Optimal Battery Capacity for Residential Rooftop PVs With Consideration of Net-Metering Scheme Compensation Period

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Abstract- With the significant increase of the prosumers in the world, the battery energy storage system (BESS) has become an important device to enhance the performance of renewable energy generation. By focusing on residential scale of rooftop PVs, BESS has been developed and applied in many aspects especially in terms of electricity charge saving. Many papers propose the methodology to control the operation of BESS, while many papers propose the methodology to determine the battery capacity. As for this paper, the proposed methodology will simultaneously determine the operation schedule and battery capacity of BESS for rooftop PVs under a net-metering scheme (NMS). The main objective is to maximize the net present value (NPV) of the prosumers. The battery capacity will be constrained by the period of the NMS compensation which will be effective for only one year of each electricity bill. The numerical results show that, for the TOU tariff structure without demand charge, an appropriate BESS should have $C_{NOM,DC}$ as high as possible to increase the revenue from BESS and have $P_{NOM,DC}$ as low as possible to reduce the total investment cost (TTC). Also, by considering the limit period of the NMS compensation, an appropriate battery capacity should not be higher than monthly residential load consumption. Lastly, the sensitivity analysis of electricity tariff shows that the NPV will increase proportionally by the increment of electricity price, which will reduce the break-even year of the investment.

Keywords Battery Energy Storage System (BESS), Electricity Charge Saving, Net-Metering Scheme (NMS), Net Present Value (NPV), Operation Schedule.

Nomenclature

Time Window of Interest

t	Time (1st hour = 1, 2nd hour = 2, …)
d	Day (1st day = 1, 2nd day = 2, …)
m	Month (1st month = 1, 2nd month = 2, …)
y	Year (1st year = 1, 2nd year = 2, …)
Δt	Length of the time interval (hours)
Y	A lifetime of the project (years)
S_d	Number of time intervals in day d
S_m	Number of time intervals in month m
S_y	Number of time intervals in year y

Rooftop PVs

$P_{PV,DC}(t)$	DC power from rooftop PVs at time t (kW)
$P_{PV}(t)$	AC power from rooftop PVs at time t (kW)
$\eta_{inverter}$	The efficiency of PV inverter (%)

Battery Energy Storage System

$P_{BESS}(t)$	AC power from BESS at time t (kW)
$C_{BESS}(t)$	Existing stored energy in BESS at time t (kWh)
$\eta_{Bi\text{-}inverter}$	The efficiency of battery inverter (%)
η_{RT}	Battery roundtrip efficiency (%)
$C_{NOM,DC}$	Nominal energy capacity (kWh)
$P_{NOM,DC}$	Nominal power capacity (kW)
C_{NOM}	AC nominal energy capacity (kWh)
P_{NOM}	AC nominal power capacity (kW)

$C_{REF}(t)$	Usable energy capacity at time t (kWh)
$P_{REF}(t)$	Usable power capacity at time t (kWh)
$SoC(t)$	State of charge at time t (%)
$C_{BESS, Max}(t)$	Maximum usable energy capacity (kWh)
$C_{BESS, Min}(t)$	Minimum usable energy capacity (kWh)
SoC_{Max}	Maximum state of charge (%)
SoC_{Min}	Minimum state of charge (%)
EP	Energy to power ratio
T_{BESS}	A lifetime of BESS (hours)
$P_{BESS, Max}(t)$	Maximum usable power capacity at time t (kW)
$P_{BESS, Min}(t)$	Maximum usable power capacity at time t (kW)

Integrated Residential Power Components

$r_y(t)$	Electricity tariff at time t in year y (THB/kWh)
$P_G(t)$	AC power from the grid at time t (kW)
$P_L(t)$	Load consumption at time t (kW)
$R_G(t)$	Net electricity charges at time t (THB/kWh)
$R_{G,Month}(m)$	Electricity charges at month m (THB/Month)
$R_L(t)$	Electricity charges from the load consumption at time t (THB/kWh)
$R_{PV}(t)$	Electricity charge savings from the rooftop PVs at time t (THB/kWh)
$R_{BESS}(t)$	Electricity charge savings from BESS at time t (THB/kWh)

Total Cost of BESS

j	Christian Era (2017, 2018, …)
$c_{EIC}(j)$	Energy installation cost at year j (THB/kWh)
$c_{PIC}(j)$	Power installation cost at year j (THB/kW)
$c_{TIC}(j)$	Total investment cost at year j (THB)
$c_{TOC}(j,y)$	Total operating cost at year y for battery investment in year j (THB)
c_{OP}	Rate of operating cost (%)
$c_{TTC}(j,y)$	Total cost at year y for battery investment in year j (THB)

1. Introduction

With the extreme growth of rooftop PVs for residential prosumers, a net-metering scheme (NMS) has been widely popular in many countries. By the end of 2018, the NMS has been implemented in at least 66 countries [1]. For example, in Thailand, timelines of the government's policy for rooftop PVs have been reported in [2]. From 2014-2016, the FiT scheme had been implemented, while from 2016-2019, the NMS has been gradually implemented especially in residential load. The trend to implement NMS seems to occur not only in Thailand, but also in some other countries. Therefore, this paper will consider only the NMS.

To enhance the benefit from rooftop PVs, the battery energy storage system (BESS) is applied. Many studies proposed the methodology to implement BESS with various approaches [3-6]. One of the major applications of BESS is customer energy management services [7-9]. For BESS with residential scale of rooftop PVs, the relevant studies mostly focused on the benefit of prosumers and can be classified into two main issues: (1) battery capacity sizing and (2) operation scheduling.

For battery capacity sizing, the proposed method to determine a battery capacity for a grid-connected PVs under the NMS was presented in [10]. The objective was to minimize the electricity charges and the investment while satisfying the peak shaving requirement by using the Mixed Integer Linear Programming (MILP). This approach was efficient but did not consider the NMS compensation period, which is the period that the excess energy from rooftop PVs can be effective, and the details of the total cost of BESS (TTC). In [11], the Genetic Algorithm (GA) was used to optimally investigate the size of the rooftop PVs and BESS under the self-consumption scheme. The concept of minimizing the total cost of Home Energy Management System (HEMS), including the total investment cost and the total operating cost was applied. However, the lifetime and the optimal operation schedule of BESS were not considered. Another application of GA for battery sizing was presented in [12]. An approach to design hybrid renewable energy system, which consists of PVs, wind generator and BESS, was proposed by considering multi-objective function. However, the details of the total cost and operation scheduling were not considered.

For battery scheduling for rooftop PVs under the NMS, the effective and convenient method was proposed in [13]. The objective was to maximize the operation saving while limiting the reverse power flow to the grid by applying the Quadratic Programming (QP). However, the proposed method was not appropriate for long term planning since the TTC and the lifetime of BESS were not taken into account. In [14], an approach for daily operation scheduling under the TOU tariff structure with a demand charges and self-consumption scheme was developed. The real-coded Genetic Algorithms (RCGAs) was used to minimize the energy and demand charges. However, this method was not appropriate for long term planning since the TTC and the detailed characteristics of BESS were not considered. An alternative mode-based approach for designing a real-time operation schedule of BESS by considering the rooftop PVs was proposed in [15]. By using the MILP, the proposed method was aimed to minimize the electricity charges and BESS degradation cost was determined. However, this approach did not considered the details of the total cost of BESS (TTC). In [16], the notable approach for BESS scheduling of BESS under the TOU tariff structure and NMS was proposed. The objective function was to minimize the energy and demand charges by formulating the problem to Linear Programming (LP). This method was convenient for long term planning and appropriate for further studying on battery capacity sizing.

Besides, some other studies proposed an approach for simultaneous investigation on battery capacity and operation schedule of BESS as follows. In [17], the Linear Programming (LP) was used to optimally determine the battery capacity and operation schedule of BESS under the FiT. The objective was to minimize the cost of electricity and the cost of battery degradation. The proposed method for optimal design of the integrated PVs, BESS and electric vehicle charging vehicle station system (PBES) was presented in [18]. The capacity of PVs and BESS together with the operation schedule under the NMS was determined by considering the electric vehicle charging patterns. The Multi-Agent Particle Swarm Optimization Algorithm (MAPSO) was used to minimize the levelized cost of electricity (LCOE). However, the proposed approach did not consider the lifetime of BESS and the NMS compensation period as well.

In the literature, the papers relevant to battery capacity sizing mostly focused on maximizing the electricity charge savings, while minimizing the total cost of BESS and rooftop PVs. For the battery scheduling, most papers also target to maximize the electricity charges. The MILP and LP is a convenient and effective algorithm for long term scheduling. However, the NMS compensation period, which significantly affects the battery capacity, has never been mentioned in the past researches. Therefore, this paper proposes a methodology to investigate the battery capacity and operation schedule of BESS for the prosumers who have already installed the rooftop PVs under the NMS (the cost and benefit of the rooftop PVs are excluded in this paper). The installed capacity of rooftop PVs is assumed to be equal to the maximum load of a monthly load profile for peak load shaving only. The objective is to maximize the net present value (NPV) of the prosumers while the electricity selling is constrained by the NMS compensation period. The main contributions of this paper are shown as follows:

- An optimization model simultaneously determining the appropriate battery capacity and operation schedule is proposed by considering the total cost (TTC) and the lifetime of BESS.
- The details of the NMS compensation period, which limit the benefit of electricity selling is considered to achieve a higher accuracy of battery capacity sizing.
- Linear Programming Optimization is applied in terms of the matrix form to solve the problem with a fast calculation time.

This paper is organized as follows. The modeling of residential power components consisting of rooftop PVs, BESS, residential load, and integrated system is presented in Section 2. Cost and benefit modeling from electricity charge savings is presented in Section 3. Section 4 presents the proposed methodology consisting of the detailed NMS compensation and problem formulation. The simulation results are shown in Section 5, and then the conclusions are drawn in Section 6.

2. Modeling of Residential Power Components

To formulate the problem, the modeling of residential power components (rooftop PVs, BESS, residential load, and integrated system) is applied in this paper. A brief explanation of these modeling is as follows.

2.1. Rooftop PVs

To produce power to the grid at time t, rooftop PVs convert $P_{\mathrm{PV,DC}}(t)$ from the PV module to $P_{\mathrm{PV}}(t)$ using an inverter, as shown in Eq. (1). Note that PV module degradation is neglected in this paper.

$$P_{\mathrm{PV}}(t) = P_{\mathrm{PV,DC}}(t) \times \eta_{\mathrm{inverter}} \tag{1}$$

2.2. Battery Energy Storage System

BESS converts DC to AC via the bi-directional battery inverter. The operation schedule of BESS is typically classified into the two modes of discharging and charging. For discharging, the discharged power from BESS is injected into the grid ($P_{\mathrm{BESS}}(t) \geq 0$). On the other hand, for charging, charged power from the grid is injected into BESS ($P_{\mathrm{BESS}}(t) < 0$). The amount of charged/discharged power depends on $C_{\mathrm{BESS}}(t)$, which can be determined from Eq. (2) [13].

$$C_{\mathrm{BESS}}(t) = C_{\mathrm{BESS}}(0) - \sum_{n=1}^{t} P_{\mathrm{BESS}}(n) \times \Delta t \tag{2}$$

Typically, BESS can be characterized by the following parameters (Energy Capacity, State of Charge, Power Capacity, and Lifetime of Battery):

- Energy Capacity

Nominal battery energy capacity ($C_{\mathrm{NOM,DC}}$) is the rated capacity of a battery module in kWh. To convert from DC to AC, a roundtrip efficiency (η_{RT}) and bi-directional battery inverter efficiency ($\eta_{\mathrm{Bi\text{-}inverter}}$) are considered as shown in (3). Other than the energy capacity, $C_{\mathrm{REF}}(t)$, which is the amount of energy that the battery can be fully charged with or discharged from at time *t*, is also considered in this paper. In theory, without the degradation of BESS, $C_{\mathrm{REF}}(t)$ is equal to C_{NOM}. However, $C_{\mathrm{REF}}(t)$ is practically lower due to the degradation of BESS [19-20], which will be addressed later.

$$C_{\mathrm{NOM}} = C_{\mathrm{NOM,DC}} \times \eta_{\mathrm{Bi\text{-}inverter}} \times \eta_{\mathrm{RT}} \tag{3}$$

- State of Charge

The state of charge ($SoC(t)$) of the battery is the existing stored energy in the battery ($C_{\mathrm{BESS}}(t)$) divided by the usable energy capacity ($C_{\mathrm{REF}}(t)$), as shown in Eq. (4) [19-21]. By applying Eq. (4) with the boundary of the state of charge, the lower and upper limits of $C_{\mathrm{BESS}}(t)$ can be determined by Eqs. (5) and (6), and so $C_{\mathrm{BESS}}(t)$ is constrained by Eq. (7).

$$SoC(t) = \frac{C_{\mathrm{BESS}}(t)}{C_{\mathrm{REF}}(t)} \times 100\% \tag{4}$$

$$C_{\mathrm{BESS,Min}}(t) = SoC_{\mathrm{Min}} \times C_{\mathrm{REF}}(t) \tag{5}$$

$$C_{\mathrm{BESS,Max}}(t) = SoC_{\mathrm{Max}} \times C_{\mathrm{REF}}(t) \tag{6}$$

$$C_{\mathrm{BESS,Min}}(t) \leq C_{\mathrm{BESS}}(t) \leq C_{\mathrm{BESS,Max}}(t) \tag{7}$$

- Power Capacity

Besides the energy capacity, the battery performance can also be interpreted in terms of the power in kW, known as the power capacity ($P_{\mathrm{BESS,NOM}}$). The energy to power (*EP*) ratio, which is the ratio between C_{NOM} and $P_{\mathrm{BESS,NOM}}$, can be applied with $C_{\mathrm{REF}}(t)$ to illustrate $P_{\mathrm{BESS,Max}}(t)$, as shown in Eqs. (8) and (9), respectively, while the magnitude of $P_{\mathrm{BESS,Min}}(t)$ in this paper is assumed to be equal to the magnitude of $P_{\mathrm{BESS,Max}}(t)$, as shown in Eq. (10) [19-21].

$$EP = \frac{C_{\mathrm{NOM,DC}}}{P_{\mathrm{NOM,DC}}} \quad (8)$$

$$P_{\mathrm{BESS,Max}}(t) = \frac{C_{\mathrm{REF}}(t)}{EP} \quad (9)$$

$$P_{\mathrm{BESS,Min}}(t) = -P_{\mathrm{BESS,Max}}(t) \quad (10)$$

- Lifetime of Battery

A lifetime of battery (T_{BESS}) in this paper is expressed in terms of calendric life, so that it will be more practical and convenient to apply to the financial aspect. The lifetime of a lithium-ion battery is degraded only at the end of the year and assumed to be a linear function [19, 22], as shown in Fig. 1. Therefore, $C_{\mathrm{REF}}(t)$ in each time t can be formulated as shown in Eq. (11), where L(t) is the battery degradation coefficient, which can be determined from Eq. (12). Note that lifetime of the lithium-ion battery is counted when $C_{\mathrm{REF}}(t)$ falls to 80% and the self-discharge is neglected in this paper.

$$C_{\mathrm{REF}}(t) = L(t) \times C_{\mathrm{NOM}} \quad (11)$$

$$L(t) = \begin{cases} L(t-1)\ ; & \dfrac{t}{S_y / \Delta t} \notin \mathrm{I} \\ 0.80 \times \left(\dfrac{t}{T_{\mathrm{BESS}}}\right) + \left(1 - \dfrac{t}{T_{\mathrm{BESS}}}\right) ; & \dfrac{t}{S_y / \Delta t} \in \mathrm{I} \end{cases} \quad (12)$$

2.3. Residential Load in Thailand's TOU Tariff Structure

The electricity tariff in Thailand is divided into the Normal, TOU (Time of Use), and TOD (Time of Date) structure [23]. For load profiles in Thailand's distribution systems, there are classified into eight groups. This paper considers only residential load with a TOU tariff structure, which is one of the target groups for the installation of rooftop PVs with an incentivized self-consumption scheme in Thailand as shown in Fig. 2. The electricity tariff is 4.2097 THB/kWh during on-peak period and 2.6295 THB/kWh during off. Note that load growth is neglected in this paper.

2.4. Integrated System

Configurations of a BESS with rooftop PVs are commonly categorized into AC or DC coupling systems [24]. Typically, the AC coupling system is for prosumers who already have an installed rooftop PVs. Due to the efficiency and existing technology, BESS with rooftop PVs and load in this paper is integrated with AC coupling systems as shown in Fig. 3. $P_{\mathrm{PV}}(t)$, $P_{\mathrm{G}}(t)$, $P_{\mathrm{L}}(t)$, and $P_{\mathrm{BESS}}(t)$ are subject to the power balance equation as shown in Eq. (13), where $R_{\mathrm{G}}(t)$ is the electricity charges at time t and can be determined from Eq. (14). The electricity charges on month m can be shown in terms of $R_{\mathrm{G,Month}}(m)$, which can be determined from $R_{\mathrm{PV}}(t)$, $R_{\mathrm{L}}(t)$ and $R_{\mathrm{BESS}}(t)$, as shown in Eqs (15)–(17).

$$P_{\mathrm{G}}(t) = P_{\mathrm{L}}(t) - (P_{\mathrm{PV}}(t) + P_{\mathrm{BESS}}(t)) \quad (13)$$

$$R_{\mathrm{G}}(t) = P_{\mathrm{G}}(t) \times \Delta t \times r_y(t) \quad (14)$$

$$R_{\mathrm{G,Month}}(m) = \sum_{t=1}^{S_{\mathrm{m}}} R_{\mathrm{G}}(t) \quad (15)$$

$$R_{\mathrm{G,Month}}(m) = \sum_{t=1}^{S_{\mathrm{m}}} r_y(t) \times P_{\mathrm{G}}(t) \times \Delta t \quad (16)$$

$$R_{\mathrm{G,Month}}(m) = \sum_{t=1}^{S_{\mathrm{m}}} \left[R_{\mathrm{L}}(t) - (R_{\mathrm{PV}}(t) + R_{\mathrm{BESS}}(t)) \right] \quad (17)$$

3. Cost and Benefit Modeling

The cost and benefit modeling of a BESS is proposed in this section. There are two subsections, which consist of the modeling of the total cost (TTC) and the benefit from electricity charge savings. Note that the currency exchange rate in this paper is assumed to be 35 Baht/USD.

3.1. Total Cost Modeling

Typically, the cost of BESS can be classified into two groups, the total investment cost (TIC) and the total operating cost (TOC). For the TIC, this paper considers only in terms of the hardware costs, including the cost of battery module, cost of battery inverter and balance of system cost [24]. The hardware costs are categorized by components of BESS into energy and power components.

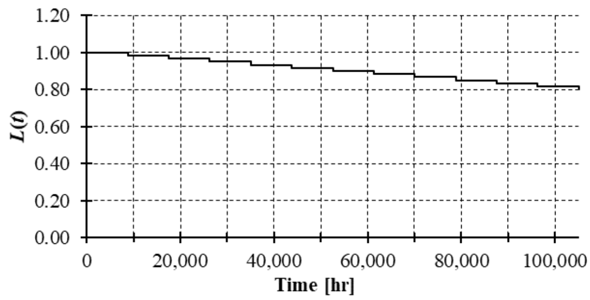

Fig. 1. Battery degradation coefficient

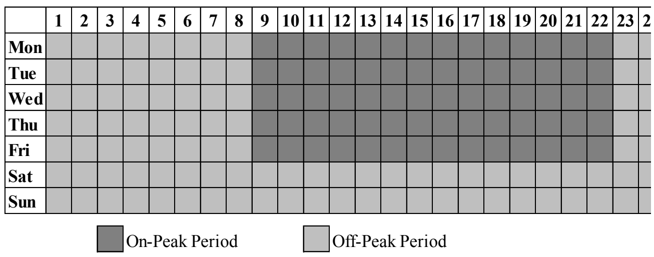

Fig. 2. TOU tariff structure in Thailand

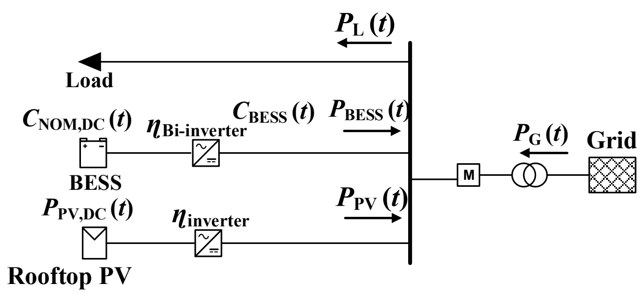

Fig. 3. Integrated system

For the energy component, the battery module cost is modeled in terms of THB/kWh, known as the energy installation cost ($c_{EIC}(j)$). $c_{EIC}(j)$ is determined by extrapolating the historical average cost of a lithium-ion battery module from the Bloomberg New Energy Finance (BNEF) [25], as shown in Fig. 4 (solid line). For the power components, including the battery inverter cost and balance of system cost, are modeled in terms of THB/kW, and are known as the power installation cost ($c_{PIC}(j)$ [21, 25]. $c_{PIC}(j)$ is determined by extrapolating the historical cost from BNEF and NREL [25-26], as shown in Fig. 4 (dash line). As a result, the TIC can be modeled in terms of $c_{EIC}(j)$, $c_{PIC}(j)$, $C_{NOM,DC,}$ and $P_{NOM,DC}$ as shown in Eq. (18).

$$c_{TIC}(j) = c_{EIC}(j)\times C_{NOM,DC} + c_{PIC}(j)\times P_{NOM,DC} \tag{18}$$

For the TOC ($c_{TOC}(j,y)$), this paper assumes to be 1% of the TIC and constant. By applying the Discount Cash Flow model (DCF), $c_{TOC}(j,y)$ can be modeled as shown in Eq.(19). It should be noted that y is the year applied for cash flow calculation starting from year 1,which is the first investment year of BESS. However, j is the Christian Era applied for extrapolating TIC, e.g. 2017, 2018, …, etc.

$$c_{TOC}(j,y) = \sum_{y=1}^{Y}\frac{c_{OP}c_{TIC}(j)}{(1+i)^{y-1}} \tag{19}$$

Therefore, by integrating the TIC and the OMC, the TTC can be modeled as shown in Eq.(20).

$$c_{TTC}(j,y) = c_{TIC}(j) + c_{TOC}(y) \tag{20}$$

3.2. Benefit of Battery Energy Storage System

The focused benefit from BESS in this paper is the electricity charge savings, which can be formulated as shown in Eq. (21). $r_y(t)$ is electricity tariff at time *t,* which will be escalated in each year *y*.

$$R_{BESS}(t) = r_y(t)P_{BESS}(t)\Delta t \tag{21}$$

To evaluate the profitability of an investment, the NPV is applied in this paper in terms of $R_{BESS}(t)$ and $c_{TTC}(j,y)$, as shown in Eq. (22). By substituting Eq.(20) into (22), the NPV can be determined as shown in Eq. (23). Note that the lifetime of the project (Y) is assumed to be equal to the lifetime of BESS in this paper.

$$\text{NPV} = \sum_{y=1}^{Y}\sum_{m=1}^{S_y}\sum_{t=1}^{S_m}\frac{R_{BESS}(t)}{(1+i)^{y}} - c_{TTC}(j,y) \tag{22}$$

$$\text{NPV} = \sum_{y=1}^{Y}\sum_{m=1}^{S_y}\sum_{t=1}^{S_m}\frac{R_{BESS}(t)}{(1+i)^{y-1}} - \sum_{y=1}^{Y}\frac{c_{OP}c_{TIC}(j)}{(1+i)^{y-1}} - c_{TIC}(j) \tag{23}$$

3. Proposed Methodology

This section presents a proposed methodology to simultaneously determine the battery capacity and operation schedule of BESS for maximizing the electricity charge savings of prosumers. There are two subsections, which consist of net-metering scheme compensation and problem formulation.

3.1. Net-Metering Scheme Compensation

The NMS allows the prosumers to get their benefit at the retail rate from the net energy injected into the grid [27-28]. Typically, the benefit is effective within one year starting from the initial date of the electricity. As shown in Fig. 5, when $R_G(t)$ is negative (total supplied energy from rooftop PVs and BESS exceed the total load consumption in a month), the excess energy can be transferred to compensate for electricity bills in another month. However, the period of compensation for excess energy must not be over the limitation of the time frame, which is typically one year. The NMS compensation period constraint is one of the significant points which will limit the benefit from BESS and impact on battery capacity sizing.

This paper will take into account the NMS compensation period and formulate it as one of the constraints of the linear optimization programming as shown in Eq.(28).

3.2. Problem Formulation

This paper applies the CPLEX Linear Programming in Matlab programming to investigate a battery capacity and operation schedule [29]. $c_{EIC}(j)$ and $c_{PIC}(j)$ are determined by selecting the year j as shown in Fig. 4. The objective function is to maximize the NPV of the investment in BESS for prosumers, as shown in Eq. (24). The decisive variables are $C_{NOM,DC}$, $P_{NOM,DC}$, $P_{BESS}(t)$.

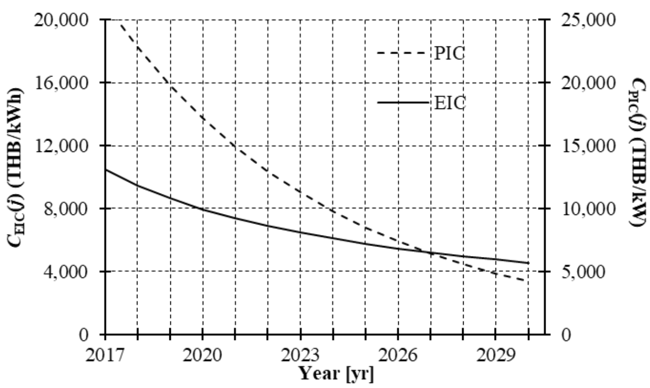

Fig. 4. Energy and power installation cost

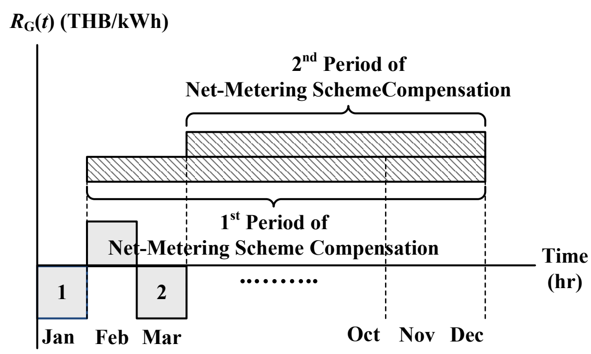

Fig. 5. The net-metering scheme compensation period

The constraints in this paper can be classified into four groups, i.e. the constraints of energy capacity, power capacity, E/P ratio, and the NMS compensation. The energy capacity constraint is formulated in terms of an inequality constraint by substituting Eqs. (2), (5) and (6) into Eq. (7) to derive Eqs. (25). The power capacity constraint is formulated in terms of an inequality constraint, as shown in Eqs. (26). To comply with the practical design of BESS, the E/P ratio constraint is formulated in terms of an inequality constraint to limit the E/P ratio, as shown in Eq. (27). The constraint of the NMS compensation is formulated as shown in Eq. (28).

Objective Function

$$\text{Maximize NPV} \tag{24}$$

Decisive Variables: $C_{\text{NOM,DC}}$, $P_{\text{NOM,DC}}$, $P_{\text{BESS}}(t)$

Subject to:

$$C_{\text{BESS,Min}}(t) \le C_{\text{BESS}}(0) - \left(\sum_{n=1}^{t} P_{\text{BESS}}(n) \times \Delta t\right) \le C_{\text{BESS,Max}}(t) \tag{25}$$

$$P_{\text{BESS,Min}}(t) \le P_{\text{BESS}}(t) \le P_{\text{BESS,MAX}}(t) \tag{26}$$

$$EP_{\text{Min}} \le EP \le EP_{\text{Max}} \tag{27}$$

$$\sum_{m=1}^{S_y}\sum_{t=1}^{S_m}\left[R_{\text{L}}(t) - (R_{\text{PV}}(t) + R_{\text{BESS}}(t))\right] \ge 0 \tag{28}$$

4. Simulation Results

The simulation results, which consist of optimal battery capacity and sensitivity of electricity tariff, are presented in this section, and are based on the residential load profile from the MEA and the rooftop PV profile from Chulalongkorn University as shown in Fig. 6 and 7 respectively. Also, the parameters and assumptions for the simulation in this paper are shown in Table 1. Note that load growth and PV module degradation are neglected in this paper.

Table 1. Parameters and assumptions

Parameters	Assumptions
1. Time Window Of Interest (Δt)	1.00 hr
2. Install Capacity of the Rooftop PVs (kW)	1.00 kW
3. Efficiency of the PV Inverter (%)	95.00%
4. Efficiency of the Battery Inverter (%)	95.00%
5. Rountrip Efficiency	80.00%
5. Maximum state of charge (%)	90.00%
6. Minimum state of charge (%)	10.00%
7. Initial state of charge (%)	30.00%
8. Lifetime of the battery (y)	12 y
9. Discount rate (i)	1.50%
10. Rate of operating cost (%)	1.00%
11. EP_{Max} / EP_{Min}	10/0.5

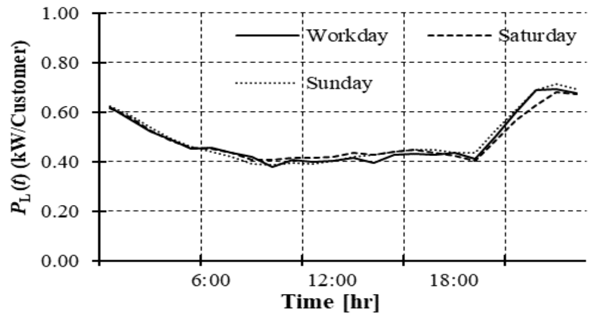

Fig. 6. Residential load profile

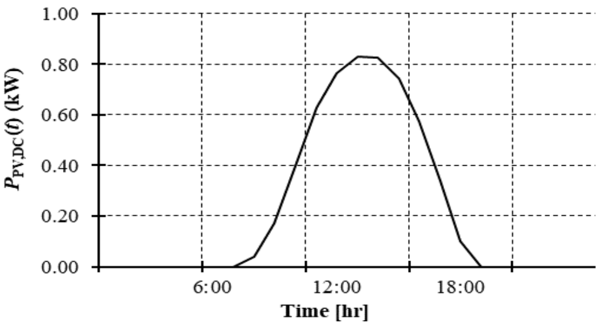

Fig. 7. Rooftop PVs profile

3.1. Optimal Battery Capacity

In this subsection, the optimal battery capacity is determined by the proposed methodology. The simulation results consist of the NPV break-even year, operation schedule, and battery capacity as follows. Note that the growth rate of electricity tariff is neglected in this subsection.

- NPV Break-Even Year

The comparison of the NPV of BESS in each year is presented as shown in Table 2. By considering the cost trend of BESS and the TOU tariff structure for Thailand's residential prosumers in this paper, the NPV break-even year is 2030. During 2017-2019, BESS should not be installed because the investment is not economically viable due to the high TTC comparing with the revenue from BESS. After 2030, the investment in BESS becomes economically viable. In the years 2030 and 2031, the NPV of BESS is 10.26 THB and 2,910.61 THB respectively. The NPV of BESS significantly increases due to the significant decrease of the TTC. It should be noted that the optimal $C_{\text{NOM,DC}}$ and $P_{\text{NOM,DC}}$ are not changed because the load growth is neglected in this paper.

Table 2. NPV break-even year

Parameter	Year				
	2017	…	2029	2030	2031
Revenue (THB)	No appropriate BESS			68,612.70	68,612.70
Total Cost (THB)				68,602.44	65,702.09
NPV (THB)				10.26	2,910.61
$C_{\text{NOM,DC}}$ (kWh)				9.75	9.75
$P_{\text{NOM,DC}}$ (kW)				0.975	0.975
E/P ratio				10	10

➢ Operation Schedule

The one-week operation schedule of BESS is presented in terms of the $SoC(t)$ and $P_G(t)$ as shown in Fig. 8 and 9 respectively. The operation schedule in this section is determined based on the investment of BESS in the year 2030.

It is obvious that the main factor that impacts on the operation schedule in this paper is the Thailand TOU tariff structure which can be divided into four scenarios, i.e., workdays (Tuesday–Thursday), pre-weekend workday (Friday), weekends (Saturday–Sunday) and post-weekend workday (Monday). In each scenario, the operation schedule can be classified into three patterns due to the different possible operation schedules during first and second off-peak period as shown in Table 3.

(1) Workdays (Tuesday–Thursday)

During the first off-peak period (0:00–9:00 h), the first charging occurs to prepare BESS for discharging during the on-peak period. BESS is charged until 80% of $SoC(t)$, which is the upper limit of $C_{BESS}(t)$. Then, during the on-peak period (9:00–22:00 h), BESS is charged and discharged repeatedly. However, the amount of discharged energy is higher than the amount of charged energy. Finally, during the first off-peak period (22:00–23:59 h), the first charging occurs. The first charging is to raise the $C_{BESS}(t)$ to the same level at the beginning of the day. Therefore, BESS is charged until 30% of the $SoC(t)$.

(2) Pre-weekend workday (Friday)

During the first off-peak period, the first charging occurs. After that, during the on-peak period, the first discharging occurs similarly on Tuesday–Thursday. The operation schedule during the first off-peak period is classified into the two possible cases of charging and no operation. To prepare for the next on-peak period on Monday, BESS can be either charged or idled during this period and charged anytime between the Friday evening and Monday morning.

(3) Weekends (Saturday and Sunday)

For weekends, there is only an off-peak period. Therefore, similar to Friday evening, BESS can be charged anytime during the weekend to prepare for the next peak-period on Monday.

Table 3. Summary of operation schedule

Time/Operation		Tue–Thu	Fri	Sat–Sun	Mon
0:00 –9:00	Discharging				
	Charging	●	●	●[1]	●[1]
	Idling			●[2]	●[2]
9:00 – 22:00	Discharging	●	●		●
	Charging			●[1]	
	Idling			●[2]	
22:00 – 0:00	Discharging				
	Charging	●	●[1]	●[1]	●
	Idling		●[2]	●[2]	

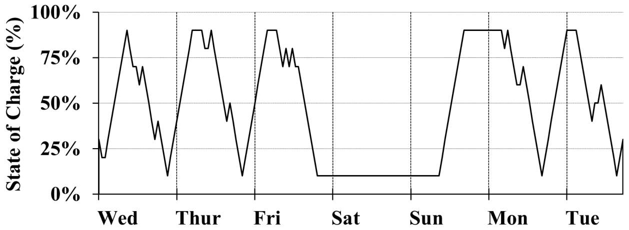

Fig. 8. State of charge in one week

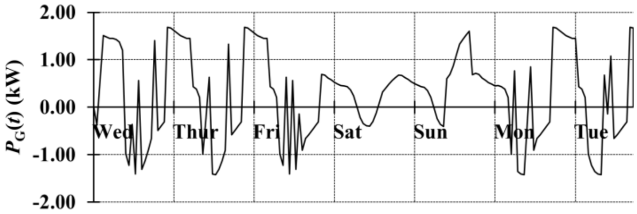

Fig. 9. Output power from grid in one week

(4) Post-weekend workday (Monday)

During the first off-peak period, there are two possible cases, either charging or idling. BESS can be charged to prepare for discharging, but if $C_{BESS}(t)$ reaches the upper limit before Monday BESS would be idled. In addition, during the on-peak period, BESS is discharged while during the first off-peak period BESS is charged similarly to the operation schedule on Tuesday–Thursday.

➢ Battery Capacity

In this part, the comparison of the battery capacity is presented based on the TIC in the year 2030, as shown in Fig. 10. The appropriate battery capacity from the proposed methodology is the capacity that will maximize the NPV of the investment of BESS. Due to the NMS compensation period, BESS operates to reduce the monthly electricity charges to be approximately zero. Therefore, the appropriate $C_{NOM,DC}$ is 9.75 kWh, which is not higher than monthly residential load consumption (11 kWh).

In the details, for the battery capacity, the maximum NPV is calculated based on the optimal capacity as shown in Fig. 10(a). In case that $C_{NOM,DC}$ is higher than the optimal capacity, due to the NMS compensation period, the NPV is reduced because of the decrease of revenue and the increase of the TTC as shown in Fig. 10(b) and 10(c), respectively.

For the power capacity, the appropriate $P_{NOM,DC}$ is 0.975 kW, which reaches the upper limit of E/P ratio as shown in Fig. 10(a). In case that $C_{NOM,DC}$ is higher or equal to the optimal capacity, the high E/P ratio (low $P_{NOM,DC}$) will lead to the high NPV because of the constant revenue and the increased TTC, as shown in Fig. 10(b) and 10(c), respectively. On the other hand, in case that $C_{NOM,DC}$ is lower than the optimal capacity, the low E/P ratio (high $P_{NOM,DC}$) will lead to a high NPV because of the increased revenue and the decreased TTC as shown in Fig. 10(b) and 10(c), respectively.

To sum up, the maximization of NPV maximizes the benefit of electricity charge savings and minimizes the TTC. As a result, the proposed methodology maximizes $C_{NOM,DC}$ and minimizes $P_{NOM,DC}$ due to the TOU tariff structure for the residential load in Thailand, which has only energy charge.

$C_{NOM,DC}$ is mainly influenced by load consumption and has a greater impact on the electricity charge savings than $P_{NOM,DC}$. Moreover, both $C_{NOM,DC}$ and $P_{NOM,DC}$ are limited by the constraints of the NMS compensation and the E/P ratio, respectively.

3.2. Electricity Tariff Sensitivity

In this section, the effect of electricity tariff is assessed by comparing the growth rate of electricity tariff and NPV as shown in Fig. 11. The NPV will increase when the electricity tariff rises because the revenue from BESS increases while the TTC is unchanged. $C_{NOM,DC}$ and $P_{NOM,DC}$ in each case are equal because the load consumption is identical.

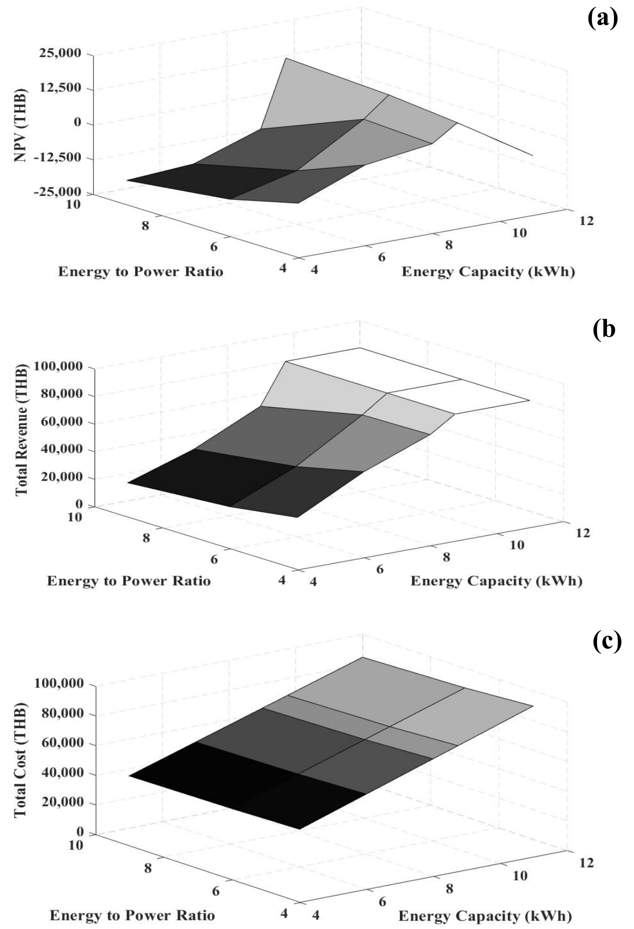

Fig. 10. The comparison of battery capacity in terms of (a) NPV, (b) Total revenue, and (c) Total cost

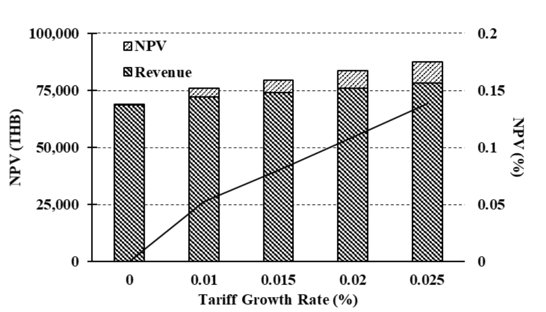

Fig. 11. The sensitivity of electricity tariff

5. Conclusion

According to the simulation results, the installation of BESS for electricity charge savings is not economically viable at present for a residential load in Thailand. However, by projecting the TIC, the installation of BESS will be economically viable after 2030.

In this paper, an appropriate BESS should have $C_{NOM,DC}$ as high as possible to increase the revenue from BESS and has $P_{NOM,DC}$ as low as possible to reduce the TTC. $C_{NOM,DC}$ has a higher impact on electricity charge saving than $P_{NOM,DC}$, due to the Thailand TOU tariff structure for residential load, which consists only of energy charge. However, the optimal $C_{NOM,DC}$ should not be over the monthly load consumption due to the NMS compensation period. Oversized battery capacity will lead to decreased NPV because of the NMS revenue limitation. Another significant factor is the growth rate of electricity tariffs. The higher rate will lead to higher NPV, which will bring BESS to be feasible faster than the prediction.

For the operation schedule of BESS, the charging will occur anytime on Friday evening, Saturday, Sunday, and Monday morning to prepare for the discharging. The discharging will mostly occur during the on-peak period of workdays. The charging and discharging of BESS are limited by the constraints of the battery energy capacity and battery power capacity. Moreover, there will be an increase of reverse power flow feeding back to the grid during the peak time of rooftop PVs (10:00 AM – 2:00 PM), which negatively affects the utility operation. However, BESS still has a positive effect by decreasing the demand during peak time at night. For the sensitivity of electricity tariff, by varying the growth rate of electricity tariff, the NPV will increase when the electricity tariff rises due to the increase in revenue gained from BESS. To sum up, the battery energy capacity is mainly influenced by load consumption and the NMS period, while the battery power capacity is mainly influenced by E/P ratio. The TTC and electricity tariff directly affect the NPV.

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