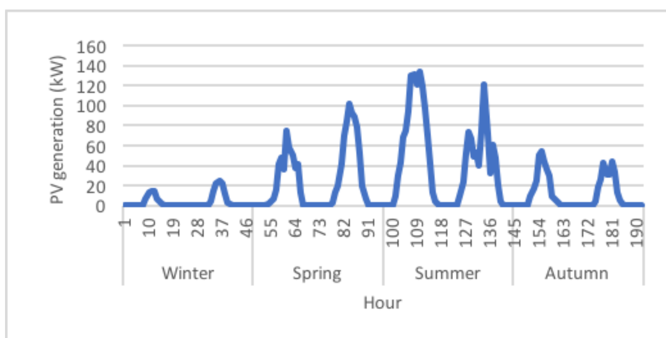

Fig. 1. Solar PV generation profile for 192 hours

B. Computational results

According to Figure 4, Utilizing vanadium-redox battery in the system could provide highest saving when the battery size is 150 kWh. This optimal size has the error margin of 9 kWh since the resolution of the proposed method is 10 kWh. The saving for the optimal capacity is around 3.76%.

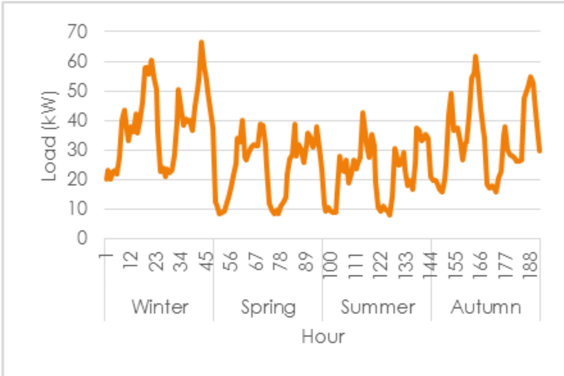

Fig. 2. Hourly load profile for 192 hours

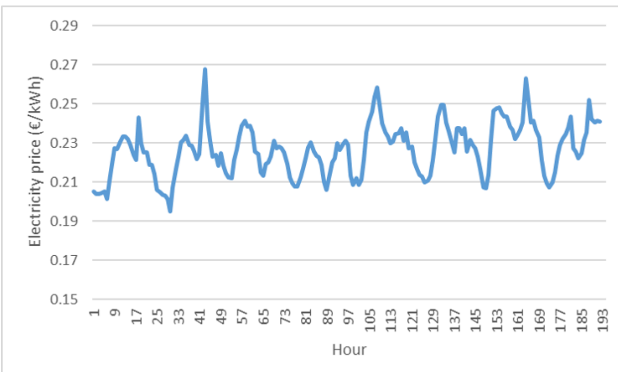

Fig. 3. Electricity price volatility

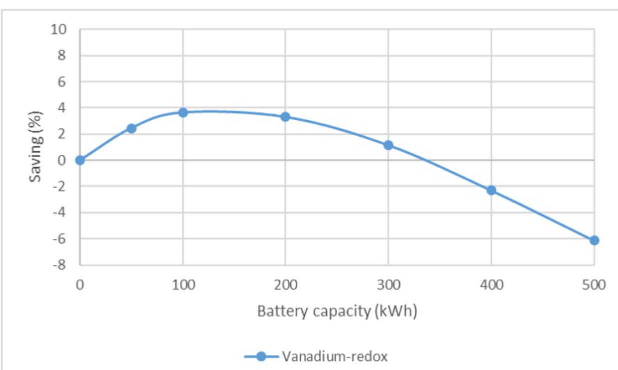

Fig. 4. Saving from vanadium-redox battery

Figure 5 depicts the optimization results of vanadium-redox battery utilization for multiple applications in the microgrid system. It illustrates the total costs and the proportion of each cost components. The total cost of the microgrid owner needs to pay when utilizing the battery for multiple applications is 3.96% lower compared to using it only for single application.

The optimal scheduling results of the microgrid system with vanadium redox battery are presented in Figure 6. The impact of involving battery usage cost in the optimization problem was conducted by comparing the DoD and the total cost between the case when the usage cost is disregarded (-U) and involved (+U). DoD is used to investigate the impact since it is one of the parameter which closely related to the

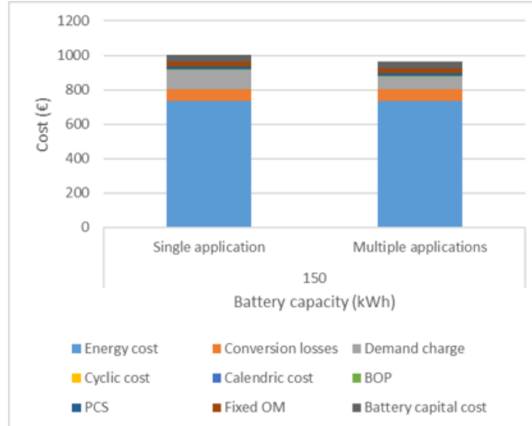

Fig. 5. Breakdown cost comparison of optimization results between single and multiple applications of vanadium-redox battery

battery usage cost [12]. By introducing battery usage cost in the optimization, the method tries to minimize the cyclic cost that leads to significant reduction of total microgrid costs.

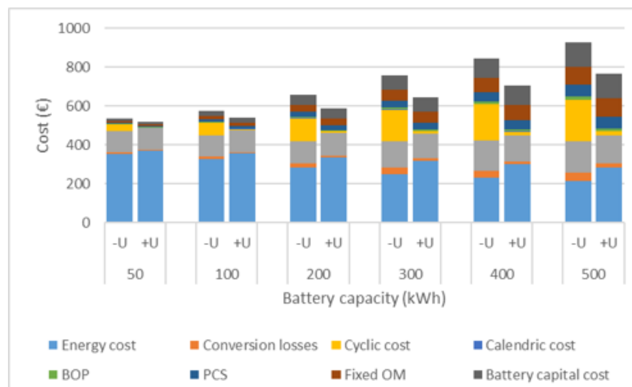

Fig. 6. Cost component comparisons between optimization which disregard (-U) and involve usage cost (+U).

IV. Conclusion

In this study, an optimization method is developed to achieve the optimal scheduling and sizing for a microgrid system with battery usage cost. Through the comprehensive analysis for the multiple applications of the battery in microgrid system, the following conclusions can be drawn:

- Usage cost, which is neglected in several studies, appeared to have a significant contribution to total battery cost. Involving usage cost in the optimization could reduce it ominously.
- In the end user level, a battery could be utilized to accommodate energy price arbitrage. The optimization method could maximize the economic benefits from the price disparity while maintaining low usage cost. The results show higher saving compared to basic charging/discharging strategy which stores the electricity during surplus periods and releases it during deficits.
- The industrial and commercial consumer need to pay demand charges for the highest 15 minutes grid consumption in a month. Utilizing battery to accommodate the

energy price arbitrage while at the same time maintaining the grid peak consumption seemed to increase the economic benefits. The results show that saving was higher when the battery was optimized for both applications.

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