

Load Profiles in Grid-Connected Residential Buildings: Experimental Studies with Rooftop PV and Battery Systems

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Abstract

The number of photovoltaic (PV) installation in many countries has increased in the past decades. The advantages of energy from PV consists of reduction of CO₂ emission, low maintenance cost, low operation cost, etc. On the other hand, the main problems of this technology consist of: (1) electrical power is relatively fluctuated and (2) the excessive energy from PV generating cannot be stored for any use in another necessary time. One of the solving solution is the integration of the PV systems with battery systems to keep the system stability. Moreover, the reduction of battery price leads the electricity users interest in the installation of battery systems with rooftop PV on their buildings. In the past, a number of works studied on PV systems with integrated batteries as the off-grid systems and evaluated by simulation programs. In this work, the load profiles of buildings in different categories (i.e. households, small offices, and home offices) of residential section are discussed. The characteristics of load profiles in residential buildings installed with a grid-connected rooftop PV system with batteries are analyzed by physical experimentations. It was found that battery systems were significantly affected the load profiles of the residential buildings. Household was found to be the highest proportion (21.68%) of excessive electricity. The ratio of PV met to load (29.15%) was smaller than the ratio of battery charging (50.17%). In addition, the excessive electricity in small office was the lowest proportion (10.39%), while the ratio of PV met to load (57.83%) was higher than the battery charging (31.78%).

Keywords: Load profile, Residential building, Rooftop PV, Battery system

1. Introduction

Nowadays, the world needs more energy to supply the increase of energy demand due to the activities of users. Renewable energy is important for reducing the proportion of electricity generated from fossil fuel sources (Shah, Mithulananthan, Bansal, & Ramachandramurthy, 2015). The progress of global installed photovoltaic (PV) capacity had been increased significantly from 2000 to 2014 (Haque & Wolfs, 2016). Moreover, according to the strategies plan of renewable energy, Thailand will have a total energy from renewable sources of 19,684 MW in 2036 (20.11% of the total energy). PV will be installed in Thailand for 6,000 MW (30.5% of the total

renewable energy sources) (Department of Renewable Energy Development and Energy Efficiency, 2015).

Nonetheless, one of the limitations of solar source was the fluctuation of the energy generation because solar arrays produce electricity depending on many factors, i.e. solar radiation, shading, temperature, etc. In case of many countries, the system with rooftop PV was connected with utility grid making electricity can be exchanged between household and utility grid. In Thailand, according to the rules of connection rooftop PV to utility grid between customers and Metropolitan Electricity Authority (MEA) or Provincial Electricity Authority (PEA), the household that equipped with

rooftop PV were forced to installed the protection relay (reverse power relay) to check the direction of electrical power. For this reason, they can receive the electricity from the grid only. They cannot feed the excessive electricity to the grid due to the stability issue of MEA or PEA systems. One of the solutions to solve this problem is installation of battery systems for electrical storage (Watson et al., 2016). Price reduction of battery systems was significant impact for installation in buildings (Posada et al., 2017). According to a fact sheet of energy storage market in Germany, the cost of battery system was reduced every year from 2011 to 2018, that was opposite from the trend of electricity tariff. For this reason, residential buildings installed with rooftop PV and battery systems are chosen to criticize and analyze about the influence of load profiles in this work.

The previous works studied on PV systems with energy storage in the parts of optimization in the energy storage systems (Lorenzi & Silva, 2016; Opiyo, 2016; Quoilin, Kavvadias, Mercier, Pappone, & Zucker, 2016; Shen, 2009), modelling the idealized load profiles (Beck, Kondziella, Huard, & Bruckner, 2016; Treado, 2015) and creating a simulation in software (Ogunjuyigbe, Ayodele, & Oladimeji, 2016). For examples; Quoilin et al. (2016) evaluated the level of self-consumption for buildings with rooftop PV and battery systems. They created a database of profiles from monitoring data and generated the household profiles. They reported that: (1) self-consumption is a non-linear function between rooftop PV and battery system size and (2) the situation of high penetration of rooftop PV may lead to unfair distribution of network charges and taxes which consumers do not have to pay.

In this work, residential buildings equipped with rooftop PV and battery systems in a grid-connected mode was studied. The physical experimentations at King Mongkut's University of Technology Thonburi (KMUTT), Bangkhuntien campus, was installed and investigated. Three different characteristics of residential sections were focused. The differences of this study from the previous works are: (1) other works focused on other groups of electricity users (e.g. Quoilin et al. (2016) investigated and criticized on the load profiles of medium general service); (2) other works studied and analyzed by the simulation data, not actual recording data from experimental site (Quoilin

et al., 2016; Treado, 2015; Ogunjuyigbe et al., 2016); and (3) the strategies related with time of use (TOU) rate were analyzed on residential section equipped with rooftop PV and battery systems in this work.

2. Methodology

2.1 The experimental site

A terrace of a building of Faculty of Media Art located at KMUTT, Bangkhuntien campus (13.5773° N, 100.4414° E), was used for creating the experimental site for the investigation. The terrace of this building was approximately 25 m in height from the ground floor. Figure 1 illustrates the area of terrace of building. It was equipped with 2.4-kW rooftop PV systems. The specification of PV arrays was Solartron rooftop PV panels (SP130E, 130-Watt) with a Leonics hybrid inverter (S-219C ia, 5,000-Watt). Figure 2 shows a diagram of the rooftop PV electrification system in the modelled building. This system was connected to the utility grid, that means this building can exchange electricity from the grid. The significance of the study in this building is the proportion of the electricity distributed to or received from the utility grid.

According to load profiles of the residential building provided by Thailand Provincial Electricity Authority (PEA), the peak of electrical power is approximately 1.7 kW, whereas rooftop PV can generate electrical power of about 1.5-2 kW due to the density of solar radiation. All remaining electricity cannot be sold to the utility grid due to the regulation of the utility authority. If this system is equipped with the battery storage system, it will back up electricity for uses in nighttime. According to TOU time table, customers must pay the monthly bill in two different rates: a peak time (09:00 a.m.-10:00 p.m. on Monday-Friday) and an off peak time (10:00 p.m.-09:00 a.m. on Monday-Friday and 24 hours on Saturday-Sunday) as shown in Table 1. In this work, the strategies to allocate the load profiles were created and related to the structure of electricity tariff in TOU rate. At daytime, rooftop PV can produce the electricity to charge the battery and feed to load for reducing the electricity proportion from grid. However, small office and home office may consume the electricity from grid due to more activities in daytime (peak rate). At nighttime

(07.00 p.m.-10.00 p.m.), battery systems were discharged by electrical load because this time was peak rate and the high consumption in household and home office.

Table 1. The electricity tariff in TOU rate.

Consumption/voltage	Energy charge (THB/kWh)		Service charge (THB/month)
	Peak	Off peak	
At voltage level lower than 22 kV	5.7982	2.6369	38.22



Figure 1. Terrace of the experimental building at KMUTT, Bangkhuntien campus.

A hybrid inverter (grid-connected type, 5 kW) and lead (Pb) acid deep-cycle batteries (125 Ah, 48 V) were equipped to the existing rooftop PV arrays (2.4 kW) on the terrace of building. All devices were connected to the utility grid and household loads. Three main characteristics of residential buildings, *i.e.* households, small offices, and home offices were studied by recording the data every minutes.

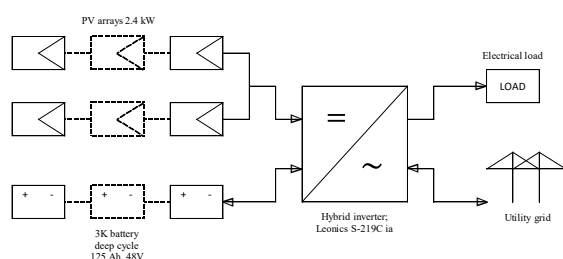
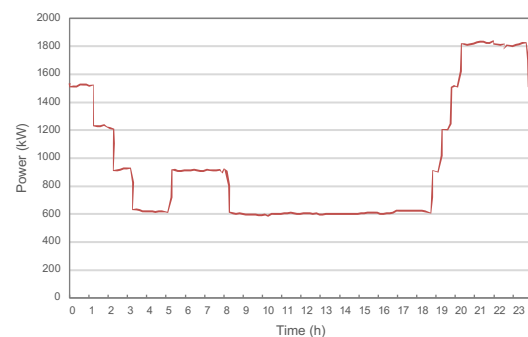


Figure 2. Schematic diagram for installations of experimental equipment.

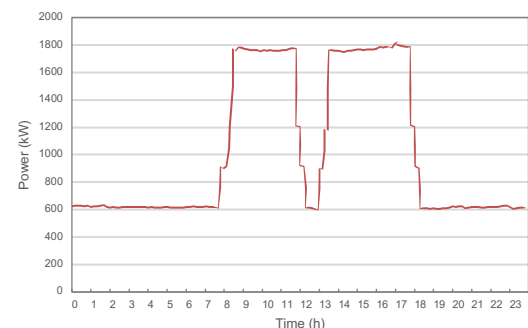
2.2 Differences of load profiles in residential buildings

Different sections of electricity uses have different characteristics, depending on the activities of electricity customers. The cases of residential

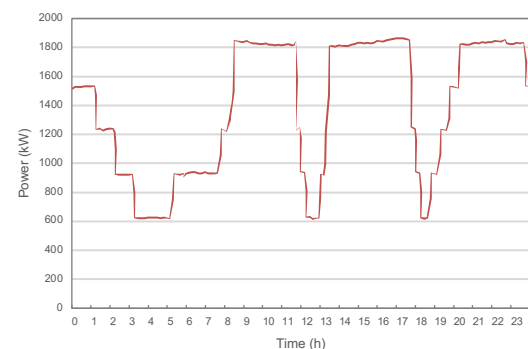
section of Thailand were used in this works. In this work, load profiles of the residential buildings were focused. Residential buildings mean households and other dwelling places, monasteries, houses of priest, and religion places of worship through a single watt-hour (Wh) meter. Figure 3 illustrates load profiles of residential buildings, including (1) households, (2) small offices, and (3) home offices. Households are the residential buildings that are used for stays only. Some residential buildings are used as small offices (for works only), while some buildings are used as home offices (for works and stays). The load profiles were produced based on the data of PEA, Thailand (Provincial Electricity Authority, 2015).



(a)



(b)



(c)

Figure 3. Load characteristics of residential buildings: (a) household, (b) small office, and (c) home office.

Load profile of household has high volume of electricity consumption in morning and evening (Figure 3(a)). Peaks of consumption rises around 20:00-23:00. According to Table 2, household load profiles has the proportion of night-time load (62.45%) more over than day-time load (37.55%). The characteristic of small office load profile looks like an actual office, i.e. high concentration of electricity consumption occurs in two periods, 08:00-12:00 and 13:00-17:00 (Figure 3(b)). In this group, the proportion of day-time load (74.90%) is higher than night-time load (25.10%) around 50%. Anyway, small offices have lower electricity consumption than the actual offices due to the ratio of quantity of electrical devices and people. Nonetheless, the characteristic of home office load profile is the combination between the load profiles of household and small office. There are two behaviors of electrical loads, (1) day-time loads from the activities that are same as the small office load profile and (2) night-time loads that are same as the household load profile (Figure 3(c)). Moreover, home office has the proportion of day-time load (64.87%) more than night-time load (35.13%) as shown in Table 2.

Table 2. The proportion of power consumption in three categories of residential buildings.

Parameter	Proportion (%)		
	Household	Small office	Home office
Day-time load	37.55	74.90	64.87
Night-time load	62.45	25.10	35.13

3. Results and Discussion

According to the recent situation of some countries, including Thailand, (1) the trend of installation of rooftop PV has increased rapidly and (2) rooftop PV with battery system was not allowed to equipped in grid connected mode for exchanging electricity with the authorities [PEA or Metropolitan Electricity Authority (MEA) in case of Thailand] due to the regulations of electrical utilities. This work was carried out to create a mini grid to investigate the influence of the installation of rooftop PV with battery systems.

Treado (2015) studied various models of PV equipped with or without battery storage system. The differences between the previous work and this work consist of: (1) day-time and night-time loads were created by constant values of load profiles for simulation in a software in the previous work,

while the physical experimentations of rooftop PV equipped with battery systems were carried out and the actual data from measurement was investigated in this work; and (2) the parameters in the previous report focused on times of electrical loads and various PV efficiencies, while the changes of load profiles were realized in this work, because the specific parameters affected to the characteristic of the load profiles.

In Figure 4, the behaviors of load profiles installed with rooftop PV and battery systems are illustrated in term of the electrical power flow.

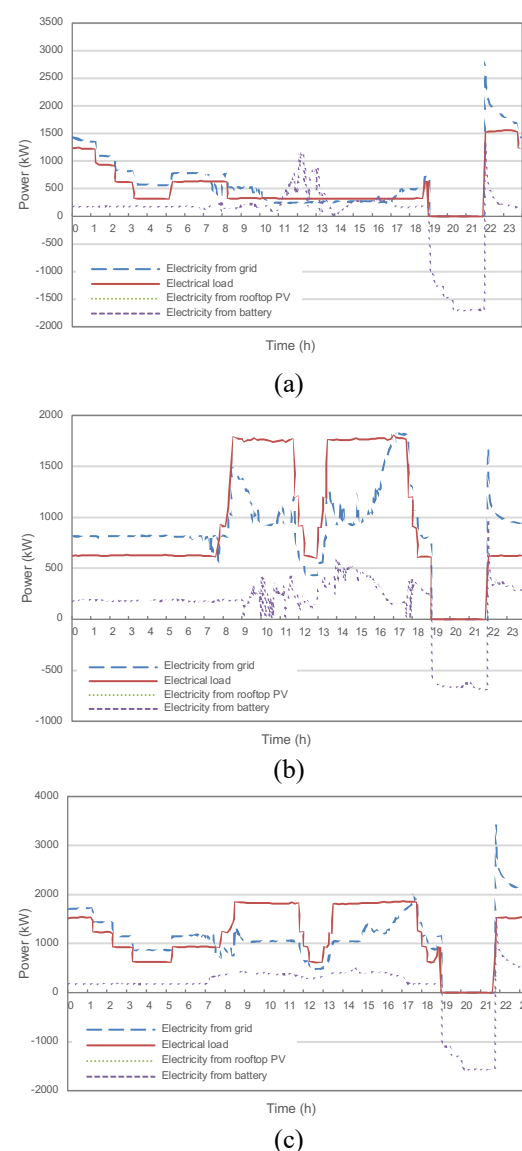


Figure 4. Electrical load profiles in residential buildings installed with rooftop PV and battery systems in (a) households, (b) small offices, and (c) home-offices.

Load profiles of three categories of residential buildings (—) were generated from the actual data based on PEA load profiles; i.e. household (Figure 4(a)), small office (Figure 4(b)), and home office (Figure 4(c)). The electricity generated from rooftop PV (.....) slightly increased due to solar radiation around 07:00 and met to load around 10:00. The excessive electricity was found in afternoon with the proportion of electrical consumption in each category. The fluctuation of the electricity generation of rooftop PV occurred around afternoon and directly affected the battery charging. The electrical power that consumed from the utility grid (—) slightly increased and varied by each type of residential buildings. Moreover, the surplus of electricity from the utility grid occurred due to the proportion of battery charging at night time. In day time, the battery charging (---) depended on the power generation from rooftop PV around 08:00-16:00 and the proportion of electricity from the utility grid decreased from night time. Besides, household has the highest proportion of battery charging compared with small office and home office, because of the number of day-time load. The excessive electricity had the inverse ratio with electricity charging to battery. The electricity from battery systems was discharged at 19:00-22:00. This proportion was fed to electrical load at 22:00 because of the reduction of the number of peak load to help the utility grid. Afterwards, the majority part of electricity to feed load came from the utility grid till morning time.

The power consumptions in three types of residential buildings are shown in Table 3. The excessive electricity in households was the highest proportion (21.68%) due to the ratio of day-time load. Furthermore, the ratio of PV generated to load (29.15%) was smaller than the ratio of battery charging (50.17%). Household utilized the battery systems with high efficiency because of the characteristic of load profiles in this category. In addition, the total electrical power can be calculated from Equation (1):

$$P_{Load}(t) = P_{PV}(t) + P_{Battery}(t) + P_{Grid}(t) \quad (1).$$

Table 3. The proportion of power consumptions in three types of residential buildings.

Parameter	Proportion (%)		
	Household	Small office	Home office
PV to load	29.15	57.83	51.09
PV to battery	50.17	31.78	29.23
Excessive electricity	20.68	10.39	19.68

In small office, the excessive electricity in this category was the lowest proportion (10.39%) because of a lot of day-time load. On the other hand, the ratio of PV generated to load (57.83%) was more proportion than the battery charging (31.78%). In this sense, the battery system in small office was less significant compared with household and home office.

According to TOU rate, the net savings with this strategy can be calculated by System Advisor Model (SAM). Net savings with strategy are the differences between costs without strategy (using battery for emergency only) and with strategy. Household and home office gain more net savings than small office as shown in Table 4 because the proportions of electrical consumption in two sections are higher than small office at 07:00 p.m.-10.00 p.m. that matched with the battery discharge to reduce the load profiles in each section.

Table 4. Net saving with strategy.

Sections	H	SO	HO
Net savings with strategy (THB)	4,938	4,211	4,986

*H is household, SO is small office, and HO is home office.

4. Conclusion

One of the solution to solve power fluctuation in PV rooftop system is the installation of a battery system. This solution will stabilize the energy and quality of the electrical power. This work aims to allocate the highest efficiency of energy consumption. The characteristics of load profiles of the residential buildings (i.e. household, small office, and home office) equipped with rooftop PV with battery systems are focused. Household showed the highest proportion of surplus electricity (20.68%) and the largest battery charging from PV (50.17%) due to the number of day-time load. In this sense, battery systems in household are significant more than that in small office and home office. The day-time load in the small office (74.90%) and the home office (64.87%) is more than household (37.55%), so

the proportion of PV feeding to load is higher than household. Moreover, net savings with strategy in household and home office show the interesting point of this strategy. In the future, the technologies of battery systems will be researched and developed. An installation of battery systems on buildings equipped rooftop PV will be more interesting, because of stability and sustainability of the systems.

5. Acknowledgement

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