Life-cycle GHG emissions of standard houses in Thailand

RESEARCH

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ABSTRACT

Greenhouse gas (GHG) emissions from building activities are one of the most prominent contributors to the problem of global warming. Life-cycle assessment (LCA) is a widely used tool to investigate GHG emissions from buildings. However, there appears to be a lack of LCA studies on buildings in tropical climates, and especially in Thailand. This study aims to improve the understanding of GHG emissions from standard Thai residential buildings. LCA was conducted on five typical house designs in Thailand in order to determine potential mitigation strategies for future design of these houses. The amount of GHG emissions over the entire life-cycle of these detached houses was estimated, and the results were analysed with different viewpoints. The results indicate that emissions from the operational energies of detached houses in Thailand have the highest share of GHG emissions. Significant emissions also came from construction materials. Improvements to the building envelope and air-conditioner usage have high GHG mitigation potential in the operational stage of the buildings, while replacing cementitious and metallic materials with low-emissions alternatives can considerably reduce embodied emissions.

POLICY RELEVANCE

The built environment has been a major source of GHG, but it also has high climate change-mitigation potential. This study explores mitigation strategies on the material and component levels of the most common building type in Thailand: detached houses. The results indicate the major sources of GHG emissions in the case study buildings, their correlation with building scale and other key design decisions. Potential mitigation solutions in different phases of the building life-cycle are identified.

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1. INTRODUCTION

1.1 BACKGROUND

The built environment has contributed significant amounts of greenhouse gas (GHG) emissions. Globally, building-related activities in their entire life-cycle emitted 13.5 GtCO_2 into the atmosphere in 2019, 38% of total global CO_2 emissions (International Energy Agency (IEA) 2020). The decarbonization of society is one goal of the Paris Agreement. To achieve this goal, every new building should be net-zero carbon in its operation phase and the embodied carbon of these buildings should be cut by 40% by 2030 (Global Alliance of Buildings and Construction 2021).

The 2022 report of the Intergovernmental Panel on Climate Change (IPCC): Working Group III stated that in the current nationally determined contributions pathway, the median global warming value will be 2.8°C by 2100. It also stated that the projected development in accordance with the nationally determined contributions pathway is slower than planned in most nations (IPCC 2022). Considering that Thailand's main climate change-mitigation strategy is focused on the energy and transport sectors, additional efforts in other sectors would be beneficial.

Life-cycle assessment (LCA) has been used to quantify the carbon footprint of buildings and other products. The European Commission has emphasized the benefit of using LCA for the assessment of potential environmental impacts. Additionally, LCA has high relevancy in the construction sector in the European Union (Sala *et al.* 2021). Some European Union member states currently regulate the GHG emissions of their buildings: the Netherlands, France, Sweden, Norway and Denmark; Finland will implement regulations by 2025 (Malabi Eberhardt *et al.* 2023).

Unfortunately, the application of LCA in buildings is still lacking in some parts of the world. Röck *et al.* (2020) conducted a review study on the LCA of 583 new buildings. They emphasized the lack of LCA studies in tropical climates, and fewer than 10% of their case studies were from the Tropics. This knowledge gap can be detrimental to the understanding and reducing GHG emissions from the global building stock (Röck *et al.* 2020).

1.2 LCA IN THAILAND

Situated in a tropical climate, Thailand is considered among the countries that have the highest potential urban growth (IPCC 2014). It is, however, on the trajectory of becoming an 'aging society' with its population expected to decline from 69.8 million in 2022 to 65.37 million in 2040. Nonetheless, the urban population in Thailand is projected to rise from 57.2% in 2020 to 74.3% in 2040 (Ministry of Natural Resources and Environment 2020).

Thailand's climate change-mitigation strategy aims to reduce 20% of GHG emissions by 2030. The primary mitigation targets are in the energy and transport sectors. However, the production of cement caused 18,000 Gg CO_2e in 2016. It was the highest emitting material in Thailand's industrial sector and contributed 5% of the total Thai GHG emissions (Ministry of Natural Resources and Environment 2020). Therefore, in addition to the current mitigation strategy, Thailand's future GHG emissions can be reduced significantly by reducing emissions from construction materials. In Thailand, more than half of the area built every year is for residential purposes. In 2020, more than 26 million m^2 of floor area from 200,000 houses were built. The total built area of all buildings that year was 62 million m^2 (National Statistical Office Thailand 2020).

In the past few decades, the built environment in Thailand has seen extensive progress in the area of energy efficiency. The energy building code is currently mandatory for buildings larger than 2000 m^2 (Climate Technology Centre and Network 2021). At the scale of residential buildings, the primary strategies are changing consumption behaviour and promoting alternative energy-efficient appliances (Meangbua *et al.* 2019). However, from a life-cycle perspective, it is important to pay attention to GHG from sources other than the energy used in buildings.

1.3 GHG EMISSIONS FROM BUILDINGS

Commonly, GHG emissions are divided into operational (emissions related to energy consumption during the use phase of the building) and embodied (emissions related to manufacturing, transport, construction, maintenance, replacement and end-of-life). The operational emissions in a standard residential building are typically about four times higher than the embodied emissions. In the case of energy-efficient buildings, however, the ratio of operational emissions can be at the same level as embodied emissions or even lower (Röck *et al.* 2020).

Satola *et al.* (2020) conducted a review of 37 LCA literatures on buildings in tropical climates. Their results showed a wide range of CO_2 emissions, depending on case study locations, the energy performance of the case study and their main structural materials. The shares of embodied emissions in their study averaged at 27% of total life-cycle GHG emissions.

Iqbal *et al.* (2018) conducted LCA studies exploring the global warming potential (GWP) reduction in an energy-efficient house. The case study had low energy demand, being a nearly net-zero house. It had two stories, an 81 m^2 floor area and a reference study period of 50 years. The house was compared with a typical house, which was created based on the geometry of the nearly net-zero house, but without building energy improvements. The result showed that a typical house produces 500 tCO_2e, while the nearly net-zero house produces 175 tCO_2e of GHG emissions. A typical house had 60 tCO_2e of embodied GHG emissions, while nearly net-zero houses had 80 tCO_2e (Iqbal *et al.* 2018). The emission factor of electricity in Thailand is 0.4 kg CO_2/kWh (Energy Policy and Planning Office 2023). This figure is close to the world average, and likely contributed to the high total emissions of the typical house in their result (Our World in Data 2023). In this study, operational emissions of the typical house were eight times higher than embodied emissions. This number is significantly higher than the results of Röck *et al.* (2020) and Satola *et al.* (2020).

Other recent LCA studies from Thailand show varying results. Tulevech *et al.* (2018) conducted LCA on a 15,000 m^2 low-energy industrial building with a 20 years-of-reference study. The energy-efficient design of this building lowers the share of operational GHG to 28% of its total life-cycle emissions, while GHG from manufacturing contributes 60% of total emissions. The rest of the emissions came from the construction process and the end-of-life (Tulevech *et al.* 2018).

A sustainably designed office building was studied by Tevis *et al.* (2019). The building had a 6300 m^2 floor area and a reference study period of 50 years. The study compared different energy supply scenarios, from conventional grid electricity systems to photovoltaic (PV) systems. In the conventional energy supply case, the contribution of the operational phase to GWP was 85%. The shares of operational GHG become lower with the integration of PV systems in different scenarios.

The results of LCA of other Southeast Asian countries appear to be different from Thailand's. In the case of residential buildings, Surahman *et al.* (2015) studied over 500 houses in Jakarta and Bandung, Indonesia. Operational emissions were found to be four to five times higher than embodied emissions for these houses. Rashid *et al.* (2017) conducted LCA on a 246 m^2 house in Kuala Lumpur, Malaysia. The assessment showed that the case study house had operational emissions three times higher than embodied emissions. The shares of operational emissions in these two studies were considerably lower than the studies conducted by Iqbal *et al.* (2018), which showed that operational emissions are eight times higher than embodied emissions. One reason for these differences seems to be that Surahman *et al.* (2015) used a different LCA approach, an input–output assessment, for the study. The results between a process-based attributional LCA and an input–output LCA can differ considerably because of different system boundaries and scopes (Säynäjoki *et al.* 2017).

At the time of the present study, relatively few LCAs of Thai buildings have been published in scientific journals. Among the studies there seems to be a certain degree of uncertainty in the results, especially in residential buildings. This translated to difficulties in detecting trends or determining life-cycle emissions from the Thai building stock.

1.4 AIMS

Information regarding the life-cycle emissions of standard buildings in Thailand is currently limited. Recently published scientific studies from Thailand focused on energy-efficient or larger scale buildings. A knowledge gap exists for the GHG emissions of standard small-scale residential buildings in Thailand.

The main objective of this study is to calculate GHG emissions over the full life-cycle of standard small-scale residential buildings in Thailand. It aims to improve the understanding of GHG emissions from the Thai residential building stock. The data produced by this study can be used to support mitigation strategies for small-scale residential buildings in Thailand. The urgency of narrowing global emission quota for GHG emissions led the authors to focus on GHGs. Other environmental indicators, *e.g.* acidification potential, eutrophication potential and metal depletion potential, would also need to be addressed in future studies.

2. MATERIALS AND METHODS

2.1 CASE STUDIES

Thailand's Ministry of Interior has published open-source drawings for Thai citizens (Department of Public Works and Town & Country Planning 2018). This project is designed to be ready-to-build, with pre-approved building permits. The Ministry has a large collection of house designs; five houses from over 30 designs were selected as case studies. The criteria for the selection were based on the most recent designs and whether they represented average houses that are being built in Thailand in terms of their scale and materials. The selection also covers the varying sizes and number of stories, which are either single- or two-storey houses. The list of houses and relevant information are shown in Table 1; rendered images of case studies are shown in Figure 1.

Table 1: Studied houses.

CASE STUDY	FLOORS	GROSS FLOOR AREA (m^2)	INDOOR AREA (m^2)	YEAR PUBLISHED	MAIN CONSTRUCTION MATERIALS
1A	1	75.91	58.52	2016	Concrete with reinforced steel and masonry
1B	1	122.59	96.80	2016	
2A	2	159.34	119.48	2016	
2B	2	256.18	194.78	2019	
2C	2	264.46	188.19	2016	

2.2 ATTRIBUTIONAL LCA

This study employs a bottom-up approach using an attributional LCA. Attributional LCA allows for a detailed investigation, which can lead to mitigation strategies that involve intervention of specific aspects or elements in each building. The majority of the buildings in Thailand in 2020 were built with a concrete frame (National Statitstical Office Thailand 2020). Buildings that use other materials as their main structure could have a lower contribution to GHG emissions and are not included in this study.

2.2.1 System boundary

The LCA conducted in this study was done in accordance with EN ISO 15978 (ISO 2012). However, several life-cycle modules were not included in this study. This exclusion was made due to the low contribution of GHG in the life-cycle of the case studies, high uncertainties or a lack of data. Details of the life-cycle modules included in the study are shown in Table 2.

Figure 1: Rendered three-dimensional images of the case studies.

Source: Department of Public Works and Town & Country Planning (2018).

2.2.2 Building inventory and quantification

Information from open-source drawings includes architectural, structural, plumbing, electrical, and heating, ventilation and air-conditioning (HVAC) drawings. The drawing packages also contain a bill of quantities (BOQ). Some of the items in the BOQ were replaced in the calculation with aggregated data. These items are in the building systems categories, *i.e.* electrical distribution, water supply and wastewater system. The replacements were used because the data of the specific equipment in those systems are not available in Thailand.

Some building components are excluded from this study. Components with small mass, such as nails, door fixtures and window fixtures, were not specified in the BOQ, and it was difficult to estimate quantities or identify specific products in the design. Items that can be used in more than one building were also excluded because the number of uses for these items has high uncertainties. Examples of these items are concrete form and scaffolding. Items that are included in the LCA are listed in Table 3. For the full list of BOQ, see ***Appendix A*** in the supplemental data online.

Table 2: Life-cycle stages included.

LIFE-CYCLE STAGE	LIFE-CYCLE MODULE		PART OF STUDY
Product stage	A1	Raw material supply	Yes
	A2	Transport	Yes
	A3	Manufacturing	Yes
Construction process stage	A4	Transport	Yes
	A5	Construction installation process	Yes
Use stage	B1	Use	No
	B2	Maintenance	No
	B3	Repair	No
	B4	Replacement	Yes
	B5	Refurbishment	No
	B6	Operational energy use	Yes
	B7	Operational water use	Yes
End of life stage	C1	De-construction demolition	Yes
	C2	Transport	Yes
	C3	Waste processing	Yes
	C4	Disposal	Yes
Benefits and loads beyond the system boundary	D	Reuse, recovery, recycling potential	No

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2.2.3 LCA tool and material data

One Click LCA was used to conduct LCA in this study (One Click LCA 2023b). In the product stage (modules A1–A3), material quantities were logged into the software, and environmental impact data for each material were selected from the software databases. Product-specific data from One Click LCA were used in the calculation if the products were available in the Thai market and had an Environmental Product Declaration (EPD). At the time of this study, the One Click LCA database was available on a commercial basis and not publicly accessible. Further information about their database is available on its website (One Click LCA 2023a).

If product-specific data could not be found in the One Click LCA database, then generic data were chosen and localised to the Thai context by converting the primary energy factors of the manufacturing of products to match Thailand's electricity mix. The data for primary energy in Thailand were retrieved from the International Energy Agency (IEA), which has the most recent data from 2020 (IEA 2023). Local emissions data for electricity production from Thai companies reported lower GHG emissions, but with high uncertainties due to different companies reporting inconsistent GHG emissions. A local database of Thai products was used to aid the selection of data by choosing the product with the most comparable GHG emissions in Thai database. The Thai database was developed by the Thailand Greenhouse Gas Management Organization (TGO) (2023). The average waste percentage for construction sites was calculated with data from the One Click LCA database, and ranged from 4% to 12%.

Table 3: Building items included.

Note: HVAC = heating, ventilation and air-conditioning.

CATEGORY	ITEMS
Foundation	• Concrete piles • Reinforcement steel in piles
Frame (beam, column)	• Concrete columns and beams • Reinforcement steel in columns and beams • Cement finish on columns and beams
Floor slab	• Concrete floor slabs • Reinforcement steel in floor slabs • Cement finish on floor slabs
Walls, partition elements	• Brick for masonry walls • Cement mortar for masonry walls • Cement finish on masonry walls
Openings	• Door frame and panels • Window frames and panels
Finishes	• Wooden plank floor finishes • Fibre cement boards floor finishes • Ceramic tiles floor and wall finishes
Building systems	• Water supply system • Wastewater system • Electrical distribution system • HVAC system
Roofs	• Roof structures and finishes • Glass wool insulation under roof
Others	• Stairs and ramps finishes • Paints and coatings

Transport distances to the construction site were based on locations in Thailand. The study assumed that all materials used for the case studies were local. The distance from Bangkok to the location of the factory that produces the specific product or the closest industrial hub were used for transport distance in transport module A4. The distance ranged from 40 to 300 km. GHG emissions from the construction installation process (module A5) came from the One Click LCA database and were calculated based on the total area of construction. A method similar to module A5 was also applied to the end-of-life stage (modules C1–C4).

The reference study period of the case studies was 50 years, which is typically used in building LCAs. The replacements of products (module B4) were based on their expected service life, as given in the EPD. Warranty periods or service life provided by Thai suppliers of comparable products were used to replace EPD data for some items. Operational energy use (module B6) includes electricity for lighting, appliances and cooling. The data for operational water usage (module B7) were retrieved from the average water consumption per person.

2.2.4 Energy simulation

Energy simulation was the method chosen to acquire the data on operational energy use (module B6). IDA ICE (Indoor Climate and Energy) software was used as the tool for the energy simulation (EQUA 2023). Climate data from the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) IWEC2 were used to simulate Thailand's climate. Bangkok, the capital of Thailand, was the chosen city of study because of its high urbanisation rate.

THERMAL TRANSMITTANCES OF BUILDING PARTS (W/(m²*K))					
EXTERIOR WALLS	INTERIORS WALLS	EXTERIOR FLOORS	INTERIOR FLOORS	ROOFS	WINDOWS
2.92	2.92	4.37	4.37	0.16	5.80
TOTAL ELECTRICITY CONSUMPTION (kWh/year) OF THE CASE STUDIES					
CASE 1A	**CASE 1B**	**CASE 2A**	**CASE 2B**	**CASE 2C**	
6,529	8,040	8,016	10,124	12,429	

Table 4: Energy performance of case studies

	CASE 1A	CASE 1B	CASE 2A	CASE 2B	CASE 2C
Bedrooms	2	3	3	3	4
Residents	3	4	4	4	5

Table 5: Numbers of bedrooms and residents in the case studies.

	AVERAGE OCCUPANCY SCHEDULE		LOW OCCUPANCY SCHEDULE		HIGH OCCUPANCY SCHEDULE	
	LIVING ROOMS	BEDROOMS	LIVING ROOMS	BEDROOMS	LIVING ROOMS	BEDROOMS
Weekdays	18.00–22.00	20.00–06.00	18.00–21.00	21.00–06.00	18.00–24.00	18.00–06.00
Weekends	12.00–22.00	20.00–14.00	15.00–21.00	21.00–12.00	9.00–24.00	18.00–15.00

Table 6: Occupancy schedule.

All case studies were designed with similar materials; therefore, they share thermal transmittances. Energy performance differs in each case study based on their sizes and geometries. Only roof elements were insulated with glass wool insulation. Floors and walls, both exterior and interior, were uninsulated. The windows in the case studies were all single-glazed. For detailed information on the energy performance of the case studies, see Table 4.

Air-conditioning systems were introduced in all case studies. The method of climate control most common in Thai households is cooling using a split-type air-to-air heat pump. This type of cooling system, called an 'air-conditioner' in Thailand, was installed in every room that accommodated prolonged activities. In all case studies, one air-conditioner was installed in each living room and bedroom. The temperature set point of the air-conditioners was set at 25°C. The operational time of the air-conditioner depends on the room occupancy and was turned off during a vacancy. The schedule of occupancy was planned based on a survey study conducted by Jareemit & Limmeechokchai (2017). The number of occupants was based on the assumption that each house is owned by two adults who occupy one bedroom. The extra bedrooms are occupied by one person. For details of the occupancy schedule and number of residents, see Tables 5 and 6.

Window-opening is the common ventilation method in Thailand. In the simulation, window-openings were scheduled during times when air-conditioners were not in use. For the prolonged uninterrupted usage of the air-conditioner, leakage was added to the wall connected to the external side of the house to simulate air leakages in actual buildings.

3. RESULTS

3.1 RESULTS

The results of LCA are shown in Table 7. Overall, the total GHG for the case studies ranges from 290 to 557 tCO_2e. The lowest GHG emissions were identified in case 1A and the largest in case 2C.

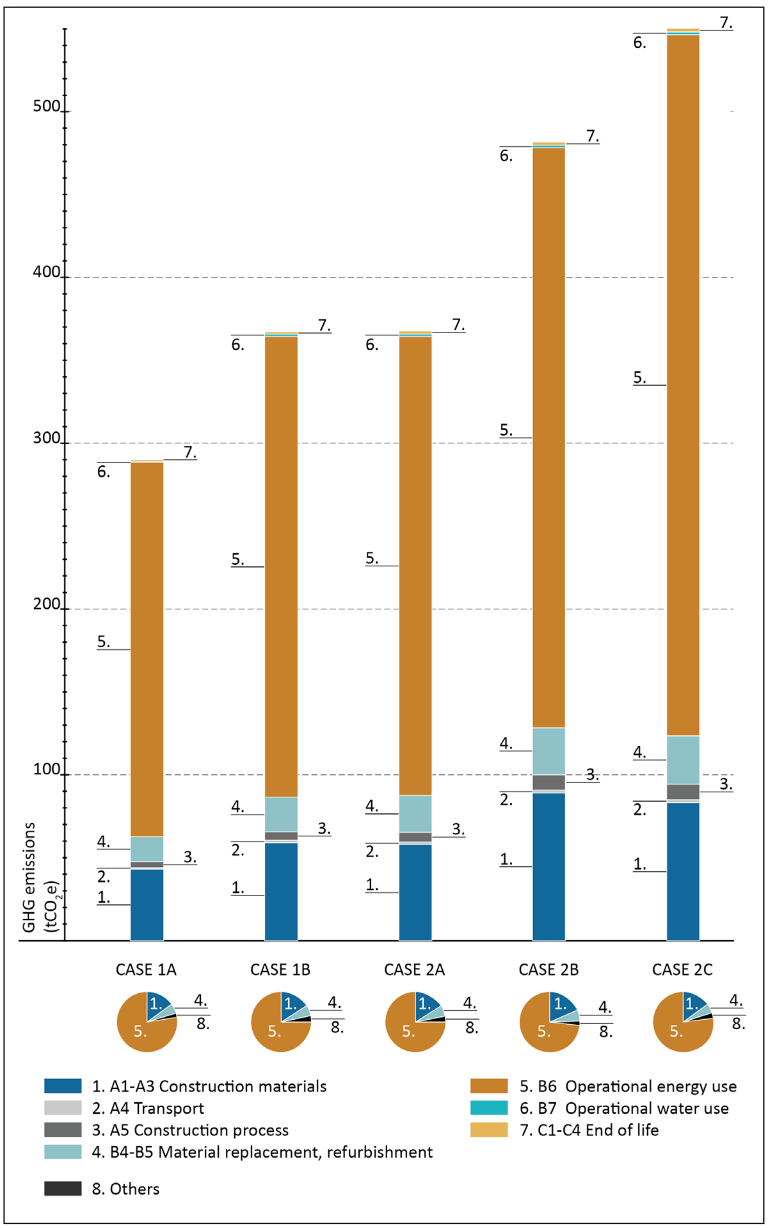

Figure 2: Shares of emissions from each life-cycle module.

3.1.1 Shares of GHG from each life-cycle module

The percentage of the GHG contribution from each module exhibits a similar pattern in all cases (Figure 2). The highest contribution of GHG emissions came from operational energy used (module B6) at around 72–78%. The second-highest share came from the production phase (modules A1–A3), which ranged between 15% and 18%. Another notable life-cycle stage is the replacement of products (module B4) which contributed approximately 5% of total emissions.

Table 7: Shares of greenhouse gases (GHG) from each life-cycle module.

MODULE	CASE 1A		CASE 1B		CASE 2A		CASE 2B		CASE 2C	
	GHG (kg CO_2e)	%	GHG (kg CO_2e)	%	GHG (kg CO_2e)	%	GHG (kg CO_2e)	%	GHG (kg CO_2e)	%
A1–A3 (Product stage)	43,100	14.9%	59,400	16.1%	57,700	15.7%	89,200	18.5%	83,200	14.9%
A4 (Transport)	1,000	0.4%	1,500	0.4%	1,400	0.4%	1,700	0.4%	1,900	0.4%
A5 (Construction installation process)	3,500	1.2%	5,200	1.4%	5,900	1.6%	9,300	1.9%	9,200	1.7%
B4 (Material replacement)	15,400	5.3%	21,200	5.8%	22,100	6.0%	28,400	5.9%	29,200	5.2%
B6 (Operational energy use)	225,700	77.7%	277,900	75.5%	277,100	75.5%	350,000	72.6%	429,700	77.1%
B7 (Operational water use)	500	0.2%	1,400	0.4%	1,400	0.4%	1,400	0.3%	1,800	0.3%
C1–C4 (End-of-life stage)	1,400	0.4%	2,100	0.4%	2,300	0.4%	3,300	0.4%	3,400	0.4%
Total	290,600		368,700		367,900		483,300		558,400	

Table 8: Area analysis of the results.

Note: GHG = greenhouse gases; GWP = global warming potential.

AREA	CASE 1A	CASE 1B	CASE 2A	CASE 2B	CASE 2C
Floor area (m^2)	75.91	122.59	159.34	256.18	264.45
Embodied GHG/gross floor area (kg CO_2e/m^2)	770.65	657.48	500.82	459.05	425.03
Operational GHG/gross floor area (kg CO_2e/m^2)	2,973.26	2,266.91	1,739.05	1,366.23	1,624.88
GWP/gross floor area (kg CO_2e/m^2)	3,828.22	3,007.59	2,308.90	1,886.56	2,111.55

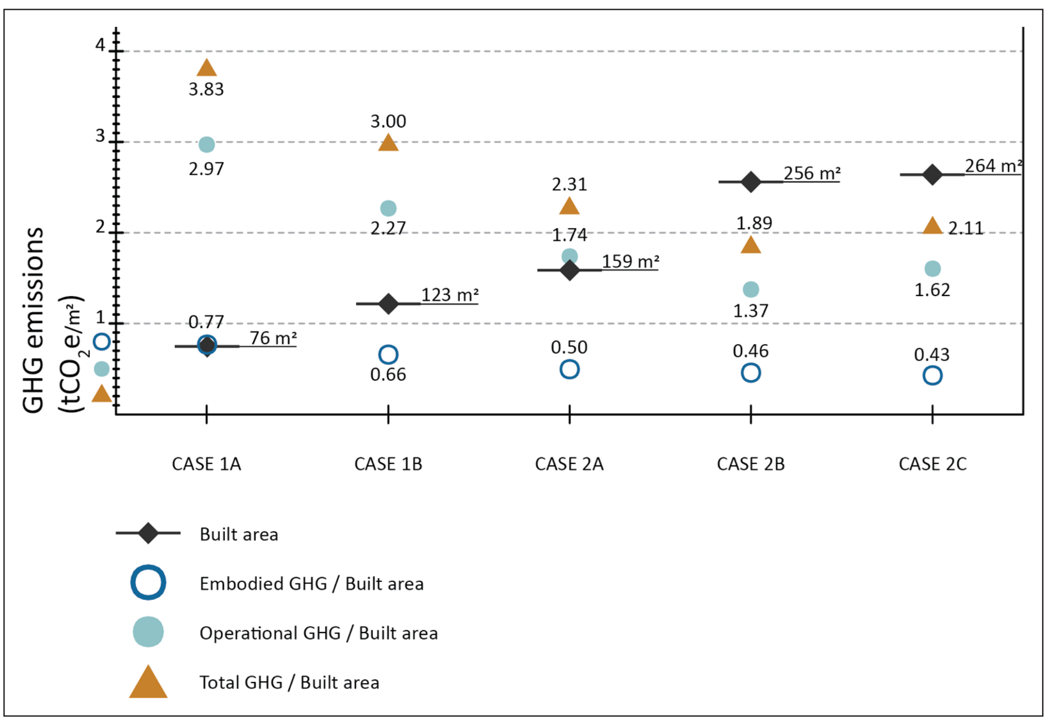

Figure 3: Area analysis.

3.1.2 Area analysis of the results

Examining emissions in these cases through emissions per built area yields different results. Analysis that includes floor area shows that case 1A has the highest GWP/m² of 3822.95 kg CO_2e/m² and case 2B has the lowest at 1881.10 kg CO_2e/m². Case studies with a larger area tend to have lower GWP/m², apart from cases 2B and 2C, since case 2C has a higher number of occupants. Two-storey buildings also have lower operational emissions due to their lower surface area per volume. For detailed results of area analysis, see Table 8 and Figure 3.

In terms of embodied emissions, GWP/m² is smaller in larger buildings: case 1A has the highest GWP/m² and case 2C has the lowest amount of embodied emissions per gross floor area. The ratio between embodied emissions and operational emissions ranges from 1:3.2 to 1:4.2.

3.1.3 GHG of case studies classified by component

Table 9 and Figure 4 show the GHG of case studies from different building components. Electricity use, which is the main source of operational emissions (module B6), has the highest impact. GWP per gross floor area in this category ranges from 1366 to 2973 kg CO_2e/m². The components with the second-highest emissions are ventilation systems, which include air-conditioners. GHG emissions in this category correlate to the number of air-conditioners in each case study. Case 1A has two air-conditioners; cases 1B, 2A and 2B all have three air-conditioners; and case 2C has four.

Foundations, floor slab and roofs are affected by building geometries. In these components, case studies with single floors (cases 1A and 1B) have a higher GWP/m² than case studies with two floors (cases 2A–2C). In addition to the number of floors, emissions from roofs are affected by their shapes. Cases 1B and 2A have simpler roof geometry than cases 1A, 2B and 2C, which results in their lower GWP/m².

There is another trend in the results for GWP/m². Cases with a larger gross floor area have a lower GWP/m² from their frames (including beams and columns).

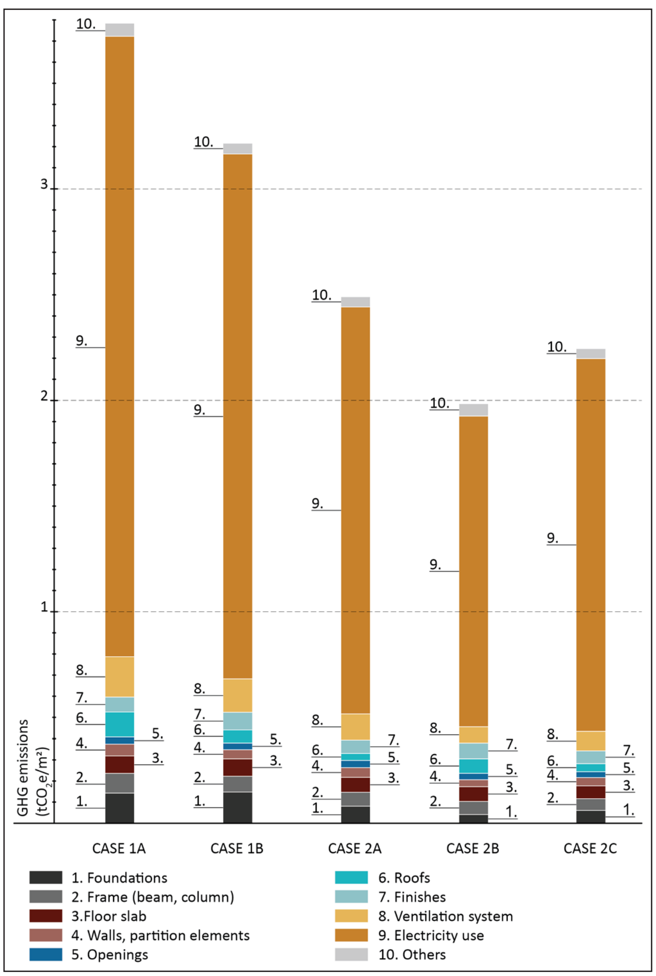

Figure 4: Greenhouse gases classified by components (GHG/m²).

COMPONENT	CASE 1A		CASE 1B		CASE 2A		CASE 2B		CASE 2C	
	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)
Foundations	10,800	142.27	18,100	147.65	12,900	80.96	10,500	40.99	16,200	61.26
Frame (beam, column)	7,100	93.53	9,200	75.05	10,500	65.90	16,200	63.24	14,600	55.21
Floor slab	6,300	82.99	9,900	80.76	11,300	70.92	17,800	69.48	16,200	61.26
Walls, partition elements	4,200	55.33	5,400	44.05	7,400	46.44	8,300	32.40	10,500	39.71
Openings	2,600	34.25	3,900	31.81	5,400	33.89	7,800	30.45	7,000	26.47
Roofs	8,900	117.24	7,400	60.36	5,200	32.63	17,400	67.92	10,200	38.57
Finishes	5,300	69.82	10,300	84.02	9,900	62.63	19,300	75.34	15,800	59.75
Ventilation system	14,700	193.65	19,500	159.07	19,500	122.38	19,500	76.12	24,400	92.27
Electricity use	225,700	2,973.26	277,900	2,266.91	277,100	1,739.05	350,000	1,366.23	429,700	1,624.88
Others	4,700	61.92	6,300	51.39	7,700	48.32	15,000	58.55	12,300	46.51
Total	290,600	3,828.22	368,700	3,007.59	367,900	2,308.90	483,300	1,886.56	558,400	2,111.55

Table 9: Greenhouse gas (GHG) emissions classified by components.

Note: GWP = global warming potential.

3.1.4 GHG classified by material types

The results of GHG emissions from the materials of case studies in this section are presented in Table 10 and Figure 5. For a detailed list of GHG emissions from each item in the building inventory, see ***Appendix B*** in the supplemental data online.

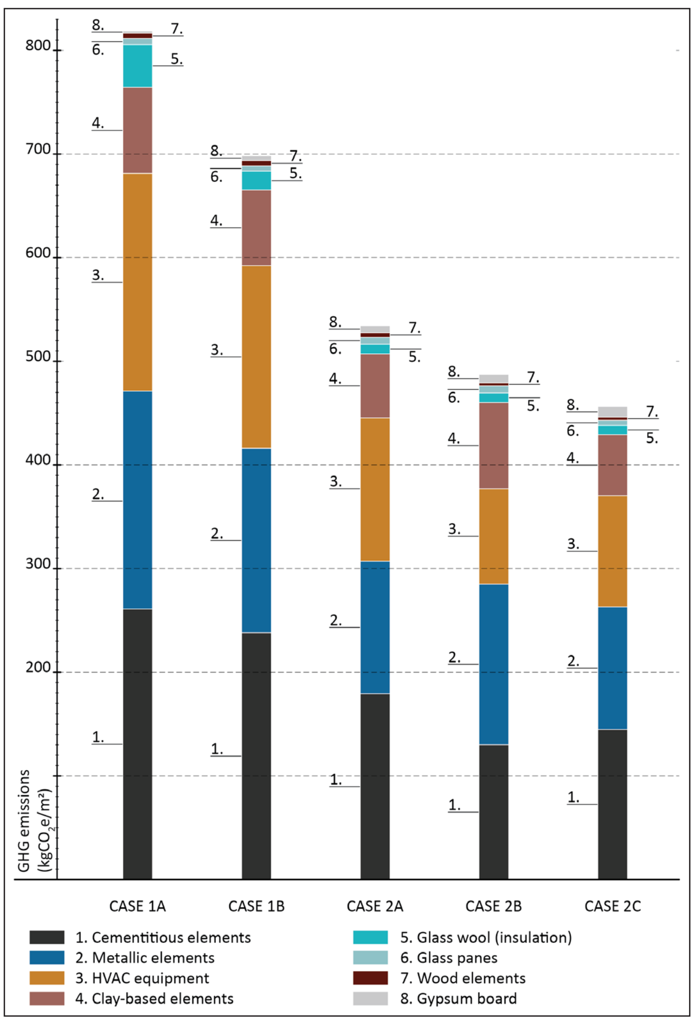

Figure 5: Emissions classified by major material types (GWP/m²).

Cementitious elements, which include structural concrete, cement finishes and cement mortar, have the highest kg CO_2e/m^2 in every case study, and range from 130.38 to 260.84 kg CO_2e/m^2. The results show higher GHG emissions in single- than in two-storey houses.

The second and third most emitting materials per gross floor area are metallic elements and HVAC equipment. Metallic elements include all steel and aluminium components. Steel is the dominant material in this group. Single-storey houses have higher emissions per gross floor area than two-storey houses in this category. Emissions from HVAC equipment depend on the number of air-conditioning units in the buildings.

Another material group that has a notable impact on GHG emissions of case studies is clay-based elements (including masonry bricks and ceramic tiles). This group is the fourth most emitting material per built area in all case studies. Other materials cause negligible GHG emissions, except for glass wool insulation in case 1A.

Table 10: Global warming potential (GWP) classified by major material types.

Note: HVAC = heating, ventilation and air-conditioning.

MAJOR MATERIAL	CASE 1A		CASE 1B		CASE 2A		CASE 2B		CASE 2C	
	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)	GWP (kg CO_2e)	GWP/M² (kg CO_2e/m^2)
Cementitious elements	19,800	260.84	29,100	237.38	28,500	178.86	33,400	130.38	38,200	144.45
Metallic elements	15,900	209.46	21,800	177.83	20,300	127.40	39,800	155.36	31,200	117.98
HVAC equipment	15,900	209.46	21,500	175.38	22,000	138.07	23,600	92.12	28,300	107.01
Clay-based elements	6,300	82.99	8,900	72.60	9,800	61.50	21,300	83.14	15,500	58.61
Glass wool (insulation)	3,100	40.84	2,200	17.95	1,400	8.79	2,200	8.59	2,500	9.45
Glass panes	500	6.59	700	5.71	1,000	6.28	1,900	7.42	1,400	5.29
Wood elements	400	5.27	500	4.08	600	3.77	700	2.73	800	3.03
Gypsum board	200	2.02	400	5.26	500	8.14	400	8.08	600	10.14

4. DISCUSSION

Conducting LCA on several houses in one study provides the opportunity to compare each case study and identify factors that correlate with their results. Floor area is one factor that has a significant impact on the amount of GHG emissions. The trend of emissions per gross floor area among the case studies is that larger houses tend to have a lower GWP/m^2 than smaller houses, especially in embodied emissions. One explanation for this trend is that the number of piles, columns and beams per built area are greater in both small houses and houses with fewer floors. Walls are also less efficient in smaller buildings since they have a larger surface area to gross floor area compared with larger buildings.

However, an exception is observable in the GWP/m^2 results. Case 2C has a higher total GWP/m^2 than case 2B, despite its larger size due to higher occupancy. Area analysis in Section 3 shows that the trend of total GHG follows the trend of GHG from module B6.

Emissions per capita give another viewpoint that can be used to determine the scale of GHG emissions at the national level (Onat & Kucukvar 2020). A comparison of GHG per number of potential residents for each case is presented in Table 11. The GWP per capita has narrower variability than the GWP per gross floor area (Figure 6). However, the uncertainties of analyzing the result using this method are high, especially if changes in residents during the service life are considered. GWP per capita is likely to grow if the area each resident occupies is larger. If the household size becomes smaller, it may result in the increase of floor area per capita and, consequently, an increase in the GWP per capita of the family. On the contrary, increasing the number of residents through the sharing of space can reduce floor area per capita, resulting in a reduction in GWP per capita. In order to create a valid outlook of national GHG emissions from residential buildings, an analysis that considers both reference units is required.

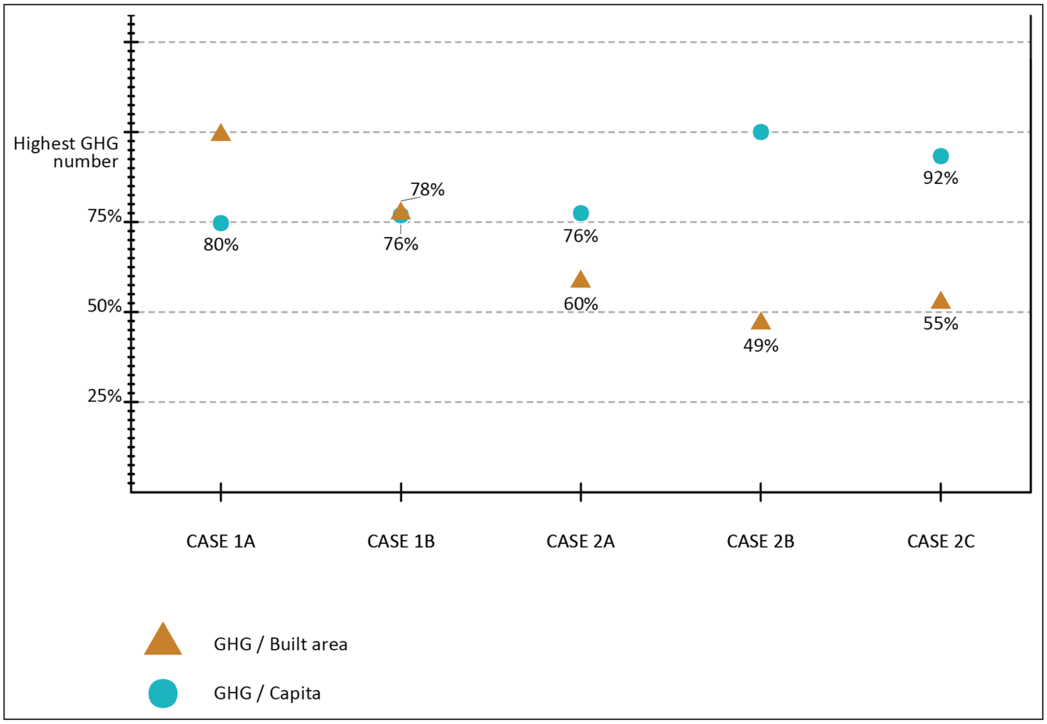

Figure 6: Spread of the greenhouse gas (GHG) results.

4.1 MITIGATION STRATEGIES FOR EMBODIED EMISSIONS

Several indications show that single-storey houses have higher embodied GHG emissions than two-storey houses. The pilings used in the foundation design in the BOQ of these case study buildings are identical. Single-storey houses usually have more roof area relative to floor area than multiple-storey houses, which further increases their embodied GWP per gross floor area. Cementitious and metallic materials are the major materials for foundation and roof structure and have high embodied GHG emissions (Allwood *et al.* 2010).

Cementitious materials, HVAC equipment and metallic materials combined contribute between 80% and 90% of embodied GHG in all case studies. Mitigation strategies that aim to reduce embodied GHG emissions from detached houses in Thailand will be more effective if embodied emissions from these three categories are the main targets.

	CASE 1A	CASE 1B	CASE 2A	CASE 2B	CASE 2C
Occupants	3	4	4	4	5
GWP/gross floor area (kg CO_2e/m^2)	3,828.22	3,007.59	2,308.90	1,886.56	2,111.55
GWP/occupants (kg CO_2e/occupant)	96,866.67	92,175.00	91,975.00	120,825.00	111,680.00

Table 11: Global warming potential (GWP) per occupant.

GHG emissions from cement and metal can be directly reduced through material efficiency by minimising the usage of concrete and steel materials in buildings. Bio-based materials can be used to replace these two materials. This mitigation strategy has the potential to remove 50% of emissions from concrete and steel. In addition to their lower emissions, bio-based materials in buildings could serve as a carbon sink (Churkina *et al.* 2020). However, the efficacy of this mitigation strategy is profoundly affected by many factors, such as material type, material origins and construction techniques. Utilising bio-based materials as a substitute for mineral-based materials is also complex in Southeast Asia since the risk of deforestation in this region is high (Estoque *et al.* 2019). Bamboo is a bio-based material grown locally in Thailand. It has been used in vernacular architecture and in some modern construction products. Earth-based bamboo plastering mortar with lower GHG emissions is used as a replacement for conventional cement mortar (Paiva *et al.* 2021). Other strategies aside from using bio-based materials also have the potential to minimise the GHG emissions from concrete. Cement substitution with secondary materials can reduce the use of cement clinker, thus reducing GHG emissions from the use of this material (Shah *et al.* 2022). The possible replacements for cementitious and metallic materials are numerous, and further studies are needed to determine their viability and climate implications in the context of Thailand.

Reducing emissions from HVAC equipment requires a different approach. Non-operational emissions from air-conditioners are mostly caused by refrigerants. R32 is the type of refrigerant specified in the EPD of the product used in LCA. Air-conditioners with this type of refrigerant are available in Thailand and are being promoted as lower emission alternatives to other refrigerants. However, R32 still emits 677 kg CO_2e/kg, which makes it a highly potent GHG (Mota-Babiloni *et al.* 2017). The recovery of refrigerant is not considered in the calculation since there is currently no standard for the treatment of electronic waste in Thailand. Therefore, it is assumed conservatively that all the refrigerants would leak into the atmosphere during and at the end of the air-conditioner service life. Refilling of refrigerants from leakages is not accounted for in this study, only emissions from the refrigerant at the end-of-life were considered. Nonetheless, including emissions from refrigerant refills can make the impact of leakages much higher. A better standard for waste treatment or product standard might be needed to alleviate refrigerant leakages and reduce life-cycle emissions from air-conditioners in Thailand.

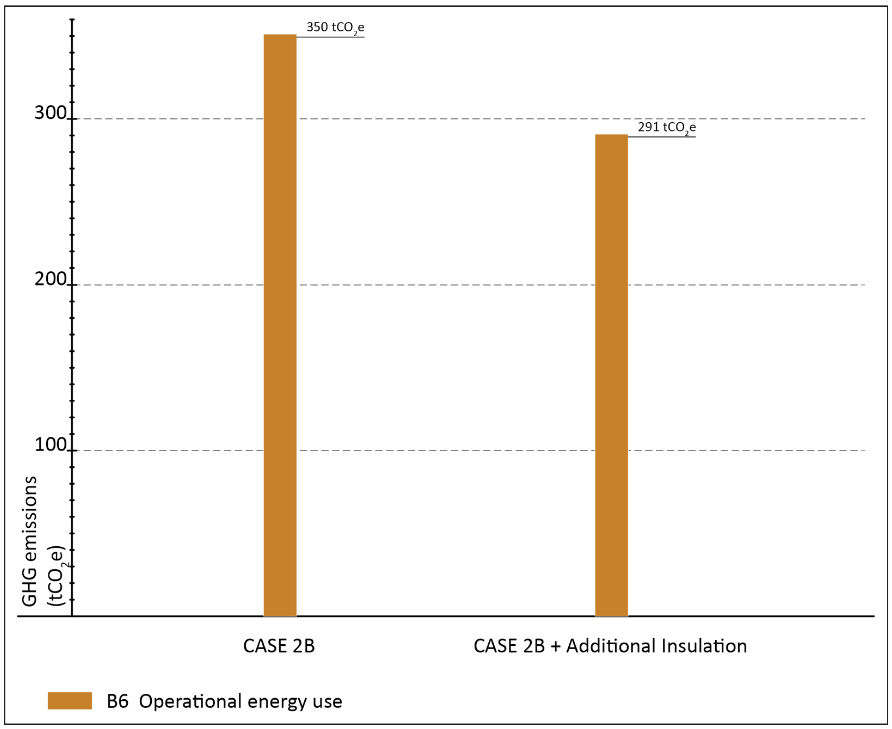

Figure 7: Operational greenhouse gases (GHG) with extra insulation.

Minimising the number of air-conditioners can reduce a significant amount of emissions, but it might decrease indoor air comfort. Additionally, the demand for air-conditioners in cities with tropical climates could be higher in the future (Colelli *et al.* 2023). However, not all Thai households are equipped with air-conditioners (Meangbua *et al.* 2019). Hence, this study used the worse case scenario with the assumption that all case studies use air conditioners.

4.2 MITIGATION STRATEGIES FOR OPERATIONAL EMISSIONS

The thermal conductivity of the structures of the building shell can affect electricity consumption from cooling considerably (Rattanongphisat & Rordprapat 2014). In the current energy model, the *U*-values of the wall and floor elements are considered poor by many standards. Improving the thermal conductivity of these elements in case 2B with 10 cm of insulation on walls and ground floor slabs and 20 cm of insulation under the roof elements, as well as changing all windows to double-glazing, resulted in a 17% reduction in electricity consumption. Information on the results is presented in Figure 7. Adding more material to improve buildings' thermal properties in this manner will result in an increase in embodied emissions. However, the overall GHG emissions from buildings with improved thermal properties should be lower than those from the typical buildings represented in this study. Satola *et al.* (2020) demonstrated that strategies related to energy efficiency or on-site energy generation are the most effective strategies to reduce GHG emissions for buildings in tropical climates.

Table 11 shows that the percentage of air-conditioning area to floor area is drastically different in all the cases. However, electricity use from cooling does not correspond to air-conditioned area; this observation is presented in Table 12. This indicates that factors other than the size of the air-conditioned area have a significant effect on electricity consumption. Since the material of the building envelopment in all cases is virtually identical, the factor that affects electricity use might be building geometry. Further investigation using building energy models is needed to verify this assumption.

4.3 OCCUPANCY SENSITIVITY ANALYSIS

Usage pattern and temperature set points are factors that substantially affect GHG from operational energy. However, they are highly dependent on the behaviour of the users. Since the survey conducted by Jareemit & Limmeechokchai (2017) shows the upper and lower operational hours of the house, a range of operational energies based on different occupancy schedules can be calculated. Figure 8 and Table 13 compare the results between the average, lowest and highest operational hours.

Table 12: Analysis of air-conditioned areas.

CASE STUDIES AREA	CASE 1A	CASE 1B	CASE 2A	CASE 2B	CASE 2C
Air-conditioned area (m^2)	49.13	70.28	59.20	117.71	126.69
Electricity use from the cooling/air-conditioned area ($kWh/m^2/year$)	110.95	94.46	114.41	74.00	83.93

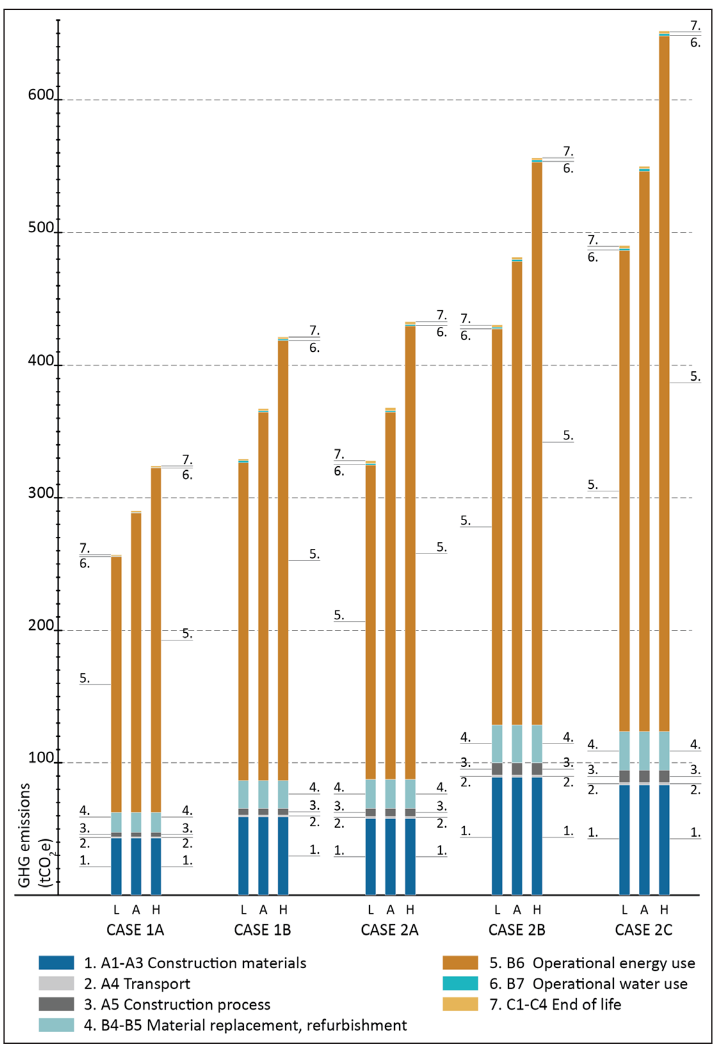

Figure 8: Greenhouse gases (GHG) from different operational schedules.

OPERATIONAL SCHEDULE	CASE 1A	CASE 1B	CASE 2A	CASE 2B	CASE 2C
Operational GHG: lowest operational hours	192,800	239,700	236,900	299,200	362,600
Operational GHG: average operational hours	225,700	277,900	277,100	350,000	429,700
Operational GHG: highest operational hours	260,100	331,600	341,800	424,700	524,800
Total GHG: lowest operational hours	257,700	330,500	327,700	432,500	491,300
Total GHG: average operational hours	290,600	368,700	367,900	483,300	558,400
Total GHG: highest operational hours	325,000	422,400	432,600	558,000	653,500

Table 13: Greenhouse gases (GHG) from different operational schedules (kg CO_2e/m^2).

Vacancies in some rooms might happen during the service life of houses, especially bedrooms. Table 14 and Figure 9 show the result of case 1A in the scenario in which one of the two bedrooms was considered vacant in the energy simulation. Between the two scenarios, the operational GHG difference is about 14–19% depending on their operational hours. These two analyses show that user behaviour and vacancies can have a significant impact on the operational GHG of the house.

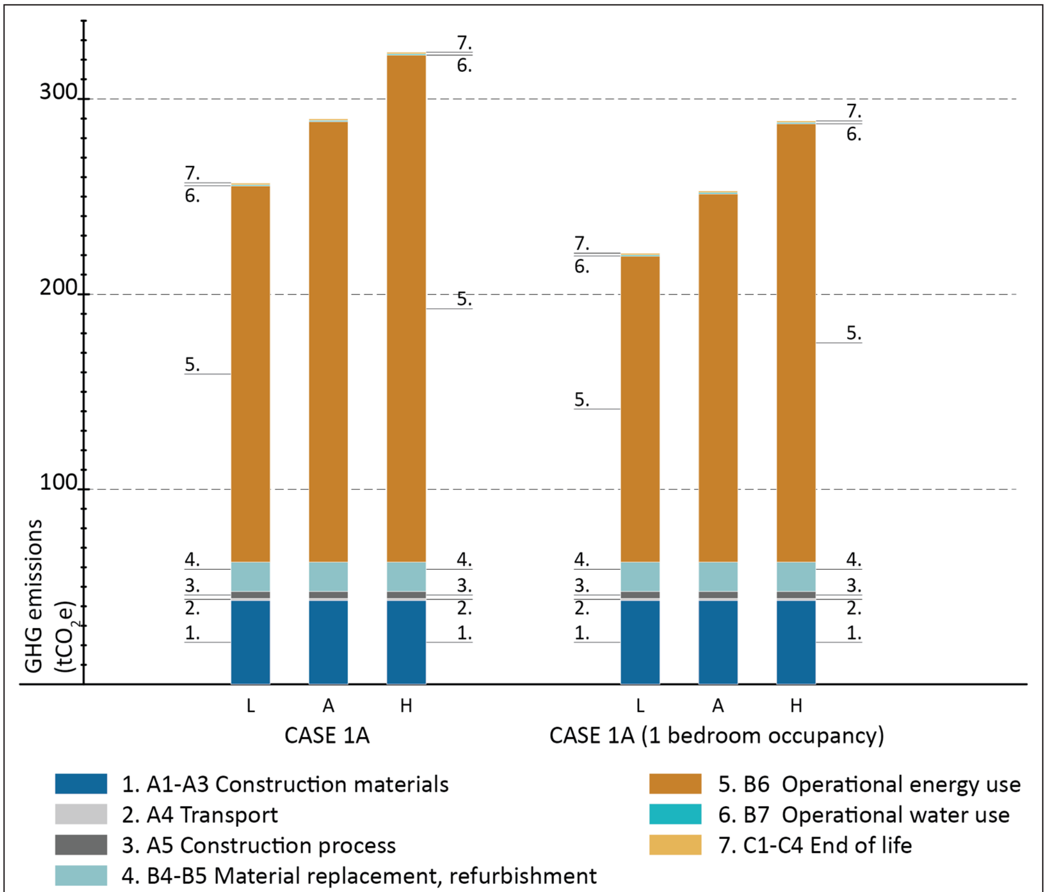

Figure 9: Greenhouse gases (GHG) from different residents scenarios.

OCCUPANCY SCENARIO	CASE 1A LOWEST OPERATIONAL HOURS	AVERAGE OPERATIONAL HOURS	HIGHEST OPERATIONAL HOURS
Operational GHG: two bedrooms	192,800	225,700	260,000
Total GHG: two bedrooms	257,700	290,600	325,000
Operational GHG: one bedroom	157,300	187,800	225,500
Total GHG: one bedroom	222,200	252,700	290,400

Table 14: Greenhouse gases (GHG) from different occupancy scenarios (kg CO_2e/m^2) for case 1A.

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4.4 UNCERTAINTIES

Due to the complex nature of building LCA, uncertainties are a commonly known problem. In this study, all case studies are open-source designs and not based on built projects. These projects can be altered and diverted from the original design when they are being constructed. The service life of the case studies was also based on a consensus among LCA studies, not on actual built projects. The service life of individual products in the LCA is subject to uncertainties as well. Although the warranty period was used to limit the uncertainties in the lifetime of these products, these numbers are expected to be conservative, or their service life can be subjected to changes in real-world conditions. The accuracy of environmental impact data is another major source of uncertainty. The availability of product-specific data from Thailand is lacking. Even though measures were taken to minimise the uncertainty, as mentioned above some level of uncertainty inevitably persisted.

The primary energy factor can have profound effects on the results of LCA. Emissions from energy production in the study are based on Thailand's electricity mix in 2020. However, the electricity grid will likely become more efficient, and the proliferation of renewable energy can increase in the future. Data from Thailand's Energy Policy and Planning Office (2023) showed that the emissions factor of electricity in Thailand has been consistently decreasing, from 0.63 in 2000 to 0.4 in 2023, and this trend is likely to continue in the future.

One major uncertainty is that the location of the buildings is not known. Since the data for buildings are retrieved from open-source drawings, it is not possible to simulate the surroundings of the case studies. For example, shading from other buildings or trees can have a significant impact on the operational emissions of the houses (Liu *et al.* 2021).

4.5 COMPARISON WITH OTHER STUDIES

Comparing the results of this study with other studies in the same region can provide additional insights into the GHG emissions of the built environment in Thailand. However, comparing the LCA results of different studies can be misleading, especially if the different studies have different building types, scopes, system boundaries, reference units or data. One example is Tulevech *et al.* (2018), who put the service life of their study at 20 years, while most of the other studies are at 50 years. The time difference of the study can also affect the comparability between two studies since the databases for material data between the two studies will most likely be different.

Among the studies mentioned above, Iqbal *et al.* (2018) has the closest parameter compared with this study. The LCA result of a typical house in Iqbal *et al.* showed that it has three major phases contributing to GHG emissions in its life-cycle: manufacturing, replacement and operational. The GHG emissions of these phases are 54,200, 3200 and 435,300 kg CO_2e, respectively. The case study that has the most similar floor area to that of Iqbal *et al.* is case 2A: both case studies have an approximate net floor area of 140 m^2. The LCA result of case 2A has manufacturing, replacement and operational GHG emissions of 57,700, 21,200 and 277,100 kg CO_2e, respectively. Comparing these two results, the biggest differences lie in the replacement and operational phases. For the replacement phase it is unclear whether or not Iqbal *et al.* have included the embodied GHG of the replacement of the air-conditioner. The embodied GHG of replacing an air-conditioner in the present study contributes to 15,000 kg CO_2e, which would correspond to the difference in emissions in replacement in both studies. For the operational phase, there is a significant difference between the two studies. Energy consumption per year in Iqbal *et al.* is 12,000 kWh/year, while for case 2A it is 8000 kWh/year. Both studies used energy simulations to determine the energy consumption of their case studies, albeit with different software. The operation time of air-conditioners can be the reason for this result discrepancy. The operational schedule of the air-conditioners in Iqbal *et al.* was not presented, therefore the effect of the air-conditioner schedule on the result is uncertain. The result from using the highest the operational hours for case 2A showed that the electricity consumption is 9900 kWh/year. This is closer to Iqbal *et al.*'s results, but it is still noticeably smaller. Overall, the big difference in operational energy consumption has a significant effect on the overall LCA result and should be investigated further.

4.6 OVERALL

According to Satola *et al.* (2020), GHG emissions of single-family houses in tropical climates ranges from 491 to 4554 kg CO_2e/m^2. This puts the result of the present study (1886.56–3828.22 kg CO_2e/m^2) in the high emission group of Satola *et al.* Since the operational phase contributes to the largest share of GHG emissions, building energy standards have significant impacts on emissions. The current situation of building energy standards in Thailand is voluntary, using a certification system. Leadership in Energy and Environmental Design (LEED) is the most prominent certification in Thailand, and between 2007 and 2016 only 201 buildings have been certified or are in the process of being certified; none of the certified buildings was for residential purposes (Lohmeng *et al.* 2017). Although large buildings are subject to regulations that limit their environmental impact, regulatory measures need to be extended to residential buildings since they contribute a significant amount of construction activity to the Thai built environment.

Another development that has the potential to reduce GHG emissions in Thailand is on-site solar energy generation. Cumulative solar PV-generating capacity has grown exponentially since 2010 and reached 2753 MW in 2016 (International Renewable Energy Agency (IRENA) 2017). This strategy of reducing GHG emissions has also been studied by Iqbal *et al.* (2018) and it can reduce the emissions significantly. Utilizing on-site solar PV appears to be the most realistic strategy for the built environment in Thailand since the emissions factor of their electricity is high and the utilization of solar panels has seen a significant increase in recent years. However, if the emissions intensity of electricity decreases, the relative emission savings from PV panels will also decrease. Additionally, the use of solar PV also requires more materials and will increase the embodied emissions of the buildings.

5. CONCLUSIONS

This study was conducted to determine the life-cycle greenhouse gases (GHG) of five typical detached houses in Thailand. The chosen case studies had a variety of scales and were either of one or two stories. Life-cycle assessment (LCA) was used to calculate the GHG emissions from each case study. The result of total global warming potential (GWP) from the reference study period of case studies varies considerably between 290 and 557 tCO_2e.

The shares of total GHG from each life-cycle stage were similar in all case studies. The majority of GHG emissions came from operational energy, which ranged between 74% and 78%. The combination of GHG from the product and replacement stages was considered as embodied emissions, which contribute 19–23% of total GHG emissions. Therefore, the ratio between embodied emissions and operational emissions is approximately 1:4.

The results from this study show a wide range of GWP per built area. The larger buildings tend to have smaller GWP/m^2 than smaller houses, unless the house has significantly high electricity use. Single-storey houses also generally have a higher GHG/m^2 than two-storey houses. Applying the number of occupants as a reference unit instead of gross floor area yielded results with a smaller spread, albeit with high uncertainties.

GHGs from embodied emissions mostly came from three groups of materials or components: cementitious elements, heating, ventilation and air-conditioning (HVAC) equipment, and metallic elements. Strategies to mitigate emissions from cementitious and metallic elements involve replacing them with materials that have lower emissions. Bio-based materials are promising substitutes for these mineral-based materials, but more studies are needed to determine their impact in the Thai context. Minimizing the number of air-conditioners can reduce emissions from HVAC equipment and operational energy as well, but might a have detrimental effect on indoor air comfort.

Temperature set points, user behaviours and the number of air-conditioners in each household are factors that have high uncertainties. Surrounding conditions also impact energy use for cooling in buildings. The primary energy factor used in this study is assumed to have remained unchanged throughout the reference study period. This factor will likely change over time due to the efficiency of electricity generation and the inclusion of renewable energy sources.

Comparing the present study with another study shows a discrepancy in operational electricity consumption. The discrepancy is drastic and influences the LCA result significantly. Different air-conditioner operation schedules might be the reason for this discrepancy, but it is not conclusive.

Understanding the life-cycle impacts of buildings can provide useful information for making a climate-conscious design in buildings and contributing to a better understanding of GHG emissions from the built environment in Thailand. Other countries that experience a similar climate to Thailand, especially those situated close by, can also benefit from the findings of this study. This knowledge is valuable to future GWP-mitigation strategies in the country and can have an impact on the global effort to minimise the effects of climate change.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA ACCESSIBILITY

The data supporting the findings of this study are available within the article and its supplementary material.

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