Journal of Architectural Research and Education

Journal homepage: https://ejournal.upi.edu/index.php/JARE/index

Optimization of PVC Foam Insulation Thickness in Container Housing Based on Life Cycle Energy Analysis (LCEA)

Muhamad Rio Baskara [1], Sri Novianthi Pratiwi[1], M. I. Ririk Winandari[1]*

[1] Master's Program in Architecture, Faculty of Civil Engineering and Planning, Trisakti University, Jakarta, Indonesia

*Correspondence: Email: srinovianthi@trisakti.ac.id

ABSTRACT

Shipping containers have increasingly been adopted as an alternative modular housing solution because they promote material reuse, reduce construction waste, and support sustainable building practices. However, their steel envelope has high thermal conductivity, resulting in excessive heat transfer and increased cooling energy demand in tropical humid climates. Previous studies have mainly focused on operational energy savings while overlooking the embodied energy of insulation materials. Consequently, the optimum insulation thickness from a life cycle energy perspective remains insufficiently investigated. This study aims to determine the optimum thickness of PVC foam insulation for the walls of a 20-foot container house using a Life Cycle Energy Analysis (LCEA) approach integrating embodied and operational energy. A quantitative methodology was employed through field measurements, EnergyPlus simulation validation, and scenario analysis. Two container houses with different insulation configurations were monitored to validate the simulation model, which was subsequently used to evaluate PVC foam insulation thicknesses of 10, 18, and 30 mm. The results demonstrate that exterior PVC foam insulation significantly improved indoor thermal performance and reduced cooling energy consumption. Based on a 10-year LCEA, the 30 mm insulation scenario achieved the lowest Life Cycle Energy of 76,971.02 MJ, indicating that life cycle-based insulation optimization provides an effective strategy for improving the long-term energy efficiency and sustainability of container housing in tropical humid climates.

ARTICLE INFO

Article History:
Submitted/Received 20 May 2026
First Revised 10 June 2026
Accepted 16 July 2026
First Available online 1 Nov 2026
Publication Date 1 Nov 2026

Keywords:
Container housing,
EnergyPlus;
PVC foam,
cooling energy,
Life Cycle Energy (LCE)

1. INTRODUCTION

Container-based housing is increasingly developing as one of the modular residential alternatives that support the principle of sustainable development (Fariña, E. A., and et al, 2024; Wei *et al.*, 2025). Used containers that are no longer used in logistics systems can be reused as building modules, extending the life of materials and reducing the need for the production of new construction materials. This approach also contributes to the reduction of construction waste, natural resource consumption, and carbon emissions related to the material production process, so that it is in line with the concept of circular economy, reuse, and recycle in the building sector (Ali *et al.*, 2024; Fariña, E. A., and et al, 2024; Wei *et al.*, 2025). In addition to having standardized dimensions, easy to move, and allowing for a faster construction process through a prefabricated system, the use of used containers also provides the potential for material savings compared to conventional construction. Nevertheless, the steel walls on the containers have high thermal conductivity so that heat from the outside environment can be quickly passed into the space. This condition is a major challenge in humid tropical climates characterized by high air temperatures, large relative humidity, and high intensity of solar radiation throughout the year. As a result, container buildings tend to experience an increase in cooling load, so that the energy consumption of air conditioning systems becomes greater than conventional buildings. Recent research shows that the thermal performance of container buildings is greatly influenced by the characteristics of the building envelope, including insulation materials, wall layer configurations, openings, air infiltration, and thermal bridges, which directly affect the energy consumption of buildings (Li and Densley Tingley, 2023; Liang *et al.*, 2024; Pinilla-Melo *et al.*, 2025).

To overcome these problems, the use of insulation materials is one of the most effective passive design strategies in improving the thermal performance of container buildings (Tong *et al.*, 2022; Kan *et al.*, 2023; Ali *et al.*, 2024; Omle *et al.*, 2024). Insulation not only functions as an additional layer, but also as a building envelope element that controls heat transfer, lowers wall surface temperature, maintains room temperature stability, and reduces cooling energy requirements Various studies report that the use of insulation materials is able to increase the energy efficiency of buildings, but its effectiveness is influenced by the type of material, installation position, insulation thickness, and climatic conditions of the research site (Ali *et al.*, 2024; Omle *et al.*, 2024). However, most studies still focus on evaluating the reduction of operational energy consumption, while the effect of increased embodied energy due to the addition of insulation material thickness is still relatively rarely considered in the design optimization process. As a result, insulation thicknesses that provide the lowest operational energy consumption may not necessarily result in the best energy performance when viewed from a lifecycle energy perspective (Grazieschi et al., 2021; Hill et al., 2018; Ounis et al., 2022; Yuan et al., 2017).

Therefore, this study proposes a Life Cycle Energy Analysis (LCEA) approach to determine the optimum thickness of PVC foam insulation on container housing walls in humid tropical climates. This approach integrates the embodied energy of the insulation material with the operational energy of the air conditioning system so that the evaluation is not only based on operational energy savings, but also considers the energy used from the material production stage. The research was carried out through field measurements on two container with different envelope configurations, validation of simulation models using EnergyPlus, and scenario analysis of variations in PVC foam thickness. The contribution of this study is to provide a more comprehensive evaluation framework to determine the optimum insulation thickness in container buildings based on the balance between increased embodied energy and operational energy savings over the life of the building analysis.

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

2. LITERATURE REVIEW

2.1. Thermal Characteristics of Container Buildings

Shipping containers have gained increasing attention as an alternative modular housing system because of their structural strength, standardized dimensions, rapid construction process, and contribution to material reuse within circular economy principles (Alegbe, 2024). Their modularity, portability, and high structural capacity have enabled their application in residential buildings, temporary shelters, and post-disaster housing (Zafra *et al.*, 2021; Alegbe, 2024). Despite these advantages, shipping containers were originally designed for cargo transportation rather than human occupancy. Their envelope consists primarily of Corten steel, which possesses high thermal conductivity and low thermal resistance, allowing solar heat to be rapidly transmitted into indoor spaces. Consequently, container buildings are highly susceptible to overheating, particularly in tropical humid climates characterized by high ambient temperatures, intense solar radiation, and elevated relative humidity (Zafra *et al.*, 2021).

Previous studies have consistently demonstrated that the thermal performance of container housing is governed not only by the thermal properties of the steel envelope but also by architectural design decisions, including building orientation, window configuration, shading devices, natural ventilation, and envelope construction (Elrayies, 2017; Zafra *et al.*, 2021; Omle *et al.*, 2024). Omle et al. (2024) showed that improving wall assemblies through multilayer configurations significantly reduced indoor heat gain, while Elrayies (2017) identified wall insulation, ventilation, and orientation as the principal factors affecting indoor thermal conditions in hot-humid climates. Likewise, Zafra et al. (2021) emphasized that although shipping containers possess excellent structural performance, achieving acceptable thermal comfort in tropical regions remains challenging due to the high heat transfer through steel walls. These findings indicate that improving the thermal characteristics of container housing requires an integrated envelope design approach rather than relying solely on the structural advantages of the container itself.

2.2. Thermal Insulation Materials for Container Buildings

Thermal insulation is widely recognized as one of the most effective strategies for mitigating excessive heat transfer through steel container walls. Recent advances in insulation technology have introduced a wide range of materials, including polyurethane, expanded polystyrene (EPS), extruded polystyrene (XPS), mineral wool, aerogel, reflective insulation, and environmentally friendly insulation products with low thermal conductivity. Ali et al. (2024) highlighted that these materials significantly improve building energy efficiency by reducing conductive heat transfer through the building envelope (Ali *et al.*, 2024). Similarly, Álvarez-Feijoo et al. (2020) reported that conventional insulation materials such as polyurethane, mineral wool, and polystyrene remain the most widely adopted solutions for container retrofitting because they effectively reduce temperature fluctuations, improve thermal comfort, and decrease HVAC energy demand (Álvarez-Feijoo *et al.*, 2020). The authors also emphasized the growing interest in phase change materials (PCMs) due to their ability to store latent heat and further enhance thermal performance.

For container housing applications, insulation performance depends not only on the thermal conductivity of the insulation material but also on the overall wall assembly configuration. Kan et al. (2023) emphasized that insulation effectiveness is strongly influenced by the combination of reflective layers, insulation thickness, and vapor permeability (Kan *et al.*, 2023). Likewise, Liang et al. (2024) demonstrated that thermal bridges, air infiltration, and windows accounted for more than 50% of the total energy consumption of a prefabricated container house, while improving thermal bridge insulation and external shading reduced the

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

total building energy consumption by approximately 25.9% (Liang *et al.*, 2024). Pinilla-Melo et al. (2025) further highlighted that because steel possesses high thermal conductivity and low thermal inertia, effective thermal conditioning of residential container buildings requires the integration of insulation systems with ventilated façades, roof assemblies, and carefully sealed envelope joints rather than relying solely on insulation materials (Pinilla-Melo *et al.*, 2025).

2.3 Life Cycle Energy Analysis for Container Buildings

Life Cycle Assessment (LCA) and Life Cycle Energy Analysis (LCEA) have become increasingly important approaches for evaluating the sustainability of buildings because they consider environmental impacts throughout the entire building life cycle rather than focusing solely on operational performance. Previous studies consistently demonstrate that operational energy has traditionally been the dominant contributor to total life cycle energy consumption in buildings, while the embodied energy associated with construction materials becomes increasingly significant as building energy efficiency improves. Schiavoni et al. (2017) applied a cradle-to-grave LCA framework to container-based nearly Zero Energy Buildings (nZEBs), integrating energy simulation with environmental assessment to identify building configurations with the lowest primary energy demand and greenhouse gas emissions (Schiavoni *et al.*, 2017). Bertolini and Guardigli (2020) further demonstrated that the environmental benefits of upcycling shipping containers depend not only on material reuse but also on the adopted thermal design and system boundaries used in life cycle assessment (Bertolini and Guardigli, 2020). More recently, Wei et al. (2025) extended this holistic perspective by integrating calibrated EnergyPlus simulations, life-cycle carbon assessment, and economic analysis, highlighting the importance of simultaneously considering operational performance and embodied environmental impacts when evaluating passive container housing (Y. Wei *et al.*, 2025). Nevertheless, most existing studies have primarily emphasized life cycle carbon emissions or overall environmental impacts, whereas investigations focusing specifically on optimizing insulation thickness based on Life Cycle Energy Analysis (LCEA), which explicitly balances the embodied energy of insulation materials with long-term operational energy savings in tropical humid container housing, remain limited.

3. RESEARCH METHODS

Figure 1 illustrates the overall research workflow. The study began with field measurements on two container houses, followed by the development and validation of an EnergyPlus simulation model. The validated model was subsequently used to evaluate PVC foam insulation thickness scenarios, and the resulting operational energy was integrated with the embodied energy of PVC foam through a Life Cycle Energy Analysis (LCEA) to determine the optimum insulation thickness.

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

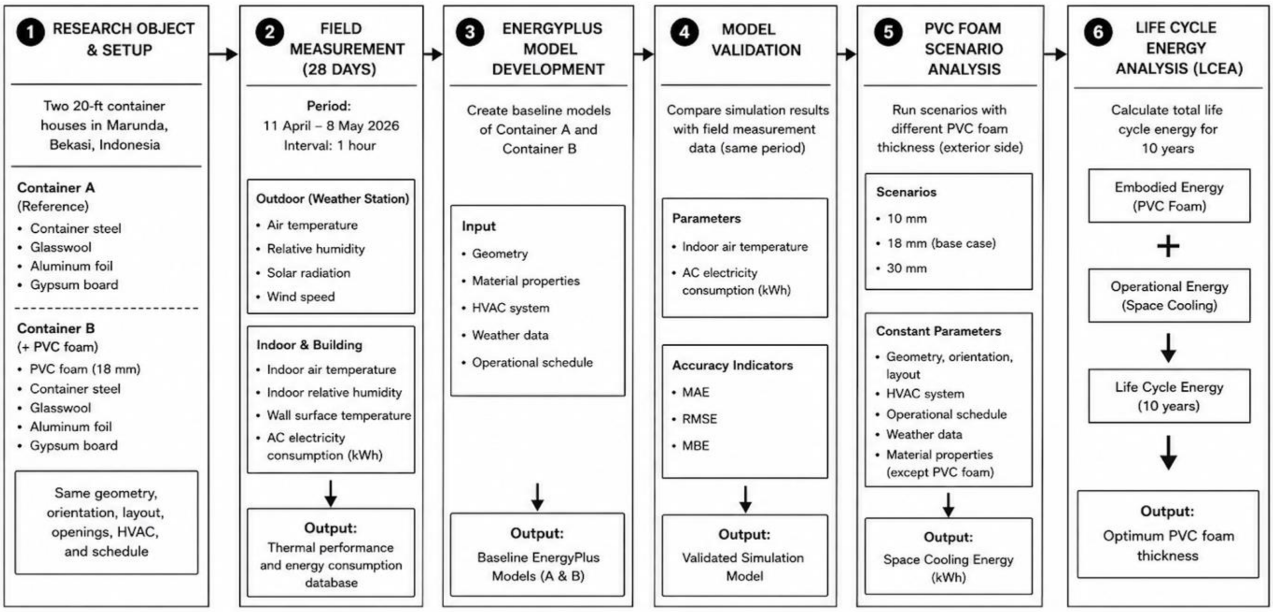


Figure 1. Research framework and methodological workflow
Source: author, 2026

3.1. Location and Research Object

This study uses a quantitative approach with comparative methods and energy simulation to evaluate the effect of the use of PVC foam insulation on the thermal performance and energy consumption of container buildings. The study was conducted on two container housing units measuring 20 feet or external dimensions of 6.06 m × 2.44 m × 2.59 m, while the dimensions of the inner space were around 5.90 m × 2.30 m × 2.35 m. Both containers have the same orientation, layout, opening, and air conditioning system, so the difference in thermal performance is mainly influenced by the variation in the configuration of the building envelope material. The research location is in Marunda, Bekasi Regency, Indonesia. Both containers were placed in the same location so as to receive identical outside climate conditions during the observation period. Figure 2 shows the configuration of the wall structure and the parameters of the material used.

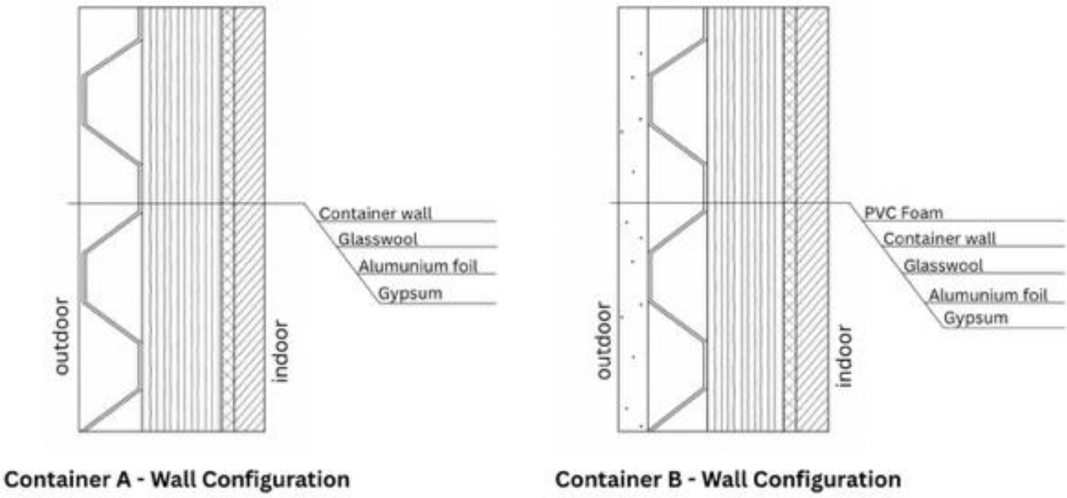


Figure 2. Configuration of the wall structure of Container A and Container B
Source: author, 2026

Container A is used as a reference building with a wall arrangement in the form of container steel, glass wool, aluminum foil, and gypsum. Container B has the same material arrangement, but a layer of PVC foam is added on the exterior side as an additional insulation material. Table 1 shows the thermal parameters of the wall.

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

Table 1. Thermal parameters of container walls

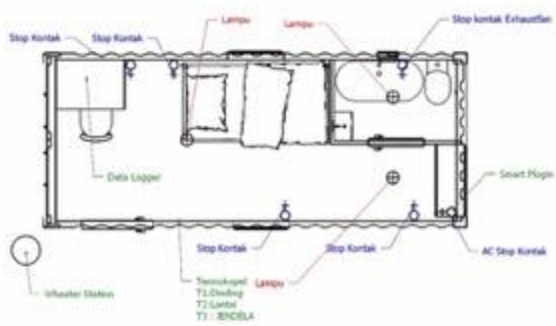
Material	Thickness (mm)	Conductivity W/(m-K)	Specific Gravity (kg/m3)	Heat Capacity (J/Kg.K)
PVC Foam	18	0,035	60	900
Container wall	40	45	7850	500
Glasswool	50	0,04	12	800
Aluminum foil	0,5	237	2700	900
Gypsum board	12	0,16	800	1090

Both buildings have the same orientation, dimensions, spatial layout, air conditioning system, and operational patterns, so the observed performance differences are mainly due to variations in the building envelope system. Field measurements were carried out for 28 consecutive days, from April 11 to May 8, 2026, with data recording intervals every one hour. The period was chosen because it represents the conditions of the beginning of the dry season in the study area, when the intensity of solar radiation and air temperature began to increase so that the cooling load of buildings became more dominant.

3.2. Thermal Performance Measurement of Container Buildings

Field measurements were carried out to obtain data on thermal conditions and actual energy consumption in both container buildings. The observed parameters include: outside air temperature, indoor air temperature, indoor air relative humidity, indoor surface temperature, indoor wall surface temperature, air conditioning electrical energy consumption, and outdoor weather conditions. Outside air temperature, humidity, solar radiation, wind speed, and other meteorological parameters were recorded using weather stations installed in open areas around the study site. Figure 3 shows one of the containers and measuring instruments used in the study.

(2a)



(2b)

(2c) (2d) (2e) (2f)

Figure 3. (2a & 2b) Container housing unit and sensor placement, (2c) Thermocouple sensor, (2d) Temperature & Humidity sensor, (2e) Weather station, (2f) kWh meter
Source: Author, 2026

Indoor air temperature, relative humidity, and inner wall surface temperature are measured using temperature and humidity data loggers and surface temperature sensors.

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

The electricity consumption of the air conditioning system is monitored using a smart plug meter that records energy usage continuously. The measurement interval on the entire sensor is 1 hour. All instruments work at the same time during the observation period so that a thermal and energy database with the same timestamp is obtained for simulation validation purposes. This stage aims to get which container has the best performance and is used as a basic model of the simulation.

3.3. Energy Simulation Modeling and Model Validation

Building energy simulation was carried out using EnergyPlus to evaluate the effect of adding PVC foam insulation on energy consumption in container housing. EnergyPlus was chosen because it is a building energy simulation software that is able to dynamically model heat transfer, energy consumption, and interactions between building envelope characteristics, climatic conditions, internal loads, and air conditioning (HVAC) systems (K. Alghoul, 2017; Fernandes *et al.*, 2018; U.S. Department of Energy. n.d. “EnergyPlus.” Accessed June 4, 2026). Two simulation models were developed based on the actual conditions of field measurement results, namely Container A as a reference model that uses the arrangement of container steel, glass wool, aluminum foil, and gypsum walls, and Container B which has the same material arrangement with an additional layer of PVC foam on the exterior side. The geometry of the two models is arranged according to the dimensions of the container, while the thermal properties of each material, including thickness, thermal conductivity, density, and heat type, are incorporated into the model based on the specifications of the materials used in the research building. Figure 4 shows the process of creating a baseline model of the container baseline with EnergyPlus.

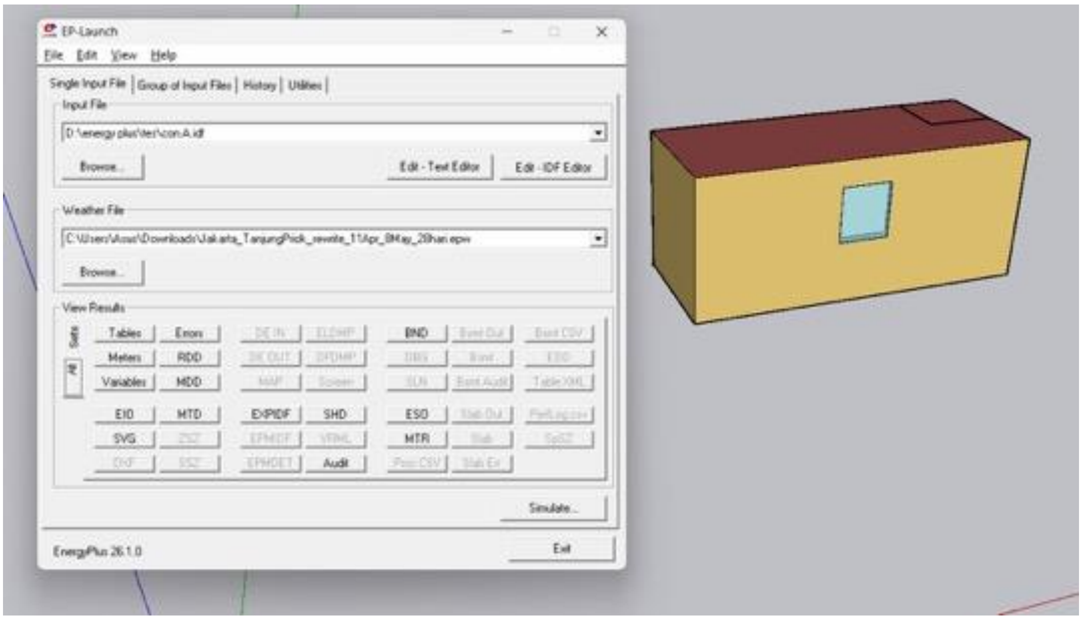


Figure 4. Geometry model of a 20-foot container on EnergyPlus
Source: Author, 2026

The simulation model that has been developed is further validated to ensure that the model is able to represent the actual condition of the container building. Validation was carried out by comparing the results of the EnergyPlus simulation with the data from field measurements in the same period, namely April 11 to May 8, 2026, with an interval of recording every hour. The parameters used in the validation process include indoor air temperature and the electrical energy consumption of the air conditioning (AC) system because both parameters directly reflect the thermal performance of the building and the cooling energy requirements.

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

Comparisons are made based on the same timestamp at each measurement interval. The accuracy level of the model is evaluated using Mean Absolute Error (MAE) to calculate the average absolute error, Root Mean Square Error (RMSE) to measure the magnitude of prediction error by giving greater weight to high errors, and Mean Bias Error (MBE) to identify the model's tendency to produce values that are higher or lower than the measurement results. The smaller the MAE, RMSE, and MBE scores, the better the level of conformity of the simulation model to actual conditions. Models that have met an adequate level of accuracy are then used to perform a scenario analysis of variations in the thickness of PVC foam insulation. MAE, RMSE, and MBE scores are calculated using equations (1) - (3).

Equations (1)

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | S_i - M_i |$$

Equations (2)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2}$$

Equations (3)

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)$$

with:

S_i = the value of the simulation results in observation ;

M_i = the value of field measurement results in observation ;

n = amount of observation data.

The simulation outputs include Space Cooling, Lighting, and Interior Equipment, with Space Cooling Energy used as the main parameter in the analysis as this study focuses on the evaluation of cooling energy needs. The simulation model that has been developed is then validated using the data from field measurements before being used to evaluate the scenario of variations in the thickness of PVC foam insulation.

3.4. PVC Foam Thickness Scenario Development

The validated simulation model was then used to develop a scenario of variation in the thickness of PVC foam insulation to evaluate its effect on the energy consumption of buildings. The PVC foam thickness variation scenario was chosen because this material is an insulation material commonly used in container buildings as an additional layer to improve the thermal performance of the building envelope. The development of the scenario is based on the container with the best thermal performance, then the model is used as a baseline in the entire scenario analysis. Three variations in the thickness of PVC foam were analyzed, namely 10 mm, 18 mm, and 30 mm. A thickness of 18 mm is used as a base condition because it represents the actual condition of the building measured in the field, while thicknesses of 10 mm and 30 mm are used to evaluate the effect of reducing and increasing insulation thickness on cooling energy requirements. In each scenario, all simulation parameters other than the thickness of PVC foam are maintained, including building geometry, orientation, other material characteristics, air conditioning system, operational schedule, internal load,

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

and weather data. Thus, the difference in simulation results can be directly attributed to changes in the thickness of PVC foam insulation. The main output analyzed is Space Cooling Energy, which is further used as the basis for the calculation of total life cycle energy by combining operational energy and embodied energy PVC foam material.

3.5. Total Life Cycle Energy Assessment

Life Cycle Energy Analysis (LCEA) is conducted to evaluate the effect of variations in PVC foam insulation thickness on the total energy needs of buildings by considering two main components, namely embodied energy and operational energy, as commonly used in building Life Cycle Energy (LCE) analysis (Dixit *et al.*, 2010; Dahiya and Laishram, 2024). In this study, the scope of analysis was limited only to the embodied energy layer of PVC foam insulation layer because the material was the only component that was varied in each simulation scenario. Meanwhile, operational energy is limited to the energy consumption of the air conditioning system (Space Cooling) obtained from the results of the EnergyPlus simulation, considering that the purpose of the research is to evaluate the effect of insulation thickness on cooling energy needs. Other building components as well as energy consumption for lighting and electrical appliances are assumed to be fixed so they are not included in the calculation. This restriction allows the effect of PVC foam thickness variations on total energy requirements to be evaluated more specifically. Embodied energy is calculated based on the volume of PVC foam in each thickness scenario, the embodied energy value uses the energy coefficient of PVC foam material of 70 MJ/kg (Alcorn, 2003). With a density of 60 kg/m³, this value is equivalent to 42.00 MJ/m² at 10 mm thickness, 75.60 MJ/m² at 18 mm, and 126.00 MJ/m² at 30 mm. Meanwhile, operational energy is obtained from the results of the EnergyPlus simulation and extrapolated over the service life of the building for 10 years. The LCE calculation is calculated using equation 4.

Equation (4):

$$LCE = EE_{PVC} + (OE_{AC} \times t)$$

With :

LCE = Life Cycle Energy

EE_{PVC} = Embodied energy PVC foam (MJ)

OE_{AC} = Air conditioning operational energy consumption per year (MJ/year)

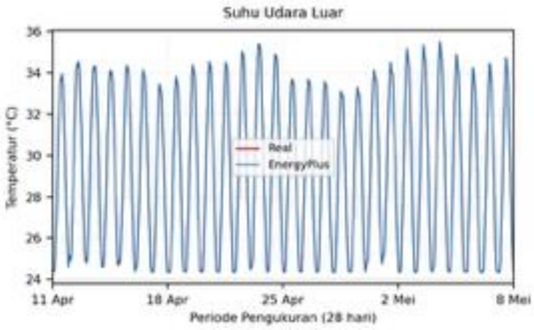
t = Age of building analysis (10 years)

4. RESULT

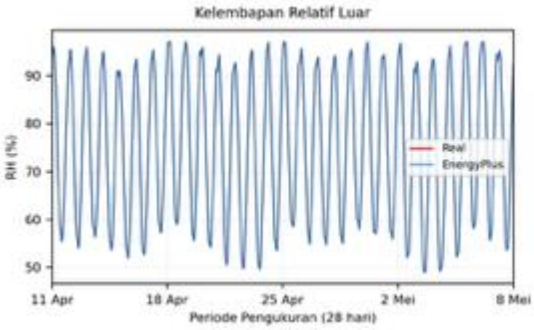
4.1. Development of PVC Foam Thickness Scenario

Thermal performance evaluation was carried out to compare the performance of two container housing that have different building envelope configurations, namely Container A without a PVC foam layer and Container B with additional PVC foam insulation on the exterior side. The comparison was made based on the results of field measurements for 28 days in the period April 11 to May 8, 2026 under the same outside climate conditions. The parameters analyzed included indoor air temperature, relative humidity, inner wall surface temperature, and air conditioning (AC) system energy consumption. This analysis aims to evaluate the effect of the addition of PVC foam insulation on the thermal conditions of the room and the cooling energy requirements before simulated modeling. Figure 5 shows the weather conditions during the measurement period of (4a) air temperature, (4b) relative humidity, (4c) solar radiation and (4d) wind speed.

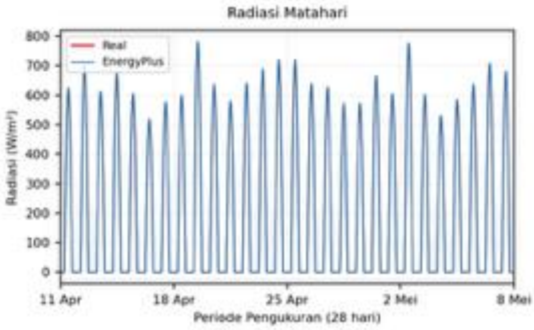
DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165



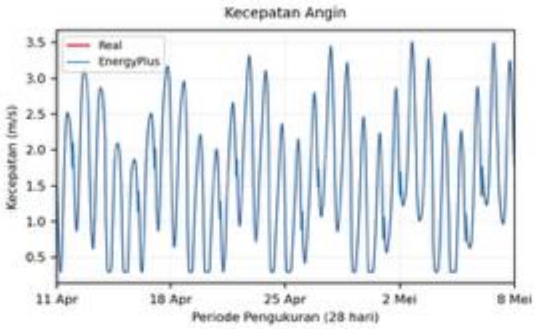
(5a) Outside air temperature °C



(5b) External relative humidity (%)



(5c) Solar radiation (W/m²)



(5d) Wind speed (m/s)

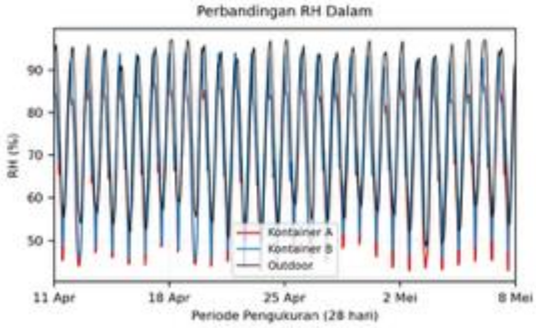
Figure 5. Weather conditions during the measurement period
Source: Author, 2026

During this period, weather conditions were relatively stable without any extreme weather events that could potentially affect the measurement results. The outside air temperature ranges from 24.40 to 35.49 °C, with an average temperature of 29.18 °C, while the relative humidity is in the range of 49.04–97.00 %. The maximum recorded solar radiation reached 780.05 W/m², with an average value of 201.93 W/m². The variation in meteorological conditions reflects the characteristics of the tropical climate at the research site and is the main factor that affects heat transfer through the building envelope and the energy requirements of the air conditioning system.

Figure 6 shows a comparison of the thermal performance between Container A and Container B during the 28-day measurement period which includes (6a) indoor air temperature, (6b) relative humidity, (6c) inner wall surface temperature, and (6d) energy consumption of the air conditioning system. In general, Container B exhibits better thermal performance than Container A in all observed parameters. The addition of a layer of PVC foam insulation is able to reduce the temperature of the inner air, reduce the surface temperature of the inner wall, maintain relatively more stable humidity, and reduce the energy consumption of the air conditioning system. These results show that the modification of the building envelope has an influence on the transfer of heat to the inner chamber thereby increasing the thermal efficiency of the container building.

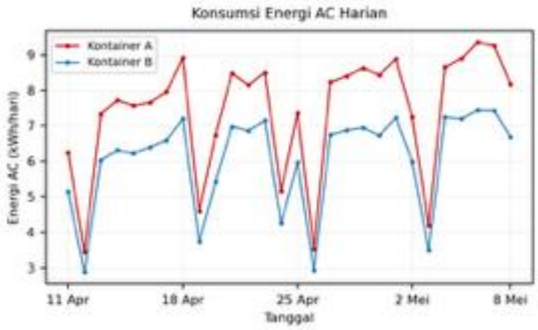
DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

(6a) Comparison of Air Temperature in Container A & B (°C)



(6b) Comparison of external relative humidity in container A & B (%)

(6c) Comparison of the surface temperature of the walls in the container A&B (°C)



(6d) Comparison of consumption of A&B container air conditioner (kWH)

Figure 6. Comparison of thermal performance between Container A and Container B during the 28-day measurement period
Source: Author, 2026

Container A with an average temperature of 27.98 °C and 28.47 °C, respectively, or a decrease of 0.49 °C (1.73 %). In addition, the temperature fluctuations in Container B were smaller with a standard deviation of 2.02 °C, compared to Container A of 2.83 °C, indicating that the thermal conditions of the room were more stable. If the measurement results show a delay in the time of reaching the maximum temperature of around 0–1 hour, this condition indicates that the PVC foam layer is able to slow down the transfer of heat to the inner chamber. In line with this, Figure (5b) shows that the relative humidity in Container B is also slightly higher but more stable than in Container A, with average values of 72.13% and 70.83%, respectively.

The increase in thermal performance is also seen from the surface temperature of the inner wall and the consumption of cooling energy. In Figure (5c), the average wall surface temperature of Container B is 29.10 °C, lower than Container A which reaches 29.83 °C, resulting in a decrease of 0.73 °C. This decrease in surface temperature shows that the PVC foam layer is able to increase the thermal resistance of the building envelope so that the heat entering the room becomes smaller. This impact is further reflected in the energy consumption of the air conditioning system shown in Figure (5d). During the measurement period, the total AC energy consumption in Container A was 207.72 kWh, while in Container B it was 170.06 kWh, resulting in energy savings of 37.66 kWh or 18.13 %. These results show that the use of PVC foam insulation not only improves the thermal condition of the space, but is also able to reduce the cooling load and improve the energy efficiency of container buildings.

Table 2 shows that the use of PVC foam in Container B lowered the air temperature in an average of 0.49 °C (1.73%), reduced the surface temperature of the wall by 0.73 °C, and

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

reduced the energy consumption of the air conditioning system by 37.66 kWh (18.13%) compared to Container A. On the other hand, the smaller standard temperature and relative humidity deviation showed that Container B was able to maintain more stable thermal conditions of the room during the measurement period.

Table 2. Summary of thermal performance measurement results of two containers

Parameters	Units	Container A	Container B	Differences	Change (%)
Average air temperature	°C	28,47	27,98	0,49	1,73
Maximum temperature	°C	34,22	31,97	2,25	6,58
Standard temperature deviation	°C	2,83	2,02	0,81	28,71
Average RH	%	70,83	72,13	1,30	1,83
Average surface temperature	°C	29,83	29,10	0,73	2,46
Total air conditioning consumption	kWh	207,72	170,06	37,66	18,13
Daily air conditioning consumption	kWh/day	7,42	6,07	1,34	18,13

Therefore, based on these results, container B was selected as the baseline model for the EnergyPlus simulation validation process and the development of a scenario of variation in PVC foam insulation thickness at the next stage of research.

4.2. Simulation Model Validation

Figure 7 shows the comparison of air temperature in the results of field measurements and the results of the EnergyPlus simulation during the observation period. In general, the simulation results are able to follow the pattern of changes in indoor air temperature observed in the field, both when there is an increase or decrease in temperature. The suitability of the pattern shows that the simulation model is able to represent the thermal response of the building to environmental conditions during the measurement period and is therefore suitable for use as a basis for further analysis.

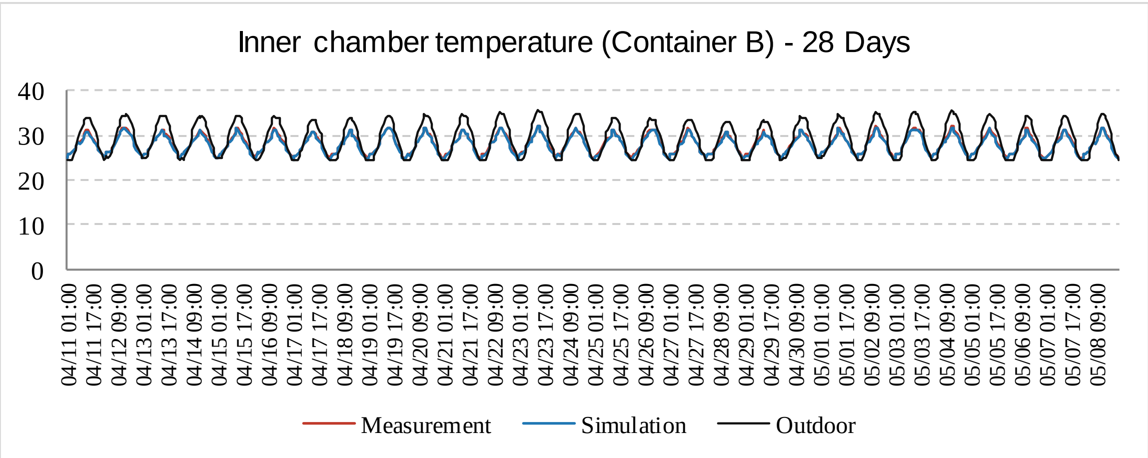


Figure 7. Validation graph of the comparison of air temperature in Container B as a result of EnergyPlus measurements and simulations
Source: Author, 2026

In addition to the deep air temperature, the validation process is also carried out on average relative humidity, average wall surface temperature, total air conditioning system energy consumption, and daily air conditioning energy consumption. The validation results showed that the MAE value was in the range of 0.12–0.51, RMSE 0.14–0.64, and MBE -0.45 to -0.11 according to the unit of each parameter, which indicated that the simulation results had a good level of conformity with the results of field measurements.

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

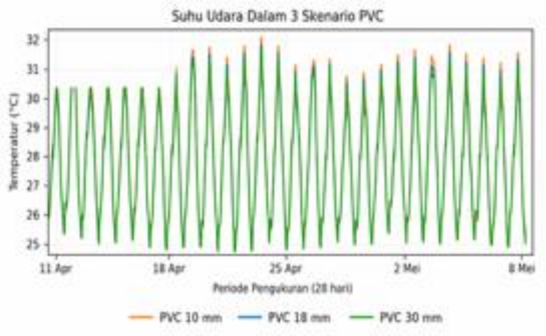
Table 3. The results of the validation of the EnergyPlus simulation model on the results of the measurement of container B field

Parameters	Measurement Results	Simulation Results	MAE	RMSE	MBE
Average air temperature (°C)	27,98	27,79	0,20	0,23	-0,19
Average relative humidity (%)	72,13	71,68	0,51	0,64	-0,45
Average surface temperature (°C)	29,10	28,92	0,18	0,21	-0,18
Daily air conditioning consumption (kWh/day)	6,07	5,96	0,12	0,14	-0,11

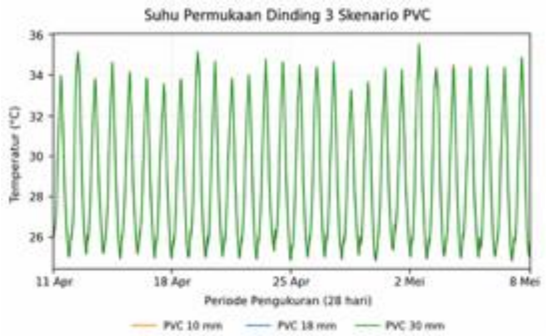
Thus, the EnergyPlus model is considered to be able to represent the actual condition of the building and can be used to evaluate the influence of variations in PVC foam insulation thickness at the scenario analysis stage.

4.3. Optimum thickness of PVC foam for container residential walls

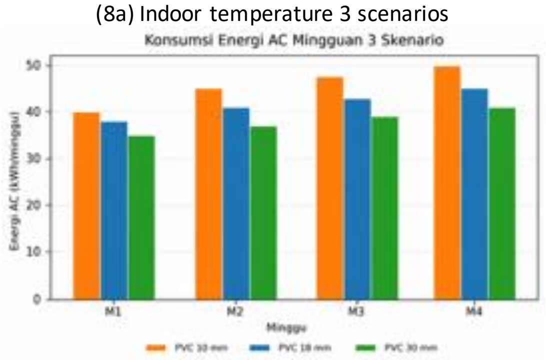
The variations in the thickness of the PVC foam analyzed included 10 mm, 18 mm, and 30 mm, while all other parameters, such as the geometry of the building, the configuration of materials other than PVC foam, weather conditions, operational schedules, and air conditioning systems were maintained. Thus, the difference in simulation results is only affected by the variation in the thickness of PVC foam insulation. Figure (8a) shows changes in indoor air temperature during the simulation period in all three variations in PVC foam thickness. In general, an increase in insulation thickness results in a lower and more stable indoor air temperature. Compared to the 10 mm model, the 18 mm model shows a decrease in the inner air temperature of 0.12 °C, while the 30 mm model provides a further decrease to 0.21 °C. The decrease occurs because the increase in insulation thickness increases the thermal resistance of the building envelope so that heat transfer from the outside environment to the inner space becomes smaller. The same conditions are also seen in the surface temperature of the inner wall (8b) where models with greater thickness produce a lower surface temperature thus reducing the heat emitted into the space.



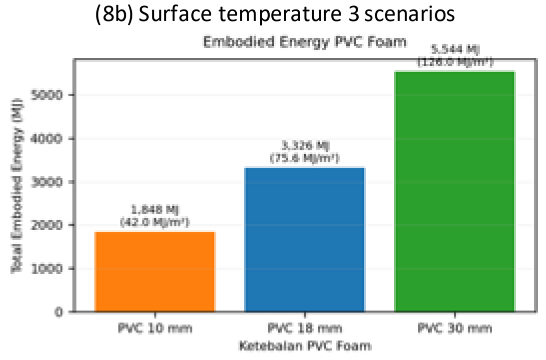
(8a) Indoor temperature 3 scenarios



(8b) Surface temperature 3 scenarios



(8c) Energy consumption 3 scenarios



(8d) Embodied energy PVC foam 3 scenario

Figure 8. Comparison of thermal performance simulation and energy consumption of three PVC foam thickness scenarios

Source: Author, 2026

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

The decrease in temperature has a direct impact on the energy requirements of the air conditioning system as shown in Figure (8c). AC energy consumption decreased from 185.48 kWh on the 10 mm model to 166.86 kWh on the 18 mm model, and reached 152.20 kWh on the 30 mm model. However, the increase in the thickness of PVC foam also increases the embodied energy of the material Figure (8d) as the volume of insulation used is getting larger. The embodied energy value increased from 42.00 MJ/m² at 10 mm thickness to 75.60 MJ/m² at 18 mm and 126.00 MJ/m² at 30 mm.

4.4. Total life cycle energy from the optimization of container occupancy wall insulation

Table 4 presents a summary of the simulation results for each PVC foam thickness variation, including embodied energy, cooling energy consumption during the 28-day simulation period, extrapolated operational energy over the 10-year analysis life, and total LCE. As the thickness of PVC foam increases from 10 mm, 18 mm, to 30 mm, the embodied energy value increases from 1,848.00 MJ to 3,326.40 MJ and 5,544.00 MJ. In contrast, the cooling energy consumption during the simulation period decreased from 185.48 kWh to 166.86 kWh and 152.20 kWh, which suggests that the increase in insulation thickness is able to improve the thermal performance of the building and reduce the need for cooling energy.

Table 4. Comparison of three scenarios of PVC foam thickness model and total energy life cycle 10 years

Models	**PVC Volume**	***Embodied Energy* per m²**	**Total *Embodied Energy***	**Operational Cooling Energy 28 days**	**10-year Energy Operations**	**Total LCE container 10 years**
PVC 10 mm	0.44 m³	42.00 MJ/m²	1,848.00 MJ	185.48 kWh	87,044.57 MJ	88,892.57 MJ
PVC 18 mm	0.79 m³	75.60 MJ/m²	3,326.40 MJ	166.86 kWh	78,306.23 MJ	81,632.63 MJ
PVC 30 mm	1.32 m³	126.00 MJ/m²	5,544.00 MJ	152.20 kWh	71,427.02 MJ	76,971.02 MJ

The balance between the decrease in operational energy and the increase in embodied energy was evaluated using LCE over the 10-year analysis life, as shown in Figure 9. Although embodied energy increases as the insulation thickness increases, the operational energy savings obtained during the building's operational life are greater than the additional energy contained in the material. Therefore, the 30 mm PVC foam model produces the lowest LCE of 76,971.02 MJ, lower than the 18 mm (81,632.63 MJ) and 10 mm (88,892.57 MJ) models. These results show that a thickness of 30 mm is the optimum thickness under the conditions of this study because it provides the best balance between improved thermal performance and total life cycle energy.

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

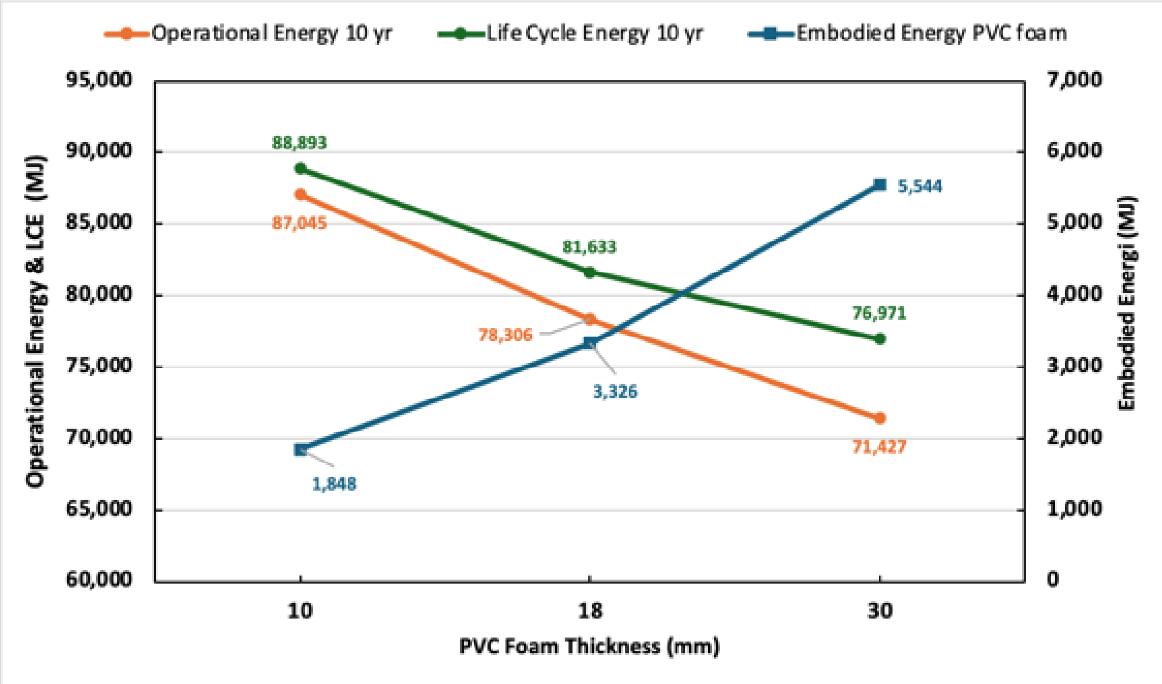


Figure 9. Comparison of Life Cycle Energy (LCE) for Three PVC Foam Thickness Scenarios over a 10-Year Life Cycle
Source: Author, 2026

5. DISCUSSION

This study shows that the addition of PVC foam insulation to the walls of container housing is able to improve the thermal performance of buildings while reducing the energy consumption of air conditioning systems. The results of field measurements showed that Container B using a PVC foam layer had a lower indoor air temperature and wall surface temperature than Container A. This finding indicates that the increase in thermal resistance in the building envelope is able to reduce the rate of heat transfer through the steel walls of the container so that the cooling load becomes smaller. These characteristics are in line with the basic principle of heat transfer in lightweight buildings, where an increase in the thermal resistance value of the building envelope contributes to a decrease in heat gain and an increase in energy efficiency (Fariña, E. A., and et al, 2024; Wei *et al.*, 2025).

The simulation results showed that increasing the thickness of PVC foam from 10 mm to 30 mm consistently lowered the cooling energy requirement. The thicker the insulation layer, the less heat enters the room so the air conditioning system requires lower energy to maintain the room temperature according to the setpoint. Nevertheless, the decrease in energy consumption is not entirely linear because after a certain thickness the additional increase in thermal resistance results in a smaller and smaller reduction in the cooling load. This suggests that an increase in insulation thickness does not necessarily result in a comparable increase in energy efficiency (Fariña, E. A., and et al, 2024).

On the other hand, the increase in insulation thickness also causes the embodied energy of PVC foam material to increase due to the increase in the volume of materials used. Therefore, the evaluation of the energy efficiency of a building is not enough to consider only operational energy, but it is also necessary to take into account the energy contained in the material from the production stage. The LCE approach used in this study allows for a more comprehensive evaluation of the building's energy performance by integrating embodied energy PVC foam and the operational energy of the air conditioning system over the life of

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

the building analysis. This approach provides a more precise decision-making basis than just using operational energy consumption as the main indicator.

Based on this analysis, the thickness of PVC foam of 30 mm produced the lowest LCE so that it became the optimal thickness under the conditions of this study. These results show that the additional embodied energy due to the use of thicker insulation can still be offset by operational energy savings over the life of the building. These results are in line with previous research by (Omle *et al.*, 2024) and (Tong *et al.*, 2022). However, the optimal thickness obtained in this study is not universal because it is influenced by the characteristics of the building, climatic conditions, operating patterns of the air conditioning system, the life of the analysis, and the type of insulation material used (Xu et al., 2025). Therefore, the application to other buildings or areas requires evaluation using parameters that are in accordance with local conditions.

6. CONCLUSION

This study successfully evaluated the effect of adding PVC foam insulation on the thermal performance and energy consumption of 20-foot container in humid tropical climates through a combination of field measurements, EnergyPlus simulation validation, and Life Cycle Energy Analysis (LCEA). The measurement results showed that the use of PVC foam was able to reduce the temperature of the inner air, the temperature of the wall surface, and the energy consumption of the air conditioning system compared to containers without PVC foam. The validated simulation model was then used to evaluate the variations in PVC foam thickness of 10 mm, 18 mm, and 30 mm, with all other building parameters maintained so that the effect of insulation thickness could be analyzed specifically.

Based on the simulation results, the increase in the thickness of PVC foam consistently lowered the cooling energy requirement, although it was followed by an increase in embodied energy material. The LCEA results showed that the 30 mm thickness produced the lowest LCE of 76,971.02 MJ during the 10-year analysis life, thus being the optimal thickness under the conditions of this study. The findings suggest that insulation thickness determination should not only be based on operational energy savings, but also consider embodied material energy as part of the lifecycle energy evaluation. Thus, this study provides a more comprehensive approach to determining the optimum insulation thickness in container buildings and can be the basis for the development of more energy-efficient modular building designs in tropical climates.

This research still has some limitations. The analysis was only carried out on one type of container housing in tropical areas with a measurement period of 28 days, while the LCE calculation was limited to embodied energy of PVC foam material and operational energy of air conditioning system without including other building material components or energy consumption other than air conditioning. The research can then develop the analysis into a more comprehensive Life Cycle Assessment (LCA) by considering all building materials, carbon emissions, life cycle costs, and evaluations of various climatic conditions to obtain broader design recommendations.

REFERENCES

Alcorn, A. (2003) “Embodied Energy And CO2 Coefficients For NZ Building Materials.”

Alegbe, M. (2024) “On the Emergence of Shipping Container Homes: Adaptation to Future Climate Projections,” *International Journal of Built Environment and Sustainability*, 11(3), pp. 1–12. Available at: https://doi.org/10.11113/ijbes.v11.n3.1215.

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

Ali *et al.* (2024) "A Comprehensive Review and Recent Trends in Thermal Insulation Materials for Energy Conservation in Buildings.," *Sustainability* [Preprint]. Available at: https://doi.org/https://doi.org/10.3390/su16208782.

Álvarez-Feijoo, M.Á. *et al.* (2020) "Effect of Insulation on the Energy Demand of a Standardized Container Facility at Airports in Spain under Different Weather Conditions," *Energies*, 13(20), p. 5263. Available at: https://doi.org/10.3390/en13205263.

Bertolini, M. and Guardigli, L. (2020) "Upcycling shipping containers as building components: an environmental impact assessment," *The International Journal of Life Cycle Assessment*, 25(6), pp. 947–963. Available at: https://doi.org/10.1007/s11367-020-01747-3.

Dahiya, D. and Laishram, B. (2024) "Life cycle energy analysis of buildings: A systematic review," *Building and Environment*, 252, p. 111160. Available at: https://doi.org/https://doi.org/10.1016/j.buildenv.2024.111160.

Dixit *et al.* (2010) "Identification of Parameters for Embodied Energy Measurement: A Literature Review.," *Energy and Buildings* [Preprint]. Available at: https://doi.org/https://doi.org/10.1016/j.enbuild.2010.02.016.

Elrayies, G.M. (2017) "Thermal Performance Assessment of Shipping Container Architecture in Hot and Humid Climates," *International Journal on Advanced Science, Engineering and Information Technology*, 7(4), p. 1114. Available at: https://doi.org/10.18517/ijaseit.7.4.2235.

Fariña, E. A., and et al (2024) "Energy Analysis of Standardized Shipping Containers for Building Applications.," *Infrastructures* [Preprint]. Available at: https://doi.org/https://doi.org/10.3390/inventions9050106.

Fernandes, M.S. *et al.* (2018) "An Aiding Tool for Building Design Generation, Thermal Assessment and Optimization – EnergyPlus Interaction Overview."

K. Alghoul, S. (2017) "A Comparative Study of Energy Consumption for Residential HVAC Systems Using EnergyPlus," *American Journal of Mechanical and Industrial Engineering*, 2(2), p. 98. Available at: https://doi.org/https://doi.org/10.11648/j.ajmie.20170202.16.

Kan *et al.* (2023) "Research Status and Development Trend of Thermal Insulation Envelope Materials for Marine Reefer Containers.," *ES Energy & Environment* [Preprint]. Available at: https://doi.org/https://doi.org/10.30919/esee1033.

Li, X. and Densley Tingley, D. (2023) "A whole life, national approach to optimize the thickness of wall insulation," *Renewable and Sustainable Energy Reviews*, 174, p. 113137. Available at: https://doi.org/https://doi.org/10.1016/j.rser.2022.113137.

Liang *et al.* (2024) "The Thermal Performance of a Typical Prefab Container House.," *Case Studies in Thermal Engineering* [Preprint]. Available at: https://doi.org/https://doi.org/10.1016/j.csite.2024.105445.

Omle *et al.* (2024) "Optimizing the Design of Container House Walls Using Argon and Recycled Plastic Materials.," *Buildings* [Preprint]. Available at: https://doi.org/https://doi.org/10.3390/buildings14123944.

Pinilla-Melo *et al.* (2025) "Design of a Shipping Container-Based Home: Structural, Thermal, and Acoustic Conditioning.," *Buildings* [Preprint]. Available at: https://doi.org/https://doi.org/10.3390/buildings15173127.

Schiavoni, S. *et al.* (2017) "A nZEB housing structure derived from end of life containers: Energy, lighting and life cycle assessment," *Building Simulation*, 10(2), pp. 165–181. Available at: https://doi.org/10.1007/s12273-016-0329-9.

Tong *et al.* (2022) "Analysis of Thermal Insulation Thickness for a Container House in the Yanqing Zone of the Beijing 2022 Olympic and Paralympic Winter Games.," *International*

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165

Journal of Environmental Research and Public Health [Preprint]. Available at: https://doi.org/https://doi.org/10.3390/ijerph192416417.

U.S. Department of Energy. n.d. "EnergyPlus." Accessed June 4 (2026) "EnergyPlus.," *Accessed June* [Preprint]. Available at: https://energyplus.net/.

Wei *et al.* (2025) "A Multidimensional Assessment of Passive Container Houses: Energy, Emissions, and Economics.," *Journal of Building Engineering* [Preprint]. Available at: https://doi.org/https://doi.org/10.1016/j.jobe.2025.113507.

Zafra, R.G. *et al.* (2021) "Structural and Thermal Performance Assessment of Shipping Container as Post-Disaster Housing in Tropical Climates," *Civil Engineering Journal*, 7(8), pp. 1437–1458. Available at: https://doi.org/10.28991/cej-2021-03091735.

DOI: https://doi.org/10.17509/jare.v8i2.103731
p- ISSN 2798-2246 e- ISSN 2798-2165