Enhancing Energy Efficiency with Insulation Materials in Taipei, Taiwan Residential Redevelopment

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Abstract

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This thesis aims to identify insulation materials and building construction factors that can lower carbon dioxide (CO_2) usage for residential redevelopment in Taipei and New Taipei, Taiwan. The growth in energy usage over the last 50 years has been explosive; most of Taiwan's electricity (89.9%) is generated from non-renewable sources. The subtropical climate of Taiwan is mostly hot and humid, and cooling accounts for the largest portion of residential power consumption, particularly in the aging housing stock that is largely uninsulated. I focused on identifying the best insulation materials in terms of low embodied energy and their potential to lower operational energy use. In this paper, I developed a simulation model to test different parameters such as insulation material, material thickness, building orientation, and window wall ratio, and evaluate their effects on insulation energy efficiency. The goals of this thesis are to 1) find insulation materials that have low embodied and operational energy in Taiwan in order to install them in old housing stock and 2) mitigate the amount of CO_2 produced by building cooling and heating needs. Improving the thermal envelope in new and re-developed housing in Taiwan has the potential to decrease residential energy consumption, lower CO_2 emissions from electricity usage in residential buildings 9.72%-35%, reduce heating and cooling costs and improve the quality of life for the people of Taiwan.

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Nomenclature

EEWH = Ecology, Energy, Waste, Reduction, and Health (Taiwan certification system)

CFA = C (temperate), F (no dry season), A (hot summer) from the Köppen–Geiger climate classification system

XPS = Extruded polystyrene

EPS = Expanded polystyrene

PU = Foamed polyurethane

PE = Polyethylene foam

HDPE = High Density Polyethylene

GF = Glass Fiber

PET = Polyethylene terephthalate

GWP = Global Warming Potential

U-value/factor (W/m^2*K) = Thermal transmittance, the rate of transfer of heat through a structure includes three major ways heat is lost: conduction, convection, and radiation.

R-value (m^2*K/W)= A measure of resistance to heat flow through a given thickness of material

Thermal conductivity (W/m*K) = How easily heat flows through a specific type of material, independent of the thickness of the material in question

WWR = Window-wall ratio is the fraction of above grade wall area that is covered by openings in the building envelope (e.g. windows, doors, skylights, curtain walls)

Emission Reduction = an emission reduction unit (ERU) represents a reduction of greenhouse gases, where it represents one tonne of CO_2 equivalent reduced.

Carbon Dioxide = CO_2

Chapter 1: Framework

Starting in 1997, Taiwan adopted mandatory residential building energy standards which included the U-factor for thermal conductivity of roofs to be 1.2 W/m^2*K and the U-factor for thermal conductivity of walls to be 3.5 W/m^2*K. [01] In 2006, Taiwan began a pilot version of a new rating system based on the previous green building certification. In addition, the Taiwan government has proposed a voluntary green building certification system for Ecology, Energy, Waste, Reduction, and Health (EEWH) but has had little commercial success due to lack of understanding of the benefits from the stakeholders, developers, and even designers in Taiwan. These efforts show Taiwan’s commitment to green building promotion and global sustainability to develop eco-cities and mitigate the heat island effect as it combats climate change and tackles its energy dilemma. [02]

In Figure 1, the main problem is that a significant portion, 89.9%, of Taiwan's energy is non-renewable. Due to its hot and humid climate, Taiwan uses a large amount of energy for building cooling demand and electricity production alone produces over 91 million tons of CO_2 every year. With 1.2 million houses over 30 years old, there exists a great opportunity to refurbish these old houses to be more energy efficient and thus, decrease the country’s CO_2e production. The question my thesis asks: How much can you decrease CO_2e from electricity production by refurbishing old housing stock in Taipei and New Taipei? (Figure 1) Through this thesis, I investigated this question by creating a building simulation model that tested parameters such as insulation type, insulation thickness, building orientation, and window wall ratio.

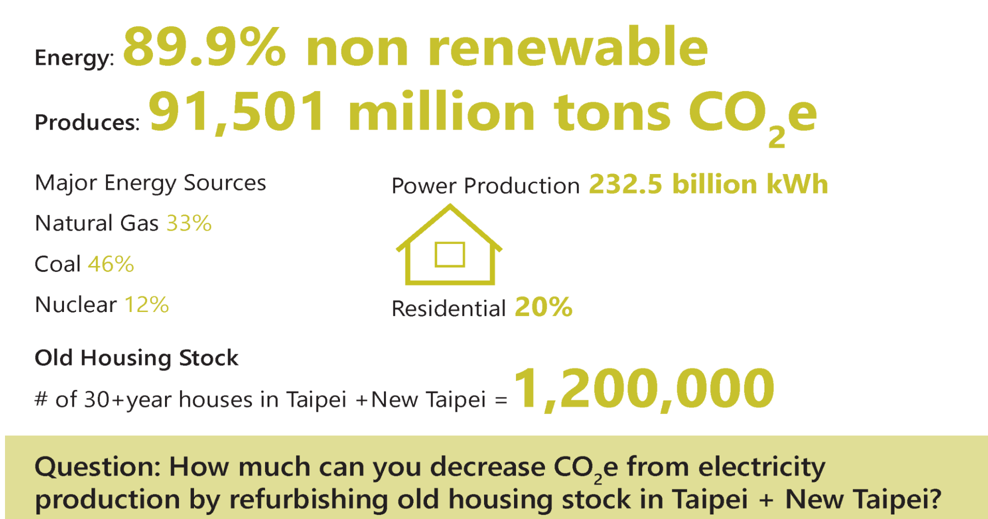

Figure 1. Problem and Main Question

1.1 Energy Production and Usage in Taiwan

The problem: Taiwan is currently facing an energy crisis. Annually, Taiwan produced 291 million tons of CO_2 emissions in 2020 compared to the USA which had almost a 4X increase in population but only 2X increase in CO_2 emission annually. (Figure 2)

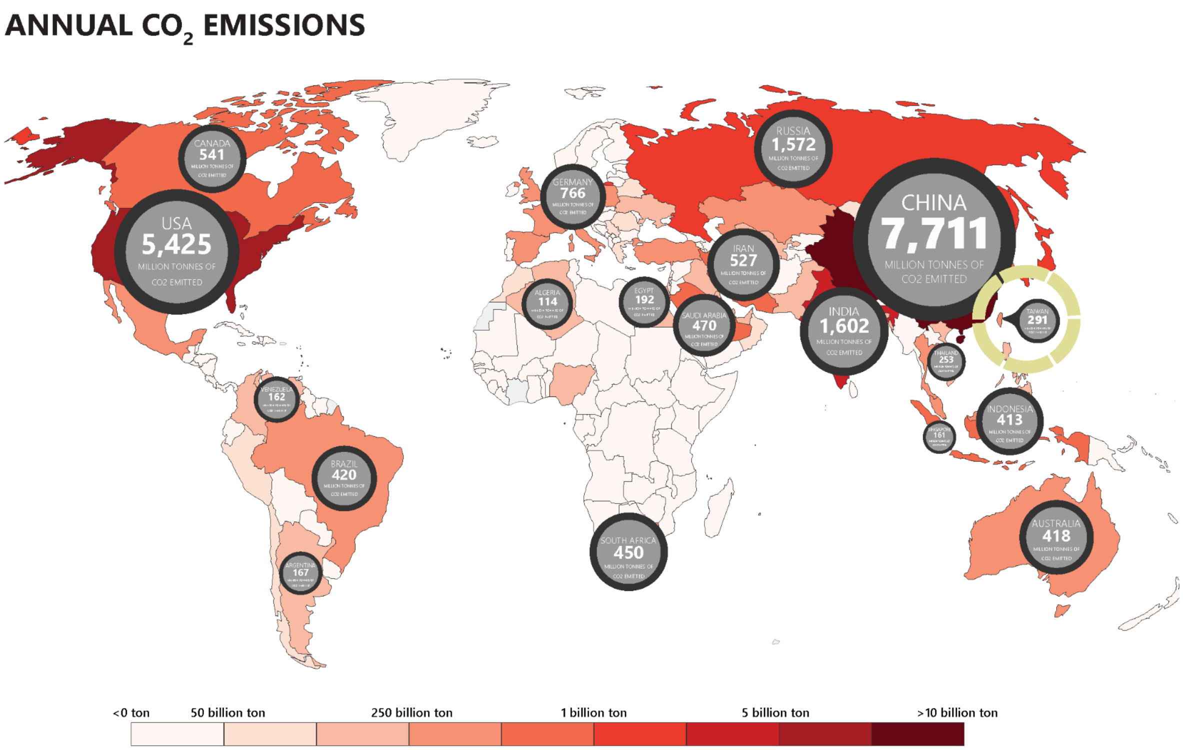

Figure 2. Annual CO_2 *Emissions. [03] [04]*

Data was collected from the Taiwanese Bureau of Energy [05] and Taipower [06] to identify energy consumption in Taiwan and energy generation that contaminates the air quality. Based on reports produced by Taipower, Taiwan's energy industry, this high CO_2 emission per capita is due to their reliance on 89.9% non renewable energy. According to the 2019 Taipower report, the electricity production for the entire island in 2019 emitted 91,501 million tons of CO_2. (Figure 3)

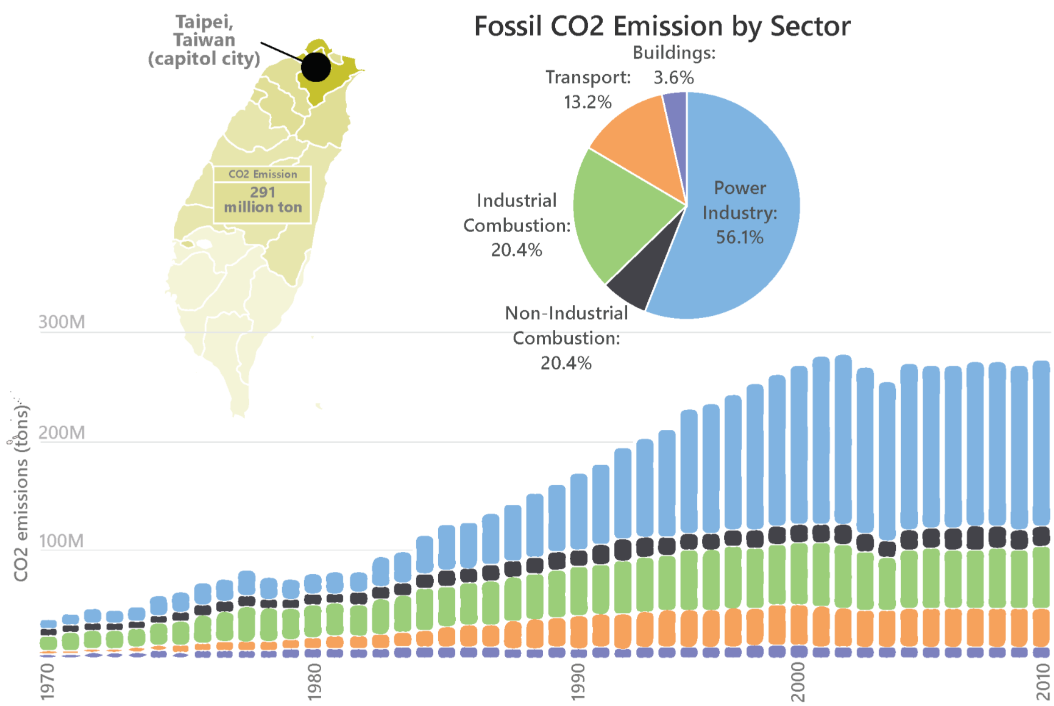

Figure 3. Taiwan CO_2 *Emissions. Adapted from Worldometer [07]*

In Figure 4, the predominant energy sources consist of coal at 46%, natural gas at 33%, and nuclear at 12%, and about 98% of the total energy sources are imported which increases the amount of CO_2 emissions due to transport. [11]

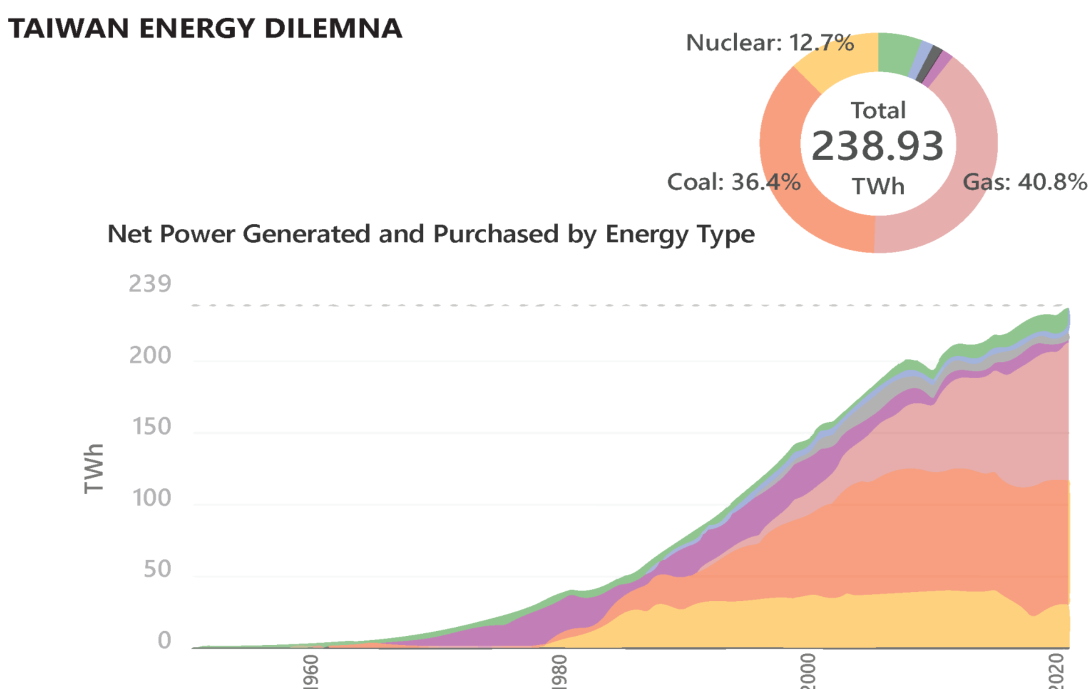

Figure 4. Taiwan Energy Dilemma. Adapted from Taiwan Power Company [08]

1.2 Taiwan Electricity Consumption

Taipower reported 232.5 billion kWh power production in 2019, Figure 06 shows that residential buildings used 20% (Figure 5), which means that residents in Taiwan used 46.5 billion kWh in 2019. [06] In the Taipower report in 2017, Taiwan's emissions factor was 0.554kg CO_2e/kWh and if Taiwan residents used 46.5 billion kWh then just the residential sector alone had 25.76 billion kg of CO_2 emitted annually. Dr Alan Lin, Deputy Executive Director of the Executive Yuan's Office of Energy and Carbon Reduction, has stated that the government's current goal is to reduce Taiwan's emissions factor to 0.394 CO_2/kWh by 2025 which would require Taiwan to adopt more renewable energy sources as well as achieve reduction targets for building emissions. [09] In addition, Figure 5 shows that Taipower has released their 2025 target for redefining Taiwan's electricity energy sources to be 50% natural gas, 30% coal, and 20% renewables. (Figure 6) This increases Taiwan's reliance on natural gas but decreases the usage of coal and slightly increases the energy production of renewables.

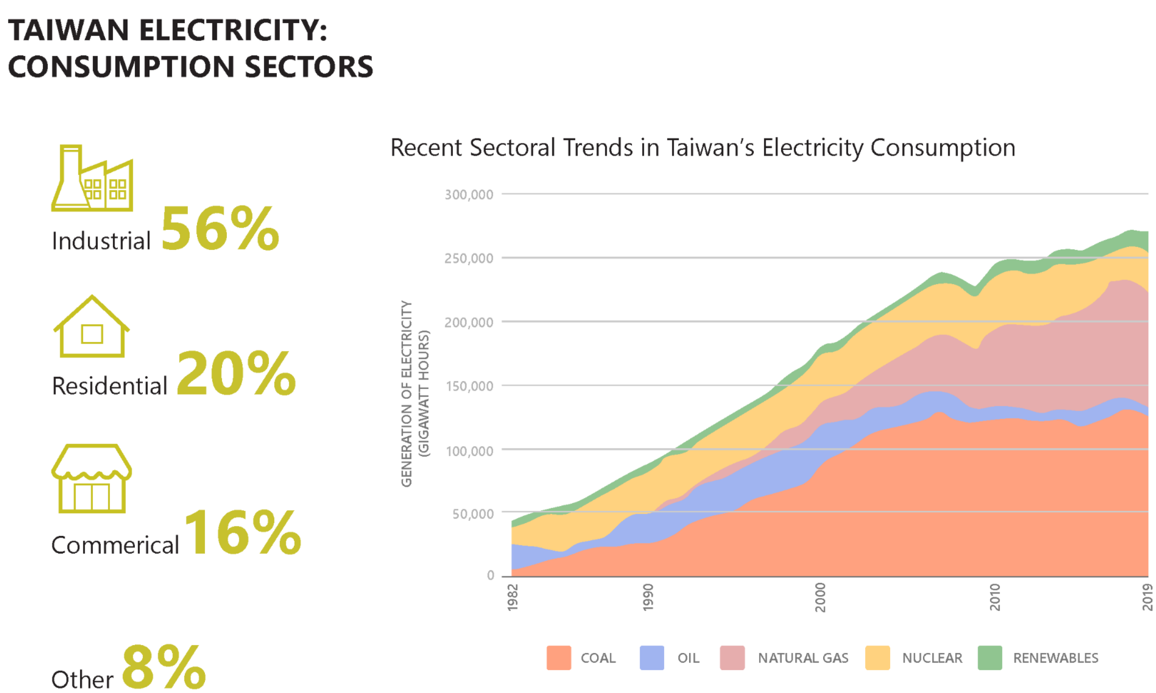

Figure 5. Taiwan Electricity Consumption Sectors. Adapted from Bureau of Energy [11]

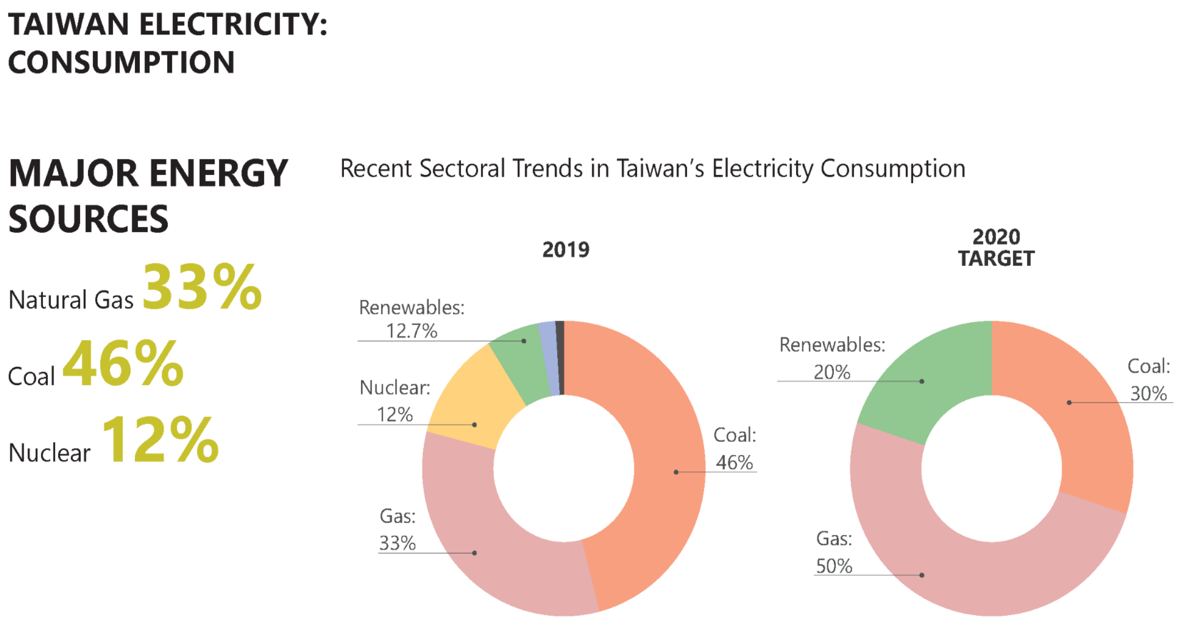

Figure 6. Taiwan Electricity Consumption. Adapted from Bureau of Energy [11]

In a study conducted in Tainan city, data was obtained by the Taiwan Power Company to create an average monthly household electricity bill and corresponding average monthly electricity consumption graph (Figure 7). Figure 7 compares national average monthly household electricity bill and the corresponding average monthly household electricity consumption, from February 2015 to January 2016, to show in TWD/household how much more electricity residents are paying and consuming in the summer months versus the winter months [12]

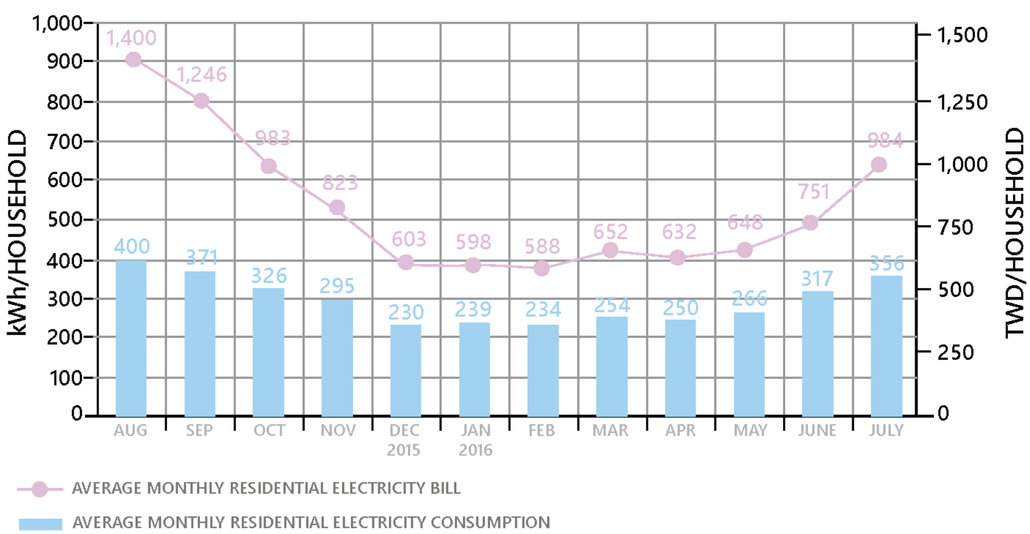

Figure 7. Taiwan Residential Electricity Bill vs. Consumption. Adapted from Chen et al [12]

1.3 Climate in Taiwan

Taiwan or Republic of China(ROC), 25.0330° N and 121.5654° E, is a 35,808 square kilometre island country in the Tropic of Cancer lying about 180 km across the Taiwan Strait from the southeastern coast of mainland China. [13] The capital city, Taipei City, lies in the northern region which is classified by the Koppen-Geiger Climate Classification as a CFA climate zone with a subtropical climate. (Figure 8) The letter "C" stands for temperate, "F" stands for no dry season, and "A" stands for hot summer.

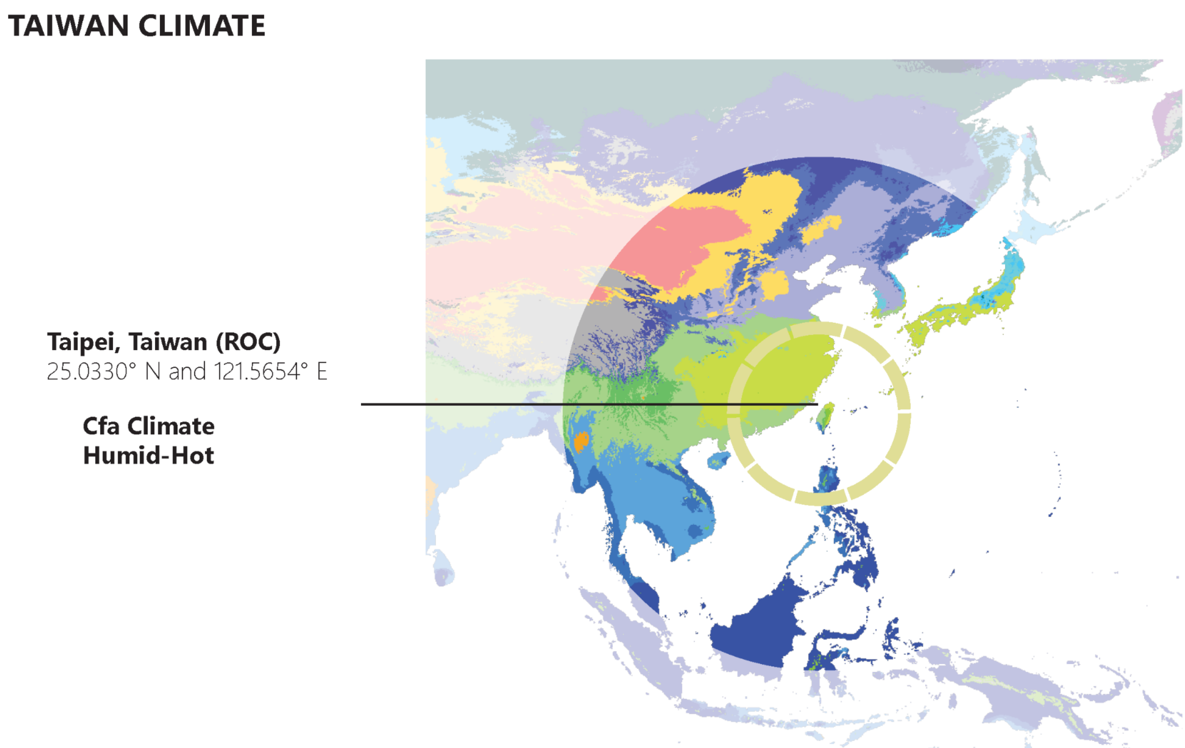

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Figure 8. Koppen-Geiger Climate Classification [14]

The island experiences especially hot and humid weather from May to September but it remains humid year-round. Due to its location on the coast of East Asia, Taiwan is heavily affected by a monsoon season from May or June and in the coming years has seen an increase in the frequency of typhoons in July through September due to climate change. In Taipei City and New Taipei City, there is a high amount of rain even in the driest months with about 221mm (87.4 inch) of annual precipitation and the average annual temperature is 21.1°C (69.9°F). [16] (Figure 9) The constantly high level of humidity and rainfall adds to the hot and humid temperature in a city that is otherwise classified as temperate. (Figure 10)

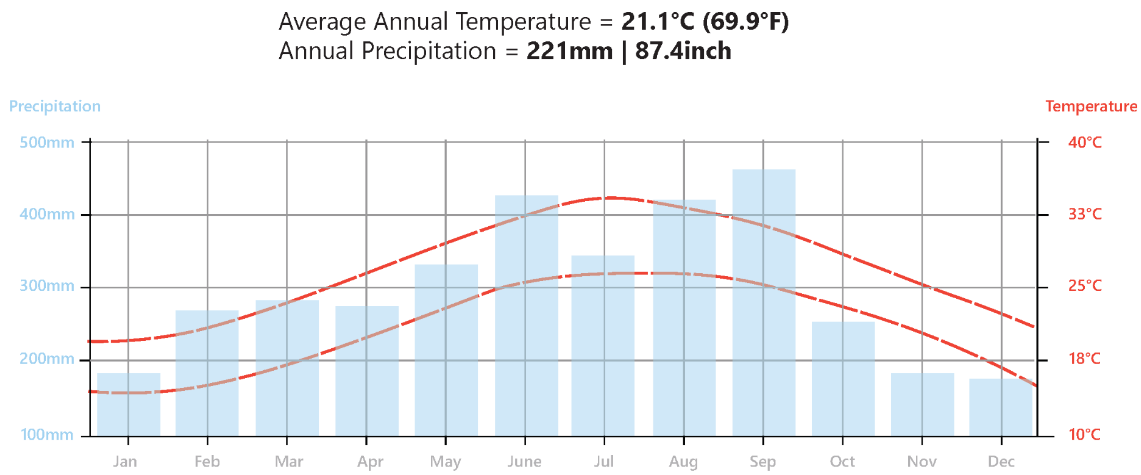

Figure 9. Average Annual Temperature and Annual Precipitation [16]

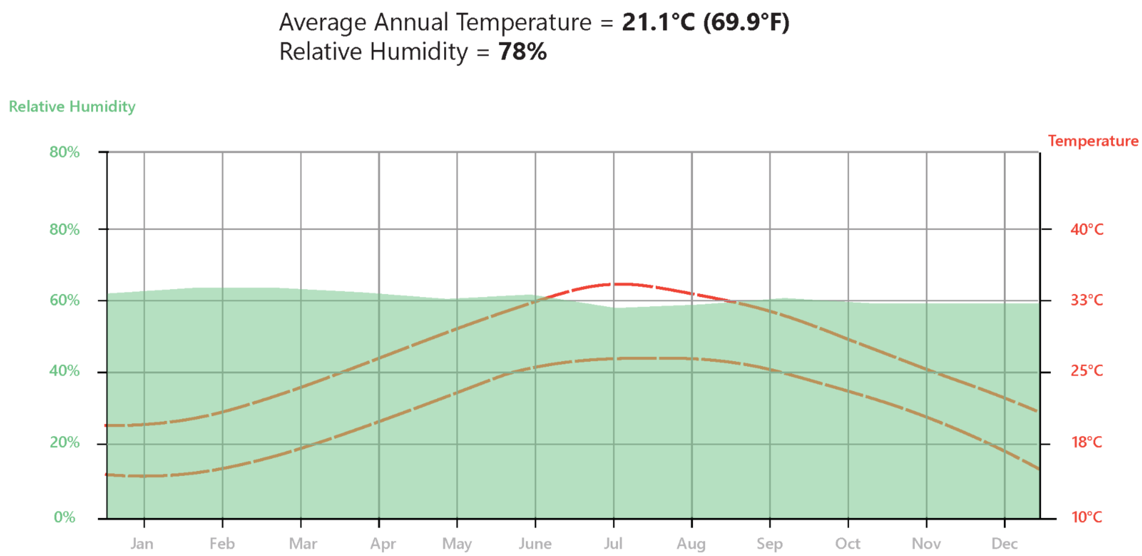

Figure 10. Average Annual Temperature and Relative Humidity [16]

Taiwan has the second lowest electricity rate at 2.55 NT$/kWh in 2017; however, it has seen a 11.9% increase in cooling hours in the summer months and during the typically hot typhoon months of August to September, cooling hours have grown by 40.5% (Figure 11). [17] Although residents do not feel the brunt of paying for electricity; however, the strain falls on Taipower company who suffered NT$14 billion in losses in 2018 and NT$10 billion in the first two months of 2019 alone. [51]

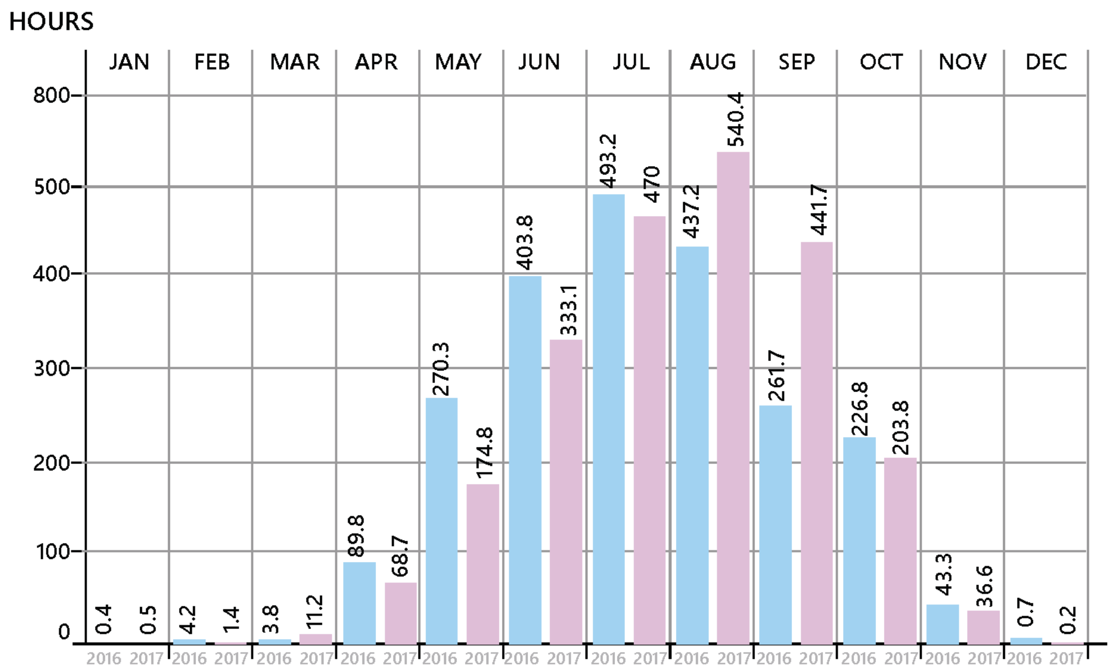

Figure 11. Run chart of monthly average cooling degree hours. Data source from Industrial Technology Research Institute (2017) [17]

1.4 Residential Buildings in Taiwan

In Taiwan, Taipei and New Taipei have an estimated population of 7,047,559 and 30% of all Taiwanese residents live in the metro area. As seen in Figure 12, Taiwan’s second and third most common housing typology are the low-rise (no elevator) and townhouse (3-5 floors, shared walls).

Figure 12. Typical Low-Rise and Townhouse Typologies seen in New Taipei and Taipei. [GoogleMap]

As seen in Figure 13, the struggle with residential housing in Taipei and Taiwan in general is the number of old housing stock and the lack of incentives to renovate. In Taipei and New Taipei, the number of 30+ year houses reached 1.2 million in 2016 and by 2026 is projected to reach over 1.75 million (Figure 13). [18]

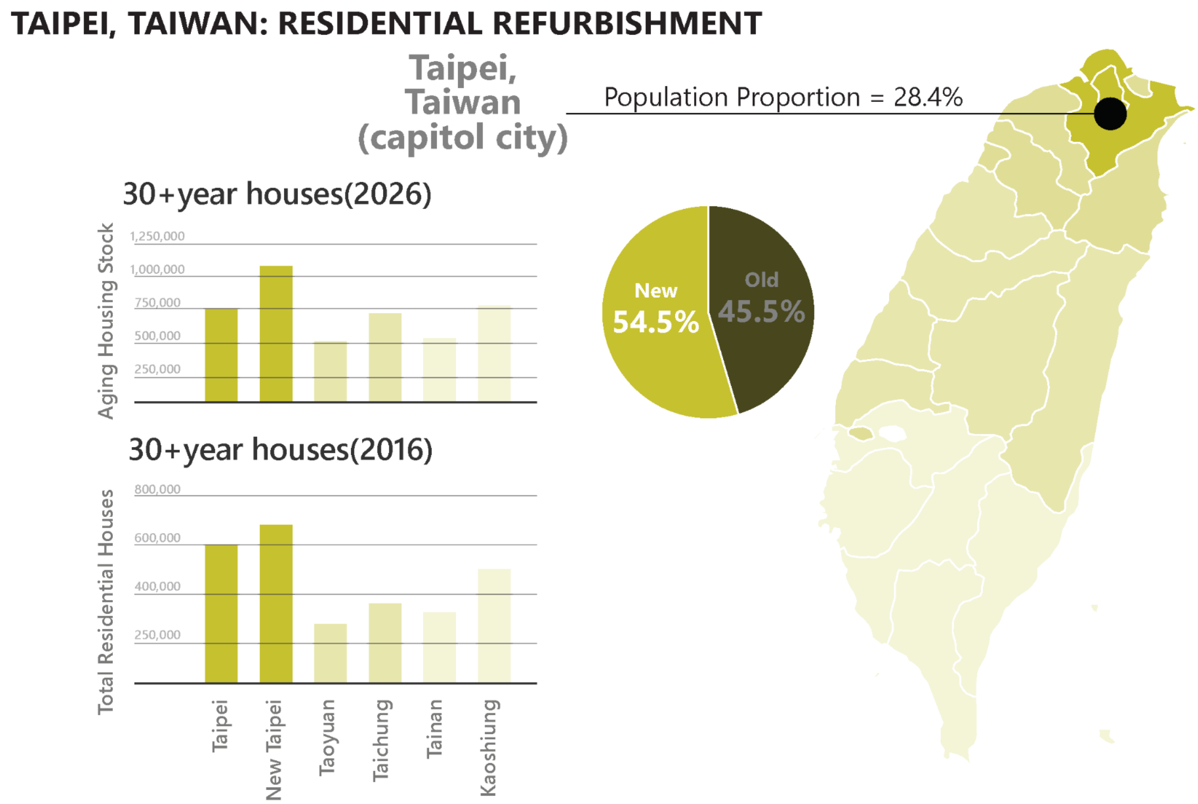

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Figure 13. 30+ year house statistics in major cities in Taiwan [18]

In addition to old housing stock, Taiwan is an earthquake-prone country that mainly uses concrete for building structural material in order to fight against earthquakes. However, concrete is a poor insulator and on a typical summer day in Taiwan, the temperature inside concrete buildings can exceed mid-30°C without air conditioning. [19] Concrete accounts for 90% of total buildings in Taiwan as of 2020 [20] even though it is not recyclable or environmentally friendly.

Chapter 2: Building Insulation Materials

2.1 Current Insulation Materials used in Taiwanese Residential Buildings

The housing conditions commonly lack insulation and heating due to the hot and humid climate in Taiwan, which in the past utilized a typical insulation for wall and roof composition such as the one seen in Table 1 that meets the basic building code requirement. This "typical insulation" represents the most common RC building envelope in Taiwan and lacks insulation in the wall and sufficient insulation in the roof. The typical glass type is a common single pane glass that is seen in aging stock buildings.

	Layer Name	Width	Density	Sp. Heat	U *
Wall Composition, U = 3.23	Ceramic Tiles	0.01	2.4	840	1.3
	Cement Mortar	0.015	2	800	1.5
	Reinforced Concrete	0.15	2.2	880	1.4
	Cement Mortar	0.01	2	800	1.5
Roof Composition, U = 1.00	Cement five-leg tile	0.05	0.7	900	1.5
	Polystyrene Foam	0.02	1.04	1130	0.04
	Concrete Lightweight	0.05	0.95	656.9	0.8
	Asphaltic Felt	0.01	1.02	900	0.11
	Cement Mortar	0.02	2	800	1.5
	Reinforced Concrete	0.15	2.2	880	1.4
	Cement Mortar	0.015	2	800	1.5
Typical Glass, U = 6.0	Glass Standard	0.006	2.3	836.8	1.05

Table 1. Typical insulation building envelope. Figure taken from Lin et al [21]

The problem with the lack of insulation in Taiwan is that residential units are frequently not refurbished so they typically do not include heating and cooling is commonly done with a single air conditioner unit per room. However, it does get cold in Taiwan albeit infrequently. According to Figure 9, there are several moments in December to March when the temperature can drop below 18°C. [16] 68°F/20°C is the ideal balance of comfort and energy efficiency according to Energy Star. This means that there are a number of days in a year where the temperature can drop below a comfortable temperature even though Taiwan is typically a hot and humid country. As Taiwan deals with an aging housing stock, it also has an aging population which reportedly has struggled with cold weather. In 2016, temperatures dropped 6.7°C (44°F) and 154 people died due to the lack of central heating and temperatures dropping below normal. [https://www.taiwannews.com.tw/en/news/3093806] In 2017, another cold spell in East Asia was attributed to the death of 85 people in Taiwan, many of whom were elderly people living in Taipei when temperatures dropped to 4°C (39°F). [https://www.bbc.com/news/world-asia-35397763] The current solution for many residents has previously been purchasing small portable heaters; however, like the heavy reliance on concrete, these methods are energy inefficient and not sustainable in the future especially as Taiwan grapples with an energy crisis.

2.2 Building Insulation as a Response to Improving Energy Efficiency

The reason why insulation is important to study when trying to design for building energy efficiency in a hot and humid climate is because insulation works as a barrier to heat flow where low thermal conductivity is typically ideal; however, insulation materials also can carry other characteristics based on what material they are made from such as structural integrity, toxic characteristics, moisture resistance, moisture absorption, and more so it is important to weigh the pros and cons of insulation materials. The benefit to using building insulation is the energy saving potential of a well-insulated house compared to a conventional house. A study proved that a well-insulated house could save between 50-90% depending on the location which makes insulation a secure investment because it can reduce thermal demand and heating and cooling demand. [Aditya, L., T. M. I. Mahlia, B. Rismanchi, H. M. Ng, M. H. Hasan, H. S. C. Metselaar, Oki Muraza, and H. B. Aditiya. 2017. "A Review on Insulation Materials for Energy Conservation in Buildings." *Renewable and Sustainable Energy Reviews* 73 (June): 1352–65. https://doi.org/10.1016/j.rser.2017.02.034.]

In response to the concern with improving energy efficiency, since Taiwan typically lacks insulation and requires an increasing amount of electricity to cool their residential buildings due to climate change and increasing energy demands, building insulation was selected as the focus of this study. As seen in Table 2, adding insulation materials such as expanded polystyrene insulation, EPS, and PU produce a low overall thermal conductivity which can effectively reduce thermal gain inside the residence.

	Layer Name	Width	Density	Sp. Heat	U *
Wall Composition, U = 1.07	Ceramic Tiles	0.01	2.4	840	1.3
	EPS	0.025	21.04	1300	0.04
	Cement Mortar	0.015	2	800	1.5
	Reinforced Concrete	0.15	2.2	880	1.4
Roof Composition, U = 0.75	Concrete 1-4 Dry	0.05	2.3	800	1.4
	PU Block	0.025	1.05	1250	0.028
	PU	0.005	1.05	1250	0.05
	Cement Mortar	0.015	2	800	1.5
	Reinforced Concrete	0.15	2.2	880	1.4
	Cement Mortar	0.015	2000	800	1.5
Low-e Glass, U = 2.5	Glass Standard	0.006	2300	836.8	1.046
	Air Gap	0.03	1.3	1004	5.56
	Glass Standard	0.006	2300	836.8	1.046

Table 2. Low thermal conductivity residence. Figure taken from Lin et al [21]

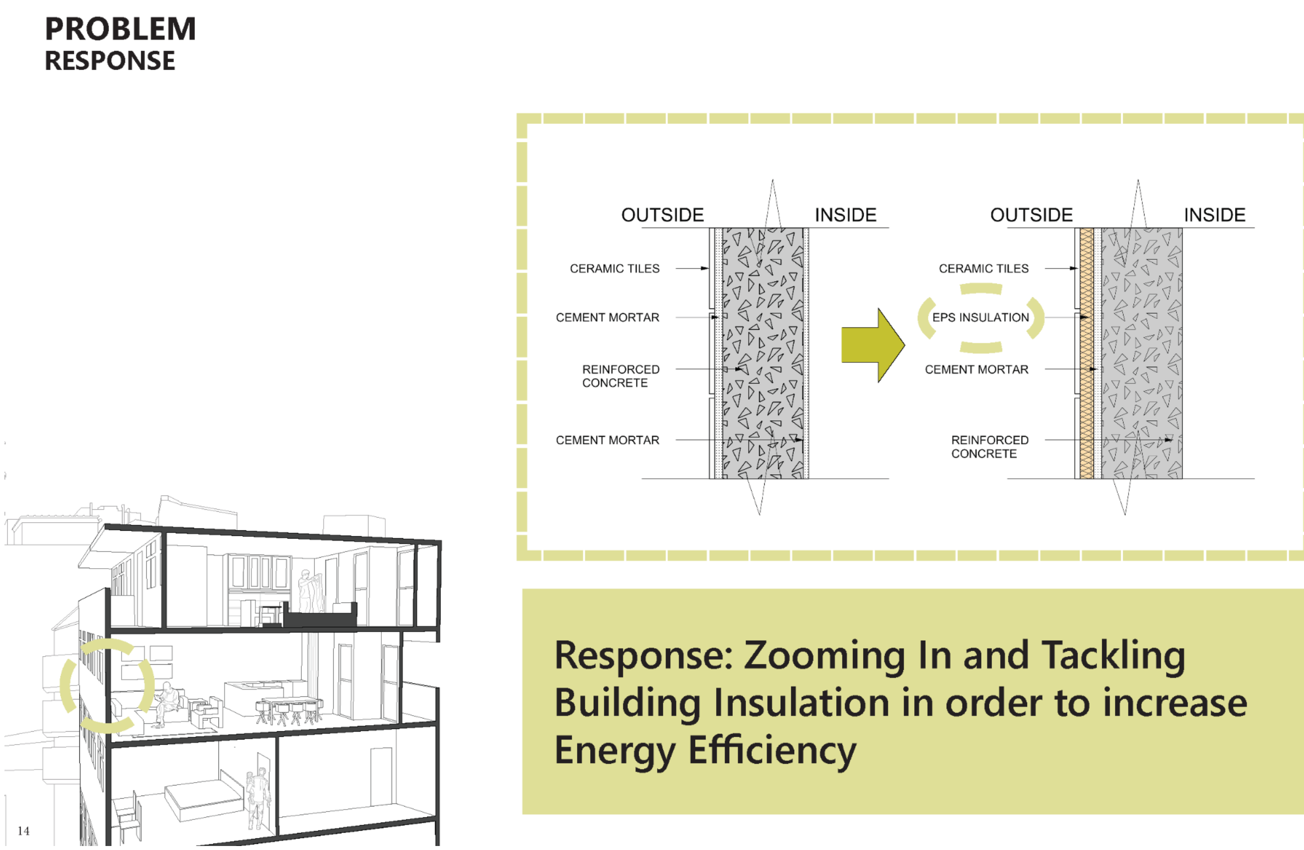


Figure 15. Building Insulation and Building Wall Makeup Development [21]

Insulation, such as EPS, can increase the ability for the building to reduce thermal gain and maintain building temperature by creating a thermal break between the outside and inside of the wall section. While concrete was previously used in Taiwan as a thermal sink and then to air condition the interior, in recent years, research has proven that this is a costly and energy-intensive method. [19] The addition of insulation to the 1.2 million 30+ year housing stock in Taipei would lead to a decrease in cooling and heating demand through residential buildings in Taiwan as well as mitigate the demand on electricity production.

Chapter 3: Precedent Study

3.1 Insulation (Taiwan - local)

A study in Taiwan investigated the relationship between insulation, cooling energy consumption, and cost efficiency in Taiwan. By studying window wall ratio and the relationship with common insulation materials, the testing sought to provide design references for insulation of roof structures. [23] The testing for a 112.5 m^2 (9x12.5x4m) simulation classroom in Taichung, Taiwan was conducted in an architectural energy simulation software PowerDOE using parameters of an annual schedule, indoor lighting density, heat dissipation of human body, heat dissipation of equipment, system loop of chilled water and heated water, the chiller, the loop system, and air-conditioning system (Table 3).

Item	Range
Location	Taichung
Azimuth	270 ℃
Area	112.5 m^2 (9 m * 12.5 m * 4 m)
Number of people	45
Area / Person	2.5 m^2
Opening ratio	40 %
Window overhang	0.4 m
U-value of Roof	1.2 ~ 0.8 (U-value input)
U-value of Wall	3.5 ~ 3.1 (U-value input)
Glass	Default Glass GTC1000 Center glass U-value: 6.31, Solar transmittance: 0.83, Desc: single clear 3 mm, Solar reflectance: 0.136 (from the inside)
Lighting	21 w/m^2
Equipment	7.5 w/m^2
Heat gain	Male: 198 Btu/h-person, Female: 254 Btu/h-person

Table 3. The simulation parameter setting of PowerDOE [23].

Material	Thickness (m)	Thermal conductivity [W/(m · K)]	Price
Reinforced concrete	0.15	1.4	Steel bar, NT. 25,700 per ton 3,000psi Concrete, NT. 2,100 per m^3
Heat-Shield-Brick	0.029	1.5	30cm*30cm, NT. 8 per piece
Foam concrete	0.100	0.8	NT. 2,800 per m^3
Rockwool	0.02	0.051	NT. 180 per m^2
Polystyrene	0.025	0.028	90cm*180cm, NT. 170 per piece
Polyethylene	0.001	0.038	NT. 160 per m^2
2 mm Polyurethane	0.002	0.050	NT. 430 per m^2
6 mm Polyurethane	0.006	0.050	NT. 770 per m^2

Table 4. The construction and insulation material setting of PowerDOE [23].

In order to calculate a cost efficiency analysis, two major types of roof insulation for school buildings, reinforced concrete and steel deck, were combined with common insulation materials (Table 4) to obtain five different U values (1.2-0.8). Construction prices as published by Taiwan Construction Research Institute Foundation in March 2008 allowed for roof insulation cost to be calculated in order to balance cost and insulation addition and to promote the benefits of roof insulation in sustainable buildings. Results showed that annual thermal load decreased by 1.5 - 1.9% when U-value of roof insulation and external wall insulation decreased by 0.1. Based solely on the reinforced concrete structure with a roof U-value of 1.2 and external wall U-value of 3.5, annual thermal loading was decreased by 5.7%, calculated in kcal, as it increased insulation cost per square meter by NT $589/m^2.

Another study in Taiwan analyzed energy consumption for concrete residences using a scientific simulation tool and two typical types of concrete residences in Taiwan. [24] Parameters for testing included weather data for three major metropolitan cities in Taiwan and building settings for the two types of concrete residences in order to investigate the impact of the following building characteristics on energy consumption: building insulation, air tightness, orientation, and location. The study tested the change between a typical wall, roof, and glass composition and a low thermal conductivity wall, roof and glass composition with data gathered from the *Construction and Planning Agency Ministry of the Interior*. [21] It validated the baseline with utility bills of a sample middle-class family and results found that air tightness alone can reduce energy consumption by

39.78%, buildings facing west consumed about 1.59 - 3.11% more energy than buildings facing north regardless of city location, and buildings in Kaohsiung (city in the South of Taiwan) consume about 45% more energy than identical buildings in Taipei (city in the North of Taiwan).
The study found that normalization was required after comparison with simulation data and measured performance from the sample middle-class family. Number of residents, floor area, and air conditioning comfort level and operational schedule were normalized to bring the simulation results closer to the measured performance data. During the study, certain assumptions were made about window open/close, occupancy number, relative humidity, and internal loading which can also affect energy consumption and will require further investigations.

Lastly, a third study in Taiwan looked at building insulation materials to determine the toxicity characteristics of commercially manufactured insulation materials using colorimetric analysis. [25] Four common insulation materials, from the categories of inorganic and organic foamy, used in Taiwan were examined for fire prevention and toxicity index, as measured by rate of build up of carbon monoxide, carbon dioxide, and oxides of nitrogen under combustion. Fire prevention studies examined how differences in insulation materials when placed on the outside of the mass, in the middle, inside the mass, and sprayed with incombustible materials in a typical wall construction would affect the speed of fire (Figure 16).

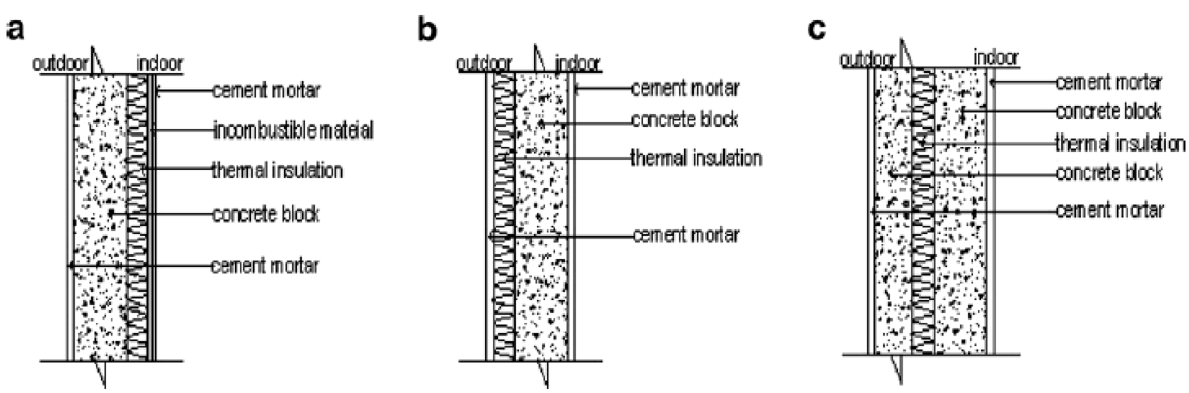


Figure 16. Thermal insulation construction methods: (a) placement inside mass; (b) placement outside mass; (c) placement in the middle. [18]

Results for fire prevention studies showed that insulation should be placed outside or in the middle and sprayed with incombustible materials in order to obtain reliable fire prevention. The toxicity index of polyethylene foam and polyurethane foam were found to be worse than untreated wood (TI52.5) and did not meet the requirements of the low fire hazard material (TI < 10). The results for toxicity varied in the range of 5.386-18.239 where polyethylene (18.239) > polyurethane (12.35) > rock wool (6.949) > fiberglass (5.386).

3.2 Insulation (CFA climate)

A study in the Chinese zone of humid subtropical climate compared the optimum insulation thicknesses and energy conservation ability of aerogel and four commonly-used insulation materials. [26] In this study, several other papers were cited that proved that the thermal performance of the building envelope has been identified as a major factor that can lose up to 25-30% thermal energy. [27] Especially for buildings in humid subtropical climates, high thermal performance requirements make thermal insulation an effective way to improve building energy efficiency and increase indoor quality of life. [28] The results found that payback periods for extruded polystyrene (XPS), expanded polystyrene (EPS), polyurethane (PU), glass fiber (GF) and aerogel in an aerate composite wall were 6.40 years, 7.09 years, 7.95 years, 6.89 years, and 26.57 years. The minimum optimum insulation thickness for XPS (44mm), EPS (70mm), PU (38mm), GF (45mm) and aerogel (3.7mm). In Figure 17, the effects of insulation thickness on energy savings are maxed out at optimized insulation thickness and beyond a certain thickness, there is a visible decrease in energy savings. Finally, with a decrease in price of aerogel materials, the optimum insulation thickness increases and payback period is reduced, which would reduce annual cooling and heating load for a shale hollow brick type wall.

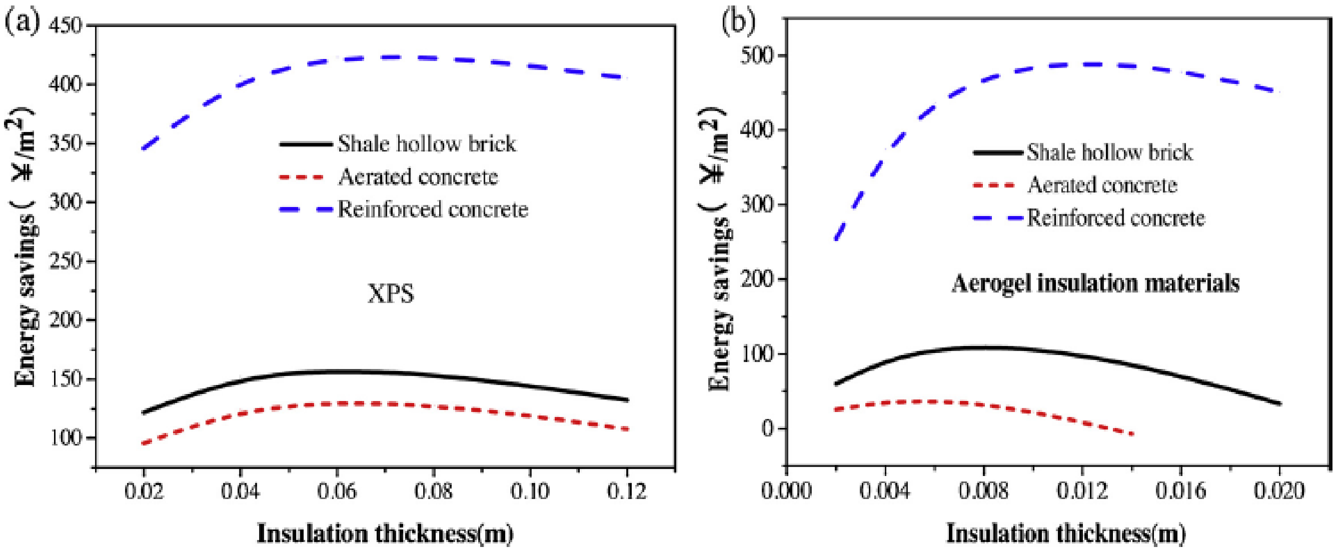


Figure 17. Effects of insulation thickness on energy savings for XPS and aerogel [19].

This study noted that many previous thermal insulation studies to reduce cooling and heating demands utilized inorganic wall insulation materials (e.g., XPS, EPS, PU). However, inorganic wall insulation materials are combustible and produce toxic gases during combustion, which make them less than ideal for building insulation materials.

3.3 Insulation (General)

In a study that reviewed unconventional sustainable building insulation materials, natural or recycled materials were collected and compared. [22] Building insulation products that are not or scarcely commercialized were selected to tackle the usage of non-renewable materials and the struggles with recycling products at the end of their life. The data on acoustic performance, thermal conductivity, specific heat and density were identified and compared. Results showed that some of the natural materials performed similarly to commercial materials such as recycled cotton insulators having a similar density and thermal conductivity to EPS, XPS, and sheep wool. Recycled PET and textiles performed better than rock wool and kenaf fiber materials with regards to their GWP value. However, because of a lack of data because many of these materials are still experimental meant that further analyses would need to be performed to assess important building insulator properties such as fire resistance and water vapor diffusion resistance. The study noted that regardless of the issues that still need to be addressed, natural material insulator usage should focus on residues and byproducts as well as availability in local materials.

Natural materials	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat (kJ/kgK)	Fire classification	Water vapor diffusion resistance factor, μ-value	References
Banana and polypropylene (PP) fiber	980–1040	0.157–0.182	1.3–1.5	NA	NA	[106]
Bagasse	70–350	0.046–0.055	NA	NA	NA	[55], [56], [57]
Corn cob	171–334	0.101	NA	NA	NA	[64], [65]
Cotton (stalks)	150–450	0.0585–0.0815	NA	NA	NA	[66]
Date palm	187–389	0.072–0.085	NA	NA	NA	[67], [68]
Durian	357–907	0.064–0.185	NA	NA	NA	[69]
Oil palm	20–120	0.055–0.091	NA	NA	NA	[56]
Pecan	600–680	0.0884–0.1030	NA	NA	NA	[76]
Pineapple leaves	178–232	0.035–0.042	NA	NA	NA	[74]
Reeds	130–190	0.045–0.056	1.2	E	1–2	[109], [110], [53], [111]
Rice	154–168	0.0464–0.566	NA	NA	NA	[76]
Sansevieria fiber	1410	0.132	1.52	NA	NA	[79]
Sunflower (cake from biorefinery)	500–585	0.0885–0.110	NA	NA	NA	[81]
Sunflower (pitch)	36–152	0.0385–0.0501	NA	NA	NA	[80]
Straw bale	50–150	0.038–0.067	0.6	NA	NA	[83], [84], [85]

Figure 18. Partial summary of thermal properties, fire classification and u-value of natural unconventional insulation material. Colors indicate qualitatively the thermal insulation performance (green = good, yellow = intermediate, red = poor). [31]

Another study analyzed the application of wall and insulation materials in green buildings and reviewed different green construction wall materials and thermal insulation materials' impact on energy and resource consumption. [29] The study reviewed published papers, journals on green and sustainable materials, and various countries' sustainable standards criterias to compare the usage and detailed aspects on recyclable building material and natural insulation material. (Figure 19)

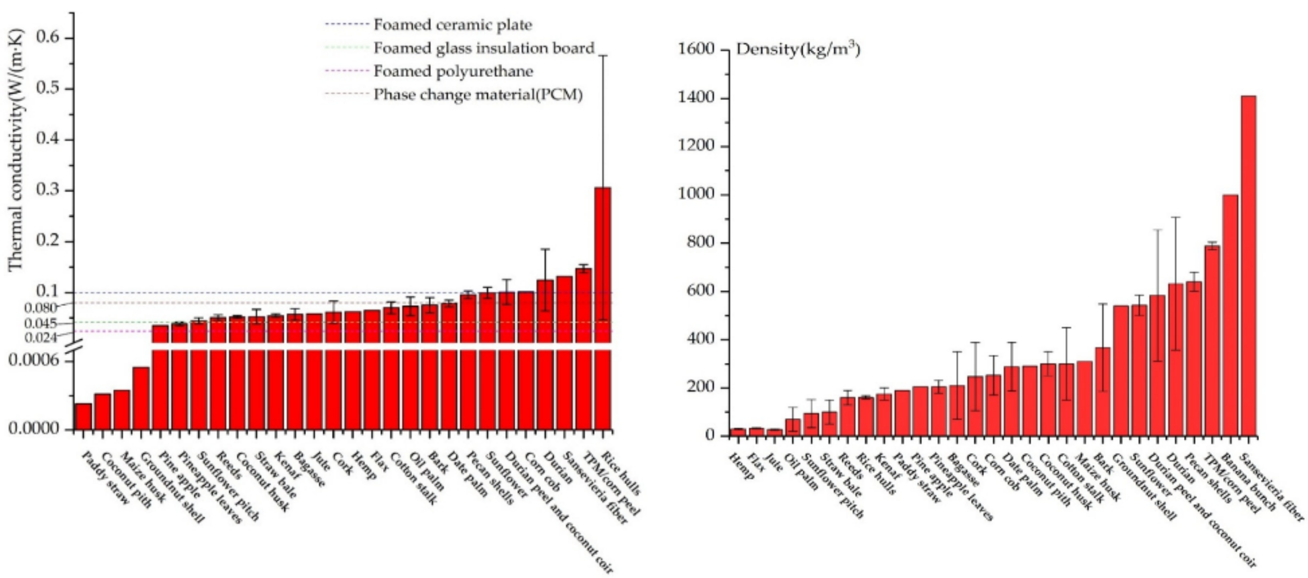


Figure 19. Thermal Conductivity and Density of different natural insulation materials [30]

Chapter 4: Methodology

Due to the timeframe of this research and the unforeseen COVID-19 pandemic, long-term investigation using a real life environment was determined to be infeasible. In order to evaluate the energy-saving performance of thermal building insulation characteristics, this study utilized a similar set of tools as the study conducted by Brian Dow who faced a similar time constraint and developed a building simulation method for Taiwan that would evaluate the energy-saving performance of a designed dynamic shading screen. [32] The building simulation model was developed using Honeybee (a plug-in program for Grasshopper that supports detailed daylighting and thermodynamic modeling https://www.ladybug.tools/honeybee.html [33]) in Grasshopper (a visual programming language and environment that runs within Rhinoceros 3D, a 3D modeling program, https://www.rhino3d.com/en/6/new/grasshopper/ [34]) to analyze energy end-use. In order to develop a model that reflects real life parameters for housing typology, building insulation, construction materials, building orientation, and occupancy rate, etc., data for residential buildings, published by the *Construction and Planning Agency Ministry of the Interior* [21], was used to create the model input information. The developed model utilized weather data for Taipei which was obtained from EnergyPlus [35].

Once the model was developed using Honeybee in Grasshopper and Rhino, the Energy-saving performance of 11 different insulation materials were run through four scenarios seen in Table 05.

Scenario	Experimental Parameter/condition	Values tested
1	Materials	Polyurethane, Polyethylene, Polystyrene, Rock Wool, Glass Wool, ICYNENE, THERMAFIBER, AEROGEL, Cellulose, Durian, Rice Hull
2	Insulation Thickness	.025m. .075m, .125m, .175m, .225m, .275m, .325m (.984" - 12.795")
3	Building Orientation	North and South, East and West
4	Window Wall Ratio	20%, 30%, 40%

Table 05. Methodology: Four Scenarios and Values Tested

In order to fully understand the value of building insulation on lowering CO_2 emissions and decreasing the strain on Taiwan's energy dilemma, the following section contains three major sets of data:

1. Impact Of Switching From A "Typical" Residence To An "Ideal" Residence
2. Cooling and Heating Load (kWh) vs. Cost
3. Operational Energy vs. Embodied Energy of Material Production (kg CO_2e)

4.1 Computational Simulation Model

In this study, energy consumption for Taipei, one of the major cities in Taiwan and the capital city, was investigated. Taipei and its adjacent area, New Taipei City, contains more than

30% of Taiwan's total population. [36] To illustrate the benefits of adding building insulation to developers, 3D simulation tools have been utilized to detail real life parameters for estimation purposes. [24] However, numerous studies have seen large discrepancies between simulated data and data gathered from real life due to a lack of precise building and environment parameters, uncertainty in occupancy behavior, and differences between real data and data inputs. [37] To improve simulation accuracy, repeated calibrations are necessary [38] but repeated calibrations are tedious and require a baseline consumption data to create a benchmarking system to determine if the model is functioning properly. [39] Even with these limitations, utilizing simulation tools to calculate building energy performance can be inexpensive, fast and reliable if calibrated properly. [40] This study runs tests with the variables seen in Table 05 to develop a baseline, taken from the worst case scenario, for a typical concrete housing typology seen in Taipei and New Taipei. After an energy consumption profile is developed in the simulation model, the building insulation characteristics that impact building energy efficiency the most are identified, cooling and heating loads are calculated and operational energy is calculated. The results ultimately will reveal the impact of insulation type, thickness, building orientation, and window wall ratio on the amount of kg CO_2 emitted with each variable.

4.1.1 Townhouse Building Typology

Taiwan currently has low-rise apartment/condos, high-rise apartments/condo, or townhouses as the most common housing typology in the country. As townhouses account for 40.49% of housing types in Taiwan [41], a 5-story single family concrete townhouse was built as a five-zone model with weather data for Taipei as a testbed. Townhouses in Taiwan are different from the rest of the world as suburban low-rise houses in Taiwan typically share one to two walls with a neighboring building due to a lack of space and increasing land cost. Another difference is Taiwan townhouses typically have windows on both sides of the house, either east and west or north and south. [42] Figure 20 shows a typical modern residence modeled in this study. The building model is a low-rise house of five stories, 2 adiabatic walls, and the total floor area is

306.5m^2 with a floor height of 3.048m (10 ft). The following variables were input for simulation purposes:

1. The occupancy is set at 6 (0.0196/m^2) as a "three generation family" with grandparents, parents, and children. [36]
2. Air conditioning is turned on when room temperature is above 26°C (80.6°F) in a 24-h setting and the heater is turned on when room temperature is below 20°C (68°F) in a 24-h setting.
3. Internal gains for lighting are set at 3 W/m^2 to meet needs of reading and writing on paper in indoor space. [32] Small Power loads such as cookers, electric kettle, hot water heaters, etc are set at 5 W/m^2 to reflect energy consumption. [19]
4. Internal design conditions: clothing is set at 1.0, lighting level at 300 lux
5. Windows remain closed all time

Data Variables

Taiwan Climate: Cfa Humid Hot

Taipei Weather Data from EnergyPlus

Cooling Setpoint = 26°C

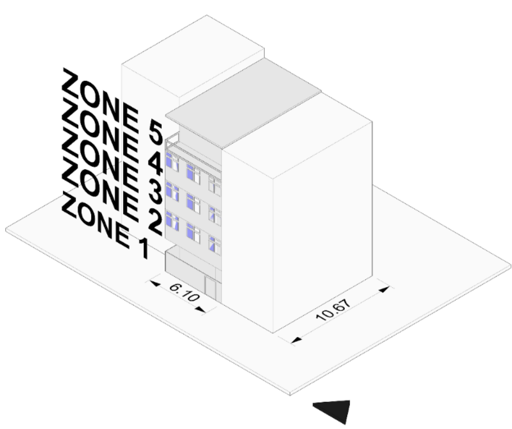
Heating Setpoint = 20°C

Program: Midrise Apartment

People = 6: 2 grandparents, 2 adults, 2 children

Lighting = 3 W/m^{2}K to meet needs of reading and writing on paper in indoor space.

Equipment = 5 W/m^{2}K to reflect energy consumption.



Typology Setup

first floor	Room 1	55.74
second floor	Room 2	65
third floor	Room 3	65
fourth floor	Room 4	65
fifth floor(roof)	Room 5	55.74
sum(m^2)		306.48

Figure 20. Methodology: Townhouse Building Typology Variables

4.1.2 Building Insulation Variables for Testing

As depicted in the tree diagram (Figure 21), the building insulation variables that are tested in the simulation are laid out in a method of input to the building simulation townhouse model and output from the townhouse model.

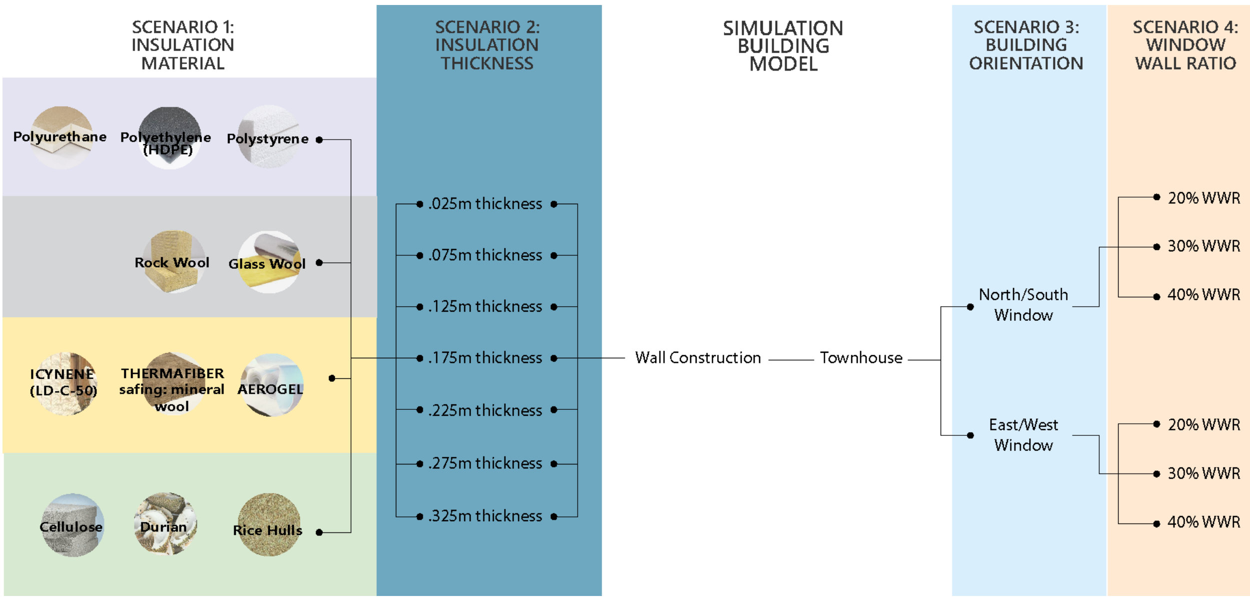


Figure 21. Tree Diagram of Variables Tested in the Building Simulation

The first step in the process was to identify insulation materials for testing that would represent a diverse selection from four different categories: Inorganic mineral-derived, organic fossil fuel-derived, organic plants/animal-derived, and innovative insulation materials. (See Figure 14)

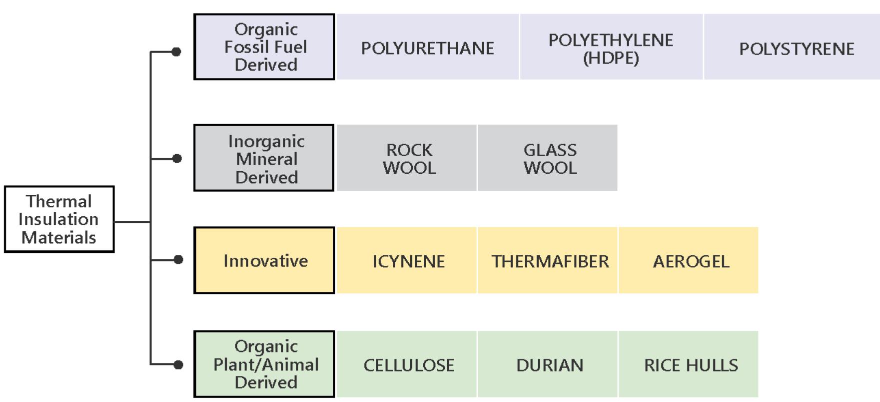


Figure 22. Building Insulation Material and Categories [22]

Each material and material category was selected carefully so that this study would show a better comparison between current insulation materials, current insulation materials that are high performance, innovative materials that can be manufactured and sold, and lastly agricultural materials that may or may not be still in the testing phase. Table 6 compares the basic characteristics of the 11 insulation materials tested in this study. Information on thermal conductivity and basic insulation characteristics were found from studies and databases seen in the last row of Table 6. Prices for insulation materials were either found from studies or from a major distributor, Alibaba.

	Polyurethane	Polyethylene (HDPE)	Polystyrene	Rock Wool	Glass Wool	ICYNENE (LD-C-50)	THERMAFIBER safing: mineral wool	AEROGEL	Cellulose	Durian	Rice Hulls
thermal conductivity W/mK	0.025	0.45	0.03	0.04	0.04	0.039	0.233	0.068	0.04	0.125	0.3
density kg/m3	30	940	25	70	25	8.3	64.07	130	50	625	175
specific heat J/kg-K	1800	1900	1380	840	840	UNK	UNK	UNK	1400	UNK	UNK
Embodied Energy kgCO2e/m3	525	6016	200	266	100	UNK	UNK	UNK	40	UNK	UNK
Cost NT/m2	770	160	413	180	441.5	2745	69	66	41	UNK	5.92
Source	Aditya et al [24] Alibaba.com [52] EPiC Database [53]	Aditya et al [24] Alibaba.com [52] EPiC Database [53]	Aditya et al [24] Alibaba.com [52] EPiC Database [53]	Aditya et al [24] Alibaba.com [52] EPiC Database [53]	Aditya et al [24] Alibaba.com [52] EPiC Database [53]	Aditya et al [24] Alibaba.com [52] EPiC Database [53]	Aditya et al [24] Alibaba.com [52] EPiC Database [53]	Aditya et al [24] Alibaba.com [52] EPiC Database [53] Huang et al [26]	Aditya et al [24] Alibaba.com [52] EPiC Database [53]	Wang et al [30] Asdrubali et al [31]	Wang et al [30] Asdrubali et al [31]

Table 6. Tested Insulation Materials and a graphical representation of their data

Organic Fossil Fuel Derived insulation materials were selected because they are made using fossil fuels which is considered highly inefficient for sustainability; however, they are some of the more commonly used materials which makes it important to compare current materials that are unsustainable and toxic with other materials that this study would like to recommend. Inorganic Mineral Derived insulation materials were selected because they are also sourced from non-renewable materials and linked to adverse health impact but they are capable of providing noise insulation and fire protection and being made from up to 90% recycled content. Innovative are the current high performance insulation materials on the market which can be manufactured today. ICYNENE and AEROGEL both can be purchased and manufactured in Taiwan which makes them valuable local innovative insulation materials. The last category is the most ideal category because it comprises only agricultural waste products which require more research but could be extremely beneficial in lowering overall CO_2 emissions because they are made from local waste material thus keeping CO_2 emissions from transportation down as well as recycling materials. [24, 25]

After the 11 materials to be tested are selected, the wall construction that is linked to the townhouse model contains the 11 insulation materials and tests the second scenario of finding optimal insulation thicknesses between the range 0.025m-0.325m (1inch-12.8inch). (Figure 21) For the third and fourth scenario, the effects of the 11 insulation materials and varying thicknesses (Table 5) are then tested in the townhouse model with WWR of 20, 30, and 40 (Figure 23) as the building windows face North + South or East + West. (Figure 24)

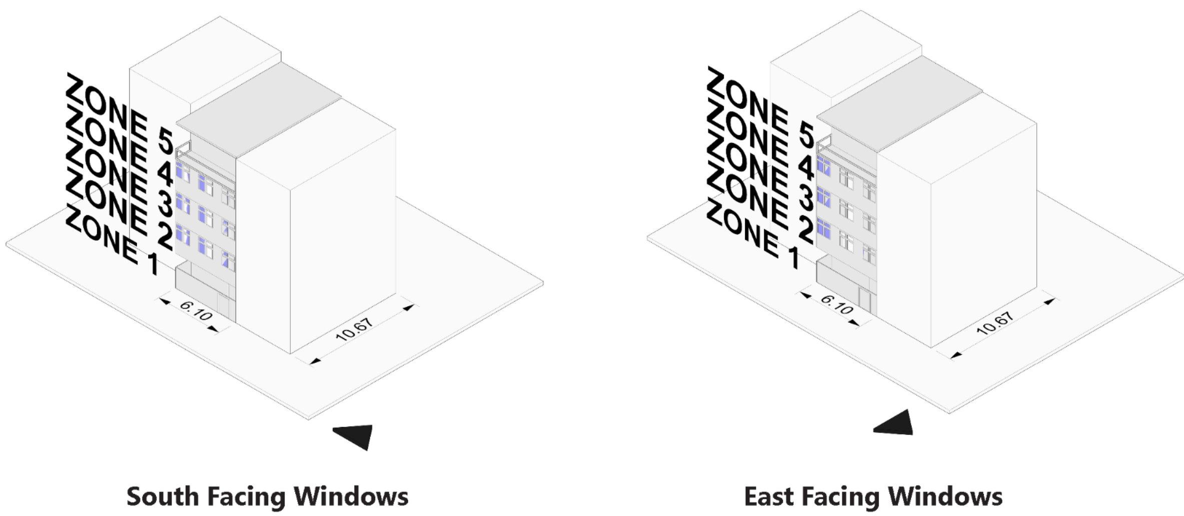


Figure 23. Townhouse Window orientation Facing South + North or East + West

Figure 24. Townhouse window wall ratio (WWR) Tested at 20%, 30%, and 40% fenestration

4.2 Calibration of Building Model

In order to calibrate this building model, a current Taiwan residence with a "typical" set of variables such as infiltration, ventilation, roof construction, wall construction, and window type was compared to a low thermal conductivity "ideal" residence set of variables (Table 6). Air tightness/infiltration/natural ventilation is measured in air changes per hour (ac/h) and typically varies between 4.17 and 8.05 when the house is not properly tightened but could fall below 0.5 if sealed properly. [43] In Taiwan, ac/h specification has yet to be enforced and a study has shown that average ac/h in a Taiwanese residence is around 3-6. [44] For the purposes of this study, a "typical" ac/h is 3.25 whereas an "ideal" ac/h is 0.5 for a sustainable building. Infiltration is unintended air leakage into a building through cracks in the building envelope or around doors or windows and is measured in cubic meters per second. Considering the typical Taiwanese infiltration rate falls in the not properly tightened range, for this study a leaky "typical" building is set at 0.0001 m^3/s and an "ideal" tight building is set at 0.0006 m^3/s. (Table 7)

Optimized Variables

VARIABLE	TYPICAL	IDEAL
INFILTRATION (M3/S)	0.0001 (LEAKY)	0.0006 (TIGHT)
VENTILATION	3.25 ACH (Taiwan Typical)	0.5 (sustainable)
ROOF	U = 1.223662	U = 0.865266
WALL	U = 7.604447	U = 1.333627
WINDOW	STANDARD GLASS SINGLE PANE	LOW-E GLASS "GLASS RITE"

Table 7. Optimized Variables to Calibrate Building Model

A "typical" residence in Taiwan fulfills the code-compliance U-factor of 3.23 W/m^2*K on the wall, 1.22 W/m^2*K on the roof, and 6.00 W/m^2*K on the windows. An "ideal" residence in Taiwan adds EPS to the wall and roof and changes to double-layered low-e glass for the windows. With EPS insulation and low-e glass the U-factor of the wall is lowered to 1.33 W/m^2*K, 0.86 W/m^2*K on the roof, and 2.5 W/m^2*K on the window. (Figure 25, 26)

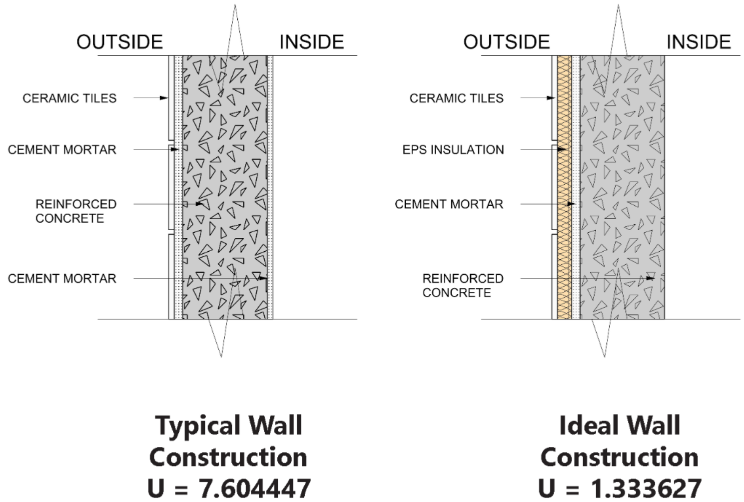


Figure 25. Typical Wall Construction vs Ideal Wall Construction [21]

Figure 26. Typical Window vs Low-e Double Pane Window [45]

Chapter 5: Results

The "typical" set of variables in a North + South orientation was run through the building simulation and annual cooling and heating load (kWh) data for all five zones was output from the model. Cooling Data and Heating Data are separately summed for total annual data for the entire townhouse. The equations for calculating the Kg CO_2e per year from cooling data and heating data as well as % change are found below:

Cooling Load (annual)

Total Annual Cooling Load = Zone 1(kWh) + Zone 2(kWh) + Zone 3(kWh) +

Zone 4(kWh) + Zone 5(kWh)

Average kWh/m^2 = Total Annual Cooling Load/Total square area of Townhouse

*Kg CO_2e per year = Average kWh/m^2 * Taiwan's electricity emissions factor (0.554 kg CO_2e/kWh) [09]*

Heating Load (annual)

Total Annual Heating Load = Zone 1 (kWh) + Zone 2 (kWh) + Zone 3 (kWh) +

Zone 4 (kWh) + Zone 5 (kWh)

Average kWh/m^2 = Total Annual Heating Load/Total square area of Townhouse

*Kg CO_2e per year = Average kWh/m^2 * Taiwan's electricity emissions factor (0.554 kg CO_2e/kWh) [09]*

In order to determine how adjusting the "typical" residence to an "ideal" residence impacted the calculation, % Change or impacting percentage is calculated by finding (newly calculated data with change - previous data)/previous data.

% Change (annual)

C_d = Total Annual Cooling Load + Total Annual Heating Load

$$\%\,Change = [(Cd\,(kWh) - Tr\,(kWh))\,/\,Tr\,(kWh)] * 100$$

During calibration tests, factors such as occupancy factor, schedule data, size of model, and others were noted as having a significant impact on the building model setup and data output from the model.

5.1 Impacting percentage adjusting "typical" to "ideal" residence

To find the impacting percentage, the typical set was calculated first and then compared to each change in optimization variable in the following order: "typical" to ideal roof and wall, standard window to low-e, tighten infiltration and ventilation, and switch building orientation. (Table 8)

		TYPICAL	CHANGE roof/wall	CHANGE window to low-e	CHANGE infiltration+ ventilation	CHANGE orientation
Cooling	Sum (kWh)	49544.72198	43799.26736	28469.78859	25231.32667	27730.92194
Cooling + Heating	Sum (kWh)	55617.06847	47773.70416	32908.6999	25957.56776	28481.09758
Cooling	kg CO2e/year	27447.77598	24264.79412	15772.26288	13978.15497	15362.93076
Cooling + Heating	kg CO2e/year	30811.85593	26466.6321	18231.41975	14380.49254	15778.52806
Cooling	% change		-11.60%	-35.00%	-11.38%	9.91%
Cooling + Heating	% change		-14.10%	-31.12%	-21.12%	9.72%

Table 8. Calibration of Building Model

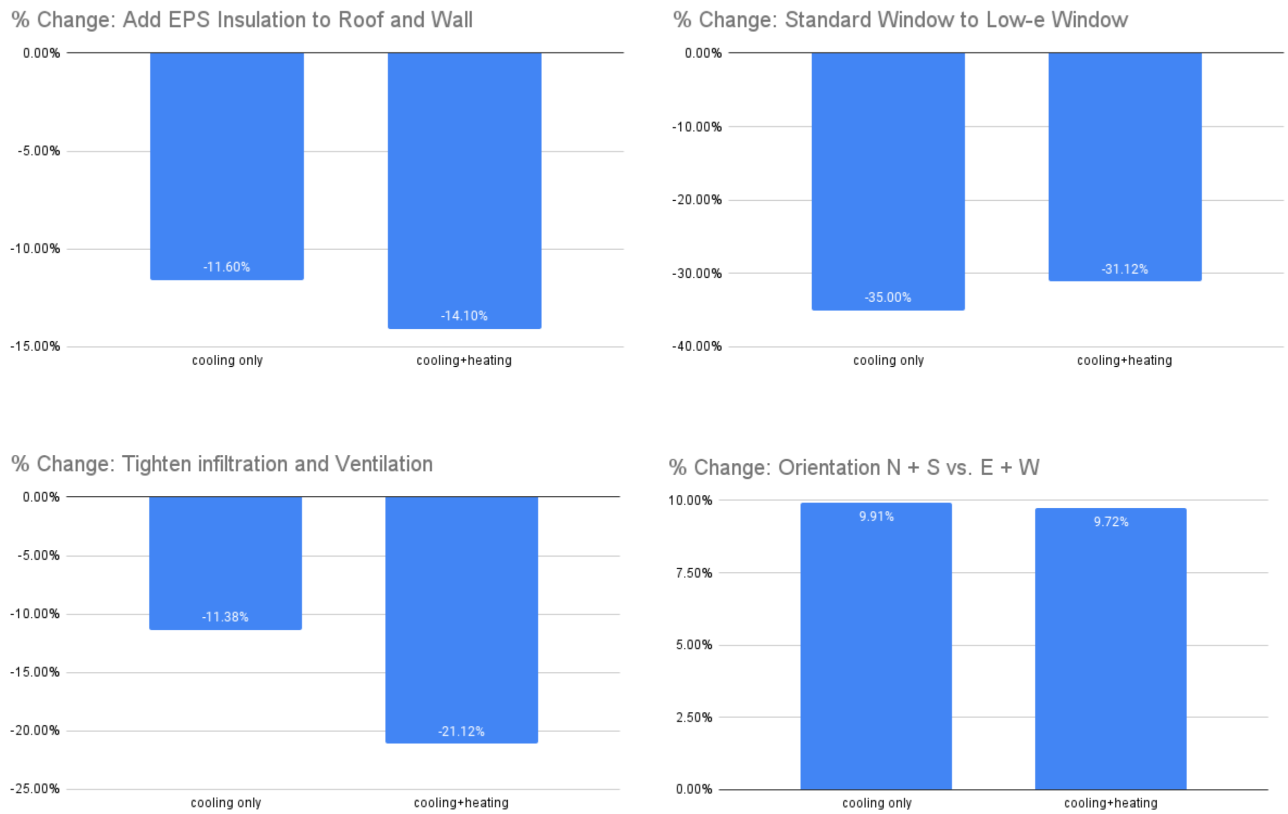


Figure 27. Graphical representation of % change with each variable

From the % change graphs, as the “typical” residence was adjusted to an “ideal” residence, the following impacts of insulation, window type, infiltration and natural ventilation, and orientation were noted for changing the amount of kg CO_2e/year to cool and heat one townhouse (Figure 27):

1. Adding EPS insulation to the Roof and Wall construction resulted in lowering the emission for cooling one townhouse by 11.6% and 14.1% for cooling and heating, respectively. This percentage makes adding insulation valuable enough, but it might be even more effective if we consider the amount saved by developers and residents when paying for electricity over a 10+ or 30+ year period.

2. The largest percentage change was seen when the standard window was switched for a low-e window type which resulted in a 35% emissions reduction for cooling but a slightly lower 31.12% emissions reduction for cooling and heating. Switching to a low-e window type reduced the emissions percentage by an impressive 31-35% which was expected which means that switching fenestration (windows, doors, skylights, curtain walls) to a more energy efficient fenestration is the most advantageous route for developers.
3. By tightening the building, there was a 11.38% emissions reduction for cooling but a much higher 21.12% emissions reduction for cooling and heating. This was a surprising result as the reduction in cooling and heating emissions was double the reduction in only cooling emissions. Tightening the building seemed to have the highest effect on lowering emissions from heating demand which makes infiltration and ventilation important parameters to further study if we intend to design buildings that don't require heating. In addition, this had almost the same amount of effect on the emissions factor as adding insulation to the roof and wall construction which means that the air tightness in a building is just as important as insulation and perhaps more because of its effect on lowering the heating load.
4. Altering building orientation from North and South to East and West resulted in a slight emissions increase, 9.91%, for cooling and an even smaller emissions increase, 9.72%, for cooling and heating. This was surprising because I thought that building orientation would have a greater effect on heating and cooling load which would affect the amount of emissions from cooling and heating. However, changing the orientation resulted in the lowest amount of change. It is important to note that buildings facing East and West have a higher cooling and heating demand which results in a higher amount of CO_2 emitted per year.

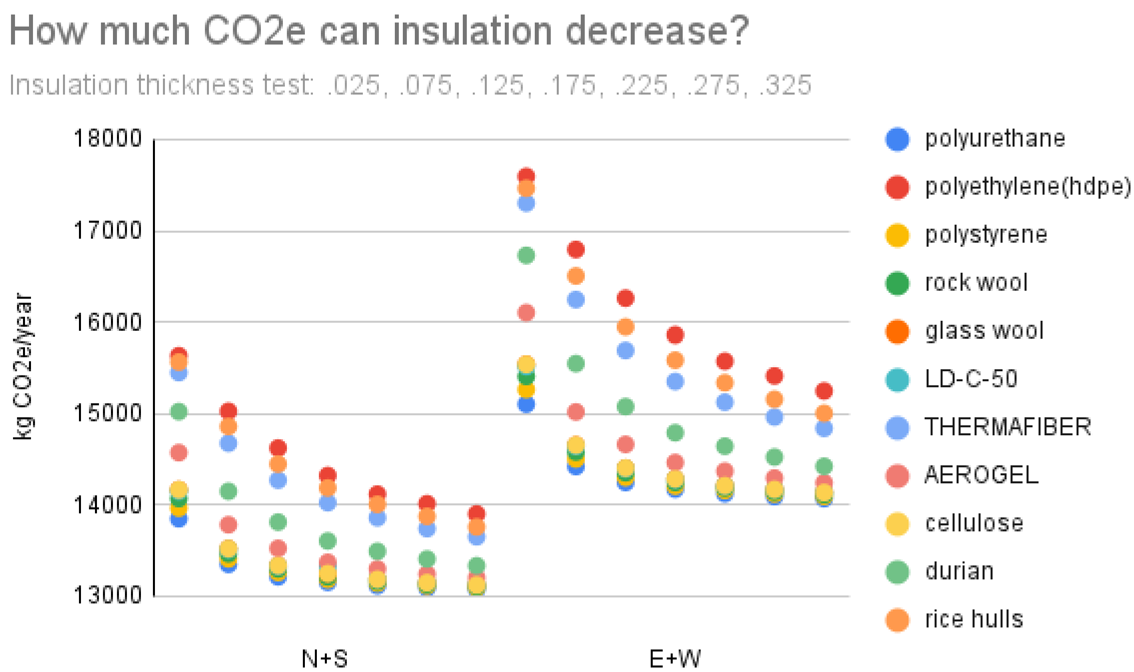


Figure 28. Cooling Load Comparison For All Insulation Types At Insulation Thickness = .025m (1inch)

With the ideal residence variables, the building simulation was run for all eleven building insulation types across the thicknesses .025, .075, .125, .175, .225, .275, .325m for cooling and heating load. There does appear to be a point where many of the insulation types, other than the organic fossil fuel insulation materials, have diminishing returns increasing past insulation thickness 0.175. (Figure 27) For example, we looked only at durian (green) in Figure 28 in North and South Orientation at 30% Fenestration.

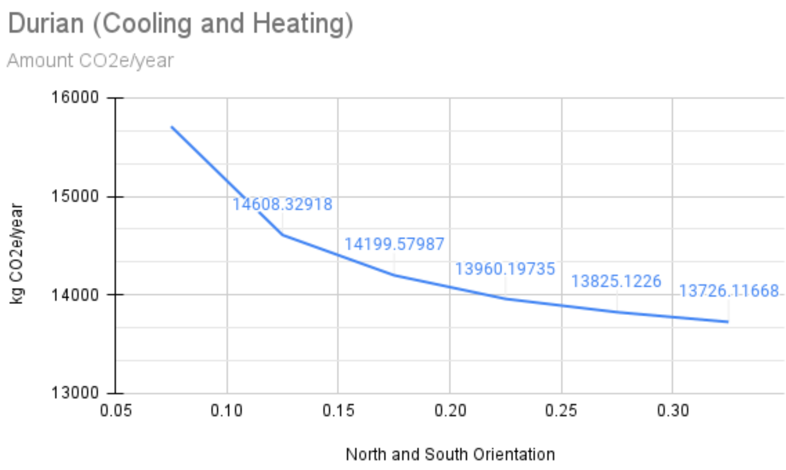


Figure 28. Durian Cooling and Heating CO_2e

Durian drops from around 15710 kg CO_2e to 13960 kg CO_2e when increasing insulation thickness from 0.025m to 0.0175m which is a 11% decrease whereas from 0.0175m to 0.325m is a 1.7% decrease in kg CO_2e.

The results of this experiment have been summarized in Table XX:

Experimental Parameter/condition	**Values tested**	**Results/Findings/Takeaways**
Materials	Polyurethane, Polyethylene, Polystyrene, Rock Wool, Glass Wool, ICYNENE, THERMAFIBER, AEROGEL, Cellulose, Durian, Rice Hull	The greatest kg CO_2e decreasing insulation material was polyethylene (HDPE), glass wool, and polyurethane.
Insulation Thickness	.025m. .075m, .125m, .175m, .225m, .275m, .325m (.984” - 12.795”)	.175m is the optimal thickness before diminishing returns on energy efficiency and increased cost
Building Orientation	North and South, East and West	North and South was more energy efficient

Window Wall Ratio	20%, 30%, 40%	Comparable effects on energy efficiency. Any WWR chosen should be offset with the proper insulation thickness and other appropriate parameters

Figure 28. Durian Cooling and Heating CO_2*e*

5.2 Cooling and Heating Load (kWh) vs. Cost

Optimum insulation thickness is correlated with cost effectiveness as an increase in thickness also increases cost. Taipower charges residents with every-second-month meter reading and charging system [06] Based on Taipower's summer rate, from June to September, electricity rates for households increase as follows:

1. 121kWh to 330 kWh per month would increase NT$2.38 per kWh, from NT$2.10
2. 501kWh to 700kWh per month would increase to NT$4.8 per kWh from NT$3.94
3. 1,000kWh or more per month would increase to NT$6.41 per kWh from NT$5.03

In a published statement, Taipower has acknowledged that summer prices could increase by 27% during the year of 2021. [46] Based on resident monthly payments for electricity and current statistics from Taipower stating that the average household consumption in Taiwan last year was 434kWh/month which increased from 291 kWh/month for the rest of the year, the yearly rate for the average household comes out to be about:

Average Household Electricity Consumption (Annual)

*Summer months = (NT $4.8 per kWh * 501kWh)*4 = NT$9,619.2*

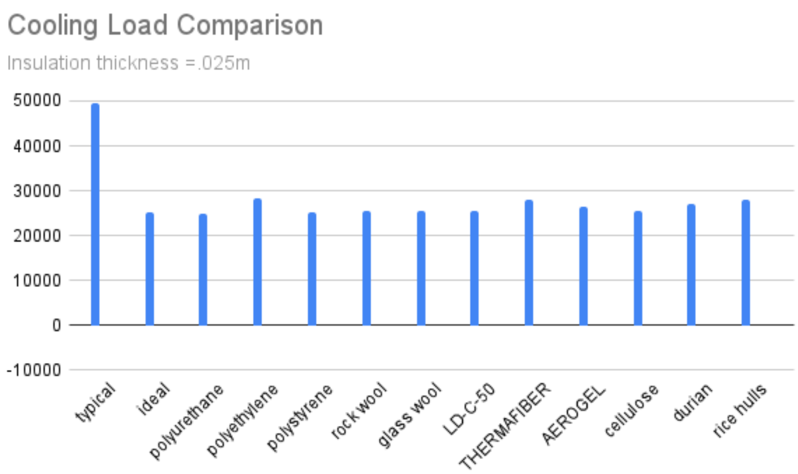
*Rest of the Year = (NT $2.38*330kWh)*8 = NT$6,283.2*

Total = Summer Months + Rest of the Year

Total = NT$15,902.4 for the whole year for the average household consumption.

There are discrepancies between the simulated model and real life data which is to be expected. As seen in Figure 28 we take the data for insulation thickness 0.025m to calculate the amount a resident would save using the simulated building model.

Based on the kWh from the simulation model, adding insulation would allow residents who would normally pay NT$317,581.67 for the year to pay as low as NT$160,247.39, a 50.4% decrease. This would save the resident more than NT$157,334 a year and NT$4,720,020 over 30 years.



INSULATION	0.025m	% change
typical	49544.72198	0.00%
ideal	25231.32667	-49.07%
polyurethane	24999.59281	-49.54%
polyethylene (hdpe)	28223.48714	-43.03%
polystyrene	25210.36577	-49.12%
rock wool	25399.7878	-48.73%
glass wool	25574.62373	-48.38%
LD-C-50	25541.68243	-48.45%
THERMAFIBER	27890.22741	-43.71%
AEROGEL	26306.90515	-46.90%
cellulose	25572.37643	-48.39%
durian	27118.74508	-45.26%
rice hulls	28098.15665	-43.29%

Figure 28. Cooling Load Comparison for all insulation types at insulation thickness = .025m (1inch)

In order to understand how cost-effective these savings really are, the cooling load for insulation materials needs to be compared to the cost of installation. Glass wool, for example, costs approximately $1.15-1.4/m2 as the thickness for insulation material increases from .025m to .2m. [47] The cost for installation of glass wool insulation in the modeled townhouse is NT$6,865.15 for 0.225m thickness insulation. (Figure 30) Glass wool insulation at .225m thickness has an annual cooling load of 23810.41 kWh which would cost the resident NT$152,624.73 (US$5448.94) per year. By adding insulation, the resident would save approximately NT$635,156.18 over 10 years if we assume a 10% increase in fuel cost each year. [48]

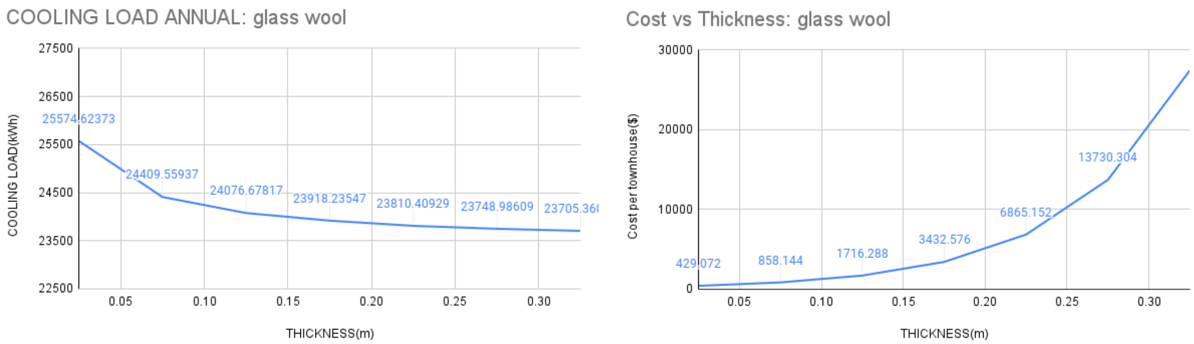


Figure 30. Cooling Load compared to Cost for glass wool insulation

5.3 Operational Energy vs. Embodied Energy of Material Production (kg CO_2e)

Embodied Energy is the energy required to produce or extract the raw materials, manufacture, transport, and assembly. For organic fossil fuel-derived insulation (polyurethane, HDPE, polystyrene) and inorganic mineral-derived (rock wool, glass wool), the embodied energy are all much higher than the operational energy which is most likely due to the process in which the raw materials are extracted, manufactured, and assembled. In this study, transportation costs and embodied energy for transportation were not determined; however, they do play an important role in the total embodied energy of a material.

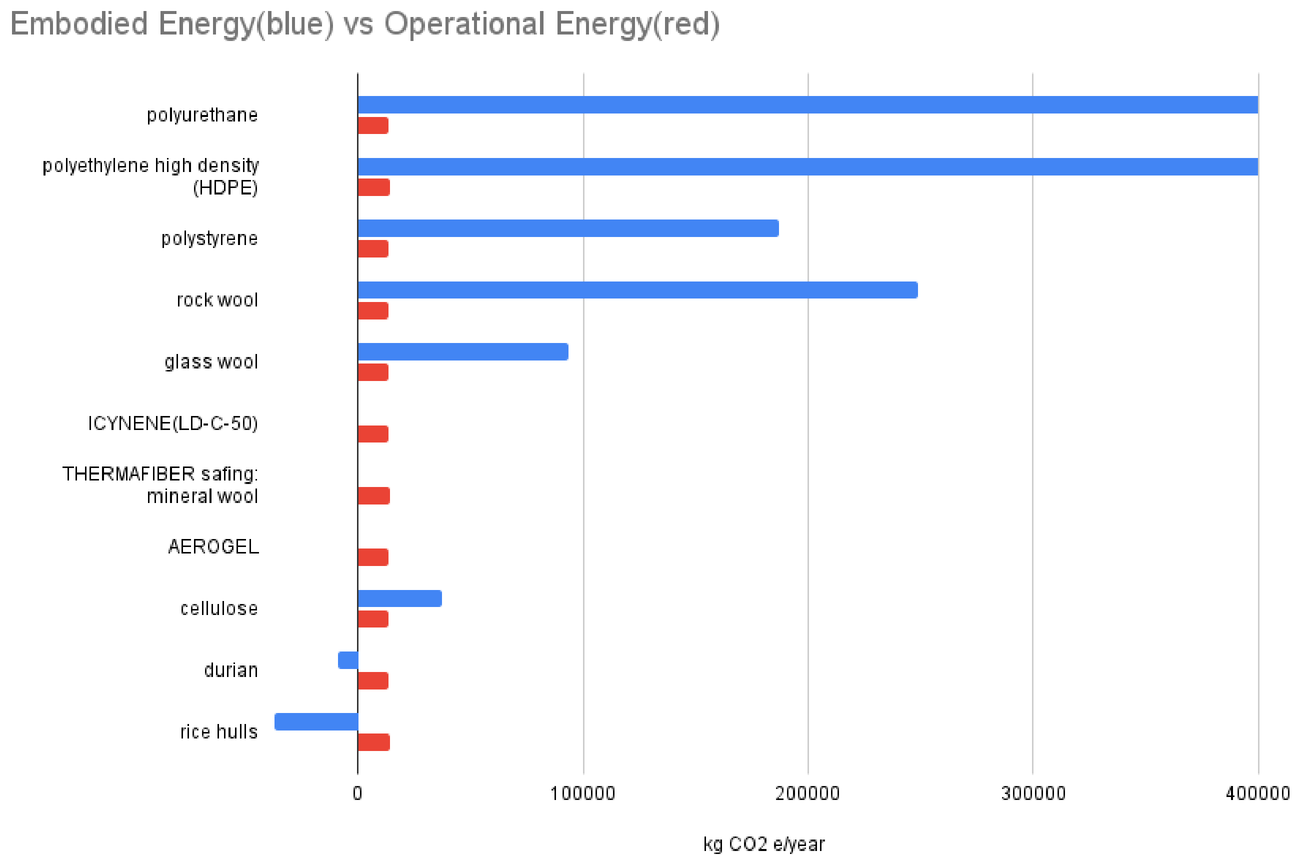


Figure 31. Embodied Energy vs Operational Energy. Note: ICYNENE, THERMAFIBER, and AEROGEL (the innovative insulation materials) lack data on embodied energy and are not simply 0 kg CO_2e/m3.

Chapter 6: Conclusion and Future Work

Based on the impact performance seen in Figure 26, the addition of insulation in a townhouse typology is able to save 14.10% energy use per household. Looking at Taipower statistics, residential buildings consume approximately 250,000 gigawatt hour. [06] Considering that old housing stock consists of 54.5% of all housing stock in Taipei and New Taipei, if all 54.5% had insulation added to their wall and roof, the amount of electricity saved by 54.5% of housing stock in Taiwan:

10 Year Savings:

250,000 gigawatt hour (electricity consumed by all residential buildings in Taiwan) 54.5% (old housing stock that could be redeveloped) * 14.10% (energy saving per household) x 10 years =* ***189,000 gigawatt hours saved*** *[32]*

30 Year Savings:

250,000 gigawatt hour (electricity consumed by all residential buildings in Taiwan) 54.5% (old housing stock that could be redeveloped) * 14.10% (energy saving per household) x 30 years =* ***576,337 gigawatt hours saved*** *[32]*

The addition of insulation as well as other parameters studied in Figure 26 greatly decrease the amount of electricity consumed by residential buildings in Taiwan. This would also reduce the Taiwanese government's reliance on imported coal and burning coal for power generation. The switch from "typical" to "ideal" residences, as seen in Figure 26, allows for a number of factors such as window type, wall insulation, roof insulation, and tightening infiltration and ventilation to have a huge impact on decreasing the amount of electricity consumed by residential buildings in Taiwan and thus reducing the burden for Taiwan's government to use non-renewable energy sources. Therefore, a small change in the building structure could lead to large gains in Taiwan's goal for sustainable design. This is valuable information and I hope that later more in depth cost efficiency studies could be conducted to determine how much each insulation material if shipped to a particular building site in Taipei would cost as opposed to how much the resident and Taipower Company would save in 10 or 30 years.

The data that was obtained from the building simulation model I created showed notable differences between simulated data and measured data from Taipower. [06] Past empirical studies have shown that noticeable differences exist between simulated and measured data for energy consumption. [49] Other studies have identified occupancy, occupant behavior, and building construction practices contribute to energy consumption variation [50] During the simulation process, this study found that occupancy load, occupancy behavior and schedule, cooling and heating schedule, relative humidity, and other factors have an influence on energy consumption; however, additional study is required in order to determine the extent of these effects as this study did not test for those factors. In addition, as Taiwan is considered a hot and humid climate, mold and humidity can be extremely concerning with regards to insulation. The performance of insulation material with humidity calculations would need further detailed investigations in the future.

Lastly, this simulation framework could be applied to other countries with suboptimal housing and old housing that could benefit from refurbishment with energy efficient structures and reducing their carbon emissions.

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