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Research Article

Feasibility Assessment of PV and Energy Storage Systems for Nearly Zero Energy Office Buildings Using Generalized Reduced Gradient Method: A Case Study of Mae Moh Training Center EGAT

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Abstract:
This study evaluates the feasibility of implementing photovoltaic (PV) and energy storage systems to achieve Nearly Zero Energy Buildings (nZEBs) status for a cluster of buildings at the Mae Moh Training Center, Thailand. Using the Generalized Reduced Gradient method, three scenarios were analyzed: full-area installation, individual building optimization, and group optimization with energy storage. The full-area installation proved inefficient with only 24% PV utilization. Individual building optimization offered the shortest payback period of 3.17 years and 42% electricity reduction. Group optimization with energy storage emerged as the most comprehensive solution, achieving 75% PV utilization and 50% grid electricity reduction with an 8.67-year payback period for the optimal configuration of a 136 kW PV system and 100 kWh storage system. This approach best aligns with nZEB principles, offering balanced energy management and operational flexibility. The study demonstrates the potential of integrated PV and storage systems in achieving nZEB status.

Keywords: *PV Module, Energy storage system, Near Zero Energy Buildings, Feasibility analysis, Economic evaluation, Generalized Reduced Gradient method*

1. Introduction

The Energy Efficiency Plan (EEP) of Thailand 2018-2037 [1] aims to reduce the energy intensity (EI) of the country by at least 30% by 2037. To achieve this goal, the Ministry of Energy has developed a policy and long-term energy conservation plan for Thailand. The plan aims to reduce EI by 30% compared to the base year 2010, in order to benefit the environment, the economy, and reduce the country's energy consumption.

Nearly Zero Energy Buildings (nZEBs) have gained significant attention worldwide as an effective approach to achieving energy efficiency in buildings. nZEBs are characterized by their minimal grid electricity consumption, achieved through a combination of highly efficient energy management systems and on-site renewable energy production that matches the building's energy demands. These buildings were designed to operate with significantly reduced reliance on grid electricity while maintaining optimal functionality [2-5].

Recent studies have highlighted the importance of considering long-term performance in nZEB design. De Masi et al. (2024) [6] found that PV system degradation and climate change impacts can affect nZEB status maintenance, with operational emissions potentially increasing by 15% over time despite initial zero energy balance achievement. Complementing this, Ascione et al. (2022) [7] demonstrated that proper system optimization and climate adaptation

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strategies can help maintain performance, with potential reductions in net primary energy consumption from 25.4 to 19.5 kWh/m²/year through 2050. This emphasizes the need for comprehensive approaches that consider both immediate energy efficiency and long-term sustainability in nZEB implementation. Research on nZEB implementation has evolved across various building types and contexts. Several studies have focused on educational institutions, with researchers examining different aspects of solar energy integration and energy consumption optimization. These include technical and economic feasibility studies of rooftop solar systems in university settings [8], mathematical modeling of solar electricity generation potential [9], and specific case studies of sports facilities [10]. Recent international research has further emphasized the role of smart energy monitoring systems in optimizing building energy consumption and management [11,12].

Mae Moh Training Center is a facility with multiple purposes, including training, seminar, conference, office buildings, and co-working areas. This results in a high electricity consumption of 287,510 kWh/year in 2022, which costs 1,201,792 baht. Energy consumption is expected to increase every year due to the policy that designates Mae Moh Training Center as the central hub for training within the area. To address this problem and respond to the Energy Conservation and Renewable Energy Plan, the Electricity Generating Authority of Thailand (EGAT) has therefore initiated a prototype project for a group of buildings with near-zero energy consumption platform by utilizing solar energy together with energy storage. This pilot projectishas selected four office buildings within the Mae Moh Training Center, as shown in Fig. 1.:

- Building A - Samanchanthatchawan is used as an office and training building.
- Building B - Khelangsadudhi is used as an office and training building.
- Building C - Maneebanphot is used as an office and training building.
- Building D - Alongkotphiman is used as a training building.

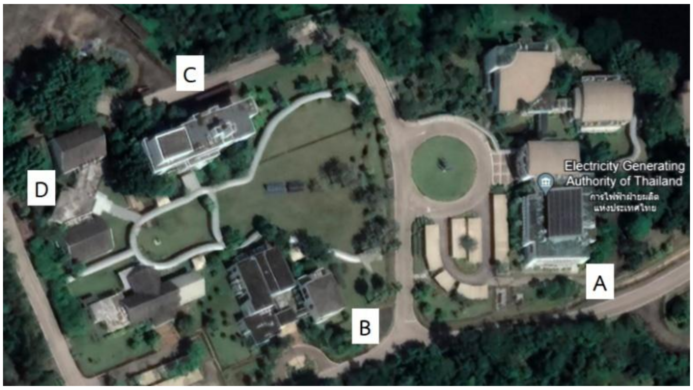


Fig. 1. Layout of selected buildings within the Mae Moh Training Center area.

This research aims to study the performance of a nZEBs platform among selected buildings which can be achieved by optimizing size of the PV and energy storage systems. The optimization process employs the Generalized Reduced Gradient (GRG) method, a powerful technique for solving non-linear optimization problems with constraints. The GRG method is particularly well-suited for this study due to its ability to handle the complex relationships between energy production, consumption, and storage in the context of nZEBs.

This work will include surveying and analyzing energy consumption behavior analysis in each building. The simulation from mathematical model, the GRG method will be implemented to evaluate the nZEBs performance and financial feasibility, providing a comprehensive approach to achieving near-zero energy condition for the Mae Moh Training Center building complex. This research focuses on managing building group towards nZEBs by measuring energy efficiency of Mae Moh Training Center using the Nikken Sekkei Research Institute (NSRI) energy efficiency index as a reference, as Thailand has lacks established standardized nZEB index.

2. nZEB approaching principle

The Nearly Zero Energy Buildings (nZEBs) concept is an architectural approach that focuses on minimizing energy consumption and use on-site renewable energy production to offset energy consumption, resulting in buildings with nearly zero energy consumption or, in some cases, energy-positive buildings.

Typically, the energy performance indicator for nZEBs is expressed in kilowatt-hours per square meter per annum (kWh/m² per annum). The determination of this indicator is often context-specific, varying by country or region. For instance, the Nikken Sekkei Research Institute (NSRI) [13,14] in Japan has developed performance indicators to establish standard criteria for evaluating nZEBs, as illustrated in Fig. 2. However, Thailand has yet to officially establish energy performance indicators or formulate standards and assessment criteria for nZEBs.

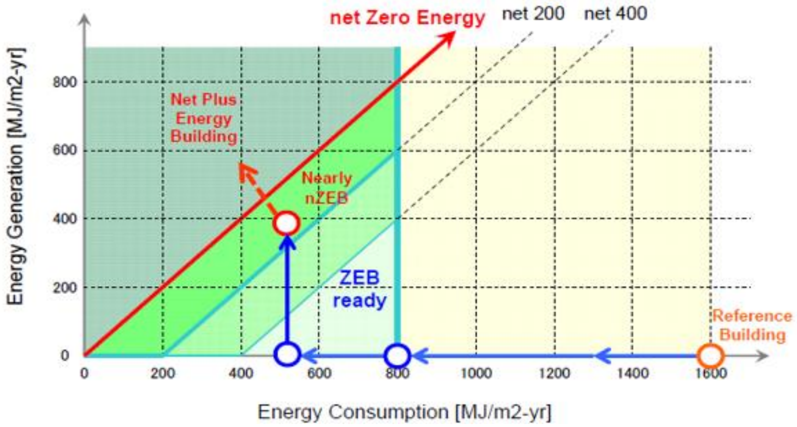


Fig. 2. nZEBs indicator from Nikken Sekkei Research Institute in Japan.

nZEBs are similar to Net Zero Energy Buildings (NZEBs) in terms of energy consumption. However, there are key differences between their approach. NZEBs do not prioritize energy efficiency analysis or cost-effectiveness studies for building improvements and renewable energy installations. Instead, they focus solely on generating enough renewable energy to offset the building's electricity consumption. On the other hand, nZEBs take a more comprehensive approach. The procedures involve data collection and analysis to optimize energy management in the building before considering renewable energy generation. This ensures that the chosen renewable energy solutions are both feasible and cost-effective. The nZEBs approaching processes can be divided into three steps, as shown in Fig. 3.:

(1) Building and energy assessment: This step involves evaluating the current state of the building and its energy consumption to identify key parameters such as energy efficiency and energy profile.

(2) Analysis of energy consumption: This step involves analyzing the parameters identified in Step 1 to determine the potential for improvement.

(3) Development of energy management measures: This step involves summarizing the findings from steps 1 and 2 and specific energy reduction and renewable energy measures based on their impact and cost-effectiveness.

By following these steps, nZEBs can achieve significant energy savings and reduce their environmental impact.

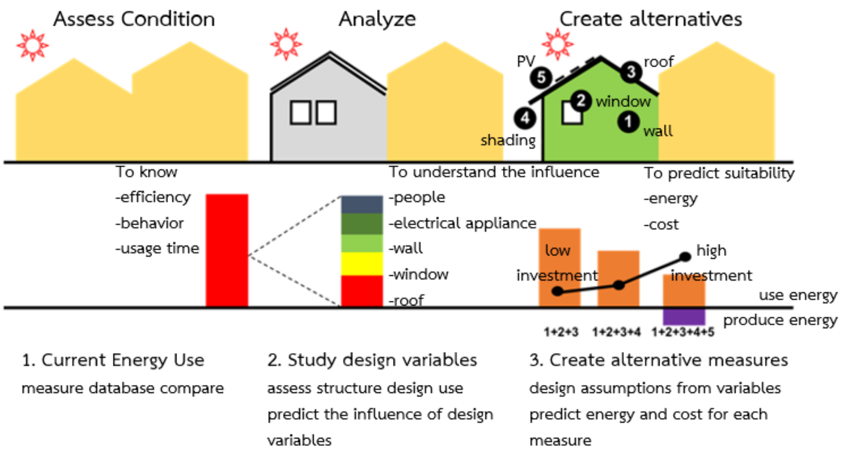


Fig. 3. nZEBs strategic approach.

2.1 Estimation of the Power Output of PV Modules

Asanakham et al. (2015) [15] developed a methodology for calculating the power output of polycrystalline photovoltaic (PV) modules under real-world operating conditions. This method was calibrated based on the climatic conditions prevalent in Chiang Mai Province, Thailand. The method was validated using the climatic parameters specifically to Chiang Mai Province, Thailand. They identified two primary factors that significantly influence the power output of PV modules: the intensity of incident solar radiation and the module temperature. The functional relationship between these variables and the module's power output can be mathematically expressed as follows:

$$P_{e,solar}(t) = f[I_T, T_m] \tag{1}$$

The solar radiation incident on a tilted surface, I_T, can be calculated using the following equation:

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{2}$$

Calculation of PV module temperature, T_m, can be obtained from the equation:

$$T_m(t) = T_a + (NOCT - 20)\frac{I_T}{800} \tag{3}$$

Ambient Temperature, T_a, can be calculated using the following equation:

$$T_a(t) = \frac{1}{2}[(T_{\max} + T_{\min}) + (T_{\max} - T_{\min})\sin(\frac{2\Pi}{24}(t-9))] \tag{4}$$

The power that a PV module can produce, P_m, can be calculated using the following equation:

$$P_m(t) = P_{m,stc}(1 - \gamma(T_m - 25))\frac{I_T}{1000} \tag{5}$$

2.2 Size of energy storage system

The sizing of energy storage system is crucial for effectively managing energy in nZEBs. The state of charge of the battery, BL_h, can be calculated using the following equation:

$$BL_h = BL_{h-1} + eB\_in_h * (\eta_{BC} * \eta_{AD}) - \frac{eB\_out_h}{\eta_{BD} * \eta_{DA}} \tag{6}$$

Subject to the constraints:

$$BL_h \geq SOC_{\min} * capB \tag{7}$$

$$BL_h \leq capB \tag{8}$$

$$BL_{h=1} = capB \tag{9}$$

$$BL_{h=24} = capB \tag{10}$$

The following set of constraints governs the maximum charge and discharge rates of the battery, as well as the battery energy flow:

$$eB\_in_h * (\eta_{BC} * \eta_{AD}) + \frac{eB\_out_h}{\eta_{BC} * \eta_{AD}} \le F_{\max} * capB * \Delta h \tag{11}$$

$$eB\_in_h \le capB * \kappa_h \tag{12}$$

$$eB\_out_h \le capB * \varphi_h \tag{13}$$

$$\kappa_h + \varphi_h \le 1 \tag{14}$$

2.3 Generalized Reduced Gradient (GRG) Method

The Generalized Reduced Gradient (GRG) method is an advanced optimization technique for solving non-linear programming problems with constraints. Developed by Abadie (1969) [16], it has been widely applied in various fields, including energy system optimization. Lasdon et al. (1978) [17] and Gabriele and Ragsdell (1977) [18] demonstrated the method's efficiency and reliability in solving complex problems. Yeniay (2005) [19] found GRG to be one of the best methods for deterministic optimization in a comparative study.

In energy system optimization, GRG has proven effective in finding optimal configurations for renewable energy systems. González-Mahecha et al. (2018) [20] successfully applied it to optimize sizing of on-site renewable technologies with storage in zero/nearly zero energy buildings. The GRG method's ability to handle complex, non-linear problems makes it particularly suitable for optimizing PV and energy storage systems in nZEBs, effectively managing the intricate relationships between energy production, consumption, and storage while considering various constraints. Gabriele & Ragsdell (1977) summarized the basic operational steps of the GRG method for fully constrained problems, as illustrated in Fig. 4.

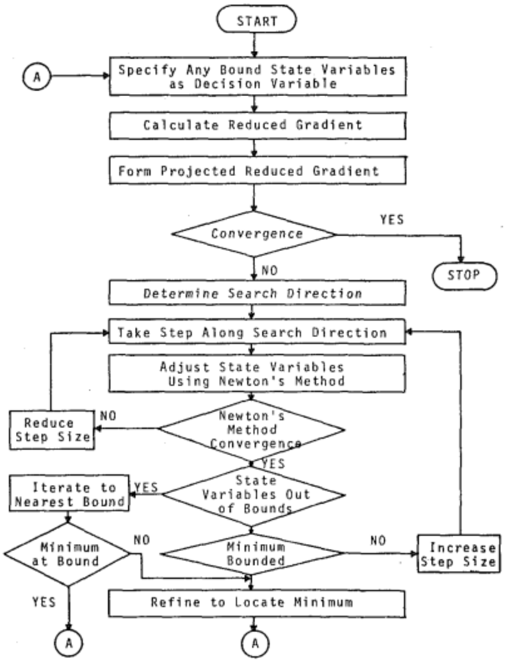


Fig. 4. Basic flowchart of reduced gradient algorithm for fully constrained problem.

2.4 Analysis of the suitability of PV and energy storage systems

The system optimization analysis will depend on the purpose of installing the renewable energy system. This research calculate the size of the PV installation, the size of the energy storage system, based on the energy consumption together with optimize installation cost.

Objective Function (OF) is a mathematical relationship objective function, which consists of factors according to the installation purpose that are related to each other. In this research, it is necessary to find the size of PV and energy storage systems that are economically and technically design, considering the size of the system that gives the lowest total present value of expenditures.

The goal is to minimize this function, which will result in the optimal sizes for the PV system and battery system is the total cost over project lifetime. The optimal point is determined by the system size that yields the lowest total cost, as illustrated in Fig. 5.

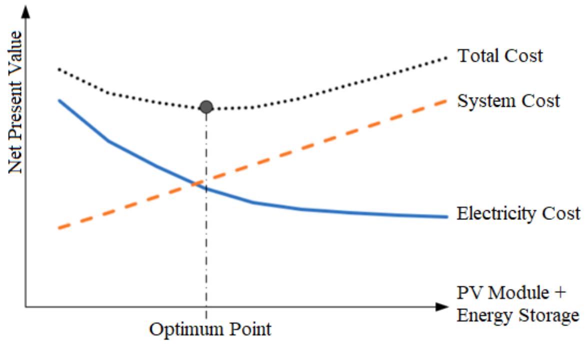


Fig. 5. Evaluation of the size with the lowest total cost.

The payback period, a critical metric in the financial analysis of energy efficiency and renewable energy projects, is defined as the time required for the cumulative benefits of an investment to equal its costs. This metric is calculated using the ratio of the Net Present Value (NPV) of the system to the Annual Value of Energy Saved. The NPV incorporates both the initial investment and projected future costs, discounted to present value, while the Annual Value of Energy Saved represents the recurring benefits derived from the system. The calculation can be expressed by the following equation:

$$\text{Payback Period} = \frac{\text{Present Value of the System}}{\text{Annual Value of Energy Saved}} \tag{15}$$

PV utilization rate can be calculated using the following equation:

$$\text{PV Utilization Rate} = \frac{\text{Energy Consumption from PV}}{\text{Annual PV Production}} \tag{16}$$

3. Research Methodology

This research aims to determine the optimal dimensions of PV and energy storage systems for the buildings within the Mae Moh Training Center to achieve nZEB. The study employs an integrated methodology that combines quantitative data analysis, simulation modeling, and economic assessment. The process commences with a comprehensive collection and analysis of energy consumption data from the building cluster, complemented by a meticulous architectural and spatial evaluation to assess PV installation feasibility. Subsequently, the study develops an objective function-based simulation model to optimize system sizing. This model incorporates multiple parameters, including energy production potential, system costs, and consumption patterns, to provide a robust optimization framework.

3.1 Data Collection and Preparation

3.1.1 Data Collection on Energy Consumption of Building Groups

The energy consumption of selected buildings within the Mae Moh Training Center has been collected from January 2022 to December 2023, for a total of 2 years. Data was collected every 15-minute interval using real-time power monitoring (RTPM) technology. The RTPM system structure, as shown in Fig. 6, consists of digital power meters with data transmission nodes, a main server for data processing and storage, network connections, and display interfaces, enabling continuous and accurate power consumption monitoring. To establish a representative baseline, the data from these two years were averaged, mitigating the effects of annual variations and anomalies. The total annual electricity consumption for the building group was found to be 287,510 kWh/year. This significant energy usage underscores the importance of implementing energy-efficient solutions and renewable energy systems. Averaged monthly energy consumption of each building and averaged daily energy profiles shown in Fig. 7. and 8. Respectively

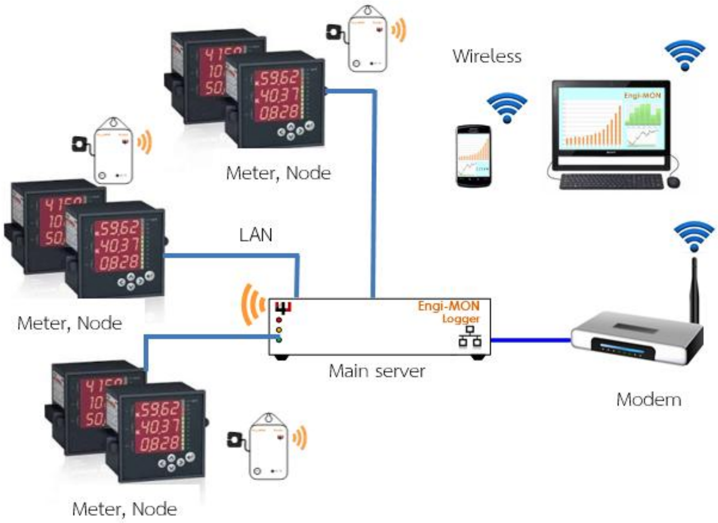


Fig. 6. Real Time Power Monitoring System Structure.

3.1.2 Architectural Configuration Assessment and Energy Consumption Behavior

An architectural assessment was conducted within the Mae Moh Training Center complex to evaluate the potential for photovoltaic (PV) module installation. This study encompassed a detailed analysis of building roof orientations and viable installation areas. The assessment utilized both on-site measurements and architectural blueprints. Subsequently, an energy consumption behavior analysis was performed for each building within the complex.
From the collected data on energy consumption and the survey of architectural features, it was found that:

- Building A operates from 8:00 AM to 4:00 PM. The building has a 55 kW PV module and a 50 kW battery installed, but it still uses average 150 kWh/day of energy from the grid. The roof area available for additional installation is 180 square meters
- Building B operates from 8:00 AM to 4:00 PM and 6:00 PM to 6:00 AM. It uses average 497 kWh/day of energy from the grid and has a roof area of 314 square meters available for installation.
- Building C operates from 8:00 AM to 4:00 PM. It uses average 56 kWh/day of energy from the grid and has a roof area of 280 square meters available for installation.
- Building D is a training building. Its operational hours is depends on the training schedule. It uses average 62 kWh/day of energy from the grid and has a roof area of 160 square meters available for installation.

The results are summarized in Table 1.

Table 1: Installation area of each building.

Building	Energy Consumption (kWh/day)	Roof Area (M^2)
A - Samanchanthatchawan	150	180
B - Khelangsadudhi	497	314
C - Maneebanphot	56	280
D - Alongkotpiman	62	360
Total	765	934

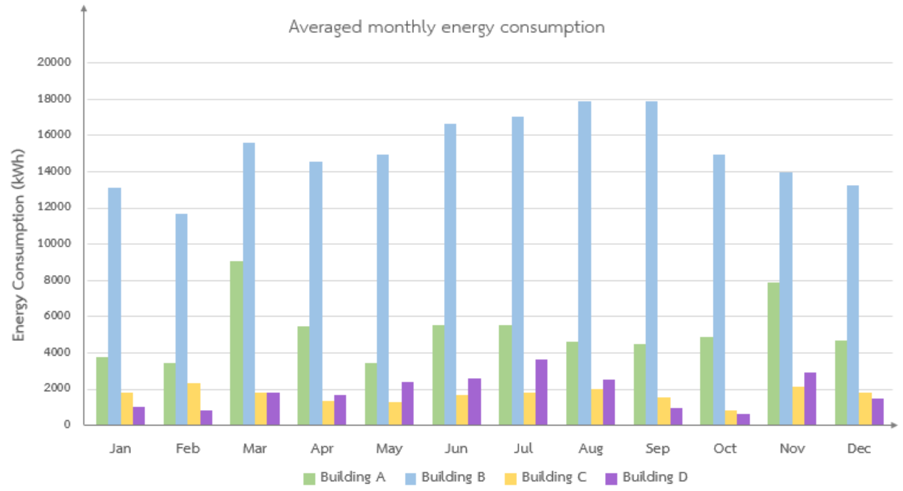


Fig. 7. Averaged monthly energy consumption of each building.

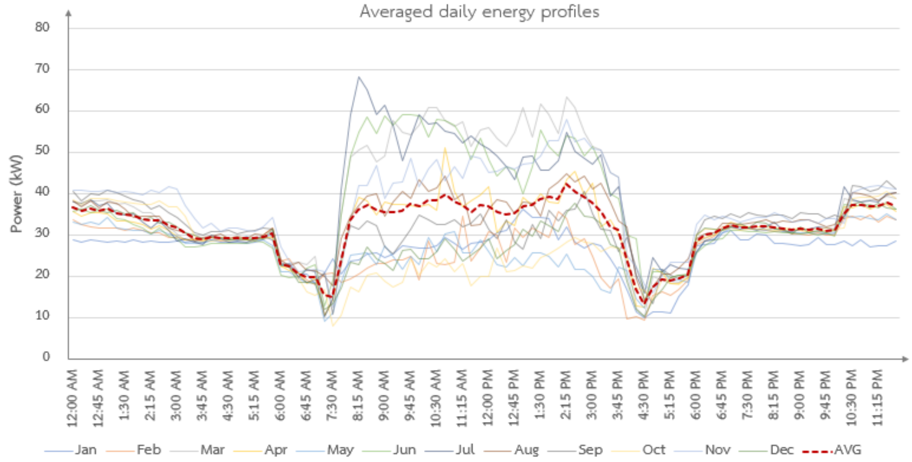


Fig. 8. Averaged daily energy profiles of all buildings over 24-hour periods.

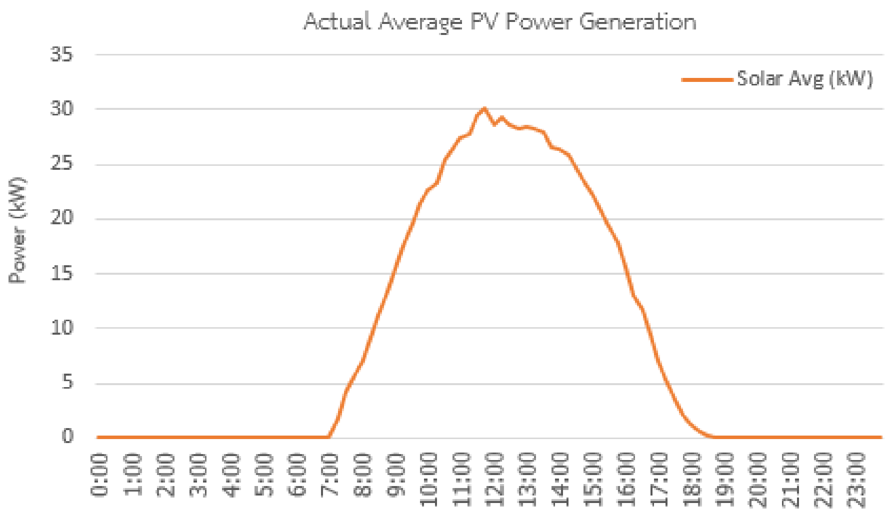


Fig. 9. Actual Average PV Power Generation from the Prototype Building.

3.2 Simulation Setup

In developing the model to determine the optimal size of the PV system and energy storage system, this study prioritizes the use of real-world PV data instead of theoretical calculations. The Energy Research and Development Institute-Nakornping at Chiang Mai University (2021) [12-13] collected electricity production data from a 55 kW PV system installed at the Mae Moh Training Center. This data, illustrated in Fig. 9, provides a realistic representation of PV performance under local environmental conditions.

Analysis of this data revealed that the actual electricity generation from PV panels in Mae Moh District, Lampang Province, has an efficiency of 53.56% compared to installation capacity.

The study employs an objective function aimed at achieving near-zero energy building status for the building group while minimizing total costs:

$$
\begin{aligned}
OF &= capPV * ccPV + capB * ccB + capINV * ccINV + ccINS \\
&+ ccM * NPV_m + (\sum_h e_{tariffh} * eGRID_h) * NPV_e - ccSV * NPV_{SV}
\end{aligned}
\tag{17}
$$

The optimal size of the PV system and energy storage system to achieve minimum grid energy consumption for the building group can be determined from:

$$
Minimize \quad OF = \sum_h eGRID_h \tag{18}
$$

To determine the optimal values of $capPV$ and $capB$, minimize the objective function subject to the following constraints:

$$
capPV \leq MaxPV \tag{19}
$$

$$
capB \leq MaxB \tag{20}
$$

$$
ePV_h + eB_h + eGRID_h \geq \sum_h eGRID_h \tag{21}
$$

$$
BL_h = BL_{h-1} + \eta_{BC} * ePV\_in_h - \frac{1}{\eta_{BD}} * \sum_h eB\_in_h \tag{22}
$$

$$
SOC_{\min} * capB \leq BL_h \leq \sum_h capB_h \tag{23}
$$

$$
0 \leq ePV\_in_h \leq \sum_h ePV_h \tag{24}
$$

The optimal size of the PV module power generation system and the energy storage system that minimizes the total cost is based on parameters, as shown in Table 2.

Table 2: Analysis Assumptions for Finding the Optimal Size.

Parameter	Value/Unit
Project Lifetime	20 Years
Cost of PV Modules	20 THB/W
Cost of Inverter	5 THB/W
Cost of Energy Storage System	20,000 THB/kWh
Cost of electricity from the grid	4.18 THB/kWh
PV Efficiency	80%
Battery Efficiency	80%
Minimum Battery State of Charge	40%
Scrap Value	1%
Discount Rate	6.25%

The study compares the potential for solar energy production across three scenarios:

- Full-Area Installation: This scenario considers the maximum installation of PV modules across all available areas.
- Individual Building PV Optimization: This scenario examines the optimal number of PV modules for each building to minimize total costs.
- Group of Building PV Optimization Including Energy Storage: This scenario evaluates the optimal number of PV modules for the entire group of buildings, in conjunction with an energy storage system, to achieve the lowest total cost.

By utilizing the GRG method in conjunction with the data from actual on-site data, this study ensures more accurate predictions of PV system performance for the Mae Moh Training Center. This approach leads to more reliable sizing and economic assessments in the subsequent analysis.

4. Result and Discussion

This section presents and analyzes the findings of our feasibility assessment on implementing PV systems to achieve nZEBs status at the Mae Moh Training Center. The results are described according to the three scenarios investigated: full-area installation, individual building PV optimization, and group of building PV optimization including Energy Storage.

4.1 Full-Area Installation

Based on the evaluation of the installable area for PV modules from site surveys and building blueprints, calculations for full-area installation indicate that the solar power generation system can produce a total of 540,367 kWh/year, as shown in Table 3. This would enable a reduction of up to 46% in the total electricity consumption of the four buildings, as detailed in Table 4

Table 3: Annual Electricity Production of PV System in Full-Area Installation Scenario.

Building	PV Modules	Installed Capacity (kW)	Annual Electricity Production (kWh/Year)	Energy Consumption from PV (kWh/Year)	PV Utilization Rate
A - Samanchanthatchawan	70	36.4	94,564	15,715	17%
B - Khelangsadudhi	150	78	202,638	82,104	41%
C - Maneebanphot	120	62.4	162,110	14,455	9%
D - Alongkotpiman	60	31.2	81,055	18,967	23%
Total	400	208	540,367	131,241	24%

Table 4: Percentage of Electricity Reduction for Each Building in Full-Area Installation Scenario.

Building	Energy Consumption from PV (kWh/Year)	Building Energy Consumption (kWh/Year)	Electricity Reduction
A - Samanchanthatchawan	15,715	62,899	26%
B - Khelangsadudhi	82,104	181,528	45%
C - Maneebanphot	14,455	20,496	71%
D - Alongkotpiman	18,967	22,587	84%
Total	131,241	287,510	46%

4.2 Individual Building PV Optimization

Using the GRG method to create a model and solve for the optimal size of the solar photovoltaic system for each building, with the objective of meeting daily energy demand and minimizing total system costs, the following optimal configurations were determined:

4.2.1 Building A – Samanchanthatchawan

The optimal installation is 10 kW (20 modules), as shown in Fig. 10a., This system can produce 71.18 kWh of electrical energy per day, which is used during the period of 06:00-18:00. This amounts to 28.75 kWh of electrical energy per day, representing a PV utilization rate of 40% and reducing the building's daily energy consumption by 17%, as shown in Fig. 11a.

4.2.2 Building B – Khelangsadudhi

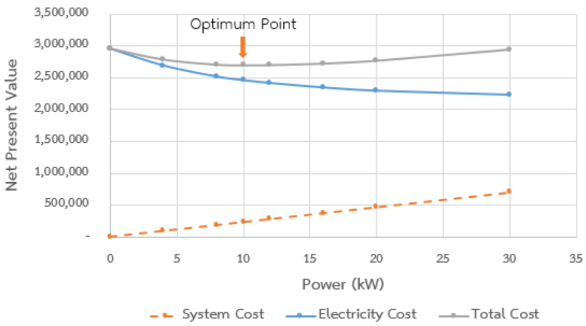
The optimal installation is 41 kW (80 modules), as shown in Fig. 10b., This system can produce 291.82 kWh of electrical energy per day, which is used during the period of 06:00-18:00. This amounts to 207.65 kWh of electrical energy per day, representing a PV utilization rate of 71% and reducing the building's daily energy consumption by 42%, as shown in Fig. 11b.

4.2.3 Building C – Maneebanphot

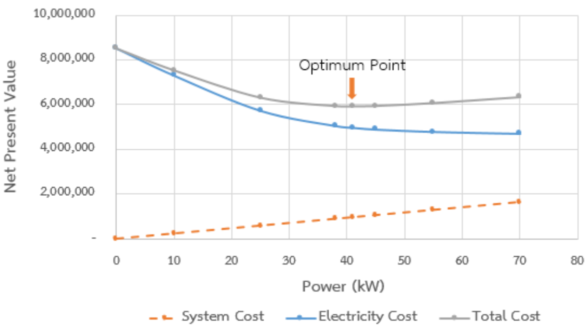
The optimal installation is 7 kW (14 modules), as shown in Fig. 10c., This system can produce 49.82 kWh of electrical energy per day, which is used during the period of 06:00-18:00. This amounts to 35.08 kWh of electrical energy per day, representing a PV utilization rate of 70% and reducing the building's daily energy consumption by 62%, as shown in Fig. 11c.

4.2.4 Building D – Alongkotpiman

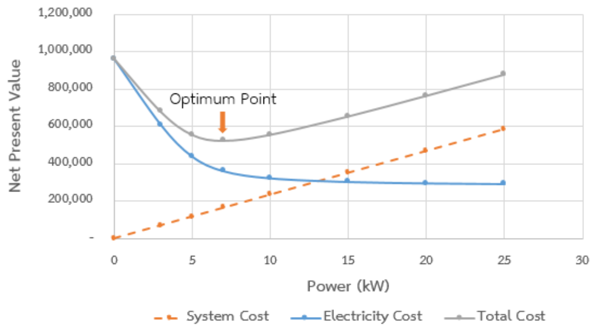
The optimal installation is 10 kW (20 modules), as shown in Fig. 10d., This system can produce 71.18 kWh of electrical energy per day, which is used during the period of 06:00-18:00. This amounts to 43.55 kWh of electrical energy per day, representing a PV utilization rate of 61% and reducing the building's daily energy consumption by 70%, as shown in Fig. 11d.



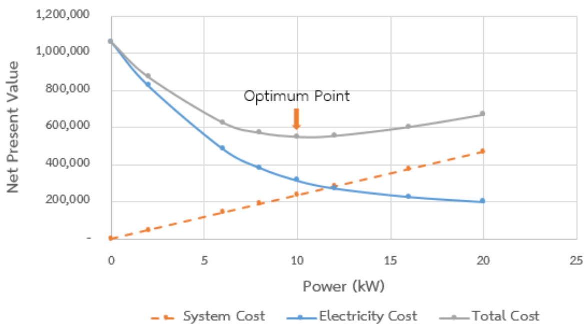
(a) Building A



(b) Building B

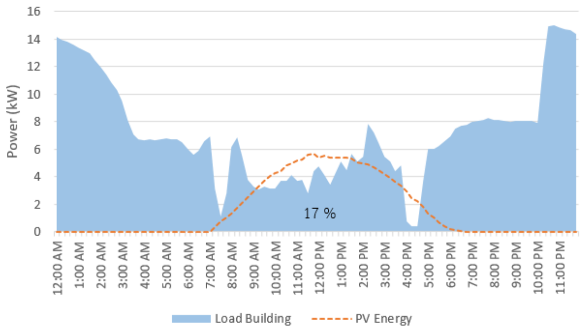


(c) Building C

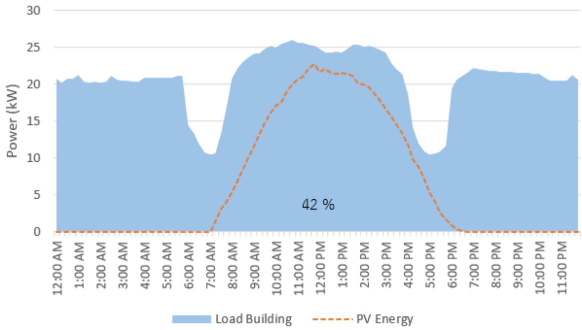


(d) Building D

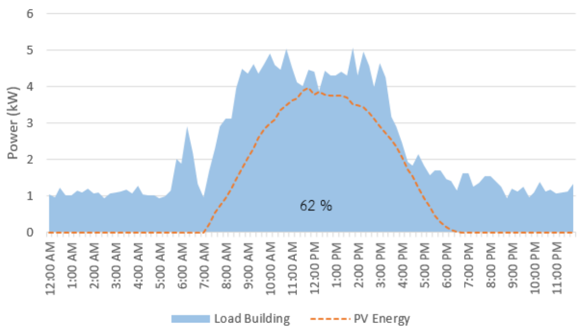
Fig. 10. Assessment of the optimal size of PV modules for each building.



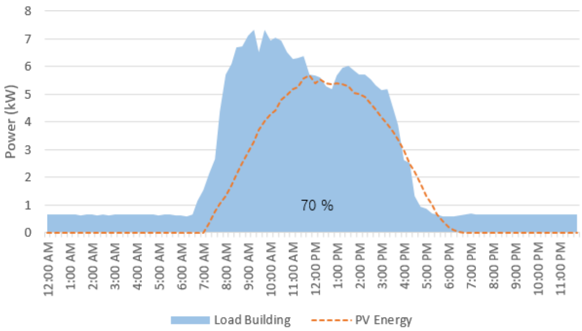
(a) Building A



(b) Building B



(c) Building C



(d) Building D

Fig. 11. Comparison of average daily energy consumption with solar energy generation.

4.3 Group of Building PV Optimization Including Energy Storage

Building upon the individual building optimization, this section analyzes the potential benefits of a centralized management approach, considering the energy demand of all four buildings collectively and incorporating an energy storage system. The GRG method was employed to determine the optimal configuration for the entire building group. The analysis focused on two main objectives: firstly, to determine the optimal system size that minimizes energy consumption from the grid for the Mae Moh Training Center building group, and secondly, to determine the optimal system size that minimizes the total system cost while significantly reducing grid electricity consumption.

4.3.1 Optimization for Minimum Energy Consumption from the Grid

The analysis of group optimization incorporating energy storage reveals a significant increase in PV system capacity compared to individual building optimization. The optimal configuration for minimizing grid energy consumption comprises a 208 kW PV system (400 modules) coupled with a 346 kWh energy storage system. As illustrated in Fig. 12, this integrated approach substantially reduces annual grid electricity consumption by 71%.

The system achieves a PV utilization rate of 60%, which is notably higher than most individual building optimizations, demonstrating the benefits of a centralized approach to energy management for the building group. Fig. 13. illustrates the daily energy profile with this optimized system, showing how the PV and storage systems work together to meet the building group's energy demand.

While this configuration effectively minimizes grid energy consumption, it comes with a higher initial investment. The total system cost is estimated at 15,666,493 THB, with a payback period of 13.8 years. Over the 20-year project lifetime, the electricity cost is reduced to 3,872,238 THB from the original 13,509,000 THB without the system.
This optimization scenario demonstrates the potential for significant reduction in grid energy consumption, aligning closely with nZEB principles. However, the extended payback period highlights the need to balance energy reduction goals with economic considerations, which is addressed in the following section on cost optimization.

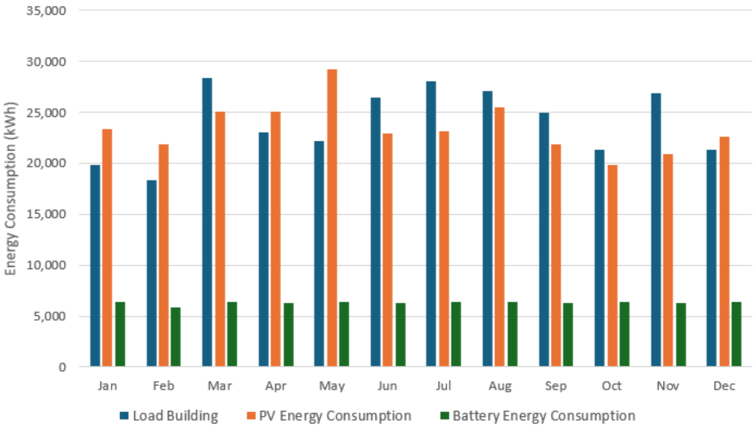


Fig. 12. Comparison of average monthly energy consumption with PV and ESS for the group of buildings to minimize grid energy consumption.

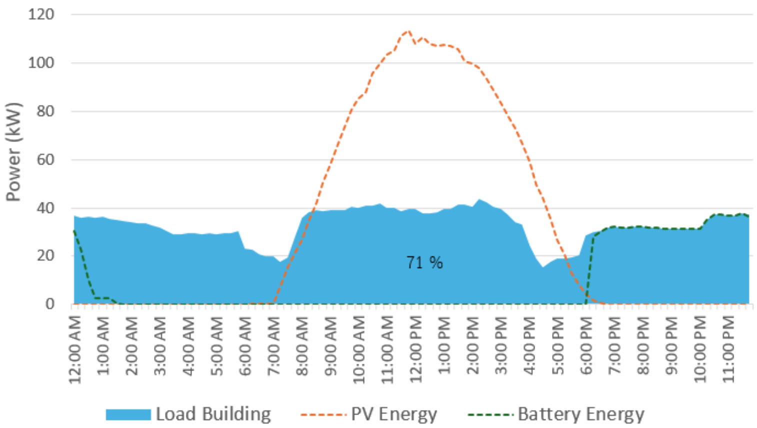


Fig. 13. Comparison of average energy consumption per hour with PV and ESS for the group of buildings to minimize grid energy consumption.

4.3.2 Optimization for Minimum Total System Cost

Given the high initial investment of the configuration that minimizes grid energy consumption, further analysis was conducted to find a balance between cost and energy reduction. The study examined three sub-scenarios, each targeting a different level of energy reduction:

4.3.2.1 25% Energy Reduction

The optimal configuration consists of a 53 kW PV system (102 modules) with no storage system. This setup achieves a 99% PV utilization rate and has a payback period of 4.27 years. The total system cost is 11,423,314 THB. Fig. 14. shows the assessment of the optimal size of PV modules and energy storage systems to minimize total costs for this scenario. Fig. 15. illustrates the comparison of average daily energy consumption with solar energy generation and storage for this configuration.

4.3.2.2 50% Energy Reduction

The optimal configuration includes a 136 kW PV system (262 modules) paired with a 100 kWh storage system. This configuration results in a 75% PV utilization rate and has a payback period of 8.67 years. The total system cost is 11,936,495 THB. Fig. 16. presents the assessment of the optimal size of PV modules and energy storage systems to minimize total costs for this scenario. Fig. 17. displays the comparison of average daily energy consumption with solar energy generation and storage for this setup.

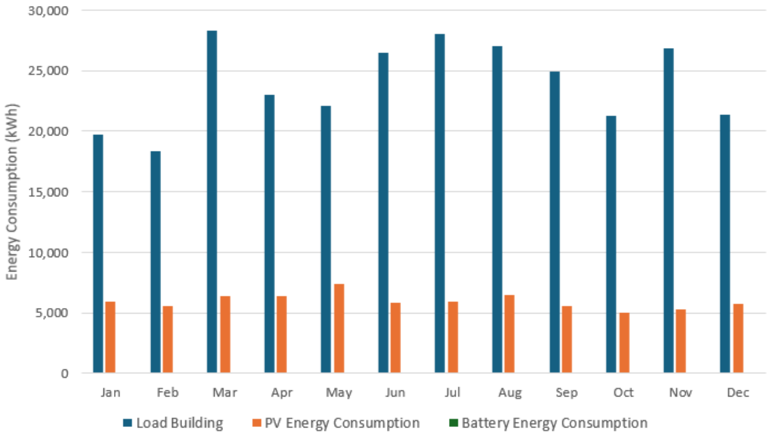


Fig. 14. Comparison of average monthly energy consumption with PV and ESS for the group of buildings to minimize total costs for the 25% energy reduction scenario.

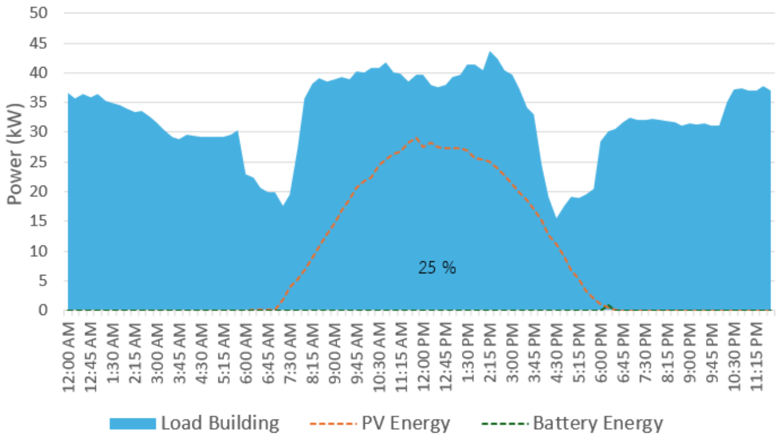


Fig. 15. Comparison of average energy consumption per hour with PV and ESS for the group of buildings to reduce 25% energy configuration.

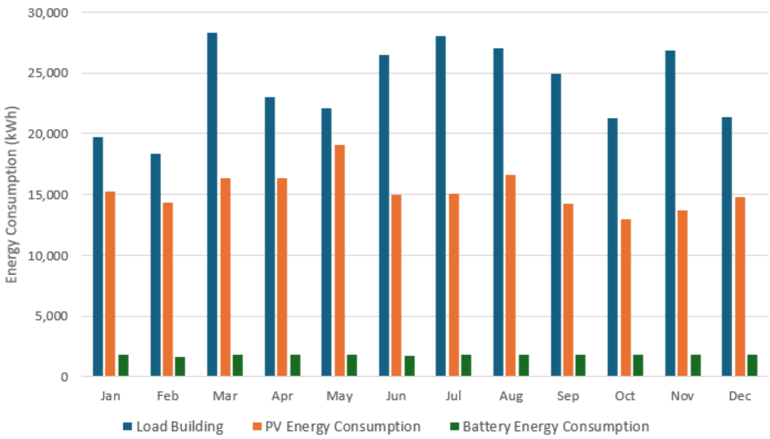


Fig. 16. Comparison of average monthly energy consumption with PV and ESS to minimize total costs for the 50% energy reduction scenario.

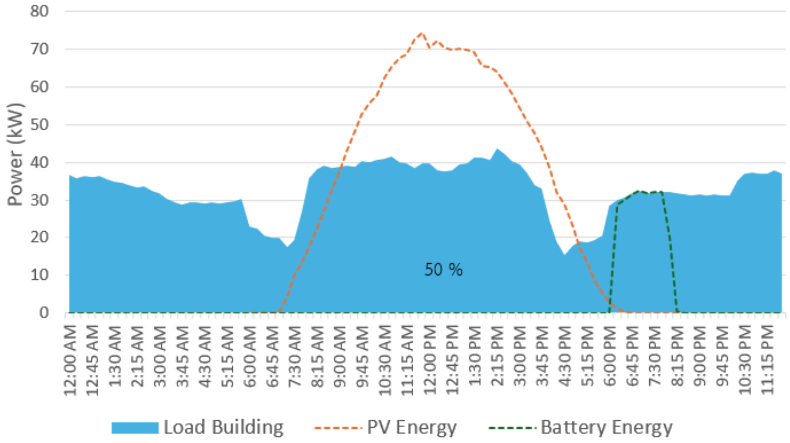


Fig. 17. Comparison of average energy consumption per hour with PV and ESS for the group of buildings to reduce 50% energy configuration.

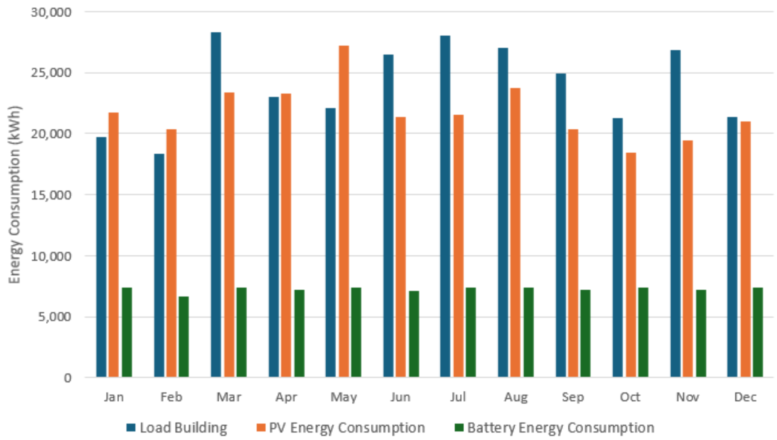


Fig. 18. Comparison of average monthly energy consumption with PV and ESS to minimize total costs for the 75% energy reduction scenario.

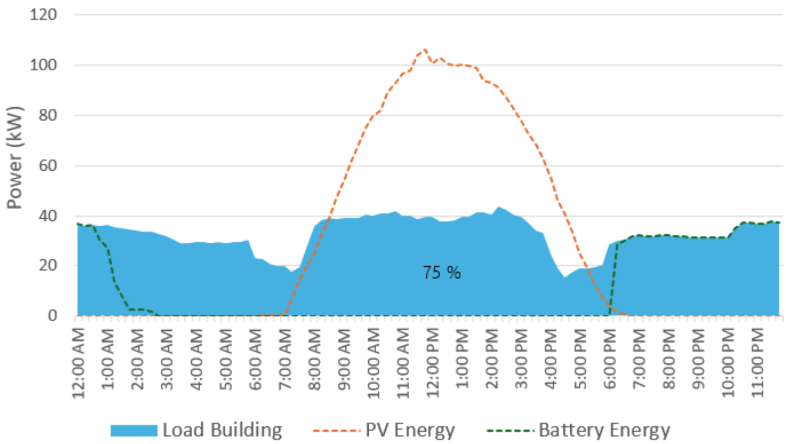


Fig. 19. Comparison of average energy consumption per hour with PV and ESS for the group of buildings to reduce 75% energy configuration.

4.3.2.3 75% Energy Reduction

The optimal setup comprises a 194 kW PV system (374 modules) and a 399 kWh storage system. This arrangement achieves a 62% PV utilization rate and has a payback period of 13.93 years. The total system cost is 15,898,958 THB. Fig. 18. shows the assessment of the optimal size of PV modules and energy storage systems to minimize total costs for this scenario. Fig. 19. illustrates the comparison of average daily energy consumption with solar energy generation and storage for this configuration.

These results demonstrate the trade-offs between energy reduction, system cost, and payback period. The 50% energy reduction scenario offers a balanced solution, achieving significant energy savings while maintaining a reasonable payback period.

Table 5 provides a comprehensive comparison of all scenarios, including key performance indicators and economic factors, facilitating a holistic evaluation of the different optimization approaches.

Table 5: Comparison of results for all scenarios.

System	**Scenario 1**	**Scenario 2**	**Scenario 3**			
			min eGRID	**25% eGrid Reduce**	**50% eGrid Reduce**	**75% eGrid Reduce**
Electrical Capacity (kW)	208	68	208	53	136	194
Number of PV Modules	400	134	400	102	262	374
Size of ESS (kWh)	-	-	346	1	100	399
Electricity Reduction Rate	46%	42%	71%	25%	50%	75%
PV Utilization Rate	24%	69%	60%	100%	75%	62%
System Cost (THB)	4,912,814	1,606,112	11,832,814	1,271,823	5,212,225	12,562,144
Electricity Cost over Project Lifetime (THB)	7,220,892	7,821,500	3,872,238	10,161,317	6,749,483	3,372,778
Total Cost (THB)	12,095,147	9,415,006	15,666,493	11,423,314	11,936,495	15,898,958
Annual Savings (THB)	559,404	505,973	857,308	297,818	601,342	901,741
Payback Period (Years)	**8.78**	**3.17**	**13.8**	**4.27**	**8.67**	**13.93**

4.4 Near Zero Buildings Evaluation

When plotting the solar energy production potential data from all three scenarios on the nZEB graph to assess the Mae Moh Training Center building cluster's proximity to zero energy consumption, using the electricity consumption index, the following observations can be made. The training center has a usable area of approximately 3,390.5 square meters and an annual energy consumption of 287,510 kWh. Fig. 20. illustrates the energy efficiency classification index for the building group. The yellow point represents the average specific energy consumption of the building cluster from 2022 to 2023, which is 84.8 kWh/m2-year. This position falls outside the defined area for a near-zero energy building cluster.

The analysis reveals that both Case 2 (Individual Building Optimization) and Case 3.3 (50% Energy Reduction in Group Optimization) can effectively bring the building group into the nZEB category. However, Case 3.3 is considered the superior option as it provides a better balance between energy reduction and production. It also offers improved resource efficiency, economic viability, and operational flexibility.

Based on these findings, the development of the Mae Moh Training Center building group into an nZEB should consider the approach outlined in Case 3.3. This strategy will most effectively achieve the goal of near-zero energy building status while optimizing system performance and economic factors. The implementation of this approach will enable the building cluster to meet nZEB criteria with the highest efficiency. However, it should be noted that PV system performance may decline due to panel degradation and climate change impacts. These factors could shift the building's position downward on the nZEB classification graph. Accordingly, system monitoring and energy management strategies are required in order to maintain nZEB status in long-term.

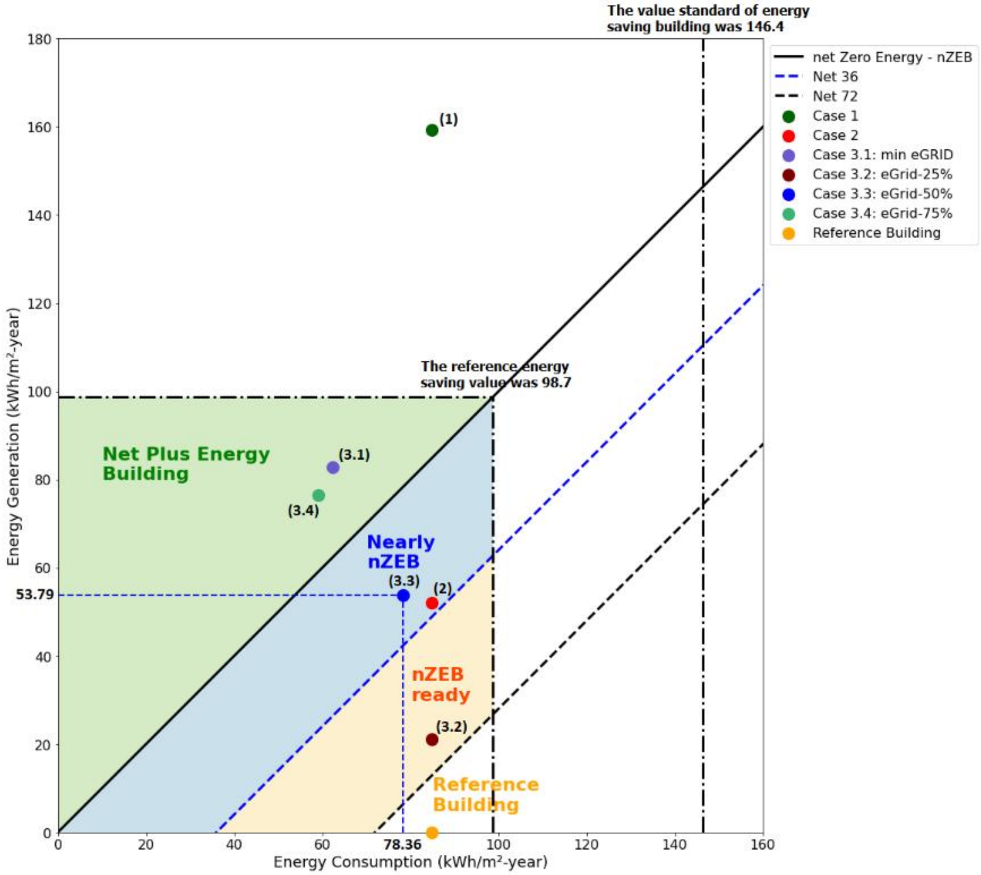


Fig. 20. Energy efficiency classification index for the group of buildings at Mae Moh Training Center.

5. Conclusion

This study evaluated the feasibility of implementing PV and energy storage systems to achieve nZEB status for a cluster of buildings at the Mae Moh Training Center. Three scenarios were analyzed: full-area installation, individual building optimization, and group optimization with energy storage. The full-area installation proved inefficient with only 24% PV utilization. Individual building optimization offered the shortest payback period of 3.17 years and 42% electricity reduction but resulted in excess generation. Group optimization with energy storage emerged as the most comprehensive solution, achieving 75% PV utilization and 50% grid electricity reduction with an 8.67-year payback period for the optimal configuration.

Both individual optimization and group optimization with storage met nZEB criteria based on electricity consumption index. However, the latter approach is deemed superior due to its balanced energy management, resource efficiency, economic viability, and operational flexibility. This group optimization, which includes a 136 kW PV system and a 100 kWh storage system, best aligns with nZEB principles and offers the most promising path forward for the Mae Moh Training Center.

A key limitation of this study is the use of monthly averaged data, both PV power and buildings consumption, in the optimization process. This may not accurately reflect short-term variations in actual energy consumption and generation patterns. Future studies should consider higher resolution data collection (weekly or daily) to improve optimization accuracy.

By applying systematically this analytical approach, stakeholders in the building sector can make more informed decisions about nZEB implementations, contributing to broader energy efficiency goals and sustainable development objectives.

Nomenclature

CRF_i	payback factor
I_T	solar irradiance, W/m^2
I_d	diffuse solar irradiance on a horizontal line, W/m^2
$F_{\max}$	maximum charge and discharge rate of the battery, %
$NOCT$	reference usage temperature for testing, ºC
$P_{m,stc}$	peak power at 25 ºC solar irradiance 1,000 W/ m^2, W
NPV_e	present value of electricity tariff
NPV_m	present value of maintenance
NPV_{SV}	present value of salvage value
$SOC_{\min}$	minimum state of charge the battery can maintain, %
T_a	ambient temperature, ºC
T_m	PV module temperature, ºC
$T_{\max}$	maximum temperature in the month under consideration, ºC
$T_{\min}$	minimum temperature in the month under consideration, ºC
$capB$	capacity of battery, kWh
$capINV$	capacity of inverter, kW
$capPV$	capacity of PV, kW
ccB	cost of battery, baht/kWh
$ccINS$	cost of installation, baht/kW
$ccINV$	cost of inverter, baht/kW
ccM	cost of maintenance, baht/kW
$ccPV$	cost of PV, baht/kW
$ccSV$	salvage value, baht/kW
eB_in_h	energy input to the battery, kWh
eB_out_h	energy output from the battery, kWh
e_{tariff}	electricity tariff from the electricity provider, baht/kWh
$eGRID_h$	electricity consumption from the electricity provider, kWh
ePV_S_he	excess electricity generated by PV, kWh
fit_{tariff}	electricity purchase rate from the service provider, baht/kWh
t	time considered in hours
ρ_g	radiant reflection condition of the ground
γ	temperature coefficient of PV module, ºC
κ_h	charging battery mode on when it takes the value of 1
φ_h	discharging battery mode on when it takes the value of 1
η_{AD}	battery discharging efficiency
η_{BC}	battery charging efficiency
η_{BD}	DC to AC conversion efficiency
η_{DA}	AC to DC conversion efficiency
η_{inv}	inverter efficiency

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