CUEE Final-Year Project Proposal (2102490)

Energy Management System for Gewertz Square

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1 Introduction

1.1 Motivation

The Department of Electrical Engineering, Chulalongkorn University, serving as a prominent hub for research and technological development in Thailand, is embarking on initiative to renovate its internal infrastructure, specifically known as Gewertz Square. Over the course of the next five years, the dedicated research team, in collaboration with the Center of Excellence in Electrical Power Technology (CEPT), is tasked with overseeing this crucial undertaking for primary objective which is to develop a prototype of net-zero energy building or further an islanding building that can autonomously operate without relying on the conventional electrical grid for its energy needs.

In line with the broader vision of promoting the sustainable development goal particularly in the aspect of sustainable cities and communities, the implementation of an Energy Management System (EMS) emerges as an indispensable element. The EMS is endowed with the intelligence and flexibility required to execute energy policies that encompass various aspects including monitoring, planning, optimizing, scheduling, and demand-side management. These capabilities are essential to meet the multifaceted demands of energy consumption that correspond to a diverse set of technical objectives, economic objectives, and environmental objectives, all simultaneously [HEBLE21].

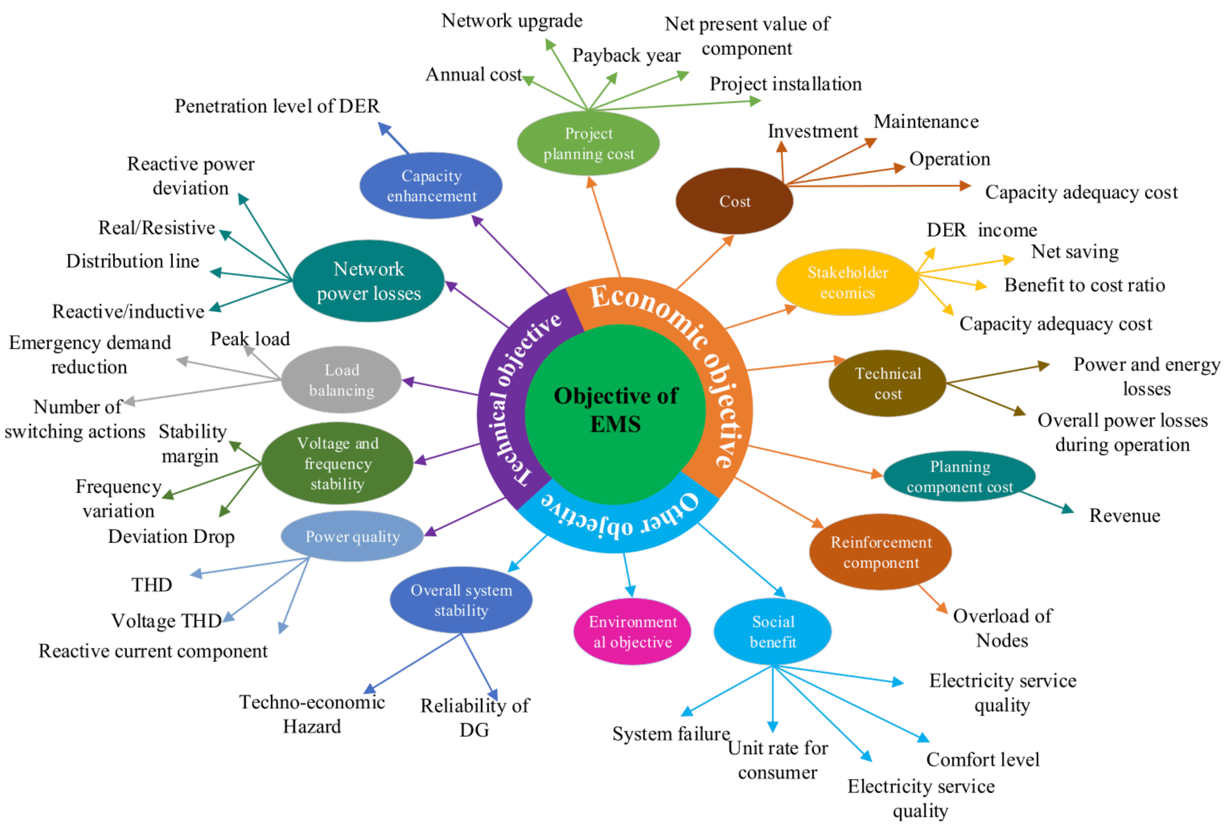


Figure 1: Hussuan et.al 2021, Multi-level EMS towards a smarter grid: a review.

In the scope of Gewertz Square, the primary focus is on the Building Energy Management System (BEMS). The typical objective of BEMS, especially when the system is connected to the utility network, is to maximize profit or minimize the cost of electricity, combining with other objectives such as the comfort level of users or peak load shaving. The investigation mainly focused on simulate the scheduling operation of the electrical components in the system. However, the scheduling operation must incorporate with the appliances, by considering value of lost load (VOLL) of the appliances as the indicator together with electricity tariff for different time interval for the objective function which is to minimize electricity cost [RFFZ16]. The focus of demand response control in various residential sizes and thermostat types centered on the characteristic of load consumption primarily from HVAC systems which also complies with ASHRAE standards illustrating the thermal comfort zone through a psychrometric chart was discussed in [YBN14]. To enhance power utility efficiency, particularly in reducing peak load power consumption, decreasing power exchanges, and addressing power imbalances, energy storage systems were also introduced within Campus of University of Calabria [MPS+18]. By integration of solar generation together with energy storage system, the objective function relating to energy price and load elasticity were also investigated for several scenarios [GS21]. In the concept of grid-independent system, the islanding microgrid operation was examined for the complicated undertaking by considering the economic and environmental perspectives [RABAC+21].

In exploring an EMS, a key factor lies in the development of mathematical formulations of the relationships among electrical components within a given system for different objective functions which can be then solved by optimization solvers. The mixed-integer linear programming (MILP) problem was modeled for an inverter-based air conditioning system together with the present of solar and battery integration for the objective of minimizing electricity cost [NRG21]. The mixed-integer quadratic programming model predictive control (MIQP-MPC) problem was also formulated for the multiobjective function which is to minimize the total electricity cost simultaneously with maximizing the use of renewable energy for a smart home [KZK18]. Additionally, MIQP was also proposed to compensate the leverage between the utility requirements and profits of selling electricity [DIT+20]. The integrated components of the proposed problem are photovoltaic cells with smart inverter, battery, electric vehicles, air conditioners, electric water heater, and grid electricity with the objective which is to minimize the cost of electricity while also smoothening buy and sell pattern using soft penalty, incorporating with reducing the trading electricity cost with the grid by penalize term power of home to grid and grid to home. The evaluation metric in this proposed problem is the ratio between peak load and mean load, another metric is the difference between the power at previous time index and the current time index, which both expected values should be small.

This investigation reveals that Gewertz Square has the potential to serve as a pioneering example of a net-zero energy building, primarily due to the effective implementation of EMS. Consequently, the primary objective of this senior project is to develop comprehensive mathematical formulations of the EMS that accommodate diverse economic and operational objectives which are four different EMS.

- EMS 1: minimize electricity cost for uncontrollable historical load consumption.
- EMS 2: maximize electricity profit for uncontrollable historical load consumption.
- EMS 3: minimize electricity cost for controllable load at machine laboratory room and student room.
- EMS 4: enabling islanding mode for controllable load at machine laboratory room and student room.

The formulations will be achieved by modeling the problem as a MILP. Subsequently, the project will simulate the solutions for various scenarios and proceed to implement these optimal solutions within OpenEMS platform, thereby establishing effective energy scheduling policies as the device simulation.

1.2 Objectives

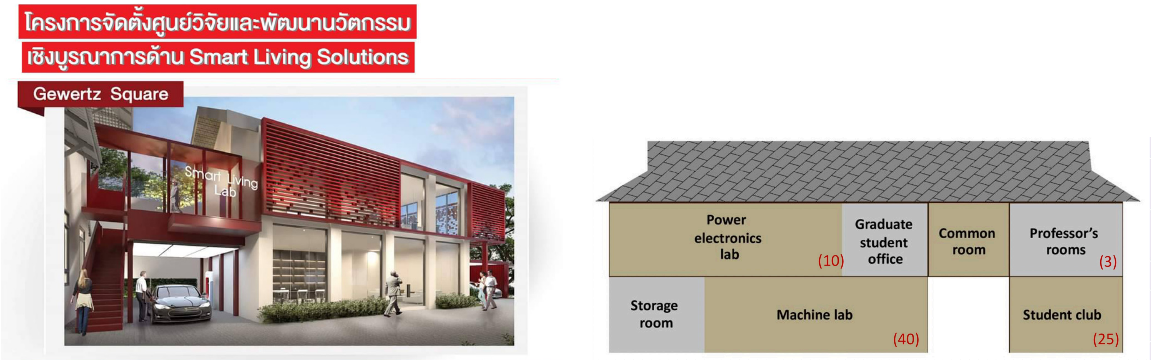
1. To study about how the EMS affects the energy policies of the desired electrical components in the system from the simulation result of each economic and operation objective.
2. To implement the optimization solution according to different EMS objectives into OpenEMS platform.

1.3 Scope

1. Implementation of the algorithm is only within the scope of Gewertz building consisting of 2 buildings (machine laboratory room & student room) as shown in Figure 2.

2. The scope of this project is to construct the mathematical formulation in the concept of an offline EMS with different economic purpose by MATLAB and Python, then implement the algorithm in OpenEMS platform.

3. The electrical components used in EMS formulation at Gewertz building includes load consumption data, solar generation data, and a battery.



(a) www.intaniamagazine.com, Gewertz Square.

(b) Gewertz Square layout.

Figure 2: Gewertz Square overview.

1.4 Expected Results

1. Mathematical formulations and simulation results of EMS optimization problem based on different economic and operation objectives.

2. The simulation energy paradigm from optimization solution to the simulated device for each economical purpose exists in OpenEMS platform.

2 Background

This section explains the fundamental knowledge about Energy Management System (EMS), optimization problem and optimization solver, mathematical formulation of models, and OpenEMS platform.

2.1 Energy Management System (EMS)

Energy Management System (EMS) is a computational and simulation-based system designed to efficiently investigate, manage, and optimize energy on a specific platform using computer technology under different purpose such as reduce the energy utility, electricity cost, and environmental effect. The EMS can be categorized into various aspects, including decision-making approaches, operational levels, operating time, and supervisory control, depending on the perspective. In this project, the primary focus of the EMS is an offline operating time, and the Building Energy Management System (BEMS) at the operational level as shown in Figure 3.

Concerning offline operating time, it implies the utilization of historical data. The distinctive feature is particularly suitable for planning, incorporating an acknowledgement of various factors such as forecasted load consumption, forecasted solar generation, and electricity tariffs to operate virtual real-time operational decision-making. Nevertheless, due to the inherent fluctuation of these variables, the initial planning may not be sufficiently precise, necessitating the transition to real-time operations to make decisions based on current conditions. The BEMS is specifically engineered to facilitate investigation, management, and enhancement of power consumption efficiency for building owners and operators. Its primary objective is the reduction of energy consumption, associated expense, and environmental impact, all while preserving the occupants' comfort or maintaining typical operational activities within

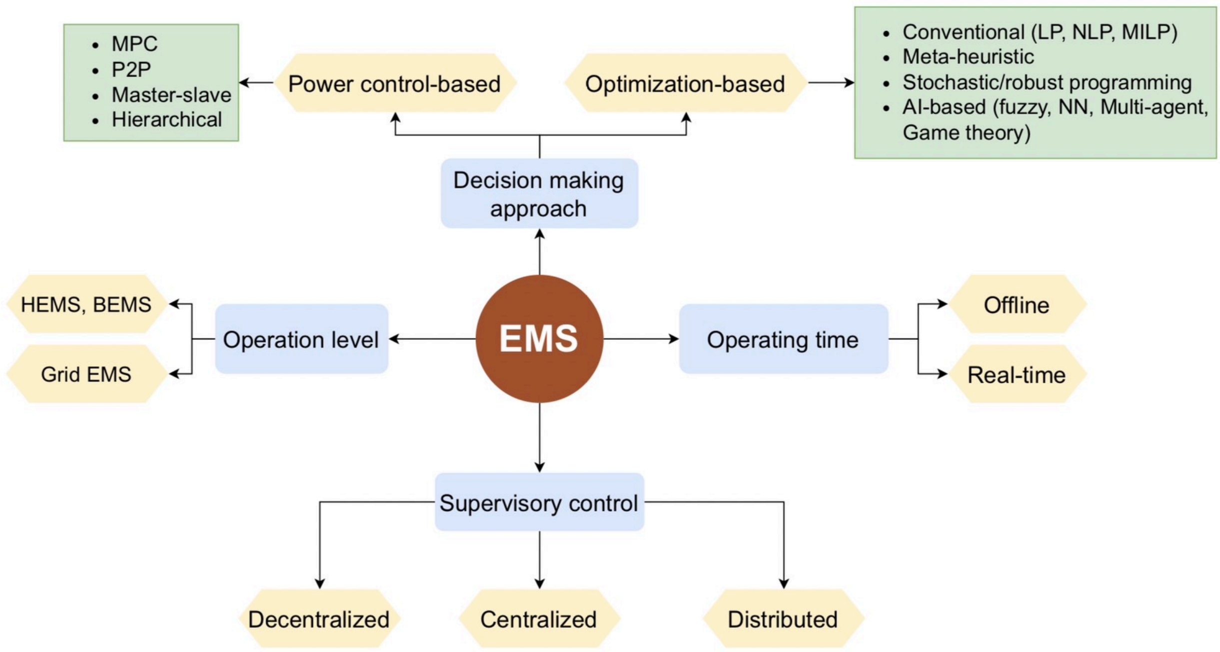


Figure 3: www.cept.eng.chula.ac.th/th/news/2023/7681/, Communication Technologies for Grid Edge, EMS problem under different perspective.

the building. The BEMS encompasses both software and hardware components, prominently featuring sensors and controllers. These integrated components function collaboratively to collect, assess, and monitor load consumption quality and profile within the building. The acquired data is then utilized to facilitate real-time adjustments to the system for optimal performance and energy efficiency.

The BEMS functions as a decentralized EMS, gathering the information from both the supply and demand sides via advanced metering systems and ICT infrastructure. It conducts comprehensive analyses to identify unnecessary electricity consumption or instances of excessive usage. Subsequently, it provides recommendations for optimizing energy utilization, highlighting opportunities for more efficient energy usage by operating computation for planing and scheduling energy policies to the devices to function in alignment with these policies to achieve the desired objectives of the operating system.

In order to enable the function of the BEMS for the system by monitoring and formulation of energy policies, the BEMS is required to effectively manage the equity of energy and power across both supply side and demand side. For energy balance, it refers to the equity of total generation of the supply must equal to total consumption of the demand over the specific time interval: day, week, month, year to achieve sufficiency and sustainability. Likewise, for power balance, it also refers that total generating power must equal to total demand power for energy sub-minute interval for stability, security, and economics and environment, which can be reflected as primary, secondary, and tertiary response respectively.

In this project the supply side is mainly from both grid power generation and solar generation. It is the necessity that this supply must satisfy the demands of systems' load consumption. The load consumption is mainly from historical based load and modeled AC systems. In order to achieve the equity of both the supply side and the demand side, the battery must be involved to manage this efficiently under the condition for economic and operational purpose such as minimizing cost of electricity. The specific feature of the EMS is the capability to monitor the energy and to control the devices in the system, leading to the mathematical formulation of the relation among the devices which is an optimization problem.

2.2 Optimization problem and optimization solver

Optimization is one of the mathematic problems of which the purpose is to determine an optimal solution of an objective function or a cost function. There are 3 elements of the optimization problem which are optimization variable, an objective function or a cost function, and constraints.

In this context, the optimization is essential for the EMS. Its primary aim is to address the inquiry of how electric devices in the system should function in order to achieve predetermined objectives while satisfying specific constraints imposed by the principles of power equality, the inherent physics governing each device, and operational limitations.

2.2.1 Mixed-Integer Linear Programming (MILP)

To initiate solving the optimization problem, it is essential to determine the type of mathematical formulation. In this project, the formulations were constructed as a Mixed-Integer Linear Programming (MILP) problem.

The MILP is an optimization problem which both objective function and constraints are linear, but restrictions on the optimization variable that has some components which are integer values. In the following, the linear objective function can be written as $c^T x$ and the optimization variable x has the component at $j+1$ to n be the integer values.

Therefore, the MILP is defined by

$$\begin{array}{ll} \text{minimize} & c^T x \\ \text{subject to} & Ax \le b \\ & Gx = h \end{array} \tag{1}$$

- $x = (x_1, x_2, \dots, x_n) \in \mathbf{R}^n$ is the optimization variable where $(x_1, x_2, \dots, x_j) \in \mathbf{R}^j$ and $(x_{j+1}, x_{j+2}, \dots, x_n) \in \mathbf{Z}^{n-j}$
- $A \in \mathbf{R}^{mxn}$ and $b \in \mathbf{R}^m$
- $G \in \mathbf{R}^{pxn}$ and $h \in \mathbf{R}^p$

In this work, we often encounter an objective function that relates to electricity expense and revenue. This quantity is typically a function of total net power which can be negative or positive (10). Hence, mathematically, we can model as,

$$c \cdot \max(0, a^T x + b), \quad \text{where } a, x \in \mathbf{R}^n \text{ and } b, c \in \mathbf{R}.$$

which is a nonlinear function. However, the epigraph form technique can be applied by introduce a new optimization variable t. Then, solve the equivalent linear programming instead, yields

$$\underset{x}{\text{minimize}} \quad c \cdot \max(0, a^T x + b) \iff \underset{x,t}{\text{minimize}} \quad t$$
$$\text{subject to } c \cdot (a^T x + b) \le t \quad \text{and} \quad 0 \le t,$$

which can be cast a linear objective function with linear constraints, and hence this is linear programming.

The important constraint for the EMS is the power equity constraint (11) which is linear in variables $P_{\text{net}}(t)$, $P_{\text{chg}}(t)$, $P_{\text{dchg}}(t)$, and $P_{\text{cload}}(t)$.
Additionally, the constraints of the system are the constraints related to the electric components which are air conditioning system, solar generation, and battery.
The constraints of airconditioning system are

- The constraint of AC power consumption (2) which is linear in variables $P_{\text{ac}}(t)$, $x_{\text{ac}}^{(1)}(t)$, $x_{\text{ac}}^{(2)}(t)$, $x_{\text{ac}}^{(3)}(t)$, and $x_{\text{ac}}^{(4)}(t)$.
- The constraint of AC operation (3) which is linear in variables $x_{\text{ac}}^{(1)}(t)$, $x_{\text{ac}}^{(2)}(t)$, $x_{\text{ac}}^{(3)}(t)$, and $x_{\text{ac}}^{(4)}(t)$.

The constraint of solar generation is

- The constraint of solar generation (4) which is linear in variable $P_{\text{pv}}(t)$.

The constraints of battery are

- The dynamic equation constraint of battery (5) which is linear in variables $\text{SoC}(t+1)$, $\text{SoC}(t)$, $P_{\text{chg}}(t)$, and $P_{\text{dchg}}(t)$.
- The limitation of charge and discharge constraints (6) and (7), which are linear in variables $P_{\text{chg}}(t)$, $P_{\text{dchg}}(t)$, $x_{\text{chg}}(t)$, and $x_{\text{dchg}}(t)$.
- The non-simultaneous charge and discharge constraint (8), which is linear in variables $x_{\text{chg}}(t)$ and $x_{\text{dchg}}(t)$.
- The limitation of maximum state of charge and minimum state of charge constraint which is linear in variable $\text{SoC}(t)$.

Since, all the constraints above are linear constraints with the binary value variables, $x_{\text{chg}}(t)$, $x_{\text{dchg}}(t)$, and $x_{\text{ac}}(t)$, which are integer. Hence, the formulated mathematical optimization in this project is MILP problem.

The 'intlinprog' is the MATLAB function we used to find the MILP solution in this proposal. According to the MATLAB documentation, the 'intlinprog' algorithm has six stages. First, the size of the problem is reduced by removing redundant constraints and variables. Next, the relaxation version of the original problem is solved as a linear programming problem. The constraints of the problem are then tightened or removed. In the following step, cut generation is applied by adding linear inequality constraints to narrow the feasible region of the LP relaxation problem. Various heuristic techniques are used to obtain the upper bound of the objective function. Finally, the Branch and Bound algorithm is used to find the optimal solution.

2.3 Mathematical formulation of models in the system

As outlined in the scope of work, the electrical components within Gewertz building includes the load consumption data, the solar generation data, and the battery. To initiate constructing the mathematical formulation, the distinctive characteristics of these electrical components in the system must be elaborated.

2.3.1 Mathematical model of air conditioning system

The majority of the load consumption data is caused by air conditioning (AC) system. There were 4 rooms that were investigated its operational AC systems at EE building which are EE 401, EE 404, EE 409, and EE 410. The investigation reveals that there is only 1 room that use inverter-based AC which is EE 401, others use non-inverter-based AC system. Based on the investigation findings, the inverter-based AC system demonstrates dynamic transient power consumption levels upon initial activation, stabilizing to its steady-state power consumption after an approximate duration of 20 minutes. However, in this project, the AC model was constructed based on only the steady-state power consumption of the inverter-based AC system at the EE 401 room which can use power for four levels of its rated power $P_{\text{ac,rated}}$ at 50, 70, 80, and 100 percent.

Let $x_{\text{ac}}^{(i)}(t)$ be the state of using the AC where a 0 indicates the state of turning off and an 1 indicates the state of turning on. The superscript (i) indicates the level of power consumption from its rated power which has 4 levels as stated above. Hence, the constraint of AC power consumption is as the following.

$$P_{\text{ac}}(t) = \left(x_{\text{ac}}^{(1)}(t) + 0.5x_{\text{ac}}^{(2)}(t) + 0.7x_{\text{ac}}^{(3)}(t) + 0.8x_{\text{ac}}^{(4)}(t)\right) P_{\text{ac,rated}} \tag{2}$$

In addition, the AC can either be turned off or set to one of the four specified levels as stated earlier. Therefore, the constraint of AC operation is as the following.

$$0 \le \sum_{i=1}^{4} x_{\text{ac}}^{(i)}(t) \le 1, \quad \text{where } x_{\text{ac}}^{(i)}(t) \in \{0,1\}, \quad \text{for } i = 1,2,3,4 \tag{3}$$

2.3.2 Mathematical model of solar generation

The solar generation in this proposal is simulated using historical data, as discussed in section 4.2. The power generated by the solar panel must be less than its MPPT (Maximum Power Point Tracking), of which the dynamic is a function of irradiance. But in this proposal, it is used based on historical solar generation data.

$$P_{\text{pv}}^{\text{max}}(t) = \text{COEFFICIENT} \cdot I(t) \le \text{INSTALLED CAPACITY}, \quad P_{\text{pv}}(t) \le P_{\text{pv}}^{\text{max}}(t) \tag{4}$$

2.3.3 Mathematical model of battery

In order to emphasize the demand for load consumption to be aligned with the solar generation, an Energy Storage System (ESS) becomes instrumental in facilitating ongoing operations with reduced reliance on grid electricity. Its primary function involves storing excess energy and subsequently releasing it when there is an insufficient supply, allowing for more efficient management of energy flow.

The battery behaves as the energy storage in this project. There are some definition of the variables that need to be explained. State of Charge (SoC) represents the current battery capacity as a percentage of maximum capacity. When the battery is being charged or discharged, it is charged or discharged as the power which $P_{\text{chg}}(t)$ indicates the charging power into the battery and $P_{\text{chg}}(t)$ indicates the discharging power out from the battery with charging efficiency η_c and discharging efficiency η_d. The battery is modeled to behave relatively similar to its physical counterpart using dynamic equations for the energy stored in the current time index and the percentage of charge or discharge. Hence, the dynamic equation constraint is described by its state of charge, governed by a first-order state equation as shown below.

$$\text{SoC}(t+1) = \text{SoC}(t) + \frac{100}{\text{BattCapacity}} \left(\eta_c P_{\text{chg}}(t)\Delta t - \frac{P_{\text{dchg}}(t)\Delta t}{\eta_d} \right) \tag{5}$$

where BattCapacity is total battery capacity and Δt is time resolution.

In addition, the charge and discharge rate must less than its maximum charging rate and maximum discharging rate respectively. Let $x_{\text{chg}}(t)$ and $x_{\text{dchg}}(t)$ be variables indicating the status of charging and discharging the battery respectively, where 0 indicates the status that is not operating and an 1 indicates the status that is operating. Hence, the constraints limitation of charging and discharging the battery can be shown as below.

$$P_{\text{chg}}(t) \le x_{\text{chg}}(t) \cdot \text{MAX CHARGE RATE} \tag{6}$$
$$P_{\text{dchg}}(t) \le x_{\text{dchg}}(t) \cdot \text{MAX DISCHARGE RATE} \tag{7}$$

Moreover, the battery cannot be charged and discharged simultaneously. Therefore, for any time index, only one of $x_{\text{chg}}(t)$ and $x_{\text{dchg}}(t)$ is 1. The non-simultaneous charge and discharge constraint is shown below.

$$0 \le x_{\text{chg}}(t) + x_{\text{dchg}}(t) \le 1 \quad \text{where } x_{\text{chg}}(t) \in \{0,1\} \text{ and } x_{\text{dchg}}(t) \in \{0,1\} \tag{8}$$

Due to the fact that the physical battery may degrade when it is fully charged or runs out of energy, so the constraint limitation of maximum charge and minimum charge is added to enforce that the energy stored should be within this interval.

$$\text{SoC}_{\text{min}} \le \text{SoC}(t) \le \text{SoC}_{\text{max}} \tag{9}$$

where SoC_{min} and SoC_{max} are minimum and maximum state of charge of the battery respectively. In this project, the SoC_{min} and SoC_{max} were given to be 40% and 70% respectively.

2.4 Open Energy Management System (OpenEMS)

Open Energy Management System (OpenEMS) is an open-source platform designed for managing energy in diverse applications. This platform serves as a robust simulation platform for energy management built by Java.

There are 3 main pillars in OpenEMS for IoT stack as can be seen in Figure 4. OpenEMS Edge is used to simulate the electric devices for individual site enabling monitor, control, and communicate with the backend. The user-friendly OpenEMS UI provides a web-based interface for local device configuration, allowing users to adjust the characteristics of the devices in details. Meanwhile, OpenEMS backend is the centralized server on clouds which can run the decentralized edge units, ensuring comprehensive oversight and management of the entire edge system. The role of the OpenEMS edge is to collect information from each device and send it to the OpenEMS backend. The information from the OpenEMS backend is then passed to the forecast module to predict solar generation and load consumption. After this, the forecasted information for load consumption and solar generation, including the state of devices, is sent to the EMS optimization module. Next, the optimal schedule for each device is passed through the OpenEMS backend to the OpenEMS edge. Finally, the OpenEMS edge converts the optimal schedule into a control signal, which is then sent to each device. The block diagram of the OpenEMS system is shown in Figure 5.

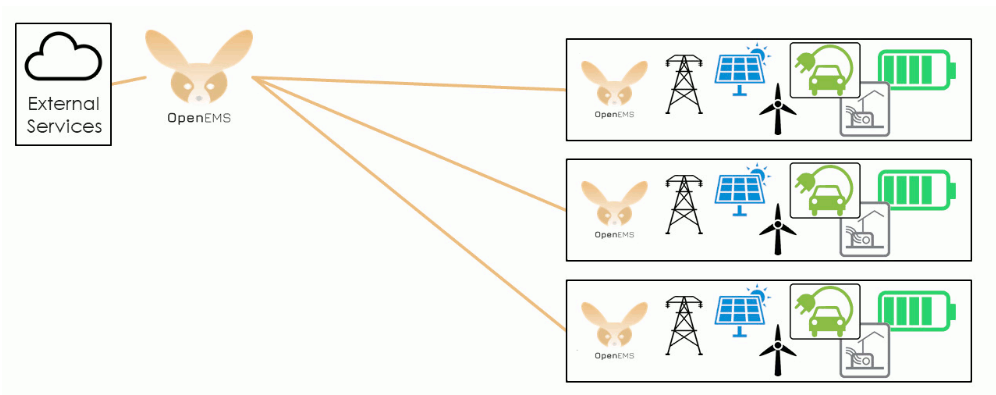


Figure 4: www.openems.github.io, OpenEMS structure.

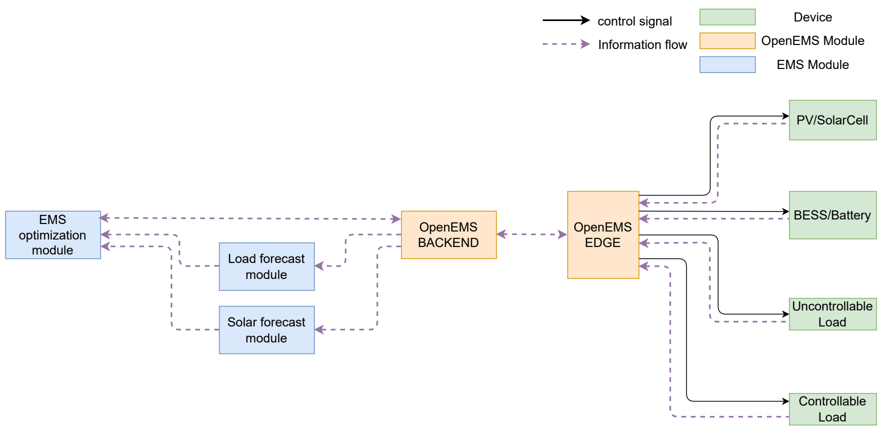


Figure 5: OpenEMS overview.

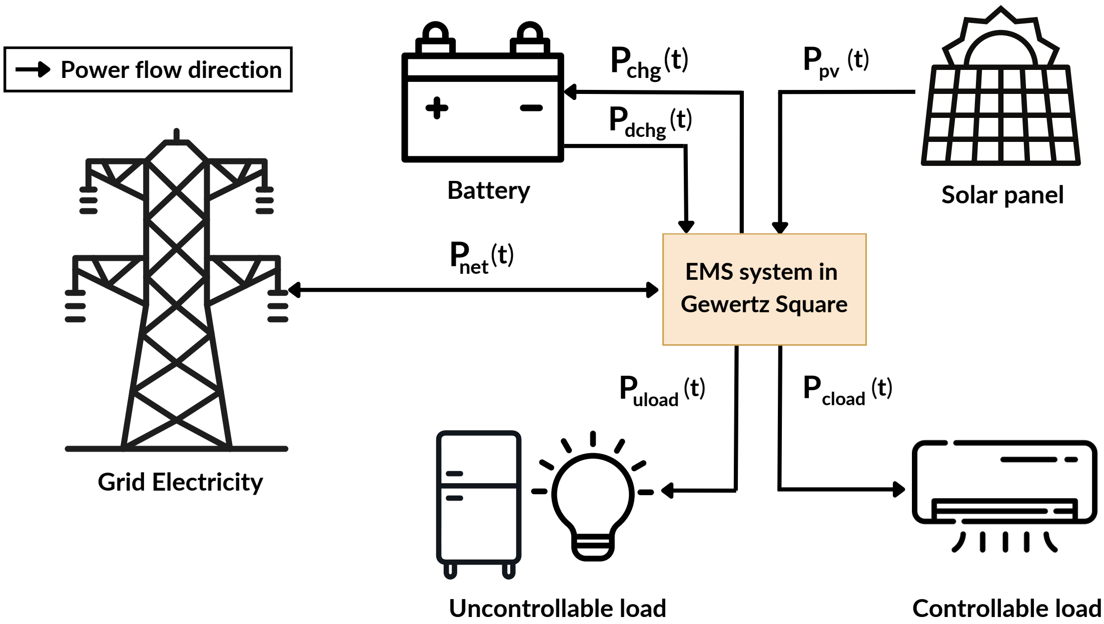


Figure 6: Overall system of EMS.

3 Methodology

The components of the Gewertz building consist of (i) controllable load, (ii) uncontrollable load, (iii) a solar panel, (iv) a battery, and (v) the grid. The load consumption of Gewertz building can be separated into uncontrollable load and controllable load. The uncontrollable load represented loads that cannot be shifted or interrupted in their schedule, such as lights or refrigerators, while the controllable load in the proposal included the air conditioner systems in the machine laboratory room and student room, as discussed in section 2.3.1. The solar panel is the main power source for Gewertz building's load consumption during daytime, the constraint of solar panel was considered when it was treated as a variable as discussed in section 2.3.2. The battery power can be on either the generation or consumption side depending on the mode, which can be either charging or discharging. The battery model was further explained in section 2.3.3. The last important component is the grid, which is used to buy electricity when the generated power is not adequate and sell electricity when there is excess power generation. The power flow of each component can be shown in Figure 6.

In this project, the methodology consists of 2 sections which are optimization simulation and deployment by testing in OpenEMS platform as shown in Figure 7 and Figure 8 respectively.

The optimization simulation procedure of this project commences with obtaining historical load consumption and solar generation data from CUBEMS and Prof. Surapong's meters. Subsequent preprocessing and archival steps are followed by user inputs, including battery specifications, and electricity tariffs, which are added for an EMS simulation. Next, the schedule for each device is obtained by solving optimization problem. The simulation results are then interpreted, assessing the chosen EMS formulation's feasibility and readiness for implementation in OpenEMS platform, culminating in a conclusive analysis of its mathematical completeness and effectiveness in covering usage scenarios.

After obtaining the complete optimization solutions for different mathematical formulations of optimization problems under different economic and operational objectives, the next step is the testing OpenEMS procedure. First, the load consumption data, solar generation data, and dynamical model of the battery must be prepared by the simulation before deployment in OpenEMS platform as the offline simulation. The load forecasted simulation data and the solar forecasted data are obtained from the existing machine learning model, while the dynamical model of the battery can be obtained from the simulation by Simscape. Hence, the input for implementation in OpenEMS platform are the set of energy policies from the optimization solutions, the load and solar forecasted data, and the battery

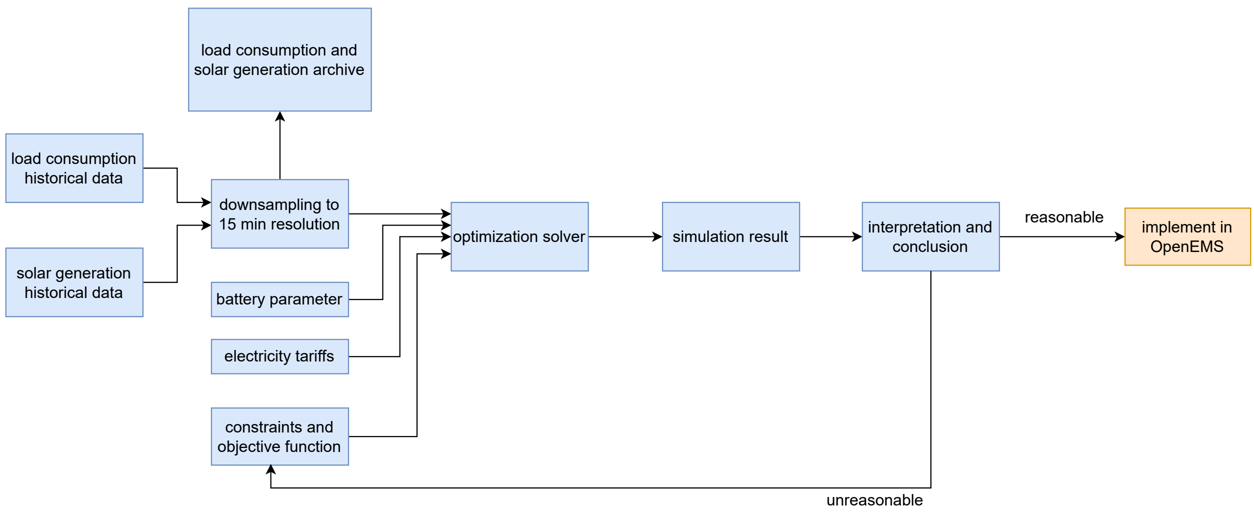


Figure 7: The optimization simulation procedure.

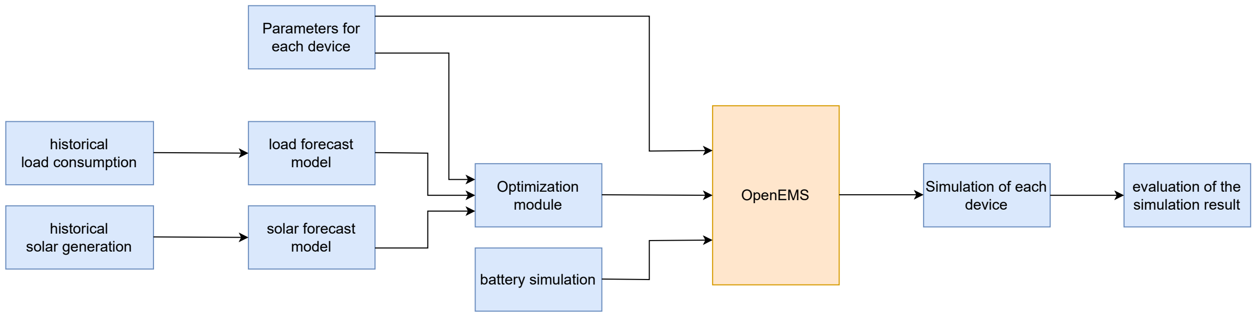


Figure 8: The optimization simulation procedure.

simulation. The result of running OpenEMS as the offline operation is the simulation result of how electrical components in the system function. Finally, analyze and investigate the correctness of the simulation results.

In this project, the mathematical formulations for different economic and operational objectives were proposed. The list of variables and parameters used in an EMS are shown in Table 1 and Table 2. Also, the values of the parameters used in each EMS are shown in Table 3.

Table 1: Variables in the system.

Variable	Description	unit
t	Time index	no unit
T	Maximum time index	no unit
Δt	Time resolution	hour
$P_{\text{net}}(t)$	Generation power - Consumption power	kW
$P_{\text{pv,hist}}(t)$	Historical solar generation power	kW
$P_{\text{pv}}(t)$	Solar generation power	kW
$P_{\text{chg}}(t)$	Power charged to the battery	kW
$P_{\text{dchg}}(t)$	Power discharged from the battery	kW
$P_{\text{uload}}(t)$	Power of uncontrollable load	kW
$P_{\text{cload}}(t)$	Power of controllable load	kW
$P_{\text{ac,m}}(t)$	Power of AC in machine laboratory room	kW
$P_{\text{ac,s}}(t)$	Power of AC in student room	kW
$\text{SoC}(t)$	State of charge of battery	%
$x^{(i)}_{\text{ac,m}}(t)$	AC status at level i of machine laboratory room	no unit
$x^{(i)}_{\text{ac,s}}(t)$	AC status at level i of student room	no unit
$x_{\text{chg}}(t)$	Battery charging status	no unit
$x_{\text{dchg}}(t)$	Battery discharging status	no unit

Table 2: Parameters in the system.

Parameter	Description	unit
$P_{\text{ac,m,rated}}$	Rated power of AC in machine laboratory room	kW
$P_{\text{ac,s,rated}}$	Rated power of AC in student room	kW
SoC_{min}	Minimum state of charge of battery	%
SoC_{max}	Maximum state of charge of battery	%
η_c	Battery charging efficiency	no unit
η_d	Battery discharging efficiency	no unit
$b(t)$	Electricity buy rate	THB/kWh
$s(t)$	Electricity sell rate	THB/kWh
w_m	Weight of AC status of machine laboratory room	no unit
w_s	Weight of AC status of student room	no unit
w_b	Weight of encouragement to charge battery	no unit

Table 3: Parameter values in each EMS simulation.

Parameter	EMS 1	EMS 2	EMS 3	EMS 4	unit
BattCapacity	150	150	150	150	kWh
SoC(0)	50	50	50	50	%
MAX CHARGE RATE	45	45	45	45	kW
MAX DISCHARGE RATE	75	75	75	75	kW
PV install capacity	48	48	16	16	kW
P_{uload}	-	-	< 0.3	< 0.3	kW
$P_{\text{ac,m,rated}}$	-	-	11.13	11.13	kW
$P_{\text{ac,s,rated}}$	-	-	6.62	6.62	kW
w_m	-	-	2	2	THB
w_s	-	-	1	1	THB
w_b	-	-	0.1	0.1	THB/%

3.1 Mathematical formulation of EMS

In this project, a set of four distinct EMS formulations were proposed, each formulation was constructed to address various economic and operational objectives associated with the electrical components within the system over discrete time index in the horizon t = 1, 2, ..., T with time resolution 15 minutes. Concerning the historical data used in the formulations, it implies an offline operating system which particularly suitable for planning and scheduling. In the following formulation, the historical data included load consumption data, solar generation data, and the other parameters such as battery parameters and the power rated of the load consumption due to air conditioning system.

In the system operation the power of all electrical devices in the system must satisfy the power equity which is the generation power must equal to the consumption power. Because of this, the variable $P_{\text{net}}(t)$ was defined in order to calculate how much the electricity needs from the grid, calculating from

$$P_{\text{net}}(t) = \text{total generation power} - \text{total consumption power}. \tag{10}$$

The total generation power includes solar generation power and power discharged from the battery and the total consumption power includes the power used to charge the battery and load consumption which can be further categorized into controllable and uncontrollable loads, as used in EMS 3 and EMS 4. Consider the sign of $P_{\text{net}}(t)$, if

- $P_{\text{net}}(t) \geq 0$, there is excess generation, no require power from the grid, and if
- $P_{\text{net}}(t) \leq 0$, there is insufficient power to satisfy the demand side, meaning that the power from the grid is required.

Hence, the power equity can be shown as below

$$P_{\text{net}}(t) = P_{\text{pv}}(t) + P_{\text{dchg}}(t) - P_{\text{uload}}(t) - P_{\text{cload}}(t) - P_{\text{chg}}(t). \tag{11}$$

There are several constraints relating to the electrical components in the system. In the proposed mathematical formulation of EMS 1 and EMS 2, the load consumption data is historical, meaning that it is parameter in the optimization problem. But in the mathematical formulation EMS 3 and EMS 4 the load becomes controllable mainly from air conditioning system, hence the constraints are AC power consumption (2) and AC operation (3). The battery involves in every scenario so the constraints are dynamic equation of the state of charge of the battery (5), limitation of charging and discharging (6) and (7), non-simultaneous charge and discharge (8) and limitation of maximum charge and minimum charge (9). The solar generation data is parameter in the EMS 1, EMS 2, and EMS 3 formulation. But in EMS 4 the the solar generation data becomes the variable which has the constraint (4).

3.1.1 EMS 1: minimize electricity expense

The overall system of EMS 1 is shown in Figure 9.

Assumption The assumption of the first proposed EMS is that the Gewertz building was connected to the MEA grid and could purchase electricity when needed. Because of this, the supply side of the system was from both the grid and solar generation, while the demand side was only from the total load consumption of Gewertz building. The historical load consumption was treated as uncontrollable load and solar generation data was treated as a problem parameter. Also, the energy storage was installed with characteristics as specified in (5).

Goal The mathematical formulation of EMS 1 was designed in order to simulate the decision-making process of the EMS regarding electricity purchase and battery scheduling under the objective function which is to minimize the electricity expense.

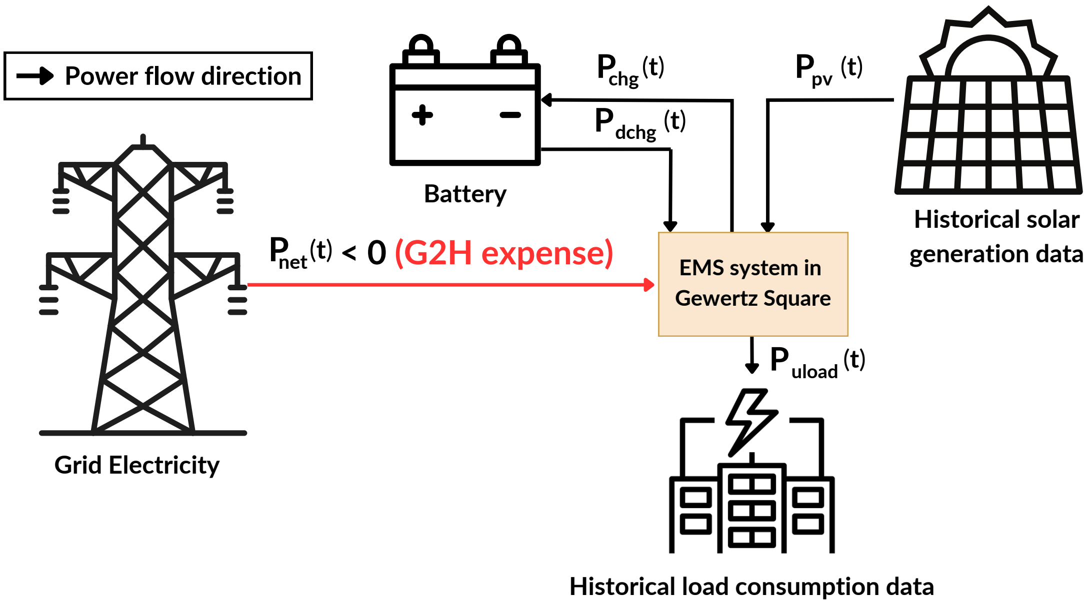


Figure 9: Overall system of EMS 1.

To investigate the decision-making process of the EMS, the decision variables in this mathematical formulation include the net power required from the grid $P_{\text{net}}(t)$, the charging power and discharging power of the battery with their respective statuses $P_{\text{chg}}(t)$, $P_{\text{dchg}}(t)$, $x_{\text{chg}}(t)$, $x_{\text{dchg}}(t)$, and the state of charge of the battery SoC(t).

The objective function of this EMS 1 is simply to minimize the cost of buying electricity when the generation is not adequate for consumption, i.e., when $P_{\text{net}}(t)$ is negative. The expense can be calculated from

$$\text{expense} = \text{buy rate (THB/kWh)} \cdot \text{electricity unit (kWh)}.$$

The max function was introduced in order to obtain the magnitude of the power required from the grid when $P_{\text{net}} \leq 0$, then the electricity price in the positive value is

$$\sum_{t=1}^{T} b(t) \max(0, -P_{\text{net}}(t))\Delta t,$$

where $b(t)$ is a predetermined electricity buy rate (THB/kWh) and Δt is time resolution (hour).

Since this proposed formulation investigated how the battery works, the constraints in EMS 1 involved with the battery constraints (5) - (9) and the power equity (11).

The proposed mathematical formulation of **EMS 1: minimize electricity expense** is shown as below.

Let $z = \left(P_{\text{net}}(t), P_{\text{chg}}(t), P_{\text{dchg}}(t), x_{\text{chg}}(t), x_{\text{dchg}}(t), \text{SoC}(t)\right)$ be the optimization variable for $t = 1, ..., T$.
The optimization EMS 1 is

$$\begin{aligned}
\underset{z}{\text{minimize}} \quad & \sum_{t=1}^{T} b(t)\max(0, -P_{\text{net}}(t))\Delta t \\
\text{subject to} \quad & P_{\text{net}}(t) = P_{\text{pv}}(t) + P_{\text{dchg}}(t) - P_{\text{uload}}(t) - P_{\text{chg}}(t), \quad \text{for } t = 1, ..., T \\
& \text{SoC}(t+1) = \text{SoC}(t) + \frac{100}{\text{BattCapacity}}\left(\eta_c P_{\text{chg}}(t)\Delta t - \frac{P_{\text{dchg}}(t)\Delta t}{\eta_d}\right), \quad \text{for } t = 1, ..., T \\
& \text{SoC}_{\text{min}} \le \text{SoC}(t) \le \text{SoC}_{\text{max}}, \quad \text{for } t = 1, ..., T \\
& P_{\text{chg}}(t) \le x_{\text{chg}}(t) \cdot \text{MAX CHARGE RATE}, \quad \text{for } t = 1, ..., T \\
& P_{\text{dchg}}(t) \le x_{\text{dchg}}(t) \cdot \text{MAX DISCHARGE RATE}, \quad \text{for } t = 1, ..., T \\
& 0 \le x_{\text{chg}}(t) + x_{\text{dchg}}(t) \le 1, \quad \text{for } t = 1, ..., T
\end{aligned} \tag{12}$$

where $x_{\text{chg}}(t), x_{\text{dchg}}(t) \in \{0, 1\}$,
with variables $P_{\text{net}}(t)$, $P_{\text{chg}}(t)$, $P_{\text{dchg}}(t)$, $x_{\text{chg}}(t)$, $x_{\text{dchg}}(t)$, and $\text{SoC}(t)$, for $t = 1, 2, ..., T$.

3.1.2 EMS 2: maximize electricity profit

The overall system of EMS 2 is shown in Figure 10.

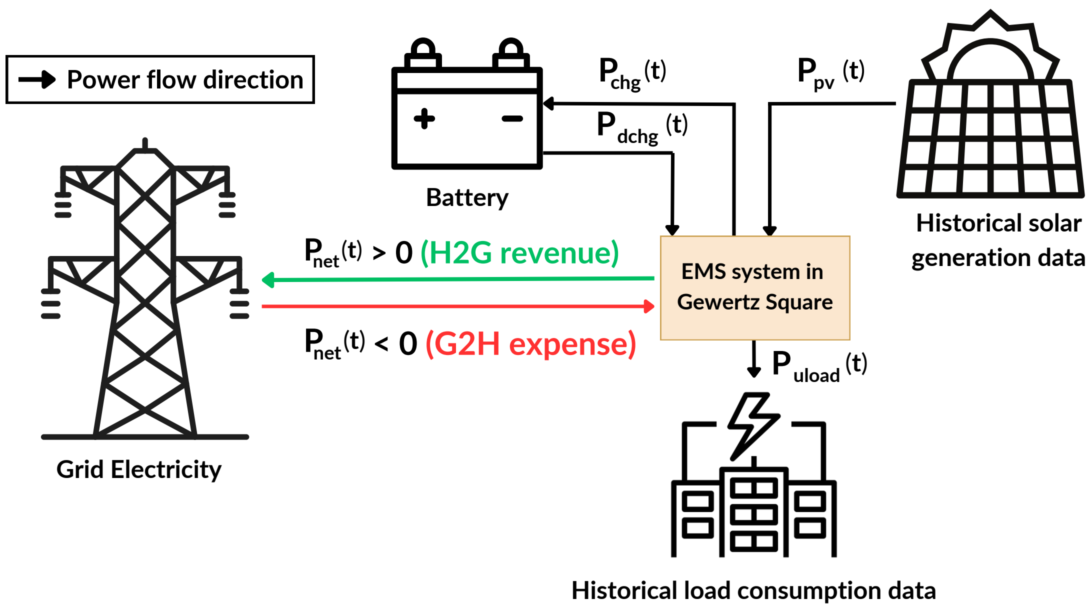


Figure 10: Overall system of EMS 2.

Assumption To further advancing EMS 1, a critical addition has been made by assuming that the system can sell electricity to the grid (referred to as home-to-grid). Despite this enhanced feature, the electric components within the system remain consistent with those of the EMS 1.

Goal Since the addition of the assumption in EMS 2 is that the system can also sell excess electricity back to the grid, the objective term accounting for this was added, and the objective function was changed to be maximizing the electricity profit which is

$$\text{profit} = \text{revenue - expense}$$

where each term is calculated from

$$\begin{aligned}\text{revenue} &= \text{sell rate (THB/kWh)} \cdot \text{electricity unit (kWh)} = s(t)\max(0, P_{\text{net}}(t))\Delta t \\ \text{expense} &= \text{buy rate (THB/kWh)} \cdot \text{electricity unit (kWh)} = b(t)\max(0, -P_{\text{net}}(t))\Delta t\end{aligned}$$

where $s(t)$ is predetermined electricity sell rate (THB/kWh).
So, the profit can be written as

$$\sum_{t=1}^{T} \left[s(t)\max\left(0, P_{\text{net}}\right) - b(t)\max\left(0, -P_{\text{net}}\right)\right]\Delta t$$

To maximize the profit we can minimize the negative profit, which is

$$\sum_{t=1}^{T} \left[b(t)\max(0, -P_{\text{net}}(t)) - s(t)\max(0, P_{\text{net}}(t))\right]\Delta t$$

Since the investigation of this proposed mathematical formula is similar to the mathematical formulation in the EMS 1, the constraints are the same which are the battery constraints (5) - (9) and the power equity (11).

The proposed mathematical formulation of **EMS 2: maximize electricity profit** is shown as below.
Let $z = \left(P_{\text{net}}(t), P_{\text{chg}}(t), P_{\text{dchg}}(t), x_{\text{chg}}(t), x_{\text{dchg}}(t), \text{SoC}(t)\right)$ be the optimization variable where $t = 1, ..., T$.
The optimization EMS 2 is

$$\begin{aligned}\underset{z}{\text{minimize}} \quad & \sum_{t=1}^{T}[b(t)\max(0, -P_{\text{net}}(t)) - s(t)\max(0, P_{\text{net}}(t))]\Delta t \\ \text{subject to} \quad & P_{\text{net}}(t) = P_{\text{pv}}(t) + P_{\text{dchg}}(t) - P_{\text{uload}}(t) - P_{\text{chg}}(t), \quad \text{for } t = 1, ..., T \\ & \text{SoC}(t+1) = \text{SoC}(t) + \frac{100}{\text{BattCapacity}}\left(\eta_c P_{\text{chg}}(t)\Delta t - \frac{P_{\text{dchg}}(t)\Delta t}{\eta_d}\right), \quad \text{for } t = 1, ..., T \\ & \text{SoC}_{\text{min}} \le \text{SoC}(t) \le \text{SoC}_{\text{max}}, \quad \text{for } t = 1, ..., T \\ & P_{\text{chg}}(t) \le x_{\text{chg}}(t) \cdot \text{MAX CHARGE RATE}, \quad \text{for } t = 1, ..., T \\ & P_{\text{dchg}}(t) \le x_{\text{dchg}}(t) \cdot \text{MAX DISCHARGE RATE}, \quad \text{for } t = 1, ..., T \\ & 0 \le x_{\text{chg}}(t) + x_{\text{dchg}}(t) \le 1, \quad \text{for } t = 1, ..., T\end{aligned} \tag{13}$$

where $x_{\text{chg}}(t), x_{\text{dchg}}(t) \in \{0, 1\}$,
with variables $P_{\text{net}}(t)$, $P_{\text{chg}}(t)$, $P_{\text{dchg}}(t)$, $x_{\text{chg}}(t)$, $x_{\text{dchg}}(t)$, and SoC(t) for $t = 1, 2, ..., T$.

3.1.3 EMS 3: minimize electricity expense with controllable load

The overall system of EMS 3 is shown in Figure 11.

Assumption The assumptions of EMS 3 are similar to EMS 1, except for the load consumption, which is now separated into uncontrollable and controllable loads. The uncontrollable load is obtained by using the base load in historical load consumption, and the controllable load consists of the air conditioners in the machine laboratory room and student room, which have characteristics as specified in the section 2.3.2. With the assumptions above, the net power, $P_{\text{net}}(t)$, for EMS 3 is now defined as follows.

$$P_{\text{net}}(t) = P_{\text{pv}}(t) + P_{\text{dchg}}(t) - P_{\text{uload}}(t) - P_{\text{chg}}(t) - P_{\text{ac,m}}(t) - P_{\text{ac,s}}(t).$$

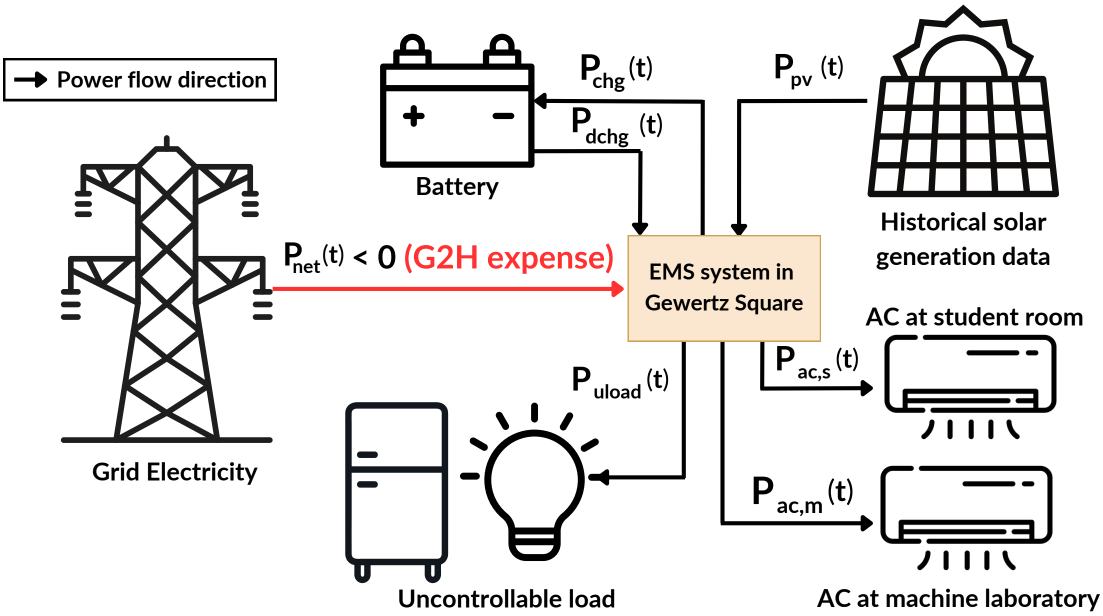


Figure 11: Overall system of EMS 3.

Goal The objective function for EMS 3 is to minimize expenses while encouraging air conditioner utilization in a permissive schedule for encourage air conditioner utilization. Therefore, a soft constraint is added to the objective function. Additionally, to promote battery charging when there is excess power generation, a penalty term for state-of-charge (SoC) deviation is also included.

$$\sum_{t=1}^{T}[b(t)\max(0,-P_{\text{net}}(t))\Delta t + w_b(\text{SoC}_{\text{max}} - \text{SoC}(t))] - \sum_{t\in O}[w_m \sum_{i=1}^{4} x_{\text{ac,m}}^{(i)} + w_s \sum_{i=1}^{4} x_{\text{ac,s}}^{(i)}]$$

where O is an index set containing the time indices for which AC is encouraged,
w_b is a positive weight to promote battery charging,
w_m is a positive weight to encourage air conditioner utilization in machine laboratory room, and
w_s is a positive weight to encourage air conditioner utilization student room. Given that the air conditioner in the machine laboratory has higher priority than the one in the student room, w_m is chosen to be larger than w_s which both AC systems have the permissible schedule during 1.00 - 4.00 p.m.

Since this proposed mathematical formulation investigated the encouragement of the activation of the air conditioning system, so the constraints are including (2) and (3), how the battery works, the constraints are including the battery constraints (5) - (9), and the power equity (11).

In essence, EMS 3 has been developed to simulate the battery and AC schedules, aiming to minimize electricity expenses by strategically utilizing air conditioners within permissible schedules, incorporating with the encouragement of battery charging during periods of excess solar generation.
The proposed mathematical formulation of **EMS 3: controllable load at machine laboratory room and student room** is shown as below.
Let $z = \left(P_{\text{net}}(t), P_{\text{chg}}(t), P_{\text{dchg}}(t), x_{\text{chg}}(t), x_{\text{dchg}}(t), \text{SoC}(t), P_{\text{ac,m}}(t), P_{\text{ac,s}}(t), x_{\text{ac,m}}^{(i)}(t), x_{\text{ac,s}}^{(i)}(t)\right)$
be the optimization variable where $t = 1, \dots, T$ and O be an index set containing the time indices for which AC is encouraged,

The optimization EMS 3 is

$$
\begin{aligned}
\underset{z}{\text{minimize}} \quad & \sum_{t=1}^{T}[b(t)\max(0, -P_{\text{net}}(t))\Delta t + w_b(\text{SoC}_{\text{max}} - \text{SoC}(t))] - \sum_{t\in O}[w_m \sum_{i=1}^{4} x_{\text{ac,m}}^{(i)}(t) + w_s \sum_{i=1}^{4} x_{\text{ac,s}}^{(i)}(t)] \\
\text{subject to} \quad & P_{\text{net}}(t) = P_{\text{pv}}(t) + P_{\text{dchg}}(t) - P_{\text{uload}}(t) - P_{\text{chg}}(t) - P_{\text{ac,m}}(t) - P_{\text{ac,s}}(t), \quad \text{for } t = 1, \dots, T \\
& P_{\text{ac,m}}(t) = (x_{\text{ac,m}}^{(1)}(t) + 0.5x_{\text{ac,m}}^{(2)}(t) + 0.7x_{\text{ac,m}}^{(3)}(t) + 0.8x_{\text{ac,m}}^{(4)}(t))P_{\text{ac,m,rated}}, \quad \text{for } t = 1, \dots, T \\
& P_{\text{ac,s}}(t) = (x_{\text{ac,s}}^{(1)}(t) + 0.5x_{\text{ac,s}}^{(2)}(t) + 0.7x_{\text{ac,m}}^{(3)}(t) + 0.8x_{\text{ac,s}}^{(4)}(t))P_{\text{ac,s,rated}}, \quad \text{for } t = 1, \dots, T \\
& 0 \leq \sum_{i=1}^{4} x_{\text{ac,m}}^{(i)}(t) \leq 1, \quad \text{for } t = 1, \dots, T \\
& 0 \leq \sum_{i=1}^{4} x_{\text{ac,s}}^{(i)}(t) \leq 1, \quad \text{for } t = 1, \dots, T \\
& \text{SoC}(t+1) = \text{SoC}(t) + \frac{100}{\text{BattCapacity}}\left(\eta_c P_{\text{chg}}(t)\Delta t - \frac{P_{\text{dchg}}(t)\Delta t}{\eta_d}\right), \quad \text{for } t = 1, \dots, T \\
& \text{SoC}_{\text{min}} \leq \text{SoC}(t) \leq \text{SoC}_{\text{max}}, \quad \text{for } t = 1, \dots, T \\
& P_{\text{chg}}(t) \leq x_{\text{chg}}(t) \cdot \text{MAX CHARGE RATE}, \quad \text{for } t = 1, \dots, T \\
& P_{\text{dchg}}(t) \leq x_{\text{dchg}}(t) \cdot \text{MAX DISCHARGE RATE}, \quad \text{for } t = 1, \dots, T \\
& 0 \leq x_{\text{chg}}(t) + x_{\text{dchg}}(t) \leq 1, \quad \text{for } t = 1, \dots, T
\end{aligned}
\tag{14}
$$

where $x_{\text{ac,m}}^{(i)}(t), x_{\text{ac,s}}^{(i)}(t) \in \{0, 1\}$, for $i = 1, 2, 3, 4$ and $x_{\text{chg}}(t), x_{\text{dchg}}(t) \in \{0, 1\}$,
with variables $P_{\text{net}}(t)$, $P_{\text{chg}}(t)$, $P_{\text{dchg}}(t)$, $x_{\text{chg}}(t)$, $x_{\text{dchg}}(t)$, $\text{SoC}(t)$, $P_{\text{ac,m}}(t)$, $P_{\text{ac,s}}(t)$, $x_{\text{ac,m}}^{(i)}(t)$, and $x_{\text{ac,s}}^{(i)}(t)$ for $t = 1, 2, \dots, T$.

3.1.4 EMS 4: islanding mode with net-zero power equity

The overall system of EMS 4 is shown in Figure 12.

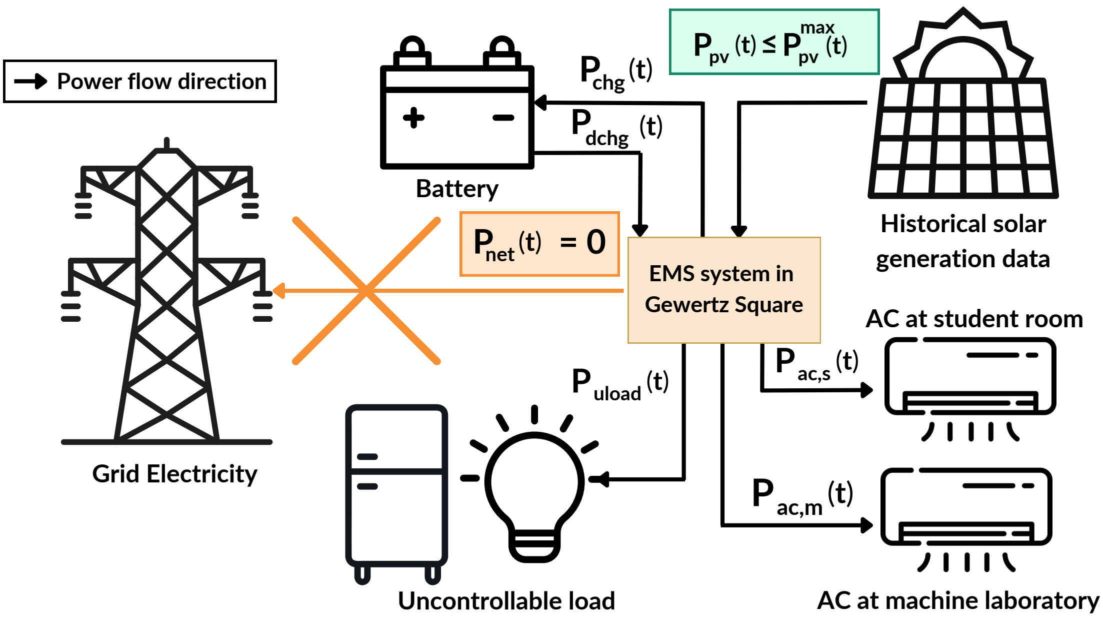


Figure 12: Overall system of EMS 4.

Assumption The foundation of EMS 4's mathematical formulation revolves around enabling the EMS to effectively regulate energy consumption in an islanding mode, where the requirement on grid power is eliminated. The main challenge in islanding occurs when generation exceeds load demand, potentially damaging components in the system. To prevent reverse power flow, solar generation can be curtailed by controlling its inverter, ensuring the total power remains at zero by the specific change within the variable $P_{\text{net}}(t)$. In contrast to the previous three EMS formulations, the solar generation has been exclusively dependent on the historical data. In order to emphasize the islanding mode with net-zero power equity, the solar generation must be transformed into the variable, enabling it to dynamically adjust its value during periods of excess solar generation by reducing the power generation from its MPPT (maximum power point tracking),

$$P_{\text{pv}}(t) \leq P_{\text{pv}}^{\text{max}}(t),$$

where $P_{\text{pv}}^{\text{max}}(t)$ is the historical solar generation power.
The other electrical components remain the same as in EMS 3,

$$P_{\text{net}}(t) = P_{\text{pv}}(t) + P_{\text{dchg}}(t) - P_{\text{uload}}(t) - P_{\text{chg}}(t) - P_{\text{ac,m}}(t) - P_{\text{ac,s}}(t),$$

but the variable $P_{\text{net}}(t)$ was enforced to be zero,

$$P_{\text{net}}(t) = 0.$$

Goal As the system operates in islanding mode, grid electricity becomes unnecessary. Consequently, the objective function within this EMS aims to promote AC operation and prioritize battery charging during periods of excess solar generation.

The proposed mathematical formulation of **EMS 4: islanding mode with net-zero power equity** is shown as below.
Let $z = \left(P_{\text{net}}(t), P_{\text{pv}}(t), P_{\text{chg}}(t), P_{\text{dchg}}(t), x_{\text{chg}}(t), x_{\text{dchg}}(t), \text{SoC}(t), P_{\text{ac,m}}(t), P_{\text{ac,s}}(t), x^{(i)}_{\text{ac,m}}(t), x^{(i)}_{\text{ac,s}}(t)\right)$ be the optimization variable where $t = 1, \dots, T$ and O be an index set containing the indices for which AC is encouraged to operate.

$$
\begin{aligned}
\underset{z}{\text{minimize}} \quad & \sum_{t=1}^{T} w_b \left(\text{SoC}_{\text{max}} - \text{SoC}(t)\right) - \sum_{t \in O} [w_m \sum_{i=1}^{4} x^{(i)}_{\text{ac,m}}(t) + w_s \sum_{i=1}^{4} x^{(i)}_{\text{ac,s}}(t)], \\
\text{subject to} \quad & P_{\text{net}}(t) = P_{\text{pv}}(t) + P_{\text{dchg}}(t) - P_{\text{uload}}(t) - P_{\text{chg}}(t) - P_{\text{ac,m}}(t) - P_{\text{ac,s}}(t) = 0, \quad \text{for } t = 1, \dots, T \\
& P_{\text{pv}}(t) \leq P^{\text{max}}_{\text{pv}}(t), \quad \text{for } t = 1, \dots, T \\
& P_{\text{ac,m}}(t) = \left(x^{(1)}_{\text{ac,m}}(t) + 0.5 x^{(2)}_{\text{ac,m}}(t) + 0.7 x^{(3)}_{\text{ac,m}}(t) + 0.8 x^{(4)}_{\text{ac,m}}(t)\right) P_{\text{ac,m,rated}}, \quad \text{for } t = 1, \dots, T \\
& P_{\text{ac,s}}(t) = \left(x^{(1)}_{\text{ac,s}}(t) + 0.5 x^{(2)}_{\text{ac,s}}(t) + 0.7 x^{(3)}_{\text{ac,m}}(t) + 0.8 x^{(4)}_{\text{ac,s}}(t)\right) P_{\text{ac,s,rated}}, \quad \text{for } t = 1, \dots, T \\
& 0 \leq \sum_{i=1}^{4} x^{(i)}_{\text{ac,m}}(t) \leq 1, \quad \text{for } t = 1, \dots, T \\
& 0 \leq \sum_{i=1}^{4} x^{(i)}_{\text{ac,s}}(t) \leq 1, \quad \text{for } t = 1, \dots, T \\
& \text{SoC}(t+1) = \text{SoC}(t) + \frac{100}{\text{BattCapacity}} \left(\eta_c P_{\text{chg}}(t) \Delta t - \frac{P_{\text{dchg}}(t) \Delta t}{\eta_d}\right), \quad \text{for } t = 1, \dots, T \\
& \text{SoC}_{\text{min}} \leq \text{SoC}(t) \leq \text{SoC}_{\text{max}}, \quad \text{for } t = 1, \dots, T \\
& P_{\text{chg}}(t) \leq x_{\text{chg}}(t) \cdot \text{MAX CHARGE RATE}, \quad \text{for } t = 1, \dots, T \\
& P_{\text{dchg}}(t) \leq x_{\text{dchg}}(t) \cdot \text{MAX DISCHARGE RATE}, \quad \text{for } t = 1, \dots, T \\
& 0 \leq x_{\text{chg}}(t) + x_{\text{dchg}}(t) \leq 1, \quad \text{for } t = 1, \dots, T
\end{aligned}
\tag{15}
$$

where $x^{(i)}_{\text{ac,m}}(t), x^{(i)}_{\text{ac,s}}(t) \in \{0, 1\}$, for $i = 1, 2, 3, 4$ and $x_{\text{chg}}(t), x_{\text{dchg}}(t) \in \{0, 1\}$,
with variables $P_{\text{net}}(t)$, $P_{\text{pv}}(t)$, $P_{\text{chg}}(t)$, $P_{\text{dchg}}(t)$, $x_{\text{chg}}(t)$, $x_{\text{dchg}}(t)$, $\text{SoC}(t)$, $P_{\text{ac,m}}(t)$, $P_{\text{ac,s}}(t)$, $x^{(i)}_{\text{ac,m}}(t)$, and $x^{(i)}_{\text{ac,s}}(t)$ for $t = 1, 2, \dots, T$.

4 Data Description

This section explains the data which relate to the components and formulations of this project. In the scope of Gewertz building, the electrical components includes load consumption, solar generation, and battery. The historical data of load consumption and solar generation for 4 consecutive days were archived as (.mat & .csv) and were categorized into 4 types, which are high-load & high-solar, high-load & low-solar, low-load & high-solar, and low-load & low-solar since October 2022 until July 2023. The data spanned from October 2022 to July 2023, resulting in 48 batches of archived historical data. These batches served as parameters for simulating solar generation and uncontrollable load within the context of this project.

4.1 Load consumption data

The analyzed data of load consumption was received from CUBEMS website and Prof. Surapong's meters at Gewertz building with time resolution approximately 1 s and 670 ms respectively. Then, the data was preprocessed by downsampling to 15 mins.

4.2 Solar generation data

Similar to the load consumption, the analyzed data of solar generation was received from CUBEMS and Prof. Surapong's meters at the EE building, and then scaled up to be sufficient for load consumption, which Prof. Surapong has designed for Gewertz building with time resolutions of 1 second and 670 milliseconds, respectively. The PV installed capacity is different in each EMS as follows: EMS 1 and EMS 2 have 48 kW, while EMS 3 and EMS 4 have 16 kW. Finally, this data was also preprocessed by downsampling to 15 minutes. An example of load consumption and solar generation data is illustrated in Figure 13.

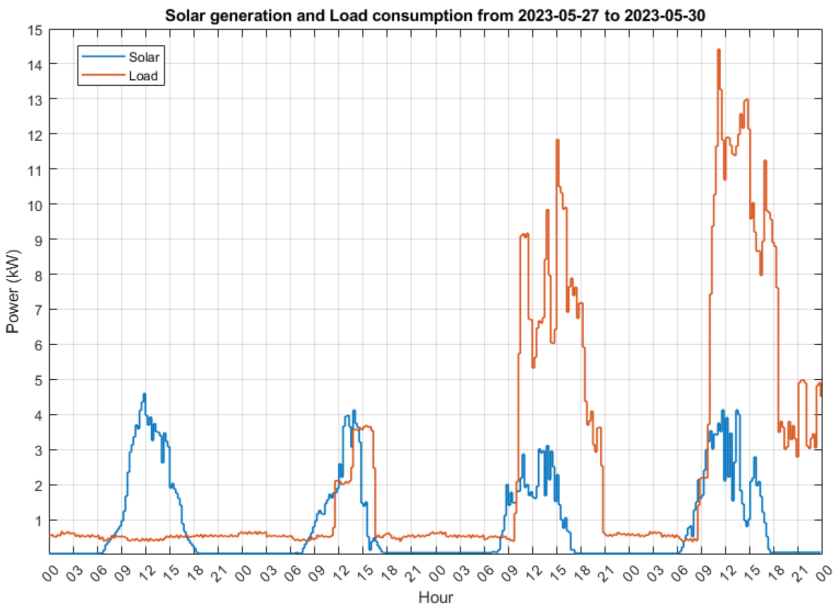


Figure 13: Load consumption and solar generation data during May 27-30, 2023.

4.3 Electricity tariffs

Electricity tariffs refer to the purchasing rate for electricity that vary with time of use. In this project, the calculation method utilized is known as Time of Use (TOU) for the university building, due to its installed voltage within the range of 22-33 kV. Under this TOU scheme, there are 2 schemes used in this project which is TOU 0 and TOU 1.

The TOU 0 scheme uses the energy charge for this residential category is 5.8 THB/kWh during On-Peak (9.00 a.m. - 00.00 a.m.) and 2.6 THB/kWh during Off-Peak (00.00 a.m. - 9.00 a.m.). In selling scenario, the sell rate is fixed at 2 THB/kWh.

The TOU 1 scheme uses the step energy charge 2 THB/kWh (11.00 p.m. - 10.00 a.m.), 3 THB/kWh (10.00 a.m. - 3.00 p.m.), 5 THB/kWh (3.00 p.m. - 6.00 p.m.), and 7 THB/kWh (6.00 p.m. - 11.00 p.m.). In selling scenario, the sell rate is fixed at 2 THB/kWh during 11.00 p.m. - 6.00 a.m. and 2.5 THB/kWh during 6.00 a.m. - 11.00 p.m.

The example of TOU 0 and TOU 1 are illustrated in Figure 14.

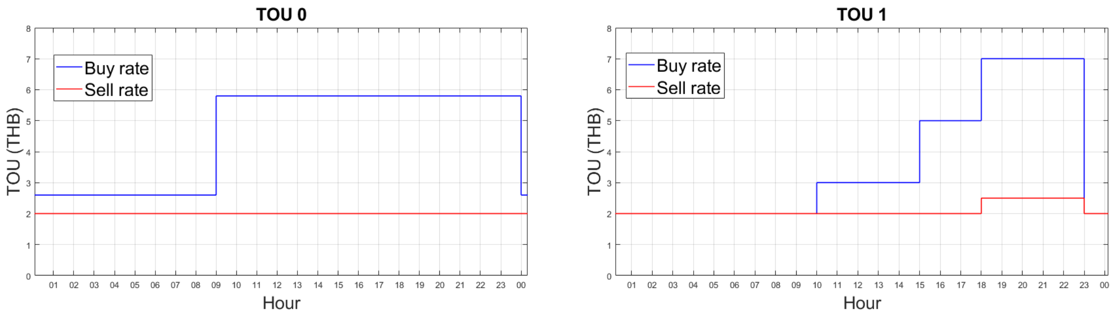


Figure 14: Buy rate and sell rate under TOU 0 and TOU 1 scheme.

5 Preliminary results

The preliminary results consist of four sections for each distinct EMS. Each subsection explains the purpose of the formulation under different economic and operational objectives, the advantages of the EMS from an evaluation metric based on the simulation results, the best scenario where the EMS efficiently impacts the energy management policies, the battery functionality, and RE100 feasibility of the system.

5.1 EMS 1: electricity cost saved by EMS

The primary objective of the mathematical formulation of EMS 1 is to simulate the decision-making process of the EMS regarding the electricity purchase and battery scheduling under the objective function which is to minimize the electricity expense. The assumption is that the system can purchase the electricity from the grid when necessary. The parameters are shown in Table 3.

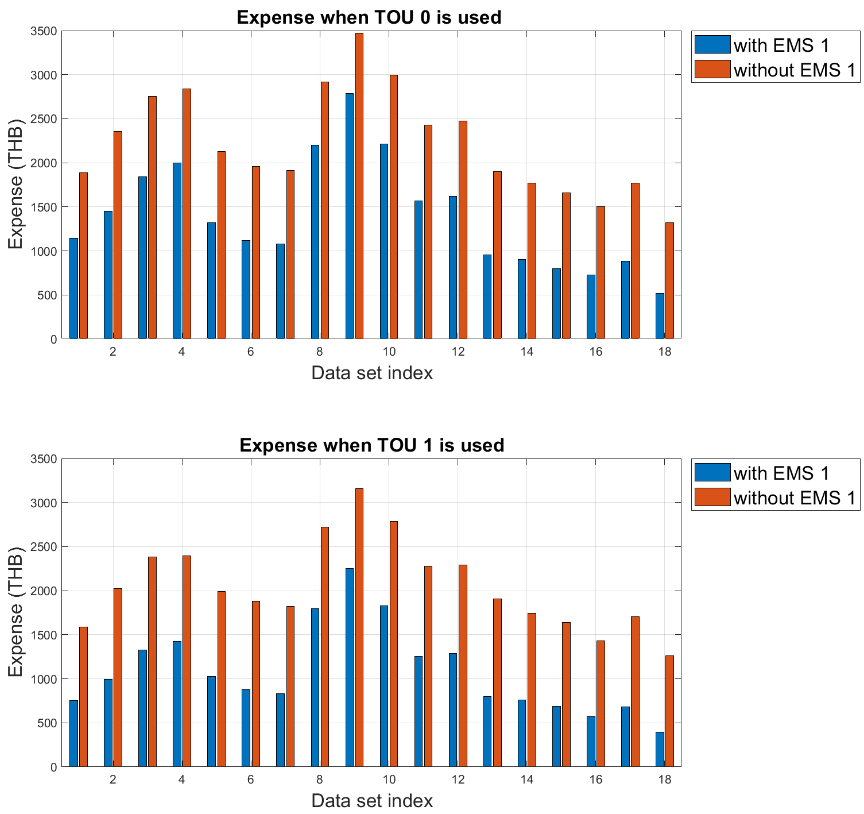
The evaluation metric of this EMS is to compare electricity expenses of a dataset which is in high load & high solar scenario under TOU 0 and TOU 1.

Figure 15(b) and Figure 15(c) elaborately illustrated that without EMS the expense is around 3,500 THB for TOU 0 and 3,200 THB for TOU 1. The histograms as can be seen in Figure 15(a) indicate that when both solar generation and load consumption are high, EMS 1 can generally save expenses from without EMS amounting to 850 THB and 950 THB under TOU 0 and TOU 1 respectively, which can be concluded that because the charaterisitic of TOU 1 that has higher price in the evening results to the charge of battery during daytime to discharge in the nighttime instead of utilizing grid electricity in order to reduce the expense.

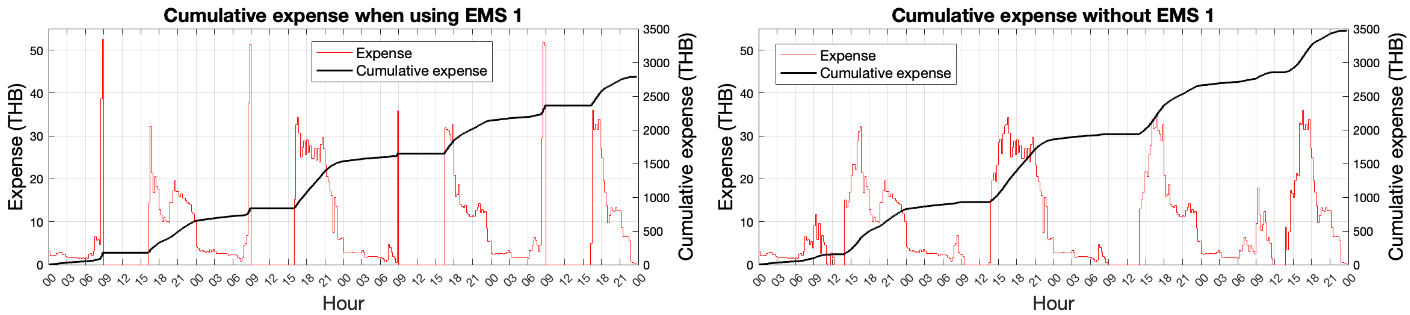
The EMS has the impact in the reduction of electricity expense, another same dataset was illustrated as in Figure 16 and Figure 17 can reduce the electricity expense up to 950 THB under TOU 0 and up to 1,150 THB under TOU 1. Additionally, the EMS is beneficial to the purpose of reduction the electricity cost in every scenario for both TOU 0 and TOU 1 as can be seen in Appendix A.

Also, the EMS effectively manages battery operations. As can be seen in Figure 16 that when solar generation exceeds consumption, the battery charges; conversely, when consumption surpasses solar generation, the battery discharges within the maximum and minimum state of charge, avoiding simultaneous charging and discharging. Since the buy rate during day time is flat, the charge and discharge of the battery depend only on the excess power generation. But when the TOU is changed to be a ladder as can be seen in Figure 17, the battery is enforced to charge significantly during low price period of TOU 1 by both excess power generation and grid power utilization in order to discharge to supply the load during high price period of TOU 1. Moreover, in the last day, there is a huge amount of expense even the SoC is maximum, the reason is that the generation and discharging battery are not sufficient to supply the huge demands which results to the utilization of grid electricity.

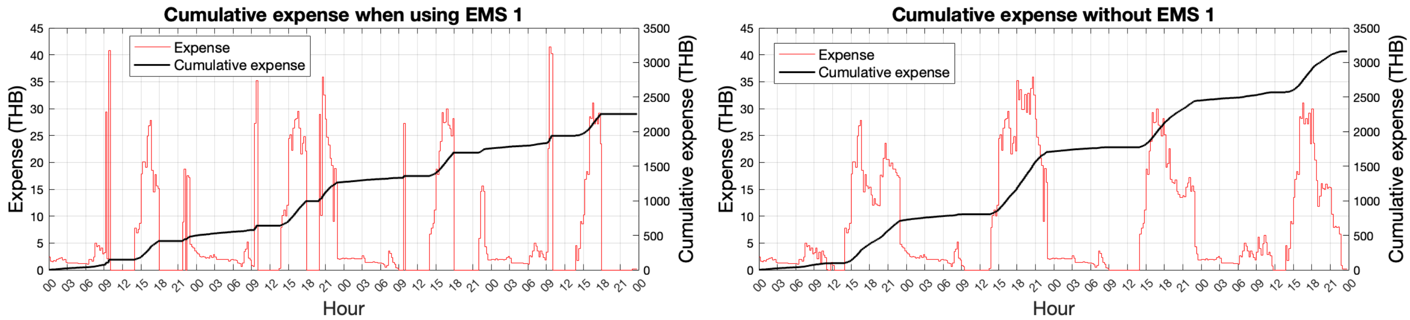
The indicator illustrating the RE100 feasibility of the system is presented as histograms in Figure 18. Considering RE100 attainment reliant on the net energy drawn from the grid—where a low grid electricity requirement suggests a higher potential for achieving RE100—both TOU scenarios exhibit similar grid electricity utilization. This leads to the conclusion that despite both TOUs requiring the same power from the grid, the difference in TOU settings influences the battery functionality, thereby enabling more efficient power management. Consequently, the electricity expenses saved from without EMS under TOU 1 are higher than those under TOU 0. Even though the energy required is mostly 75 kWh, the system can achieve the RE100 by purchasing clean energy from other buildings that have excess generation instead of grid electricity.



(a) Histogram of expenses saved by EMS 1 under TOU 0 and TOU 1.



(b) Electricity expenses saved by EMS 1 under TOU 0.



(c) Electricity expenses saved by EMS 1 under TOU 1.

Figure 15: Electricity expenses saved by EMS 1 in high load & high solar scenario.

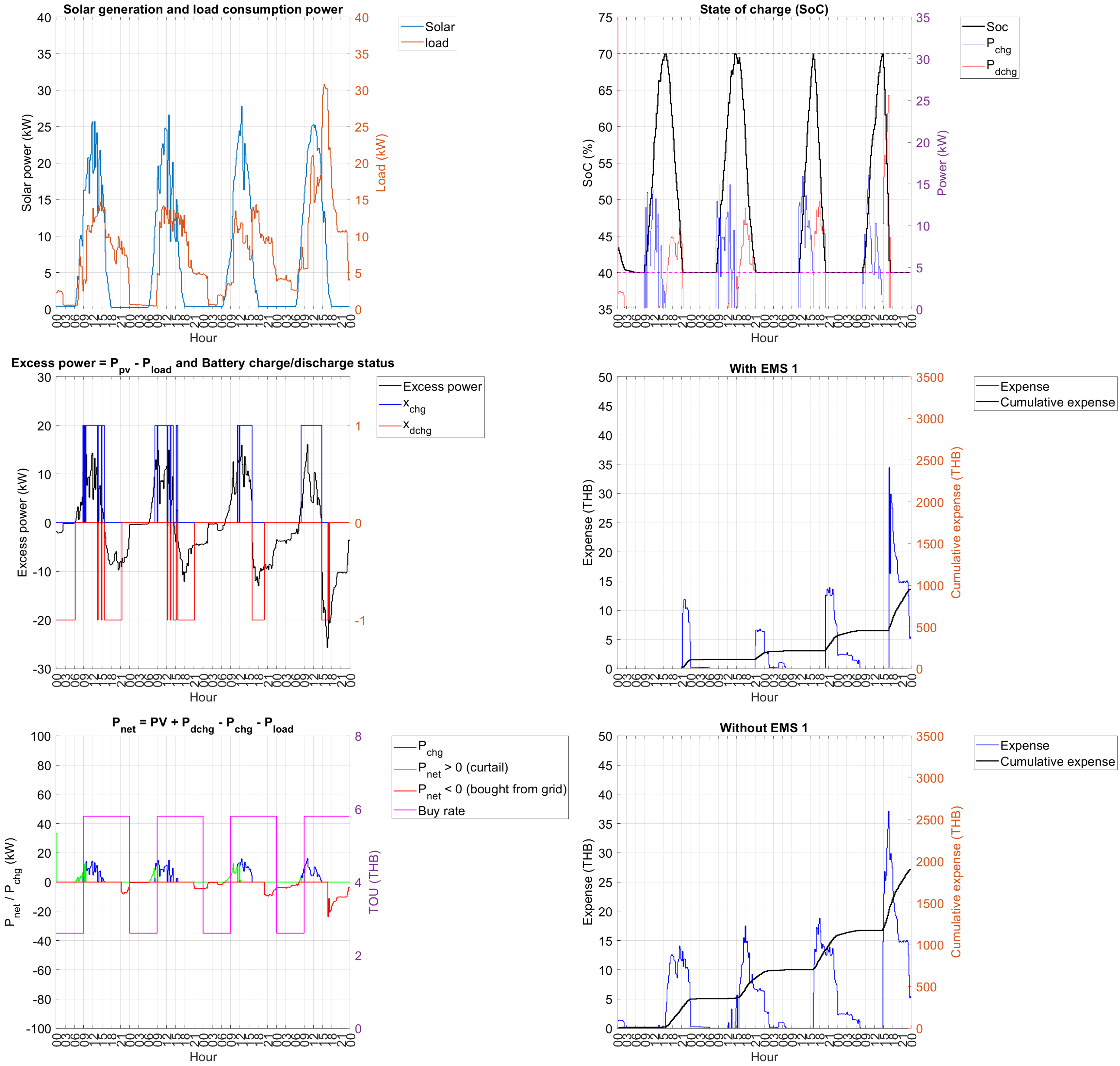


Figure 16: Overall operation of EMS 1 under **TOU 0** in high solar & high load scenario.

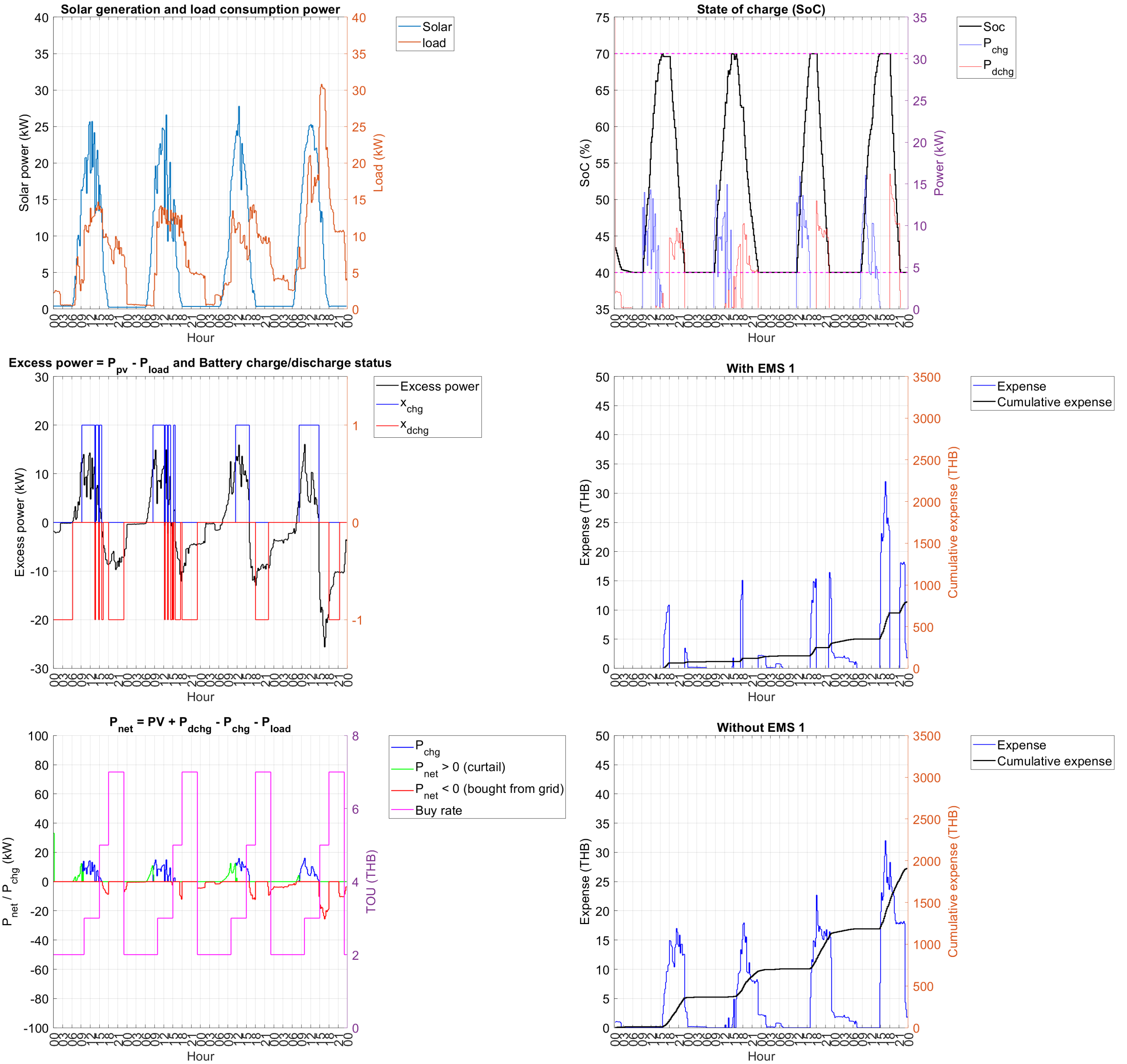


Figure 17: Overall operation of EMS 1 under **TOU 1** in high solar & high load scenario.

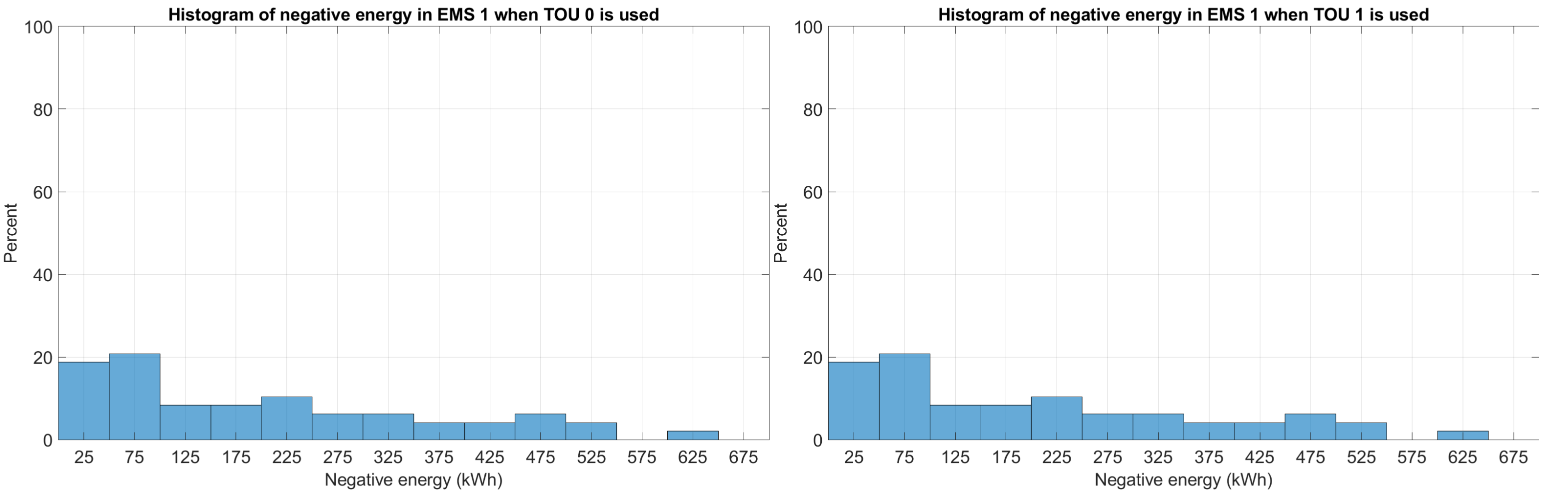


Figure 18: Histograms of negative energy in EMS 1 under TOU 0 and TOU 1.

5.2 EMS 2: electricity profit increased by EMS

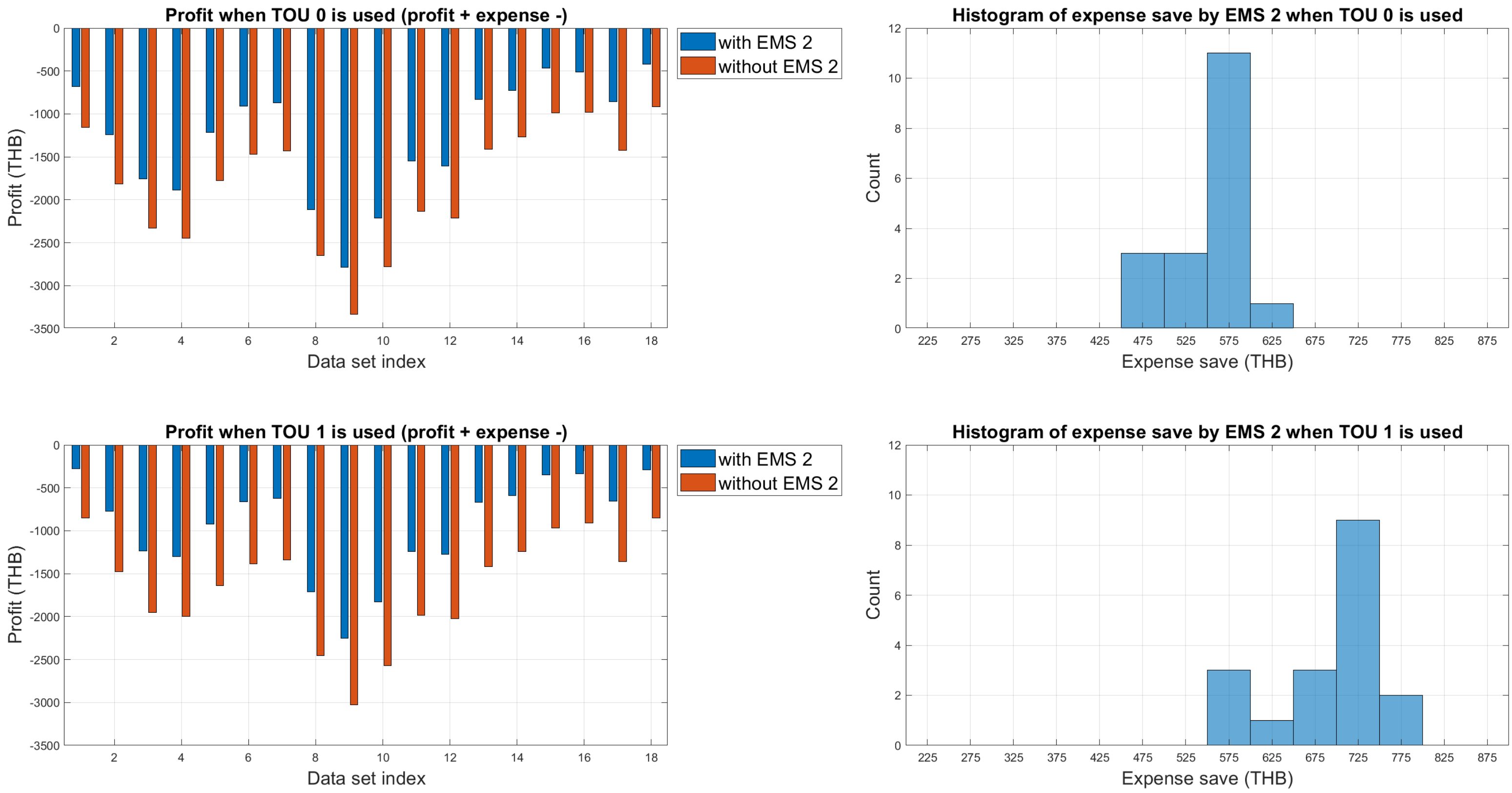
The mathematical formulation of EMS 2 was further proposed similarly to the EMS 1, but the difference is in the assumption that the system is capable of selling the electricity to the grid. Hence, the consideration of the simulation results is quite similar to the EMS 1. The setting parameter is shown in Table 3.

The evaluation metric of this EMS is to compare electricity profit of a dataset which is in high load & high solar scenario under TOU 0 and TOU 1.

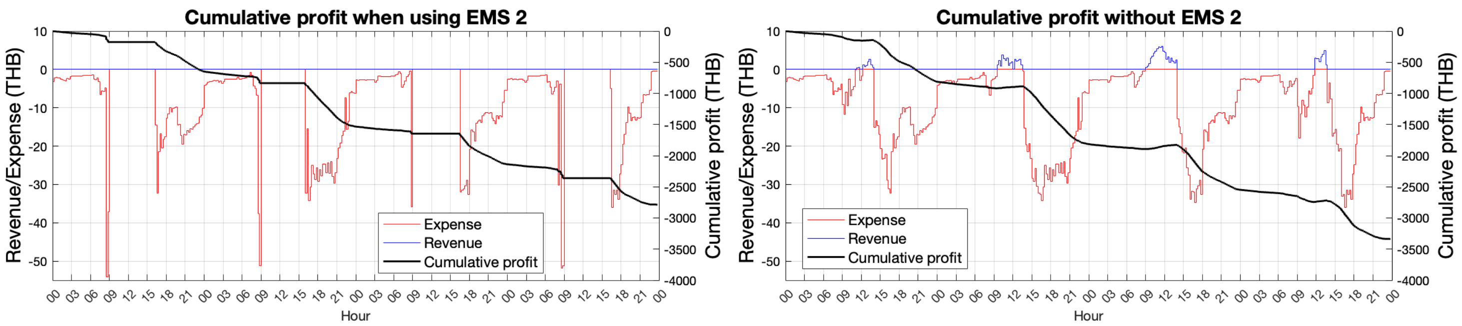
Without EMS, the net expense for 4 days period is around 3,300 THB for TOU 0 and 3,000 THB for TOU 1. The details corresponding to that period of days under TOU 0 and TOU 1 were plotted as in Figure 19(b) and Figure 19(c) respectively, of which the cumulative profit shows that using EMS lowers electricity costs from without EMS, reducing them by about 550 THB for TOU 0 and 750 THB for TOU 1. Similar to the EMS 1, the histograms as can be seen in Figure 19(a) indicate that when both solar generation and load consumption are high, EMS 2 can generally save expenses amounting to 575 THB and 725 THB under TOU 0 and TOU 1, respectively, which can be concluded that because the charateristic of TOU 1 that has higher price in the evening results to the charge of battery during daytime to discharge in the nighttime instead of utilizing grid electricity in order to reduce the expense.

The EMS 2 has the impact in the increase of electricity profit. Another same dataset which is in high solar & low load scenario was illustrated in Figure 20 and Figure 21, which gained the profit up to 300 THB under TOU 0 and 250 THB under TOU 1. The expenses saved by EMS 2 for the other scenarios can be seen in the Appendix B.

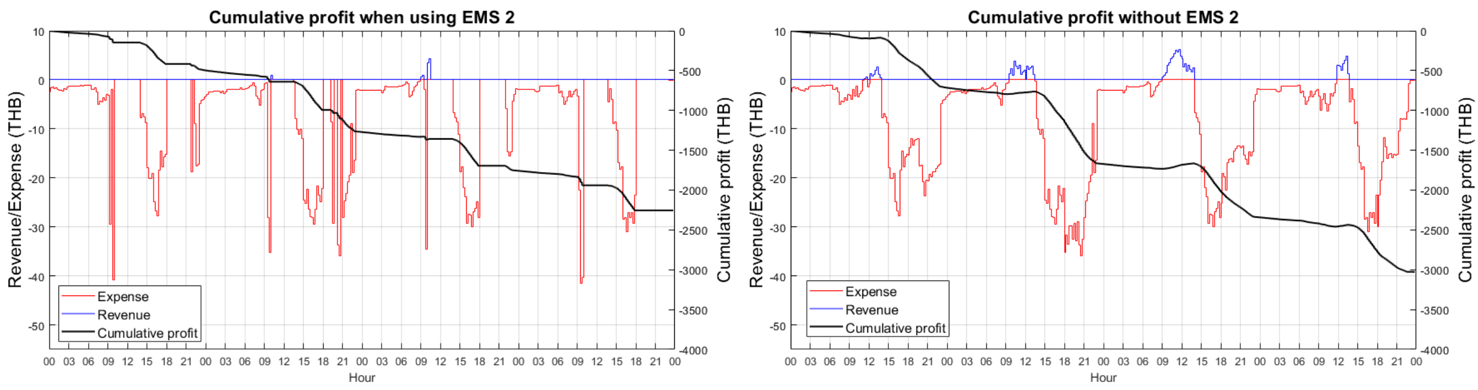
Similar to the EMS 1, the EMS 2 effectively manages battery operations. But in this EMS that is capable of selling the electricity to the grid, it can be seen in Figure 20 that under TOU 0 on day 2, the battery is charged during excess generation period but there is some period that the power is sell to the grid instead of charging the battery in order to obtain the revenue. Besides, the battery always discharges when there is insufficient excess generation especially when the electricity price is high. But in the case under TOU 1 as can be seen in Figure 21, the battery managed to sell the electricity from discharging the battery during high selling price period in order to obtain the revenue as mush as possible while maintain the less expense for the entire period to satisfy the objective function which is to maximize electricity profit.



(a) Histogram of expenses saved by EMS 2 under TOU 0 and TOU 1.



(b) Electricity expenses saved by EMS 2 under TOU 0.



(c) Electricity expenses saved by EMS 2 under TOU 1.

Figure 19: Electricity expenses saved by EMS 2 in high load & high solar scenario.

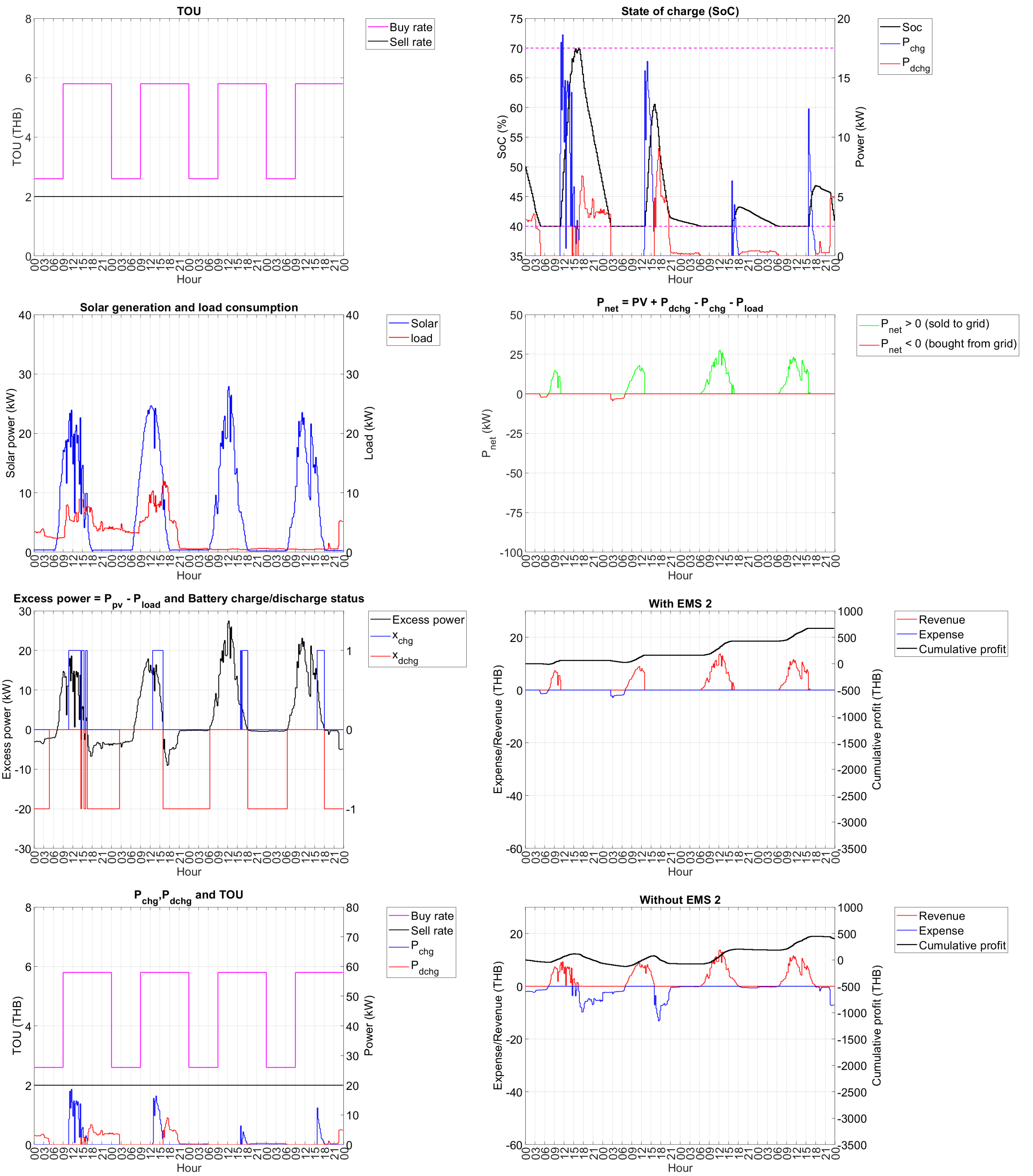


Figure 20: Overall operation of EMS 2 under **TOU 0** in high solar & low load scenario.

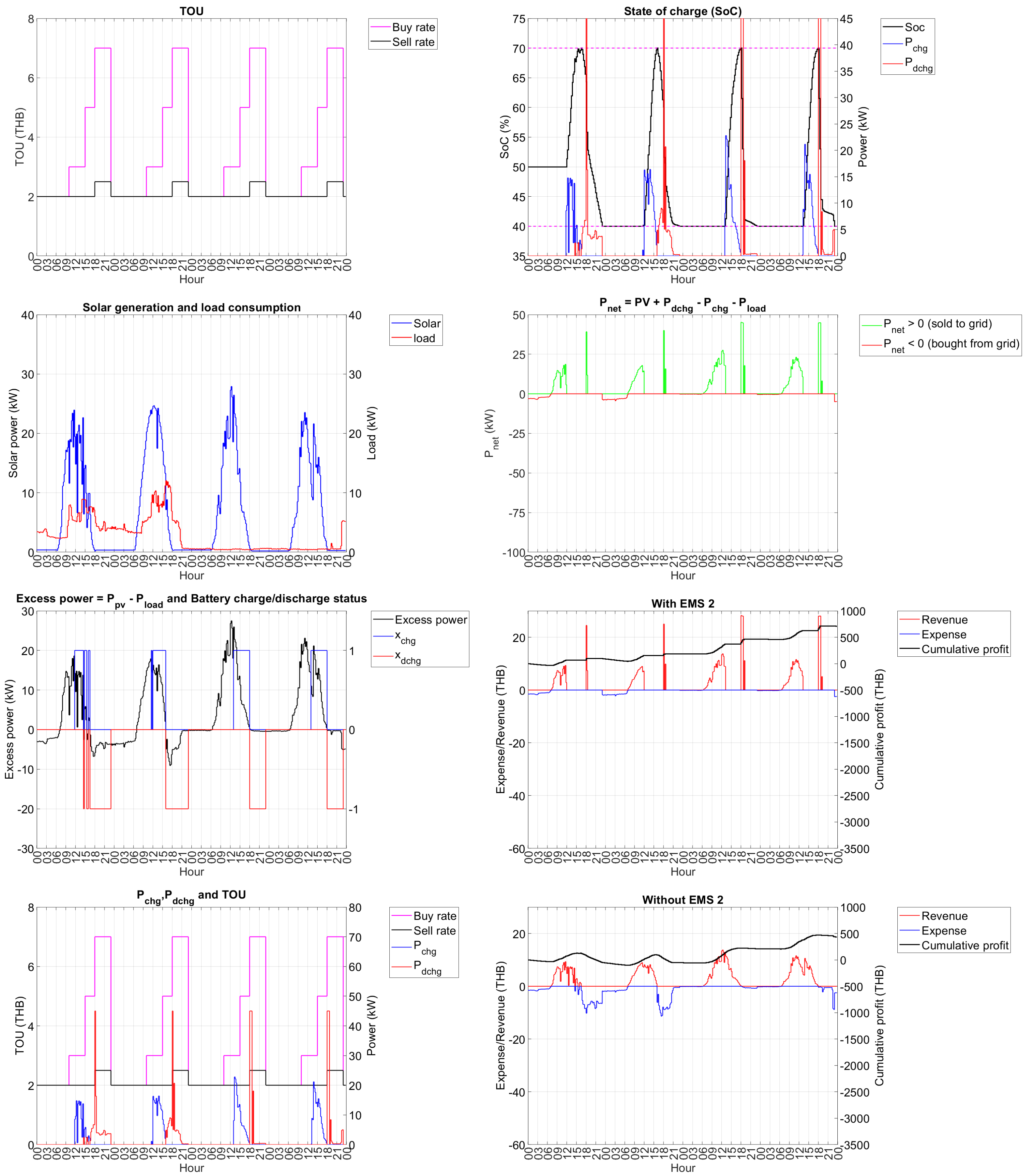


Figure 21: Overall operation of EMS 2 under **TOU 1** in high solar & low load scenario.

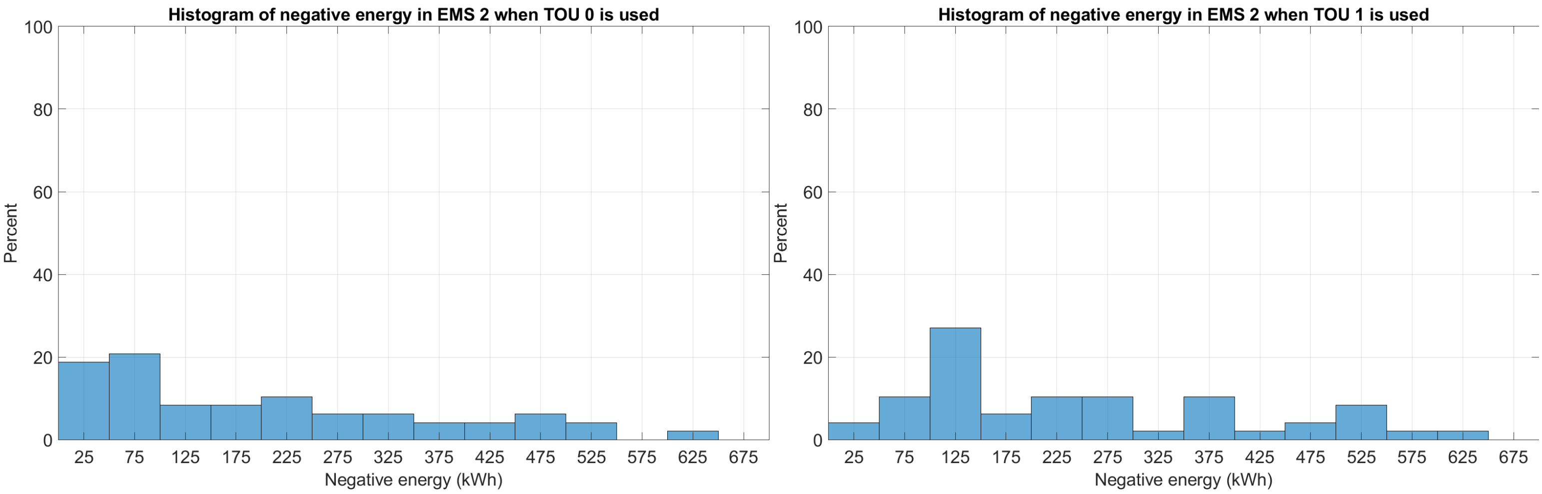


Figure 22: Histograms of negative energy in EMS 2 under TOU 0 and TOU 1.

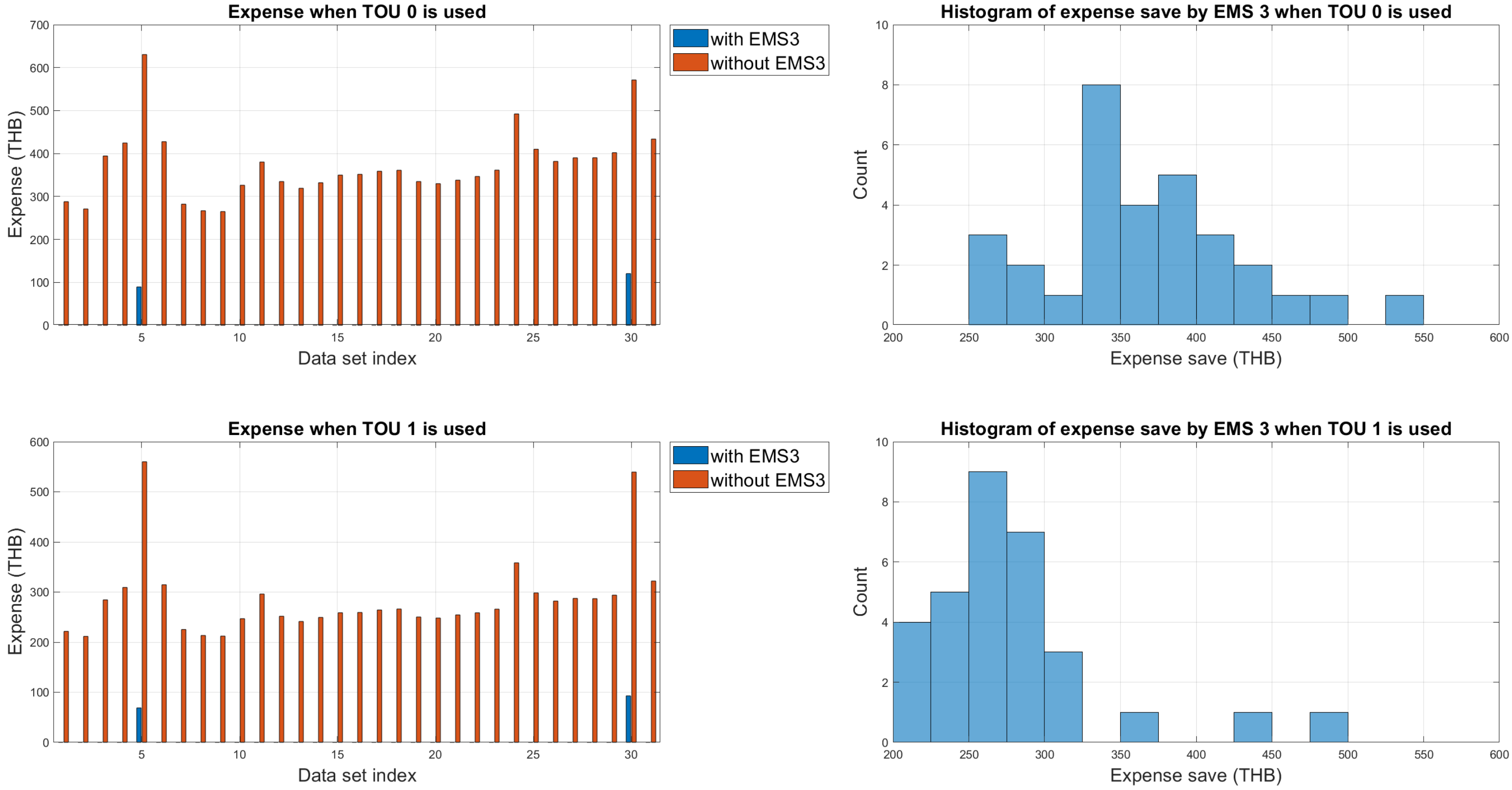
5.3 EMS 3: encourage AC utilization while minimizing electricity expense by EMS

In this mathematical model, the controllable load originating mainly from the machine laboratory room and student room was studied with the goal of activation within the permissible schedule from 1:00 p.m. to 4:00 p.m. The setting parameter is shown in Table 3.

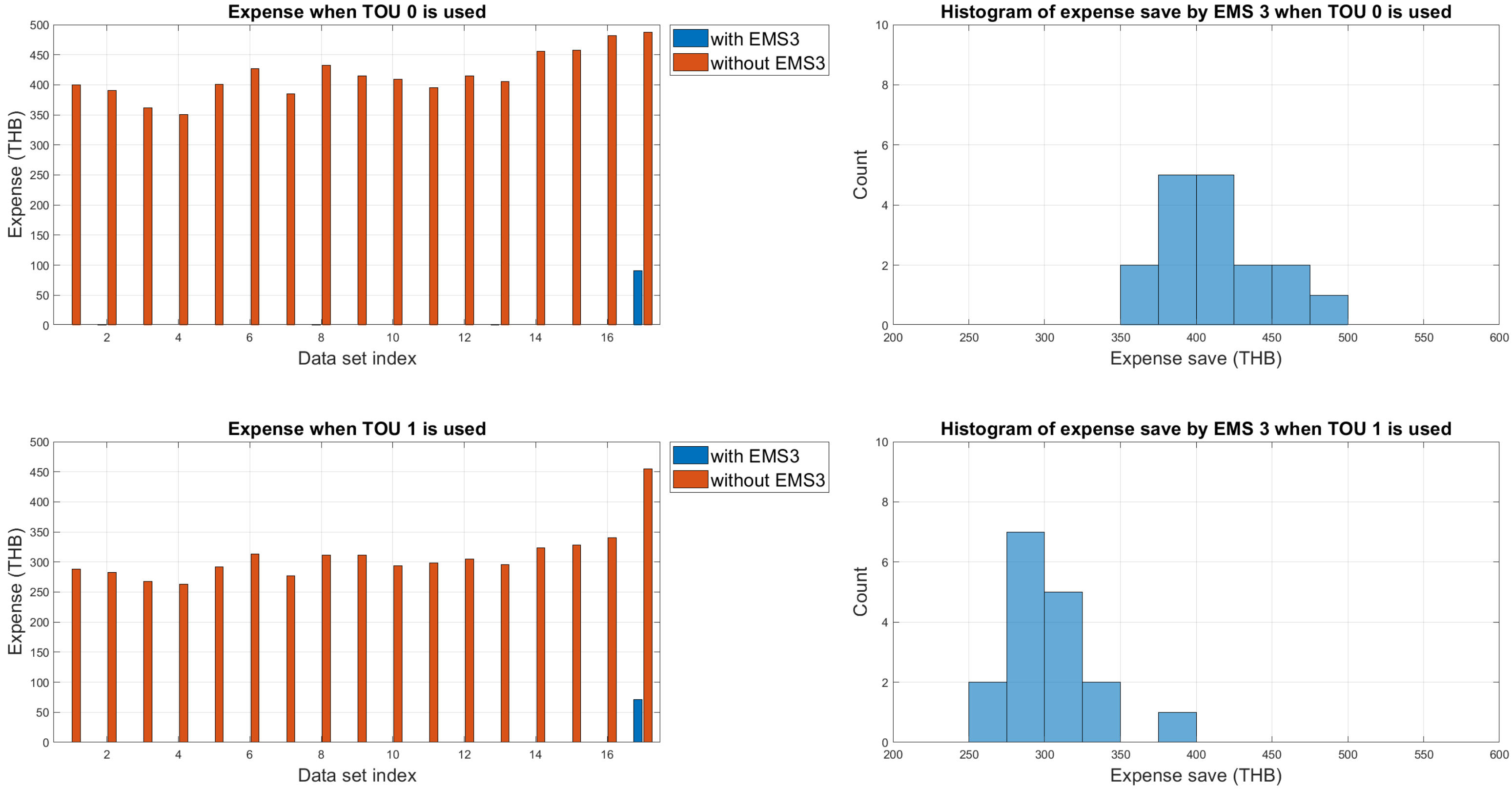
Since the load consumption is controllable, the evaluation metric is to compare the electricity expense required to turn on the air conditioning system in both the machine laboratory room and student room under two scenarios which are high solar generation and low solar generation as can be seen in Figure 23. The EMS can enhance the islanding mode of the system, since with EMS in both scenarios, expenses for most datasets are zero, while without EMS, there are always expenses. The EMS can significantly save the electricity expense from without the EMS as the histogram of expense saved shown.

The EMS 3 significantly enhances the activation of the air conditioning system. Figure 24 shows the most beneficial result is the encouragement of activating the air conditioning systems in both the machine laboratory room and the student room without incurring high expenses in the high solar scenario. Conversely, it enforces the need to turn the AC off in a low solar scenario, as evident in Figure 25. Also, the case that requires the grid electricity is shown in Figure 26 which will be discussed later in section 5.4.

Figure 27 shows the percentage of air conditioner utilization in both the student and machine laboratory rooms in high solar and low solar scenarios, respectively. In this figure, 100% AC utilization means the air conditioner has been utilized in the encouragement period for four days, at the lowest level of power consumption which is 50% of rated power of AC, and 0% AC utilization means the air conditioner has not been utilized at all. In the high solar generation scenario, the air conditioner in both rooms is utilized for four days in most of the high solar generation cases. However, when the solar generation is low, the student's air conditioner is utilized for four days in only half of the low solar generation cases. When comparing TOU 0 with TOU 1, air conditioner utilization in both rooms is nearly identical, as most of the cases have zero expenses.



(a) High solar generation scenario.



(b) Low solar generation scenario.

Figure 23: Histogram of expenses saved by EMS 3 under TOU 0 and TOU 1.

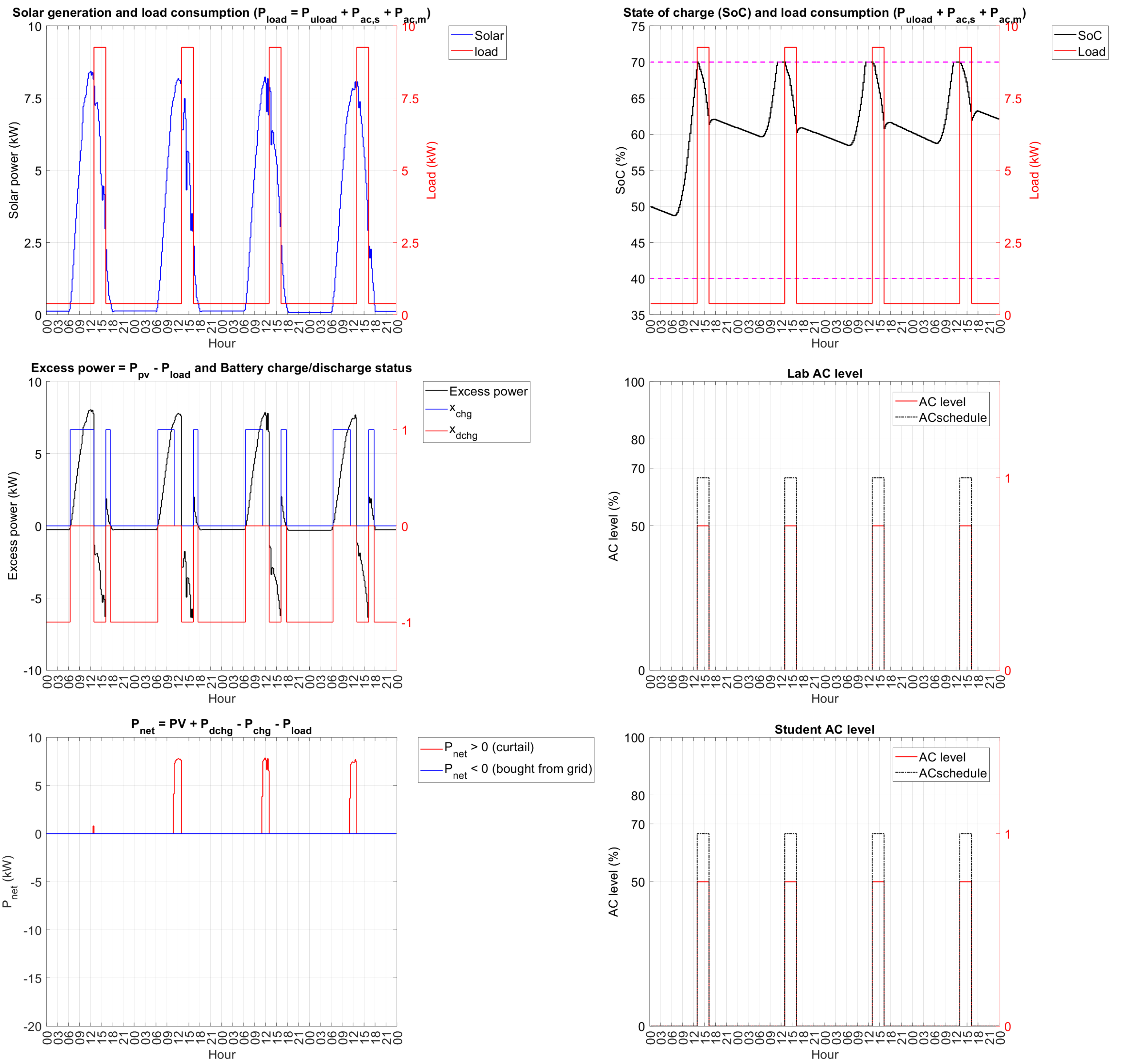


Figure 24: Encouraging the use of AC in both the machine laboratory room and the student room under **high solar generation scenario**.

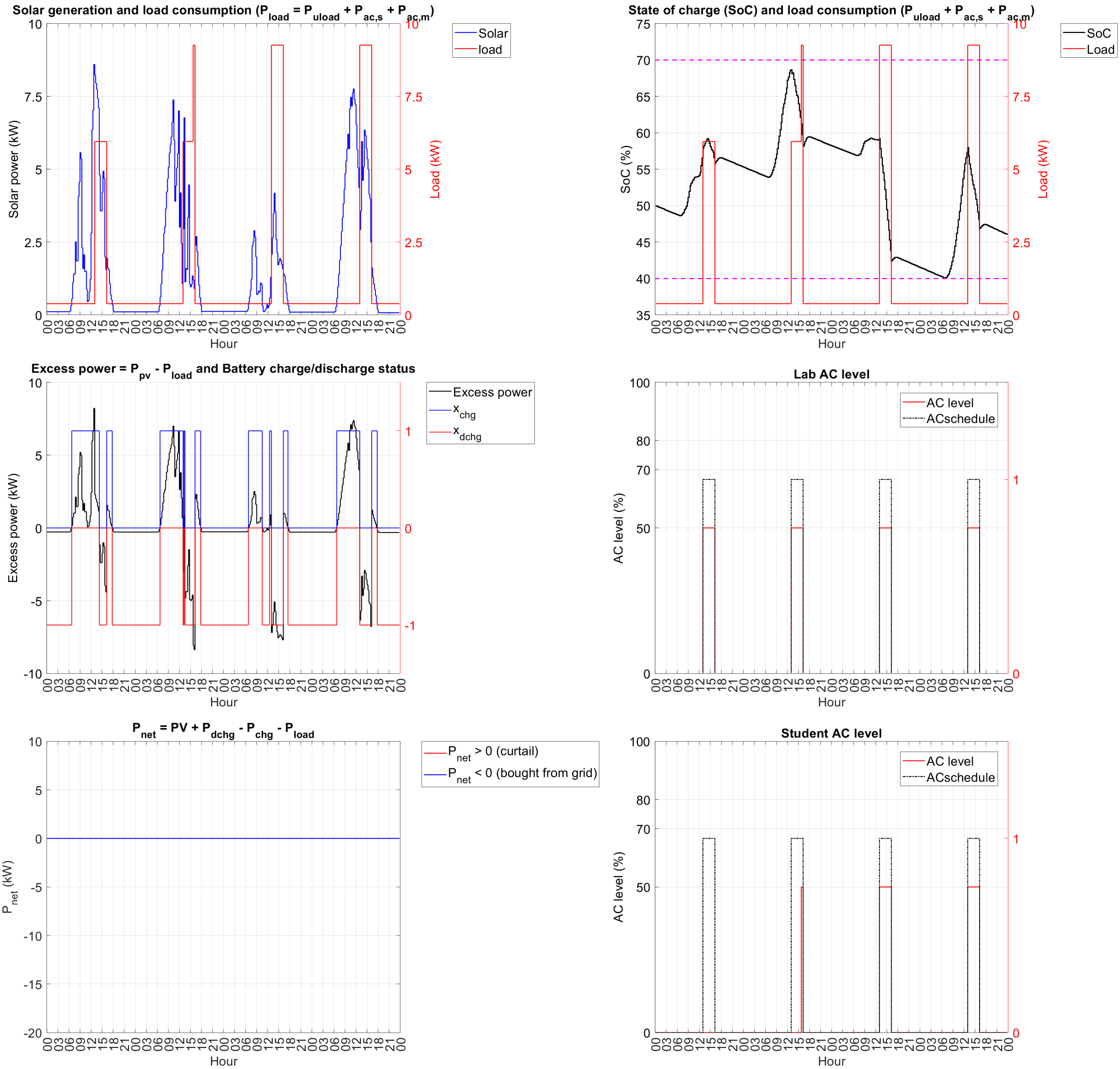


Figure 25: Encouraging the use of AC in both the machine laboratory room and the student room under **low solar generation scenario**.

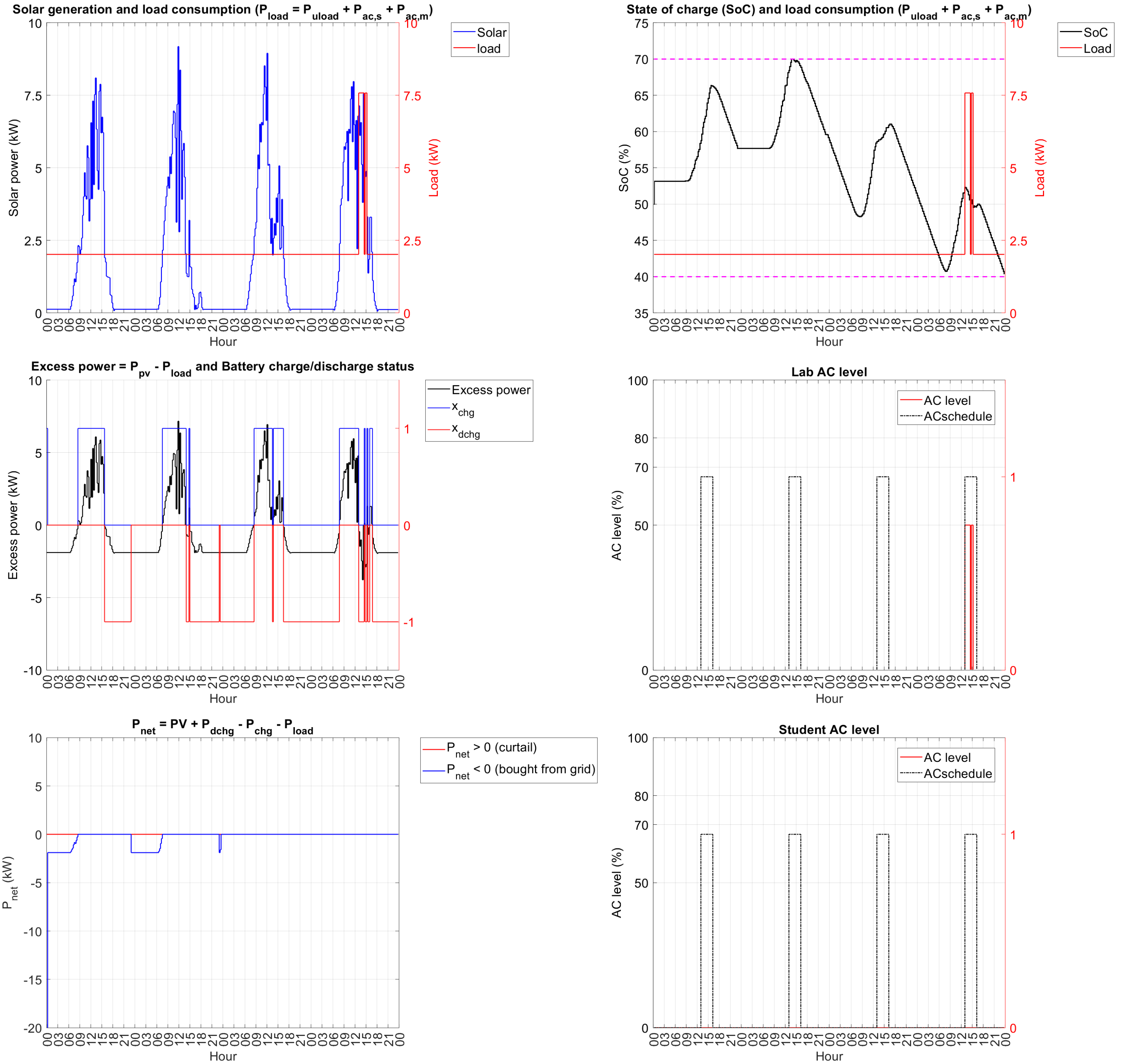
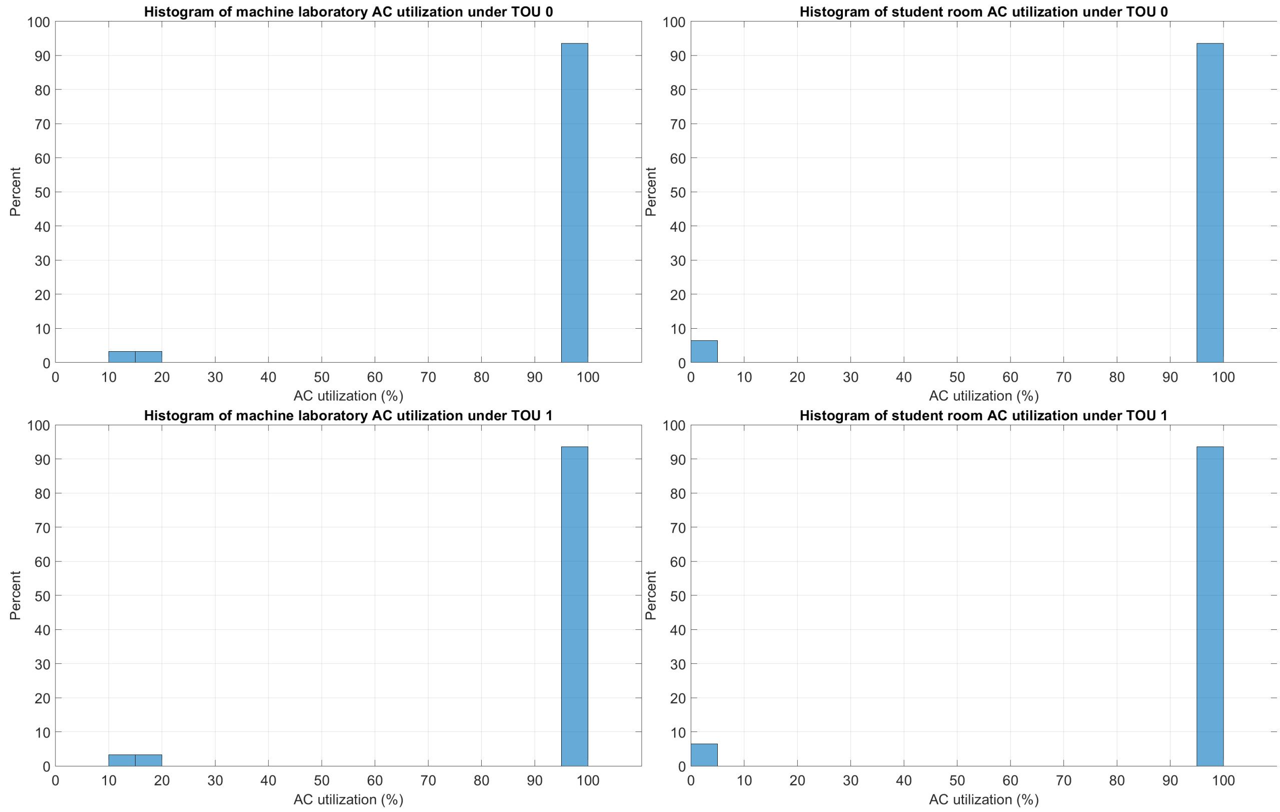
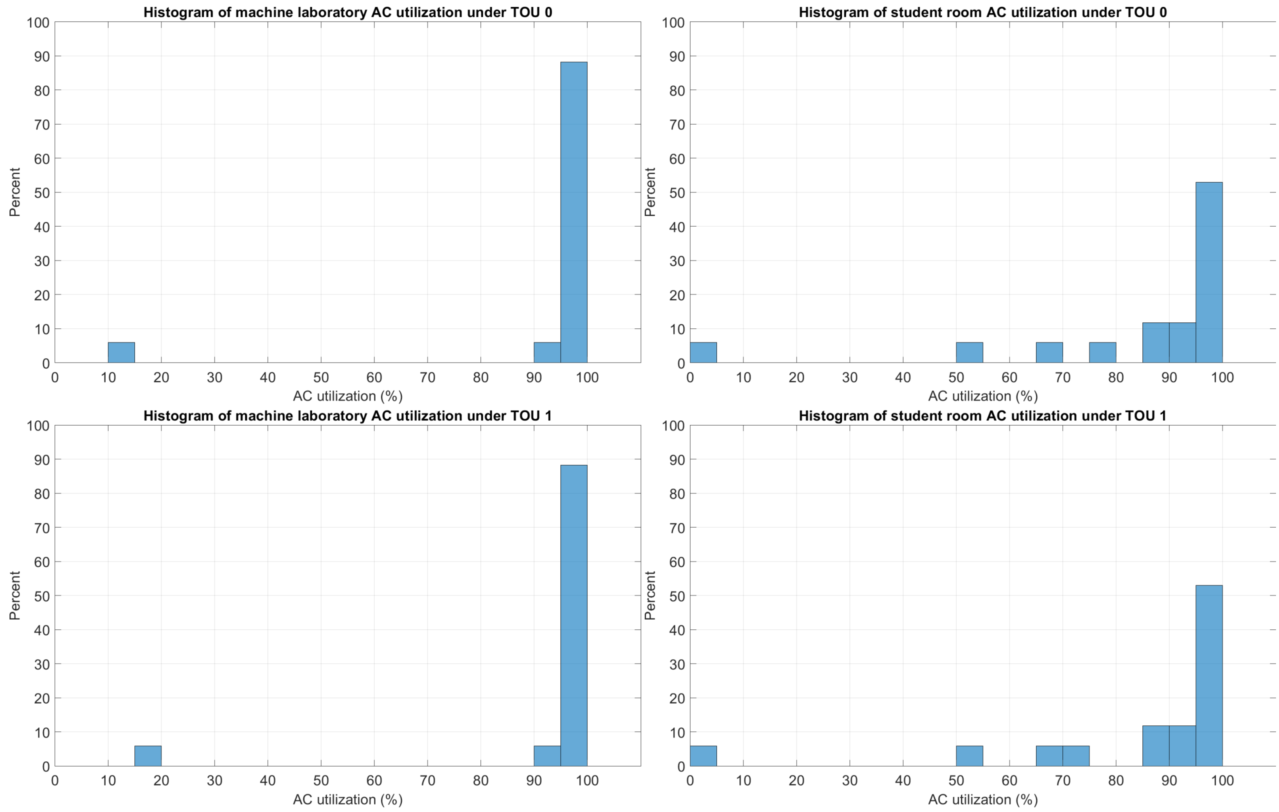


Figure 26: The infeasible case of being an islanding mode.



(a) High solar generation scenario.



(b) Low solar generation scenario.

Figure 27: Histogram of AC utilization by EMS 3 under TOU 0 and TOU 1.

5.4 EMS 4: number of different scenarios for being islanding mode

Figure 28 and Figure 29 demonstrate the overall operation of EMS 4 in high solar and low solar generation, respectively. In the high solar generation scenario, the air conditioners in both rooms are always utilized in the encouragement schedule, and some solar generation needs to be curtailed in order to enforce zero-export to the grid. However, in the low solar generation scenario, the air conditioner in the student room is not utilized in the first two days, and the solar generation is not curtailed. In both cases, the battery is at the heart of EMS 4 strategy by charging solar energy and discharging for the air conditioners and base load. Out of 48 batches, three batches could not run in islanding mode due to abnormally high base load compared to the other 45 batches. This suggests that islanding mode may be possible when the base load is small, and the comfort of users is not considered.

To elaborate the infeasibility of the EMS 4 in order to operate in the islanding mode, the root of infeasibility was illustrated in Figure 26. Despite both the lab room and student room being turned off, the system consistently demands power from the grid (P_{net} is always negative.) due to the high amount of based load consumption during daytime, resulting the system unable to sustain itself independently. Although SoC reached its maximum on the second day, activating the air conditioning in both the machine laboratory room and student room was not feasible. Doing so the SoC would be inadequate for power consumption by the base load later on, leading to the cause that SoC drop down below 40 %. The initial charge was occur because the EMS anticipated that by the end of day 4, the SoC would need to be utilized as much as possible to supply the base load until it reached its minimum threshold. Moreover, the initial charging of the battery probably results from excessive weight w_b, so the EMS may manage the system to minimize the gap between SoC(t) and SoC_{max}. In this EMS, investigating the system's infeasibility can be achieved by setting parameters within the EMS 3. For instance, the solutions for infeasible cases are similar, involving turning off all ACs in both rooms. Then, the base load becomes the sole factor that solar generation must supply. If the initial solar generation is lower than the base load, the battery must self-discharge by at most 10% to supply the base load; if insufficient, grid electricity usage becomes necessary. Therefore, grid electricity is used to charge the battery initially, ensuring later provision of the base load.

Figure 30 shows the percentage of air conditioner utilization in both the student and machine laboratory rooms in high solar and low solar scenarios, respectively. In Figure 30(a) and Figure 30(b), 100% AC utilization means the air conditioner has been utilized in the encouragement period for four days, at the lowest level of power consumption which is 50% of rated power of AC, and 0% AC utilization means the air conditioner has not been utilized at all. In the high solar generation scenario, the air conditioner in both rooms is utilized for four days in most of the high solar generation cases. However, when the solar generation is low, the student's air conditioner is utilized for four days in only half of the low solar generation cases.

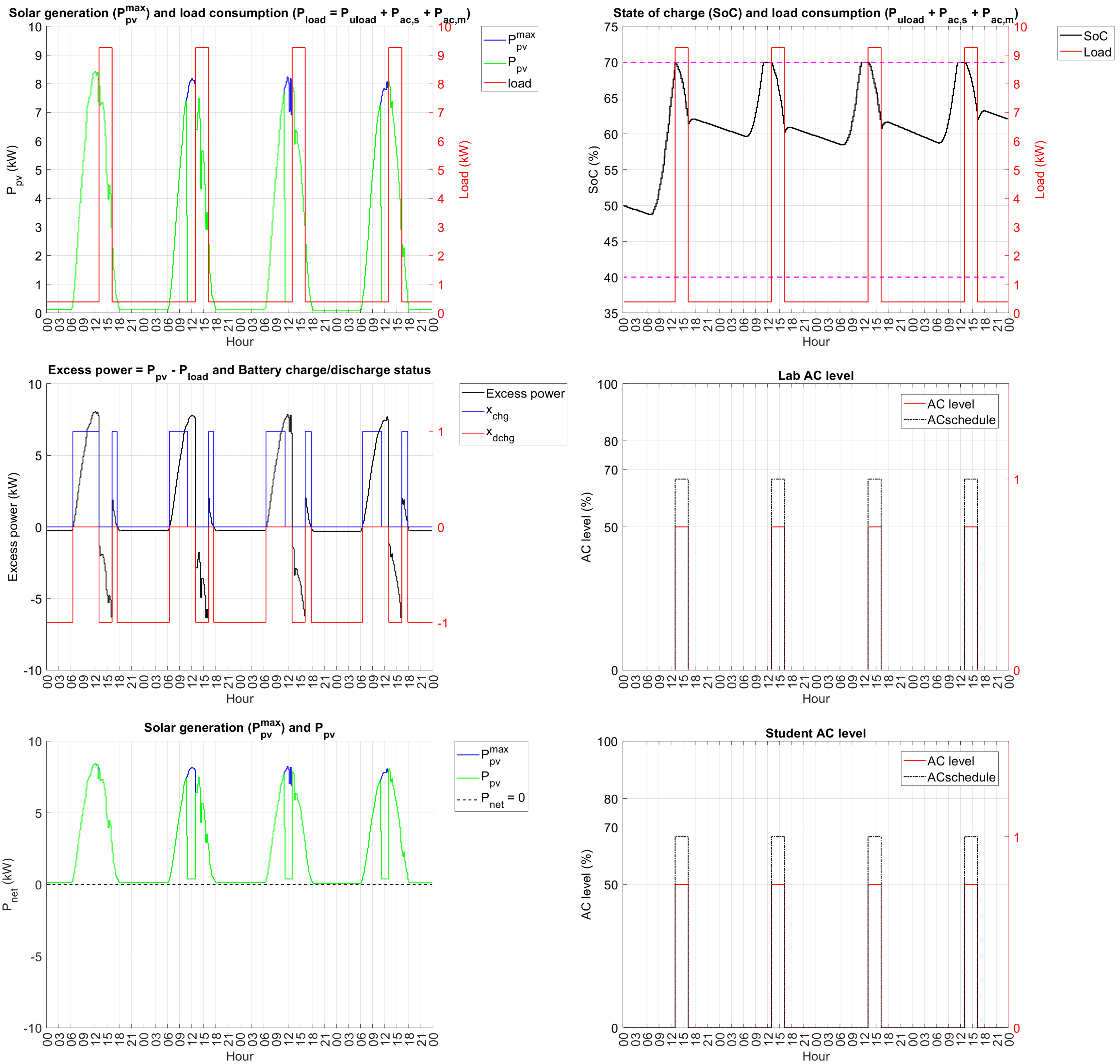


Figure 28: Overall operation of EMS 4 under **high solar generation**.

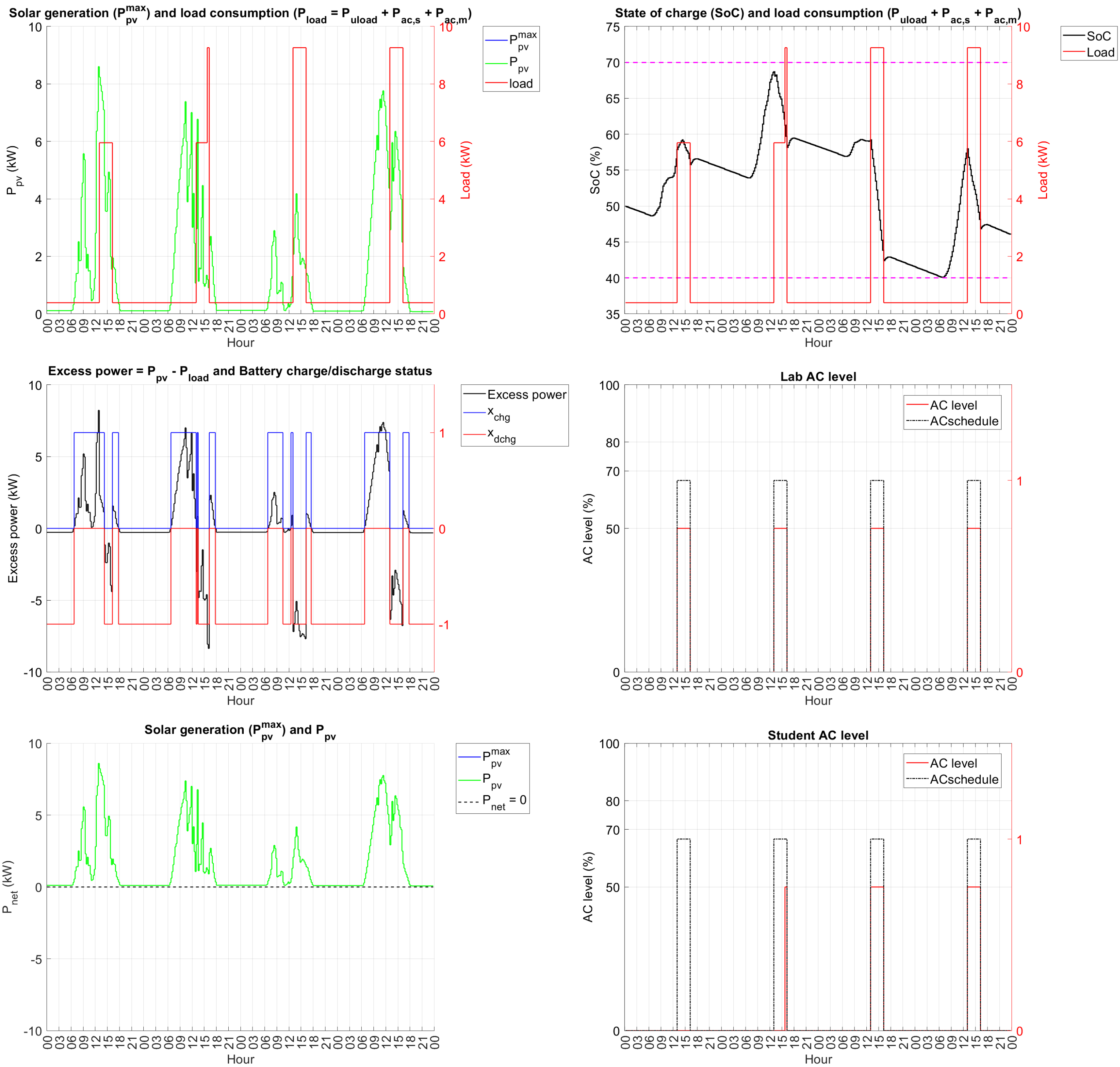
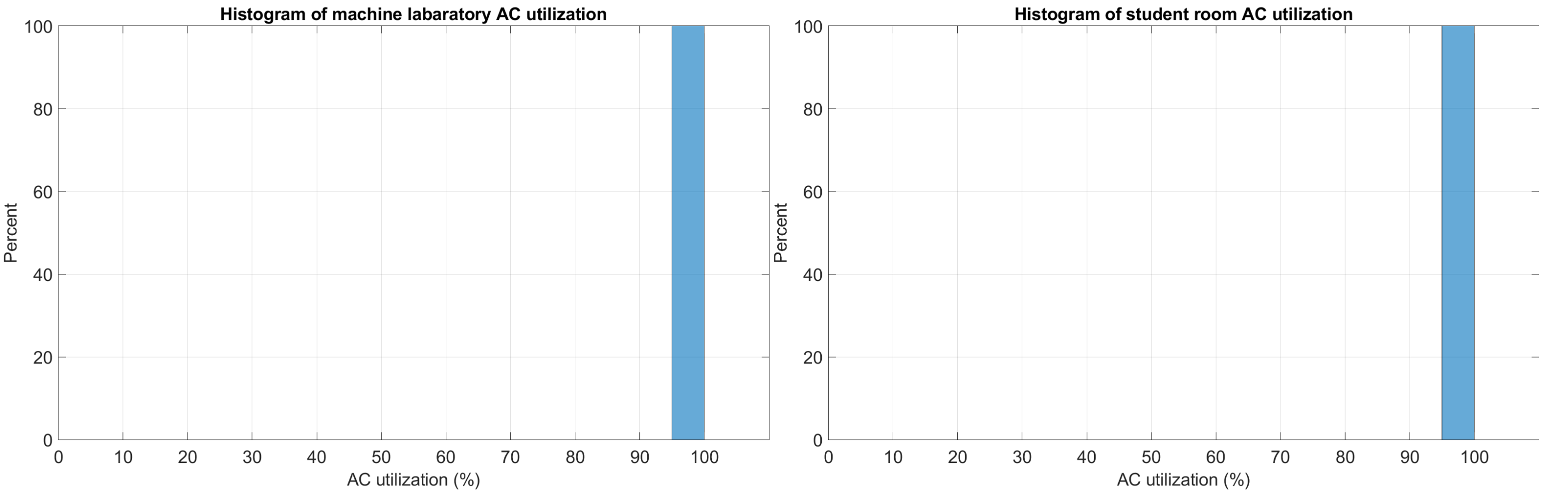
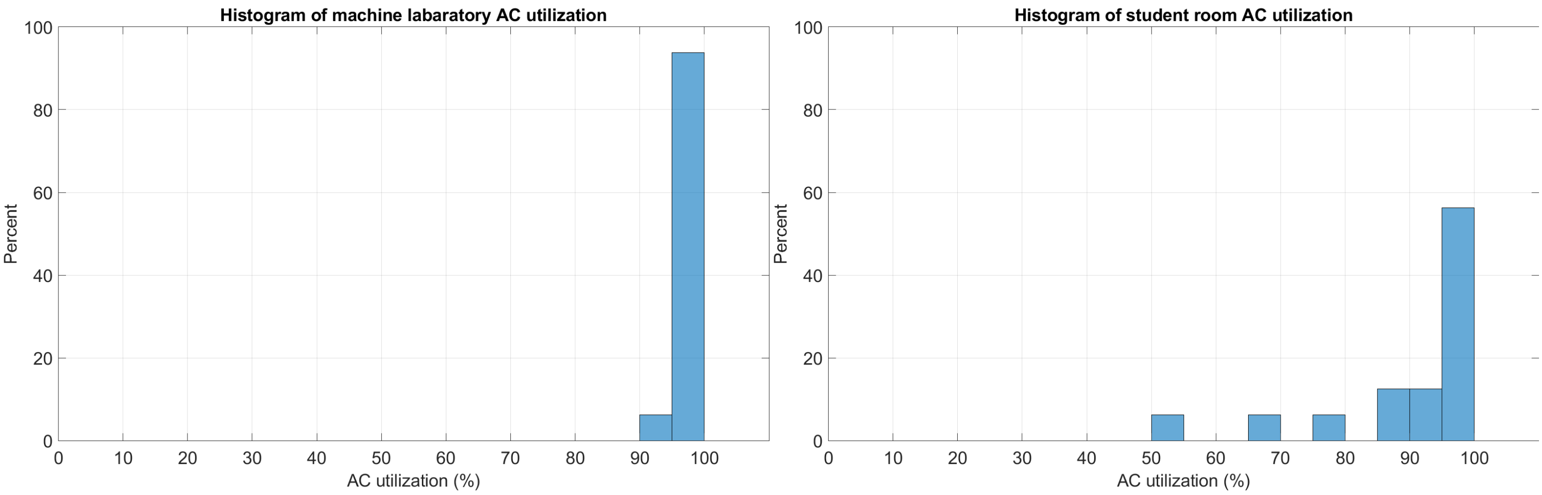


Figure 29: Overall operation of EMS 4 under **low solar generation**.



(a) High solar generation scenario.



(b) Low solar generation scenario.

Figure 30: Histogram of AC utilization by EMS 4.

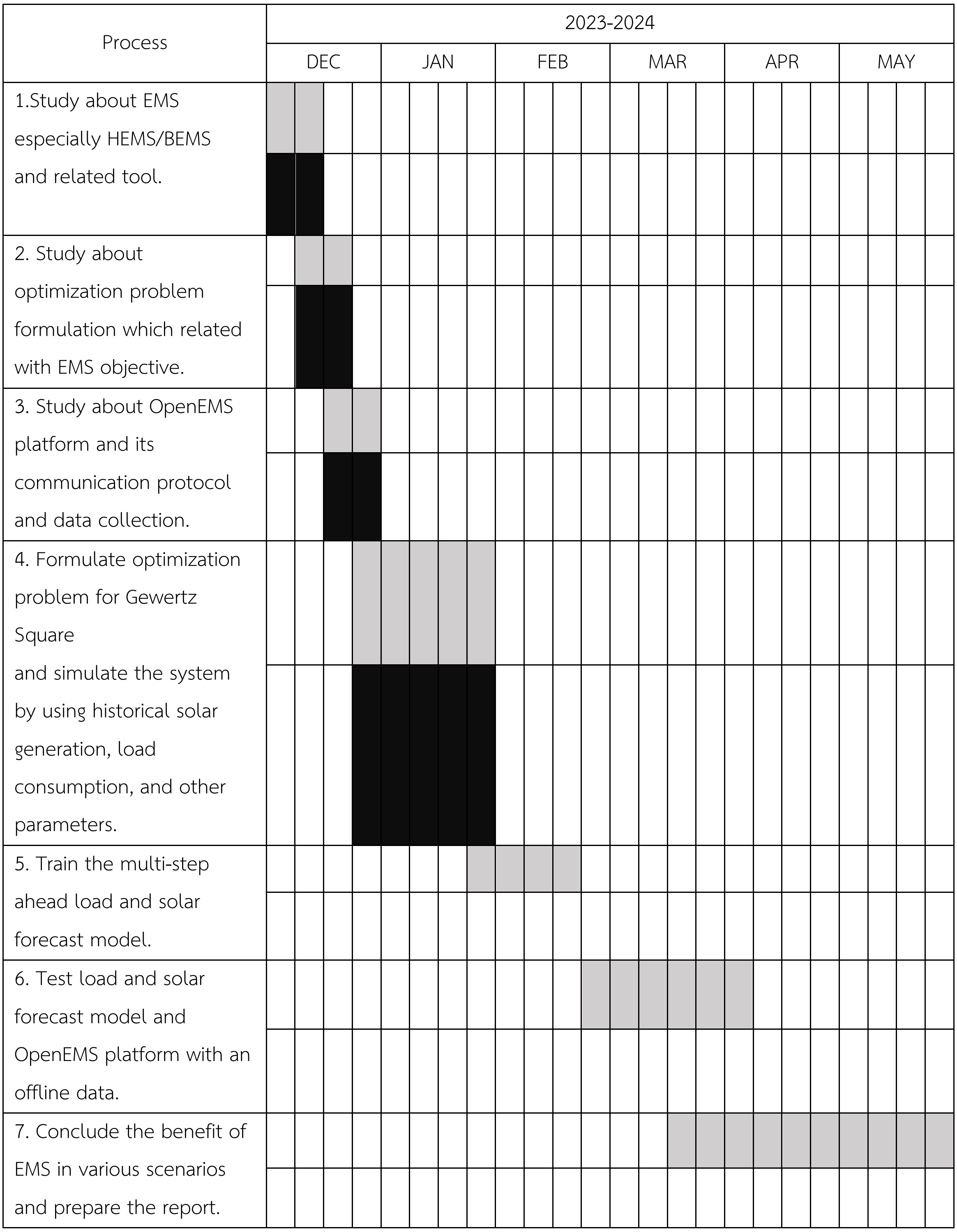
6 Conclusion

6.1 Progress results

Based on preliminary optimization simulation results exploring various economic and operational objectives of the EMS, we have investigated the impact of EMS to the electrical devices in the system. The upcoming step involves implementing these optimization solutions within the OpenEMS platform alongside forecasting load consumption and solar generation.

6.2 Project plans

The plan for this project in the next semester consists of three main parts: the literature review, the construction of a load forecast model and a solar forecast model, and the implementation of the EMS on the OpenEMS platform, as shown in Figure 31.



Grey color means the planned progress of the project
Black color means the current progress of the project.

Figure 31: The Gantt chart of this project.

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7 Appendices

7.1 Appendix A

The histogram depicting expenses saved by EMS 1 under various scenarios illustrates how the EMS impacts the reduction of electricity expenses.

- **High solar & low load scenario**: saved up to 850 THB for TOU 0 and 1150 for TOU 1.
- **Low solar & low load scenario**: saved up to 850 THB for TOU 0 and 950 for TOU 1.
- **Low solar & high load scenario**: saved up to 850 THB for TOU 0 and 950 for TOU 1.

In conclusion, the EMS can reduce the electricity expenses in every dataset and can be saved better in TOU 1.

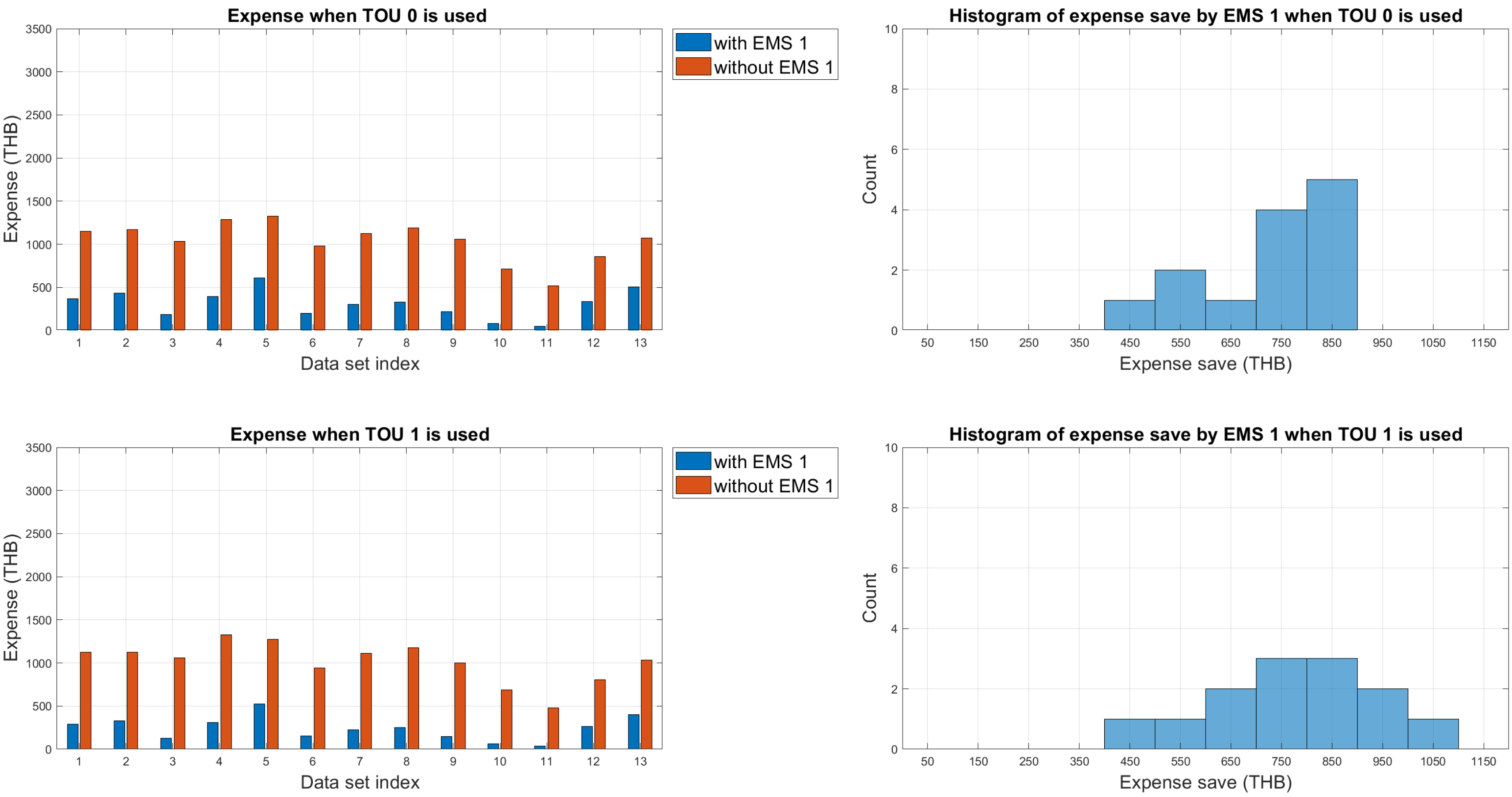

Figure 32: Histogram of expenses saved by EMS 1 in the scenario of **high solar & low load** under TOU 0 and TOU 1.

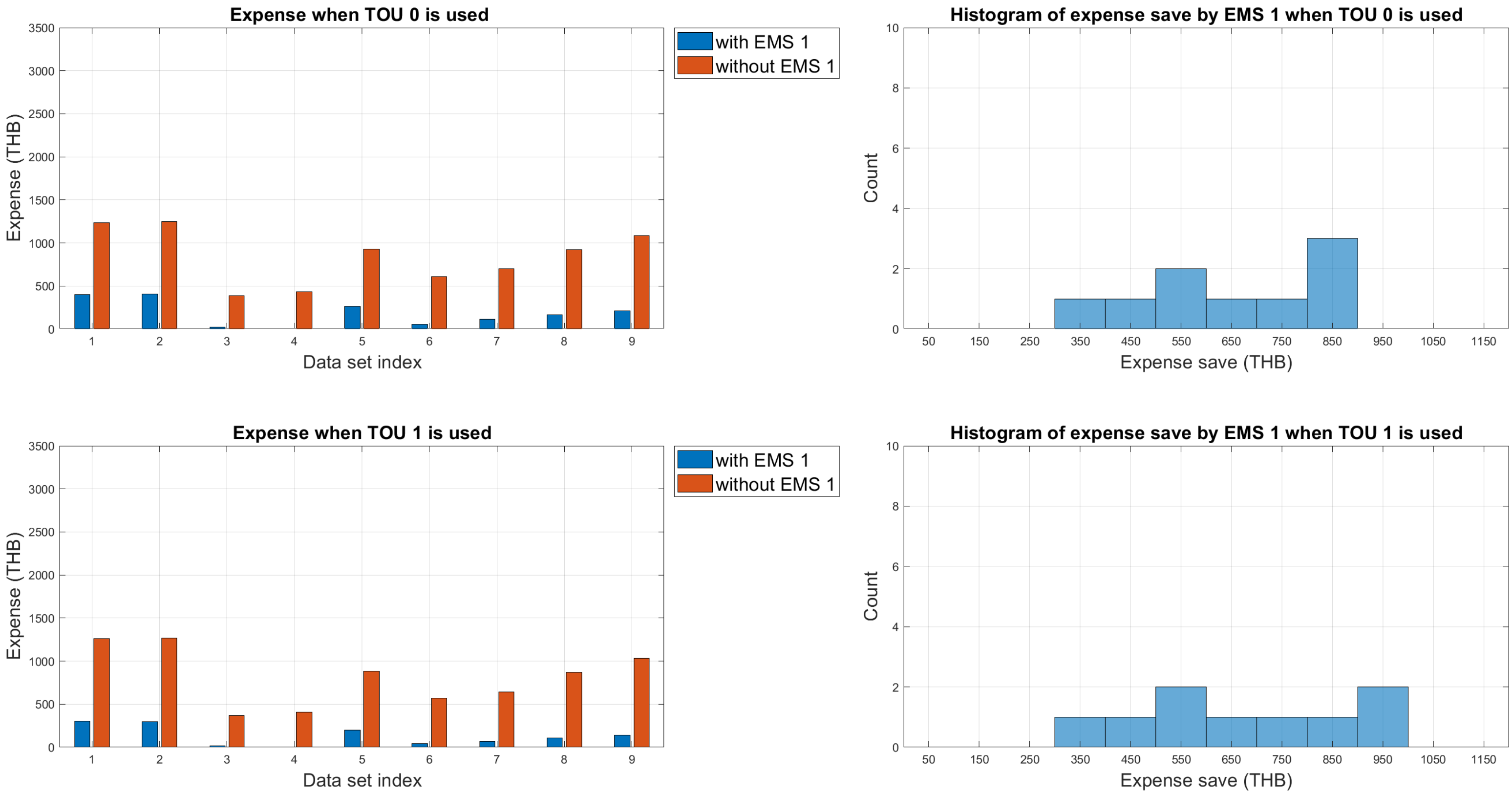

Figure 33: Histogram of expenses saved by EMS 1 in the scenario of **low solar & low load** under TOU 0 and TOU 1.

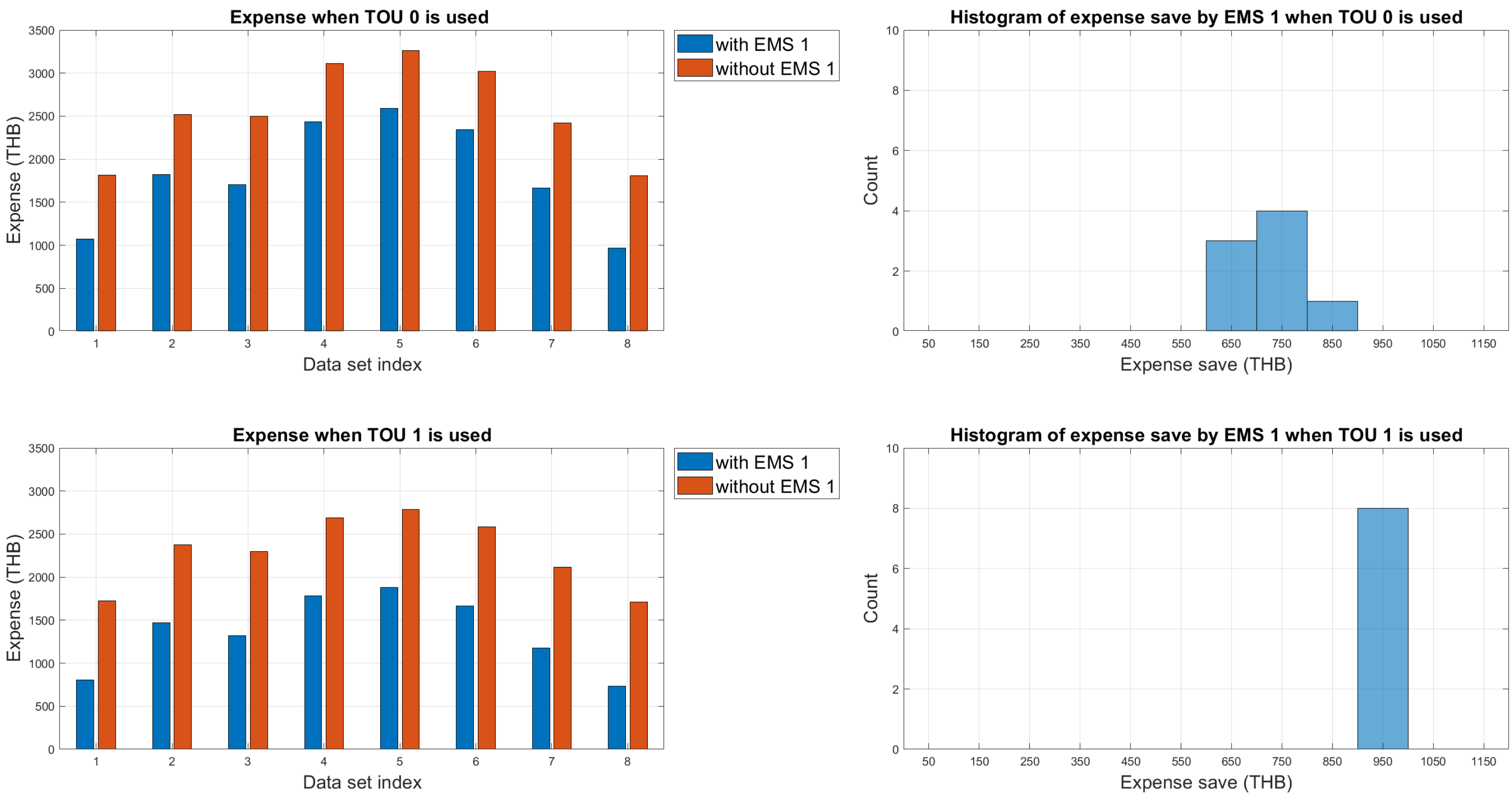

Figure 34: Histogram of expenses saved by EMS 1 in the scenario of **low solar & high load** under TOU 0 and TOU 1.

7.2 Appendix B

The histogram depicting expenses saved by EMS 2 under various scenarios illustrates how the EMS impacts the reduction of electricity expenses.

- **High solar & low load scenario**: saved up to 525 THB for TOU 0 and 675 for TOU 1.
- **Low solar & low load scenario**: saved up to 575 THB for TOU 0 and 675 for TOU 1.
- **Low solar & high load scenario**: saved up to 575 THB for TOU 0 and 775 for TOU 1.

In conclusion, the EMS can reduce the electricity expenses in every dataset and can be saved better in TOU 1.

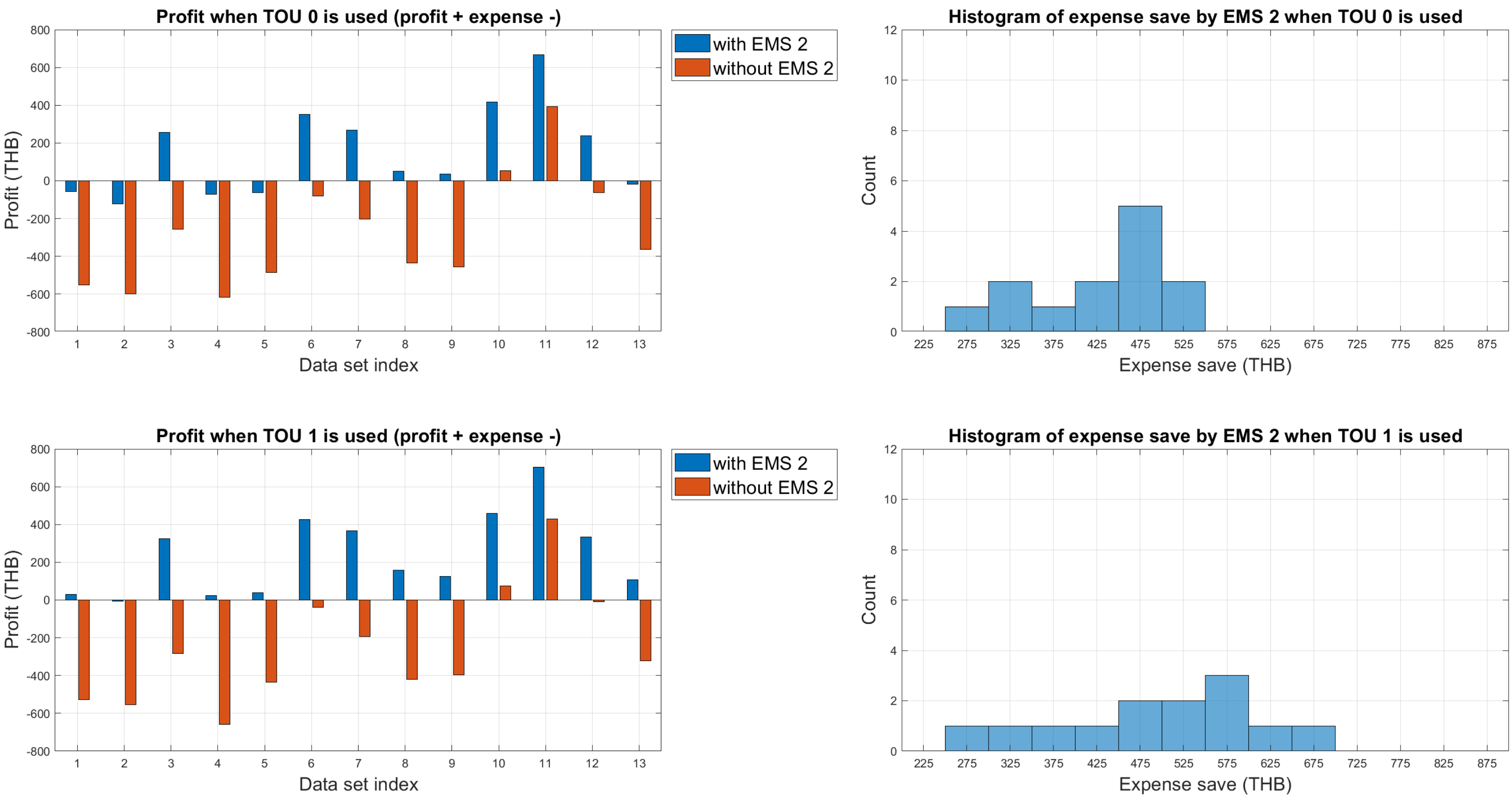

Figure 35: Histogram of expenses saved by EMS 2 in the scenario of **high solar & low load** under TOU 0 and TOU 1.

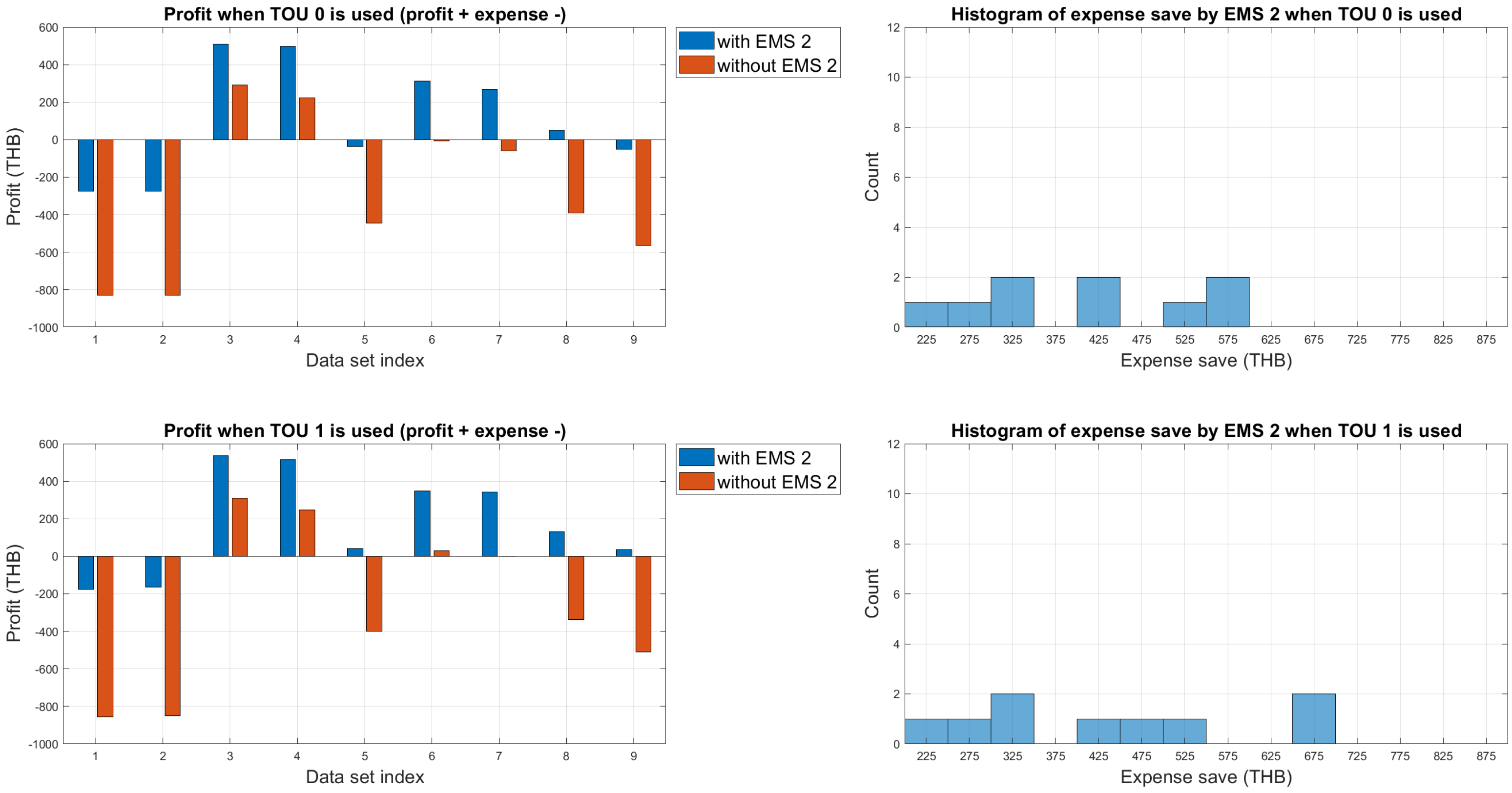

Figure 36: Histogram of expenses saved by EMS 2 in the scenario of **low solar & low load** under TOU 0 and TOU 1.

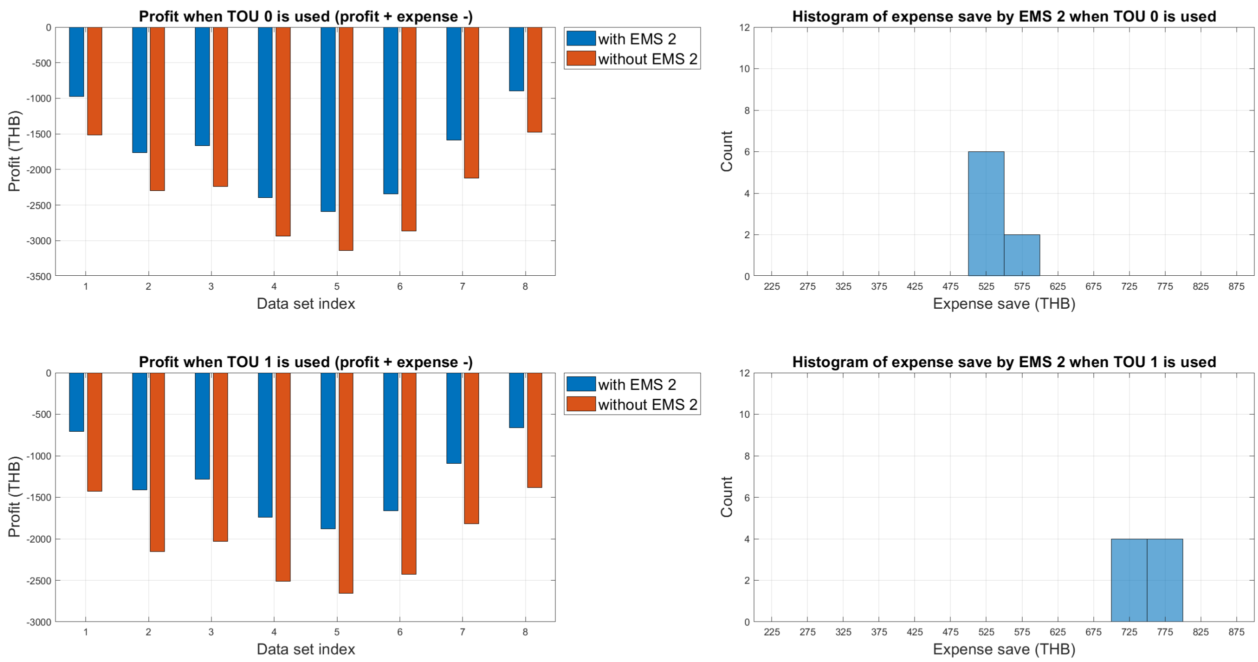

Figure 37: Histogram of expenses savedby EMS 2 in the scenario of **low solar & high load** under TOU 0 and TOU 1.