Simulation of near-real-time energy management system in Gewertz Square environment

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Outline

1. Introduction
2. Background
3. Methodology
4. Result & Discussion
5. Conclusion

INTRODUCTION

MOTIVATION

- **The Gewertz Square building,** under the Department of Electrical Engineering at Chulalongkorn University, plans to install a 50 kW rooftop solar system and two 215 kWh batteries.
- **The goal** is to increase the share of renewable energy used within the building.
- **Due to the intermittent nature of solar energy,** an Energy Management System (EMS) is required.
- **The EMS will manage energy production, consumption, and storage to ensure optimal system performance.**

photo credit: http://www.sustainability.chula.ac.th/th/report/3594/

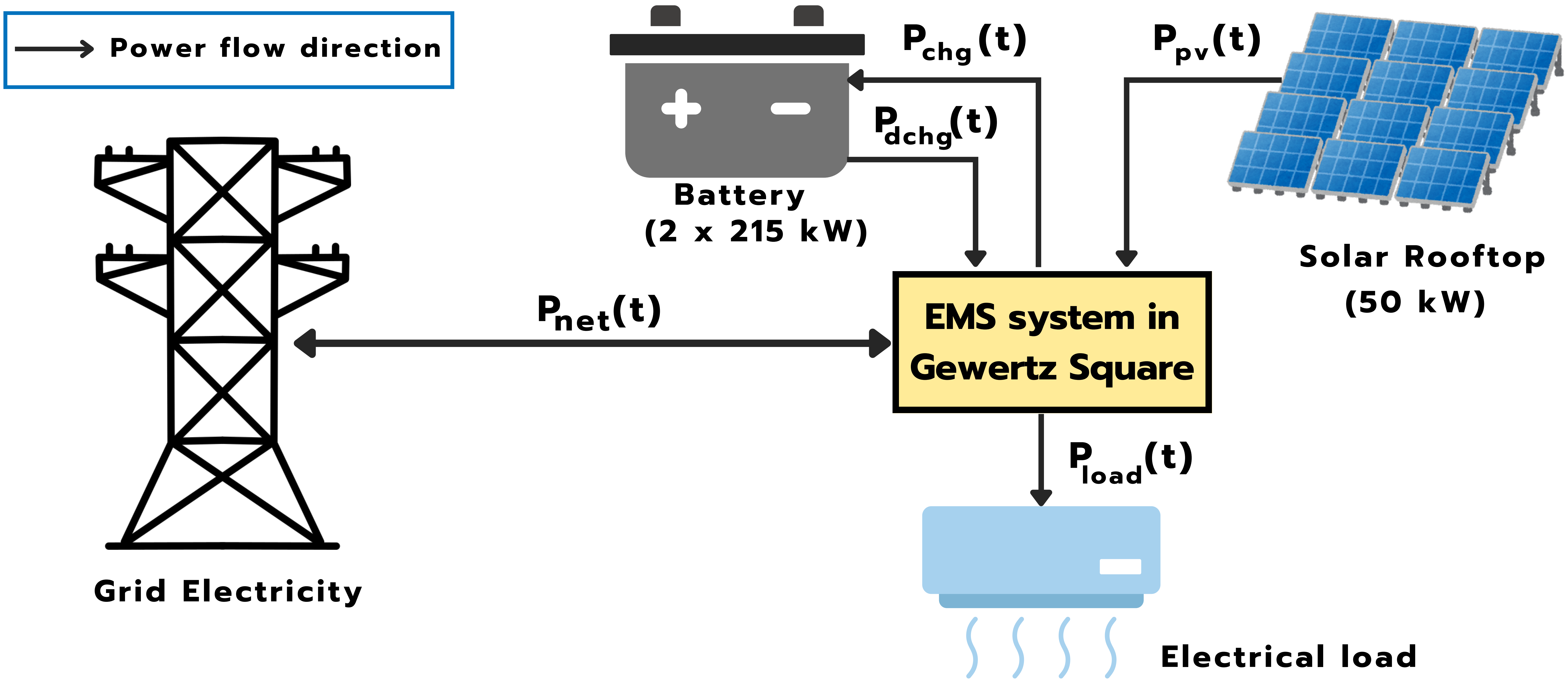
OBJECTIVE

- **To develop and enhance the Energy Management System (EMS) for the Gewertz Square building using real-world simulation, in order to evaluate the performance of the improved EMS from the 2023 project.**

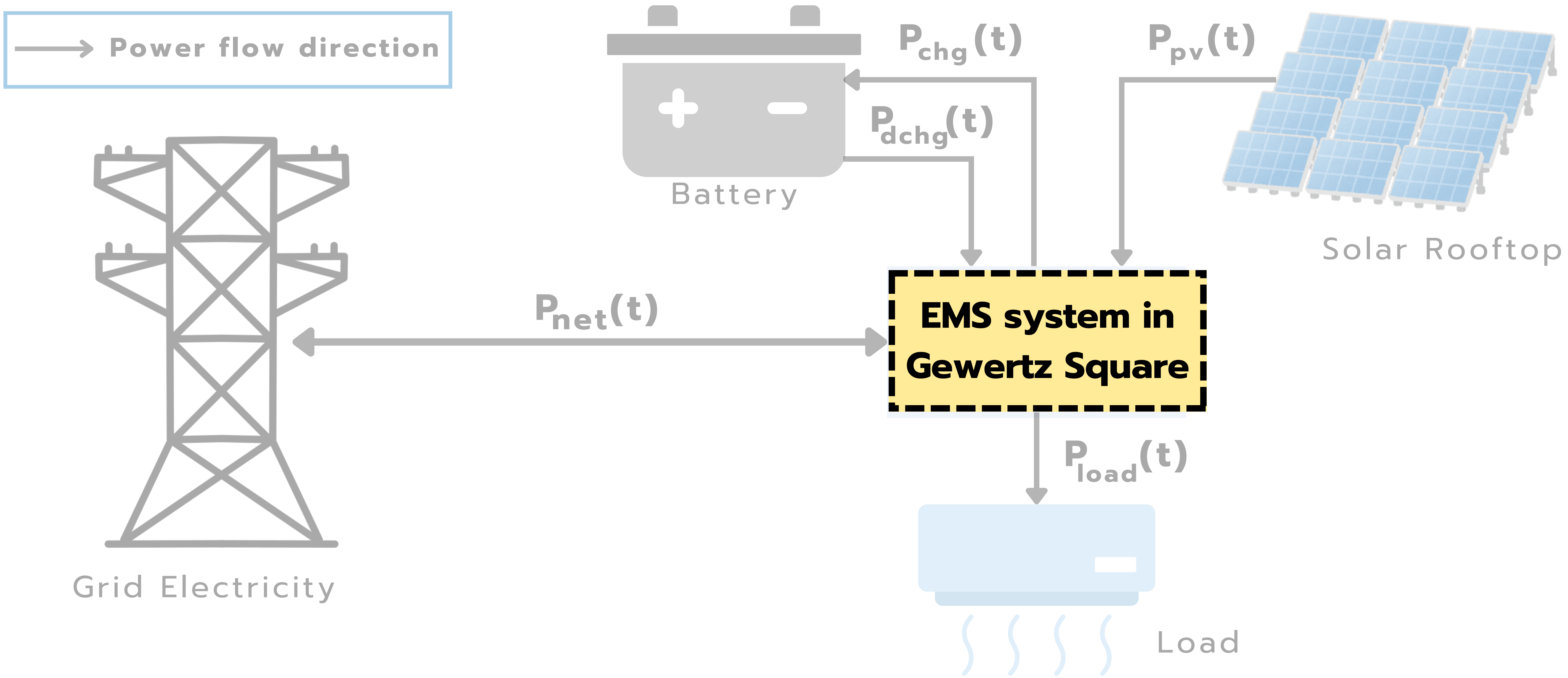
BACKGROUND

Energy Management System (EMS)

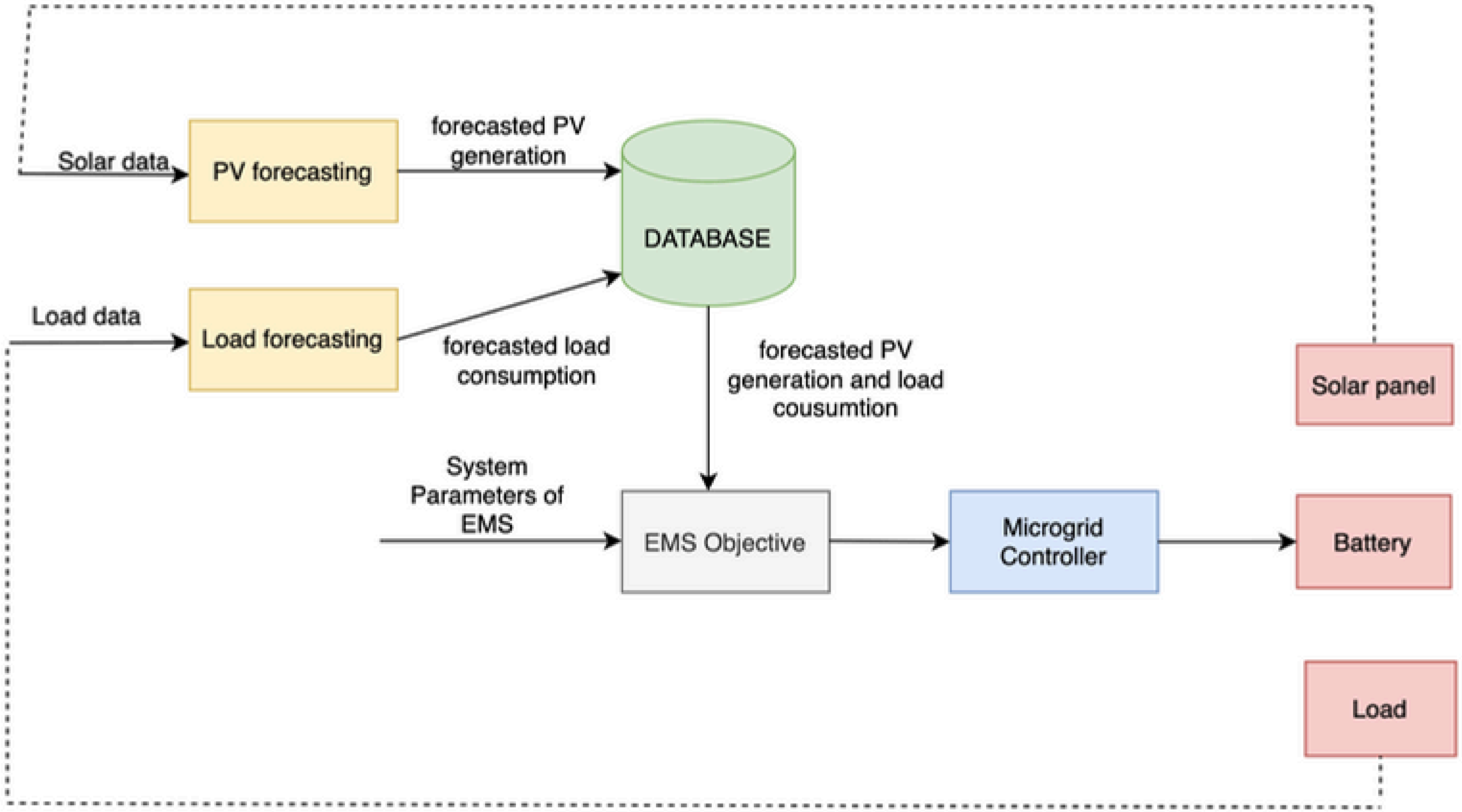
EMS COMPONENTS



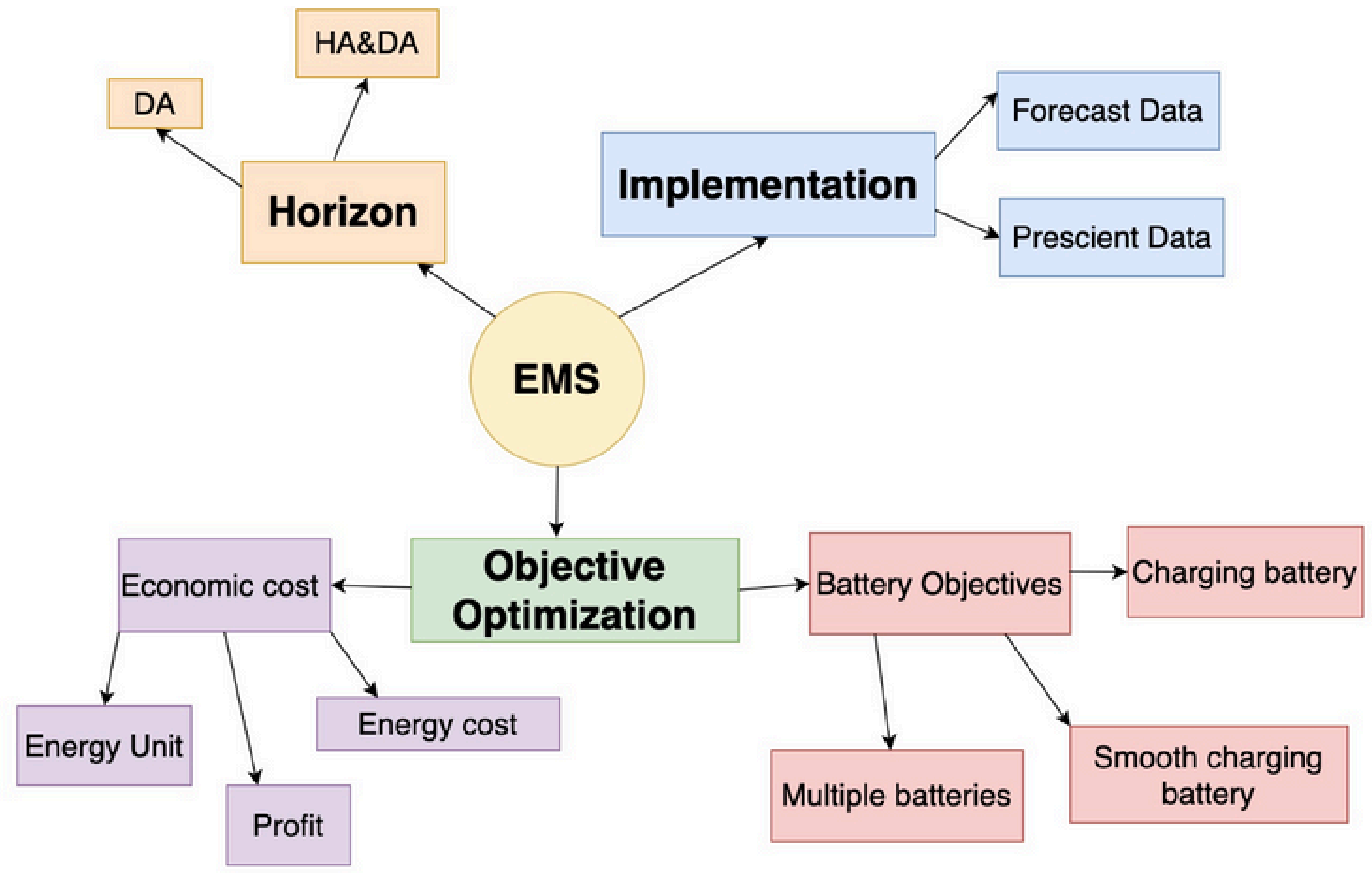
EMS


Power flow direction
Battery
$P_{chg}(t)$
$P_{dchg}(t)$
$P_{pv}(t)$
Solar Rooftop
Grid Electricity
$P_{net}(t)$
EMS system in Gewertz Square
$P_{load}(t)$
Load

EMS


Solar data
PV forecasting
forecasted PV generation
DATABASE
Load data
Load forecasting
forecasted load consumption
forecasted PV generation and load cousumtion
Solar panel
System Parameters of EMS
EMS Objective
Microgrid Controller
Battery
Load

EMS DIAGRAM

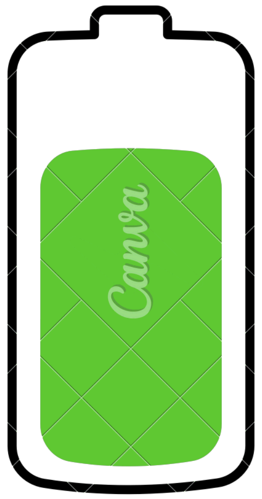

HA&DA
DA
Horizon
Implementation
Forecast Data
Prescient Data
EMS
Objective Optimization
Economic cost
Battery Objectives
Charging battery
Energy Unit
Energy cost
Profit
Multiple batteries
Smooth charging battery

EMS

The results show that implementing the EMS leads to greater electricity cost savings and higher profit compared to the scenario without EMS.

BATTERY

THE DYNAMIC EQUATION CONSTRAINT OF BATTERY



$$\mathrm{SoC}_i(t+1) = \mathrm{SoC}_i(t) + \frac{100}{\mathrm{BattCapacity}}\left(\eta_c P^{(i)}_{\mathrm{chg}}(t)\Delta t - \frac{P^{(i)}_{\mathrm{dchg}}(t)\Delta t}{\eta_d}\right) \quad (1)$$

where :

$\mathrm{SoC}_i(t)$: The state of charge (SoC) of battery i

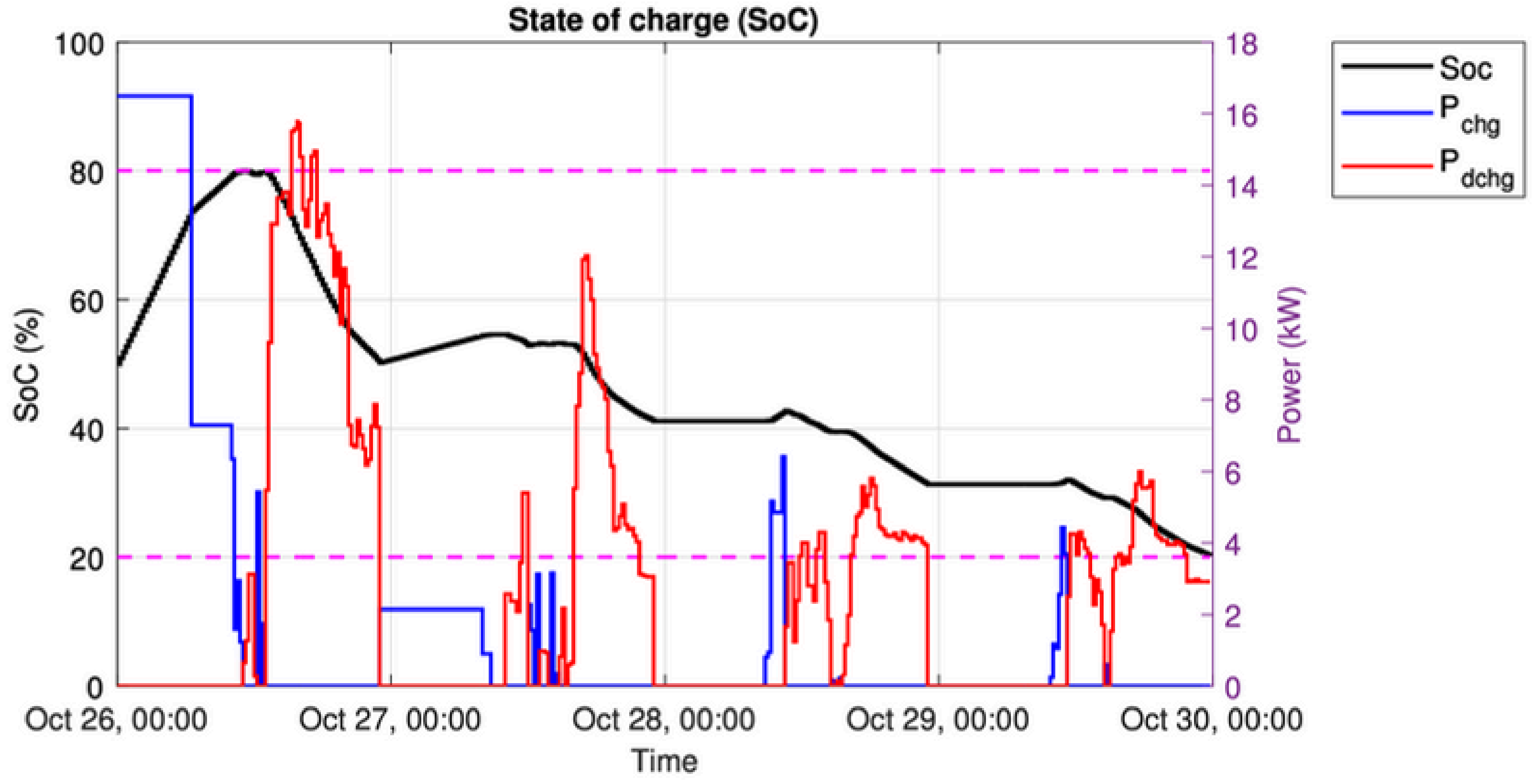
$P^{(i)}_{\mathrm{chg}}(t)$: charge power of battery i

$P^{(i)}_{\mathrm{dchg}}(t)$: discharge power of battery i

BattCapacity :battery Capacity

Δt : time resolution

$\eta_d, \eta_c < 1$: Charging/discharging efficiency



BATTERY CONSTRAINT

The limitation of charging and discharging the battery constraints

$$P_{\text{chg}}^{(i)}(t) \leq \text{MAX CHARGE RATE}, \quad t = 1, 2, \ldots, T \quad i = 1, 2, \ldots, N_{\text{Batt}} \qquad (2)$$

$$P_{\text{dchg}}^{(i)}(t) \leq \text{MAX DISCHARGE RATE}, \quad t = 1, 2, \ldots, T \quad i = 1, 2, \ldots, N_{\text{Batt}} \qquad (3)$$

The limitation of maximum state of charge and minimum SoC constraint

$$\text{SoC}_{\min,i} \leq \text{SoC}_i(t) \leq \text{SoC}_{\max,i} \qquad (4)$$

Battery terminal SoC constraint

$$\text{SoC}_i(T) \geq 40 \qquad (5)$$

BATTERY

Batteries

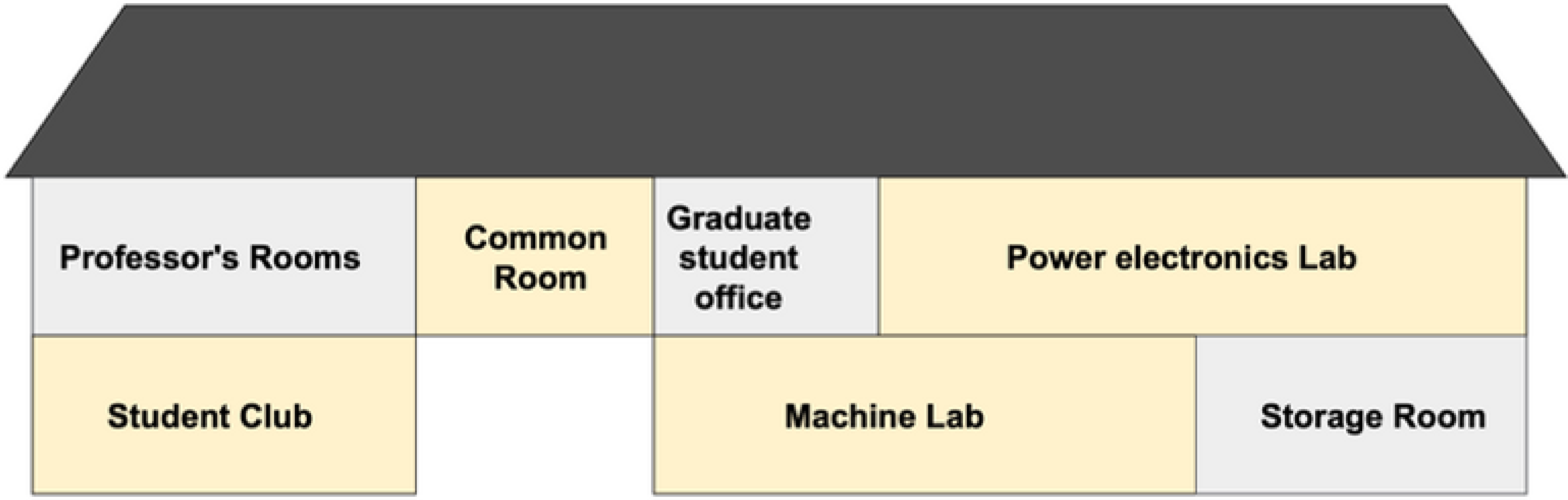
- The CEPT research team plans to purchase 2 battery units.

Jinko battery with a capacity of 215 kWh

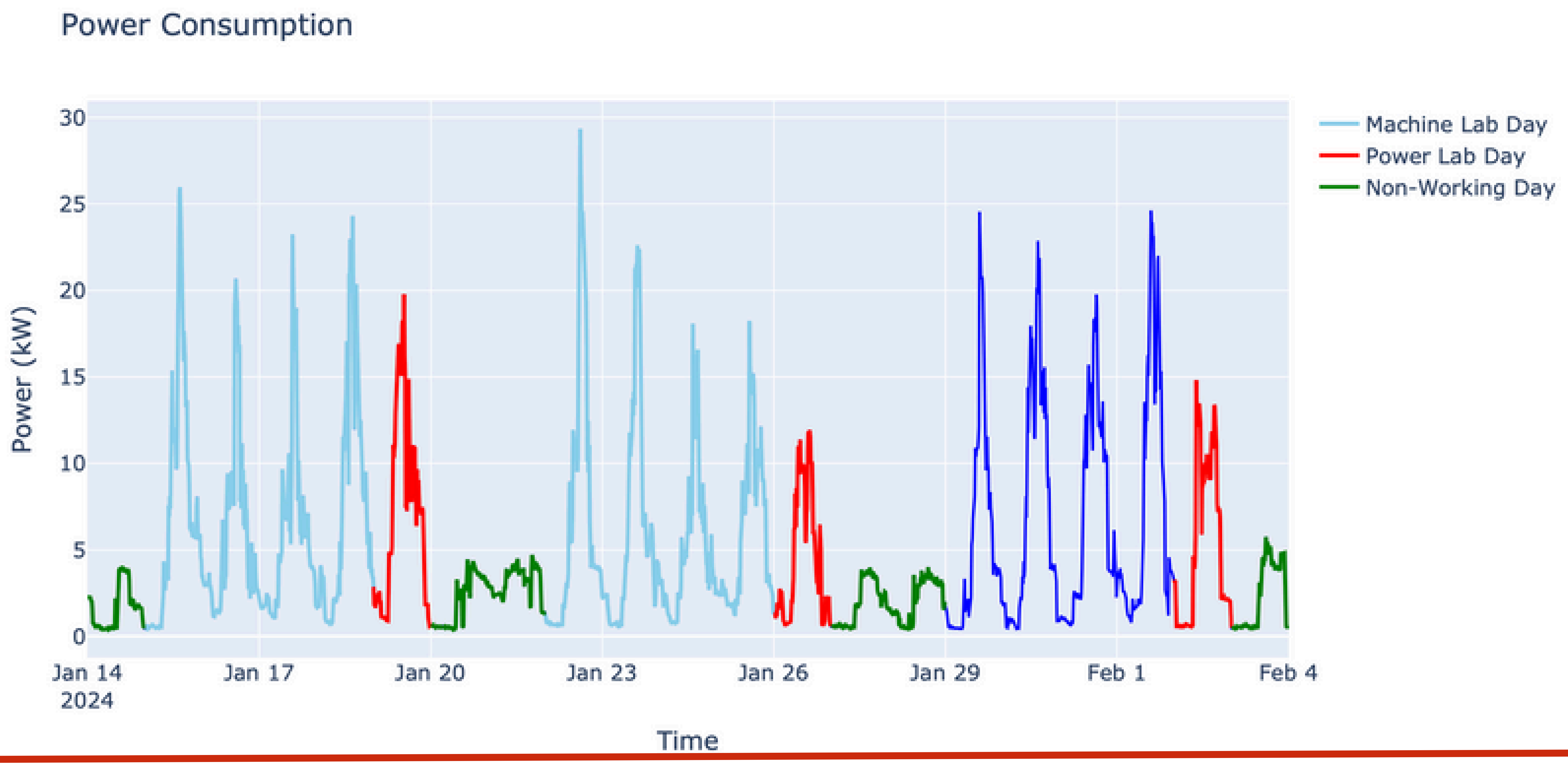
https://jinkosolarenergystorage.com.au/product/jks-215klaa-100plaa/

ELECTRICAL LOAD

The electricity load at Gewertz Square building from March 2023 to December 2024 peaked at approximately 35 kW.



ELECTRICAL LOAD

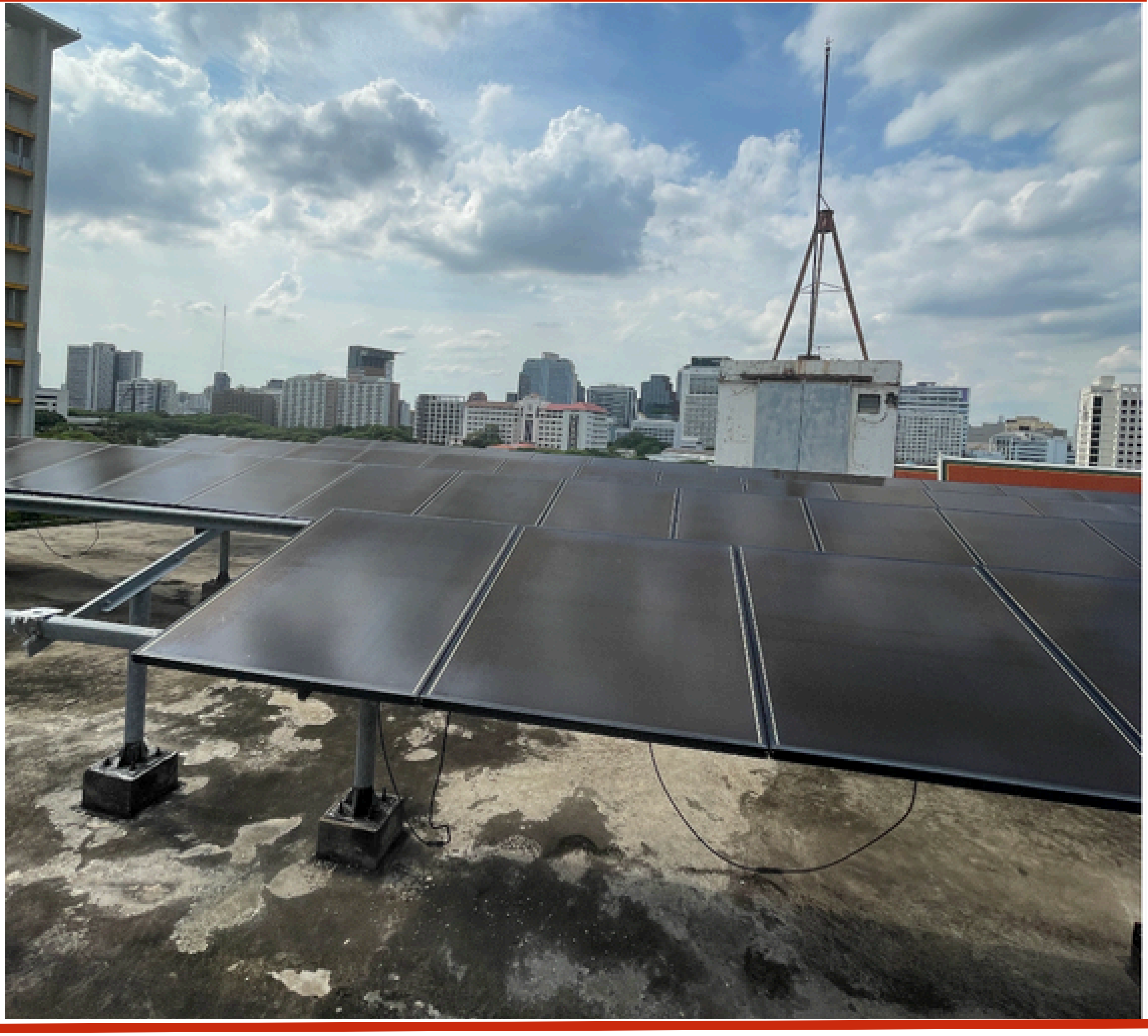


SOLAR ROOFTOP

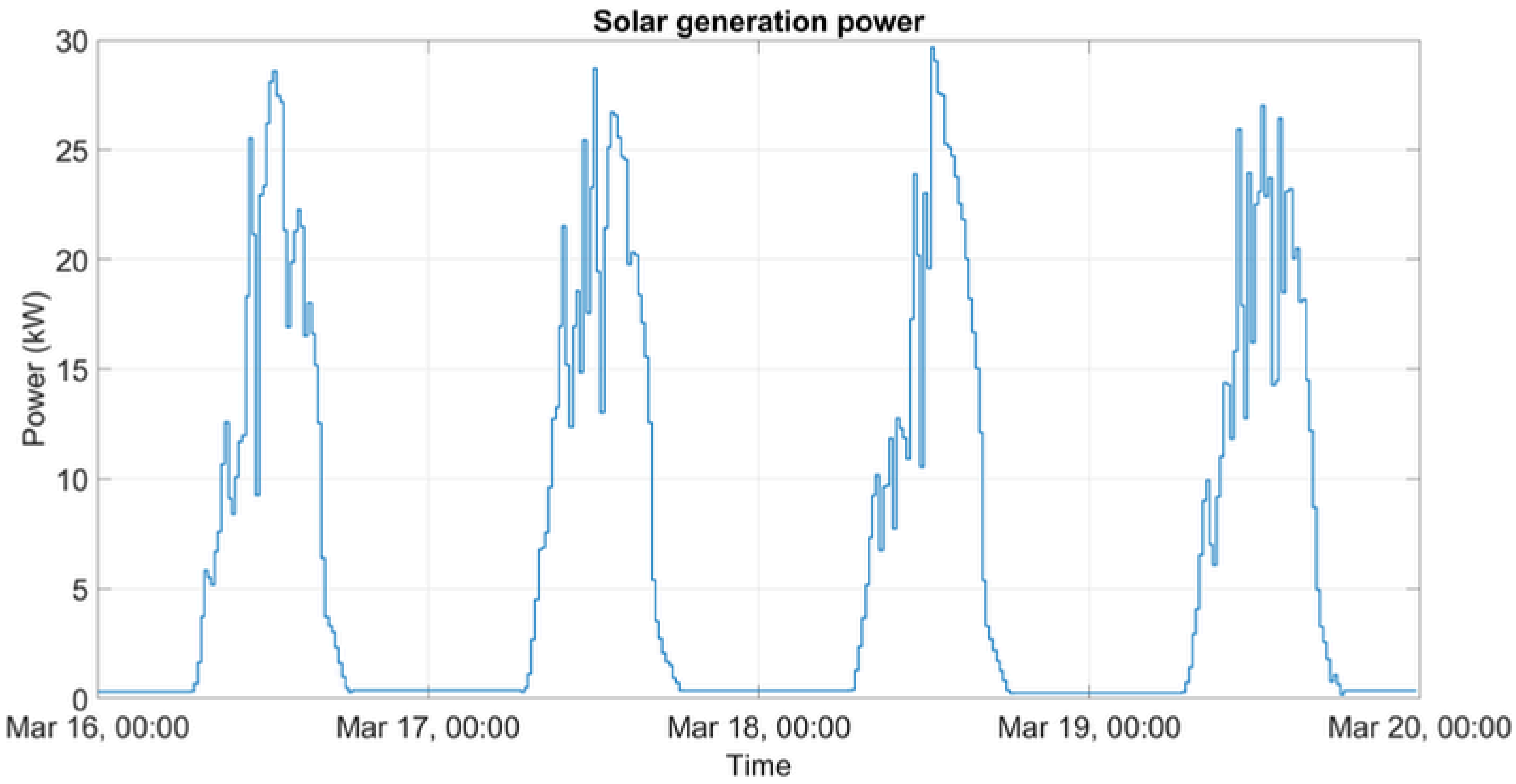
- The solar panel system connected to the **Boonrawd building** with a total capacity of 8 kW.

- The solar panels to be installed at **Gewertz Square building** have a maximum generation capacity of 50 kW.

- The power generation data from the Boonrawd building's solar panels were scaled up to match a maximum capacity of 50 kW

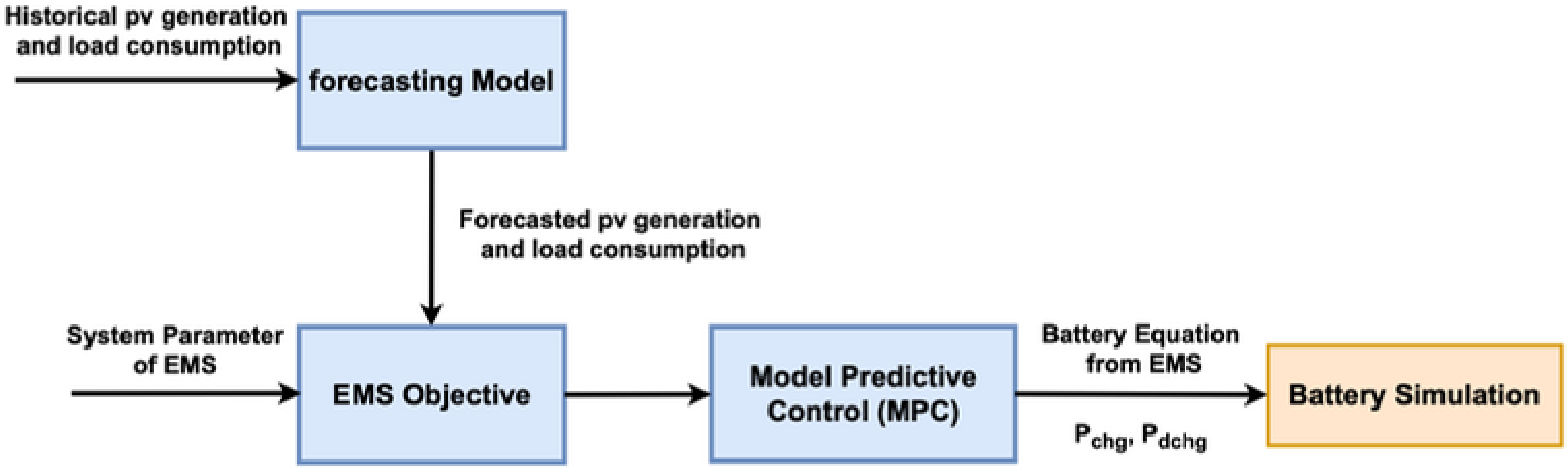


SOLAR ROOFTOP



METHODOLOGY

METHODOLOGY



EMS OPTIMIZATION

EMS OPTIMIZATION

EMS DECISION VARIABLES

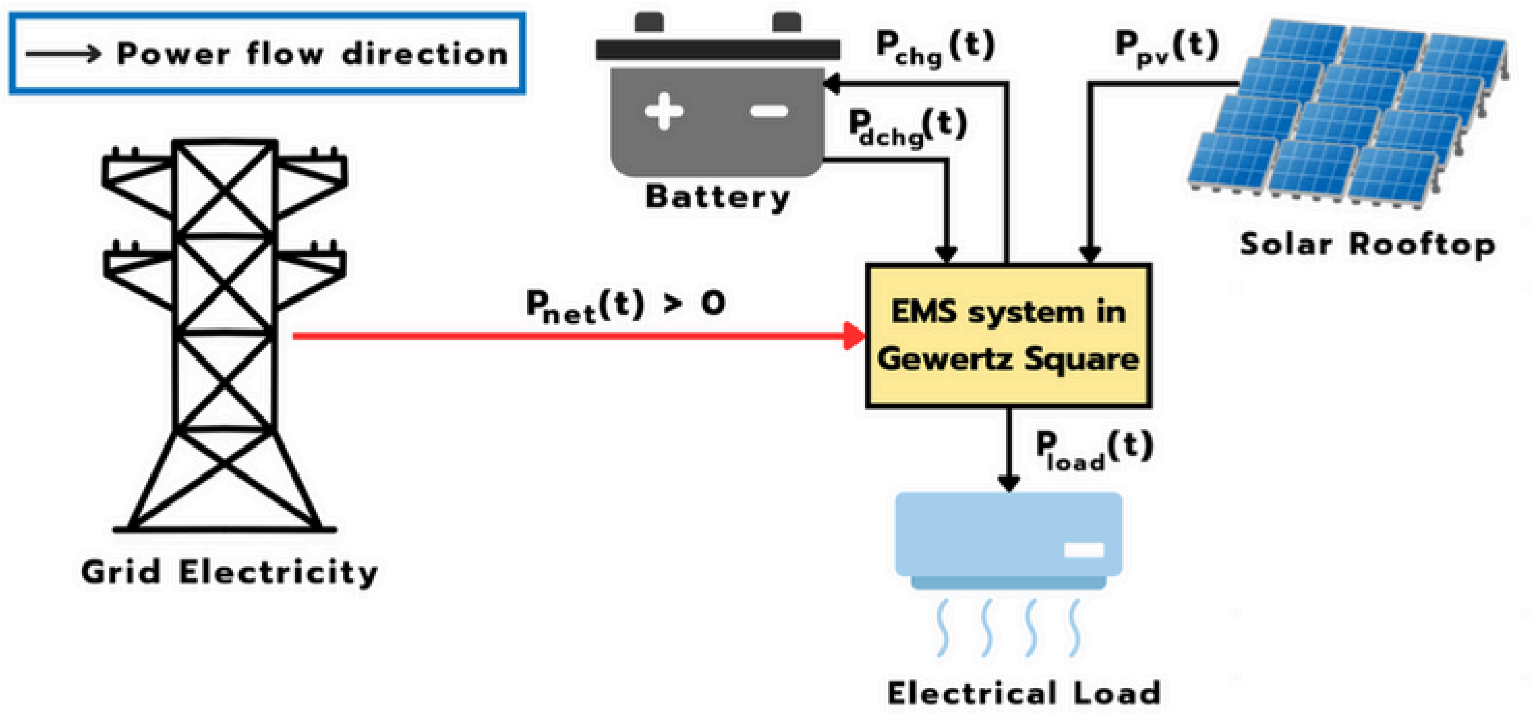
Variable	Description	Unit
$P_{\text{net}}(t)$	Consumption power - Generation power	kW
$P^{(i)}_{\text{chg}}(t)$	Power charged from the i^{th} battery	kW
$P^{(i)}_{\text{dchg}}(t)$	Power discharged from the i^{th} battery	kW
$\text{SoC}_i(t)$	State of charge of i^{th} battery	%

EMS CONSTRAINTS

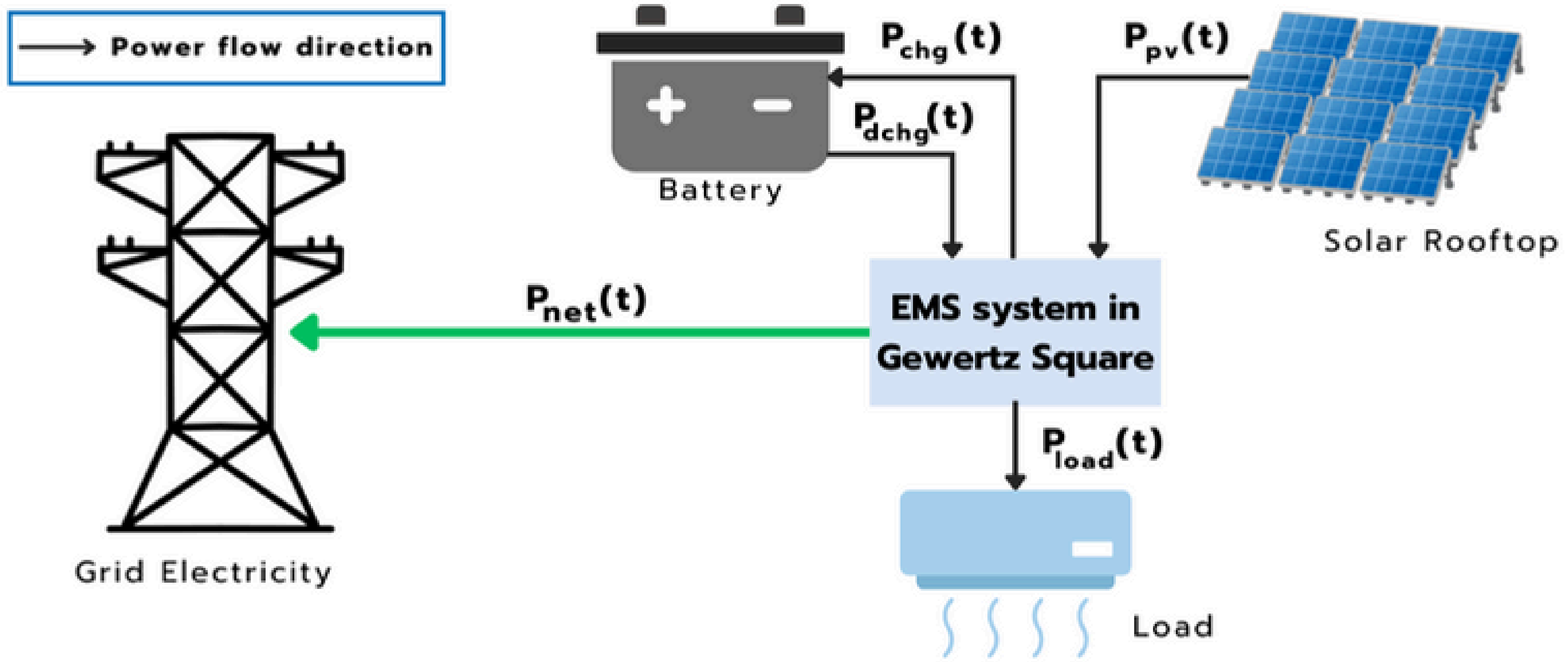
POWER BALANCE CONSTRAINTS

$$P_{\text{net}}(t) = P_{\text{load}}(t) - P_{\text{pv}}(t) + \sum_{i=1}^{n} \left(P_{\text{chg}}^{(i)}(t) - P_{\text{dchg}}^{(i)}(t) \right), \qquad t = 1,2,\ldots,T \qquad (6)$$

- $P_{\text{net}} > 0$: The system needs to draw electricity from the grid



- $P_{\text{net}} < 0$: The system does not need to draw electricity from the grid and can sell electricity back to it.



EMS CONSTRAINTS

Power balance constraints (1)

Battery charge/discharge constraints (2)-(3)

Battery’s SoC constraints (4)

Battery’s terminal SoC (5)

Constraints (1)–(5) are linear in the variables Pnet, Pchg, Pdchg and SoC ,which allows the problem to be formulated and solved as a linear program

EMS Objective

Economic **Battery Objective**

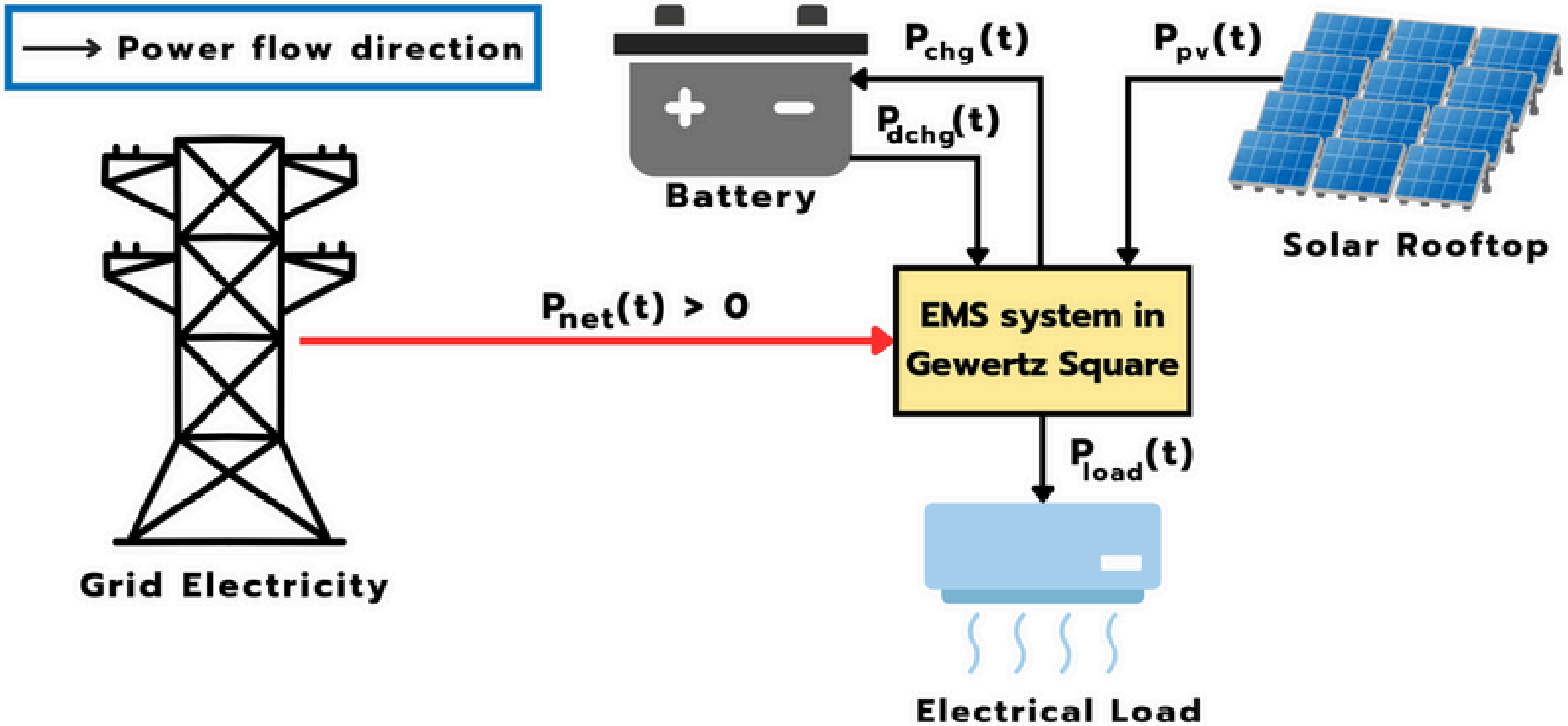
$$\begin{aligned}\text{minimize} \quad & \boxed{J_{\text{cost}}} + \boxed{w_m J_{\text{multibatt}} + w_s J_{\text{smooth charge}} + w_c J_{\text{charge batt}}} \\ \text{subject to} \quad & \text{Power balance constraints} \quad (6) \\ & \text{Battery dynamic} \quad (1) \\ & \text{Battery charge/discharge constraints} \quad (2)\text{-}(3) \\ & \text{Battery's terminal SOC} \quad (5) \\ & \text{Battery's SOC constraint} \quad (4)\end{aligned}$$

ECONOMIC EMS

ECONOMIC EMS

- **Energy Unit**

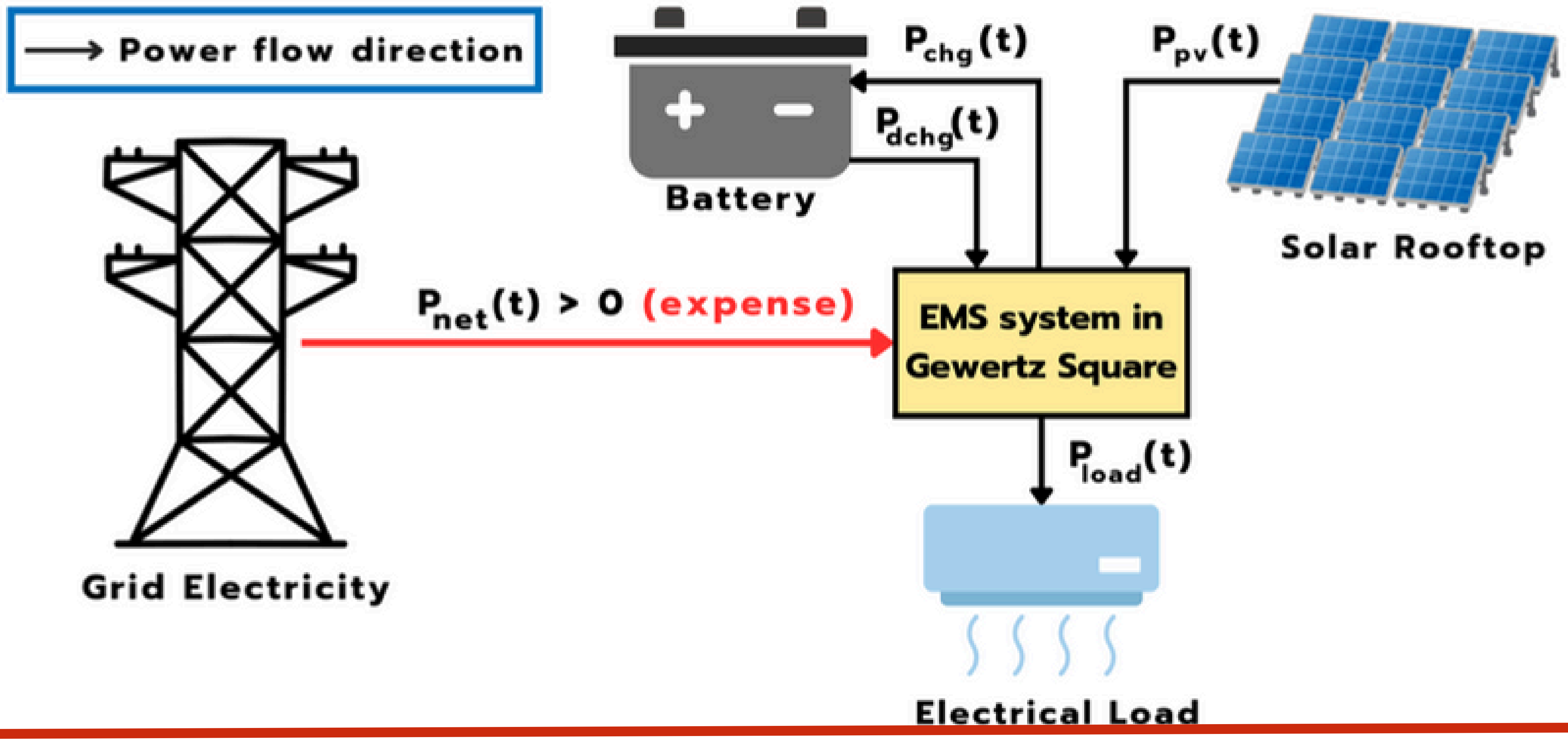
$$J_{cost} = \text{Energy unit} = \sum_{t=1}^{T} \max(0, P_{net}(t))\Delta t \qquad (11)$$



ECONOMIC EMS

- **Energy Cost**

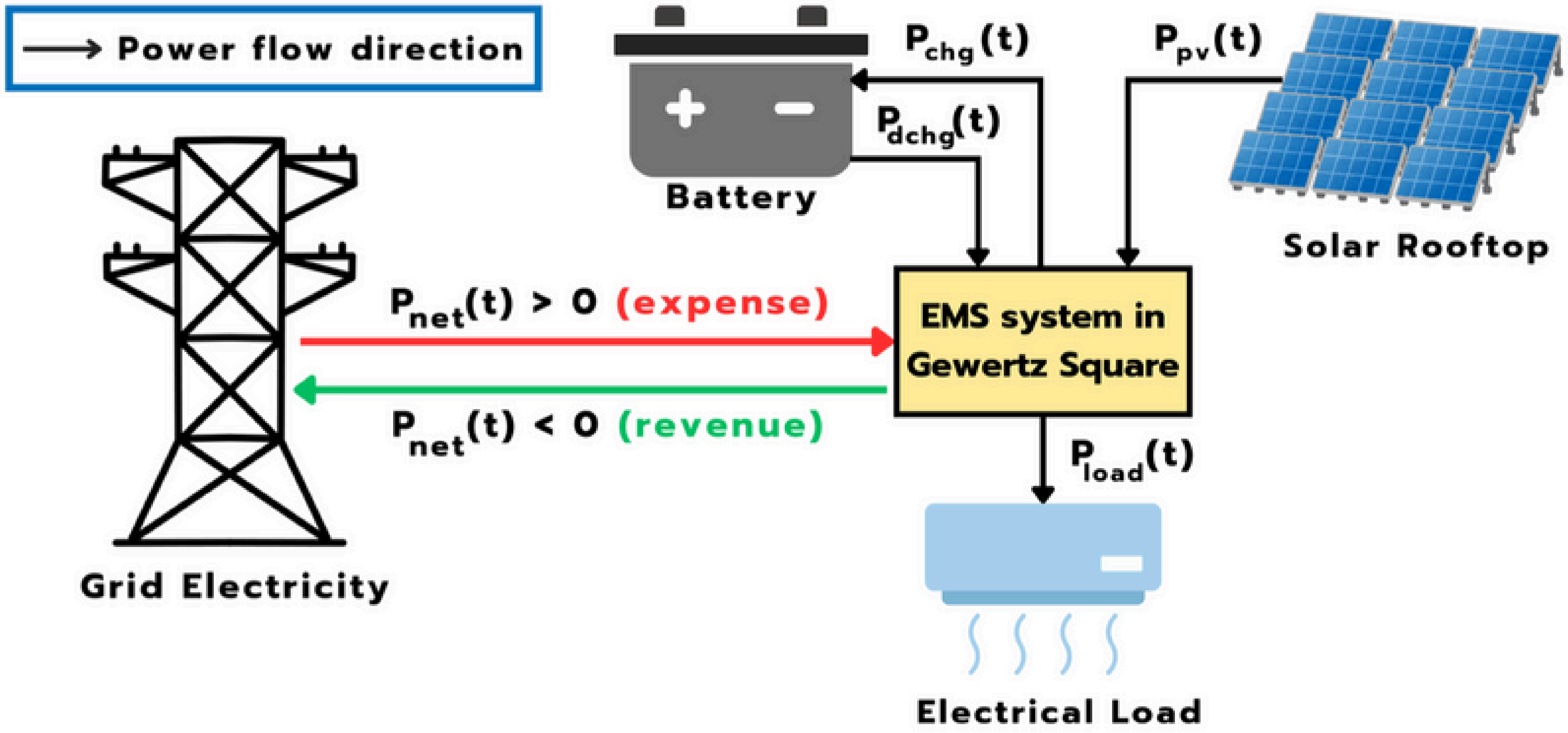
$$J_{\text{cost}} = \text{Energy cost} = \sum_{t=1}^{T} b(t)\max(0, P_{\text{net}}(t))\Delta t \qquad (12)$$



ECONOMIC EMS

- **Profit**

$$J_{\text{cost}} = \sum_{t=1}^{T} \left[b(t)\max(0, P_{\text{net}}(t)) - s(t)\max(0, -P_{\text{net}}(t)) \right] \Delta t \qquad (13)$$

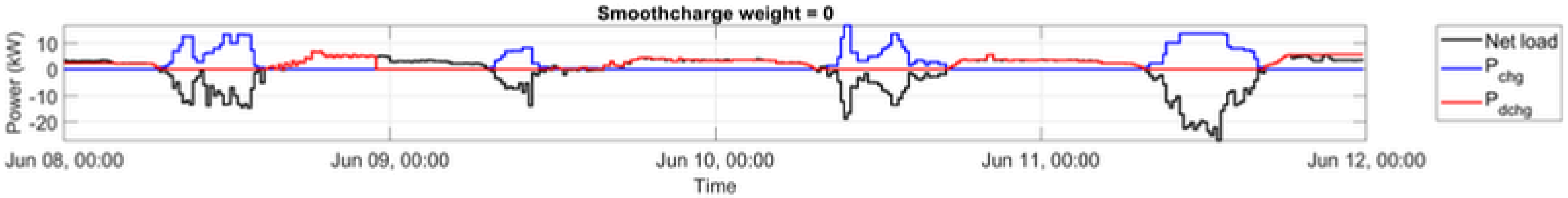


BATTERY OBJECTIVE

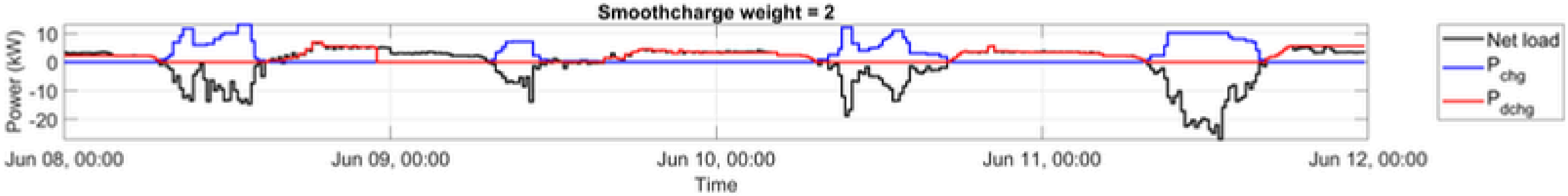
BATTERY OBJECTIVE

- **Smooth charging**

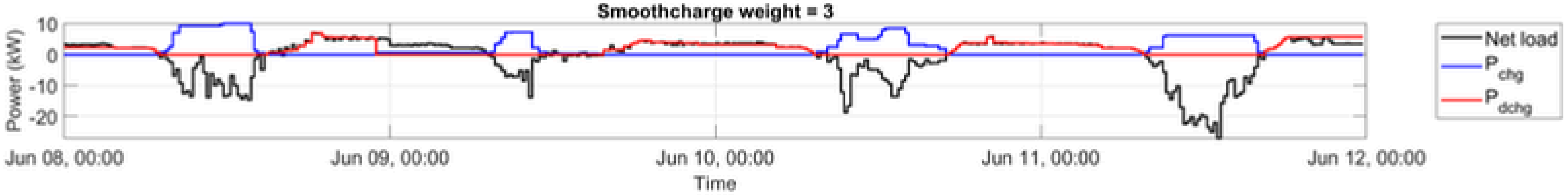
$w_s = 0$



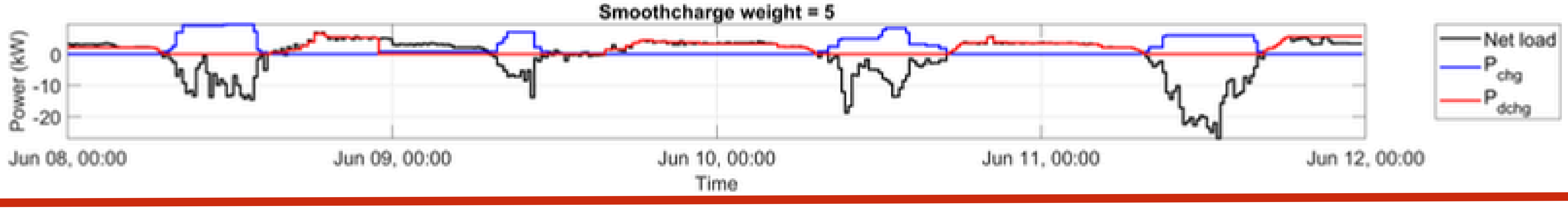
$w_s = 2$



$w_s = 3$

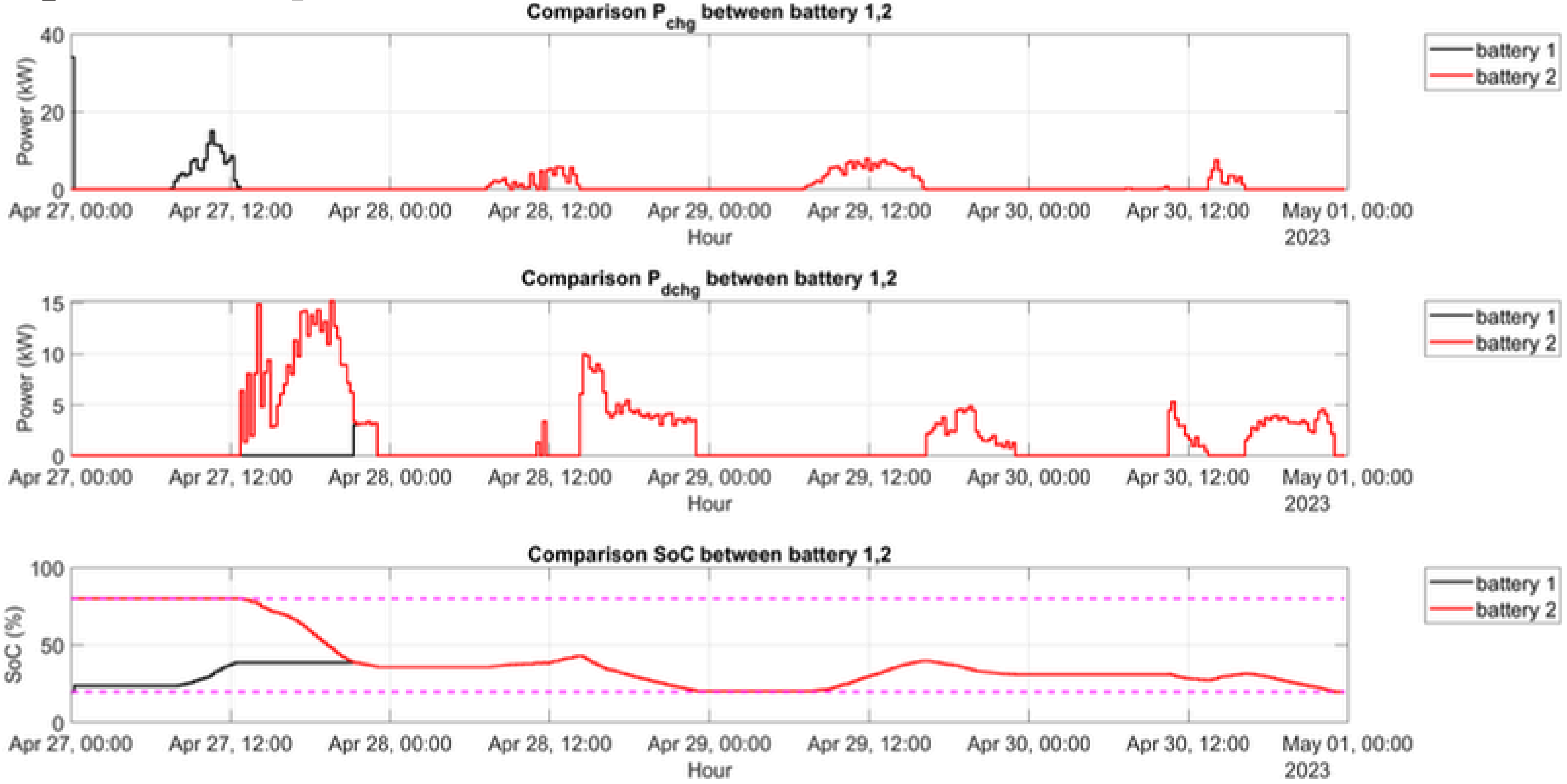


$w_s = 5$



BATTERY OBJECTIVE

- **Managing multiple batteries**



BATTERY OBJECTIVE

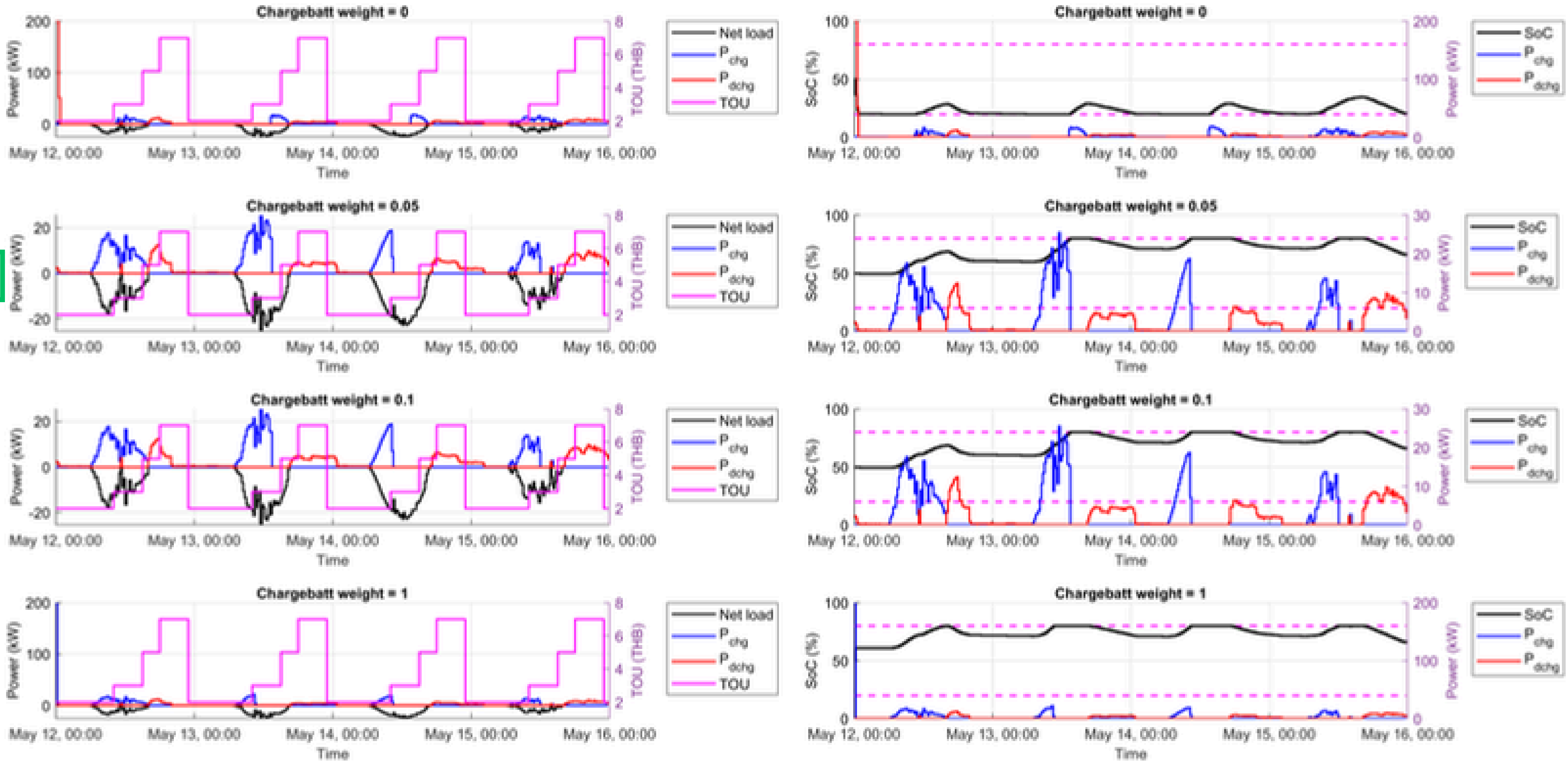
- **Encouragement to charge battery**

$\boxed{w_c = 0}$

$\boxed{w_c = 0.05}$

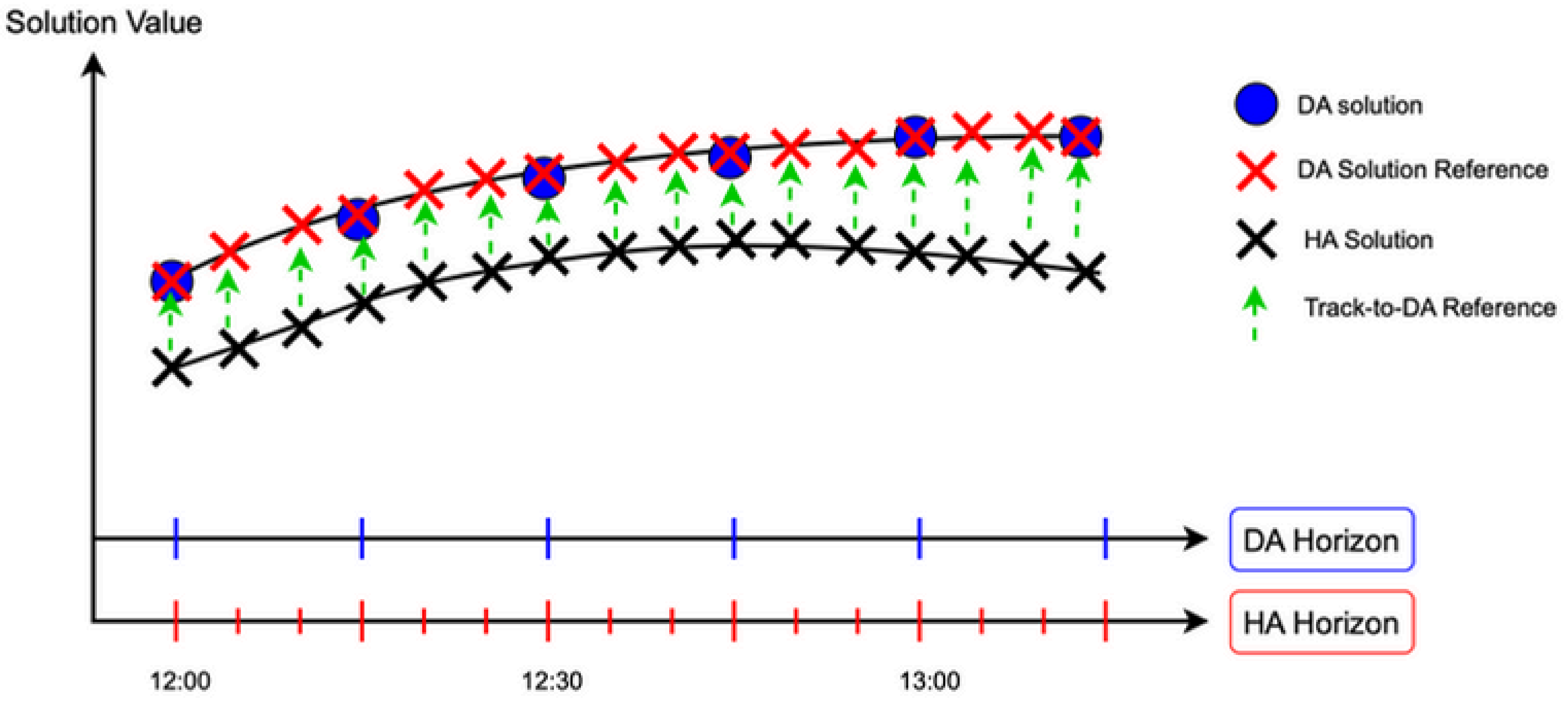
$\boxed{w_c = 0.1}$

$\boxed{w_c = 1}$



DAY-AHEAD TRACKING FUNCTION (TRACK DA)

- **Short-sighted focus:** Since the Hour-Ahead plan focuses on short-term decision-making, it often overlooks long-term impacts.



TRACK DA

- **Solution through TrackDA:** This is achieved by integrating the TrackDA function to align Hour-Ahead decisions with Day-Ahead plans.

$$J_{\text{trackDA}} = \sum_{t=1}^{T} \left\{ w_{\text{chg}} \sum_{i=1}^{2} \frac{\left| P^{(i)}_{\text{chg,HA}}(t) - P^{(i)}_{\text{chg,ref}}(t) \right|}{R_{\text{chg,max}}} + w_{\text{dchg}} \sum_{i=1}^{2} \frac{\left| P^{(i)}_{\text{dchg,HA}}(t) - P^{(i)}_{\text{dchg,ref}}(t) \right|}{R_{\text{dchg,max}}} \right\} \quad (14)$$

EMS OPTIMIZATION

DA EMS OPTIMIZATION PROBLEM

minimize	$J_{\text{cost}} + w_m J_{\text{multibatt}} + w_s J_{\text{smooth charge}} + w_c J_{\text{charge batt}}$
subject to	Power balance constraints (6)
	Battery dynamic (1)
	Battery charge/discharge constraints (2)-(3)
	Battery's terminal SOC (5)
	Battery's SOC constraint (4)

IT CAN BE FORMULATED AS A LINEAR PROGRAMING

EMS OPTIMIZATION

HA EMS OPTIMIZATION PROBLEM

$$
\begin{array}{ll}
\text{minimize} & J_{\text{cost}} + w_m J_{\text{multibatt}} + w_s J_{\text{smooth charge}} + w_c J_{\text{charge batt}} + \boxed{J_{\text{trackDA}}} \\
\text{subject to} & \text{Power balance constraints} \quad (6) \\
& \text{Battery dynamic} \quad (1) \\
& \text{Battery charge/discharge constraints} \quad (2)\text{-}(3) \\
& \text{Battery's terminal SOC} \quad (5) \\
& \text{Battery's SOC constraint} \quad (4)
\end{array}
$$

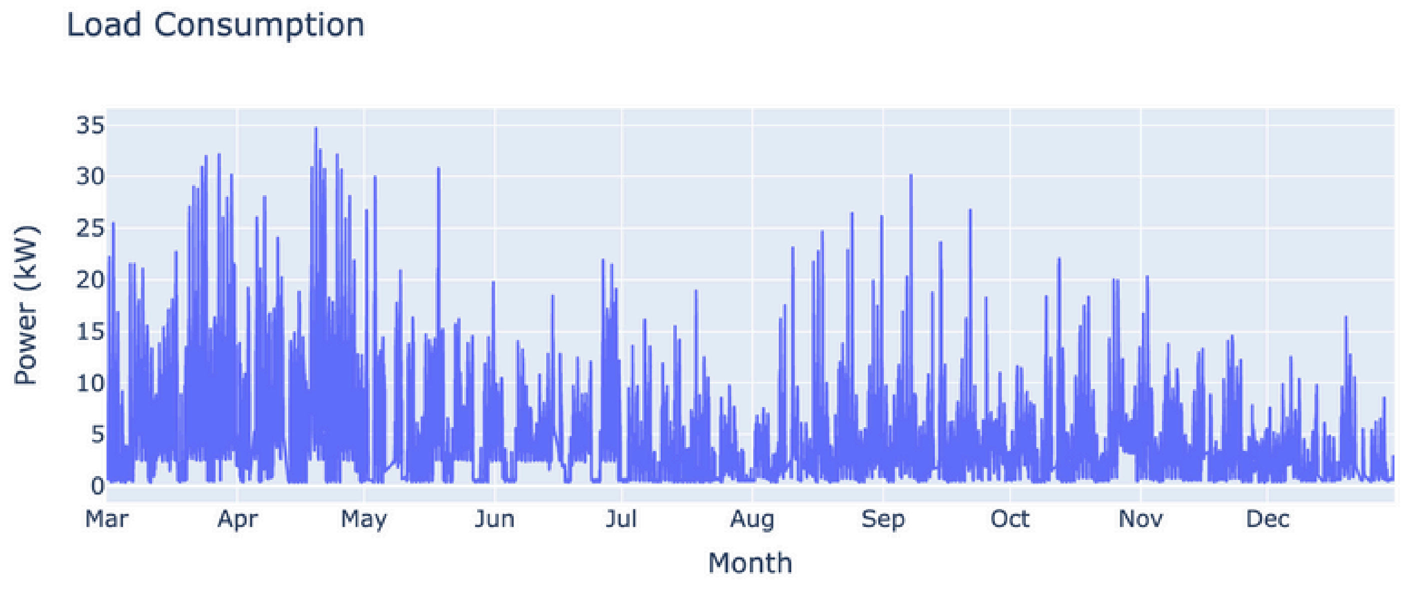
IT CAN BE FORMULATED AS A LINEAR PROGRAMING

DATA PREPARATION

DATA PREPARATION

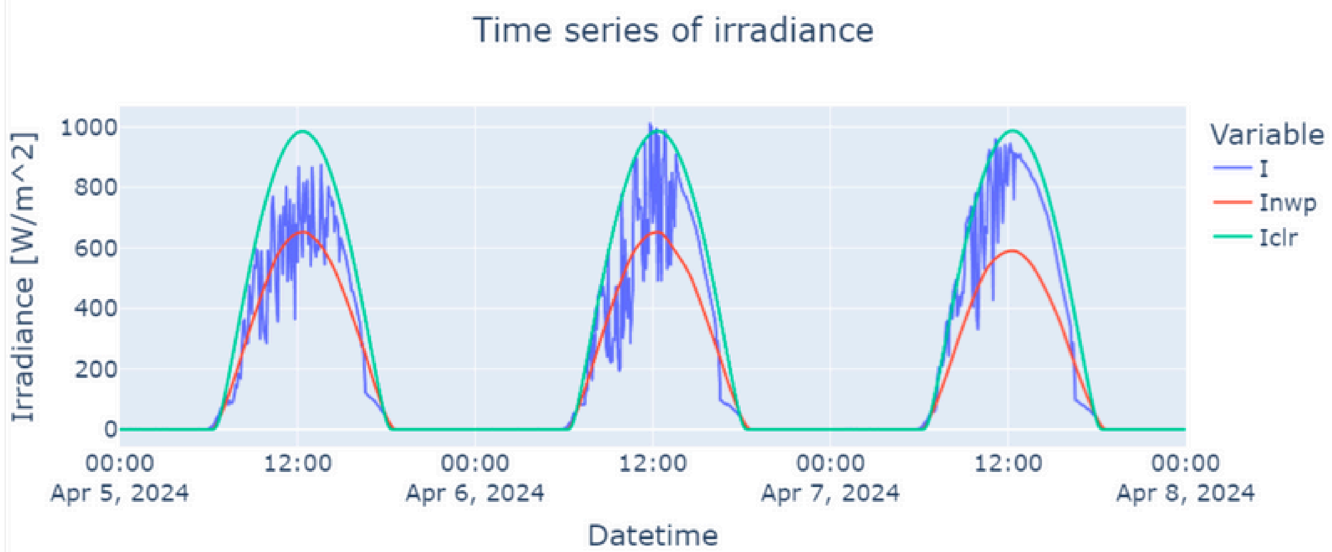
Load consumption

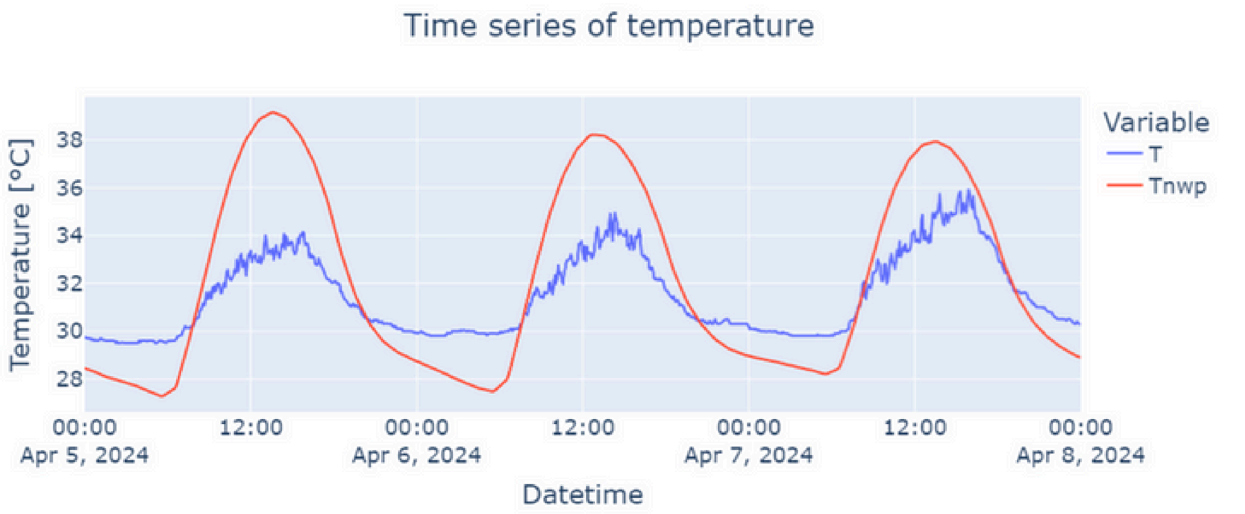
- Load data were sourced from CUBEM and Prof. Surapong's meter.
- Ranging from March 2023 to December 2024
- Resampled to 5- and 15-minute .



Solar irradiance and ambient temperature

- Obtained from CUEE, SoDa (INWP, TNWP), and Clear Sky Model (Iclr)
- Resampled to 5- and 15-minute

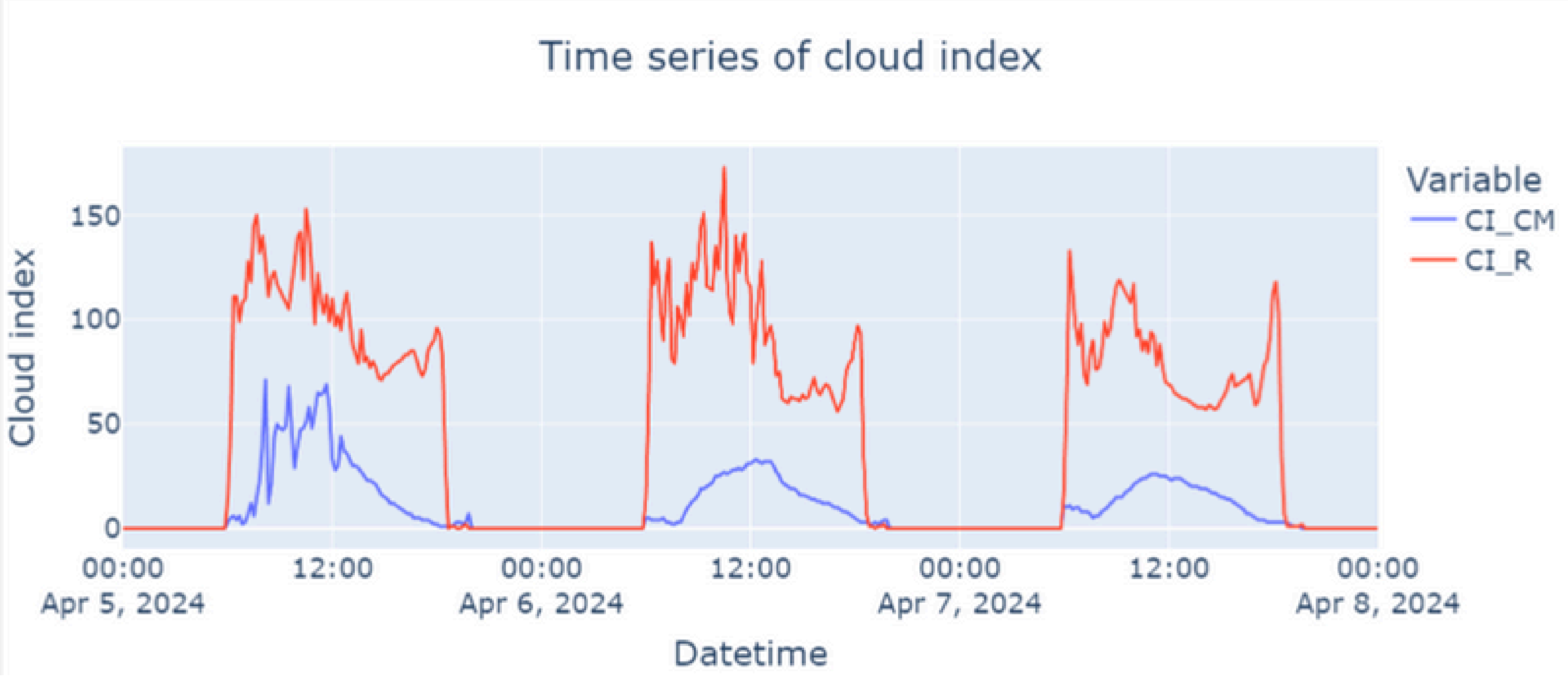




DATA PREPARATION

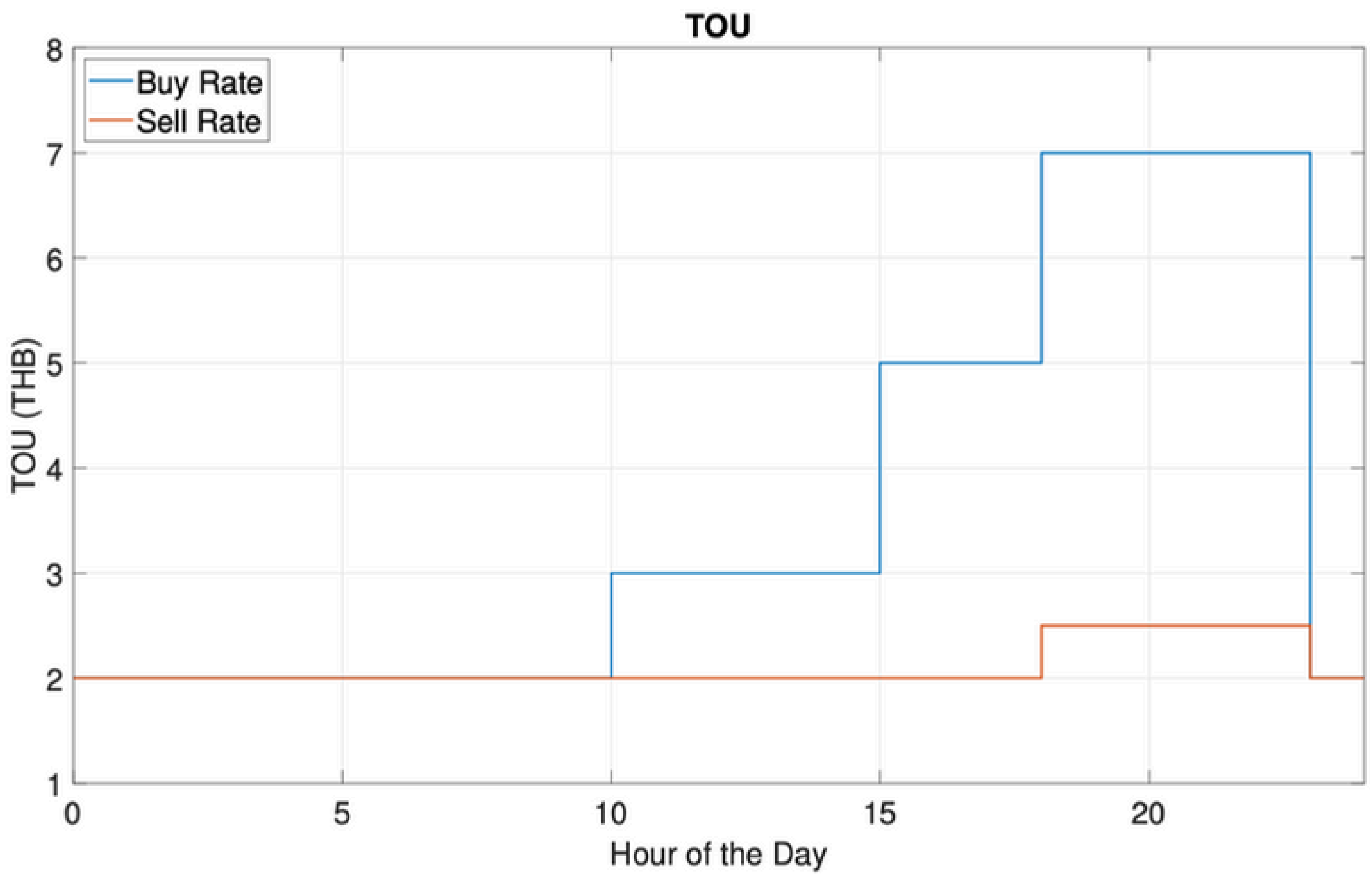
Cloud index (CI)

- Extracted from Himawari satellite images at the Boonrawd Building, Chulalongkorn University



Electricity tariffs

- Buy-Sell rate



FORCASTING MODEL

FORCASTING MODEL

LOAD FORCASTING MODEL

INPUT FEATURES

- **LAG FEATURE**
  - ACTUAL LOAD CONSUMPTION POWER
- **FUTURE EXOGENOUS FEATURES**
  - AMBIENT TEMPERATURE FROM NWP
  - LAB HOUR
  - LAB DAY
  - WORKDAY

OUTPUT TARGET

- PREDICTED LOAD CONSUMPTION POWER

IRRADIANCE FORCASTING MODEL

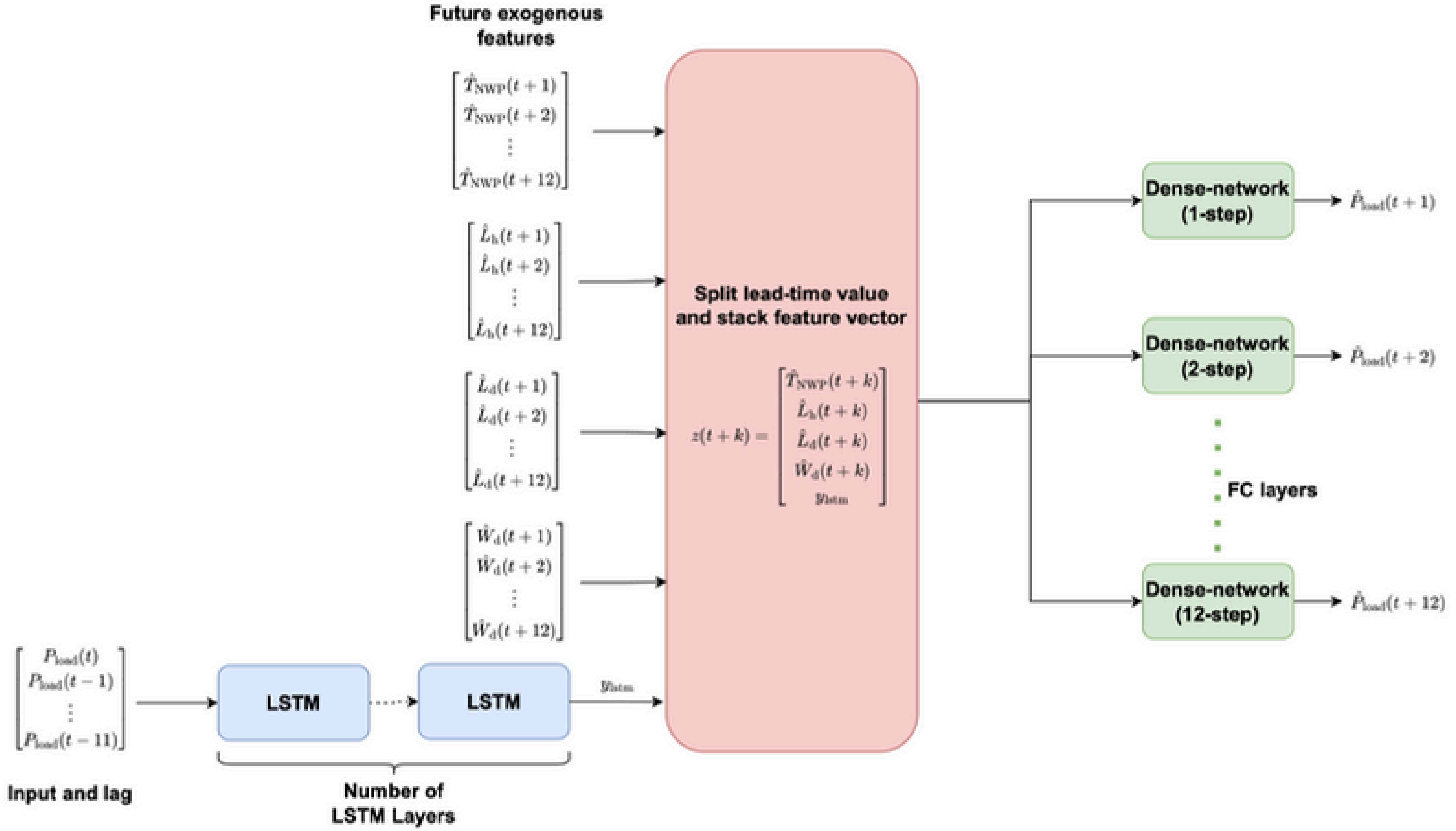
INPUT FEATURES

- **LAG FEATURE**
  - ACTUAL SOLAR IRRADIANCE
- **FUTURE EXOGENOUS FEATURES**
  - SOLAR IRRADIANCE FROM NWP
  - SOLAR IRRADIANCE FROM CLEAR SKY MODEL
  - AMBIENT TEMPERATURE FROM NWP
  - CLOUD INDEX RED CHANNEL
  - CLOUD INDEX GRAYSCALE

OUTPUT TARGET

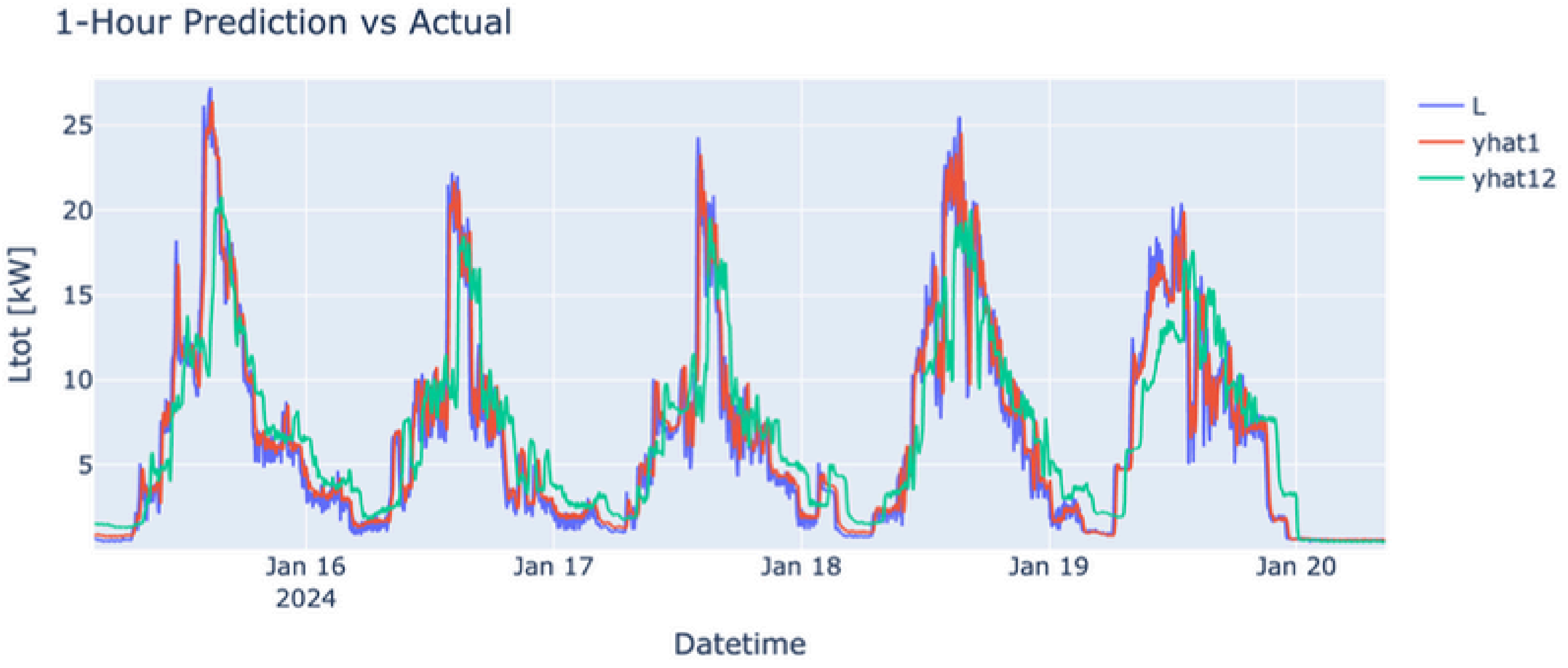
- PREDICTED SOLAR IRRADIANCE

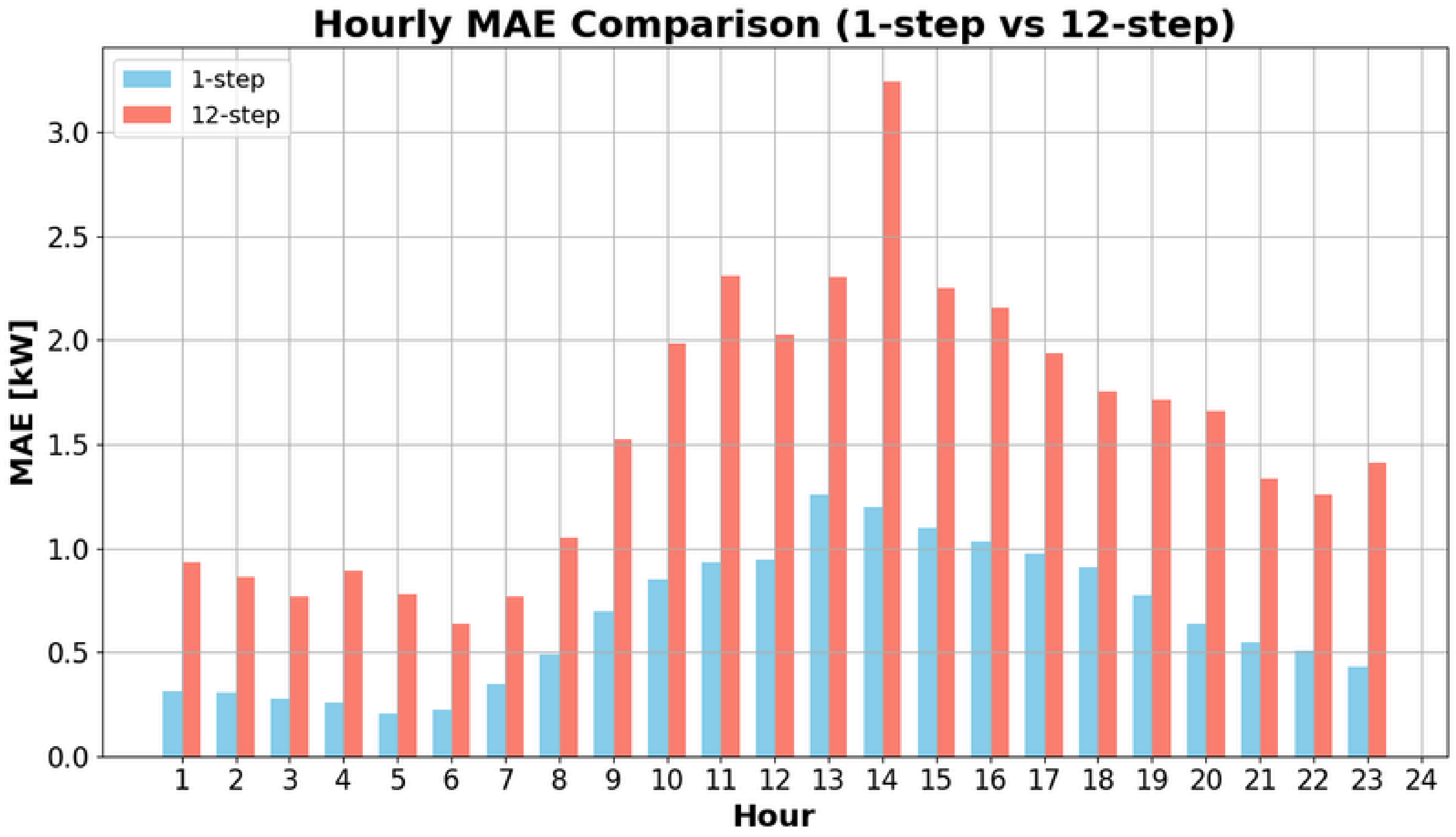
LOAD FORCASTING MODEL



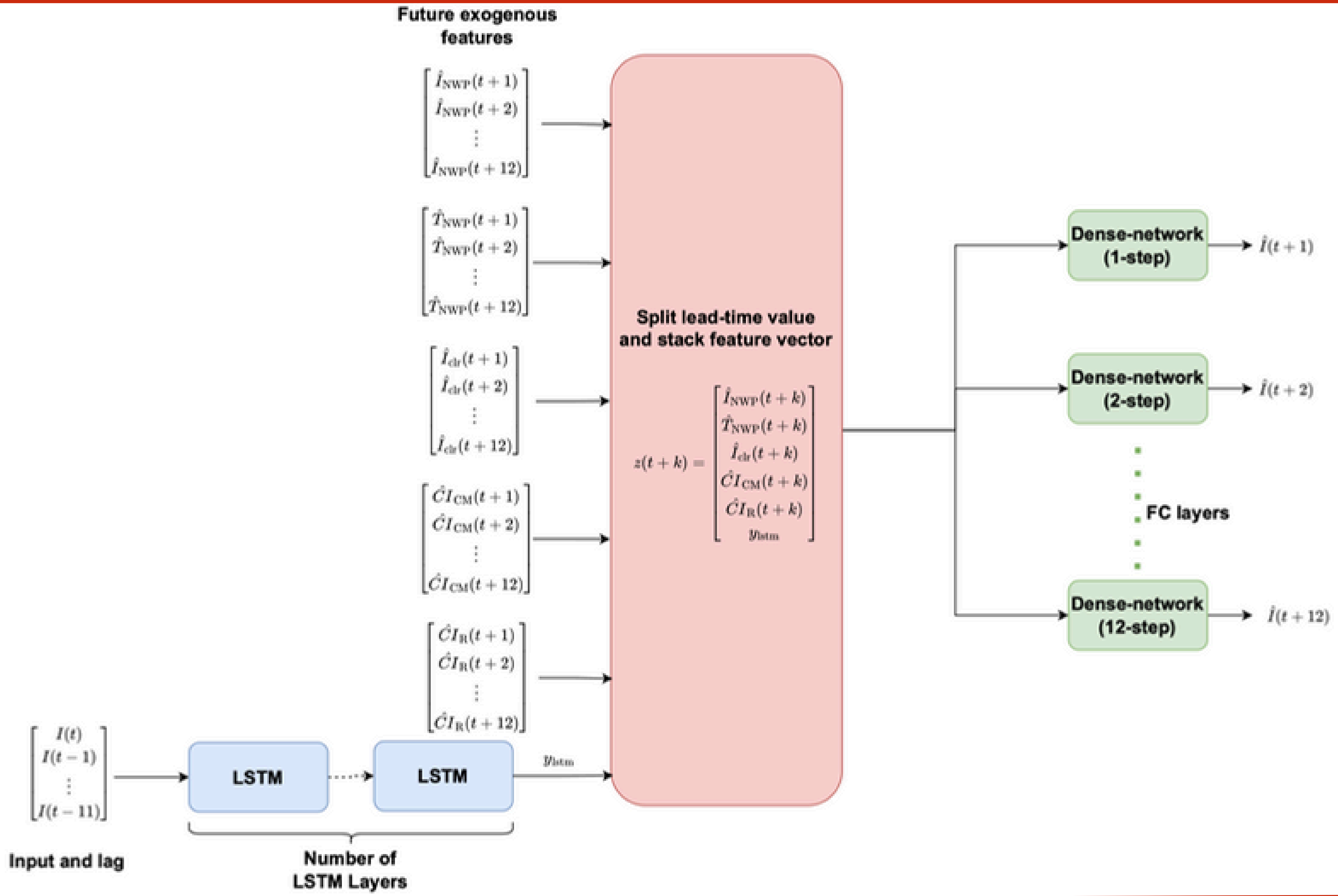
LOAD FORCASTING MODEL

The actual loadtime series is compared with two predicted series Lhat1 (5-minute ahead) and Lhat12 (1-hour ahead). The 5-minute model yields lower errors, with MAE of 0.25 to 1.3 kW (4% of peak load), compared to MAE of 0.65 to 3.2 kW (10% of Peak Load) for the 1-hour model.



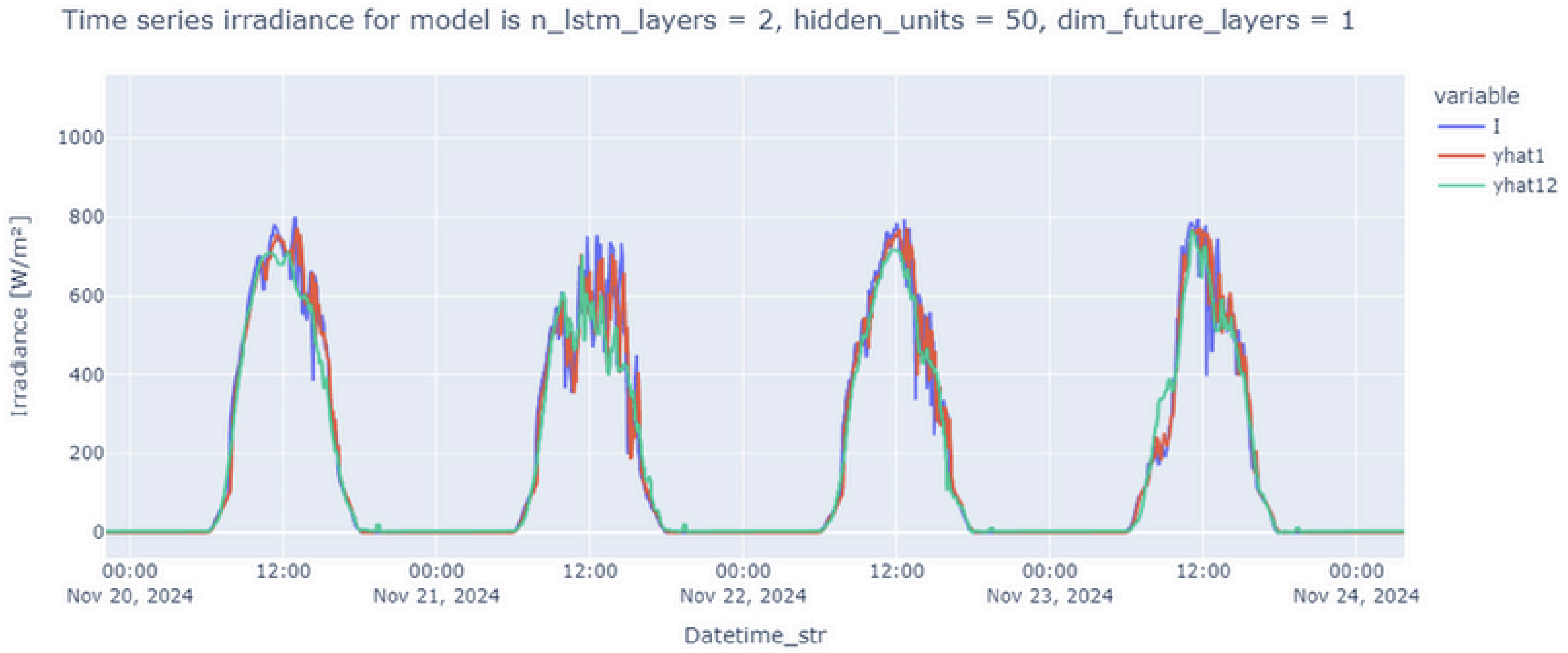


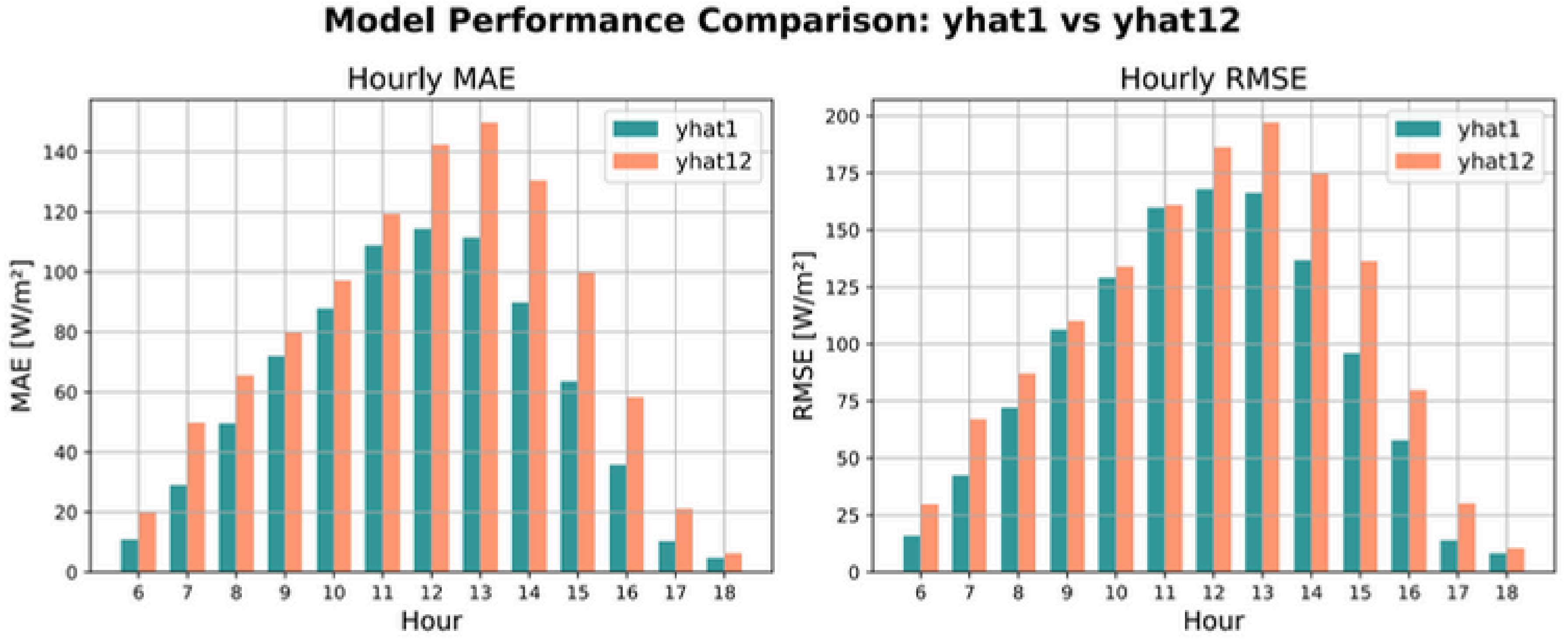
IRRADIANCE FORCASTING MODEL



IRRADIANCE FORCASTING MODEL

The actual irradiance time series is compared with two predicted series Ihat1 (5-minute ahead) and Ihat12 (1-hour ahead). The 5-minute model yields lower errors, with MAE of 5 to 115 W/m^2 (12% of peak) and RMSE of 12 to 170 W/m^2 (17% of peak), compared to MAE of 6 to 151 W/m^2 (15% of peak) and RMSE of 14 to 191 W/m^2 (20% of peak) for the 1-hour model. Both models show increased error around midday, coinciding with rapid fluctuations in solar radiation.

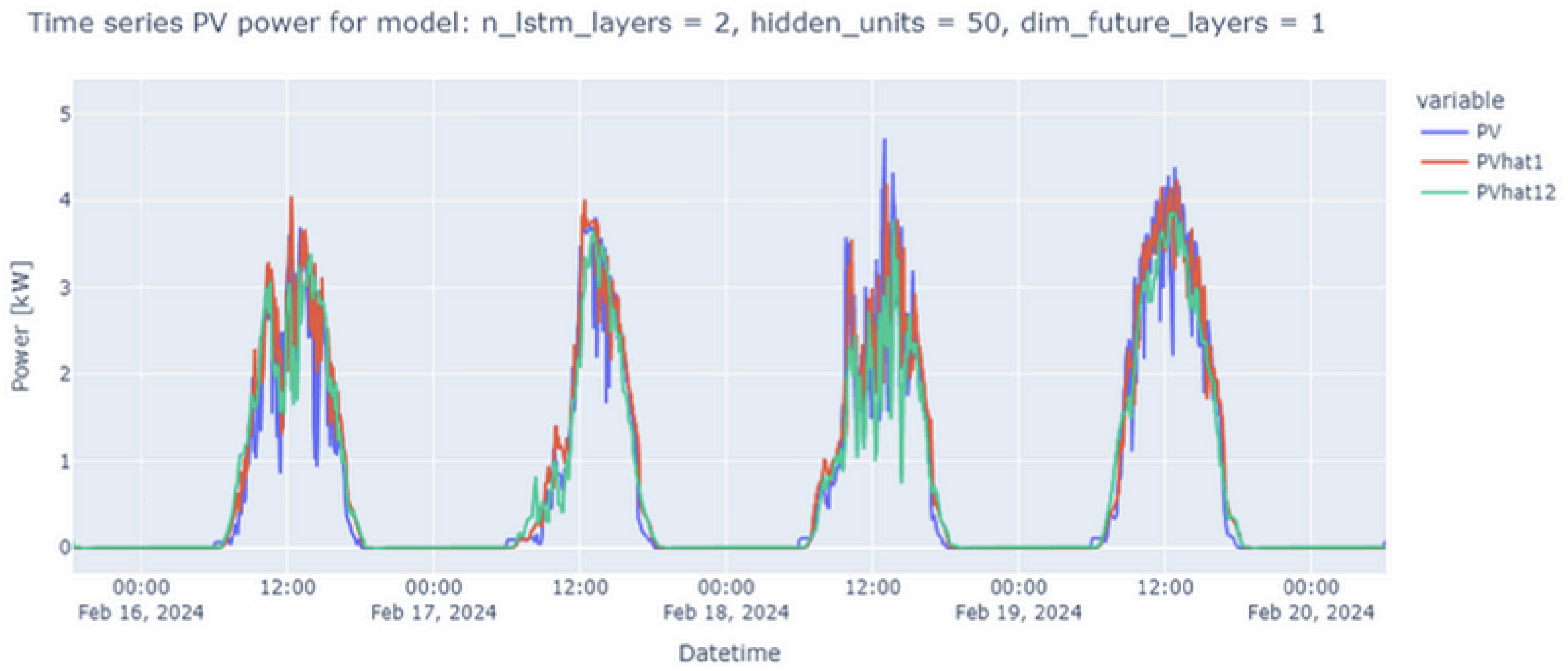




CONVERTED SOLAR POWER

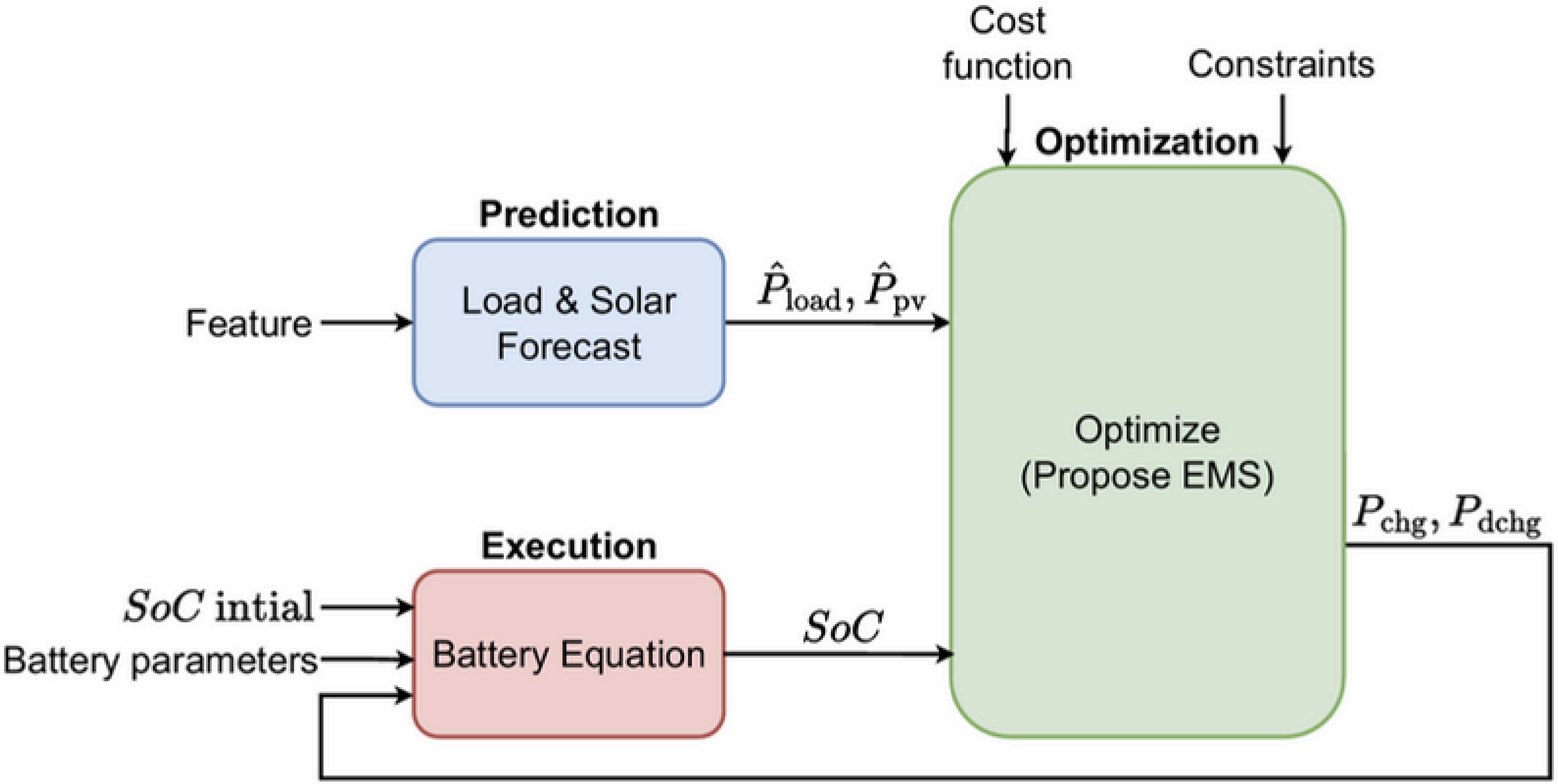
The actual PV generation time series is compared with two predicted series PVhat1 (5-minute ahead) and PVhat12 (1-hour ahead), both derived from the linear relationship P=αI, where α is a monthly average conversion factor calculated from actual PV output and irradiance data. The 5-minute prediction more closely follows the actual PV profile, especially during periods of rapid variation, while the 1-hour prediction shows smoother trends but greater deviations.

$$\boxed{P_{\text{pv}} = \alpha(t) \cdot I(t)}$$



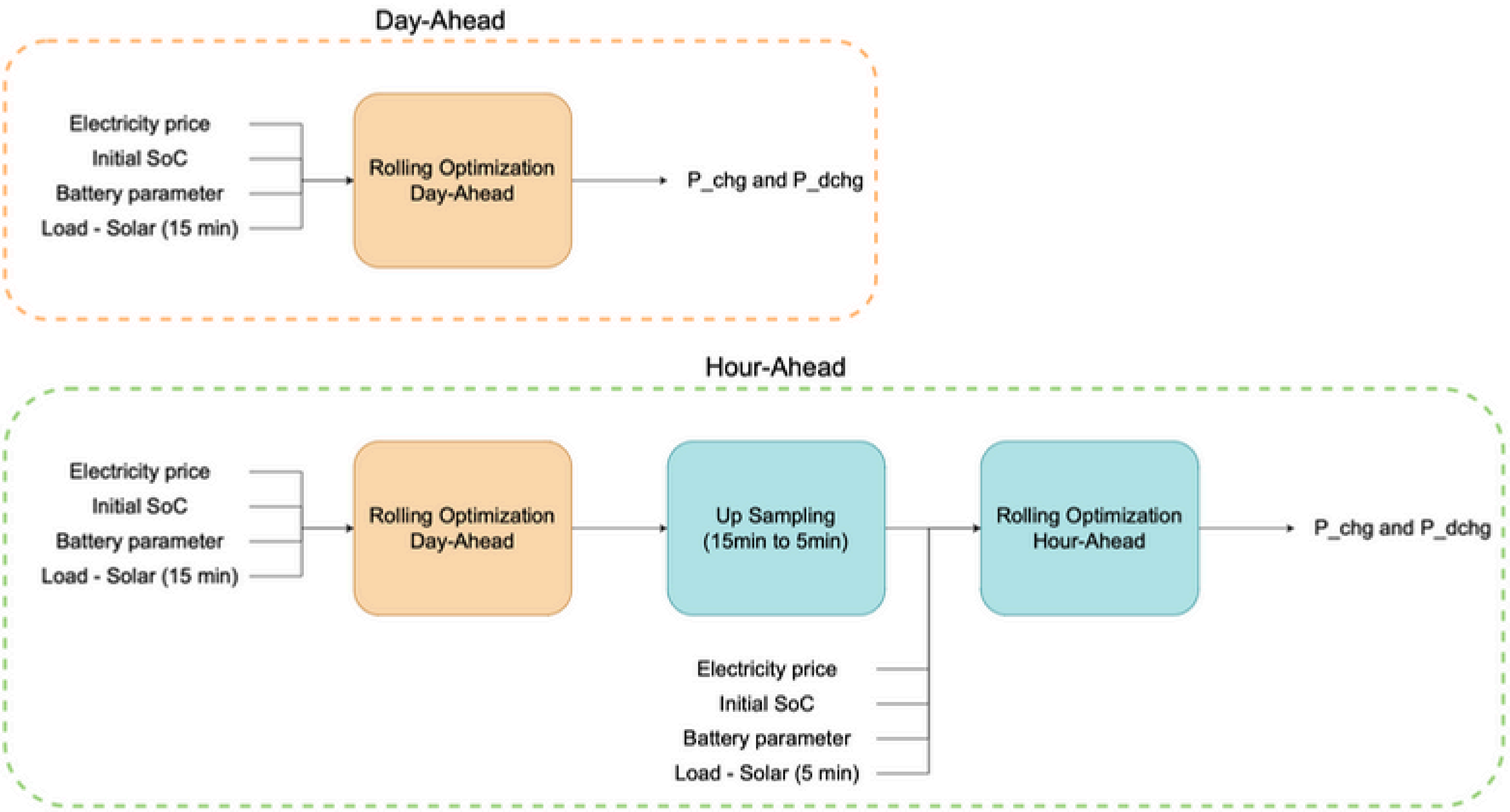
MODEL PREDICTIVE CONTROL (MPC)

MPC IN EMS


Cost function
Constraints
Optimization
Prediction
Load & Solar Forecast
Feature
$\hat{P}_{\text{load}}, \hat{P}_{\text{pv}}$
Optimize (Propose EMS)
$P_{\text{chg}}, P_{\text{dchg}}$
Execution
SoC intial
Battery parameters
Battery Equation
SoC

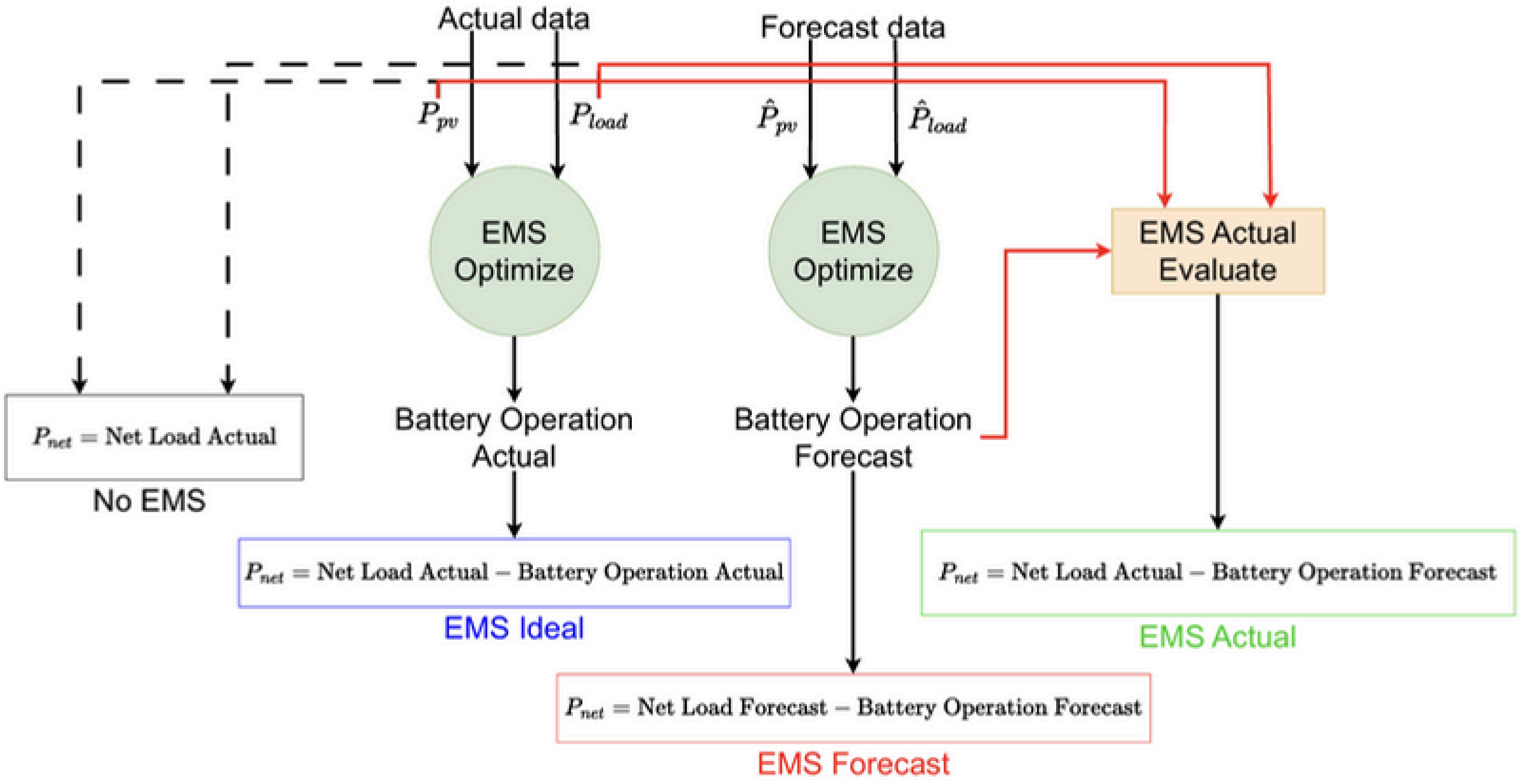
RESULT & DISCUSSION

EMS Horizon


Day-Ahead
Electricity price
Initial SoC
Battery parameter
Load - Solar (15 min)
Rolling Optimization Day-Ahead
P_chg and P_dchg
Hour-Ahead
Electricity price
Initial SoC
Battery parameter
Load - Solar (15 min)
Rolling Optimization Day-Ahead
Up Sampling (15min to 5min)
Rolling Optimization Hour-Ahead
P_chg and P_dchg
Electricity price
Initial SoC
Battery parameter
Load - Solar (5 min)

Experiment Scenario

Experiment Scenario



HOUR-AHEAD MPC

OBJECTIVE PROFIT

Hour-Ahead MPC (Profit)

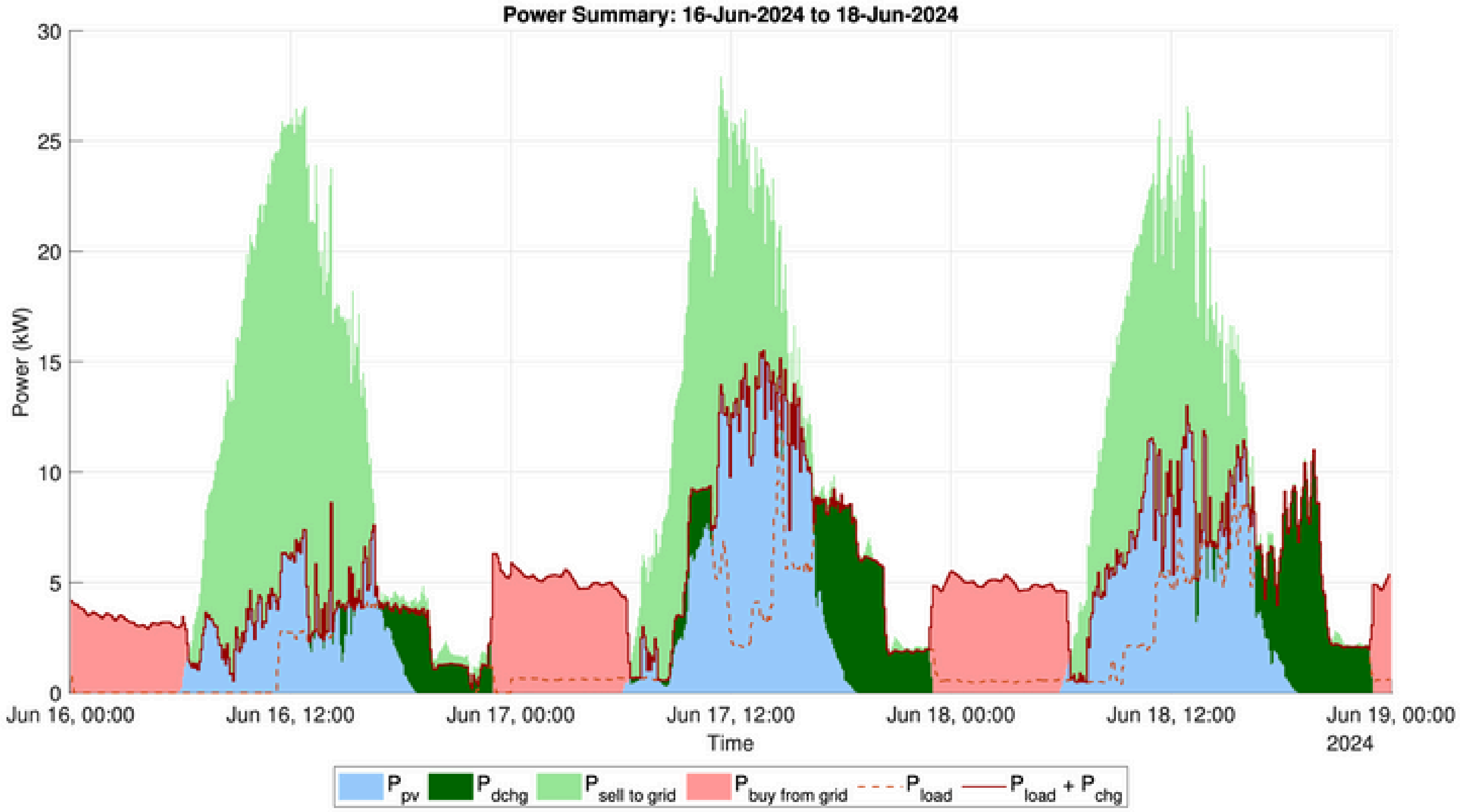
The objective is to compare the total electricity cost between 4 Pnet cases (EMS ideal, EMS forecast, EMS actual, NoEMS).

Parameter	Value	Unit
η_c	0.95	-
η_d	$0.95 * 0.93$	-
Max charge rate	100	kW
Max discharge rate	100	kW
Battery capacity	215	kWh
$\mathrm{SoC}_1(1)$	50	%
$\mathrm{SoC}_2(1)$	50	%
$\mathrm{SoC}_{\mathrm{min}}$	20	%
$\mathrm{SoC}_{\mathrm{max}}$	80	%
Final SoC target	0	%
Nominal voltage	$\frac{672+864}{2}$	V
Number of batteries	2	units
w_{s}	3	-
w_{m}	10^{-4}	-
w_{c}	0.05	-
w_{net}	0	-
w_{chg}	5	-
w_{dchg}	5	-

$$
\begin{array}{ll}
\text{minimize} & J_{\text{cost}} + w_{\text{m}} J_{\text{multibatt}} + w_{\text{s}} J_{\text{smooth charge}} + w_{\text{c}} J_{\text{charge batt}} + J_{\text{trackDA}} \\
\text{subject to} & \text{Power balance constraints } (\boxed{6}) \\
 & \text{Battery dynamic } (\boxed{1}) \\
 & \text{Battery charge/discharge constraints } (\boxed{2}) - (\boxed{3}) \\
 & \text{Battery's SOC constraint } (\boxed{4})
\end{array}
$$

Hour-Ahead MPC (Profit)

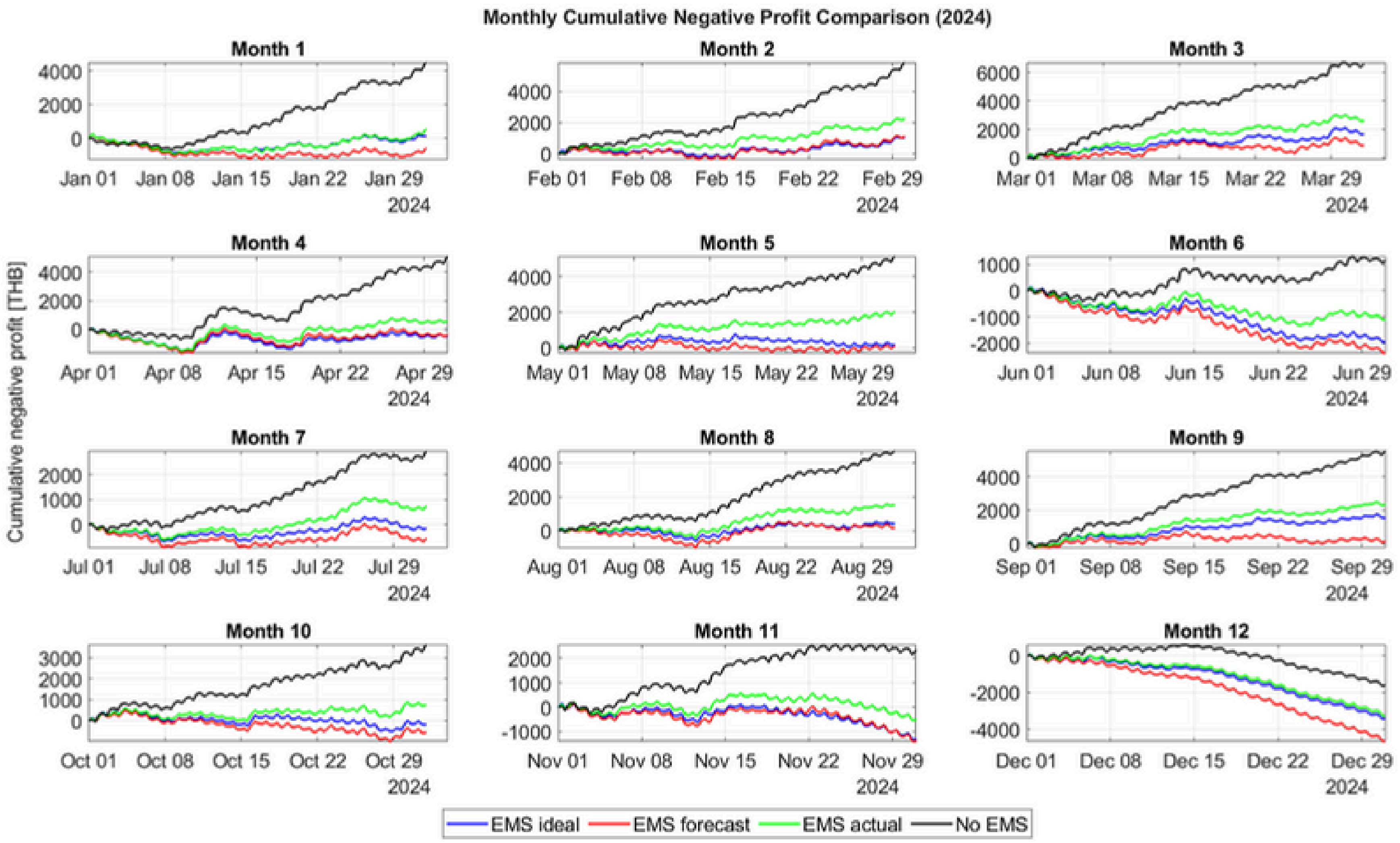
- **23.00 - 06.00:** During this period, solar generation is unavailable, so electricity is purchased from the grid to charge the battery. The battery is charged to be ready for daytime use.
- **06.00 - 15.00:** Solar generation meets the load demand, and excess energy is used to charge the battery. Any surplus energy is sold back to the grid, making the system more self-sufficient.
- **15.00 - 23.00:** As solar generation decreases in the afternoon, the battery discharges to meet the load demand. The system relies more on stored energy to power the load during this period.



Hour-Ahead MPC (Profit)

The comparison shows that EMS actual consistently outperforms No EMS. In some months, such as December, the cost gap is smaller by 1,651 THB, suggesting seasonal or operational factors influencing EMS performance.

Additionally, EMS actual closely tracks EMS ideal, indicating effective real-world EMS implementation. The largest gap occurs in May, where EMS actual outperforms EMS ideal by 1,859 THB, possibly due to higher solar generation or reduced load.



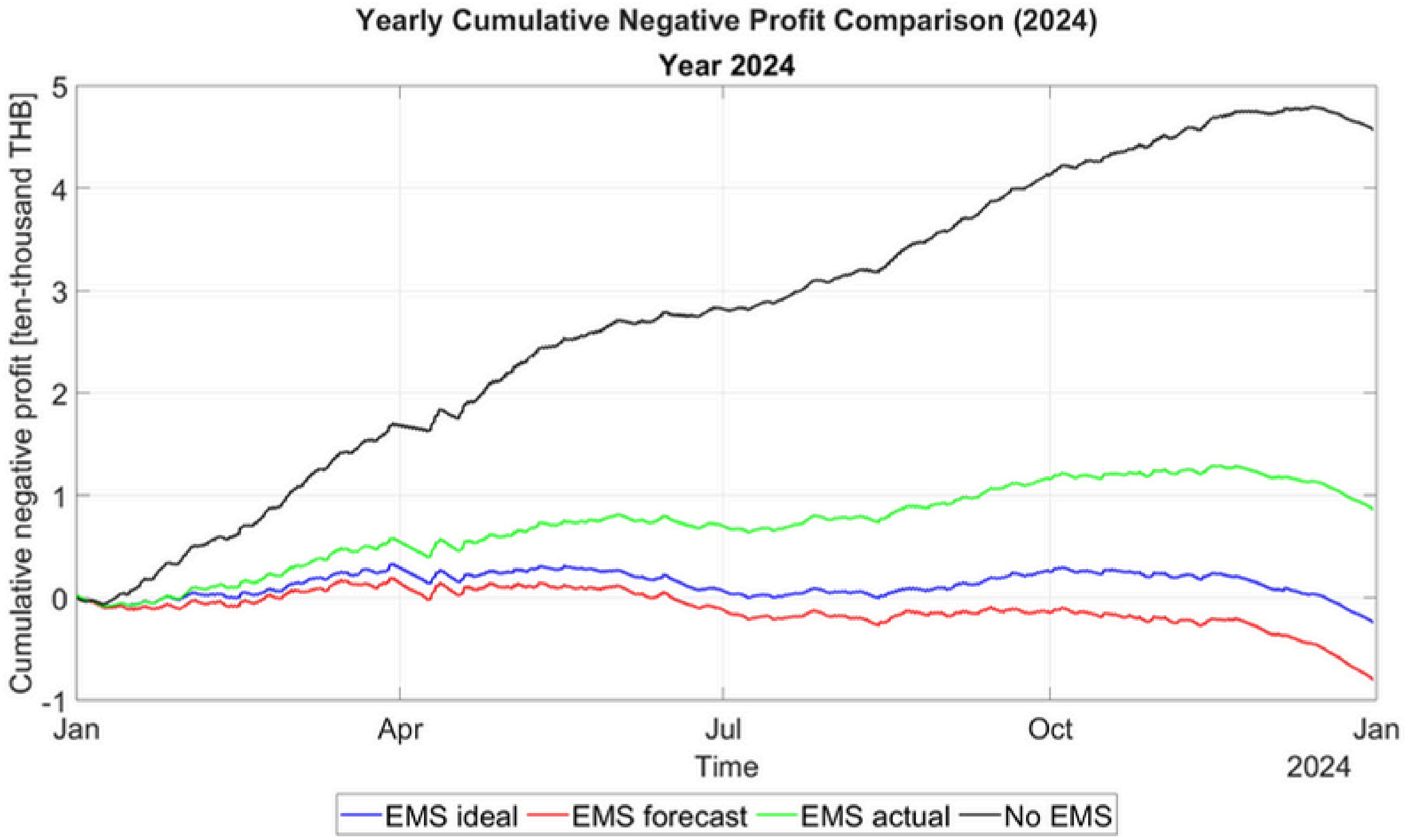
Month	Ideal (THB)	EMS (THB)	Actual (THB)	NoEMS (THB)	Actual – Ideal (THB)	Actual – NoEMS (THB)
January	156	-595	548	4,507	392	-3,958
February	1,062	1,135	2,277	5,841	1,216	-3,563
March	1,667	883	2,618	6,537	951	-3,919
April	-459	-389	608	5,072	1,067	-4,463
May	176	111	2,032	5,129	1,856	-3,097
June	-1,948	-2,361	-1,103	1,130	845	-2,234
July	-137	-554	745	2,949	882	-2,204
August	422	171	1,515	4,702	1,093	-3,187
September	1,566	176	2,389	5,529	822	-3,141
October	-178	-569	756	3,627	934	-2,871
November	-1,313	-1,378	-515	2,324	799	-2,838
December	-3,435	-4,654	-3,256	-1,605	178	-1,651
Total	-2,421	-8,025	8,615	45,743	11,036	-37,128

Note: Negative Profit = Cost of Purchase - Revenue from Sale

Hour-Ahead MPC (Profit)

The comparison shows that EMS actual consistently outperforms No EMS over the course of the year, with a total annual cost saving of 37,128 THB. This suggests that seasonal or operational factors may influence EMS performance.

Additionally, EMS actual closely tracks EMS ideal, indicating effective real-world EMS implementation. Compared to EMS ideal, EMS actual incurs a higher annual cost of 11,036 THB, which may be attributed to forecasting errors or real-world operational constraints that limit optimal performance.



Note: Negative Profit = Cost of Purchase - Revenue from Sale

CONCLUSION

Conclusion

Implementing EMS

- **Objective**

  The EMS is implemented with an objective that considers three key cost components: energy units, energy prices, and profit. It also incorporates battery management and Day-Ahead (DA) schedule tracking to ensure efficient energy utilization and reliable system operation.

- **Time Frame**

  The EMS uses a hierarchical time structure for planning and control:
  - Day-Ahead (DA): Uses 15-minute resolution data to compute a 3-day-ahead schedule.
  - Hour-Ahead (HA): Uses 5-minute resolution data to update the schedule 1 hour ahead.

- **Use of Linear Programming (LP)**

  A linear programming (LP) formulation is used to solve the optimization problem efficiently. This approach allows the EMS to operate with high-resolution control at both 5-minute and 15-minute intervals.

Conclusion

Profit Objective

- The EMS actual electric cost is higher than the EMS ideal by 11,036 THB per year, which corresponds to an average of approximately 920 THB per month.

- The EMS actual electric cost is lower than that without EMS by 37,128 THB annually, or about 3,094 THB per month on average.

THANK YOU

BACKGROUND

Experiment Scenario

Ideal : $$P_{\text{net, ideal}}(t) = P_{\text{load}}(t) - P_{\text{pv}}(t) + \sum_{i=1}^{n} \left(P_{\text{chg}}^{(i)}(t) - P_{\text{dchg}}^{(i)}(t) \right)$$

EMS : $$P_{\text{net, ems}}(t) = \boxed{\hat{P}_{\text{load}}(t) - \hat{P}_{\text{pv}}(t)} + \sum_{i=1}^{n} \boxed{\left(\hat{P}_{\text{chg}}^{(i)}(t) - \hat{P}_{\text{dchg}}^{(i)}(t) \right)}$$

Actual : $$P_{\text{net, actual}}(t) = P_{\text{load}}(t) - P_{\text{pv}}(t) + \sum_{i=1}^{n} \boxed{\left(\hat{P}_{\text{chg}}^{(i)}(t) - \hat{P}_{\text{dchg}}^{(i)}(t) \right)}$$

No EMS : $$P_{\text{net, noems}}(t) = P_{\text{load}}(t) - P_{\text{pv}}(t)$$

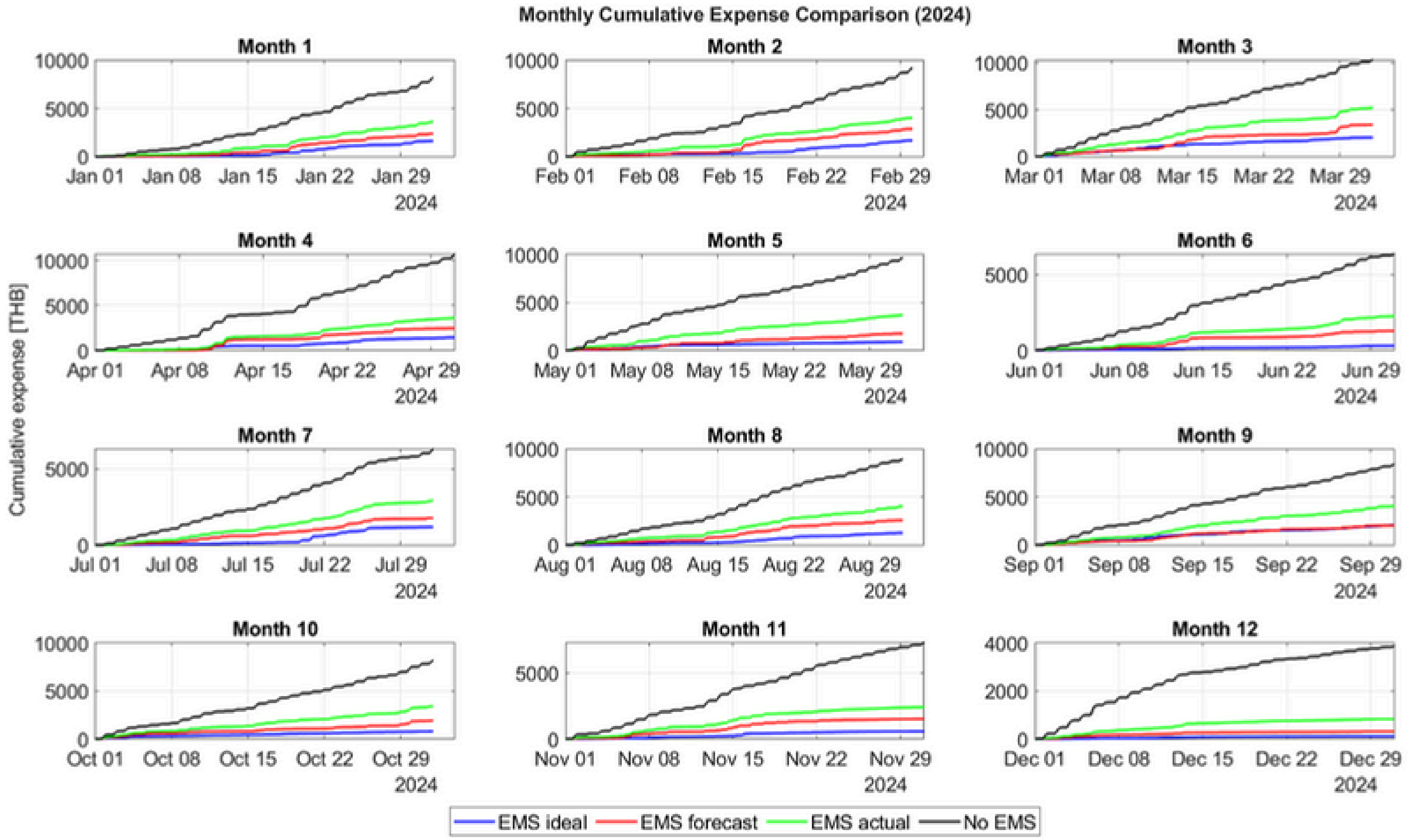
Hour-Ahead MPC (Energy Cost)

The objective is to compare the total electricity cost between 4 Pnet cases (Ideal, EMS, Actual, NoEMS).

$$
\begin{array}{ll}
\text{minimize} & J_{\text{cost}} + w_{\text{m}} J_{\text{multibatt}} + w_{\text{s}} J_{\text{smooth charge}} + w_{\text{c}} J_{\text{charge batt}} + J_{\text{trackDA}} \\
\text{subject to} & \text{Power balance constraints } (\boxed{6}) \\
& \text{Battery dynamic } (\boxed{1}) \\
& \text{Battery charge/discharge constraints } (\boxed{2}) \text{ - } (\boxed{3}) \\
& \text{Battery's SOC constraint } (\boxed{4})
\end{array}
$$

Parameter	Value	Unit
η_c	0.95	-
η_d	$0.95 * 0.93$	-
Max charge rate	100	kW
Max discharge rate	100	kW
Battery capacity	215	kWh
$\text{SoC}_1(1)$	50	%
$\text{SoC}_2(1)$	50	%
SoC_{min}	20	%
SoC_{max}	80	%
Final SoC target	0	%
Nominal voltage	$\frac{672+864}{2}$	V
Number of batteries	2	units
w_{s}	3	-
w_{m}	10^{-4}	-
w_{c}	0.05	-
w_{net}	0	-
w_{chg}	5	-
w_{dchg}	5	-

Hour-Ahead MPC (Energy Cost)



Hour-Ahead MPC (Energy Cost)

Month	Ideal (THB)	EMS (THB)	Actual (THB)	NoEMS (THB)	Actual – Ideal (THB)	Actual – NoEMS (THB)
January	1,628	2,389	3,605	8,170	1,977	-4,565
February	1,688	2,880	4,025	9,189	2,337	-5,164
March	2,051	3,409	5,222	10,308	3,171	-5,086
April	1,447	2,471	3,626	10,669	2,179	-7,043
May	909	1,761	3,674	9,634	2,766	-5,959
June	319	1,289	2,258	6,337	1,939	-4,079
July	1,188	1,782	2,916	6,321	1,727	-3,406
August	1,268	2,578	4,043	8,919	2,776	-4,875
September	2,075	2,032	4,058	8,406	1,983	-4,348
October	790	1,903	3,404	8,155	2,614	-4,752
November	576	1,530	2,426	7,290	1,850	-4,864
December	113	310	833	3,856	721	-3,023
Total	14,051	24,333	40,091	97,256	26,040	-57,164

Hour-Ahead MPC (Energy Cost)