OPTIMAL SIZING OF BATTERY ENERGY STORAGE SYS TEM WITH ROOFTOP PV GENERATION SYSTEM

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การเลือกขนาดระบบกักเก็บพลังงานประเภทแบตเตอรี่ที่เหมาะสมร่วมกับระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคา

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ชวินทร์ ประภานุกูล : การเลือกขนาดระบบกักเก็บพลังงานประเภทแบตเตอรี่ที่เหมาะสมร่วมกับระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคา. (OPTIMAL SIZING OF BATTERY ENERGY STORAGE SYSTEM WITH ROOFTOP PV GENERATION SYSTEM) อ.ที่ปรึกษาหลัก : รศ. ดร.สุรชัย ชัยทัศนีย์

การเติบโตอย่างรวดเร็วของระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคาภายใต้การเชื่อมต่อประเภทหลังมิเตอร์นั้น ทำให้ระบบกักเก็บพลังงานประเภทแบตเตอรี่ได้รับการพัฒนาขึ้นเพื่อเพิ่มประสิทธิภาพในการผลิตไฟฟ้าจากระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคาในหลากหลายรูปแบบการใช้งาน โดยหนึ่งในการรูปแบบที่สำคัญ และได้รับความนิยม คือ การใช้งานเพื่อลดค่าไฟฟ้า ทั้งนี้โดยทั่วไปการเชื่อมต่อประเภทหลังมิเตอร์นั้นจะ สามารถจำแนกออกเป็น 3 ประเภท ได้แก่ รูปแบบการเชื่อมต่อเพื่อการผลิตไฟฟ้าแบบใช้เอง รูปแบบการเชื่อมต่อเพื่อการผลิตไฟฟ้าแบบหักลบหน่วยอัตโนมัติ และรูปแบบการเชื่อมต่อเพื่อการผลิตไฟฟ้าแบบแยกหน่วยซื้อขายไฟฟ้า นอกเหนือจากรูปแบบมาตรฐานดังกล่าวแล้ว ในปัจจุบันรูปแบบที่กำลังพัฒนา และได้รับความนิยม คือ รูปแบบสัญญาซื้อขายไฟฟ้าตรงจากผู้ผลิตไฟฟ้า รูปแบบดังกล่าวนี้นักลงทุน หรือผู้ผลิตไฟฟ้าจะเสนอขายไฟฟ้าจากระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคาให้กับผู้ใช้ไฟฟ้าโดยตรงโดยไม่ผ่านทรัพย์สินของการไฟฟ้า อาทิเช่น มิเตอร์ไฟฟ้า สายป้อนในระบบจำหน่าย เป็นต้น โดยราคาที่ผู้ผลิตไฟฟ้าเสนอขายนั้นโดยทั่วไปจะอยู่ในรูปแบบของส่วนลดจากอัตราค่าไฟฟ้าตามช่วงเวลาของการใช้ของการไฟฟ้า ดังนั้น วิทยานิพนธ์ฉบับนี้จึงนำเสนอถึงวิธีการคำนวณหาขนาด และตารางการทำงานของระบบกักเก็บพลังงานประเภทแบตเตอรี่ รวมถึงอัตราส่วนลดค่าไฟฟ้าที่เหมาะสม สำหรับระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคาภายใต้การเชื่อมต่อประเภทหลังมิเตอร์ และรูปแบบสัญญาซื้อขายไฟฟ้าตรงจากผู้ผลิตไฟฟ้า โดยการคำนวณหาตารางการทำงานของระบบกักเก็บพลังงานประเภทแบตเตอรี่นั้นจะพัฒนาจากหลักการทำงานตามโหมดของแบตเตอรี่ ซึ่งสามารถประยุกต์ใช้ได้กับทุกรูปแบบของการเชื่อมต่อประเภทหลังมิเตอร์ และรูปแบบสัญญาซื้อขายไฟฟ้าโดยตรงจากผู้ผลิตไฟฟ้า ทั้งนี้ สำหรับวิธีการคำนวณหาขนาด และรูปแบบการทำงานของระบบกักเก็บพลังงานประเภทแบตเตอรี่ที่เหมาะสม ภายใต้การเชื่อมต่อประเภทหลังมิเตอร์นั้นจะมีวัตถุประสงค์เพื่อลดค่าใช้ไฟฟ้าของผู้ใช้ไฟฟ้าให้มากที่สุดเท่านั้น ในขณะที่สำหรับรูปแบบสัญญาซื้อขายไฟฟ้าโดยตรงจากผู้ผลิตไฟฟ้านั้นจะมีวัตถุประสงค์ที่ลดค่าใช้ไฟฟ้าของผู้ใช้ไฟฟ้าให้มากที่สุด โดยที่จะสามารถรักษาระดับอัตราผลตอบแทนภายในของนักลงทุนได้ อีกทั้งในวิทยานิพนธ์ฉบับนี้จะประยุกต์ใช้อัตราค่าไฟฟ้าตามช่วงเวลาของการใช้ของการไฟฟ้านครหลวง สำหรับผู้ใช้ไฟฟ้าขนาดใหญ่ เพื่อวิเคราะห์ถึงผลกระทบของขนาดกำลังผลิตติดตั้งของระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคา ขนาดของระบบกักเก็บพลังงานประเภทแบตเตอรี่ อัตราขายสำหรับไฟฟ้าส่วนเกิน และการเสื่อมของแบตเตอรี่ โดยจากผลการวิเคราะห์จะพบว่า กำลังผลิตติดตั้งของระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคา และอัตราขายสำหรับไฟฟ้าส่วนเกินนั้นส่งผลกระทบต่อ ขนาด และรูปแบบการทำงานของระบบกักเก็บพลังงานประเภทแบตเตอรี่ รวมถึงอัตราส่วนลดค่าไฟฟ้าที่เหมาะสม โดยสำหรับรูปแบบของการเชื่อมต่อประเภทหลังมิเตอร์นั้น การเพิ่มขนาดกำลังผลิตติดตั้งของระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคาจะทำให้ขนาดของระบบกักเก็บพลังงานประเภทแบตเตอรี่ และการทำงานในโหมดจ่ายไฟฟ้า และรับไฟฟ้ามีค่าสูงขึ้น เมื่อมีการอนุญาตให้มีกระแสไฟฟ้าไหลย้อนเข้าสู่ระบบ และมีอัตราขายสำหรับไฟฟ้าส่วนเกินสูงกว่าอัตรารับซื้อไฟฟ้า โดยการพิจารณาการเสื่อมของแบตเตอรี่จะทำให้ขนาดของระบบกักเก็บพลังงานประเภทแบตเตอรี่มีค่าสูงขึ้น ในขณะที่สำหรับรูปแบบสัญญาซื้อขายไฟฟ้าโดยตรงจากผู้ผลิตไฟฟ้านั้นอัตราส่วนลดค่าไฟฟ้าที่ผู้ผลิตไฟฟ้าเสนอจะถูกจำกัดเมื่อขนาดของระบบกักเก็บพลังงานประเภทแบตเตอรี่มีค่าสูงขึ้น และขนาดกำลังผลิตติดตั้งของระบบผลิตไฟฟ้าจากพลังงานแสงอาทิตย์แบบติดตั้งบนหลังคามีขนาดใหญ่เกินความจำเป็น โดยการพิจารณาการเสื่อมของแบตเตอรี่จะเป็นการจำกัดอัตราส่วนลดค่าไฟฟ้าที่ผู้ผลิตไฟฟ้าเสนอ

สาขาวิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อนิสิต ....
ปีการศึกษา	2563	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

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Chawin Prapanukool : OPTIMAL SIZING OF BATTERY ENERGY STORAGE SYSTEM WITH ROOFTOP PV GENERATION SYSTEM. Advisor: Assoc. Prof. SURACHAI CHAITUSANEY, Ph.D.

With a significant growth of the rooftop photovoltaic systems (PVs) under the behind-the-meter scheme (BTMS), the battery energy storage systems (BESS) have been developed to enhance the performance of rooftop PVs in many aspects, especially the electricity charge savings. The BTMS can be typically classified into three schemes of self-consumption scheme, net-metering scheme, and net-billing scheme. Other than these schemes, the solar power purchase agreement (SPPA) has been developed to be one the most attractive business models. The SPPA is the scheme where the investors propose to directly sell an electricity from rooftop PVs with BESS to the customers without passing through the utility's infrastructure, such as electricity meter, distribution line, etc. The proposed rates are typically performed in terms of the discount rates on Time-of-use (TOU) tariff. Therefore, this dissertation proposes a novel methodology to investigate the battery capacity, operation schedule of the BESS and SPPA discount rates for rooftop PVs under the BTMS and SPPA. The mode-based operation of the BESS was adopted and developed for self-consumption, net-metering, net-billing schemes, and SPPA. For the typical BTMS, the objective was only to minimize the electricity charge of the customers. For the SPPA, the main objective was to minimize the electricity charges of the customers while maintaining the internal rate of return of the investors. In addition, as a working example, the TOU tariff with demand charges for large general service load in Thailand was implemented with the proposed methodology to evaluate the effects of installed capacity of rooftop PVs, battery capacity, rate of excess energy and battery degradation. The result showed that the installed capacity of rooftop PVs, the rate of excess energy and the battery degradation have significant effects on the battery capacity, operation modes of the BESS and SPPA discount rates. Under the typical BTMS, it is obvious that an increase of the installed capacity of rooftop PVs will extremely increase the battery capacity and operation modes in charging and discharging modes when the reverse power flow is available with high rate of excess energy. In addition, the consideration of battery degradation will lead to an increase of battery capacity. Under the SPPA, the proposed SPPA discount rates from the investors will be constrained when the battery capacity is increased, and the installed capacity of rooftop PVs is oversized. The consideration of the battery degradation will also limit the proposed SPPA discount rates.

Field of Study:	Electrical Engineering	Student's Signature ....
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Chawin Prapanukool

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LIST OF ABBREVIATION

Time Window of Interest

t	Time (1st hour = 1, 2nd hour = 2, …)
t_{peak}	Time of peak output power from grid
m	Month (1st month = 1, 2nd month = 2, …)
y	Year (1st year = 1, 2nd year = 2, …)
Δt	Length of the time interval (hours)
Y	Lifetime of the project (years)
S_m^{on}	Number of on-peak time intervals in month m
S_m^{off}	Number of off-peak time intervals in month m
S_y	Number of time intervals in year y

Rooftop PVs with Battery Energy Storage Systems

$P_{\text{pv,dc}}$	Installed capacity of rooftop PVs (kW)
$P_{\text{pv}}(t)$	Output power from rooftop PVs at time t (kW)
$P_{\text{g}}(t)$	Output power from the grid at time t (kW)
$P_{\text{l}}(t)$	Load consumption at time t (kW)
$P_{\text{bess}}(t)$	Output power from BESS at time t (kW)
$P_{\text{bess,ch}}(t)$	Charged power from BESS at time t (kW)
$P_{\text{bess,dis}}(t)$	Discharged power from BESS at time t (kW)
$C_{\text{bess}}(t)$	Stored energy in BESS at time t (kWh)
$C_{\text{nom,dc}}$	Rated battery energy capacity (kWh)
C_{nom}	Usable battery energy capacity (kWh)

$C_{\text{avail}}(t)$	Available battery energy capacity at time *t* (kWh)
$P_{\text{nom,dc}}$	Rated battery power capacity (kW)
P_{nom}	Usable battery power capacity (kW)
$P_{\text{bess,ch}}^{\text{limit}}(t)$	Maximum charged power at time *t* (kW)
$P_{\text{bess,dis}}^{\text{limit}}(t)$	Maximum discharged power at time *t* (kW)
$\sigma(t)$	State of charge at time *t* (%)
σ_{max}	Maximum state of charge (%)
σ_{min}	Minimum state of charge (%)
$L(t)$	Battery degradation coefficient at time *t*
$L_{\text{op}}(t)$	Operating degradation coefficient at time *t*
$L_{\text{self}}(t)$	Self-degradation coefficient at time *t*
$N_{\text{count}}(t)$	Number of used cycles at time *t* (Cycles)
N_{total}	Total life cycles of BESS (Cycles)

TOU Tariff with Demand Charges

r^{on}	On-peak energy rate (THB/kWh)
r^{off}	Off-peak energy rate (THB/kWh)
r^{demand}	Demand charge rate (THB/kW)
$R_{\text{base}}^{\text{on}}(m)$	On-peak energy charges at month *m* (THB)
$R_{\text{base}}^{\text{off}}(m)$	Off-peak energy charges at month *m* (THB)
$R_{\text{base}}^{\text{demand}}(m)$	Demand charges at month *m* (THB)
$R_{\text{base}}^{\text{total}}(m)$	Electricity charges at month *m* (THB)

Financial Assumptions

i	Interest rate (%)
c_{op}	Rate of operating cost (%)
c_{pv}	Investment cost of rooftop PVs (THB/kW)
$c_{\text{pv}}^{\text{total}}$	Total cost of rooftop PVs (THB)
c_{eic}	Energy installation cost of BESS (THB/kWh)
c_{pic}	Power installation cost of BESS (THB/kW)
$c_{\text{bess}}^{\text{total}}$	Total cost of the BESS (THB)

Solar Power Purchase Agreement

α_1	SPPA on-peak discount rate
α_2	SPPA off-peak discount rate
β_1	SPPA demand charge discount rate
$r_{\text{sppa}}^{\text{on}}$	SPPA on-peak energy rate (THB/kWh)
$r_{\text{sppa}}^{\text{on}}$	SPPA off-peak energy rate (THB/kWh)
$r_{\text{sppa}}^{\text{demand}}$	SPPA demand charge rate (THB/kW)
$R_{\text{customer}}^{\text{on}}(t)$	On-peak energy charges of the customers at time t (THB)
$R_{\text{customer}}^{\text{off}}(t)$	Off-peak energy charges of the customers at time t (THB)
$R_{\text{customer}}^{\text{demand}}(m)$	Demand charges of the customers at month m (THB)
$R_{\text{customer}}^{\text{total}}(m)$	Total electricity charges of the customers at month m (THB)
$R_{\text{investor}}^{\text{on}}(t)$	On-peak revenue of the investors at time t (THB)
$R_{\text{investor}}^{\text{off}}(t)$	Off-peak revenue of the investors at time t (THB)
$R_{\text{investor}}^{\text{demand}}(m)$	Demand charge revenue of the investors at month m (THB)
$R_{\text{investor}}^{\text{total}}(m)$	Total revenue of the investors at month m (THB)

CHAPTER 1
INTRODUCTION

To begin with, this chapter presents with the problem statement which identifies the problem to be solved in this dissertation in Section 1.1. Then, the objective, scope of work, and steps of study are described in Section 1.2-1.4 respectively. Finally, the dissertation structure is shown in Section 1.5.

1.1 Problem Statement

With the trend in decentralized energy system, the growth of rooftop photovoltaic generation systems (PVs) under the behind-the-meter scheme (BTMS) has significantly increased in many countries [1, 2]. As for Thailand, the timelines of the government's policy for rooftop PVs have been reported in [3]. The BTMS has been gradually implemented since 2016. To enhance the capability of rooftop PVs, the implementation of battery energy storage systems (BESS) has widely expanded in various applications and evolved into the trendy topics [4, 5]. One of the major applications for the customers is the electricity charge saving which includes retail electric energy time shift and demand charge management. The combination of rooftop PVs and BESS under the BTMS is anticipated to become more effective and widely applicable in residential and commercial loads [6]. However, the major concern point is the economic feasibility of the rooftop PVs with BESS, which should be considered thoroughly.

The BTMS is the scheme where the rooftop PVs with BESS directly connected to the load without passing through the utility's meter. The BTMS can be categorized by the condition of the reverse power flow and rate of excess energy [7-10]. If the reverse power flow is unavailable, the BTMS can be called self-consumption scheme. On the other hand, if the reverse power flow is available, the BTMS can be either the net-metering scheme or the net-billing scheme depending the rate of excess energy injected to the utility's grid [11]. For the net-metering and net-billing scheme, the benefit from the excess energy is typically performed in terms of the electricity charge compensation over a specific period [12]. Hence, in view of economic aspect, the different metering scheme would significantly affect the design and operation of the rooftop PVs with BESS.

The reduction in the cost of rooftop PVs with BESS also leads the development of new relevant business models proposed by several investors. The business models of rooftop PVs with BESS based on the BTMS can be categorized into four groups of (1) community-owned solar, (2) solar power purchase agreement (SPPA), (3) solar leasing agreement, and (4) roof rental agreement [13]. One of the most attractive models in current market is the SPPA. The cumulative installed global capacity of the corporate renewable PPA schemes, including solar and wind, had reached 20 GW by the end of 2018 with most of the projects being SPPA [14]. The SPPA is the scheme where the investors act as a third party to directly sell electricity from their rooftop PVs with BESS to the customers at a lower rate than the utility's retail rate [15, 16]. The SPPA proposed rates are generally divided into the two options of a fixed rate and a discount on the utility's retail rate [17]. The discount rate option is more practical and convenient for applying with a time-of-use (TOU) tariff with demand charges. The benefit to the customers under the SPPA is the electricity charge savings without any capital investment, or operating expenses. For the investors, the challenge is the competitive SPPA discount rates that can propose to the customers, while the project remain the target internal rate of return.

Therefore, by considering the trend of the rooftop PVs with BESS under the BTMS and the growth of the SPPA, this dissertation proposes methodologies to determine the battery capacity and operation scheduling of the BESS for rooftop PVs under the BTMS and SPPA. The mode-based operation was adopted and developed for applying with self-consumption, net-metering and net-billing schemes. For the SPPA, the discount rates on the TOU tariff with demand charges were implemented and investigated. The proposed methodologies will be useful for the customers and investors to evaluate the economic feasibility and make an investment decision on the rooftop PVs with BESS. Moreover, for the SPPA, these proposed methodologies can be used as a criterion for adding the profit margin of the SPPA project. The main contributions of this dissertation are shown as follows:

(a) An adaptive mode-based operation model of rooftop PVs with BESS for self-consumption, net-metering, and net-billing schemes.
(b) A novel model of the solar power purchase agreement with discount rate option for rooftop PVs with BESS under the BTMS.
(c) A novel optimization model for designing the battery capacity, operation modes and SPPA discount rates on TOU tariff with demand charges for rooftop PVs with BESS under the SPPA and BTMS.
(d) Implementation case studies of the proposed methodologies with the tariff structure in Thailand to evaluate the sensitivity analysis of the installed capacity of rooftop PVs, battery capacity, and rate of excess energy.

1.2 Literature Review

Relevant studies on this dissertation can be classified into 2 main categories: (1) Techno-economic analysis of rooftop PVs with BESS and (2) Optimization model for battery capacity sizing and operation scheduling as follows:

(1) Techno-Economic Analysis of rooftop PVs with BESS

For the techno-economic analysis, many papers evaluated impact of rooftop PVs under the BTMS on electricity charge saving. In [18], the economic feasibility analysis of the customers in Thailand who invest in rooftop PV for electricity charge savings was presented. The value of the bill savings of the customers, which consist of residential load, small general service, medium general service and large general service, was evaluated with various factors, including electricity tariffs, PV-to-load ratios and metering schemes (net-metering and net-billing scheme). Under the current utility's retail rate, the values of the bill savings of residential and small general service groups are slightly higher than medium and large general service groups due to the demand charges. Load profiles do not significantly impact the values of the bill savings for all customer groups. In addition, the net-metering scheme causes a smaller variation in bill savings as compared to net-billing scheme, which would be more flexible for the customers to design the installed capacity of rooftop PVs. On the other hand, the net-billing scheme would encourage customers to limit the installed capacity of rooftop PVs to the impact on the utilities.

The similar concept to evaluate the value of bill savings from rooftop PVs for residential load in California with various installed capacity of rooftop PVs and metering scheme was presented in [19]. A comparative assessment between net-metering scheme and feed-in-tariff scheme for rooftop PVs in residential load was proposed in [20]. The effect of the installed capacity of rooftop PVs and utility's retail rate were investigated. From the results, for the residential load, it showed that the net-metering scheme becomes more profitable than the feed-in-tariff scheme. In [21], the case study to review and analyze the effect of the net-metering scheme and net-billing scheme in Chile was presented. The value of output energy from rooftop PVs under the net-metering and net-billing scheme was evaluated by using levelized cost of electricity (LCOE). From the result, to promote the rooftop PVs, the net-metering scheme would be a better policy due to the rate of the excess energy injected to the utility's grid. However, the net-billing scheme would be a better policy to prevent the excess energy injected to the utility's grid. For the customers, the benefits of this scheme would be obvious when the installed capacity of rooftop PVs is smaller than the load consumption.

Several studies evaluated an economic analysis of rooftop PVs with BESS by applying the discounted cash flow (DCF), net present value (NPV) and return on investment (ROI). In [22], an economic feasibility of residential rooftop PVs with BESS under the self-consumption scheme was proposed by applying DCF and NPV. The case study in Italy was implemented with various factors: levels of insolation, electricity purchase prices, electricity sales prices, investment costs of rooftop PVs, specific tax deduction of rooftop PVs, battery capacity, investment costs of BESS, lifetime of a battery, increases of self-consumption following the adoption of BESS, and subsidies of BESS. From the results, it showed that the increase of the share of the self-consumption scheme is the main significant factor. In [23], the ROI was used to evaluate the sensitivity analysis of the electricity price and investment cost of the BESS by varying battery capacity and ageing. This paper also analyzed the break-even year of the BESS for residential rooftop PVs by considering the German market price trends. In [24], an economic analysis of the BESS under the BTMS with an electricity charge discount program in Korea was presented. From the results, it showed that the electricity charge discount program has improved the profitability of the BESS under the BTMS in Korea market.

Furthermore, some studies evaluate an economic analysis of the BESS under the BTMS for the demand charge reduction. The study report on the BESS under the BTMS for demand charge reduction in the presence of rooftop PVs from NREL was presented in [25]. This study simulated the impact of lithium-ion batteries based on a peak-shaving control algorithm on electricity costs, and then investigate the cost-optimal battery configurations and their impact on load. From the results, it showed that the small and short-duration batteries are most cost-effective regardless of solar power levels. The concept to evaluate the ability of commercial PVs with BESS in reducing demand charges by considering the case study in Australia was also presented in [26].

For the SPPA, the relevant studies on the SPPA are limited. An economic analysis of the SPPA and solar leasing agreement were proposed using the NPV in [27]. The proposed methodology to determine the optimal solar lease payment in the solar lease business for residential load was presented by considering the benefit of the customers and the investors in [28].

(2) Optimization Model for Battery Sizing and Operation Scheduling

For the optimization model, the relevant studies can be divided into (1) operation scheduling and (2) capacity sizing. For the operation scheduling, many studies have proposed a methodology to control rooftop PVs with BESS under the BTMS for electricity charge saving and cost optimization by applying the genetic algorithm. The cost optimization model to control the BESS of the residential customers under the TOU tariff with demand charges for electricity charge savings applying the GA was presented in [29]. Another study that applied the GA for determine the operation schedule of the BESS was presented in [30]. The methodology to investigate the optimal operation scheduling of the residential BESS for two different applications, namely PV self-consumption and demand-load shifting under different dynamic tariff structures, was proposed. In addition, from the result, it showed that the greatest value of the BESS is obtained when the BESS was applied for PV self-consumption under a single, flat tariff. Moreover, by including the demand-load shifting, the value of the BESS was increased due to the decrease of the levelized cost.

Several studies proposed a notable concept of mode-based operation by applying dynamic programming (DP). [31] proposed and developed the notable model to design the charging and discharging strategy of the BESS for PV self-consumption, Peak shaving, and price arbitrage management by applying dynamic programming (DP). The similar concept of DP was also applied in [32]. This study proposed a novel mode-based methodology to design the real-time operation of the BESS by considering the rooftop PVs. The Mixed Integer Linear Programming (MILP) was implemented to minimize the electricity charges.

Another efficient methodology was proposed by applying linear programming (LP) and quadratic programming (QP). In [33], an economic analysis of the BESS under the BTMS and formulated the nonlinear optimization problem to design the operation scheduling of the BESS for minimizing the energy and demand charges under the TOU tariff with demand charges and net-metering scheme using the LP was presented. The LP and QP was also applied for operation scheduling of the BESS with rooftop PVs under the net-metering scheme in [34]. The LP was applied and formulated to maximize the operation savings of the customers. In addition, to balance the benefit of the customers and concerns of the utility, the QP was applied and formulated to maximize the operation saving while limiting the reverse power flow injected to the utility's grid. The similar concept that applied LP to simultaneously determine the operation schedule and battery capacity of the BESS for rooftop PVs under a net-metering scheme was presented in [35]. The main contribution in this paper was the consideration of the net-metering scheme compensation period in the cost optimization model.

For capacity sizing, several studies proposed a methodology to simultaneously determine battery capacity and the operation of rooftop PVs with BESS. The cost minimization concept was applied to investigate the battery capacity and operation of rooftop PVs and BESS under the BTMS with various algorithms. In [36], the cost optimization model to simultaneously investigate battery capacity and operation schedule of the BESS for rooftop PVs using the LP was proposed. The trade-off between energy purchase, feed-in remuneration, and battery aging was considered.

The economic analysis of three battery technologies, such as (1) lead-acid (PbA), (2) lithium-iron-phosphate (LFP) and (3) lithium-nickel-manganese-cobalt (NMC) cathode, was compared. From the results, it showed that different storage technology and component sizing provide the best economic performances, depending on the scenario of load demand and output power from rooftop PVs. In [37], the proposed methodology to determine size of rooftop PVs and BESS with the concept of cost minimization in home energy management system (HEMS) considering the different price mechanism was presented. The analysis also evaluated the impact of tariff structure, subsidies of rooftop PVs and uncertainty of load profiles and PV output. The methodology to determine the optimal size and power management of rooftop PVs, electric vehicle charging load, household consumption load, battery capacity, and power converters was presented in [38]. The proposed optimization aimed to enhance PV self-consumption and frequency control. The teaching-learning-based optimization (TLBO) algorithm was used to calculate the total costs and revenue. The battery aging and depth of discharge was also considered to investigate the operation schedule.

Some studies have applied a similar concept for electric vehicle charging stations to determine the size and operation of rooftop PVs and BESS. In [39], an optimization model for grid-connected PVs, BESS and electric vehicle charging station to size PVs, BESS, and investigate the operation schedule of the BESS using the multi-agent particle swarm optimization (MAPSO) algorithm was proposed. The EV charging pattern was calculated based on the load simulation model. In addition, [40] proposed a real-time charging optimization scheme using mixed-integer linear programming (MILP) to coordinate the charging or discharging power of EVs along with the power dispatches of utility's grid and BESS based on the EV charging pattern priorities and electricity price preferences.

In the literature, relevant studies evaluated the techno-economic analysis and formulated optimization model of the rooftop PVs with BESS under the BTMS with various factors and algorithms but did not consider the electricity charge compensation period. Several concepts for operation scheduling were proposed, however the mode-based operation was comfortable and convenient to develop for applying with all self-consumption, net-metering and net-billing schemes. In addition, although these proposed methodologies were efficient for ascertaining the economic feasibility of rooftop PVs with BESS under the BTMS, studies focusing on the SPPA are limited with scant details. The methodology for designing the SPPA has also not ever been reported. Moreover, the studies on the SPPA should not only focus on the minimization of the electricity cost of the customers, but also consider the revenue of the investors to ensure its long-term viability to both partners.

1.3 Objective

(a) To propose a mode-based operation model of rooftop PVs with BESS for self-consumption, net-metering, and net-billing schemes.
(b) To propose a model of the solar power purchase agreement with discount rate option for rooftop PVs with BESS under the BTMS.
(c) To propose an optimization model for designing the battery capacity, operation modes and SPPA discount rates on TOU tariff with demand charges for rooftop PVs with BESS under the SPPA and BTMS.
(d) To investigate an appropriate battery capacity for rooftop PVs under the BTMS based on the TOU tariff with demand charges in Thailand.
(e) To show the effects of installed capacity of rooftop PVs and rate of excess energy on the battery capacity, operation modes and SPPA discount rates.

1.4 Scope of Work and Limitations

(a) This dissertation considers the standard load profile and tariff structure of large commercial load from Metropolitan Electricity Authority (MEA).
(b) This dissertation considers the generation profile and seasonal effect of rooftop PVs from Chulalongkorn University and PVsyst program, respectively.
(c) This dissertation considers only rooftop PVs with BESS under the AC coupling system.
(d) This dissertation considers only the lithium-ion battery module.
(e) The losses in balance of system and distribution line are neglected.

(f) The replacement of the rooftop PVs with BESS over a project life is neglected.

1.5 Steps of Study

(a) Literature Review and Background Knowledge

1. Studying the relevant literatures on supported policy of rooftop PVs and BESS.
2. Studying the relevant literatures on BTMS for rooftop PVs.
3. Studying the relevant literatures on battery operation scheduling and capacity sizing.
4. Studying the relevant literatures on the economic feasibility of rooftop PVs with BESS.
5. Studying the relevant literatures on business models of rooftop PVs and BESS.
6. Studying the tariff structure and load profile in Thailand.
7. Studying the relevant literatures on the modeling of rooftop PVs and BESS.
8. Studying the principle of optimization programming.

(b) Problem Formulation

9. Developing the methodology to investigate operation scheduling of rooftop PVs with BESS under the self-consumption, net-metering and net-billing schemes.
10. Formulating the modeling of the electricity charge compensation period for net-metering and net-billing scheme.
11. Developing the methodology to determine battery capacity for rooftop PVs under the BTMS.
12. Developing the modeling of the solar power purchase agreement for rooftop PVs with BESS under the BTMS.
13. Developing the methodology to determine SPPA discount rates on TOU tariff with demand charges for rooftop PVs with BESS under the BTMS

14. Developing the methodology to determine SPPA discount rates operation schedule and battery capacity for rooftop PVs with BESS under the SPPA and BTMS.

(c) Simulation Results and Discussion

15. Simulating the proposed methodology by applying to the TOU tariff with demand charges in Thailand.
16. Concluding the simulation results and contribution of this dissertation.

1.6 Dissertation Structure

The rest of this dissertation is organized as follows. In the Chapter 2, the fundamental principle of rooftop PVs, BESS, load profile, retail tariff in Thailand and behind-the-meter schemes are presented. In the Chapter 3, the methodology to evaluate the economic feasibility of rooftop PVs with BESS is presented. The proposed methodology to determine the operation modes of the BESS and battery capacity for the self-consumption, net-metering and net-billing schemes are presented in the Chapter 4. The simulation results and discussion are shown in Chapter 5, and then the conclusions and future works are drawn in Chapter 6.

CHAPTER 2
ROOFTOP PVS WITH BESS

This chapter presents necessary principles of main components in this research. Firstly, modeling of rooftop PVs is presented in Section 2.1. Type of connections and relevant parameters for rooftop PVs are also presented. Secondly, principles and modeling of BESS are reviewed and illustrated in Section 2.2, including type of battery, parameters, and application in power system. Thirdly, load profiles and tariff structure in Thailand are presented in Section 2.3. The integrated system among rooftop PVs, BESS, and load is presented in Section 2.4. Lastly, the concept of the rooftop PVs with BESS under the BTMS is presented in Section 2.5.

2.1 Rooftop PVs

Rooftop photovoltaic generation systems (PVs) are the type of distributed generation (DG) that convert solar radiation into an electricity. Typically, rooftop PVs can be divided by grid connection into three types: (1) grid-connected rooftop PVs (2) off-grid rooftop PVs and (3) hybrid systems. In this dissertation, the grid-connected rooftop PVs is implemented as shown in Figure 2.1.

To produce power at time t, rooftop PVs convert DC power to AC power using a grid-connected inverter as shown in Eq. (2.1). An availability of reverse power to the utility's grid depends on the metering scheme and supported policy, which will describe in Section 2.5.

$$P_{\mathrm{pv}}(t) = \eta_{\mathrm{inverter}} \cdot P_{\mathrm{pv,dc}} \cdot p_{\mathrm{pv}}(t) \tag{2.1}$$

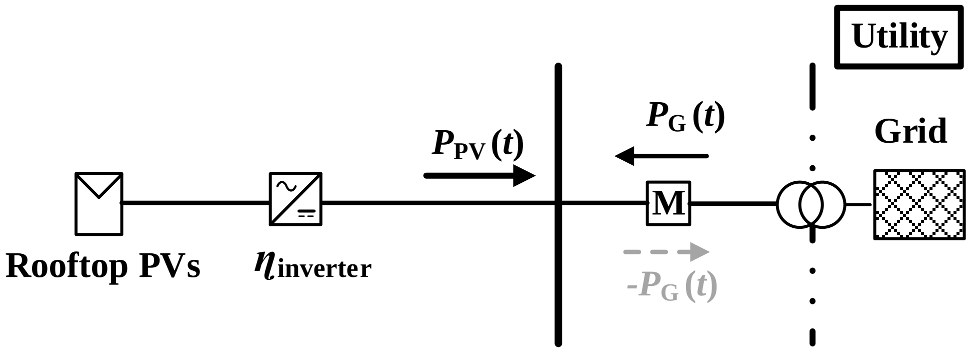

Figure 2.1 Grid-connected rooftop PVs

2.2 Battery Energy Storage Systems

Energy storage systems (ESS) are the technology that charge electricity from the utility’s grid or a power plant and discharge at a later period [41]. The role of the ESS is can be the variable load and sources depending on the purpose of the users [42]. Many technologies of ESS have been launched and developed for various applications, such as flywheels, pumped hydroelectric storage, compressed air energy storages, battery energy storage, flow battery energy storage, capacitor, super capacitor, fuel cell, thermal storage, etc. [43]. For the application with rooftop PVs, battery energy storage systems (BESS) are and considered in this dissertation.

BESS are the storage technology that store electricity by using the principle of electrochemistry. The BESS typically consist of battery module, battery inverter (bi-directional inverter), balance of system components and metering devices. The battery module is a part of the storage device. Battery inverter is the power conversion device which is a bi-directional device to convert DC to AC, or vice versa as shown in Figure 2.2. Balance of system components are other components which are necessary to maintain the health and safety of the system, such as, switchgear, disconnecting switch, etc. The metering devices are the components to monitor the parameters that the utility can also detects. This information is also necessary for the battery monitoring and control system for operation and control the BESS in compliance to the grid requirements. [5].

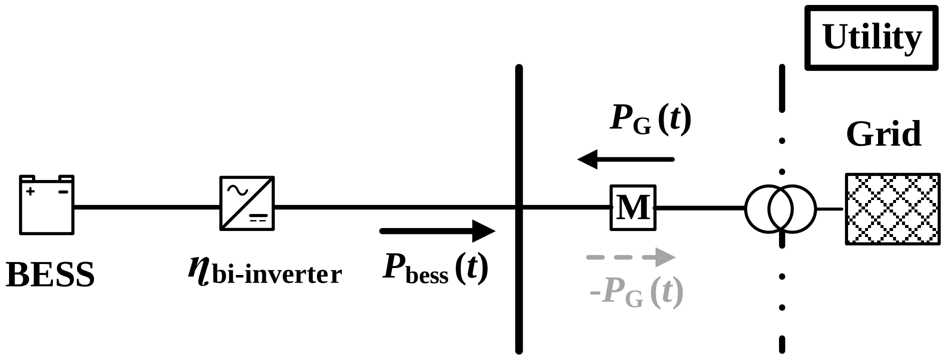

Figure 2.2 Battery Energy Storage Systems

2.2.1 Performance and Parameters

The performance and characteristics of the BESS in this dissertation can be modeled and characterized by the following parameters [34, 43-45]:

(1) Battery Capacity

Battery capacity is classified into battery energy capacity in kWh and battery power capacity in kW. The rated battery energy capacity ($C_{\text{nom,dc}}$) and power capacity ($P_{\text{nom,dc}}$) are the nominal capacity from the manufacturer. By considering the system roundtrip efficiency ($\eta_{\text{rt,sys}}$), the usable battery energy capacity (C_{nom}) which is the total amount of energy that BESS can be fully charged or discharged without any degradation is shown in Equation (2.2). The usable power capacity (P_{nom}), which is the total amount of power that BESS can be charged or discharged is shown in Equations (2.3). By applying the degradation coefficient, the available battery energy capacity at time t can be determined as shown in Equation (2.4). The relationship between battery energy and power capacity can be expressed in terms of energy to power ratio as shown in Equation (2.5).

$$C_{\text{nom}} = C_{\text{nom,dc}} \cdot \eta_{\text{rt,sys}} \tag{2.2}$$

$$P_{\text{nom}} = P_{\text{nom,dc}} \cdot \eta_{\text{rt,sys}} \tag{2.3}$$

$$C_{\text{avail}}(t) = L\ (t) \cdot C_{\text{nom}} \tag{2.4}$$

$$\text{E/P ratio} = \frac{C_{\text{nom,dc}}}{P_{\text{nom,dc}}} \tag{2.5}$$

(2) Battery Roundtrip Efficiency

Battery roundtrip efficiency or DC to DC energetic efficiency is the ratio of energy output (kWh) to energy input (kWh) of BESS during one cycle. The battery roundtrip efficiency shows the fraction of energy put into the storage that can be restore and is typically around 80%. By considering the battery round trip efficiency (η_{rt}) and the bi-directional inverter efficiency ($\eta_{\text{bi-inverter}}$), the system roundtrip efficiency can be determined from Equation (2.6) [46].

$$\eta_{\text{rt,sys}} = \eta_{\text{bi-inverter}} \cdot \eta_{\text{rt}} \tag{2.6}$$

(3) Charged and Discharged Power

The discharged and charged power from the BESS are defined to be positive and negative, respectively. The amount of charged and discharged power typically depends on the stored energy of battery, which can be determined from Equation (2.7). By applying available capacity of battery and energy to power ratio, the limits of charged and discharged power can be determined from Equations (2.8) and (2.9). In this dissertation, the energy to power ratio will be constant, therefore the limits of charged and discharged power will also decrease when the battery is degraded.

$$C_{\text{bess}}(t) = C_{\text{bess}}(0) - \sum_{n=1}^{t} P_{\text{bess}}(n) \cdot \Delta t \tag{2.7}$$

$$P_{\text{bess,dis}}^{\text{limit}}(t) = \frac{C_{\text{avail}}(t)}{\text{E/P ratio}} \tag{2.8}$$

$$P_{\text{bess,ch}}^{\text{limit}}(t) = -\frac{C_{\text{avail}}(t)}{\text{E/P ratio}} \tag{2.9}$$

(4) State of Charge

State of charge ($\sigma(t)$) is expressed the amount of stored energy in battery, as shown in Equation (2.8). By applying with the boundary of the state of charge and available capacity of battery, the lower and upper limits of stored energy in the battery were determined from Equation (2.9). By applying Equations (2.8) and (2.9), the upper energy limits and lower energy limits were determined from Equations (2.10) and (2.11), respectively:

$$\sigma(t) = \frac{C_{\text{bess}}(t)}{C_{\text{avail}}(t)} \tag{2.8}$$

$$C_{\text{avail}}(t) \cdot \sigma_{\min} \leq C_{\text{bess}}(t) \leq C_{\text{avail}}(t) \cdot \sigma_{\max} \tag{2.9}$$

$$P_{\text{bess}}^{\text{upper}}(t) = \frac{C_{\text{bess}}(t) - C_{\text{avail}}(t) \cdot \sigma_{\max}}{\Delta t} \tag{2.10}$$

$$P_{\text{bess}}^{\text{lower}}(t) = \frac{C_{\text{bess}}(t) - C_{\text{avail}}(t) \cdot \sigma_{\min}}{\Delta t} \tag{2.11}$$

(5) Lifetime of Battery

Lifetime of battery in this dissertation is formulated based on the Lithium-ion battery model. As shown in Figure 2.3 [47], the degradation of lithium-ion battery can be divided into 4 regions: (1) Region A, (2) Region B, (3) Region C and (4) Region D. The rate of battery degradation is initially high in region A and significantly decreased in region B. Battery capacity is slowly decreased in region C. In region D, battery is rapidly decreased when the battery capacity is lower than 80% of rated capacity, which is typically defined as end of battery lifetime from manufacturer. From region A to C, the lifetime of battery can approximately express as linear function with different slope. However, to simplify the model of lifetime of battery, this dissertation will consider the battery degradation as linear function with one constant slope.

The battery degradation in this dissertation is performed in term of battery degradation coefficient, which can be classified into self-degradation and operating degradation as shown in Equation (2.12). For the self-degradation, the BESS constantly degrades itself at the self-degradation rate ($\varepsilon_{\mathrm{self}}$) on a time-based characteristic as shown in Equation (2.13). For the operating degradation, it is linearly expressed in terms of cycle aging, as shown in Equation (2.14). L_{min} is the minimum operating degradation coefficient that the battery will be linearly degraded and define to be 0.80 (end of region C). By applying the concept of Coulomb Counting approach, the number of battery cycle used are formulated subjecting with the charged and discharged power of the BESS, as shown in Equation (2.15).

In addition, the methodology to estimate the battery capacity as explained in detail in Chapter 2.2.4.

$$L(t) = L_{\mathrm{self}}(t) \cdot L_{\mathrm{op}}(t) \tag{2.12}$$

$$L_{\mathrm{self}}(t) = 1 - \varepsilon_{\mathrm{self}} \tag{2.13}$$

$$L_{\mathrm{op}}(t) = 1 + \frac{(L_{\mathrm{min}} - 1)}{N_{\mathrm{total}}} \cdot N_{\mathrm{count}}(t) \tag{2.14}$$

$$N_{\mathrm{count}}(t) = \frac{\mathrm{Min}\left(\sum_{n=1}^{t} \left| P_{\mathrm{bess,ch}}(n) \right|, \sum_{n=1}^{t} \left| P_{\mathrm{bess,dis}}(n) \right| \right) \cdot \Delta t}{C_{\mathrm{avail}}(t)} \tag{2.15}$$

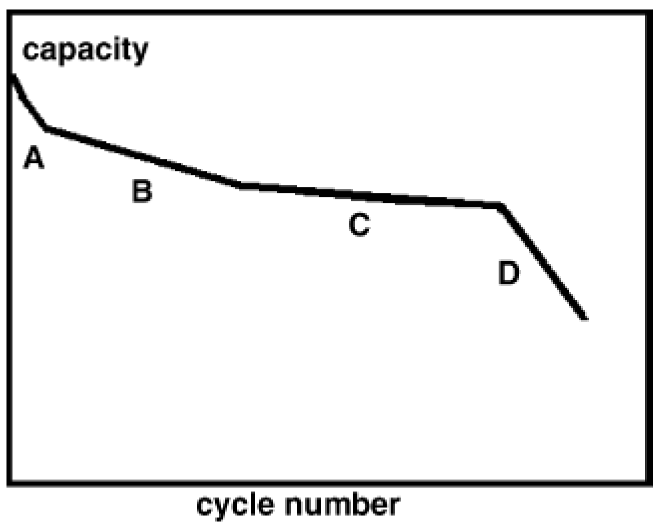

Figure 2.3 Degradation of lithium-ion battery capacity [47]

(6) Specific Energy and Energy Density

Specific energy is a battery energy capacity per unit mass in Wh/kg. Energy density is a battery energy capacity per unit volume in Wh/l.

(7) Specific Energy and Energy Density

Specific power is a battery power capacity per unit mass in W/kg. Power density is a battery power capacity per unit volume in W/l.

2.2.2 State of Charge Estimation Methodology

To evaluate the battery degradation, the methodology to estimate the state of charge of the battery is essential because it shows the stored energy and available capacity of the battery at specified time. In the literature, the estimation techniques can be classified into 5 categories as follows [48, 49]:

(1) Direct Measurement Approach

Direct measurement applies physical battery properties such as the terminal voltage and impedance to evaluate the state of charge. Typically, the direct measurement methodology can be divided into 4 groups: (1) open circuit voltage approach, (2) terminal voltage approach, (3) impedance measurement approach, and (4) impedance spectroscopy approach.

(2) Book-keeping Estimation Approach

Book-keeping estimation applies the concept of the charging and discharging current to estimate the state of charge. Under this methodology, the internal effects of battery, such as self-discharging and discharging efficiency, can be considered. There are 2 types of book-keeping estimation: (1) Coulomb Counting approach and (2) Enhance Coulomb Counting approach. Various applications in battery energy management system practically apply the Coulomb Counting approach due to its simplicity and convenience for implementation. However, there are several factors that did not be considered but should affect the accuracy of this approach, such as the battery temperature, battery history etc. Therefore, the Enhance Coulomb Counting approach is developed with more complicated function to overcome the concern points of the Coulomb Counting approach.

(3) Model-Based Approach

The model-based approach is the methodology that applied the mathematical model of a battery to estimate the state of charge by applying state space model. This approach can improve an accuracy against measurement error. There are 3 types of model-based approach: (1) Equivalent Circuit Model (ECM), (2) Empirical Model (EM) and (3) Data Driven Learning Model (DDLM). ECM is the model that applies the Thevenin equivalent circuit model and the open circuit voltage is performed as a mathematical function of the state of charge. The relationship between open circuit voltage and state of charge can be formulated by applying regression model. EM is the model that represents terminal voltage as a mathematical function of the state of charge. The EM can be classified into 3 models of (1) Shepherd model, (2) Unnewehr universal model and (3) Nemst model. The DDLM is the model that applied the data mining method in the machine learning area, such as artificial neural network (ANN) or Support Vector Machine (SVM), to formulate the state space model.

To estimate the state of charge, all state space models are applied the state estimation techniques, such as Kalman Filter (KF), Extended Kalman Filter (EKF), Adaptive Extended Kalman Filter (AEKF) and (4) Observer-Based State Estimation.

(4) Learning Algorithm Based Approach

The learning algorithm-based approach formulates the state of charge estimation problem with the novel machine learning and data mining techniques by applying the historical data of the nonlinear relationship between state of charge and measurable parameters, such as temperature, terminal voltage, etc. There are various techniques that are applied for these techniques such as Artificial Neural Network (ANN), Support Vector Machine (SVM), Extreme Learning Machine, Fuzzy Logic, Genetic Algorithm (GA), etc.

(5) Hybrid Approach

The hybrid approach applies the advantages of each methodology to estimate the optimal state of charge with high accuracy, such as, the combination of the EKF and Coulomb Counting [50], the combination direct measurement and Coulomb Counting [51], etc.

This dissertation applies the Coulomb Counting approach to estimate the state of charge of the battery, which is practically used in various application, especially in battery energy management system due to its simplicity and convenience for implementation.

2.2.3 Type of Battery

The battery can be categorized by charging capability into two groups of primary battery and secondary battery. The primary battery is the non-rechargeable batteries. The secondary battery is the rechargeable batteries. In this dissertation, the only secondary battery is considered. The secondary battery can be classified by technology into four groups as described below [43].

(1) Lithium-ion Battery

Lithium-ion batteries are the rechargeable battery in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. Lithium-ion batteries are many popular for power electronics application due to the high energy density and power density by comparing to other batteries. There are four types of materials for a lithium-ion battery, i.e., Manganese (NMC/LMO), Cobalt (NCA/LCO), Phosphate (LFP) and Titanium (LTO). Most of the lithium-ion battery in the market is NMC and LFP [43, 52, 53] .

(2) Lead-acid Battery

Lead-acid batteries are the oldest and most widely deployed rechargeable battery based on the number of installations and cumulated installed capacity. Lead-acid batteries typically utilize in a good in a wide range of applications due to the lowest cost. There are two main design forms of lead-acid batteries, i.e., vented lead acid (VLA) and sealed or valve-regulated lead acid (VRLA).

(3) High Temperature Battery

High temperature batteries or molten salt batteries are the batteries that use molten salt as an electrolyte and must operate at high temperatures. There are two typical types of high temperature batteries in the market, i.e., Sodium Sulphur (NaS) and Sodium nickel chloride (NaNiCl) [54].

(4) Flow Battery

Flow batteries are reaction stacks separated from one or more of the electrolytes held in external storage tanks. Either one or both active materials are solution in the electrolyte. There are three typical types of flow batteries, i.e., vanadium redox flow battery (VRFB), zinc-bromine flow battery (ZBFB), and polysulfide bromide flow battery (SB) [5].

The specifications of each battery, which consist of calendar life, cycle life, depth of discharge, energy density, power density, self-discharge, roundtrip efficiency and energy installation cost, are shown in Table 2.1

.

Table 2.1 Specifications of the BESS in each technology [43]

			Calendar Life (Years)			Cycle Life (Equivalent Full-Cycles)			Depth of Discharge (%)			Energy Density (Wh/L)	
Type	**Technology**	**Year**	**Worst**	**Reference**	**Best**	**Worst**	**Reference**	**Best**	**Worst**	**Reference**	**Best**	**Worst**	**Best**
Flow	**VRFB**	2016	5	12	20	12,000	13,000	14,000	100	100	100	15	70
		2030	8	19	32	12,000	13,000	14,000	100	100	100	15	70
	ZBFB	2016	5	10	20	300	10,000	14,000	100	100	100	20	70
		2030	8	16	32	300	10,000	14,000	100	100	100	20	70
High Temp	**NaNiCl**	2016	8	15	22	1,000	3,000	7,500	100	100	100	150	280
		2030	12	23	33	1,513	4,538	11,344	100	100	100	150	280
	NaS	2016	10	17	25	1,000	5,000	10,000	100	100	100	140	300
		2030	14	24	36	1,500	7,500	15,000	100	100	100	140	300
Lead-Acid	**Flooded LA**	2016	3	9	15	250	1,500	2,500	60	50	50	50	100
		2030	4	13	21	538	3,225	5,375	60	50	50	50	100
	VRLA	2016	3	9	15	250	1,500	2,500	60	50	50	50	100
		2030	4	13	21	538	3,225	5,375	60	50	50	50	100
Li-Ion	**LFP**	2016	5	12	20	1,000	2,500	10,000	84	90	100	200	620
		2030	8	18	31	1,910	4,774	19,097	84	90	100	200	620
	LTO	2016	10	15	20	5,000	10,000	20,000	84	95	100	200	620
		2030	15	23	31	9,549	19,097	38,194	84	95	100	200	620
	NCA	2016	5	12	20	500	1,000	2,000	84	90	100	200	620
		2030	8	18	31	955	1,910	3,819	84	90	100	200	620
	NMC/LMO	2016	5	12	20	500	2,000	4,000	84	90	100	200	735
		2030	8	18	31	955	3,819	7,639	84	90	100	200	735

Table 2.1 Specifications of the BESS in each technology (continued) [43]

			Power Density (W/L)		Self-discharge (%)			Roundtrip Efficiency (%)	Energy Installation Cost (USD/kWh)		
Type	Technology	Year	Worst	Best	Worst	Reference	Best	Reference	Worst	Reference	Best
Flow	VRFB	2016	1	2	1	0	0	70	1,050	347	315
		2030	1	2	1	0	0	78	360	119	108
	ZBFB	2016	1	25	34	15	8	70	1,680	900	525
		2030	1	25	34	15	8	78	576	309	180
High Temp	NaNiCl	2016	150	270	15	5	0	84	488	399	315
		2030	150	270	15	5	0	87	197	161	127
	NaS	2016	120	160	1	0	0	80	735	368	263
		2030	120	160	1	0	0	85	324	162	116
Lead-Acid	Flooded LA	2016	10	700	0	0	0	82	473	147	105
		2030	10	700	0	0	0	85	237	74	53
	VRLA	2016	10	700	0	0	0	80	473	263	105
		2030	10	700	0	0	0	83	237	132	53
Li-Ion	LFP	2016	100	10,000	0	0	0	92	840	578	200
		2030	100	10,000	0	0	0	94	326	224	77
	LTO	2016	100	10,000	0	0	0	96	1,260	1,050	473
		2030	100	10,000	0	0	0	98	574	478	215
	NCA	2016	100	10,000	0	0	0	95	840	352	200
		2030	100	10,000	0	0	0	97	347	145	82
	NMC/LMO	2016	100	10,000	0	0	0	95	840	420	200
		2030	100	10,000	0	0	0	97	335	167	79

2.2.4 Battery Energy Storage Systems in Current Markets

By surveying in the current market, most of BESS for rooftop PVs is the Lithium Iron Phosphate (LFP) and Lithium Nickel Manganese Cobalt Oxides (NMC). An example of the battery specification is shown in Table 2.2. Maximum depth of discharge is between 90 - 96%. Roundtrip efficiency is approximately 90 – 98%.

Table 2.2 Battery energy storages systems in current market

Parameters	**Specifications of each BESS in current market**				
Type of Battery	LFP	LFP	LFP	NMC	NMC
Battery Energy Capacity (kWh)	3 kWh	10.24 kWh	5.5 kWh	3.5 kWh	14 kWh
Battery Power Capacity (kWh)	1.5 kW	10 kW	5 kW	3.2 kW	5 kW
Roundtrip Efficiency	95%	-	98%	95%	90%
Depth of Discharge	90%	96%	90%	95%	96%

2.2.5 Applications of Battery Energy Storage Systems

Applications of energy storage can be categorized into three groups of (1) on-grid applications; (2) off-grid applications; and (3) transportation, as shown in Figure 2.3. For on-grid application, it can be classified into five categories of (1) bulk energy services; (2) ancillary services; (3) transmission infrastructure services; (4) distribution infrastructure services; and (5) customer energy management services.

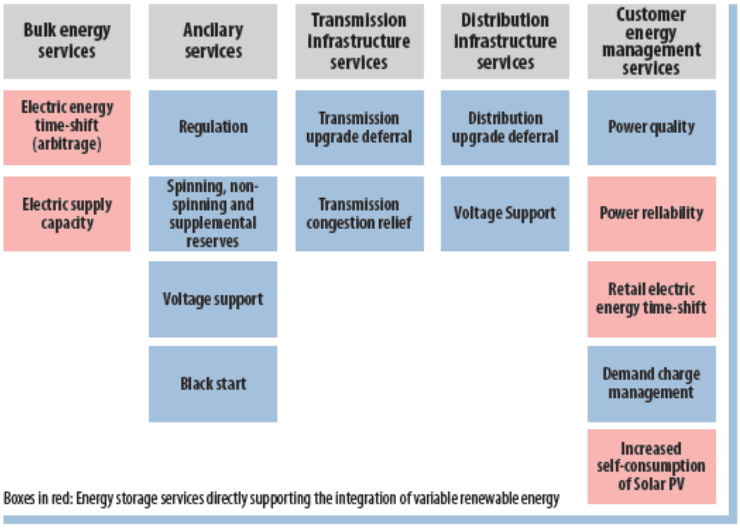

Figure 2.4 Applications of energy storage in power system [43]

(1) Bulk Energy Services

The BESS are applied to supply energy at the specified period without energy from renewable energy. This application consists of electric energy time-shift (arbitrage) and electric supply capacity.

(2) Ancillary Services

The BESS are applied to maintain grid stability and security. This application consists of frequency and voltage regulation, supplemental reserves, voltage support, and black start.

(3) Transmission Infrastructure Services

The BESS are applied to defer or reduce an investment in transmission system upgrades. This application consists of transmission upgrade deferral and transmission congestion relief.

(4) Distribution Infrastructure Services

As similar as the concept of transmission infrastructure service, the BESS are applied to defer or reduce an investment in distribution system upgrades. This application consists of distribution upgrade deferral and voltage support.

(5) Customer Energy Management Services

The BESS are applied to increase benefits of the customers. This application consists of power quality, power reliability, retail electric energy time-shift, demand charge management and increased self-consumption of solar PV. In this dissertation, the customer energy management services are implemented for electricity charge savings which include both energy and demand charges.

2.2.6 Characteristics in Power System Applications

The main characteristics of the BESS for applying to each power system application consist of battery power, discharge durations, operation cycles, and response time, as shown in Table 2.3.

Table 2.3 Characteristics of the BESS in power system applications [55]

Applications		Battery Power (MW)	Discharge Durations	Operation Cycles	Response Time
Bulk Energy Services	Electric Energy Time-Shift (Arbitrage)	100 to 2,000	8 hrs. to 24 hrs.	0.25 to 1 per day	> 1 hr.
	Electric Supply Capacity	1 to 400	1 min. to 1 hr.	0.5 to 2 per day	< 15 min.
Ancillary Services	Regulation	1 to 2,000	1 min. to 15 min.	20 to 40 per day	1 min.
	Load Following	1 to 2,000	15 min. to 24 hrs.	1 to 29 per day	< 15 min.
	Voltage Support	1 to 40	1 sec. to 1 min.	10 to 100 per day	millisec. to sec.
	Black Start	0.1 to 400	1 hr. to 4 hrs.	< 1 per year	< 1 hr.
	Spinning Reserve and Non-Spinning Reserve	10 to 2,000	15 min. to 2 hrs.	0.5 to 2 per day	< 15 min
Transmission Infrastructure Services	Transmission Upgrade Deferral	1 to 500	2 hrs. to 5 hrs.	0.75 to 1.25 per day	> 1 hr.
	Transmission Congestion Relief	10 to 500	2 hrs. to 4 hrs.	0.14 to 1.25 per day	> 1 hr.

Applications		Battery Power (MW)	Discharge Durations	Operation Cycles	Response Time
Distribution Infrastructure Services	Distribution Upgrade Deferral	1 to 500	2 hrs. to 5 hrs.	0.75 to 1.25 per day	> 1hr.
	Distribution Congestion Relief	10 to 500	2 hrs. to 4 hrs.	0.14 to 1.25 per day	> 1hr.
Customer Energy Management Services	Retail Electric Energy Time-Shift	0.001 to 1	Minutes to hours	1 to 29 per day	< 15 min.
	Demand Charge Management (Peak Reduction)	0.001 to 1	Minutes to hours	1 to 29 per day	< 15 min.

From Table 2.3, the bulk energy service generally requires high battery power and discharge duration, but low operation cycles per day. The response time are varied from less than 15 minutes to more than an hour depending on the application. For the ancillary service, the specifications are also subject to the power application. For example, the regulation, load following, and operating reserve requires high battery power with varied discharge duration. For transmission and distribution infrastructure services, the specifications are quite similar. For the customer energy management service in this dissertation, it requires low battery power with high operation cycles per day and instantaneous response time.

By considering the specification of the BESS in Table 2.1, the current technology in the market and the customer energy management services in Table 2.3, lithium iron phosphate battery is the most appropriate type because of the high cycle life and roundtrip efficiency, which was considered in this dissertation.

2.3 Load Consumption in Thailand’s Distribution System

The electricity structure in Thailand is in a form of enhanced single buyer model. For power generation system, Electricity Generating Authority of Thailand (EGAT) and private power producers are the main participants. EGAT is also act as the transmission system operator. For the distribution system, there are two distribution system operators, i.e., Metropolitan Electricity Authority (MEA) and

Provincial Electricity Authority (PEA). MEA is responsible for Bangkok and nearby provinces. PEA is responsible for the others.

Focusing on the private sector, the power producer is divided into 4 groups of (1) Independent Power Producers (IPP), (2) Small Power Producers (SPP), (3) Very Small Power Producers (VSPP), and (4) Prosumers, as shown in Table 2.4. Most residential and commercial rooftop PVs are classified as prosumer, which was considered in this dissertation.

Table 2.4 Power producers in Thailand

Power Producers	**Responsible Operators**	**Installed Capacity**
Independent Power Producers (IPP)	EGAT	> 90 MW
Small Power Producers (SPP)	EGAT, MEA, PEA	10 – 90 MW
Very Small Power Producers (VSPP)	MEA, PEA	1 - 10 MW
Prosumers	MEA, PEA	< 1 MW

2.3.1 Load Profiles

Load profiles in Thailand's distribution system are divided into 8 groups of (1) residential load; (2) small general service; (3) medium general service; (4) large general service; (5) specific business service; (6) non-profit organization; (7) agricultural pumping; (8) temporary service [56]. The load profiles of each group on Workday, Saturday and Sunday are shown in Figure. 2.4-2.9. In this dissertation, only large general service was considered.

(1) Residential Load

The load profiles of residence, which include households, monasteries, house of priest, and religious places of worship are shown in Figure 2.4, the load profiles on Workday, Saturday and Sunday are quite similar. The peak period is approximately from 8.00 pm to 11.00 pm, while the load profiles are steady during the daytime. The tariff structures for the residential load are classified into 2 types depending on the customer's purpose: (1) Normal rate and (2) Time-of-Use (TOU).

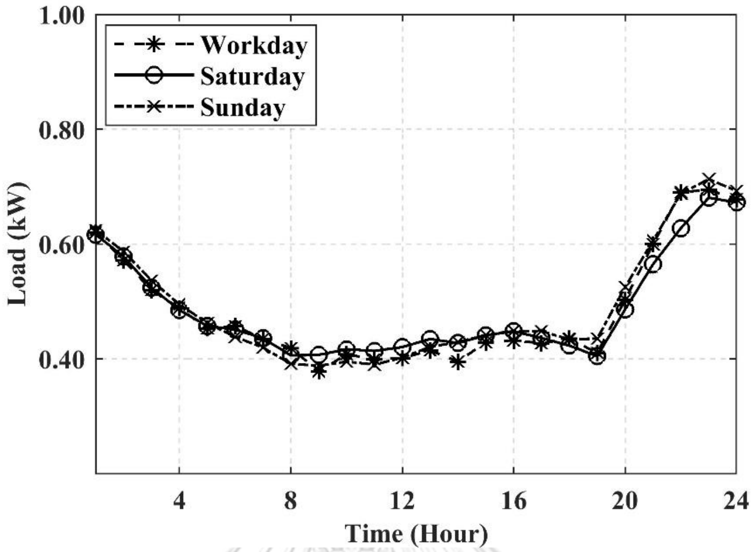

Figure 2.5 Residential Load

(2) Small General Service

The load profiles of small general service, which include businesses with residential, industrials, government institutions, local authorities, state enterprises, embassies, establishments related to foreign countries or international organizations, and so on, including their compounding with an average load demand in 15 minutes lower than 30 kW, are shown in Figure 2.5.

The load profile on Workdays is higher than the others, especially during on-peak period. On Workdays and Saturday, there are two peak period on daytime: (1) First-peak period (10.00 am to 12.00 am) and (2) Second-peak period (2.00 pm to 4.00 pm). On Sunday, the load profile is quite steady with small peak on nighttime (from 8.00 pm to 11.00 pm). The tariff structures for the small general service are also classified into 2 types depending on the customer's purpose: (1) Normal rate and (2) Time-of-Use (TOU).

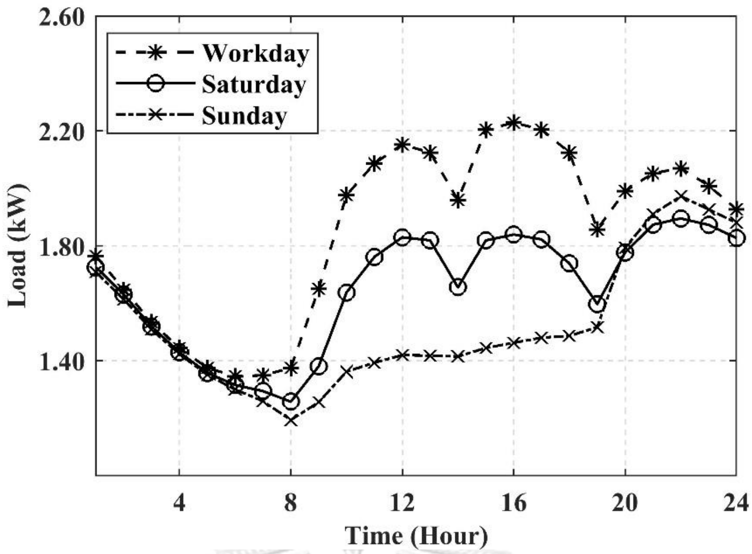

Figure 2.6 Small general service

(3) Medium General Service

The load profiles of medium general service, which include businesses, industrials, government institutions, local authorities, state enterprises, embassies, establishments related to foreign countries or international organizations, and so on, including their compounding with an average load demand in 15 minutes from 30 kW to 1,000 kW and an average load consumption in the last 3 consecutive months is not over 250,000 kWh per month, are shown in Figure 2.6.

The load profile on Workdays is also higher than the others, especially during on-peak period. On Workdays and Saturday, there are two peak period on daytime as well: (1) First-peak period (10.00 am to 12.00 am) and (2) Second-peak period (2.00 pm to 4.00 pm). However, on Sunday, the load profile is quite steady without any peak-period for all time. The tariff structures for the medium general service are also classified into 2 types depending on the customer’s purpose and the starting date of electricity use: (1) Normal rate with demand charges and (2) Time-of-Use (TOU) with demand charges.

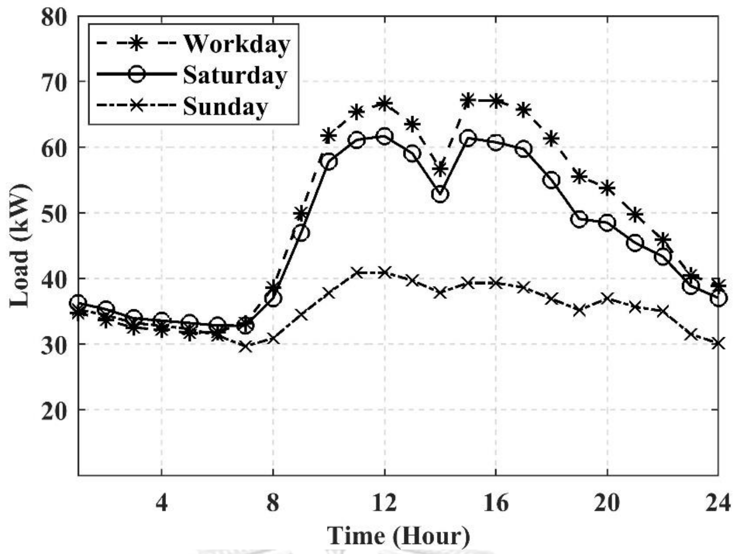

Figure 2.7 Medium general service

(4) Large General Service

The load profiles of large general service, which include businesses, industrials, government institutions, local authorities, state enterprises, embassies, establishments related to foreign countries or international organizations, and so on, including their compounding with an average load demand in 15 minutes from 1,000 kW and over or an average load consumption in the last 3 consecutive months is over 250,000 kWh per month, are shown in Figure 2.7.

The load profile on Workdays is also higher than the others and includes two peak periods with small difference. The load profile of on Saturday is also similar. For the load profile on Sunday, there is the small peak period during daytime. The tariff structures for the medium general service are also classified into 2 types depending on the customer’s purpose and the starting date of electricity use: (1) Time-of-Day (TOD) with demand charges and (2) Time-of-Use (TOU) with demand charges.

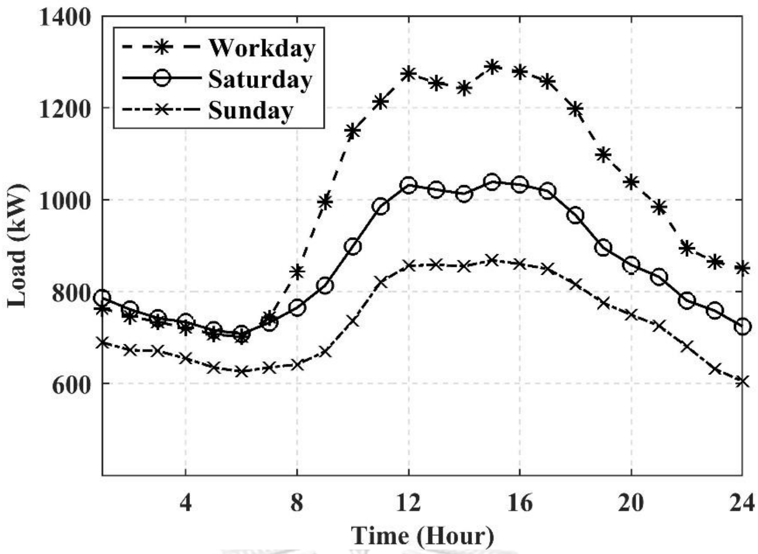

Figure 2.8 Large general service

(5) Specific Business Service

The load profiles of specific business service, which include hotels, guest houses or lodging businesses, including the load that an average demand in 15 minutes from 30 kW and over, are shown in Figure 2.8. The trend of all load profiles on Workdays, Saturday and Sunday is quite similar, while the load demand on Sunday is the smallest. The tariff structures for the medium general service are also classified into 2 types: (1) Normal rate with demand charges and (2) Time-of-Use (TOU) with demand charges. All customers under the specific business service must be applied to TOU, while the customers who have not installed the TOU meter can temporarily be applied to Normal rate.

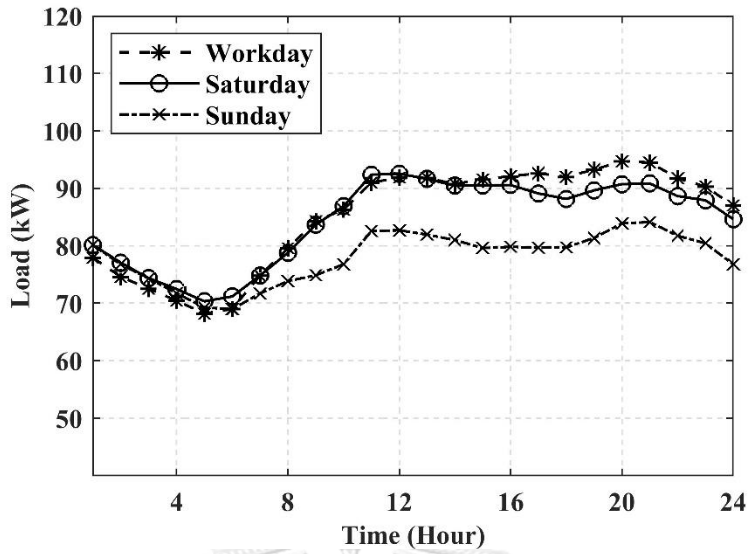

Figure 2.9 Specific business service

(6) Non-Profit Organization

The load profiles of non-profit organizations that offering non-charge services are shown in Figure 2.9. It is obvious that the load profile on Workdays is the highest with the two peak periods from 10.00 am to 12.00 am and 2.00 pm to 4.00 pm. The load profiles on Saturday and Sunday are similar with the smaller peak from 10:00 am to 3:00 pm. The tariff structures for the medium general service are also classified into 2 types: (1) Normal rate and (2) Time-of-Use (TOU) with demand charges.

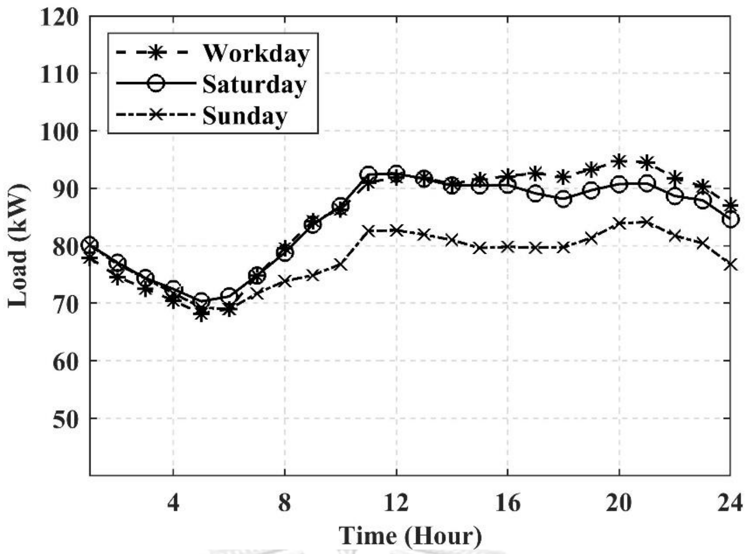

Figure 2.10 Non-profit organization

(7) Agricultural Pumping and Temporary Services

For the agricultural pumping and temporary services, the load profiles are subject to the purpose of the customers. The agricultural pumping is the electricity usage of water pumps for agricultural purposes of government, agricultural cooperatives, farmer groups that have been registered and farmer groups that are legalized by government. The tariff structures for the agriculture pumping are classified into 2 types: (1) Normal rate and (2) Time-of-Use (TOU) with demand charges. In addition, the temporary service is the electricity use for construction, temporarily special events, places without registration number and electricity customers who are not followed utility's grid codes.

2.3.2 Retail Tariff in Thailand

In this section, the details of retail tariff in Thailand are presented by dividing into tariff components and structures as follows:

2.3.2.1 Tariff Components

The retail tariff in Thailand is consisted of 7 components: (1) Energy charge; (2) Demand charge; (3) Service charge; (4) Power factor charge; (5) Minimum charge; (6) Automatic tariff adjustment (Ft); and (7) Value added tax (VAT). The details of each components are shown as follows:

(1) Energy Charge

Energy charge is an electricity charge, which measures energy used in terms of THB/kWh. The energy charge is reflected cost of power plants, transmission and distribution system construction and operation according to the voltage level.

(2) Demand Charge

Demand charge is an electricity charge, which measures peak demand in terms of THB/kW. The peak demand is typically an average in 15 minutes of maximum demand during the on-peak period in any specified month. Demand charge is reflected cost of power plants, transmission and distribution system construction and operation according to the voltage level.

(3) Service Charge

Service charge is a customer cost, which includes administration fee, operation fee and service fee from the utility

(4) Power Factor Charge

Power factor charge is collected from the customer who causes the lagging power factor. When the maximum of an average reactive power demand is higher than 61.97% of the maximum of an average active power demand in any period, the power factor charge will be considered.

(5) Minimum Charge

Minimum charge is the minimum electricity charge that the customers must pay. The minimum charge typically cannot be lower than 70% of maximum demand charge in the last 12 months.

(6) Automatic Tariff Adjustment (Ft)

Automatic tariff adjustment or Ft is an adjustment tariff in THB/kWh. The FT is reflected the cost of fuel for power generation system and typically adjusted in every 4 months.

(7) Value Added Tax (VAT)

Value added tax or VAT in Thailand is currently 7%.

2.3.2.2 Retail Tariff Structures

With the formulation of each tariff components in 2.3.2.1, the retail tariff structure in Thailand is divided into 3 types of (1) Normal rate; (2) Time-of-Date (TOD); and Time-of-Use (TOU).

(1) Normal Rate

Normal rate can be divided into 2 types: (1) Normal rate and (2) Normal rate with demand charges. For the typical normal rate, there only consists of the energy charges and service charges. The electricity bills will be calculated based on load consumption in kWh. The tariff rate will be higher if the monthly load consumption is higher. The normal rate is applicable to the residential load, small general service, non-profit organization, agricultural pumping and temporary service. For the normal rate with demand charges, it consists of energy charges, demand charges and service charges, which is only applied to the medium general service.

(2) Time-of-Date

The Time-of-Date (TOD) tariff is the structure that consists of energy charges, demand charges and service charges. The demand charges are divided into peak demand charges and partial demand charges. Under this structure, the peak period is from 6:30 pm to 9:30 pm every day and the partial peak period is from 8:00 am to 6:30 pm every day. The TOD is only implemented to the large general service who applied this scheme before November 2015.

(3) Time-of-Use

The Time-of-Use (TOU) tariff can be divided into 2 types: (1) TOU tariff and (2) TOU tariff with demand charges. The TOU tariff, which consists only energy charges and service charges, is only applicable to residential load and small general service. The energy charges are divided into on-peak energy charges and off-peak energy charges. Another structure is TOU tariff with demand charges, which is applicable to medium general service, large general service, specific business service, non-profit organization, and agricultural pumping. In this dissertation, the rooftop PVs with BESS for large general service under the TOU tariff with demand charges was considered.

The on-peak energy charges, off-peak energy charges and demand charges in this dissertation can be determined from Equations (2.16)-(2.19). The on-peak period is from 9:00 AM to 10:00 PM on Workdays (Monday–Friday) and the remaining time is the off-peak period, as shown in Figure 2.10.

$$R_{\text{base}}^{\text{on}}(m) = \sum_{t=1}^{S_m^{\text{on}}} r^{\text{on}} \cdot P_g(t) \cdot \Delta t \tag{2.16}$$

$$R_{\text{base}}^{\text{off}}(m) = \sum_{t=1}^{S_m^{\text{off}}} r^{\text{off}} \cdot P_g(t) \cdot \Delta t \tag{2.17}$$

$$R_{\text{base}}^{\text{demand}}(m) = P_{\text{g}}(t_{\text{peak}}) \cdot r^{\text{demand}} \tag{2.18}$$

$$R_{\text{base}}^{\text{total}}(m) = R_{\text{base}}^{\text{on}}(m) + R_{\text{base}}^{\text{off}}(m) + R_{\text{base}}^{\text{demand}}(m) \tag{2.19}$$

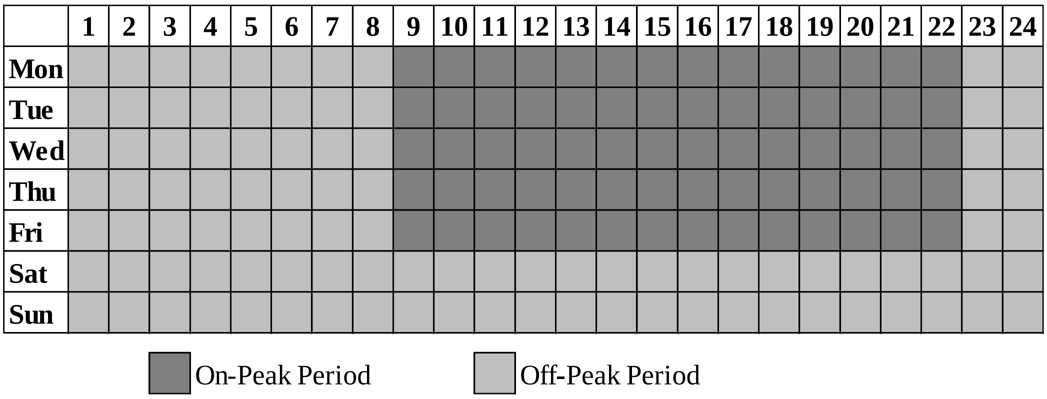

Figure 2.11 On-peak and off-peak periods in Thailand

From Section 2.3.1 and 2.3.2, the retail tariff for each load group are summarized as shown in Table 2.5.

Table 2.5 Summary of retail tariff for each load group in Thailand

No	Group	Types	Demand Charges	Energy Charges	Service Charges	P.F. Charges	Minimum Charges	VAT	Ft
1	Residential Load	Normal, TOU		✓	✓			✓	✓
2	Small General Service	Normal, TOU		✓	✓			✓	✓
3	Medium General Service	Normal, TOU	✓	✓	✓	✓	✓	✓	✓
4	Large General Service	TOD, TOU	✓	✓	✓	✓	✓	✓	✓
5	Spec. Business Service	TOU	✓	✓	✓	✓	✓	✓	✓
6	Non-Profit Organization	Normal, TOU		✓	✓		✓	✓	✓
7	Agricultural Pumping	Normal, TOU	✓	✓	✓		✓	✓	✓
8	Temporary Service	Normal		✓				✓	✓

2.4 Rooftop PVs with BESS

To produce power at time *t*, rooftop PVs convert DC power from the PV module to AC power using a PV inverter. The configurations of rooftop PVs with BESS can typically be divided into four groups of (1) AC coupling system, and (2) DC coupling system (3) AC battery system and (4) Hybrid system [57].

(1) DC Coupling System

DC coupling system is the configuration that the BESS are connected to rooftop PVs at the DC power system. The MPPT solar charge controller is required to control the direct DC charged power from rooftop PVs to the BESS as shown in Figure 2.12. The efficiency of the BESS is typically high by using the MPPT solar charge controller. However, this configuration is only convenient for small load demand. It would be more complicated to additionally install the PV or battery module if the load demand is higher. Therefore, this configuration is typically applied for off-grid application. The notable manufacturer for this inverter type is such as Victron Energy Multiplus [58].

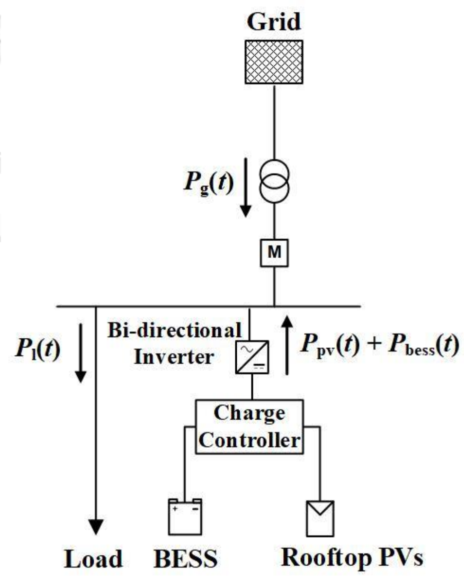

Figure 2.12 DC Coupling System

(2) AC Coupling System

AC coupling system is the configuration that the rooftop PVs and BESS are operated separately and connected at the AC power system. The inverter and balance of system for each rooftop PVs and BESS are required as shown in Figure 2.13. The efficiency of the BESS is slightly less than the DC coupling system. However, this configuration is comfortable for high load demand and typically applied for on-grid application. The notable manufacturer for this type of battery inverter is such as SMA Sunny Boy inverter, Victron Energy Multiplus and Quattro inverter [58, 59].

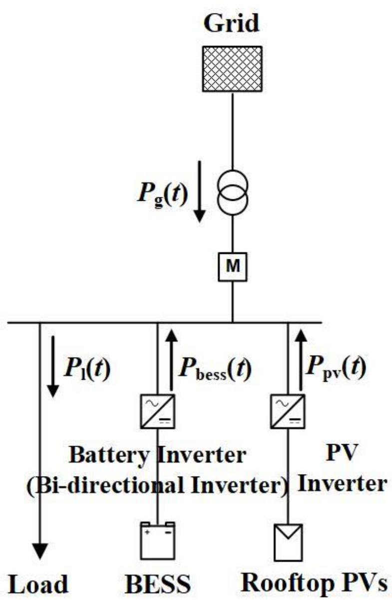

Figure 2.13 AC Coupling System

(3) AC Battery System

AC battery system is the configuration that the BESS is connected to AC power system without any additional inverter. AC battery system is the all-in-one package that consists of the battery module, battery management system and battery inverter. The inverter and balance of system for each rooftop PVs and BESS are required as shown in Figure 2.14. The efficiency of the BESS is typically less than the DC and AC Coupling system. This configuration will be convenient for the customers who have an existing rooftop PVs and need to additionally install the new BESS at the AC power system. The notable manufacturer for this inverter type is such as Tesla Powerwall 2 and Sonnen Batterrie Eco [60, 61].

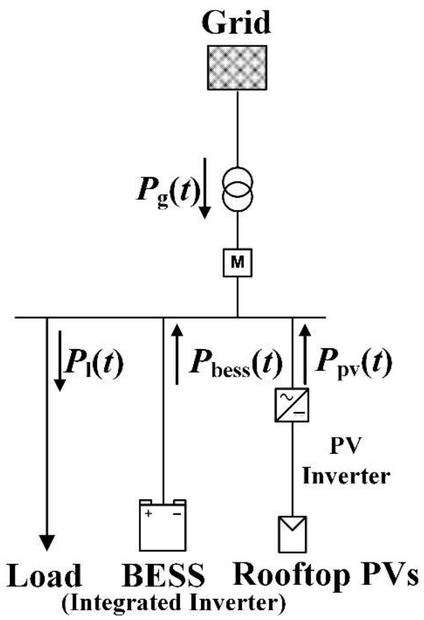

Figure 2.14 AC Battery System

(4) Hybrid System

Hybrid system is the configuration that rooftop PVs with BESS can be either operated in on-grid and off-grid application. The battery inverter for this system is the multi-mode invertor which can function in AC and DC coupling system. The efficiency of the BESS depends on the application of the end users. The notable manufacturer for this inverter type is such as SMA Sunny Island inverter, Victron Energy Multiplus and Quattro inverter and Selectronic SP Pro inverter [58, 62, 63].

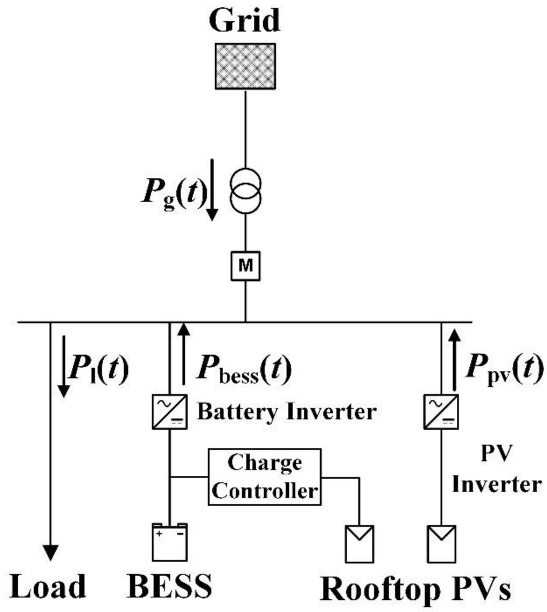

Figure 2.15 Hybrid System

In this dissertation, rooftop PVs, BESS, and load were integrated with AC Coupling systems. Accordingly, $P_{pv}(t)$, $P_g(t)$, $P_l(t)$, and $P_{bess}(t)$ are subject to the power balance equation, as shown in Equation 2.19,

$$P_g(t) = P_l(t) - P_{pv}(t) - P_{bess}(t) \tag{2.20}$$

2.5 Behind-The-Meter Scheme

In this section, the concepts of the rooftop PVs with BESS under the behind-the-meter scheme (BTMS) are presented. Firstly, the modeling of rooftop PVs with BESS under the BTMS and the concept of the compensation period are presented in Section 2.5.1. Type of the BTMS, which can be divided into self-consumption scheme, net-billing scheme (NBS), and net-metering scheme (NMS), is presented in Section 2.5.2. The concept of solar power purchase agreement (SPPA) is presented in Section 2.5.3

2.5.1 Rooftop PVs with BESS under Behind-the-Meter Scheme

The BTMS is the scheme where the rooftop PVs directly connected to the load without passing through the utility's meter. The customers who installed the rooftop PVs with BESS under the BTMS can be called "prosumers", to reflect the role of both producers and customers [10]. However, in this dissertation, the output power produced from rooftop PVs will be firstly supplied to the load. If the output power of rooftop PVs is higher than the load demand, the excess power can be used to compensate an electricity bills depending on the government's policy. The main components typically consist of the PV module, battery module, PV and battery inverters, and metering scheme. The metering system under the BTMS is typically a bi-directional meter. The bi-directional meter is operated by spinning forward to measures the amount of electricity a customer consumes and spinning backward to measures the amount of electricity a customer generates. Therefore, the meter will run backwards when the customer's electricity production exceeds the load consumption. The BTMS can be categorized into self-consumption and net-billing, and net-metering scheme, as described in Section 2.5.2.

2.5.2 Type of Behind-the-Meter Scheme

Type of the BTMS can be classified by the condition of the reverse power flow [7-10]. If the reverse power flow is unavailable, the BTMS can be called "self-consumption scheme" or "non-incentivized self-consumption scheme". On the other hand, if the reverse power flow is available, the BTMS can be called "incentivized self-consumption scheme", which can be either the net metering scheme or the net billing scheme depending the rate of excess energy injected to the utility's grid [11].

2.5.2.1 Self-Consumption Scheme

The self-consumption scheme is the scheme which the customers consume output power from rooftop PVs to supply only the demand of the customers, as shown in Figure 2.13. Under this scheme, the reverse power flow is unavailable. If the output power from rooftop PVs is higher than the load demand, it will be curtailed to be equal to the load by zero export controller.

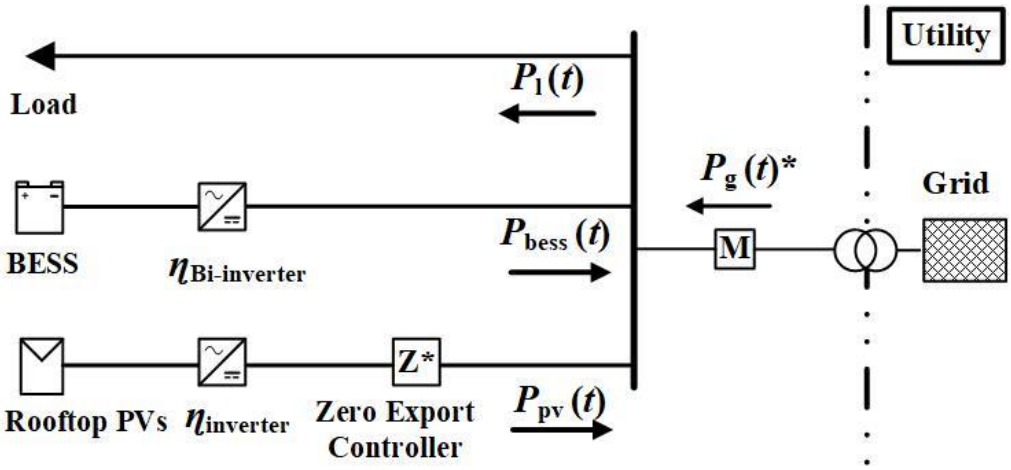

Figure 2.16 Self-consumption scheme

2.5.2.2 Net-Metering and Net-Billing Scheme

With an availability of the reverse power flow, net-metering scheme (NMS) and net-billing scheme (NBS) are a tariff-based supported policy to evaluate the value of the excess energy injected to the utility's grid by the customers who have an on-site renewable energy system, which is the rooftop PVs with BESS in this dissertation. The NMS and NBS are classified by the rate of excess energy, which can be performed in terms of the utility's retail rate, as shown in Equations (2.20)-(2.21). The NMS is the scheme where the rate of excess energy is equal to the utility's retail rate. On the other hand, the NBS is the scheme where the rate of the rate of excess energy is different from the utility's retail rate [7, 64, 65].

$$r_{\text{Excess}}^{\text{On}} = \gamma \cdot r^{\text{On}} \tag{2.20}$$

$$r_{\text{Excess}}^{\text{Off}} = \gamma \cdot r^{\text{Off}} \tag{2.21}$$

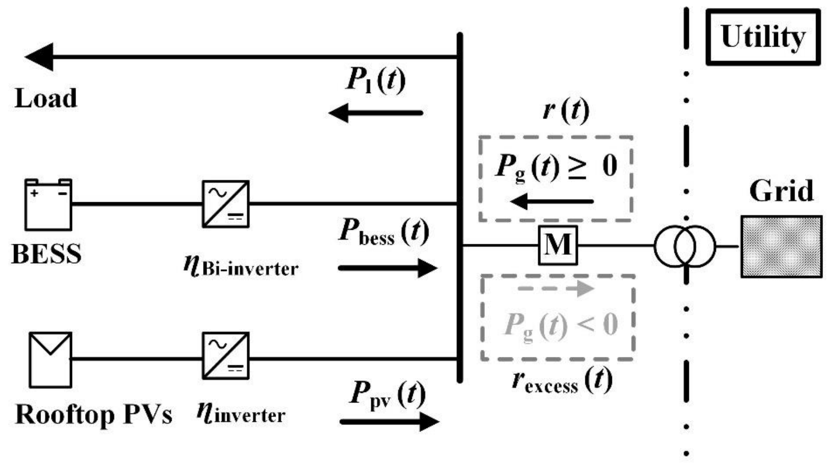

Figure 2.17 Net-metering and net-billing scheme

The benefit of the NMS and NBS is typically performed in term of an electricity charge compensation. Under these schemes, the output power from rooftop PVs with BESS will be deducted from load demand at the end of the billing cycle. The utility bills the customers based on the net energy, regardless of when the electricity was produced or absorbed. If the total production from rooftop PVs with BESS exceed the monthly load consumption, the excess energy can be “rolled over” or transferred as a credit to the next billing cycle. This concept was applied in this dissertation as electricity charge compensation period as shown in Figure 2.15. The electricity charge compensation period is typically effective within one year. At the end of the period, if there is any remaining credit left, it would be reset to be zero.

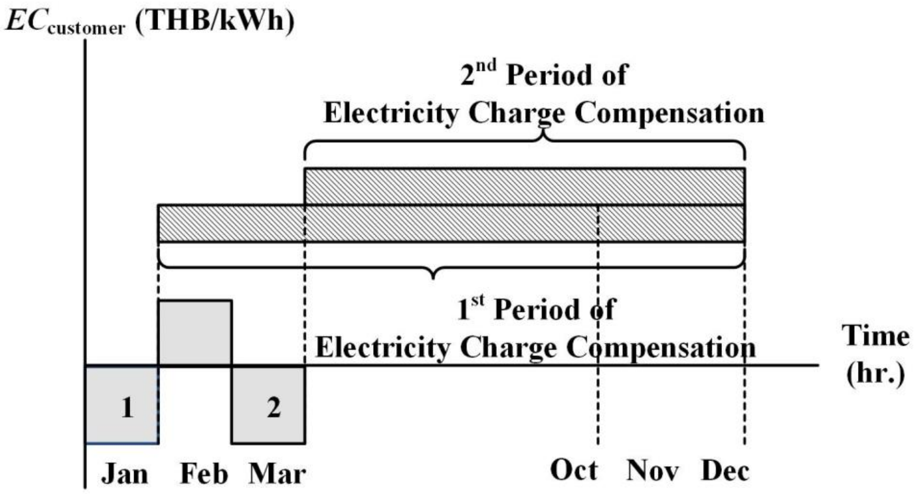

Figure 2.18 Electricity charge compensation period

2.5.2.3 Solar Power Purchase Agreement

The SPPA is a power purchase agreement, where the investors invest, install, and operate rooftop PVs on the customers' site. As shown in Figure 2.16, the rooftop PVs directly produce and supply electricity to the customers without having to pass the utility's infrastructure [17]. Under this scheme, the investors offer an electricity rate that is lower than the utility's retail rate to the customers for a specified number of years. The investors must take responsibility for the operation and maintenance of the rooftop PVs during the period of the SPPA. In addition, at the end of the SPPA, the ownership of rooftop PVs can be transferred to the customers in some cases, depending on the agreement. There are two common options for the proposed electricity rates. The first option is a fixed rate with an escalation over the contract period, while the other option is a discount on the utility's retail rate. The second option is practically more favorable for the customer to easily express the electricity charge saving under the TOU tariff.

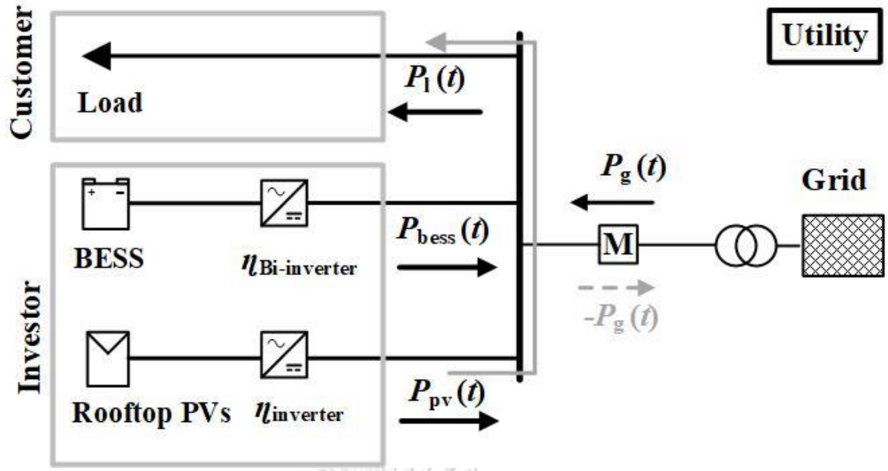

Figure 2.19 Solar power purchase agreement

CHAPTER 3
ECONOMIC FEASIBILITY ANALYSIS

To evaluate the economic feasibility and make an investment decision on the project, the modeling of cost and revenue of the rooftop PVs with BESS should be carefully formulated. To begin with, the total project cost, which consists of the total cost of rooftop PVs and BESS, is presented in Section 3.1. Secondly, the modeling of revenue is presented in Section 3.2 by dividing into three schemes of (1) self-consumption scheme, (2) net-metering and net-billing scheme, and (3) solar power purchase agreement. In Section 3.3, methodologies to evaluate economic feasibility of rooftop PVs with BESS are presented by applying net present value and internal rate of return.

3.1 Modeling of Project Cost

The total project cost (TPC) was formulated by dividing into the total cost (TC) of rooftop PVs and the BESS [43, 66, 67], the TC of each component consists of the total investment cost (TIC) and the total operation cost (TOC). The TIC is the amount of money spent to purchase and install the rooftop PVs with BESS, which considered only the hardware cost in this dissertation. The TOC is the amount of money spent on operation and maintenance of rooftop PVs with BESS. The TOC in each year (y) was assumed to be a percentage of the TIC and constant in every year. The currency exchange rate in this dissertation was assumed to be 30 Baht/USD and the TIC was projected by least mean square method.

3.1.1 Total Cost of Rooftop PVs

The TIC of rooftop PVs can be breakdown into two categories, i.e., soft costs and hard costs, as shown in Figure 3.1. Soft costs include installation, labor, and development cost. Hard costs include hardware costs, i.e., inverter, PV module cost and balance of system cost. Approximately 60 percent TIC is hard costs. In this dissertation, the TIC considered only PV module, PV inverter and balance of system cost. By considering the trend of TIC over the past 10 years, the TIC of residential PV, which is typically a rooftop PVs, has significantly decreased. The component, which has the highest reduced cost, is the PV module.

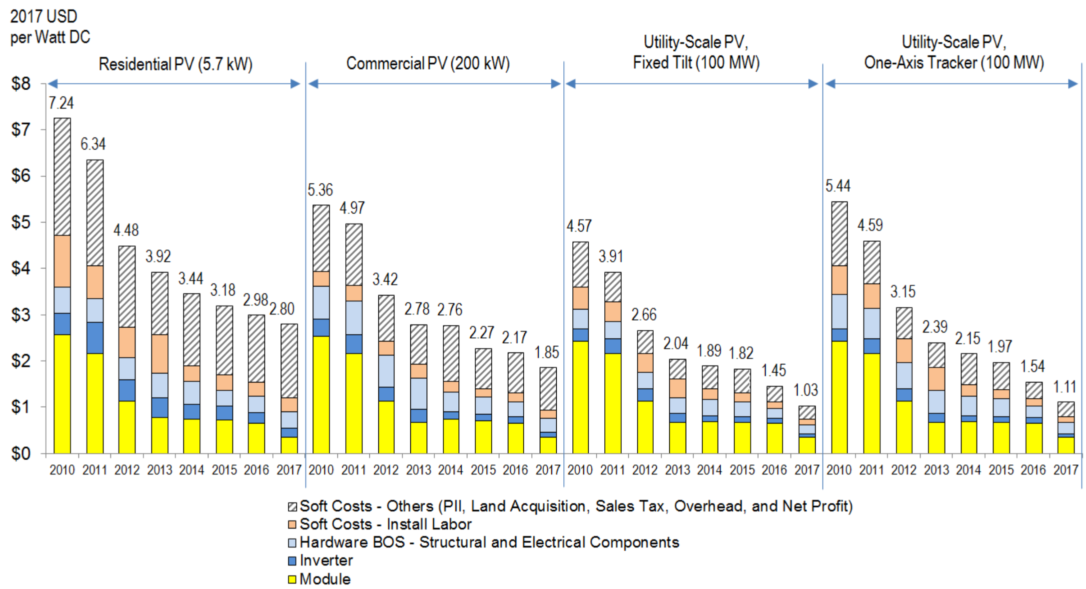

Figure 3.1 Total investment cost of photovoltaic systems [68]

For the TOC in each year, it was modeled in terms of the percentage of the TIC of rooftop PVs. As a result, the TC of rooftop PVs can be formulated by applying the discount cash flow methodology as shown in Equation (3.1),

$$c_{\mathrm{pv}}^{\mathrm{total}} = P_{\mathrm{pv,dc}} \cdot c_{\mathrm{pv}} \left(1 + \sum_{y=1}^{Y} \frac{c_{\mathrm{op}} \cdot r_{\mathrm{inf}}}{(1+i)^{y-1}} \right) \tag{3.1}$$

3.1.2 Total Cost of Battery Energy Storage Systems

For the battery energy storage system (BESS), the TIC of the BESS for rooftop PVs consists of the cost of battery module, cost of battery inverter, and balance of system cost, as shown in Figure 3.2. The TIC can be categorized into energy installation cost and power installation cost [43, 66]. The TOC of the BESS was modeled in terms of the percentage of the TIC of the BESS. As a result, the TC of the BESS can be formulated by applying the discount cash flow methodology as shown in Equation (3.2),

$$c_{\text{bess}}^{\text{total}} = \left(C_{\text{nom,dc}} \cdot c_{\text{eic}} + P_{\text{nom,dc}} \cdot c_{\text{pic}} \right) \left(1 + \sum_{y=1}^{Y} \frac{c_{\text{op}} \cdot r_{\text{inf}}}{(1+i)^{y-1}} \right) \tag{3.2}$$

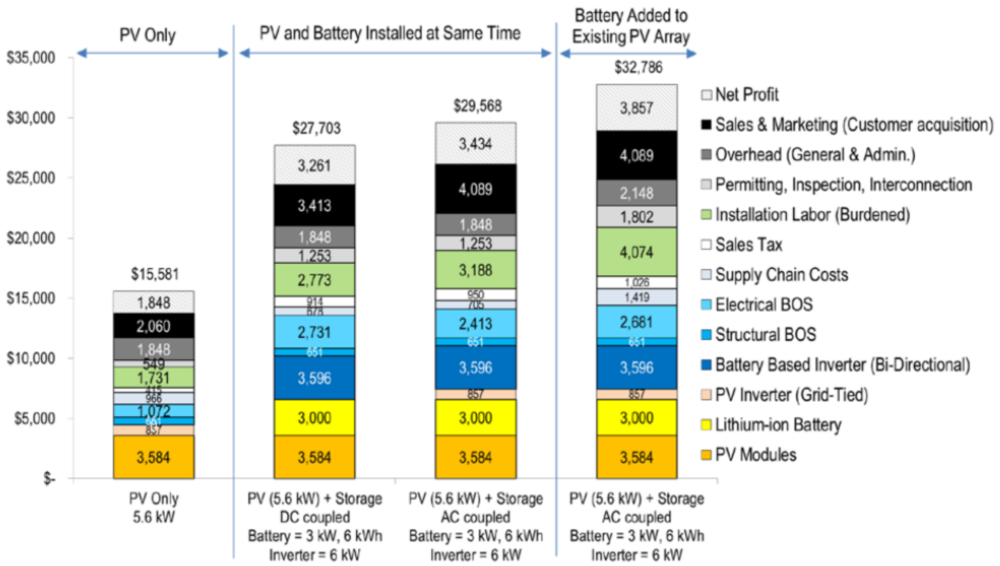

Figure 3.2 Total investment cost of the rooftop PVs with BESS [66]

(1) Energy Installation Cost

Energy installation cost is the cost of battery module, which is modeled in term of THB/kWh. The trend of cost of battery module is extremely decreased the past 10 years [43, 66]. By extrapolating the historical average cost of lithium-ion battery module from Bloomberg New Energy Finance (BNEF) and IRENA, the energy installation cost can be projected as shown in Figure 3.3.

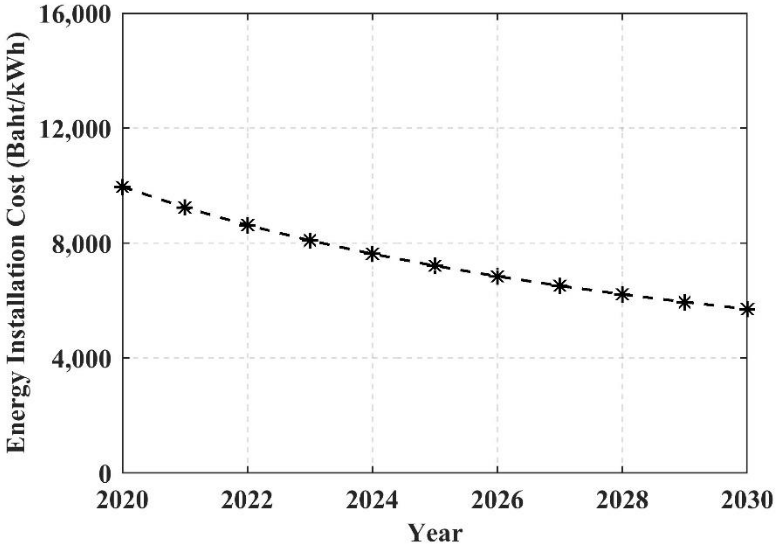

Figure 3.3 The trend of the energy installation cost

(2) Power Installation Cost

Power installation cost covers the cost of battery inverter and balance of system cost, which are modeled in term of THB/kW. The trend of cost of battery inverter in this research was assumed following the trend of Module-Level Power Electronics (MLPE) inverter. By extrapolating the historical cost [11], the trend of cost of MLPE inverter, balance of system cost and battery power installation cost can be projected as shown in Figure 3.4.

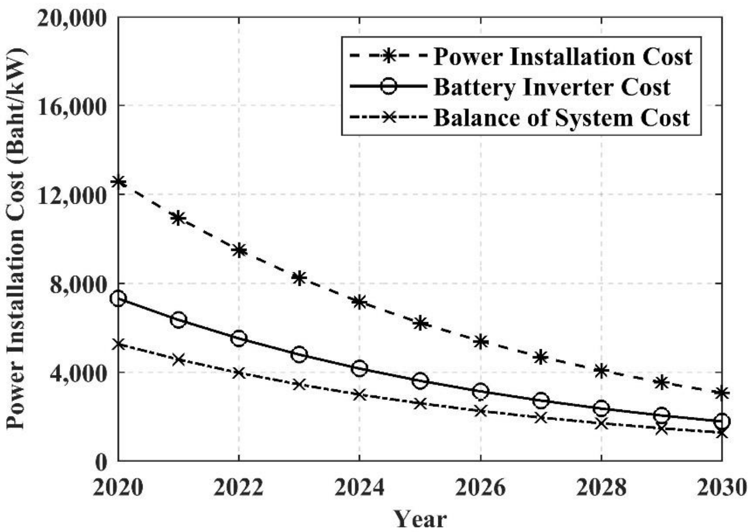

Figure 3.4 The trend of the power installation cost

3.1.3 Total Cost of Rooftop PVs with BESS

For the rooftop PVs with BESS, the AC coupling system have a higher TIC than the DC coupling system due to the cost of PV inverter and battery inverter. In addition, in case that the BESS was added to the existing rooftop PVs, the TIC will be higher due to balance of plant cost. The TC of rooftop PVs with BESS were formulated as shown in Equation (3.3),

$$c^{\text{total}} = c_{\text{pv}}^{\text{total}} + c_{\text{bess}}^{\text{total}} \tag{3.3}$$

3.2 Modeling of Revenue

This section presents the concept of the revenue from rooftop PVs with BESS under the BTMS, which can be divided into three schemes: (1) Self-consumption scheme (2) Net-metering and Net-billing scheme and (3) Solar power purchase agreement.

3.2.1 Revenue under the Self-Consumption Scheme

The self-consumption scheme is the scheme where the customers consume the output power from rooftop PVs with BESS for their local demand only. The investment capital and operating expenses are responsible by the customers as shown in Figure 3.5. The investors act as the contractor that are hired for installation, operation, and maintenance. The utility only must monitor the reverse power flow from the customers, which is unavailable. Therefore, the revenue of the customers under this scheme is the electricity charges saving.

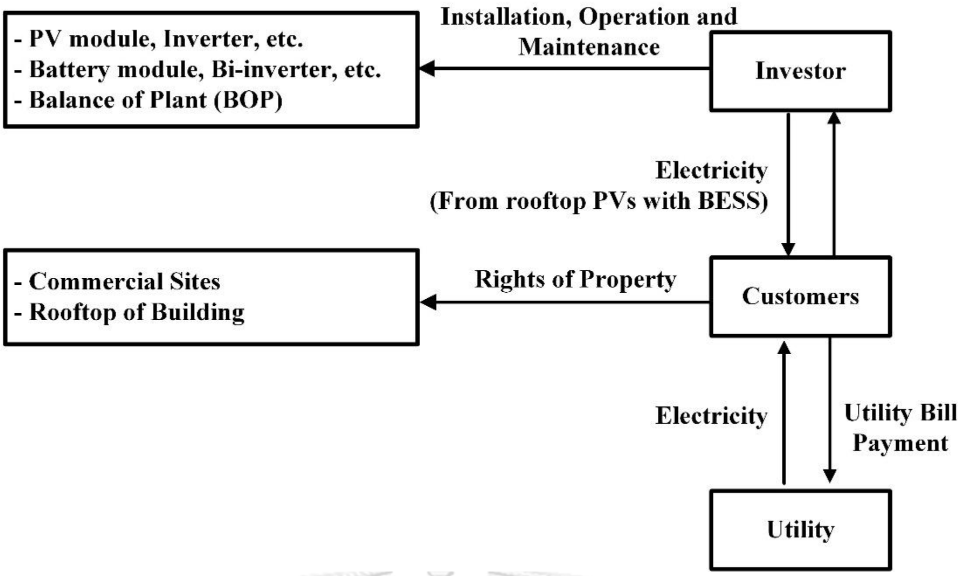

Figure 3.5 Business mechanism of the self-consumption scheme

3.2.2 Revenue under the Net-Metering and Net-Billing Scheme

The net-metering scheme (NMS) and net-billing scheme (NBS) are the scheme where the customers consume the output power from rooftop PVs with BESS for their local demand and export the excess energy to the utility with the specified rate. The investment capital and operating expenses are responsible by the customers as shown in Figure 3.6. The investors also act as the contractor that are hired for installation, operation, and maintenance. The reverse power flow is available and considered as the additional revenue to the customers. The utility has to compensate the excess energy from the customers. Therefore, under these schemes, the revenue of the customers is from electricity charge savings and excess energy injected to the utility's grid.

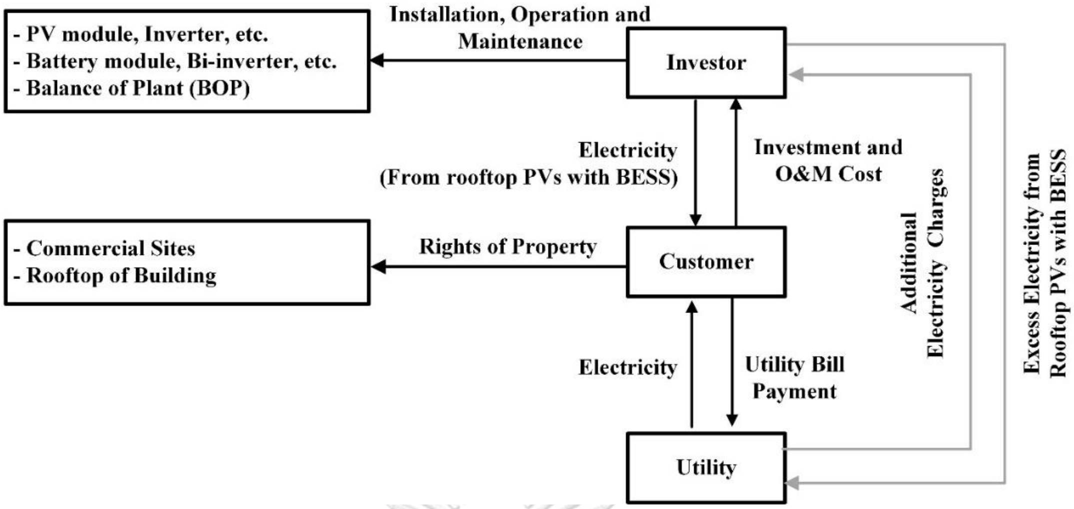

Figure 3.6 Business mechanism of the net-metering and net-billing scheme

3.2.3 Revenue under the Solar Power Purchase Agreement

The solar power purchase agreement (SPPA) is a power purchase agreement, where the investors invest, install, and operate rooftop PVs on with BESS the customers' site. The rooftop PVs with BESS directly produce and supply electricity to the customers without having to pass the utility's infrastructure. Under this scheme, the investors offer an electricity rate that is lower than the utility's retail rate to the customers for a specified number of years. The investors must take responsibility for the operation and maintenance of the rooftop PVs during the period of the SPPA as shown in Figure 3.7. The customers can save the electricity charges without any investment capital and operation expenses. In addition, at the end of the SPPA, the ownership of rooftop PVs with BESS can be transferred to the customers in some cases, depending on the agreement. In case that the reverse power flow is available, it can be considered as the additional benefit to the investors.

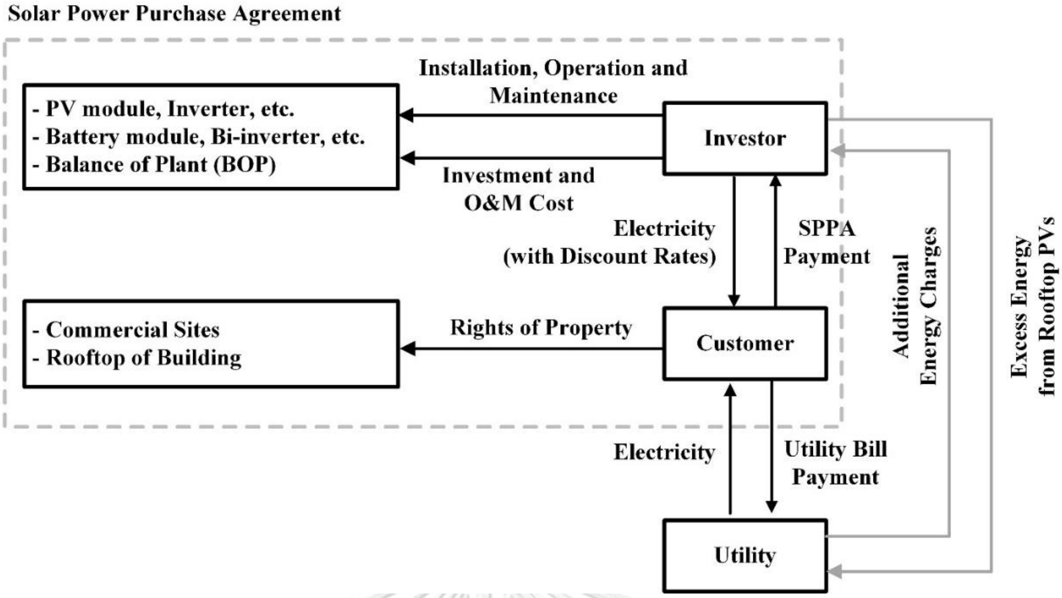

Figure 3.7 Business mechanism of the solar power purchase agreement

There are two common options for the SPPA proposed rates. The first option is a fixed rate with an escalation over the contract period, while the other option is a discount on the utility's retail rate. The second option is practically more favorable for the customer in order to easily express the electricity charge saving under the TOU tariff with demand charges. Therefore, the modeling of the SPPA in this dissertation was formulated by applying the SPPA discount rate options, which can be classified into three variables: SPPA on-peak discount rate (α_1), SPPA off-peak discount rate (α_2), and SPPA demand charge discount rate (β_1), as shown in Equations (3.4)-(3.6):

$$r_{\text{sppa}}^{\text{on}} = \left(1 - \alpha_1\right) \cdot r^{\text{on}} \tag{3.4}$$

$$r_{\text{sppa}}^{\text{off}} = \left(1 - \alpha_2\right) \cdot r^{\text{off}} \tag{3.5}$$

$$r_{\text{sppa}}^{\text{demand}} = \left(1 - \beta_1\right) \cdot r^{\text{demand}} \tag{3.6}$$

3.3 Economic Feasibility Analysis

The economic feasibility in this dissertation was evaluated by applying net present value (NPV) and internal rate of return (IRR). NPV is the present value of the net cash flow over a period as shown in Equation (3.7). The NPV is applied for capital budgeting and investment planning to analyze the economic feasibility of a projected investment. For the IRR, it is a metric used in capital budgeting measuring the profitability of potential investments. Internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero by applying the NPV formula, as shown in Equation (3.8):

$$\mathrm{NPV} = \sum_{t=1}^{S} \frac{c(t)}{(1+i)^{t}} - c_0 \tag{3.7}$$

$$0 = \sum_{t=1}^{S} \frac{c(t)}{(1+IRR)^{t}} - c_0 \tag{3.8}$$

In this dissertation, by applying the TC of rooftop PVs with BESS in Equation (3.3), the economic feasibility of the rooftop PVs with BESS can be determined as shown in Equation (3.8). The model of the revenue depends on the scheme of the project as shown in Equation (3.9),

$$\mathrm{NPV} = \sum_{y=1}^{Y} \sum_{m=1}^{S_y} \frac{R^{\mathrm{total}}(m)}{(1+IRR)^{y}} - c_{\mathrm{pv}}^{\mathrm{total}} - c_{\mathrm{bess}}^{\mathrm{total}} \tag{3.9}$$

CHAPTER 4
OPTIMAL BATTERY OPERATION AND CAPACITY SIZING

This chapter presents the proposed methodology, which consists the operation principle of rooftop PVs with BESS and the methodology for sizing BESS. In Section 4.1, the operation principle of rooftop PVs with BESS was proposed by dividing into operation mode and operation power. The operation mode of the BESS was formulated by classifying to charging, discharging, and idling modes. For the operation power, the methodology for self-consumption, net-metering and net-billing schemes were proposed. In Section 4.2, the modeling of the SPPA and the methodology to design the SPPA for rooftop PVs were proposed. In Section 4.3, the methodology for sizing the BESS was formulated by dividing into 3 schemes: (1) Self-consumption scheme, (2) Net-metering and net-billing scheme and (3) Solar power purchase agreement.

4.1 Operation Principle of Battery Energy Storage Systems

In Section 4.1, the operation principle of rooftop PVs with BESS was proposed by dividing into operation mode and operation power. The operation mode of the BESS was formulated by classifying to charging, discharging, and idling modes. For the operation power, the methodology for self-consumption, net-metering and net-billing schemes were proposed. In Section 4.2, the modeling of the SPPA and the methodology to design the SPPA for rooftop PVs were proposed. In Section 4.3, the methodology for sizing the BESS was formulated by dividing into 3 schemes: (1) Self-consumption scheme, (2) Net-metering and net-billing scheme and (3) Solar power purchase agreement.

4.1.1 Operation Mode

Operation modes of the BESS are typically classified into the three modes of charging, discharging, and idling. $K(t)$ was formulated to represent each selected operation mode. The charging and discharging mode, $K(t)$, are defined to be -1 and 1 respectively. The charged power ($P_{\text{bess,ch}}(t)$) and discharged power ($P_{\text{bess,dis}}(t)$) are defined to be negative and positive respectively. For the idling mode, $K(t)$ is defined to be 0 and the output power from the BESS is zero.

(1) Charging Mode

Charging mode is the operation mode that the BESS put an energy into a battery module via electromechanical process. The charging process depends on the energy capacity, power capacity and type of battery. In this dissertation, the charging mode is the operation mode that the BESS can be charged from the rooftop PVs and utility's grid.

(2) Discharging Mode

Discharging mode is the operation mode that the BESS export the stored energy from the battery module to the load or utility's grid. The discharging process depends on the energy capacity, power capacity, load demand, metering scheme and type of battery. In this dissertation, the discharging mode is the operation mode that the BESS is prioritized to supply the load. If the load demand is satisfied, the excess energy injected to the utility's grid will depend on the metering scheme.

(3) Idling Mode

Idling mode is the operation mode that the BESS operate with zero charged or discharged power.

4.1.2 Operation Power

The operation power can be divided into the charged and discharged power, which were subject load demand, battery energy limit and battery power limits. In addition, the rooftop PVs is designed to satisfy load demand firstly. If the output power from rooftop PVs is higher than the load demand, the excess energy can be used for charging the BESS. For the BESS, the BESS is also designed to satisfy load demand firstly. If the load demand is satisfied and there is the stored energy, the BESS can be discharged to the grid in case that the reverse power flow is available. By considering the constraint of reverse power flow, the modeling of the operation power was classified into (1) Self-consumption scheme and (2) Net-metering and net-billing scheme.

(1) Self-Consumption Scheme

The charged and discharged power are expressed in terms of rooftop PVs, load and utility's grid. For the charged power, the BESS can be charged from the rooftop PVs and utility's grid. The amount of charged power is subject to output power from rooftop PVs, load demand, maximum charged power limit, and upper energy limit, as shown in Equations (4.1)-(4.3):

$$P_{\text{bess,ch}}(t) = P_{\text{bess, ch}}^{\text{pv}}(t) + P_{\text{bess, ch}}^{\text{grid}}(t) \tag{4.1}$$

$$P_{\text{bess, ch}}^{\text{pv}}(t) = \text{Min}\,(0,\ \text{Max}\,(P_{\text{l}}\ (t) - P_{\text{pv}}(t), P_{\text{bess}}^{\text{upper}}(t), P_{\text{bess, ch}}^{\text{limit}}(t))) \tag{4.2}$$

$$\begin{aligned} P_{\text{bess, ch}}^{\text{grid}}(t) = \text{Min}\,(0,\ \text{Max}\,(&P_{\text{bess}}^{\text{upper}}(t) - P_{\text{l}}\ (t) - P_{\text{pv}}(t),\ P_{\text{bess}}^{\text{upper}}(t), \\ &P_{\text{bess, ch}}^{\text{limit}}(t) - P_{\text{l}}\ (t) - P_{\text{pv}}(t), P_{\text{bess, ch}}^{\text{limit}}(t))) \end{aligned} \tag{4.3}$$

Under the self-consumption scheme, the discharged power is formulated to supply the load only due to the unavailability of the reverse power flow. The amount of discharged power is subject to output power from rooftop PVs, load demand, maximum discharged power limit, and lower energy limit, as shown in Equations (4.4)-(4.5):

$$P_{\text{bess,dis}}(t) = P_{\text{bess, dis}}^{\text{load}}(t) \tag{4.4}$$

$$P_{\text{bess, dis}}^{\text{load}}(t) = \text{Max}\,(0,\ \text{Min}\,(P_{\text{l}}\ (t) - P_{\text{pv}}(t),\ P_{\text{bess}}^{\text{lower}}(t),\ P_{\text{bess, dis}}^{\text{limit}}(t))) \tag{4.5}$$

(2) Net-metering and net-billing scheme

For the net-metering and net-billing scheme, the charged and discharged power are also expressed in terms of load and utility's grid. The formulations for the charged power are also the identical to the self-consumption scheme, as shown in Equations (4.1)-(4.3). For the discharged power, the BESS is formulated and prioritized to supply the load. If the load demand is satisfied, the BESS can be discharged to the utility's grid depending on the condition energy and power limits. The amount of the discharged power is subject to output power from rooftop PVs, load demand, maximum discharged power limit, and lower energy limit, as shown in Equations (4.6)-(4.8):

$$P_{\text{bess,dis}}(t) = P_{\text{bess, dis}}^{\text{load}}(t) + P_{\text{bess, dis}}^{\text{grid}}(t) \tag{4.6}$$

$$P_{\text{bess, dis}}^{\text{load}}(t) = \text{Max}\,(0,\ \text{Min}\,(P_{\text{l}}\ (t) - P_{\text{pv}}(t),\ P_{\text{bess}}^{\text{lower}}(t),\ P_{\text{bess, dis}}^{\text{limit}}(t))) \tag{4.7}$$

$$P_{\text{bess, dis}}^{\text{grid}}(t) = \text{Max}\,(0,\ \text{Min}\,(P_{\text{bess}}^{\text{lower}}(t) - P_{\text{l}}\ (t) - P_{\text{pv}}(t),\ P_{\text{bess, dis}}^{\text{limit}}(t) - P_{\text{l}}\ (t) - P_{\text{pv}}(t),\ P_{\text{bess}}^{\text{lower}}(t),\ P_{\text{bess, dis}}^{\text{limit}}(t))) \tag{4.8}$$

As a result, as shown in Figure 4.1, the procedure for designing operation modes and power of BESS can be summarized as follows:

(1) Operation Mode Initialization

To begin with, $K(t)$ for each time over the project period will be randomly generated and initially selected from the genetic algorithm (GA).

(2) Battery Operation Mode Verification

Transforming the value of $K(t)$ for each time t into the operation modes of the BESS: Charging mode ($K(t)$ is -1), Discharging mode ($K(t)$ is 1) and Idling mode ($K(t)$ is 0).

(3) Battery Energy Limit Verification

For the charging mode and discharging mode, the battery energy limit at time t, has to be confirmed. To operate in charging mode, the lower energy limit would be considered to verify that there is the amount of capacity that can be charged from rooftop PVs or grid. On the other hand, for discharging mode, the upper energy limit would be considered to verify that there is the amount of energy that can be discharged to load or grid. If the energy limit is not satisfied, the BESS would be assigned to operate in idling mode.

(4) Load demand and PV output power

The charged and discharged power will firstly be subjected to the condition of load demand and output power from rooftop PVs. For the charging mode, if the load demand is higher than the output power from rooftop PVs, the BESS would be directly charged from the grid. For the discharging mode, if the load demand is lower than the output power from rooftop PVs the BESS would be directly discharged to the grid.

(5) Excess Energy from Rooftop PVs

The excess energy from rooftop PVs and the energy limit will be considered. For charging, if the excess energy is not higher than the upper energy limit, the BESS will be charged from rooftop PVs only. Otherwise, the BESS will be charged from both rooftop PVs and grid. For discharging, if the excess energy is not lower than the lower energy limit, the BESS will be discharged to load only. Otherwise, the BESS will be discharged to load and grid.

(6) Fitness Function Calculation

When all operation power over the project period have been determined, the fitness function will be calculated depending the objective function and constraints.

(7) Revised Operation Modes

If the operation modes are not the optimal value, the revised operation mode of the BESS will be generated by genetic algorithm process, which consist of (1) Selection process, (2) Crossover process and (3) Mutation process. The genetic algorithm process will be repeated until the stopping criteria is satisfied. In this dissertation, the GA will stop when there is no improvement of the operation modes for 50 iterations

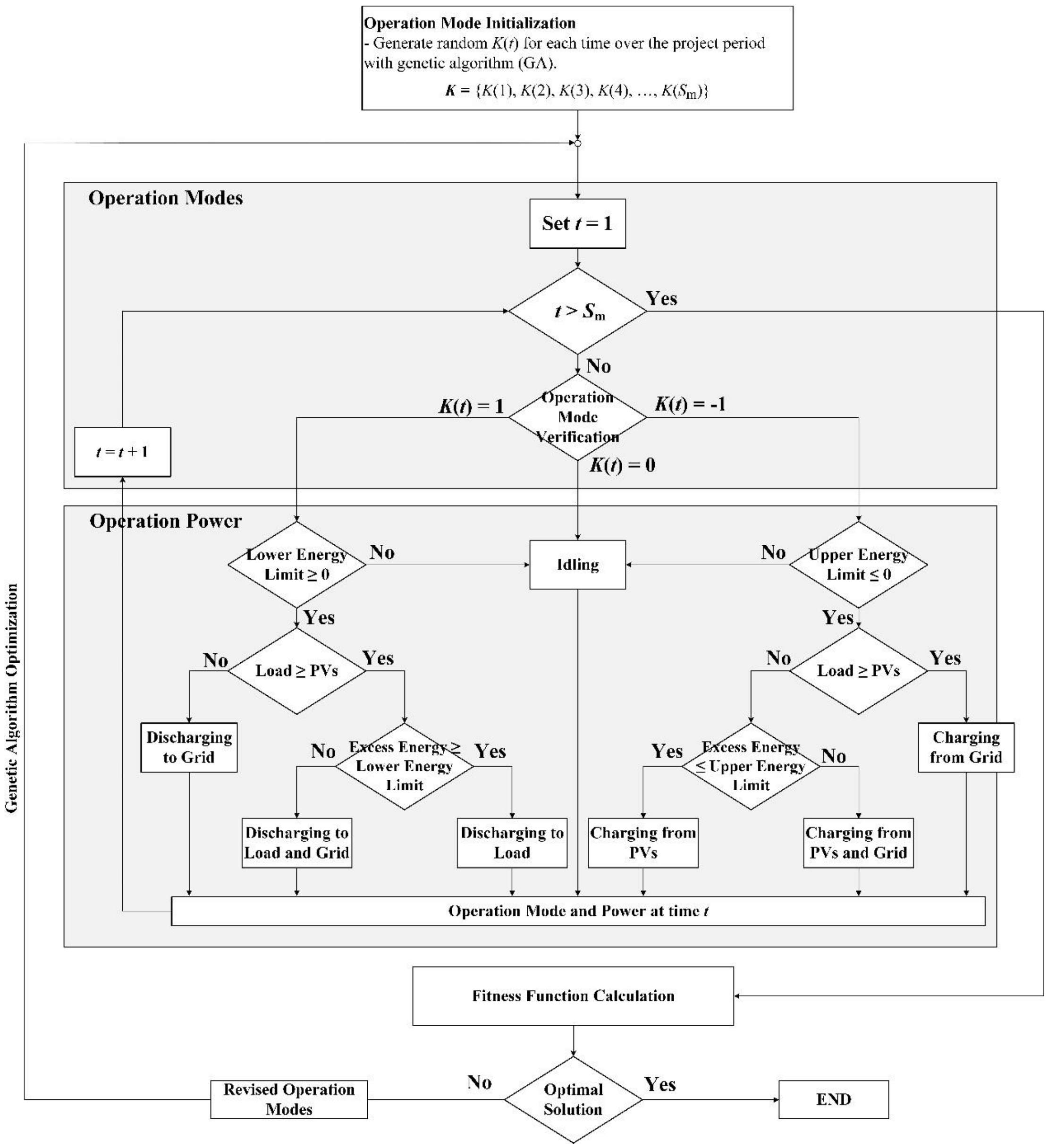

Figure 4.1 Flowchart showing the approach to design operation modes and power of BESS

4.2 Designing SPPA Discount Rates

The modeling of the SPPA was formulated by dividing into (1) SPPA with the self-consumption scheme and (2) SPPA with the net-metering and net-billing scheme. In addition, the proposed methodology to design the SPPA discount rates for rooftop PVs was proposed by applying the cost and revenue concept of each scheme.

In each scheme, the modeling of the SPPA for rooftop PVs was formulated by dividing into (1) Customers' side and (2) Investors' side. For the customers' side, the modeling of the total electricity charges under the SPPA was formulated based on the TOU tariff with demand charges, as shown in Equation (4.9). For the investors' side, the modeling of the revenue under the SPPA was also formulated by applying the concept of the internal rate of return, as shown in Equation (4.10):

$$EC_{\text{customer}} = \sum_{y=1}^{Y} \sum_{m=1}^{S_y} \frac{R_{\text{customer}}^{\text{total}}(m)}{(1+i)^y} \tag{4.9}$$

$$\sum_{y=1}^{Y} \sum_{m=1}^{S_y} \frac{R_{\text{investor}}^{\text{total}}(m)}{(1+IRR_{\text{investor}})^y} - c_{\text{pv}}^{\text{total}} = 0 \tag{4.10}$$

4.2.1 SPPA with the Self-Consumption Scheme

Under the SPPA with the self-consumption scheme, the modeling of the electricity charges of the customers consists of SPPA on-peak energy charges ($R_{\text{customer}}^{\text{on}}(t)$), SPPA off-peak energy charges ($R_{\text{customer}}^{\text{off}}(t)$), and SPPA demand charges ($R_{\text{customer}}^{\text{demand}}(m)$). The electricity charges of each component were formulated as shown in Equations (4.11)-(4.14):

<u>Electricity Charges of the Customers</u>

$$R_{\text{customer}}^{\text{on}}(t) = \begin{cases} r_{\text{sppa}}^{\text{on}} \cdot P_{\text{l}}(t) \cdot \Delta t & ; P_{\text{g}}(t) = 0 \\ r^{\text{on}} \cdot P_{\text{g}}(t) \cdot \Delta t + r_{\text{sppa}}^{\text{on}} \cdot P_{\text{pv}}(t) \cdot \Delta t & ; P_{\text{g}}(t) > 0 \end{cases} \tag{4.11}$$

$$R_{\text{customer}}^{\text{off}}(t)=\begin{cases} r_{\text{sppa}}^{\text{off}}\cdot P_{1}(t)\cdot\Delta t & ;P_{\text{g}}(t)=0 \\ r^{\text{off}}\cdot P_{\text{g}}(t)\cdot\Delta t+r_{\text{sppa}}^{\text{off}}\cdot P_{\text{pv}}(t)\cdot\Delta t & ;P_{\text{g}}(t)>0 \end{cases} \quad (4.12)$$

$$R_{\text{customer}}^{\text{demand}}(m)=\begin{cases} r_{\text{sppa}}^{\text{demand}}\cdot P_{1}(t_{\text{peak}}) & ;P_{\text{g}}(t_{\text{peak}})=0 \\ r^{\text{demand}}\cdot P_{\text{g}}(t_{\text{peak}})+r_{\text{peak}}^{\text{demand}}\cdot P_{\text{pv}}(t_{\text{peak}}) & ;P_{\text{g}}(t_{\text{peak}})>0 \end{cases} \quad (4.13)$$

$$R_{\text{customer}}^{\text{total}}(m)=\sum_{t=1}^{S_{\text{m}}^{\text{on}}}R_{\text{customer}}^{\text{on}}(t)+\sum_{t=1}^{S_{\text{m}}^{\text{off}}}R_{\text{customer}}^{\text{off}}(t)+R_{\text{customer}}^{\text{demand}}(m) \quad (4.14)$$

For the investors' side, the modeling of the total revenue ($R_{\text{investor}}^{\text{total}}(m)$) was also formulated based on the TOU tariff with demand charges, which consists of SPPA on-peak revenue ($R_{\text{investor}}^{\text{on}}(t)$), SPPA off-peak revenue ($R_{\text{investor}}^{\text{off}}(t)$), and SPPA demand charge revenue ($R_{\text{investor}}^{\text{demand}}(m)$), as shown in Equations (4.15)-(4.18). With an unavailability of the reverse power flow, the revenue was only from sold power of rooftop PVs to the customers

Revenue of the Investors

$$R_{\text{investor}}^{\text{on}}(t)=r_{\text{sppa}}^{\text{on}}\cdot P_{1}(t)\cdot\Delta t \quad (4.15)$$

$$R_{\text{investor}}^{\text{off}}(t)=r_{\text{sppa}}^{\text{off}}\cdot P_{1}(t)\cdot\Delta t \quad (4.16)$$

$$R_{\text{investor}}^{\text{demand}}(m)=r_{\text{sppa}}^{\text{demand}}\cdot P_{1}(t_{\text{peak}})\cdot\Delta t \quad (4.17)$$

$$R_{\text{investor}}^{\text{total}}(m)=\sum_{t=1}^{S_{\text{m}}^{\text{on}}}R_{\text{investor}}^{\text{on}}(t)+\sum_{t=1}^{S_{\text{m}}^{\text{off}}}R_{\text{investor}}^{\text{off}}(t)+R_{\text{investor}}^{\text{demand}}(m) \quad (4.18)$$

4.2.2 SPPA with the Net-Metering and Net-Billing Scheme

Under the SPPA with the net-metering and net-billing scheme, the modeling of the electricity charges of the customers consists of SPPA on-peak energy charges ($R_{\text{customer}}^{\text{on}}(t)$), SPPA off-peak energy charges ($R_{\text{customer}}^{\text{off}}(t)$), and SPPA demand charges ($R_{\text{customer}}^{\text{demand}}(m)$). The electricity charges of each component were formulated as shown in Equations (4.19)-(4.22)

Electricity Charges of the Customers

$$R_{\text{customer}}^{\text{on}}(t)=\begin{cases} r_{\text{sppa}}^{\text{on}}\cdot P_{\text{l}}(t)\cdot\Delta t & ;P_{\text{g}}(t)\le 0 \\ r^{\text{on}}\cdot P_{\text{g}}(t)\cdot\Delta t + r_{\text{sppa}}^{\text{on}}\cdot P_{\text{pv}}(t)\cdot\Delta t & ;P_{\text{g}}(t)>0 \end{cases} \tag{4.19}$$

$$R_{\text{customer}}^{\text{off}}(t)=\begin{cases} r_{\text{sppa}}^{\text{off}}\cdot P_{\text{l}}(t)\cdot\Delta t & ;P_{\text{g}}(t)\le 0 \\ r^{\text{off}}\cdot P_{\text{g}}(t)\cdot\Delta t + r_{\text{sppa}}^{\text{off}}\cdot P_{\text{pv}}(t)\cdot\Delta t & ;P_{\text{g}}(t)>0 \end{cases} \tag{4.20}$$

$$R_{\text{customer}}^{\text{demand}}(m)=\begin{cases} r_{\text{sppa}}^{\text{demand}}\cdot P_{\text{l}}(t_{\text{peak}}) & ;P_{\text{g}}(t_{\text{peak}})\le 0 \\ r^{\text{demand}}\cdot P_{\text{g}}(t_{\text{peak}}) + r_{\text{peak}}^{\text{demand}}\cdot P_{\text{pv}}(t_{\text{peak}}) & ;P_{\text{g}}(t_{\text{peak}})>0 \end{cases} \tag{4.21}$$

$$R_{\text{customer}}^{\text{total}}(m)=\sum_{t=1}^{S_{\text{m}}^{\text{on}}} R_{\text{customer}}^{\text{on}}(t)+\sum_{t=1}^{S_{\text{m}}^{\text{off}}} R_{\text{customer}}^{\text{off}}(t)+R_{\text{customer}}^{\text{demand}}(m) \tag{4.22}$$

For the investors' side, the modeling of the total revenue ($R_{\text{investor}}^{\text{total}}(m)$) was also formulated based on the TOU tariff with demand charges, which consists of SPPA on-peak revenue ($R_{\text{investor}}^{\text{on}}(t)$), SPPA off-peak revenue ($R_{\text{investor}}^{\text{off}}(t)$), and SPPA demand charge revenue ($R_{\text{investor}}^{\text{demand}}(m)$), as shown in Equations (4.23)-(4.25). The different point was the excess energy injected to the utility's grid, which was valued as additional revenue to the investors, as shown in Equations (4.26):

Revenue of the Investors

$$R_{\text{investor}}^{\text{on}}(t)=\begin{cases} r_{\text{sppa}}^{\text{on}}\cdot P_{\text{l}}(t)\cdot\Delta t - r_{\text{ex}}^{\text{on}}\cdot P_{\text{g}}(t)\cdot\Delta t & ;P_{\text{g}}(t)\le 0 \\ r^{\text{on}}\cdot P_{\text{l}}(t)\cdot\Delta t & ;P_{\text{g}}(t)>0 \end{cases} \tag{4.23}$$

$$R_{\text{investor}}^{\text{off}}(t)=\begin{cases} r_{\text{sppa}}^{\text{off}}\cdot P_{\text{l}}(t)\cdot\Delta t - r_{\text{ex}}^{\text{off}}\cdot P_{\text{g}}(t)\cdot\Delta t & ;P_{\text{g}}(t)\le 0 \\ r^{\text{off}}\cdot P_{\text{l}}(t)\cdot\Delta t & ;P_{\text{g}}(t)>0 \end{cases} \tag{4.24}$$

$$R_{\text{investor}}^{\text{demand}}(m)=\begin{cases} r_{\text{sppa}}^{\text{demand}}\cdot P_{\text{l}}(t_{\text{peak}}) & ;P_{\text{g}}(t_{\text{peak}})\le 0 \\ r_{\text{sppa}}^{\text{demand}}\cdot P_{\text{pv}}(t_{\text{peak}}) & ;P_{\text{g}}(t_{\text{peak}})>0 \end{cases} \tag{4.25}$$

$$R_{\text{investor}}^{\text{total}}(m)=\sum_{t=1}^{S_{\text{m}}^{\text{on}}} R_{\text{investor}}^{\text{on}}(t)+\sum_{t=1}^{S_{\text{m}}^{\text{off}}} R_{\text{investor}}^{\text{off}}(t)+R_{\text{investor}}^{\text{demand}}(m) \tag{4.26}$$

To design the SPPA discount rates for both scheme in Section 4.2.1 and 4.2.2, the cost optimization model was formulated by applying the formulation in Equations (4.10)-(4.11). The objective was to minimize the electricity charges of the customers, while maintaining the target internal rate of return (IRR) of the investors, as shown in Figure 4.1. The objective function and constraints are shown in Equations (4.27)-(4.32). The decisive variables are SPPA on-peak discount rate (α_1), SPAA off-peak discount rate (α_2), SPPA demand charge discount rate (β_1). Noted that the constraint of the electricity charge compensation period in Equation (4.32) was only applied for the SPPA under the net-metering and net-billing scheme

Objective Function

$$\text{Min} \quad EC_{\text{customer}} \tag{4.27}$$

Constraints

$$IRR_{\text{investor}} \geq IRR_{\text{target}} \tag{4.28}$$

$$\alpha_1 \geq 0 \tag{4.29}$$

$$\alpha_2 \geq 0 \tag{4.30}$$

$$\beta_1 \geq 0 \tag{4.31}$$

$$\sum_{m=1}^{S_y} \sum_{t=1}^{S_m} \left[P_l(t) - (P_{\text{pv}}(t) + P_{\text{bess}}(t)) \right] \cdot \Delta t \quad \geq 0 \tag{4.32}$$

4.3 Battery Capacity Sizing

The proposed methodology for designing the optimal battery capacity was proposed by dividing into three models of (1) Self-consumption scheme, (2) Net-metering and net-billing schemes and (3) Solar power purchase agreement. The cost optimization model was applied the cost and revenue concept of each scheme as follows:

4.3.1 Self-Consumption Scheme

For the self-consumption scheme, the installation of the rooftop PVs with BESS is only for electricity charge saving of the customers, while the reverse power flow is unavailable. The modeling of the electricity charges of the customers under the self-consumption scheme was formulated based on the TOU tariff with demand charges, which consist of on-peak energy charges ($R^{\text{on}}_{\text{customer}}(t)$), off-peak energy charges ($R^{\text{off}}_{\text{customer}}(t)$), and demand charges ($R^{\text{demand}}_{\text{customer}}(m)$), as shown in Equations (4.33)-(4.36):

<u>Electricity Charges of the Customers</u>

$$R^{\text{on}}_{\text{customer}}(t) = r^{\text{on}} \cdot P_{\text{g}}(t) \cdot \Delta t \tag{4.33}$$

$$R^{\text{off}}_{\text{customer}}(t) = r^{\text{on}} \cdot P_{\text{g}}(t) \cdot \Delta t \tag{4.34}$$

$$R^{\text{demand}}_{\text{customer}}(m) = r^{\text{demand}} \cdot P_{\text{g}}(t_{\text{peak}}) \tag{4.35}$$

$$R^{\text{total}}_{\text{customer}}(m) = \sum_{t=1}^{S^{\text{on}}_{\text{m}}} R^{\text{on}}_{\text{customer}}(t) + \sum_{t=1}^{S^{\text{off}}_{\text{m}}} R^{\text{off}}_{\text{customer}}(t) + R^{\text{demand}}_{\text{customer}}(m) \tag{4.36}$$

The modeling of the total electricity charge saving from rooftop PVs with BESS over the project life was formulated by applying the NPV and the electricity charges of the customers ($EC_{\text{customer}}(t)$) under the self-consumption scheme, as shown in Equation (4.37). The modeling of the target internal rate of return of the customers was formulated as shown in Equation (4.38):

$$EC_{\text{customer}} = \sum_{y=1}^{Y} \sum_{m=1}^{S_y} \frac{R^{\text{total}}_{\text{base}}(m) - R^{\text{total}}_{\text{customer}}(m)}{(1+i)^y} \tag{4.37}$$

$$\sum_{y=1}^{Y} \sum_{m=1}^{S_y} \frac{R^{\text{total}}_{\text{base}}(m) - R^{\text{total}}_{\text{customer}}(m)}{(1+IRR)^y} - c^{\text{total}}_{\text{pv}} - c^{\text{total}}_{\text{bess}} = 0 \tag{4.38}$$

To design the energy capacity, power capacity and operation mode of the BESS, the cost optimization model was formulated by applying the Equations (4.37)-(4.38). The objective was to minimize the electricity charges of the customers, while maintaining the target internal rate of return (IRR) of the customers under the self-consumption scheme, as shown in Figure 4.2. The objective function and constraints are shown in Equations (4.39)-(4.40). The decisive variables are battery energy capacity (C_{nom}), battery power capacity (P_{nom}), and operation modes at time t ($K(t)$).

Objective Function

$$\text{Min} \quad EC_{\text{customer}} \tag{4.39}$$

Constraints

$$IRR_{\text{customer}} \geq IRR_{\text{target}} \tag{4.40}$$

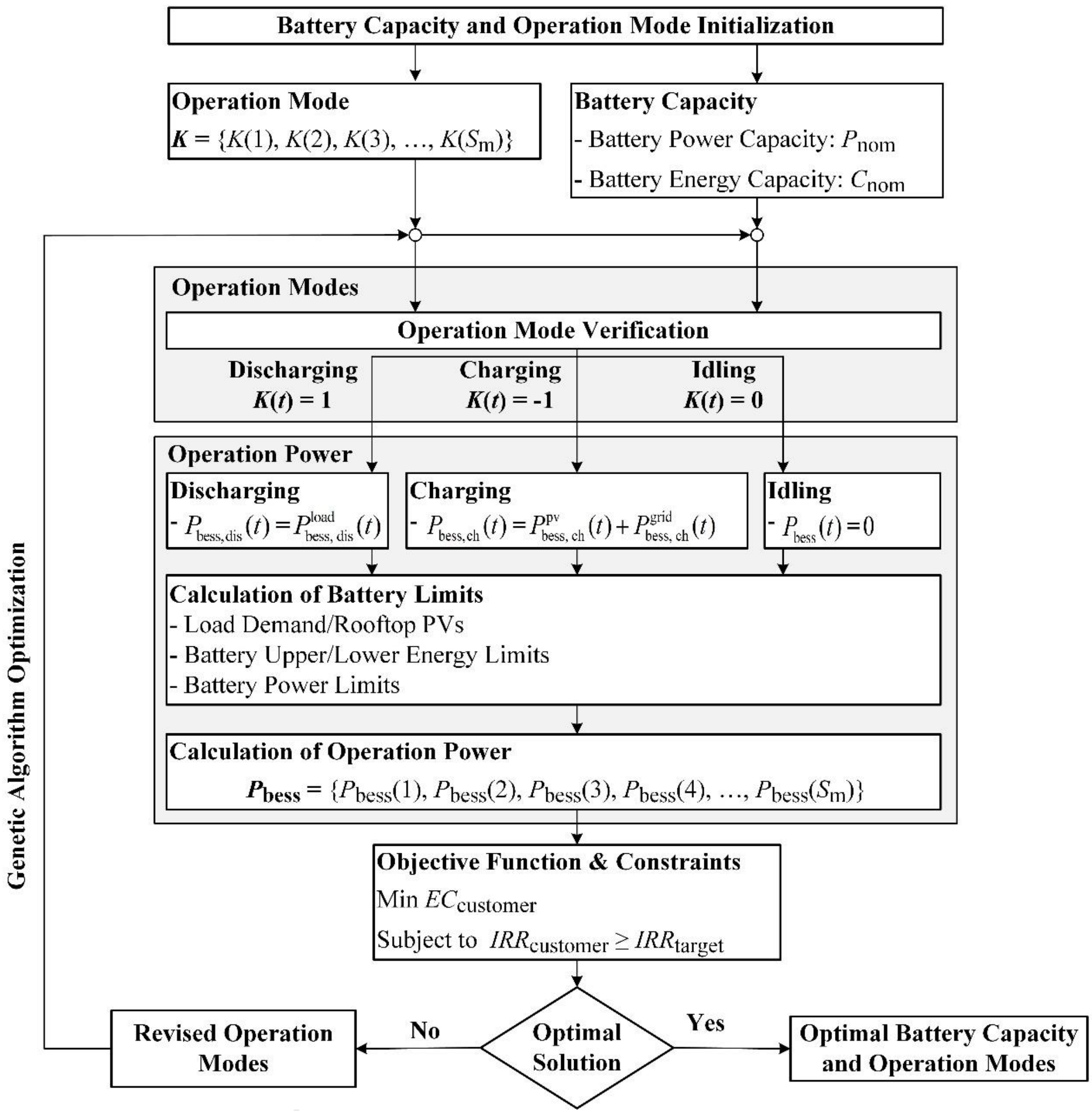

Figure 4.2 Flowchart showing the optimization approach to size the BESS under the self-consumption scheme

4.3.2 Net-Metering and Net-Billing Scheme

For the net-metering and net-billing scheme, the installation of the rooftop PVs with BESS is only for electricity charge saving of the customers and the reverse power flow is available. The excess energy injected to the utility's grid was considered as the electricity compensation of the customers within the specific period. The modeling of the electricity charges of the customers under the self-consumption scheme was formulated based on the TOU tariff with demand charges, which consist of on-peak energy charges ($R^{\text{on}}_{\text{customer}}(t)$), off-peak energy charges ($R^{\text{off}}_{\text{customer}}(t)$), and demand charges ($R^{\text{demand}}_{\text{customer}}(m)$), as shown in Equations (4.41)-(4.44):

Electricity Charges of the Customers

$$R^{\text{on}}_{\text{customer}}(t)=\begin{cases} r^{\text{on}}\cdot P_{\text{l}}(t)\cdot\Delta t + r^{\text{on}}_{\text{ex}}\cdot P_{\text{g}}(t)\cdot\Delta t & ;P_{\text{g}}(t)\le 0 \\ r^{\text{on}}\cdot P_{\text{g}}(t)\cdot\Delta t & ;P_{\text{g}}(t)>0 \end{cases} \tag{4.41}$$

$$R^{\text{off}}_{\text{customer}}(t)=\begin{cases} r^{\text{off}}\cdot P_{\text{l}}(t)\cdot\Delta t + r^{\text{off}}_{\text{ex}}\cdot P_{\text{g}}(t)\cdot\Delta t & ;P_{\text{g}}(t)\le 0 \\ r^{\text{off}}\cdot P_{\text{g}}(t)\cdot\Delta t & ;P_{\text{g}}(t)>0 \end{cases} \tag{4.42}$$

$$R^{\text{demand}}_{\text{customer}}(m)=r^{\text{demand}}\cdot P_{\text{g}}(t_{\text{peak}}) \tag{4.43}$$

$$R^{\text{total}}_{\text{customer}}(m)=\sum_{t=1}^{S^{\text{on}}_{\text{m}}} R^{\text{on}}_{\text{customer}}(t)+\sum_{t=1}^{S^{\text{off}}_{\text{m}}} R^{\text{off}}_{\text{customer}}(t)+R^{\text{demand}}_{\text{customer}}(m) \tag{4.44}$$

The cost optimization model under the NMS and NBS for designing the energy capacity, power capacity and operation mode was formulated by applying the similar concept of the NPV and the electricity charges of the customers under the self-consumption scheme in Equations (4.37)-(4.38). The main different point is the benefit from excess energy injected to the grid. The objective was to minimize the electricity charges of the customers, while maintaining the target internal rate of return (IRR) under the net-metering and net-billing scheme, as shown in Figure 4.3. The objective function and constraints are shown in Equations (4.45)-(4.47). The decisive variables are battery energy capacity (C_{nom}), battery power capacity (P_{nom}), and operation modes at time t ($K(t)$)

Objective Function

$$\text{Min}\quad EC_{\text{customer}} \tag{4.45}$$

Constraints

$$IRR_{\text{customer}}\ge IRR_{\text{target}} \tag{4.46}$$

$$\sum_{m=1}^{S_y}\sum_{t=1}^{S_m}\left[P_{\text{l}}(t)-(P_{\text{pv}}(t)+P_{\text{bess}}(t))\right]\cdot\Delta t\quad\ge 0 \tag{4.47}$$

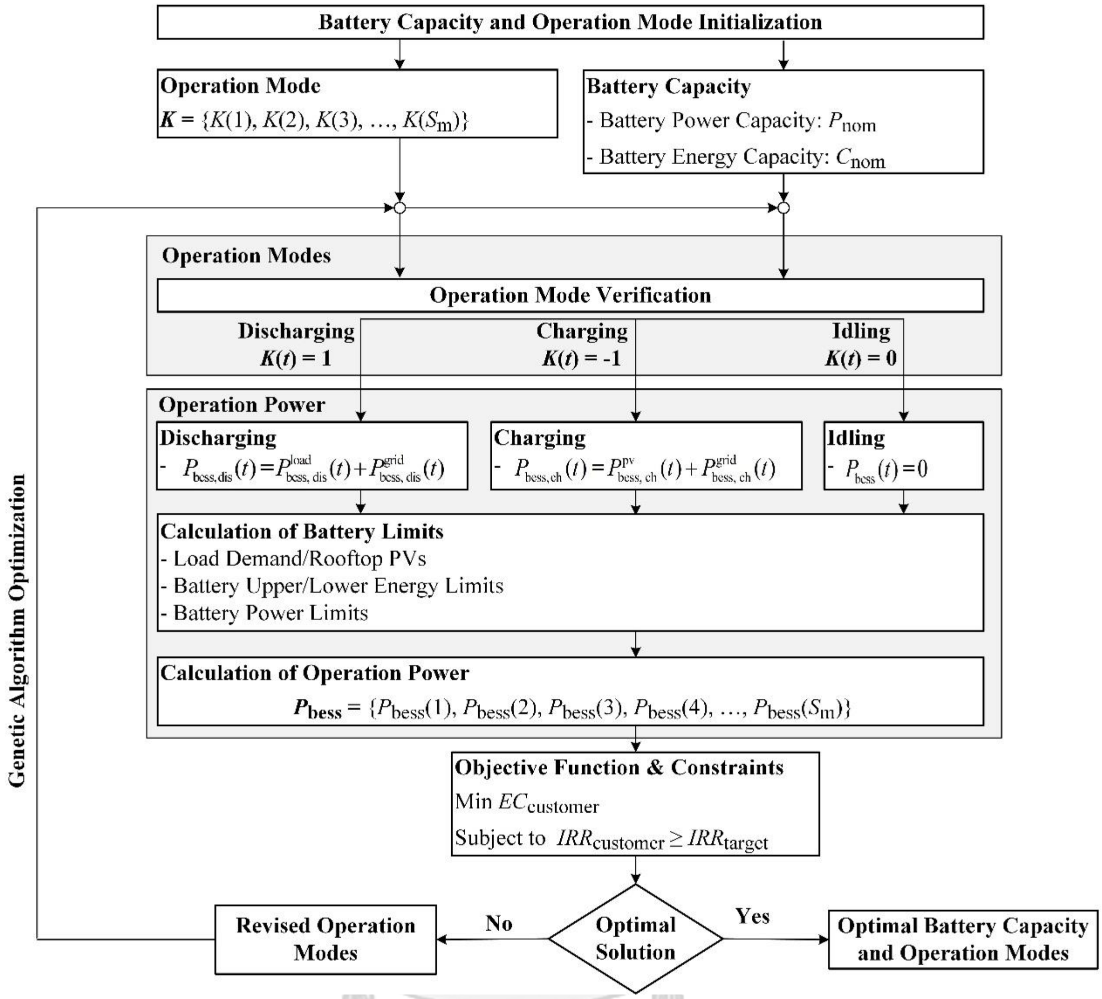

Figure 4.3 Flowchart showing the optimization approach to size the BESS under the net-metering and net-billing scheme

4.3.3 Solar Power Purchase Agreement

The proposed methodology for designing the battery capacity, operation modes of the BESS and discount rates was formulated by classifying into two schemes: (1) SPPA under the self-consumption scheme and (2) SPPA under the net-metering and net-billing schemes. The main difference is the availability of the reverse power flow with the rate of excess energy.

In each scheme, the modeling of the SPPA for rooftop PVs with BESS was formulated by dividing into (1) Customers' side and (2) Investors' side. For the customers' side, the modeling of the total electricity charges under the SPPA was formulated based on the TOU tariff with demand charges, as shown in Equation (4.48). For the investors' side, the modeling of the revenue under the SPPA was also formulated by applying the concept of the internal rate of return, as shown in Equation (4.49):

$$EC_{\text{customer}} = \sum_{y=1}^{Y}\sum_{m=1}^{S_y} \frac{R_{\text{customer}}^{\text{total}}(m)}{(1+i)^y} \tag{4.48}$$

$$\sum_{y=1}^{Y}\sum_{m=1}^{S_y} \frac{R_{\text{investor}}^{\text{total}}(m)}{(1+IRR)^y} - c_{\text{pv}}^{\text{total}} - c_{\text{bess}}^{\text{total}} = 0 \tag{4.49}$$

4.3.3.1 Solar Power Purchase Agreement with the Self-consumption Scheme

For the SPPA with the self-consumption scheme, the modeling of the electricity charges of the customers consists of SPPA on-peak energy charges ($R_{\text{customer}}^{\text{on}}(t)$), SPPA off-peak energy charges ($R_{\text{customer}}^{\text{off}}(t)$), and SPPA demand charges ($R_{\text{customer}}^{\text{demand}}(m)$). The electricity charges of each component were formulated as shown in Equations (4.50)-(4.53):

<u>**Electricity Charges of the Customers**</u>

$$R_{\text{customer}}^{\text{on}}(t) = \begin{cases} r_{\text{sppa}}^{\text{on}} \cdot P_{\text{l}}(t) \cdot \Delta t & ; P_{\text{g}}(t) = 0 \\ r^{\text{on}} \cdot P_{\text{g}}(t) \cdot \Delta t + r_{\text{sppa}}^{\text{on}} \cdot (P_{\text{pv}}(t) + P_{\text{bess}}(t)) \cdot \Delta t & ; P_{\text{g}}(t) > 0 \end{cases} \tag{4.50}$$

$$R_{\text{customer}}^{\text{off}}(t) = \begin{cases} r_{\text{sppa}}^{\text{off}} \cdot P_{\text{l}}(t) \cdot \Delta t & ; P_{\text{g}}(t) = 0 \\ r^{\text{off}} \cdot P_{\text{g}}(t) \cdot \Delta t + r_{\text{sppa}}^{\text{off}} \cdot (P_{\text{pv}}(t) + P_{\text{bess}}(t)) \cdot \Delta t & ; P_{\text{g}}(t) > 0 \end{cases} \tag{4.51}$$

$$R_{\text{customer}}^{\text{demand}}(m) = \begin{cases} r_{\text{sppa}}^{\text{demand}} \cdot P_{\text{l}}(t_{\text{peak}}) & ; P_{\text{g}}(t_{\text{peak}}) = 0 \\ r^{\text{demand}} \cdot P_{\text{g}}(t_{\text{peak}}) & ; P_{\text{g}}(t_{\text{peak}}) > 0 \\ \quad + r_{\text{peak}}^{\text{demand}} \cdot (P_{\text{pv}}(t_{\text{peak}}) + P_{\text{bess}}(t_{\text{peak}})) & \end{cases} \tag{4.52}$$

$$R_{\text{customer}}^{\text{total}}(m) = \sum_{t=1}^{S_{\text{m}}^{\text{on}}} R_{\text{customer}}^{\text{on}}(t) + \sum_{t=1}^{S_{\text{m}}^{\text{off}}} R_{\text{customer}}^{\text{off}}(t) + R_{\text{customer}}^{\text{demand}}(m) \tag{4.53}$$

For the investors' side, the modeling of the revenue was also formulated based on the TOU tariff with demand charges, which consists of SPPA on-peak revenue, SPPA off-peak revenue, and SPPA demand charge revenue, as shown in Equations (4.54)-(4.57). With an unavailability of the reverse power flow, the revenue was only from sold power of rooftop PVs with BESS to the customers.

Revenue of the Investors

$$R_{\text{investor}}^{\text{on}}(t) = r_{\text{sppa}}^{\text{on}} \cdot P_{l}(t) \cdot \Delta t \tag{4.54}$$

$$R_{\text{investor}}^{\text{off}}(t) = r_{\text{sppa}}^{\text{off}} \cdot P_{l}(t) \cdot \Delta t \tag{4.55}$$

$$R_{\text{investor}}^{\text{demand}}(m) = r_{\text{sppa}}^{\text{demand}} \cdot P_{l}(t_{\text{peak}}) \cdot \Delta t \tag{4.56}$$

$$R_{\text{investor}}^{\text{total}}(m) = \sum_{t=1}^{S_{\text{m}}^{\text{on}}} R_{\text{investor}}^{\text{on}}(t) + \sum_{t=1}^{S_{\text{m}}^{\text{off}}} R_{\text{investor}}^{\text{off}}(t) + R_{\text{investor}}^{\text{demand}}(m) \tag{4.57}$$

To design the SPPA discount rates, energy capacity, power capacity and operation mode, the cost optimization model was formulated by applying the formulation in Equations (4.48), (4.49), (4.53) and (4.57). The objective was to minimize the electricity charges of the customers, while maintaining the target internal rate of return (IRR) of the investors under the SPPA with self-consumption scheme, as shown in Figure 4.4. The objective function and constraints are shown in Equations (4.58)-(4.62). The decisive variables are SPPA on-peak discount rate (α_1), SPAA off-peak discount rate (α_2), SPPA demand charge discount rate (β_1), battery energy capacity (C_{nom}), battery power capacity (P_{nom}), and operation modes at time t ($K(t)$)

Objective Function

$$\text{Min} \quad EC_{\text{customer}} \tag{4.58}$$

Constraints

$$IRR_{\text{investor}} \geq IRR_{\text{target}} \tag{4.59}$$

$$\alpha_1 \geq 0 \tag{4.60}$$

$$\alpha_2 \geq 0 \tag{4.61}$$

$$\beta_1 \geq 0 \tag{4.62}$$

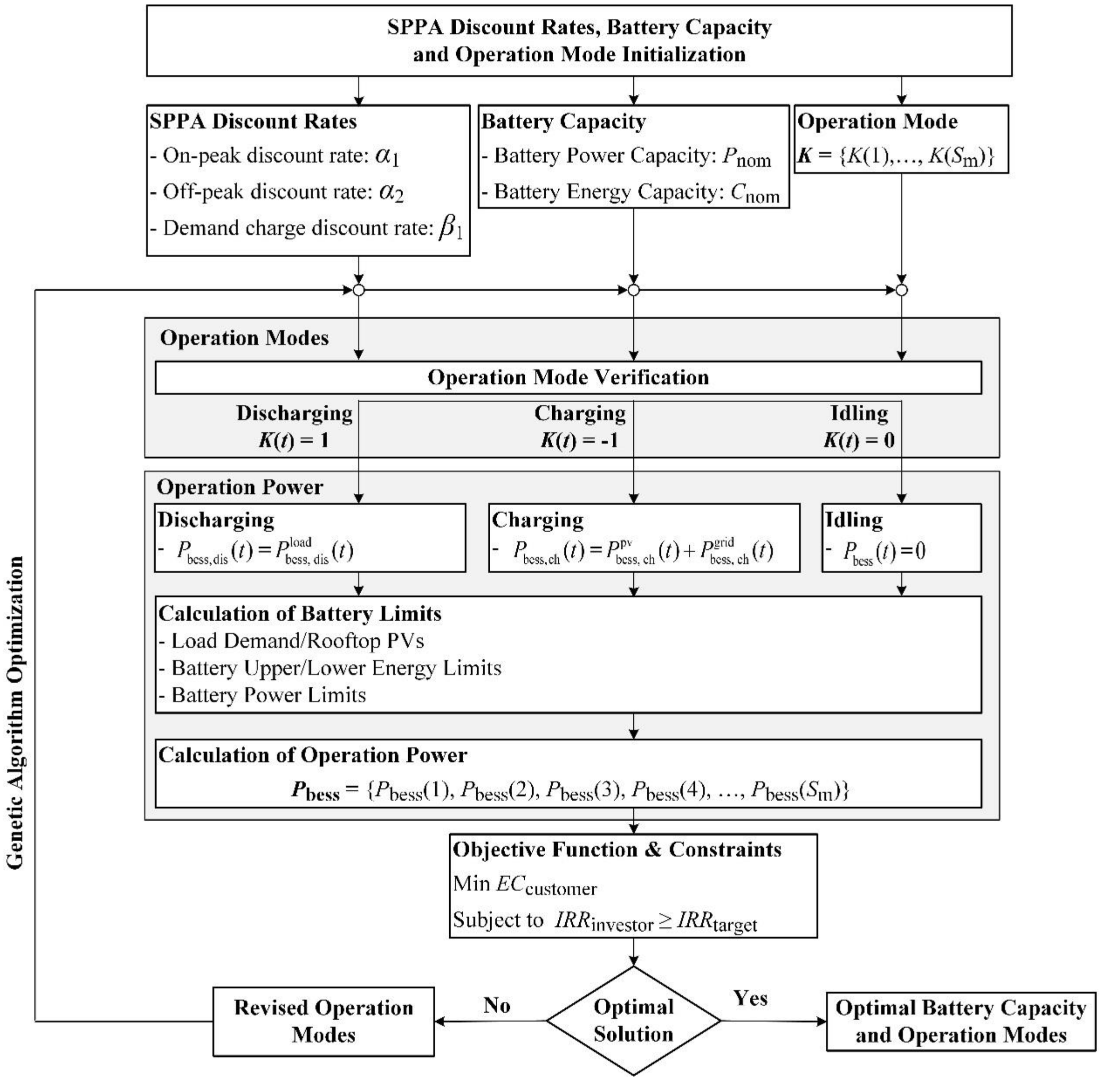

Figure 4.4 Flowchart showing the optimization approach to size the BESS under SPPA with the self-consumption scheme

4.3.3.2 Solar Power Purchase Agreement with the Net-Metering and Net-Billing Scheme

For the SPPA with the net-metering and net-billing scheme, the modeling of the electricity charges of the customers consists of SPPA on-peak energy charges ($R^{\text{on}}_{\text{customer}}(t)$), SPPA off-peak energy charges ($R^{\text{off}}_{\text{customer}}(t)$), and SPPA demand charges ($R^{\text{demand}}_{\text{customer}}(m)$). The electricity charges of each component were formulated as shown in Equations (4.63)-(4.66):

<u>**Electricity Charges of the Customers**</u>

$$R^{\text{on}}_{\text{customer}}(t) = \begin{cases} r^{\text{on}}_{\text{sppa}} \cdot P_{\text{l}}(t) \cdot \Delta t & ; P_{\text{g}}(t) \le 0 \\ r^{\text{on}} \cdot P_{\text{g}}(t) \cdot \Delta t + r^{\text{on}}_{\text{sppa}} \cdot (P_{\text{pv}}(t) + P_{\text{bess}}(t)) \cdot \Delta t & ; P_{\text{g}}(t) > 0 \end{cases} \tag{4.63}$$

$$R^{\text{off}}_{\text{customer}}(t) = \begin{cases} r^{\text{off}}_{\text{sppa}} \cdot P_{\text{l}}(t) \cdot \Delta t & ; P_{\text{g}}(t) \le 0 \\ r^{\text{off}} \cdot P_{\text{g}}(t) \cdot \Delta t + r^{\text{off}}_{\text{sppa}} \cdot (P_{\text{pv}}(t) + P_{\text{bess}}(t)) \cdot \Delta t & ; P_{\text{g}}(t) > 0 \end{cases} \tag{4.64}$$

$$R^{\text{demand}}_{\text{customer}}(m) = \begin{cases} r^{\text{demand}}_{\text{sppa}} \cdot P_{\text{l}}(t_{\text{peak}}) & ; P_{\text{g}}(t_{\text{peak}}) \le 0 \\ r^{\text{demand}} \cdot P_{\text{g}}(t_{\text{peak}}) & ; P_{\text{g}}(t_{\text{peak}}) > 0 \\ \quad + r^{\text{demand}}_{\text{peak}} \cdot (P_{\text{pv}}(t_{\text{peak}}) + P_{\text{bess}}(t_{\text{peak}})) & \end{cases} \tag{4.65}$$

$$R^{\text{total}}_{\text{customer}}(m) = \sum_{t=1}^{S^{\text{on}}_{\text{m}}} R^{\text{on}}_{\text{customer}}(t) + \sum_{t=1}^{S^{\text{off}}_{\text{m}}} R^{\text{off}}_{\text{customer}}(t) + R^{\text{demand}}_{\text{customer}}(m) \tag{4.66}$$

For the investors' side, the revenue of the investors ($R^{\text{total}}_{\text{investor}}(m)$))) was formulated based on the similar concept to the electricity charges of the customers, which consists of on-peak revenue ($R^{\text{on}}_{\text{investor}}(t)$),), off-peak revenue ($R^{\text{off}}_{\text{investor}}(t)$), and demand charge revenue ($R^{\text{demand}}_{\text{investor}}(m)$). The different point was the excess energy injected to the utility's grid, which was valued as additional revenue to the investors, as shown in Equations (4.67) - (4.70):

<u>Revenue of the Investors</u>

$$R_{\text{investor}}^{\text{on}}(t)=\begin{cases} r_{\text{sppa}}^{\text{on}}\cdot P_{\text{l}}(t)\cdot\Delta t- r_{\text{ex}}^{\text{on}}\cdot P_{\text{g}}(t)\cdot\Delta t & ;P_{\text{g}}(t)\le 0 \\ r_{\text{sppa}}^{\text{on}}\cdot P_{\text{l}}(t)\cdot\Delta t & ;P_{\text{g}}(t)>0 \end{cases} \tag{4.67}$$

$$R_{\text{customer}}^{\text{off}}(t)=\begin{cases} r_{\text{sppa}}^{\text{off}}\cdot P_{\text{l}}(t)\cdot\Delta t - r_{\text{ex}}^{\text{off}}\cdot P_{\text{g}}(t)\cdot\Delta t & ;P_{\text{g}}(t)\le 0 \\ r_{\text{sppa}}^{\text{off}}\cdot P_{\text{g}}(t)\cdot\Delta t & ;P_{\text{g}}(t)>0 \end{cases} \tag{4.68}$$

$$R_{\text{customer}}^{\text{demand}}(m)=\begin{cases} r_{\text{sppa}}^{\text{demand}}\cdot P_{\text{l}}(t_{\text{peak}}) & ;P_{\text{g}}(t_{\text{peak}})\le 0 \\ r^{\text{demand}}\cdot(P_{\text{pv}}(t_{\text{peak}})+P_{\text{bess}}(t_{\text{peak}})) & ;P_{\text{g}}(t_{\text{peak}})>0 \end{cases} \tag{4.69}$$

$$R_{\text{investor}}^{\text{total}}(m)=\sum_{t=1}^{S_{\text{m}}^{\text{on}}}R_{\text{investor}}^{\text{on}}(t)+\sum_{t=1}^{S_{\text{m}}^{\text{off}}}R_{\text{investor}}^{\text{off}}(t)+R_{\text{investor}}^{\text{demand}}(m) \tag{4.70}$$

To design the SPPA discount rates, battery capacity and operation mode, the cost optimization model was formulated by applying the formulation in Equations (4.48), (4.49), (4.66) and (4.70). The objective was to minimize the electricity charges of the customers, while maintaining the target internal rate of return (IRR) of the investors under the SPPA with net-metering and net-billing scheme, as shown in Figure 4.5. The objective function and constraints are shown in Equations (4.71)-(4.76). The decisive variables are SPPA on-peak discount rate (α_1), SPAA off-peak discount rate (α_2), SPPA demand charge discount rate (β_1), battery energy capacity (C_{nom}), battery power capacity (P_{nom}) and operation modes at time t ($K(t)$):

Objective Function

$$\text{Min} \quad EC_{\text{customer}} \tag{4.71}$$

Constraints

$$IRR_{\text{investor}} \ge IRR_{\text{target}} \tag{4.72}$$

$$\alpha_1 \ge 0 \tag{4.73}$$

$$\alpha_2 \ge 0 \tag{4.74}$$

$$\beta_1 \ge 0 \tag{4.75}$$

$$\sum_{m=1}^{S_y}\sum_{t=1}^{S_m}\left[P_l(t)-(P_{pv}(t)+P_{bess}(t))\right]\cdot\Delta t \quad \geq 0 \tag{4.76}$$

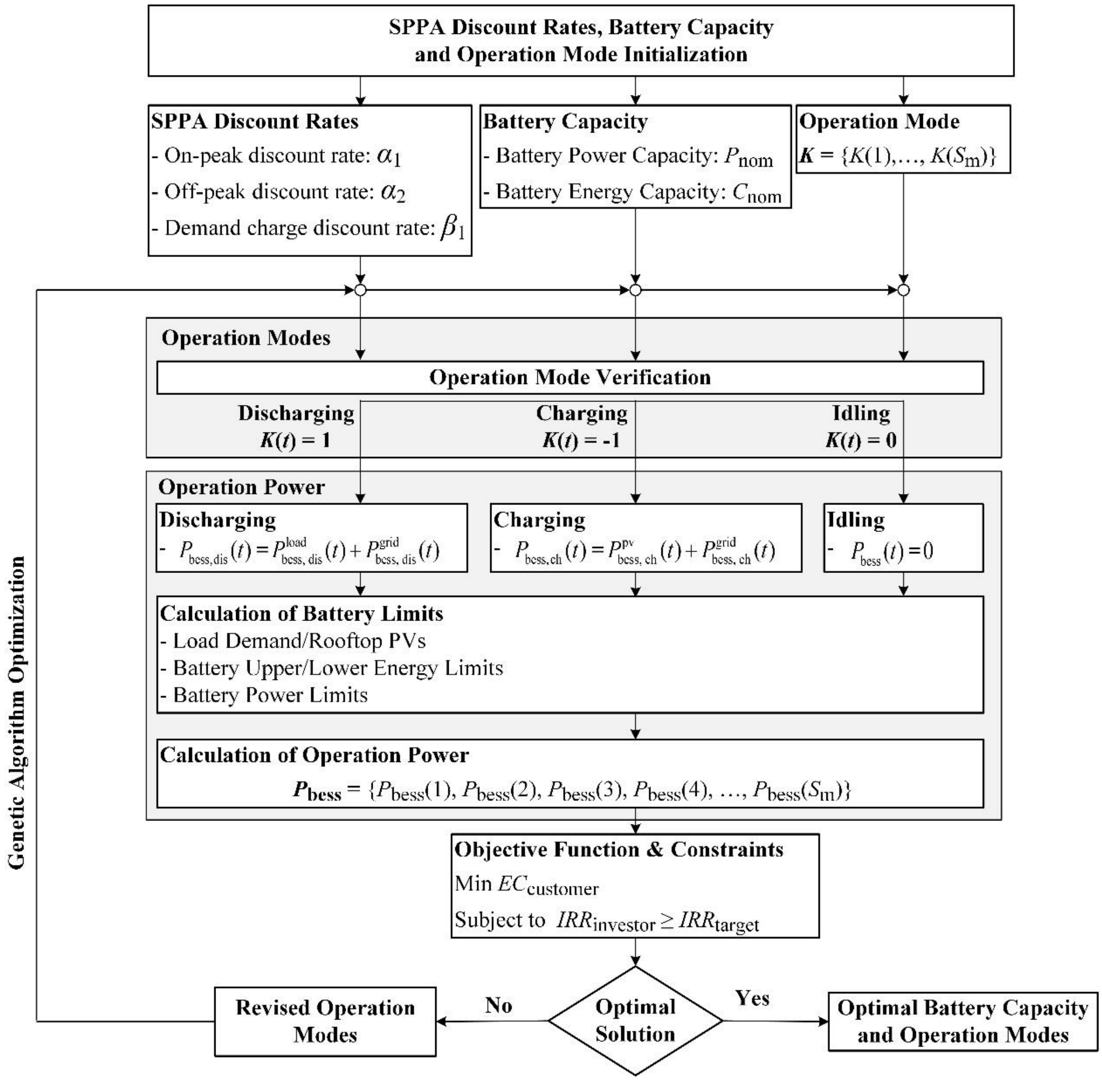

Figure 4.5 Flowchart showing the optimization approach to size the BESS under SPPA with the net-metering and net-billing scheme

CHAPTER 5
SIMULATION RESULTS AND DISCUSSIONS

The simulation results and discussion are presented in this chapter. The TOU tariff with demand charges were implemented and simulated based on the load profile. The case studies were simulated based on three main schemes of (1) Self-consumption schemes, (2) Net-metering and net-billing scheme and (3) Solar power purchase agreement.

5.1 Problem Description

Case studies in this dissertation were simulated and classified into 3 main groups: (1) Self-consumption, (2) Net-metering and Net-billing scheme and (3) Solar power purchase agreement. For the self-consumption scheme, the effects of installed capacity of rooftop PVs and battery degradation on the battery capacity and operation modes were evaluated in Section 5.2. For the net-metering and net-billing scheme, the effects of installed capacity of rooftop PVs, rate of excess energy and battery degradation on the battery capacity and operation modes were evaluated in Section 5.3. For the SPPA, the effects of the installed capacity of rooftop PVs, battery power capacity, battery energy capacity, rate of excess energy and battery degradation on the SPPA discount rates and operation modes were evaluated in Section 5.4. The proposed designing of the battery capacity, SPPA discount rates and operation modes under each SPPA scheme were also investigated.

In addition, the annual rooftop PVs profile with seasonal effects from PVsyst and standard load profiles of large general service customers from metropolitan electricity authority (MEA) were implemented. The installed capacity of rooftop PVs and battery power capacity are shown by comparing to the peak demand. The battery energy capacity is shown by comparing to the daily load consumption. The rate of excess energy is shown by comparing to the utility’s retail rate. The operation of the BESS in each mode is shown in term of the total operation time of the BESS over the project period, which was assumed to be 8 years in this dissertation. The results were determined by applying the proposed methodology with the GA optimization in MATLAB.

5.2 Self-Consumption Scheme

In this section, the rooftop PVs with BESS under the self-consumption were simulated base on the parameters and assumptions in Table 5.1. The battery power capacity, battery energy capacity and the total operation time of BESS for each installed capacity of rooftop were investigated. The effect of battery degradation was also evaluated. In addition, the energy installation cost and power installation cost of BESS in this section were assumed to be 40% of the cost projection in Chapter 3.

Table 5.1 Parameters and assumptions for case studies under the self-consumption schemes

Parameters and Assumptions	**Self-Consumption Scheme**	
	PV Size	**Battery Degradation**
Battery Energy Storage Systems		
Battery energy capacity (%)	Determined	Determined
Battery power capacity (%)	Determined	Determined
Depth of discharge (%)	20%	20%
Life cycles (Full cycles)	6,000	6,000
Roundtrip efficiency (%)	90%	90%
Battery inverter efficiency (%)	90%	90%
Self-degradation (%)	0.025%	0.025%
Financial parameters		
Financial discount rate (%)	1.50%	1.50%
Rate of operation cost (%)	1.00%	1.00%
Target internal rate of return (%)	6.00%	6.00%
EIC of the BESS (THB/kWh)	3,706	3,706
PIC of the BESS (THB/kW)	5,430	5,430
TIC of rooftop PVs (THB/kWdc)	55,000	55,000
Project life (year)	8	8
Load		
Daily load consumption (kWh)	23,849	23,849
Peak demand (kW)	1,290	1,290
Rooftop PVs		
PV inverter efficiency (%)	90%	90%
Installed capacity of rooftop PVs (%)	Varying	100%
PV module annual degradation (%)	0.60%	0.60%
Tariff Rate		
Demand charges (THB/kW)	132.93	132.93
On-peak energy charges (THB/kWh)	4.1839	4.1839
Off-peak energy charges (THB/kWh)	2.6037	2.6037

5.2.1 Effect of Installed Capacity of Rooftop PVs

The battery energy capacity, battery power capacity and total operation time of BESS for each installed capacity of rooftop PVs were investigated as shown in Figure 5.1-5.2. If the installed capacity was not exceeding the peak demand (100%), the battery power capacity and battery energy capacity were increased. However, when the installed capacity was over the peak load, the battery power and energy capacity were significantly decreased due to the increase of total cost of the rooftop PVs. For operation modes, the total operation time of the BESS in the charging and discharging modes was slightly increased when the installed capacity was increased. When the installed capacity of rooftop PVs is over 150%, the internal rate of return of the project will not reach the target.

In this scenario, it can be implied the installed capacity of rooftop PVs has a direct effect to the battery capacity, which will depend on the peak demand and the total cost of rooftop PVs with BESS.

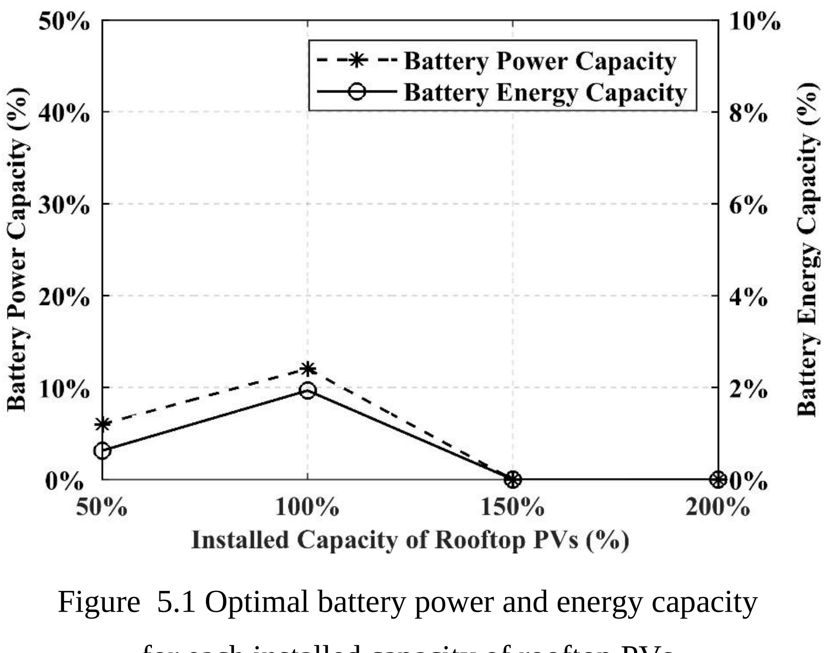

Figure 5.1 Optimal battery power and energy capacity for each installed capacity of rooftop PVs

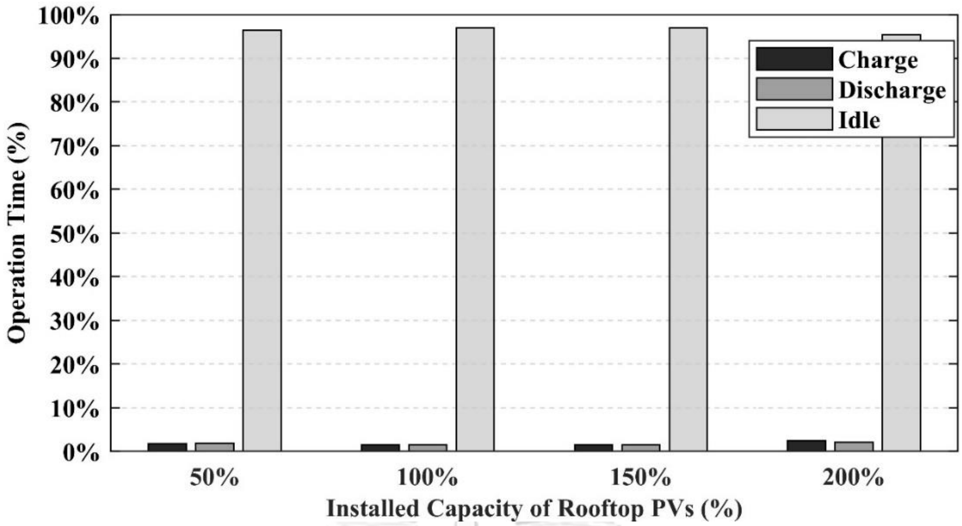

Figure 5.2 Operation time of the BESS
for each installed capacity of rooftop PVs

5.2.2 Effect of Battery Degradation

The battery energy capacity, battery power capacity and total operation time of BESS with and without consideration of battery degradation were investigated as shown in Figure 5.3-5.4. The battery power capacity and battery energy capacity were increased when the battery degradation was considered. For operation modes, the total operation time of the BESS in the charging and discharging modes was decreased.

In this scenario, it can be implied that the battery degradation has a significant effect to the battery capacity and operation time of BESS. The consideration of battery degradation will lead to an increase of the optimal battery capacity.

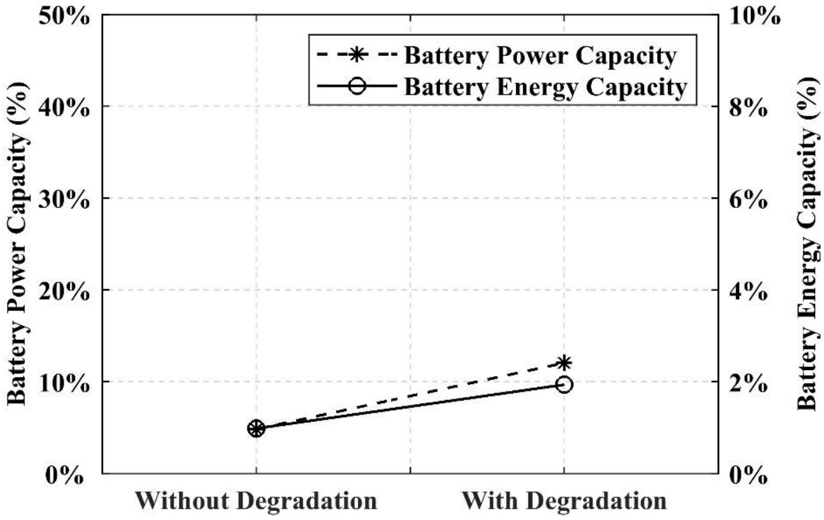

Figure 5.3 Optimal battery power and energy capacity
with and without battery degradation

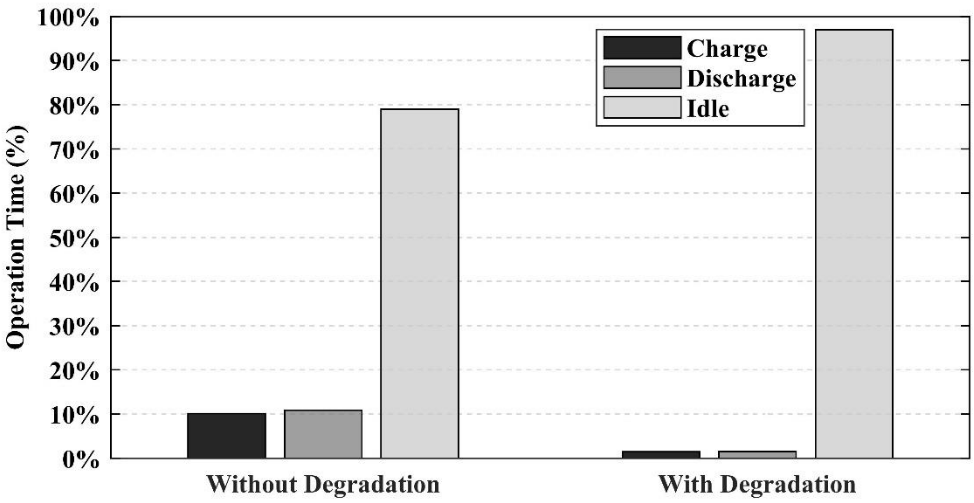

Figure 5.4 Operation time of the BESS
with and without battery degradation

5.3 Net-Metering and Net-Billing Scheme

In this section, the rooftop PVs with BESS under the net-metering and net-billing scheme was simulated base on the parameters and assumptions in Table 5.2. The simulation was divided by dividing into 2 cases of (1) the installed capacity of rooftop PVs and (2) rate of excess energy. The battery power capacity, battery energy capacity and the total operation time of BESS for each installed capacity of rooftop PVs and rate of excess energy were investigated. The energy installation cost and power installation cost of BESS in this section were also assumed to be 40% of the cost projection in Chapter 3.

Table 5.2 Parameters and assumptions for case studies under the net-metering and net-billing schemes

Parameters and Assumptions	Net-metering and Net-billing Scheme		
	PV Size	**Rate of Excess Energy**	**Battery Degradation**
Battery Energy Storage Systems			
Battery energy capacity (%)	Determined	Determined	Determined
Battery power capacity (%)	Determined	Determined	Determined
Depth of discharge (%)	20%	20%	20%
Life cycles (Full cycles)	6,000	6,000	6,000
Roundtrip efficiency (%)	90%	90%	90%
Battery inverter efficiency (%)	90%	90%	90%
Self-degradation (%)	0.025%	0.025%	0.025%
Financial Parameters			
Financial discount rate (%)	1.50%	1.50%	1.50%
Rate of operation cost (%)	1.00%	1.00%	1.00%
Target internal rate of return (%)	6.00%	6.00%	6.00%
EIC of the BESS (THB/kWh)	3,706	3,706	3,706
PIC of the BESS (THB/kW)	5,430	5,430	5,430
TIC of rooftop PVs (THB/kWdc)	55,000	55,000	55,000
Project life (year)	8	8	8
Load			
Daily load consumption (kWh)	23,849	23,849	23,849
Peak demand (kW)	1,290	1,290	1,290
Rooftop PVs			
PV inverter efficiency (%)	90%	90%	90%
Installed capacity of rooftop PVs (%)	Varying	200%	100%
PV module annual degradation (%)	0.60%	0.60%	0.60%
Tariff Rate			
Demand charges (THB/kW)	132.93	132.93	132.93
On-peak energy charges (THB/kWh)	4.1839	4.1839	4.1839

Parameters and Assumptions	Net-metering and Net-billing Scheme		
	PV Size	Rate of Excess Energy	Battery Degradation
Off-peak energy charges (THB/kWh)	2.6037	2.6037	2.6037
Rate of excess energy (%)	100%	Varying	100%

5.3.1 Effect of Installed Capacity of Rooftop PVs

The battery energy capacity, battery power capacity and total operation time of BESS for each installed capacity of rooftop PVs were investigated as shown in Figure 5.5-5.6. When the installed capacity of rooftop PVs was increased, battery energy and power capacity were slightly increased. For operation modes, the total operation time of the BESS in discharging and charging mode were also increase accordingly.

In this scenario, it can be implied installed capacity of rooftop PVs has affected on the battery capacity in the opposite direction of the self-consumption scheme. The battery capacity is increased when the installed capacity of rooftop PV increased. The operation time of battery in discharging and charging mode are also increased.

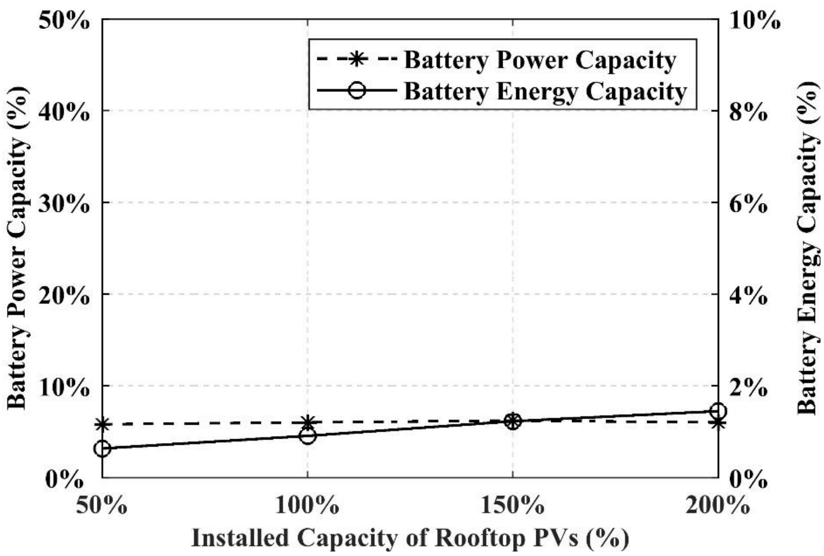

Figure 5.5 Optimal battery power and energy capacity for each installed capacity of rooftop PVs

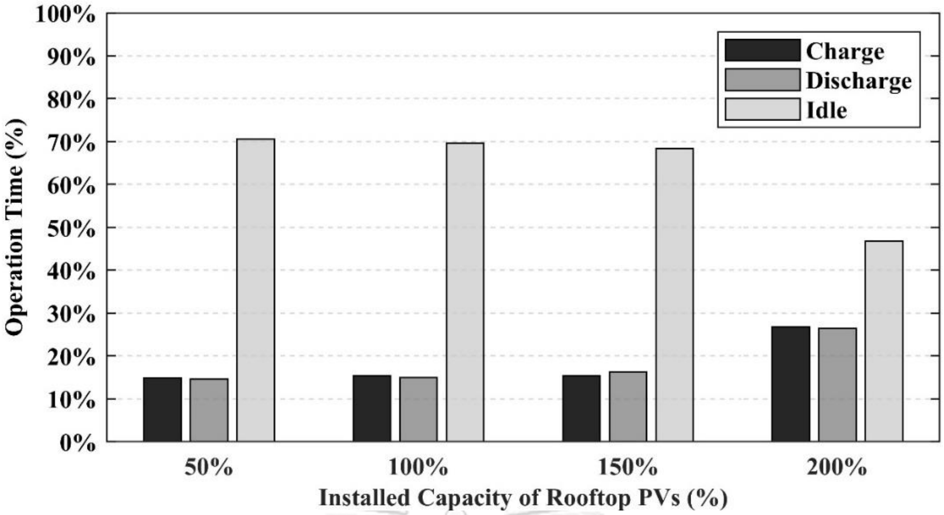

Figure 5.6 Operation time of the BESS
for each installed capacity of rooftop PVs

5.3.2 Effect of Rate of Excess Energy

The battery energy capacity, battery power capacity and total operation time of BESS for each rate of excess energy were investigated as shown in Figure 5.7-5.8. When the rate of excess energy (γ) was lower than 50%, the BESS should not install due to the high cost of the BESS. On the other hand, when the rate of excess energy was over 50%, battery energy and power capacity were significantly increased due to the benefit from excess energy. For operation modes, the total operation time of the BESS in discharging and charging mode were also significantly increased.

In this scenario, it can be implied that rate of excess energy has directly affected on the battery capacity, especially the battery energy capacity. The battery capacity is increased when the rate of excess energy increases. As a result, the operation time of battery in discharging and charging mode are also increased.

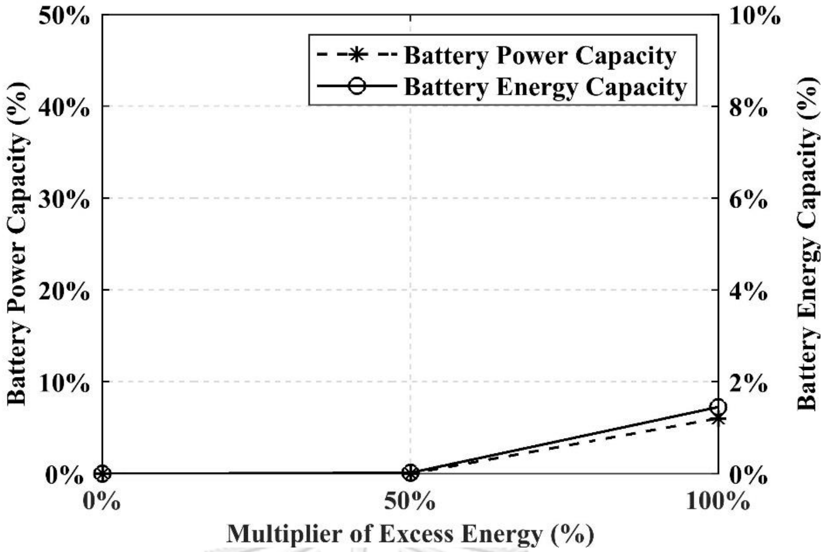

Figure 5.7 Optimal battery power and energy capacity for each rate of excess energy

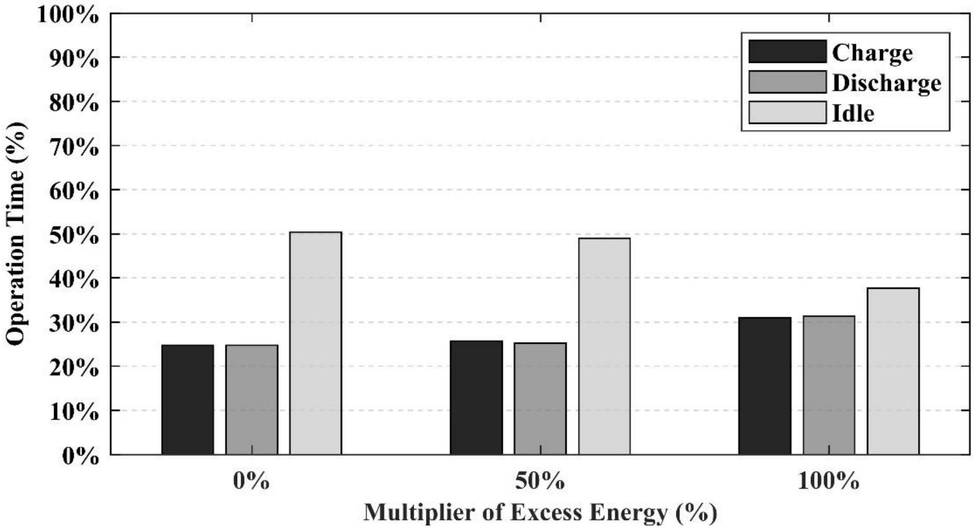

Figure 5.8 Operation time of the BESS for each installed capacity of rooftop PVs

5.3.3 Effect of Battery Degradation

The battery energy capacity, battery power capacity and total operation time of BESS with and without consideration of battery degradation were investigated as shown in Figure 5.9-5.10. When the battery degradation was considered, the battery power capacity was increased while the battery energy capacity was slightly similar. For operation modes, the total operation time of the BESS in the charging and discharging modes with and without consideration of battery degradation were slightly constant.

In this scenario, it can be implied the battery degradation has a significant effect to the battery capacity especially the battery power capacity.

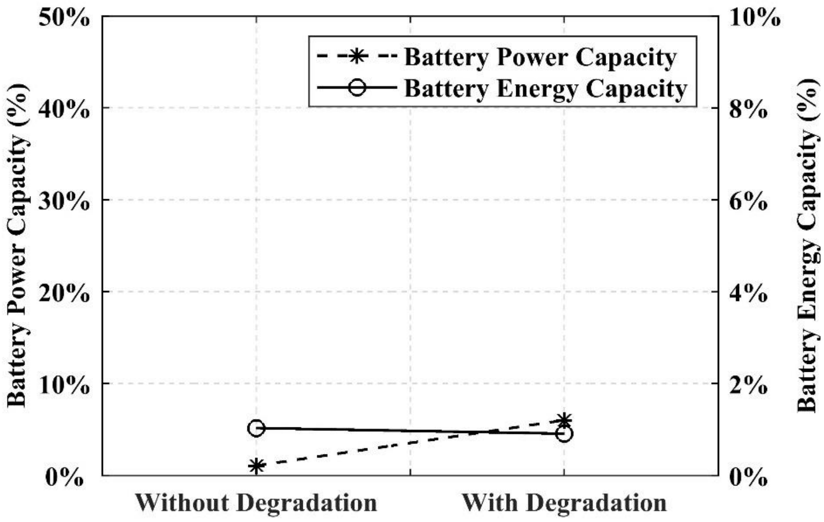

Figure 5.9 Optimal battery power and energy capacity with and without battery degradation

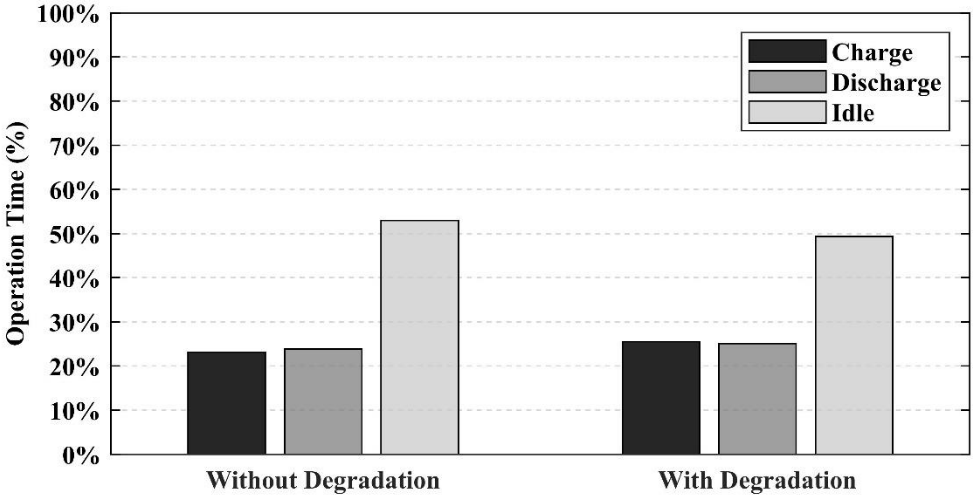

Figure 5.10 Operation time of the BESS
with and without battery degradation

5.4 Solar Power Purchase Agreement

In this section, the SPPA for rooftop PVs with BESS was designed and simulated by classifying into (1) SPPA for Rooftop PVs (2) SPPA with the self-consumption scheme for Rooftop PVs with BESS and (3) SPPA with the net-metering and net-billing scheme for Rooftop PVs with BESS.

5.4.1 Rooftop PVs under the SPPA

The rooftop PVs under the SPPA was simulated base on the parameters and assumptions in Table 5.3.

Table 5.3 Parameters and assumptions for case studies of rooftop PVs under the SPPA

Parameters and Assumptions	**SPPA for Rooftop PVs**		
	Self-Consumption Scheme	**Net-Billing Scheme**	**Net-Metering Scheme**
Solar Power Purchase Agreement			
SPPA on-peak discount rate (%)	Determined		
SPPA off-peak discount rate (%)	Determined		
SPPA demand charge discount rate (%)	Determined		
Financial parameters			
Financial discount rate (%)	5.00%	5.00%	5.00%
Rate of operation cost (%)	1.00%	1.00%	1.00%
Target internal rate of return (%)	12.00%	12.00%	12.00%
TIC of rooftop PVs (THB/kWdc)	55,000	55,000	55,000
Project life (year)	8	8	8
Load			
Daily load consumption (kWh)	23,849	23,849	23,849
Peak demand (kW)	1,290	1,290	1,290
Rooftop PVs			
PV inverter efficiency (%)	90%	90%	90%
Installed capacity of rooftop PVs (%)	200%	200%	200%
PV module annual degradation (%)	0.60%	0.60%	0.60%
Tariff Rate			
Demand charges (THB/kW)	132.93	132.93	132.93
On-peak energy charges (THB/kWh)	4.1839	4.1839	4.1839
Off-peak energy charges (THB/kWh)	2.6037	2.6037	2.6037
Rate of excess energy (%)	-	50%	100%

The SPPA discount rates under SPPA with the self-consumption, net-metering and net-billing scheme were investigated, as shown in Figure. 5.11. When the rate of excess energy was increased, all SPPA discount rates were significantly increased. In addition, in case that γ was lower than 50%, although all discount rates were zero, the IRR could not reach to the target because of the low revenue.

In this scenario, it can also be implied that SPPA on-peak discount rate (α_1) is the most significant variable that the investors should strictly controlled. In addition, the investors can propose higher SPPA discount rates if the rooftop PVs was implemented under the SPPA with net-billing scheme and the rate of excess energy is higher than the utility’s retail rate.

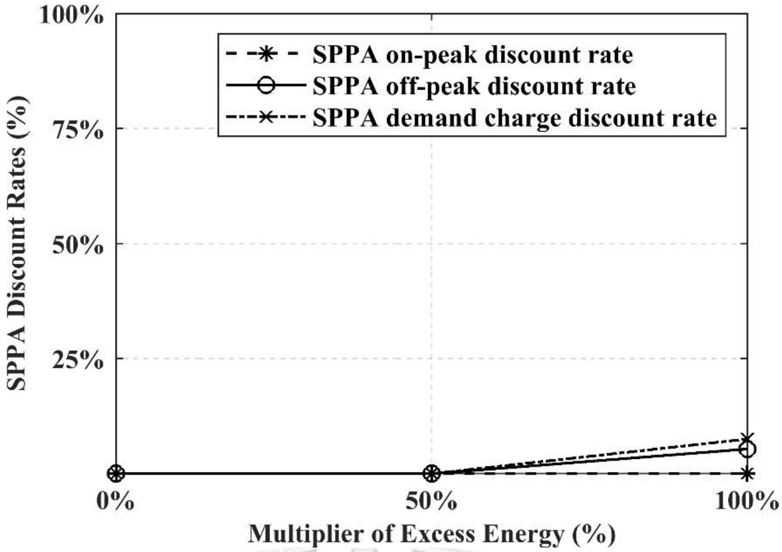

Figure 5.11 Optimal SPPA discount rates
for rooftop PVs under the SPPA

5.4.2 Rooftop PVs with BESS under the SPPA with the Self-Consumption Scheme

The rooftop PVs with BESS under the SPPA with the self-consumption scheme was simulated based on the parameters and assumptions in Table 5.4. The SPPA discount rates and operation modes of the BESS were determined to evaluate the sensitivity of installed capacity of rooftop PVs, battery power capacity and battery energy capacity, as shown in Section 5.4.2.1-5.4.2.3. In addition, the SPPA discount rates, operation modes of the BESS, battery power capacity and battery energy capacity were simultaneously investigated under the assumption in the end of this section.

Table 5.4 Parameters and assumptions for case studies of rooftop PVs with BESS under the SPPA with the self-consumption scheme

Parameters and Assumptions	Solar Power Purchase Agreement with the Self-Consumption Scheme				
	PV Size	Battery Power Capacity	Battery Energy Capacity	Battery Degradation	Designing
Battery Energy Storage Systems					
Battery energy capacity (%)	1.00%	2.50%	Varying	1.00%	Determined
Battery power capacity (%)	10.0%	Varying	50.00%	10.0%	Determined
Depth of discharge (%)	20%	20%	20%	20%	20%
Life cycles (Full cycles)	6,000	6,000	6,000	6,000	6,000
Roundtrip efficiency (%)	90%	90%	90%	90%	90%
Battery inverter efficiency (%)	90%	90%	90%	90%	90%
Self-degradation (%)	0.025%	0.025%	0.025%	0.025%	0.025%
Solar Power Purchase Agreement					
SPPA on-peak discount rate (%)	Determined				
SPPA off-peak discount rate (%)	Determined				
SPPA demand charge discount rate (%)	Determined				
Financial parameters					
Financial discount rate (%)	1.50%	1.50%	1.50%	1.50%	1.50%
Rate of operation cost (%)	1.00%	1.00%	1.00%	1.00%	1.00%
Target internal rate of return (%)	6.00%	6.00%	6.00%	6.00%	6.00%
EIC of the BESS (THB/kWh)	9,265	9,265	9,265	9,265	9,265
PIC of the BESS (THB/kW)	13,576	13,576	13,576	13,576	13,576
TIC of rooftop PVs (THB/kWdc)	55,000	55,000	55,000	55,000	55,000
Project life (year)	8	8	8	8	8
Load					
Daily load consumption (kWh)	23,849	23,849	23,849	23,849	23,849
Peak demand (kW)	1290	1290	1290	1290	1290
Rooftop PVs					
PV inverter efficiency (%)	90%	90%	90%	90%	90%
Installed capacity of rooftop PVs (%)	Varying	100%	100%	100%	100%
PV module annual degradation (%)	0.60%	0.60%	0.60%	0.60%	0.60%
Tariff Rate					
Demand charges (THB/kW)	132.93	132.93	132.93	132.93	132.93
On-peak energy charges (THB/kWh)	4.1839	4.1839	4.1839	4.1839	4.1839
Off-peak energy charges (THB/kWh)	2.6037	2.6037	2.6037	2.6037	2.6037

5.4.2.1 Effect of Installed Capacity of Rooftop PVs

The SPPA discount rates and total operation time of BESS for each installed capacity of rooftop PVs under the SPPA with the self-consumption scheme were investigated, as shown in Figure 5.12-5.13. In case that the installed capacity was smaller than 150%, all SPPA discount rates were increased when the installed capacity was increased. However, when the installed capacity was larger than 150%, the SPPA discount rates were significantly decreased to maintain the IRR. For operation modes, the total operation time of the BESS in the charging and discharging modes for each case were approximately slightly increased when the installed capacity was increased.

In this scenario, it can be implied that the installed capacity of rooftop PVs has directly affected on the SPPA discount rates. However, if the installed capacity of rooftop PVs is oversized, the SPPA discount rates will be significantly decreased to maintain the target IRR.

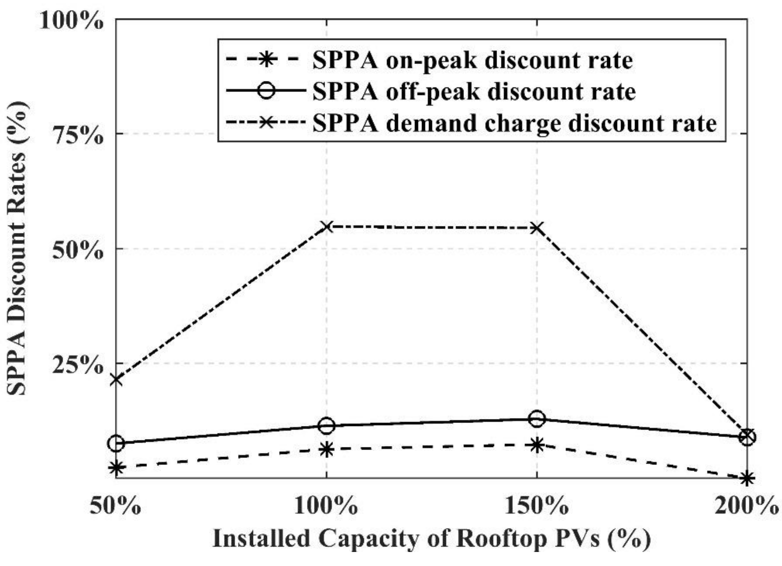

Figure 5.12 Optimal SPPA discount rates
for each rate installed capacity of rooftop PVs

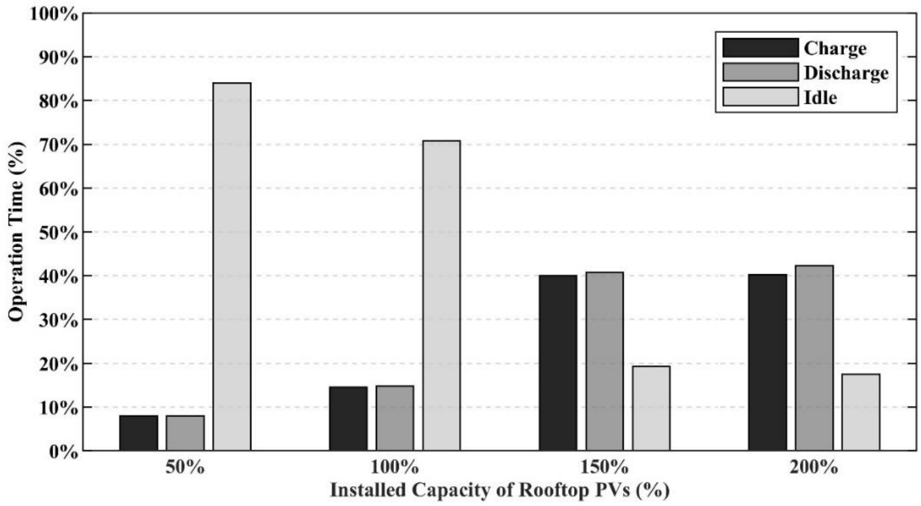

Figure 5.13 Operation time of the BESS
for each installed capacity of rooftop PVs

5.4.2.2 Effect of Battery Power Capacity

The SPPA discount rates and total operation time of BESS for each battery power capacity, at 2.5% of battery energy capacity, under the SPPA with the self-consumption scheme were investigated, as shown in Figure. 5.14 - 5.15. For the SPPA discount rates, all SPPA discount rates were significantly decreased while the power capacity was increased. In addition, in case that the battery power capacity was higher than 100%, although all SPPA discount rates were zero, the IRR could not reach to the target because of the high total cost. For operation modes, the total operation time of the BESS in the charging and discharging modes was significantly increased when the battery power capacity was increased.

In this scenario, it can be implied that α_1 and β_1 are the significant variables that the investors should strictly control, while α_2 is more flexible. The battery power capacity has a direct effect on the SPPA discount rates and operation time of the BESS. If the battery power capacity is increased, the operation time of the BESS in discharging and charging modes are increased while the SPPA discount rates should be reduced to maintain the target IRR.

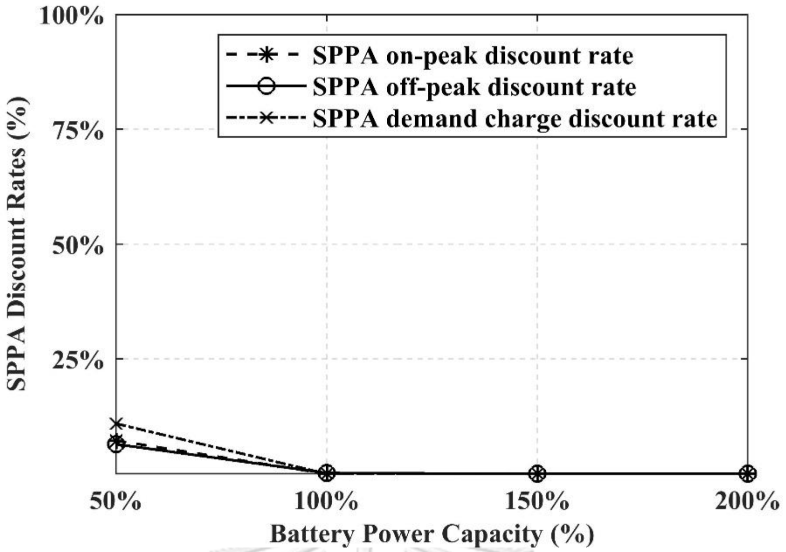

Figure 5.14 Optimal SPPA discount rates
for each battery power capacity

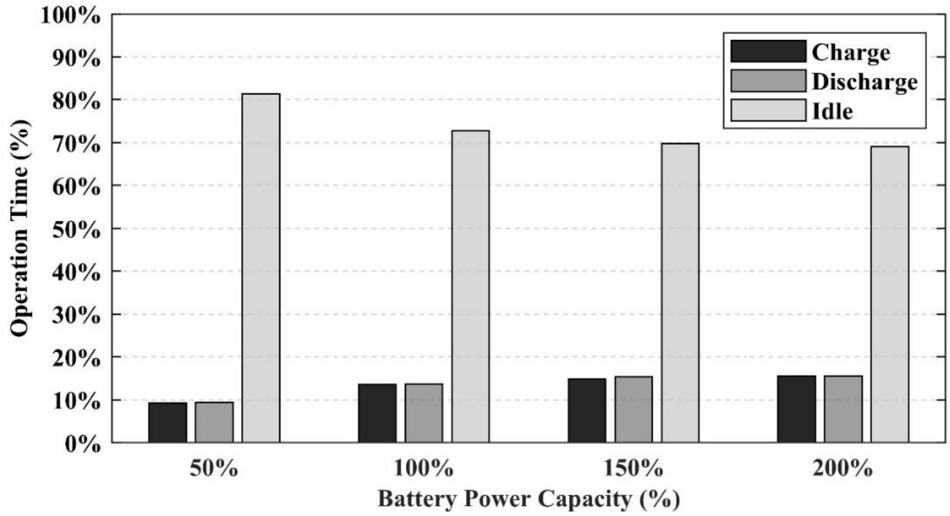

Figure 5.15 Operation time of the BESS
for each battery power capacity

5.4.2.3 Effect of Battery Energy Capacity

The SPPA discount rates and total operation time of BESS for each battery energy capacity, at 50% of battery power capacity, under the SPPA with the self-consumption scheme were investigated, as shown in Figure. 5.16-5.17. For the SPPA discount rates, when the battery energy capacity was increased, α_1 was significantly decreased, while α_2 and β_1 were slightly increased. For operation modes, the total operation time of the BESS in the charging and discharging modes for each case were increased when the battery energy capacity was.

In this scenario, it can also be implied that α_1 is the most significant variable that the investors should strictly control to remain the target IRR. The battery energy capacity also has a direct effect on the SPPA discount rates and operation time of the BESS. If the battery energy capacity is increased, the operation time of the BESS in discharging and charging modes are increased.

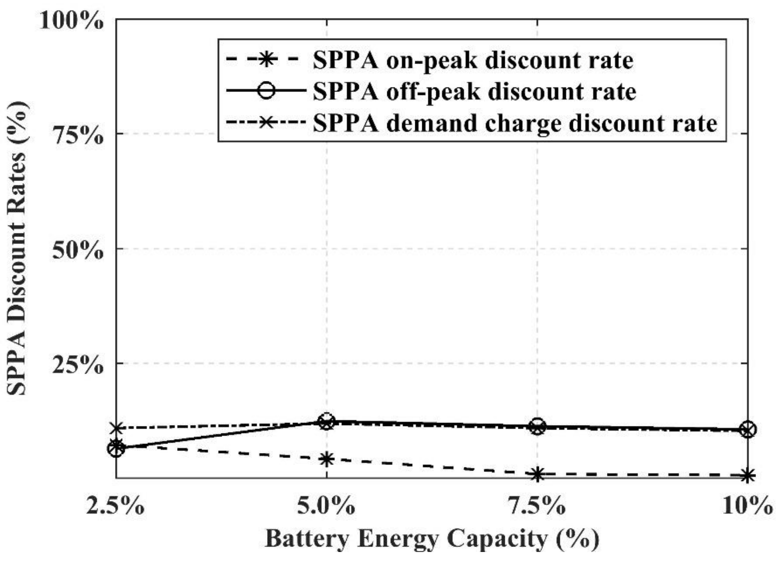

Figure 5.16 Optimal SPPA discount rates for each battery energy capacity

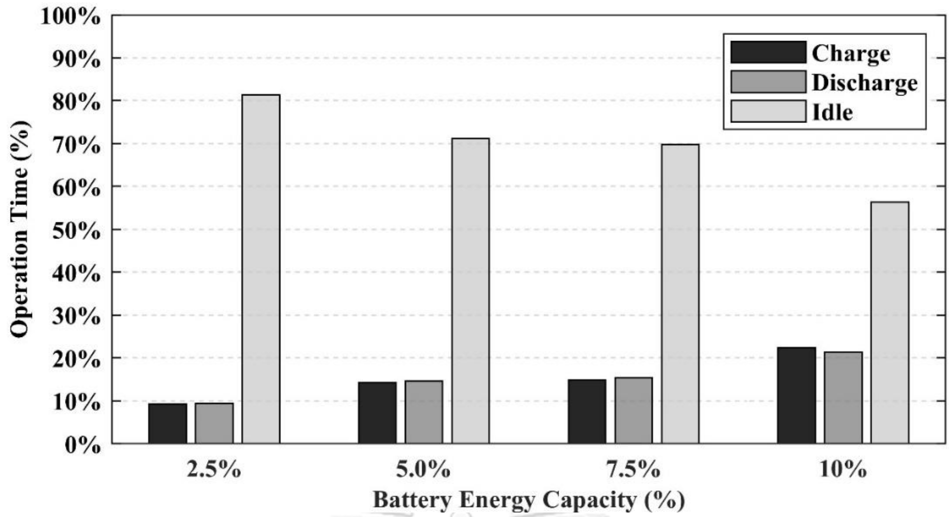

Figure 5.17 Operation time of the BESS
for each battery energy capacity

5.4.2.4 Effect of Battery Degradation

The SPPA discount rates and total operation time of BESS with and without consideration of battery degradation were investigated as shown in Figure 5.18-5.19. When battery degradation was considered, β_1 was significantly decreased while α_1 and α_2 were similar. For operation modes, the total operation time of the BESS was decreased when the battery degradation was considered.

In this scenario, it can be implied the battery degradation has a significant effect to the SPPA discount rates and operation time of BESS. The consideration of battery degradation will lead to the decrease of the SPPA discount rates.

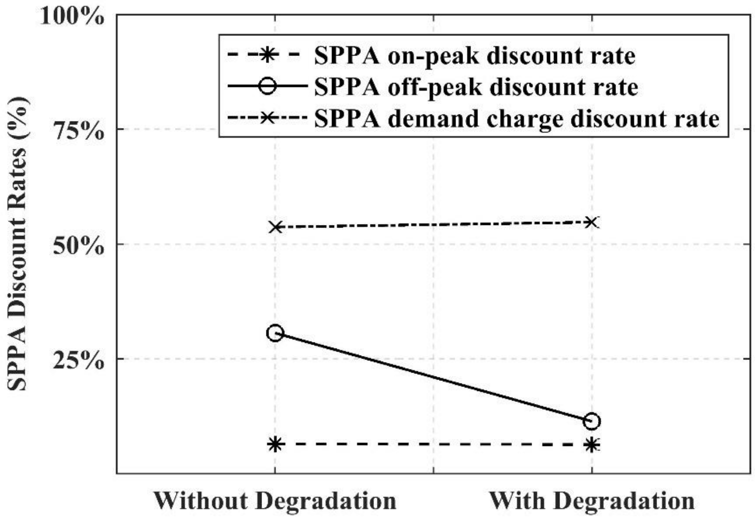

Figure 5.18 Optimal SPPA discount rates
with and without battery degradation

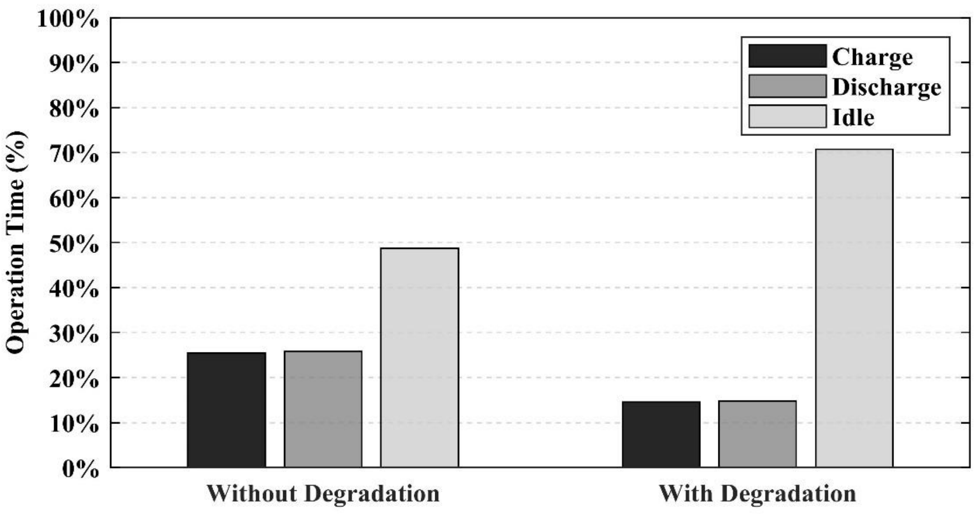

Figure 5.19 Operation time of the BESS
with and without battery degradation

Based on the assumption in the Table 5.4, for the optimal designing of the SPPA under the self-consumption scheme, the proposed battery energy capacity, battery power capacity, SPPA discount rates and total operation time of BESS were shown in Table 5.5. The total operation time in charging and discharging mode was approximately 37%

The battery degradation coefficient and life cycle left over the project period (8 years) is shown in Figure 5.20. At the end of the project, the life cycle left is 2,135 cycles and the battery degradation coefficient is 0.8709.

Table 5.5 The proposed SPPA discount rates and batter capacity for SPPA under the self-consumption scheme

On-peak Discount Rate	Off-peak Discount Rate	Demand Charges Discount Rate	Battery Energy Capacity	Battery Power Capacity
0.0056	0.1050	0.2743	3.97%	10.61%

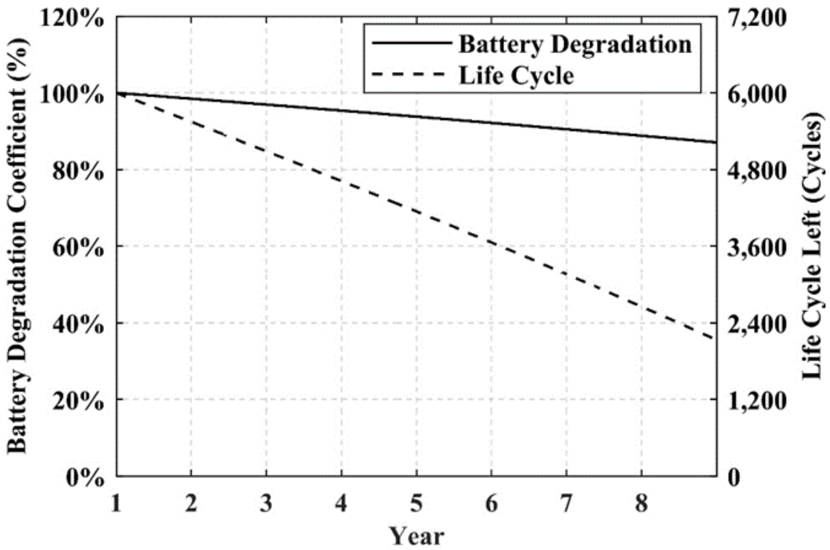

Figure 5.20 Battery degradation coefficient and life cycle of BESS over the project period

5.4.3 Rooftop PVs with BESS under the SPPA with the Net-Metering and Net-Billing Scheme

The rooftop PVs with BESS under the SPPA with the net-metering and net-billing scheme was simulated based on the parameters and assumptions in Table 5.6. The SPPA discount rates and operation modes of the BESS were determined to evaluate the sensitivity of installed capacity of rooftop PVs, battery power capacity, battery energy capacity and rate of excess energy, as shown in Section 5.4.3.1-5.4.3.4. In addition, the SPPA discount rates, operation modes of the BESS, battery power capacity and battery energy capacity were simultaneously investigated under the assumption in the end of this section.

Table 5.6 Parameters and assumptions for case studies of rooftop PVs with BESS under the SPPA with the net-metering and net-billing scheme

Parameters and Assumptions	Solar Power Purchase Agreement with Net-Metering and Net-Billing Scheme					
	PV Size	Battery Power Capacity	Battery Energy Capacity	Rate of Excess Energy	Battery Degradation	Designing
Battery Energy Storage Systems						
Battery energy capacity (%)	1.00%	2.50%	Varying	7.50%	1.00%	Determined
Battery power capacity (%)	10.0%	Varying	50.00%	100%	10.0%	Determined
Depth of discharge (%)	20%	20%	20%	20%	20%	20%
Life cycles (Full cycles)	6000	6,000	6,000	6,000	6000	6,000
Roundtrip efficiency (%)	90%	90%	90%	90%	90%	90%
Battery inverter efficiency (%)	90%	90%	90%	90%	90%	90%
Self-degradation (%)	0.025%	0.025%	0.025%	0.025%	0.025%	0.025%
Solar Power Purchase Agreement						
SPPA on-peak discount rate (%)	Determined					
SPPA off-peak discount rate (%)	Determined					
SPPA demand charge discount rate (%)	Determined					
Financial parameters						
Financial discount rate (%)	1.50%	1.50%	1.50%	1.50%	1.50%	1.50%
Rate of operation cost (%)	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%
Target internal rate of return (%)	8.00%	8.00%	8.00%	8.00%	8.00%	8.00%
EIC of the BESS (THB/kWh)	9,265	9,265	9,265	9,265	9,265	9,265
PIC of the BESS (THB/kW)	13,576	13,576	13,576	13,576	13,576	13,576
TIC of rooftop PVs (THB/kWdc)	55,000	55,000	55,000	55,000	55,000	55,000
Project life (year)	8	8	8	8	8	8
Load						
Daily load consumption (kWh)	23,849	23,849	23,849	23,849	23,849	23,849
Peak demand (kW)	1,290	1,290	1,290	1,290	1,290	1,290

Parameters and Assumptions	Solar Power Purchase Agreement with Net-Metering and Net-Billing Scheme					
Rooftop PVs						
PV inverter efficiency (%)	90%	90%	90%	90%	90%	90%
Installed capacity of rooftop PVs (%)	Varying	100%	100%	100%	100%	100%
PV module annual degradation (%)	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%
Tariff Rate						
Demand charges (THB/kW)	132.93	132.93	132.93	132.93	132.93	132.93
On-peak energy charges (THB/kWh)	4.1839	4.1839	4.1839	4.1839	4.1839	4.1839
Off-peak energy charges (THB/kWh)	2.6037	2.6037	2.6037	2.6037	2.6037	2.6037
Rate of excess energy (%)	100%	100%	100%	Varying	100%	100%

5.4.3.1 Effect of Installed Capacity of Rooftop PVs

The SPPA discount rates and total operation time of BESS for each installed capacity of rooftop PVs were investigated as shown in Figure 5.21-5.22. In case that the installed capacity was smaller than 150%, all SPPA discount rates were increased when the installed capacity of rooftop PVs was increased. However, when the installed capacity was larger than 150%, α_1 and β_1 were approximately constant while α_2 was significantly decreased to remain the target IRR. For operation modes, the total operation time of the BESS in the charging and discharging modes for each case were approximately slightly increased when the installed capacity of rooftop PVs was increased.

In this scenario, it can be implied that α_2 is the most flexible variable that the investors can initially adjust to maintain the target IRR. α_1 and β_1 are the variables that have the high effect on the electricity charges because the highest output power from rooftop PVs and the peak demand are typically occurred during the on-peak period. In addition, the installed capacity of rooftop PVs also affect the operation time of the BESS. If the installed capacity is increased, the operation time of the BESS in discharging and charging modes are increased.

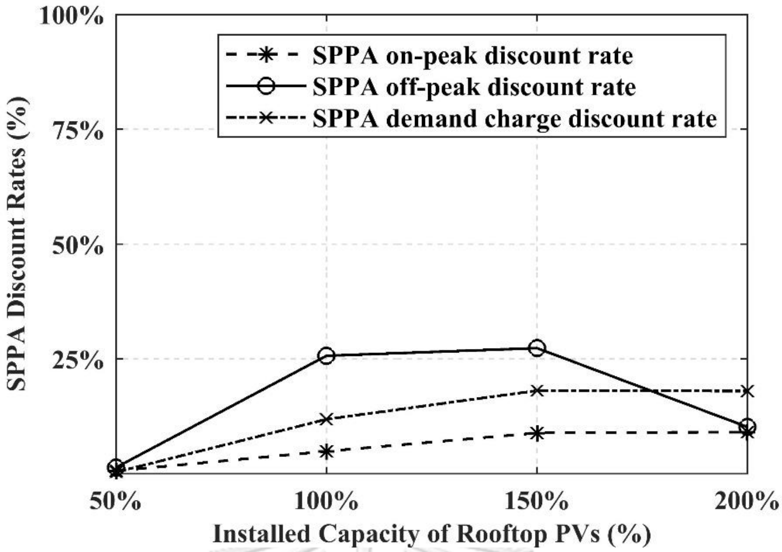

Figure 5.21 Optimal SPPA discount rates for each installation of rooftop PVs

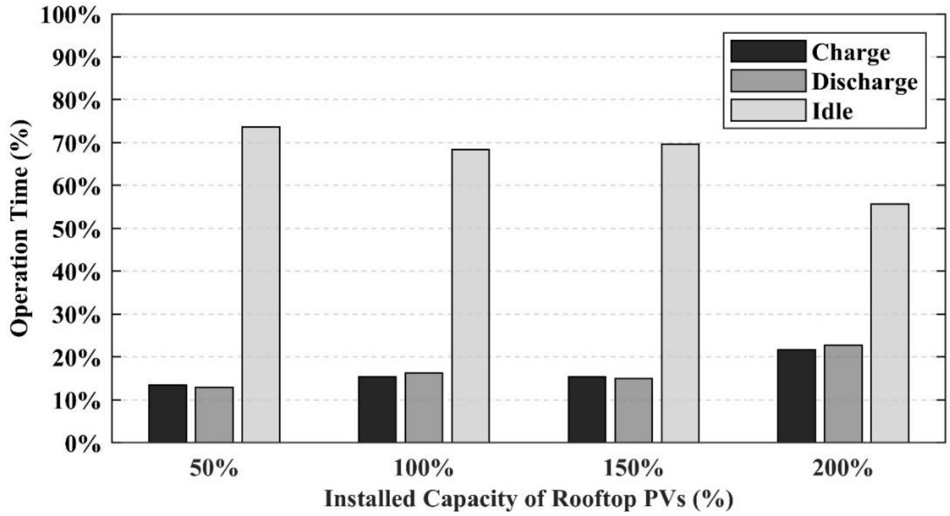

Figure 5.22 Operation time of the BESS for each installation of rooftop PVs

5.4.3.2 Effect of Battery Power Capacity

The SPPA discount rates and total operation time of BESS for each battery power capacity, at 2.5% of battery energy capacity, were investigated as shown in Figure 5.23-5.24. When the battery power capacity was increased, all SPPA discount rates were also significantly decreased. In addition, in case that the battery power capacity was higher than 100%, although all discount rates were zero, the IRR could not reach the target the because of the high total cost. For operation modes, the total operation time of the BESS in the charging and discharging modes for each case were approximately equal and significantly increased when the battery power capacity was increased.

In this scenario, it can be implied that α_1 and β_1 are the significant variables that the investors should strictly control. The battery power capacity has a direct effect on the discount rates and operation time of the BESS. If the battery power capacity is increased, the operation time of the BESS in discharging and charging modes are increased while the SPPA discount rates should be reduced to maintain the target IRR.

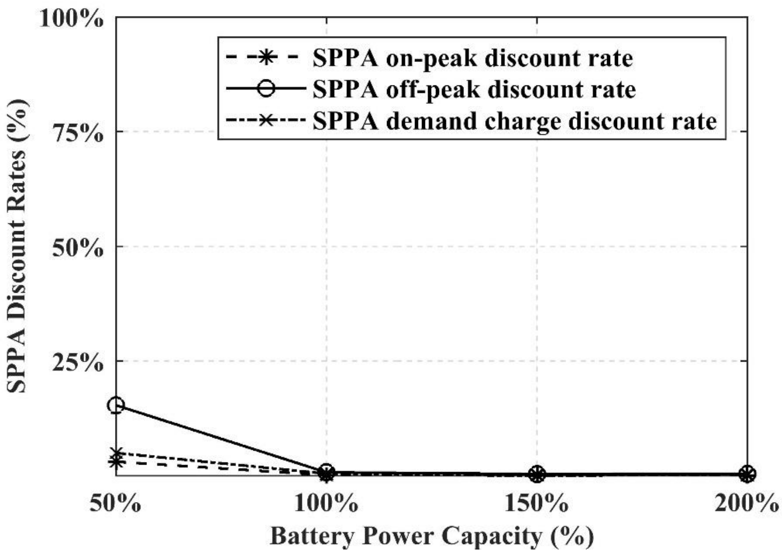

Figure 5.23 Optimal SPPA discount rates
for each battery power capacity

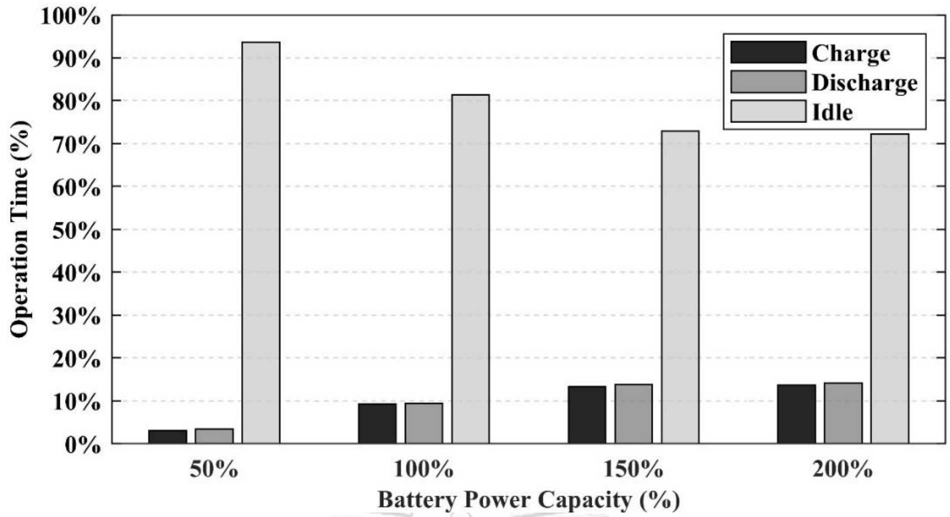

Figure 5.24 Operation time of the BESS
for each battery power capacity

5.4.3.3 Effect of Battery Energy Capacity

The SPPA discount rates and total operation time of BESS for each battery energy capacity, at 50% of battery power capacity, were investigated as shown in Figure 5.25-5.26. When the battery energy capacity was increased, all proposed discount rates were significantly decreased to remain the target IRR. For operation modes, the total operation time of the BESS in the charging and discharging modes for each case were approximately equal and significantly escalated when the battery energy capacity was increased.

In this scenario, it can be implied that α_2 is also the most flexible variable that the investors can propose to the customers with high discount. The battery energy capacity also has a direct effect on the discount rates and operation time of the BESS. If the battery energy capacity is increased, the operation time of the BESS in discharging and charging modes are increased while the proposed discount rates should be reduced to maintain the target IRR.

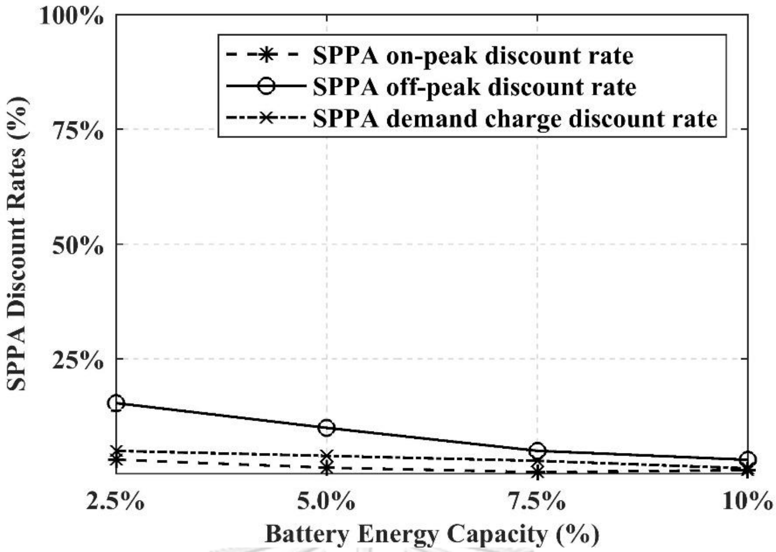

Figure 5.25 Optimal SPPA discount rates
for each battery energy capacity

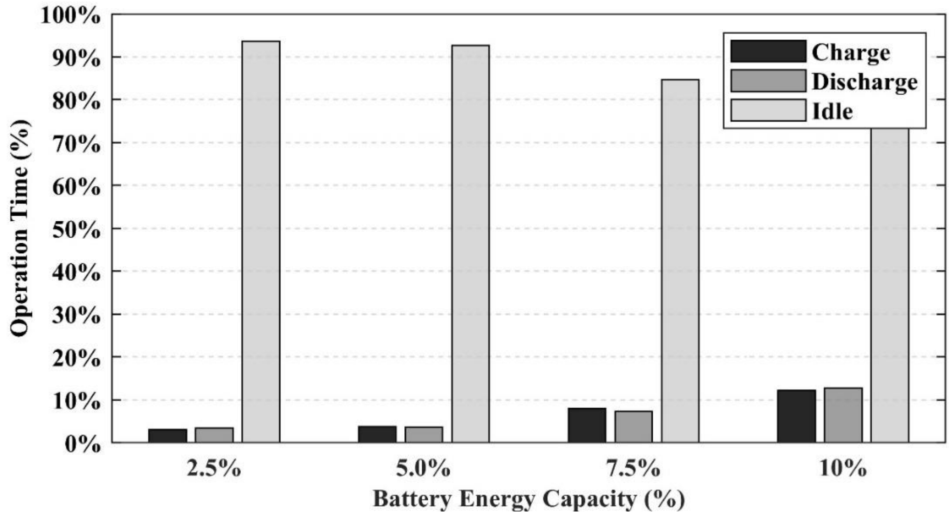

Figure 5.26 Operation time of the BESS
for each battery energy capacity

5.4.3.4 Effect of Rate of Excess Energy

The SPPA discount rates and total operation time of BESS for each rate of excess energy were investigated as shown in Figure 5.27-5.28. When the rate of excess energy was increased, all SPPA discount rates were significantly increased. In addition, in case that the rate of excess energy (γ) was lower than 100%, although all SPPA discount rates were zero, the IRR could not reach to the target because of the low revenue and high total cost. For operation modes, the total operation time of the BESS for each case were approximately equal.

In this scenario, it can be implied that α_1 is the most significant variable that the investors should strictly control. If γ is increased, the proposed discount rates could be increased and more flexible. There is no effect of rate of excess energy on the operation time of the BESS.

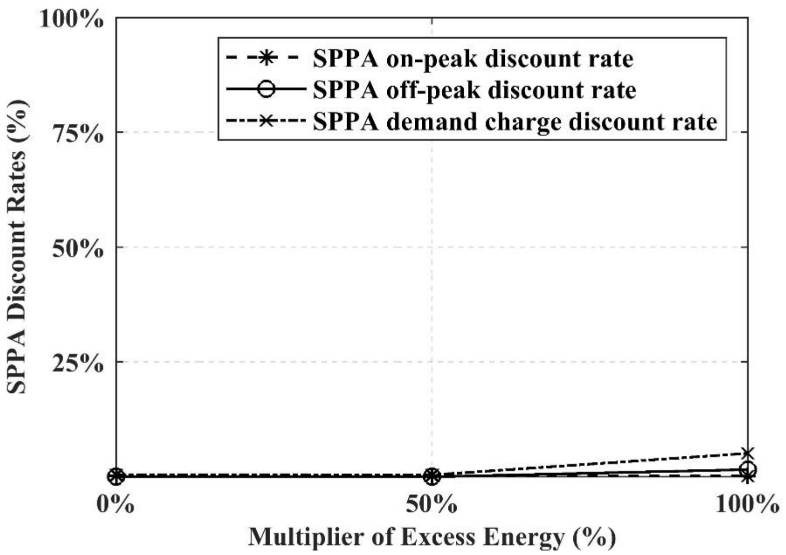

Figure 5.27 Optimal SPPA discount rates
for each rate of excess capacity

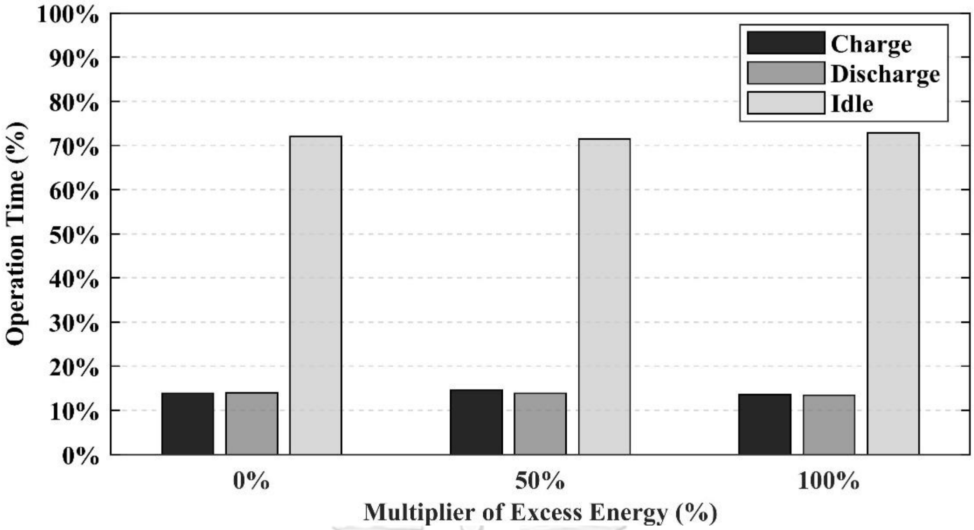

Figure 5.28 Operation time of the BESS
for each rate of excess energy

5.4.3.5 Effect of Battery Degradation

The SPPA discount rates and total operation time of BESS with and without consideration of battery degradation were investigated as shown in Figure 5.29-5.30. When battery degradation was considered, α_1 was significantly decreased while β_1 was increased. For operation modes, the total operation time of the BESS with and without consideration of battery degradation were approximately constant.

In this scenario, it can be implied the battery degradation has a significant effect to the SPPA discount rates and operation time of BESS. The consideration of battery degradation will lead to the decrease of the significant variable, especially α_1.

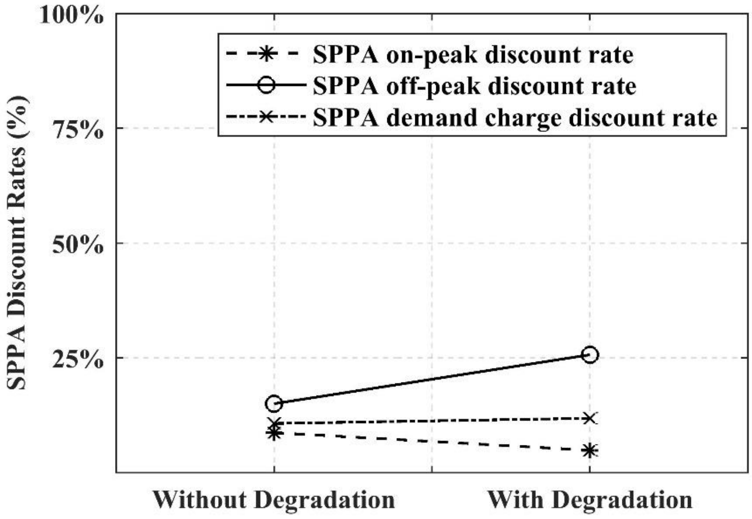

Figure 5.29 Optimal SPPA discount rates
with and without battery degradation

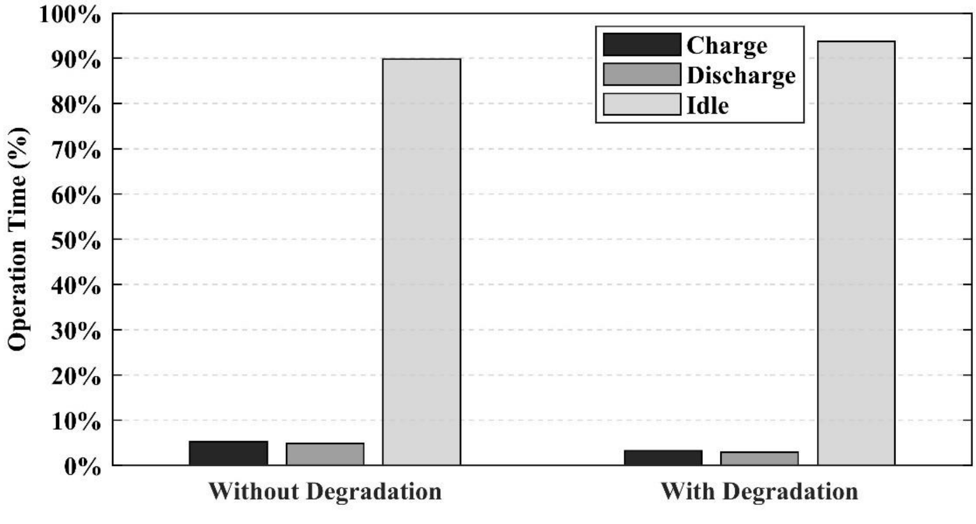

Figure 5.30 Operation time of the BESS
with and without battery degradation

Based on the assumption in the Table 5.6, for the optimal designing of the SPPA under the net-metering scheme, the proposed battery energy capacity, battery power capacity, SPPA discount rates and total operation time of BESS were shown in

Table 5.7. The total operation time in charging and discharging mode was approximately 21%. The battery degradation coefficient and life cycle left over the project period (8 years) is shown in Figure 5.31. At the end of the project, the life cycle left is 2,164 cycles and the battery degradation coefficient is 0.8718.

Table 5.7 The proposed SPPA discount rates and batter capacity for SPPA under the net-metering scheme

On-peak Discount Rate	Off-peak Discount Rate	Demand Charges Discount Rate	Battery Energy Capacity	Battery Power Capacity
0.0227	0.3575	0.3113	0.05%	0.27%

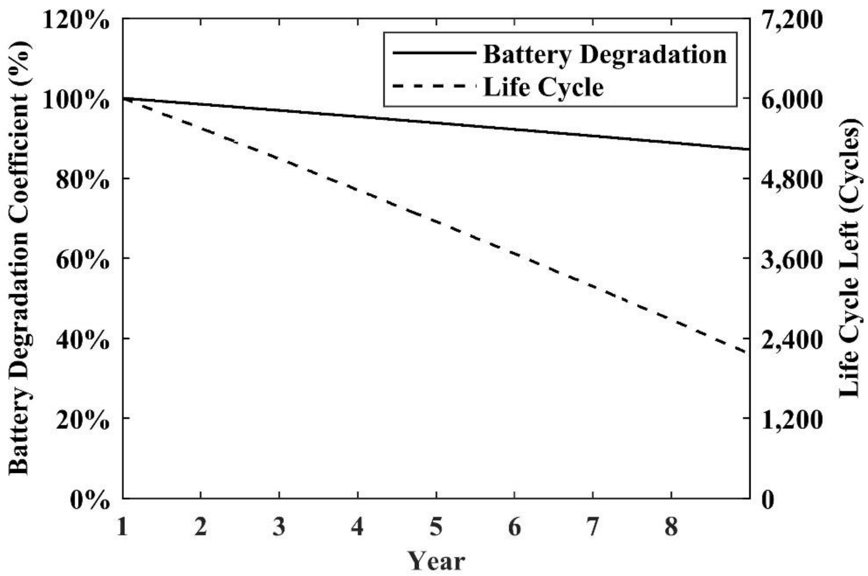

Figure 5.31 Battery degradation coefficient and life cycle of BESS over the project period

5.5 Result Discussions

From the simulation results in Section 5.2-5.4, the summary for the sensitivity analysis of rooftop PVs with BESS under the typical BTMS are presented in Table 5.8. Under the self-consumption scheme, the battery capacity will decrease when the installed capacity of rooftop PVs is increased due to the higher cost of the project, especially when the installed capacity of rooftop PVs is higher than the peak demand.

By considering the battery degradation, the usable energy capacity and usable power capacity will decrease due to reduction of degradation coefficient, especially the operating degradation efficiency. The high operation of the BESS in charging and discharging mode will lead to the significant decrease of the operating degradation coefficient. Therefore, to operate the BESS at the same condition of load demand and output power from rooftop PVs, the battery capacity will increase when the battery degradation is considered. On the other hand, if the battery degradation is neglected, the battery capacity will be significantly lower. Without the consideration of battery degradation, due to the limit of the reverse power flow and the decrease of the battery capacity, the total operation time of the BESS will significantly increase. The lower battery capacity will limit the discharged power from the BESS, which is also constrained by the load demand and output power from rooftop PVs.

Under the net-metering and net-billing scheme, the battery capacity will slightly increase when the installed capacity of rooftop PVs is increased due to the increase of revenue from excess energy injected to the utility's grid. For the rate of excess energy, when the rate of excess energy is increased, the battery capacity will significantly increase. The effect of the rate of excess energy will be apparent when the installed capacity of rooftop PVs is higher than the load demand. By considering the battery degradation, with the similar concept to the self-consumption scheme, the battery capacity will also increase when the battery degradation is considered to maintain the operation of the BESS. On the other hand, if the battery degradation is neglected, the battery capacity will be lower while the total operation time of the BESS is quite similar. The effect of the battery degradation for the net-metering scheme and net-billing scheme will be less than the self-consumption scheme due to the availability of the reverse power flow. For the net-metering and net-billing scheme, although the battery capacity is decreased, the BESS still can be fully discharged to the load and grid without any constraints from load and output power from rooftop PVs.

From the simulation results in Section 5.4, the summary for the sensitivity analysis of rooftop PVs with BESS under the SPPA with BTMS are presented in Table 5.9. For the installed capacity of rooftop PVs, the proposed SPPA discount rates are subject to the installed capacity of rooftop PVs and the peak demand. The oversized of rooftop PVs will limit the SPPA discount rates. The total operation time of the BESS in charging and discharging modes will also increase accordingly. An increase of battery power capacity will decrease the SPPA discount rates, while the operation time of the BESS in charging and discharging modes will quite similar. For the battery energy capacity, the SPPA discount rates will also decrease when the battery energy capacity is increased. The total operation time of the BESS in charging and discharging modes will increase due to the decrease of the SPPA discount rates. For the rate of excess energy, the higher rate of excess energy makes the higher SPPA discount rates to the customers. By considering the battery degradation, with the similar concept to the typical BTMS, the usable energy capacity and usable power capacity will decrease due to reduction of degradation coefficient. It means that, at the same condition of rated battery capacity, load demand and output power from rooftop PVs, the revenue from the BESS will be less. As a result, the SPPA discount rates will decrease to maintain the internal rate of return of the investors. Moreover, for the SPPA discount rates, it can be concluded that the SPPA on-peak discount rate is the most significant variable, while the most flexible variable is the SPPA off-peak discount rate.

Table 5.8 Summary for the sensitivity analysis of rooftop PVs with BESS under the BTMS

Variable Parameters	**Self-Consumption Scheme**		**Net-Metering and Net-Billing Scheme**	
	Battery Capacity	**Operation Modes**	**Battery Capacity**	**Operation Modes**
Installed Capacity of Rooftop PVs	When the installed capacity of rooftop PVs is lower than the peak demand, battery energy and power capacity will increase when the installed capacity is increased. Otherwise, the trend of the battery capacity will perform in the opposite direction when the installed capacity is higher than the peak demand.	The operation time of the BESS in charging and discharging modes will slightly increase when the installed capacity of rooftop PVs is higher than the peak demand.	Battery energy and power capacity will increase when the installed capacity of rooftop PVs is increased.	The operation time of the BESS in charging and discharging modes will slightly increase when the installed capacity of rooftop PVS is higher than the peak demand.
Rate of Excess Energy	-	-	Battery energy and power capacity will increase when the rate of excess energy is increased. The impact is obvious when the rate of excess energy is equal to the utility's retail rate.	The operation time of the BESS in charging and discharging modes will slightly increase when the rate of excess energy is equal to the utility's retail rate.
Battery Degradation	Battery energy and power capacity will increase when the battery degradation is considered.	The operation time of the BESS in charging and discharging modes will decrease when the battery degradation is considered.	Battery energy and power capacity will increase when the battery degradation is considered.	The operation time of the BESS in charging and discharging modes has been less affected from the battery degradation.

Table 5.9 Summary for the sensitivity analysis of rooftop PVs with BESS under the SPPA with BTMS

Variable Parameters	SPPA with the Self-Consumption Scheme		SPPA with the Net-Metering and Net-Billing Scheme	
	SPPA Discount Rates	**Operation Modes**	**SPPA Discount Rates**	**Operation Modes**
Installed Capacity of Rooftop PVs	SPPA discount rates are subject to the installed capacity of rooftop PVs and operation modes of the BESS. If the installed capacity is higher than the peak demand, the SPPA discount rates should be decreased to maintain the target internal rate of return.	The operation time of the BESS in charging and discharging modes will increase when the installed capacity of rooftop PVS is increased.	SPPA discount rates are subject to the installed capacity of rooftop PVs and operation modes of the BESS. If the installed capacity is higher than the peak demand, the SPPA should be decreased to maintain the target internal rate of return.	The operation time of the BESS in charging and discharging modes will increase when the installed capacity of rooftop PVS is increased.
Battery Power Capacity	SPPA discount rates will decrease when the battery power capacity is increased.	The operation time of the BESS in charging and discharging modes is quite similar.	SPPA discount rates will decrease when the battery power capacity is increased.	The operation time of the BESS in charging and discharging modes will increase when the battery power capacity is increased.
Battery Energy Capacity	SPPA discount rates will decrease when the battery energy capacity is increased.	The operation time of the BESS in charging and discharging modes will increase when the battery energy capacity is increased and the SPPA on-peak discount rates is decreased.	SPPA discount rates will decrease when the battery energy capacity is increased.	The operation time of the BESS in charging and discharging modes will increase when the battery energy capacity is increased.
Rate of Excess Energy	-	-	SPPA discount rates will significantly increase when the rate of excess energy is increased.	The operation time of the BESS in charging and discharging modes will be constant when the rate of excess energy is increased.

Variable Parameters	SPPA with the Self-Consumption Scheme		SPPA with the Net-Metering and Net-Billing Scheme	
	SPPA Discount Rates	**Operation Modes**	**SPPA Discount Rates**	**Operation Modes**
Battery Degradation	SPPA discount rates will decrease when the battery degradation is considered.	The operation time of the BESS in charging and discharging modes will decrease when the battery power capacity is increased.	SPPA discount rates will decrease when the battery degradation is considered.	The operation time of the BESS in charging and discharging modes will decrease when the battery degradation is considered.

CHAPTER 6
CONCLUSIONS

In this chapter, the conclusion of this dissertation, which consist of the concept of the proposed methodology and the simulation results from the case studies, are summarized in Section 6.1. The future works which have not been considered in this dissertation are also presented in Section 6.2.

6.1 Dissertation Summary

This dissertation proposes a novel methodology to investigate the battery capacity, operation schedule of the BESS for rooftop PVs under the BTMS and SPPA. The mode-based operation of the BESS is proposed and divided into two main concepts of operation modes and power. The operation modes consist of discharging, charging and idling mode. For the operation power, the charged and discharge power are formulated in terms load and utility’s grid by considering the condition of load demand, PV output power and characteristics of the BESS. In addition, the proposed methodology is categorized into two main groups of (1) typical BTMS and (2) SPPA.

The typical BTMS, which consists the self-consumption, net-metering, and net-billing scheme, is the scheme where the output power from rooftop PVs with BESS of the customers directly supply to the load only for electricity charge savings. The benefit from the reverse power flow depends on the type of the metering scheme. In this dissertation, for the typical BTMS, the cost optimization problem to simultaneously investigate the battery power capacity, battery energy capacity and operation modes is formulated. The main objective is to minimize the total electricity charge of the customers. By applying the load profile of large general service and tariff rate in Thailand, the sensitivity of the installed capacity of rooftop PVs, rate of excess energy and battery degradation on the battery capacity and operation schedule for each scheme are evaluated.

From the result, it is obvious that the installed capacity of rooftop PVs, the rate of excess energy and the battery degradation will significantly affect the design of battery capacity and operation. An increase of the installed capacity of rooftop PVs can either support or obstruct the installation of the BESS depending on the metering scheme and the peak demand. The higher rate of excess energy will support the installation of the BESS. The consideration of battery degradation is also necessary to accurately determine the battery capacity and operation schedule of the BESS. Without the consideration of the battery degradation, the design of the BESS may oversize or undersize, which will mislead the economic feasibility and expected internal rate of return of the project.

The SPPA is the business model which is developed from the typical BTMS. Under the SPPA, the investors proposed to directly sell electricity from rooftop PVs with BESS to the customers at a lower rate than the utility's retail rate. The customers under the SPPA can reduce their electricity charges without any performance risk, capital investment, or operating expenses. In this dissertation, the SPPA proposed rates are typically formulated in term of the discount rates on the time-of-use (TOU) tariff with demand charges and categorized into three variables, which consist of SPPA on-peak discount rate (α_1), SPPA off-peak discount rate (α_2) and SPPA demand charge discount rate (β_1). The modeling of the SPPA is categorized into (1) SPPA with the self-consumption scheme and (2) SPPA with the net-metering and net-billing scheme. The cost optimization problem to simultaneously investigate the SPPA discount rates, battery power capacity, battery energy capacity and operation modes for each scheme is formulated. The main objective is to minimize the electricity charges of the customers while maintaining the internal rate of return of the investors. By applying the load profile of large general service and tariff rate in Thailand, the sensitivity of the installed capacity of rooftop PVs, battery power capacity, battery energy capacity, and rate of excess energy on the SPPA discount rates and operation schedule for each scheme are evaluated.

From the result, it shows that the investors can propose higher SPPA discount rates when the installed capacity of rooftop PVs and rate of excess energy are increased. On the other hand, the SPPA discount rates will be restricted when the battery energy and power capacity are increased. The oversized rooftop PVs will also limit the SPPA discount rates. Moreover, it is obvious that the consideration of battery degradation also significantly affects the design of the SPPA discount rates. Without the consideration of the battery degradation, the investors may propose the over SPPA discount rates, which will also mislead the economic feasibility and expected internal rate of return of the project. Finally, it can be implied that the SPPA on-peak discount rate is the significant variable that the investors should strictly control while the SPPA off-peak discount rate is the most flexible variable that the investor can proposed higher discount rate to the customers.

6.2 Future Works

There are many topics relevant to the rooftop PVs with BESS which have not been considered in this dissertation. The possible future works are shown as follows.

(a) Different load profile in Thailand should be considered. Besides large general service in this dissertation, the load profile of residential load, small general service, medium general service, and others should be studied to evaluate the effects of load profile on the battery capacity, operation schedule of the BESS and the SPPA discount rates.

(b) The modeling of the SPPA under the normal rate for the residential load should be thoroughly developed. With the significant reduction of the total cost of rooftop PVs with BESS, the residential load should become to the target group of the SPPA in the next few years.

(c) The replacement of the battery module over the project period should be considered. Typically, the lifetime of the rooftop PVs project is approximately 20 years while the lifetime of the lithium-ion battery is approximately not over than 12 years. Therefore, the restoration cost, time, and performance of replaced battery should be studied.

(d) The operation of BESS should be improved and developed by applying more efficient and complicated battery degradation model that will consider more significant parameters and increase the accuracy of the results.

(e) Other than the objective to minimize the electricity charge savings, some additional objective or constraints should be considered, such as, the concept to maximize the lifetime of the BESS or minimize the loss in distribution system.

(f) The modeling of the distribution system and load in different households should be considered. The proposed modeling of the SPPA can be extend for determining an optimal battery capacity and the tariff rate under the peer-to-peer energy trading.

REFERENCES

[1] REN21, *Renewables 2019 Global Status Report*, Paris, France: REN21 Secretariat, 2019. [Online]. Available: https://ren21.net/gsr-2019/. Accessed on: 27 July 2020.

[2] A. Roux, A. Shanker, and C. Borlazza, *Net metering and PV self-consumption in emerging countries*, 2018. [Online]. Available: https://iea-pvps.org/wp-content/uploads/2020/01/T9_NetMeteringAndPVDevelopmentInEmergingCountries_EN_Report.pdf. Accessed on: 18 June 2020.

[3] T. Potisat, "Thailand Solar PV Policy Update 01/2017." [Online]. Available: http://www.thai-german-cooperation.info/admin/uploads/publication/384bf513d3c90d94c609e739be270b3den.pdf

[4] L. A. Wong, V. K. Ramachandaramurthy, P. Taylor, J. B. Ekanayake, S. L. Walker, and S. Padmanaban, "Review on the optimal placement, sizing and control of an energy storage system in the distribution network," *Journal of Energy Storage*, vol. 21, pp. 489-504, 2019/02 2019, doi: 10.1016/j.est.2018.12.015.

[5] S. N. Laboratories, "DOE/EPRI 2015 Electricity Storage Handbook in Collaboration with NRECA," Albuquerque, Livermore, California, 2015.

[6] I. S. Bayram and T. S. Ustun, "A survey on behind the meter energy management systems in smart grid," *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 1208-1232, May 2017, doi: https://doi.org/10.1016/j.rser.2016.10.034.

[7] O. R. Zinaman, T. Bowen, and A. Y. Aznar, "An Overview of Behind-the-Meter Solar-Plus-Storage Regulatory Design: Approaches and Case Studies to Inform International Applications," Office of Scientific and Technical Information (OSTI), 2020/03/19 2020. [Online]. Available: http://dx.doi.org/10.2172/1606152

[8] IRENA, IRENA, Ed. *Innovation landscape brief: Behind-the-meter batteries*. Abu Dhabi, 2019.

[9] T. D. Couture, D. Jacobs, W. Rickerson, and V. Healey, "The Next Generation of Renewable Electricity Policy: How Rapid Change is Breaking Down Conventional Policy Categories," Office of Scientific and Technical Information (OSTI), 2015/02/01 2015. [Online]. Available: http://dx.doi.org/10.2172/1172282

[10] G. Masson, J. I. Briano, and M. J. Baez, "A Methodology For the Analysis of PV Self-consumption Policies," 2016. Accessed: 20 October 2020. [Online]. Available: https://iea-pvps.org/wp-content/uploads/2020/01/IEA-PVPS_-_A_methodology_for_the_Analysis_of_PV_Self-Consumption_Policies.pdf

[11] S. Cox, T. Walters, S. Esterly, and S. Booth, "Solar Power. Policy Overview and Good Practices," Office of Scientific and Technical Information (OSTI), 2015/05/01 2015. [Online]. Available: http://dx.doi.org/10.2172/1215246

[12] H. E. Company, "Guide to Net Energy Metering." [Online]. Available: https://www.hawaiianelectric.com/documents/products_and_services/customer_renewable_programs/nem/guide_to_nem.pdf

[13] S. Tongsopit, S. Moungchareon, A. Aksornkij, and T. Potisat, "Business models

and financing options for a rapid scale-up of rooftop solar power systems in Thailand," *Energy Policy*, vol. 95, pp. 447-457, 2016/08 2016, doi: 10.1016/j.enpol.2016.01.023.

[14] S. P. Europe, "Global Market Outlook For Solar Power / 2018 - 2022." Accessed: 9 October 2017. [Online]. Available: http://www.euractiv.com/wp-content/uploads/sites/2/2017/08/Global-Market-Outlook-2017-2021-1.pdf

[15] BNEF, "Global Trends I Renewable Energy Investment 2019," 2019.

[16] E. Reid and S. Dingenen, *Bird & Bird & Corporate PPAs: An international perspective*, 2019. [Online]. Available: https://www.twobirds.com/en/news/articles/2018/global/bird-and-bird-and-corporate-ppas-an-international-perspective. Accessed on: 27 July 2020.

[17] NREL, "Using Power Purchase for Solar Deployment at Universities." [Online]. Available: https://www.nrel.gov/docs/gen/fy16/65567.pdf

[18] A. Chaianong, S. Tongsopit, A. Bangviwat, and C. Menke, "Bill saving analysis of rooftop PV customers and policy implications for Thailand," *Renewable Energy*, vol. 131, pp. 422-434, 2019/02 2019, doi: 10.1016/j.renene.2018.07.057.

[19] N. R. Darghouth, G. Barbose, and R. Wiser, "The impact of rate design and net metering on the bill savings from distributed PV for residential customers in California," *Energy Policy*, vol. 39, no. 9, pp. 5243-5253, 2011/09 2011, doi: 10.1016/j.enpol.2011.05.040.

[20] A. Poullikkas, "A comparative assessment of net metering and feed in tariff schemes for residential PV systems," *Sustainable Energy Technologies and Assessments*, vol. 3, pp. 1-8, 2013/09 2013, doi: 10.1016/j.seta.2013.04.001.

[21] D. Watts, M. F. Valdés, D. Jara, and A. Watson, "Potential residential PV development in Chile: The effect of Net Metering and Net Billing schemes for grid-connected PV systems," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1037-1051, 2015/01 2015, doi: 10.1016/j.rser.2014.07.201.

[22] F. Cucchiella, I. D'Adamo, M. Gastaldi, and V. Stornelli, "Solar Photovoltaic Panels Combined with Energy Storage in a Residential Building: An Economic Analysis," *Sustainability*, vol. 10, no. 9, p. 3117, 2018/08/31 2018, doi: 10.3390/su10093117.

[23] M. Naumann, R. C. Karl, C. N. Truong, A. Jossen, and H. C. Hesse, "Lithium-ion Battery Cost Analysis in PV-household Application," *Energy Procedia*, vol. 73, pp. 37-47, 2015/06 2015, doi: 10.1016/j.egypro.2015.07.555.

[24] B.-K. Jo, S. Jung, and G. Jang, "Feasibility Analysis of Behind-the-Meter Energy Storage System According to Public Policy on an Electricity Charge Discount Program," *Sustainability*, vol. 11, no. 1, p. 186, 2019/01/01 2019, doi: 10.3390/su11010186.

[25] J. Neubauer and M. Simpson, "Deployment of Behind-The-Meter Energy Storage for Demand Charge Reduction," Office of Scientific and Technical Information (OSTI), 2015/01/01 2015. [Online]. Available: http://dx.doi.org/10.2172/1168774

[26] A. Park and P. Lappas, "Evaluating demand charge reduction for commercial-scale solar PV coupled with battery storage," *Renewable Energy*, vol. 108, pp. 523-532, 2017/08 2017, doi: 10.1016/j.renene.2017.02.060.

[27] M. A. Hayat, F. Shahnia, and G. M. Shafiullah, "Economic Viability of Roof

Leasing for Rooftop Photovoltaic Systems from a Leasing Company's Perspective," presented at the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), 2018/06, 2018. [Online]. Available: http://dx.doi.org/10.1109/pvsc.2018.8547423.
[28] T. Hong *et al.*, "A model for determining the optimal lease payment in the solar lease business for residences and third-party companies – With focus on the region and on multi-family housing complexes," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 824-836, 2018/02 2018, doi: 10.1016/j.rser.2017.09.068.
[29] Y. Yoon and Y.-H. Kim, "Charge scheduling of an energy storage system under time-of-use pricing and a demand charge," (in eng), *ScientificWorldJournal*, vol. 2014, pp. 937329-937329, 2014, doi: 10.1155/2014/937329.
[30] A. Pena-Bello, M. Burer, M. K. Patel, and D. Parra, "Optimizing PV and grid charging in combined applications to improve the profitability of residential batteries," *Journal of Energy Storage*, vol. 13, pp. 58-72, 2017/10 2017, doi: 10.1016/j.est.2017.06.002.
[31] A. Moiteaux, "Analysis Of Grid-Connected Battery Energy Storage And Photovoltaic Systems For Behind-the-meter Applications: Case Study for a commercial building in Sweden," KTH School of Industrial Engineering and Management Energy Technology, 2016.
[32] G. Henri, N. Lu, and C. Carrejo, "Design of a novel mode-based energy storage controller for residential PV systems," presented at the 2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2017/09, 2017. [Online]. Available: http://dx.doi.org/10.1109/isgteurope.2017.8260258.
[33] T. A. Nguyen and R. H. Byrne, "Maximizing the cost-savings for time-of-use and net-metering customers using behind-the-meter energy storage systems," presented at the 2017 North American Power Symposium (NAPS), 2017/09, 2017. [Online]. Available: http://dx.doi.org/10.1109/naps.2017.8107380.
[34] E. L. Ratnam, S. R. Weller, and C. M. Kellett, "Scheduling residential battery storage with solar PV: Assessing the benefits of net metering," *Applied Energy*, vol. 155, pp. 881-891, 2015/10 2015, doi: 10.1016/j.apenergy.2015.06.061.
[35] C. Prapanukool and S. Chaitusaney, "Optimal Battery Capacity for Residential Rooftop PVs With Consideration of Net-Metering Scheme Compensation Period," *International Journal of Renewable Energy Research*, vol. 9, 2019.
[36] H. Hesse, R. Martins, P. Musilek, M. Naumann, C. Truong, and A. Jossen, "Economic Optimization of Component Sizing for Residential Battery Storage Systems," *Energies*, vol. 10, no. 7, p. 835, 2017/06/22 2017, doi: 10.3390/en10070835.
[37] L. Zhou, Y. Zhang, X. Lin, C. Li, Z. Cai, and P. Yang, "Optimal Sizing of PV and BESS for a Smart Household Considering Different Price Mechanisms," *IEEE Access*, vol. 6, pp. 41050-41059, 2018, doi: 10.1109/access.2018.2845900.
[38] M. Gomez-Gonzalez, J. C. Hernandez, D. Vera, and F. Jurado, "Optimal sizing and power schedule in PV household-prosumers for improving PV self-consumption and providing frequency containment reserve," *Energy*, vol. 191, p. 116554, 2020/01 2020, doi: 10.1016/j.energy.2019.116554.

[39] Q. Dai, J. Liu, and Q. Wei, "Optimal Photovoltaic/Battery Energy Storage/Electric Vehicle Charging Station Design Based on Multi-Agent Particle Swarm Optimization Algorithm," *Sustainability*, vol. 11, no. 7, p. 1973, 2019/04/03 2019, doi: 10.3390/su11071973.

[40] L. Yao, Z. Damiran, and W. H. Lim, "Optimal Charging and Discharging Scheduling for Electric Vehicles in a Parking Station with Photovoltaic System and Energy Storage System," *Energies*, vol. 10, no. 4, p. 550, 2017/04/17 2017, doi: 10.3390/en10040550.

[41] G. Fitzgerald, J. Mandel, J. Morris, and H. Touati, "The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid.," Rocky Mountain Institute, September 2015. Accessed: 20 October 2020. [Online]. Available: http://www.rmi.org/electricity_battery_value

[42] EPRI, "ESIC Energy Storage Implementation Guide 2016.," Palo Alto, CA, 2016.

[43] IRENA, *Electricity Storage And Renewables: Costs And Markets To 2030*. Abu Dhabi: International Renewable Energy Agency, 2017.

[44] B. Xu, "Degradation-limiting Optimization of Battery Energy Storage Systems Operations," Master Thesis, the Federal Institute of Technology Zurich (ETH Zurich), 2013.

[45] Y. Riffonneau, S. Bacha, F. Barruel, and S. Ploix, "Optimal Power Flow Management for Grid Connected PV Systems With Batteries," *IEEE Transactions on Sustainable Energy*, vol. 2, no. 3, pp. 309-320, 2011/07 2011, doi: 10.1109/tste.2011.2114901.

[46] H. Energy. Homer Pro 3.16 [Online] Available: https://www.homerenergy.com/products/pro/docs/latest/index.html

[47] R.Sponitz, "Simulation of capacity fade in lithium-ion batteries," *Journal of Power Sources*, vol. 113, no. 1, pp. 72-80, 2003, doi: https://doi.org/10.1016/S0378-7753(02)00490-1.

[48] S. Saha, "A Comprehensive Review on Battery Capacity Estimation Methods." [Online]. Available: https://issuu.com/dnvgl/docs/ad75a5cbc6b54a568e297424f34df625

[49] W.-Y. Chang, "The State of Charge Estimating Methods for Battery: A Review," *International Scholarly Research Notices*, vol. 2013, 2013, doi: https://doi.org/10.1155/2013/953792.

[50] Q. Wang, J. Wang, P. Zhao, F. Yan, and C.Du, "Correlation between the model accuracy and model-based SOC estimation," *Electrochimica Acta*, vol. 228, pp. 146-159, 2017.

[51] V. Pop, H. J. Bergveld, P. H. L. Notten, J. H. G. O. h. Veld, and P. P. L. Regtien, "Accuracy analysis of the state-of-charge and remaining run-time determination for lithium-ion batteries," *Measurement*, vol. 42, pp. 1131-1138, 2009, doi: https://doi.org/10.1016/j.measurement.2008.03.009.

[52] B. University. "Learn About Batteries." http://batteryuniversity.com/learn/ (accessed 8 October 2017.

[53] MIT, "A guide to understanding battery specifications," no. 13 October 2017. [Online]. Available: http://web.mit.edu/evt/summary_battery_specifications.pdf

[54] IRENA, "Battery Storage For Renewables: Market Status And Technology

Outlook," 2015. [Online]. Available: https://www.irena.org/documentdownloads/publications/irena_battery_storage_report_2015.pdf

[55] IEA. "Technology Roadmap - Energy Storage." https://www.iea.org/reports/technology-roadmap-energy-storage (accessed 15 October 2017.

[56] MEA, "Electricity Tariffs." [Online]. Available: http://www.mea.or.th/en/profile/109/111

[57] J. Svarc. "Solar Battery System Types - AC Vs DC Coupled." https://www.cleanenergyreviews.info/blog/ac-coupling-vs-dc-coupling-solar-battery-storage (accessed 8 December 2020).

[58] *Self-consumption & energy storage*. [Online]. Available: https://www.victronenergy.com/upload/documents/Brochure-Energy-Storage-EN_web.pdf. Accessed: 8 December2020.

[59] *Sunny Boy Storage 3.8-US / 5.0-US / 6.0-US*. [Online]. Available: https://files.sma.de/downloads/SBSXX-US-DS-en-20.pdf?_ga=2.74165714.1703477973.1607225638-1730722781.1607225638. Accessed: 8 December 2020.

[60] *Technical Data SonnenBatterie eco 8.0*. [Online]. Available: https://sonnenbatterie.de/sites/default/files/datenblatt_sonnenbatterie_eco_8.0_row.pdf. Accessed: 8 December 2020.

[61] *TESLA Powerwall*. [Online]. Available: https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall%202_AC_Datasheet_en_northamerica.pdf. Accessed: 8 December 2020.

[62] *Solution Brochure*. [Online]. Available: http://download.selectronic.com.au/brochure/BR0018_01%20Solutions%20Brochure%20October%202019%20Web.pdf. Accessed: 8 December 2020.

[63] *Sunny Island 4.4M / 6.0H / 8.0H*. [Online]. Available: https://files.sma.de/downloads/SI44M-80H-13-DS-en-21.pdf. Accessed: 8 December 2020.

[64] G. Masson, J. I. Briano, and M. J. Baez, *Review And Analysis of PV Self-Consumption Policies*, 2016. [Online]. Available: http://www.vindogsol.dk/assets/iea-pvps---self-consumption-policies---2016.pdf.

[65] S. Franz and B. F, "Regulatory Trends in Renewable Energy Self-Supply," 2016. Accessed: 20 October 2020. [Online]. Available: https://www.international-climate-initiative.com/fileadmin/Dokumente/2016/160223_Regulatory_Trends_NetMetering_eng.pdf

[66] K. Ardani, E. O'Shaughnessy, R. Fu, C. McClurg, J. Huneycutt, and R. Margolis, "Installed Cost Benchmarks and Deployment Barriers for Residential Solar Photovoltaics with Energy Storage: Q1 2016," Office of Scientific and Technical Information (OSTI), 2016/12/01 2016. [Online]. Available: http://dx.doi.org/10.2172/1338670

[67] C. Curry, *Lithium-ion Battery Costs and Market: Squeezed Margins Seek Technology Improvements & New Business Models*: BNEF, 2017. [Online]. Available: https://data.bloomberglp.com/bnef/sites/14/2017/07/BNEF-Lithium-ion-battery-costs-and-market.pdf. Accessed on: 27 July 2020.

[68] R. Fu, D. Feldman, R. Margolis, M. Woodhouse, and K. Ardani, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017," 2017. Accessed: 7 October 2017. [Online]. Available: https://www.nrel.gov/docs/fy17osti/68925.pdf.

APPENDIX

Appendix A

The detailed data of generation profile of 1,000 kW_{dc} rooftop PVs in each month from PVsyst is shown in Table A.1. The load profile of large general service and TOU tariff of MEA are shown in Table A.2 and A.3 respectively.

Table A.1 Annual generation profile of 1,000 kWdc rooftop PVs

Hours	Output Power of Rooftop PVs in kW											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:00	0	0	0	0	0	0	0	0	0	0	0	0
1:00	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0
6:00	0	0	8.74	40	61	59.33	41.61	32.39	28.9	29.81	18.63	0
7:00	86.55	102.39	156.1	211.97	219.94	203.67	183.06	158.87	150.9	166.29	162.3	122.16
8:00	265.1	296.79	367.39	416.77	399.39	347.07	341.87	317.45	306.2	349.77	339.93	300.52
9:00	427.65	481.61	562.74	563.43	528.61	461.67	471.94	444.19	424.4	471.97	485.9	490.29
10:00	574.52	626.75	681	679.23	643.39	551.83	575.42	559.45	507.63	537.13	583.13	615.58
11:00	687.06	669.61	741	742.1	645.23	586.03	549.16	580.29	557.07	615.48	643.1	698.55
12:00	680.81	703.96	766.87	747.53	670.9	594.97	619.87	605.06	606.57	618.16	665.57	692.16
13:00	624.26	677.86	717.9	705.23	625.65	591.13	563.29	547.03	577.77	549.1	615.47	655.52
14:00	555.29	585.29	630.32	605.37	554.42	533.43	505.77	499.97	475.33	495.71	526	546.58
15:00	428.77	448.68	484.23	458.83	437.13	428.37	414.1	373.23	349.33	366.97	384.4	378.87
16:00	252.42	273.64	302.29	302.07	291.81	283.47	283.26	261.06	218	178.13	200.03	192.81

Hours	Output Power of Rooftop PVs in kW											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
17:00	73.77	101.32	125.29	119.5	123.42	140	135.16	121.68	69.9	37.55	31.57	35.39
18:00	0	0	0	0	7.35	19.13	19.29	11.45	0	0	0	0
19:00	0	0	0	0	0	0	0	0	0	0	0	0
20:00	0	0	0	0	0	0	0	0	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0

Table A.2 Load profile of large general service

Hours	Load Demand (kW)		
	Workday	Saturday	Sunday
0:00	764.25	786.45	689.80
1:00	746.46	761.46	673.23
2:00	734.19	742.64	671.22
3:00	721.35	734.06	655.09
4:00	707.46	716.38	635.27
5:00	702.10	708.39	626.49
6:00	743.93	732.72	635.37
7:00	842.97	765.28	641.79
8:00	995.20	813.28	670.07
9:00	1150.08	898.73	736.69
10:00	1213.77	985.94	821.03
11:00	1273.90	1031.85	856.47
12:00	1254.21	1021.87	858.66
13:00	1243.34	1012.96	855.35
14:00	1289.55	1038.72	868.42
15:00	1278.32	1032.96	860.35
16:00	1257.78	1019.09	849.52
17:00	1197.29	966.50	816.31
18:00	1098.29	895.54	775.79
19:00	1038.72	858.27	749.87
20:00	985.19	832.32	726.04
21:00	894.53	780.85	680.96
22:00	865.09	758.93	632.45
23:00	851.49	724.53	605.22

Table A.3 TOU tariff for large general service load

Hours	Tariff Rate (THB/kWh)		
	Workday	Saturday	Sunday
0:00	2.6037	2.6037	2.6037
1:00	2.6037	2.6037	2.6037
2:00	2.6037	2.6037	2.6037
3:00	2.6037	2.6037	2.6037
4:00	2.6037	2.6037	2.6037
5:00	2.6037	2.6037	2.6037
6:00	2.6037	2.6037	2.6037
7:00	2.6037	2.6037	2.6037
8:00	2.6037	2.6037	2.6037
9:00	4.1839	2.6037	2.6037
10:00	4.1839	2.6037	2.6037
11:00	4.1839	2.6037	2.6037
12:00	4.1839	2.6037	2.6037
13:00	4.1839	2.6037	2.6037
14:00	4.1839	2.6037	2.6037
15:00	4.1839	2.6037	2.6037
16:00	4.1839	2.6037	2.6037
17:00	4.1839	2.6037	2.6037
18:00	4.1839	2.6037	2.6037
19:00	4.1839	2.6037	2.6037
20:00	4.1839	2.6037	2.6037
21:00	4.1839	2.6037	2.6037
22:00	4.1839	2.6037	2.6037
23:00	2.6037	2.6037	2.6037

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