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Design Strategies to Lead Thailand's Building Sector toward Net-Zero Greenhouse Gas Emissions: A Review

Rataphong Rahong and Trakarn Prapaspongsa*

Graduate Program in Environmental and Water Resources Engineering,
Department of Civil and Environmental Engineering, Faculty of Engineering,
Mahidol University, Nakhon Pathom 73170, Thailand
*E-mail : trakarn.pra@mahidol.ac.th

Abstract

The building sector is one of the intensive greenhouse gas (GHG) emitters in Thailand. Furthermore, Thailand also aims to reach net-zero GHG emissions by 2065. This study therefore aims to evaluate whether the current design strategies are adequate to lead the building sector to net-zero emissions. The study initially finds that the embodied and operational phases have equal chances of becoming hotspot of buildings as the emissions from each phase can be influenced by choice of material, choice of energy-saving retrofits, and electricity grid profiles. Since either phase could become the hotspot of buildings, this study reviews two international and national green-building guidelines each to identify the design strategies used for buildings' GHG mitigation. The review highlights five main strategies: to substitute low-carbon materials for carbon-intensive materials, to improve structural performances of carbon-intensive materials, to increase the circularity of buildings; as well as, to use passive and active energy-saving retrofits. Afterward, the efficiencies and limitations of the aforesaid strategies are assessed through 46 Life Cycle Assessment (LCA) studies and relevant documents such as reports by Thailand's government, building code, etc. The assessment indicates that, in theory, the aforesaid strategies show great potential on leading Thailand's building sector to net-zero GHG emissions, given a condition that all buildings use renewable energy-based on-site electricity generators on a large scale. However, in reality, there are various limitations preventing this ideal situation to arise. Thus, this study posts five possible research improvements and a hands-on management strategy as a means to provide practical benefits and push forward Thailand's building sector toward the net-zero GHG emissions goal ultimately.

Keywords : building sector; design strategies; net-zero; greenhouse gas; review

Introduction

From a life cycle perspective, buildings emit GHG during their operational and embodied phases. The former is the period when buildings are used. Meanwhile, the latter is the period before and after buildings are used. The latter includes raw-material extraction, material production, transportation, construction, maintenance, demolition, and waste management. In 2021, Thailand's building sector consumed about 97,265 GWh of electricity through their operations such as cooling, lighting, etc. [1]. This caused the sector to release about 42 million tons of GHG, representing 17% of the nation's total GHG emissions [1]. Furthermore, the sector also emits GHG during their embodied phase [2]. Nonetheless, the embodied GHG were normally included within the transportation and industrial sectors [2], making them account for 71.5 and 70.6 million tonnes of GHG in the year 2021 respectively [1]. However, if one were to extract the embodied emissions hidden within the aforesaid two sectors and sum them with the operational emissions, one would thus safely find that the GHG emissions contributed by Thailand's building sector may well be around 49 million tonnes, representing 20% the nation's total GHG emissions. In response to the GHG level, Thailand's Ministry of Energy (MOE) has established Energy Efficient Plans [3, 4] as a means to make all economy sectors less energy intensive. For the building sector, this plan specifically suggests designers to apply design strategies advised by international and national standards while designing buildings. Given that this plan is well executed, the MOE has projected that the building sector will contribute to about 9,718 ktoe of energy saving [3, 4]. This saving will then contribute to the nation's total energy reduction of 49,064 ktoe; and thus, leading Thailand to achieve 20-25% GHG emission reduction by 2030 [3-5]. Despite the projected achievement of the 2030 goal, the MOE has forecasted that the country's final energy consumption will reach 126,867 ktoe by 2037, with the building sector being one of the main energy consumers [4]. This issue thus raises an academic and a practical concern of whether the building sector can and will achieve net-zero GHG emission by 2065 as planned in [6]. Following this concern, this study has established three-fold goals: (1) to indicate buildings' hot-spots and their factors, (2) to identify design strategies and their efficiencies to mitigate the GHG emissions, (3) to evaluate the adequacies of the design strategies on leading Thailand's building sector to become a net-zero GHG emission sector; and highlighting future research needs and suggestions.

Methodology

As buildings are intensive GHG emitters throughout their lifetime, this study thereby chose to review LCA-related studies which allowed the authors to analyze the environmental performances of buildings holistically [7, 8]. This study firstly conducted an online search through Scopus database for LCA studies of buildings with alterations of electricity grid supplies and energy-saving retrofits. The time restriction for the publication was between 2015 and 2022, while the language was limited to English. The keywords were LCA, buildings, different locations and different electricity grid mixes. The journal studies that holistically assessed buildings with both alterations of electricity supplies and energy-saving retrofits were included. On the contrary, the journal studies (1) that assessed buildings with only one of the aforesaid alterations, and (2) that assessed buildings either at embodied or at operational phase were excluded. Through the search method shown in Figure 1, 13 journal studies were selected to assess building hotspots when electricity grids and retrofits are altered. Secondly, this study reviewed Thailand's long-term plans [3, 4, 9, 10] in order to identify the international and national standards for building designs. Through the review, four guidelines [11-14] were identified. Further review was then conducted on [11-14] to identify design strategies for GHG mitigation. Afterward, five design strategies were identified: to substitute low-carbon materials for carbon-intensive materials, to improve structural performance of carbon-intensive materials, to increase the circularity of buildings, and to use passive and active measures. Thirdly, this study searched through Scopus database under the previously mentioned restrictions for LCA studies of buildings that apply the aforesaid design strategies. The keywords searched included LCA, buildings, concrete, steel, timber, hollow, lightweight, high-strength, design for disassembly, orientation, vegetation, envelope, bioclimatic, ventilation, solar-cell, air condition and heating. Through the search for studies related to materials, journal studies that performed LCA on alternative and conventional materials in term of structural materials were included. Contrariwise, the journal studies (1) that performed LCA analysis on alternative materials in term of non-structural materials, (2) that performed LCA analysis on buildings equipped with dissimilar retrofits, and (3) that performed LCA analysis on floor elements without considering their supporting elements were excluded. Likewise, through the search for studies related to energy-saving retrofits, journal studies which performed LCA analysis on buildings that are equipped with both passive and active measures were included. Whereas the journal studies which performed LCA on buildings that are equipped with only one of the aforesaid measures were excluded. Fourthly, this study collected journal studies which performed LCA on buildings in Thailand. Through the search method shown in Figure 1, 46 studies were collected. This study lastly collected relevant documents [15-18] to evaluate the adequacies of the design strategies on leading Thailand's building sector to net-zero GHG emissions goal and to highlight potential research improvements.

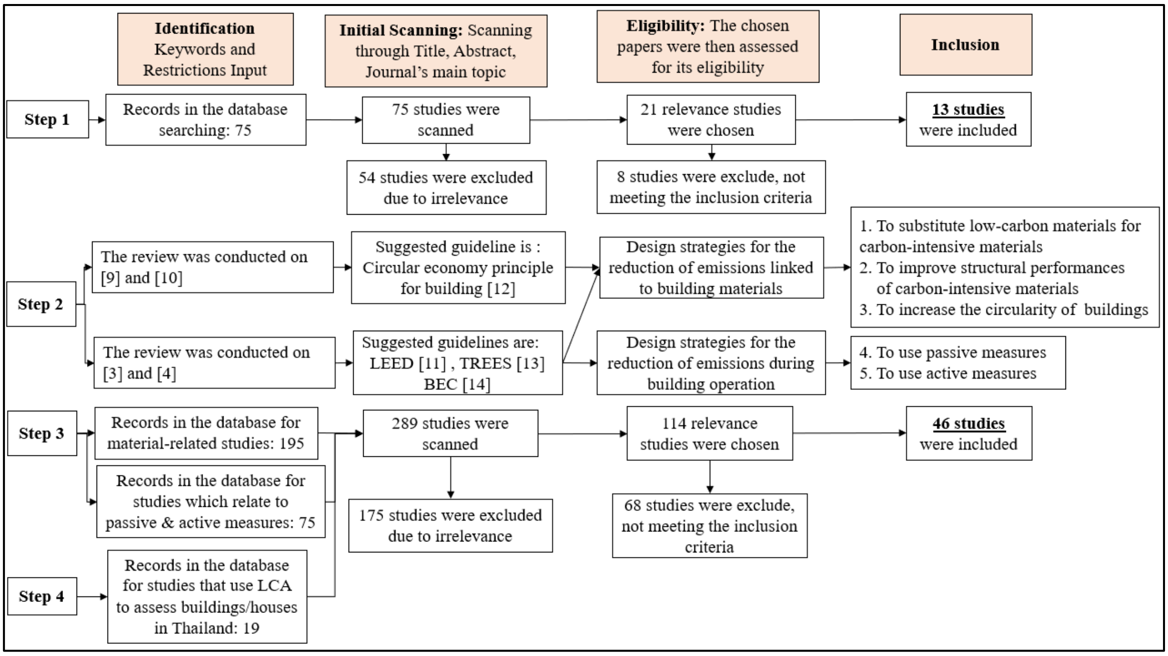

Figure 1 The schematic diagram on reference searching (from step 1 to 4)

Results and Discussion

Hotspots for building and their influencing factors

The embodied and operational phases have equal chances of becoming the hotspot of buildings as the emissions in each phase are linked to design-related and policy-related factors. The former is the choice of energy-saving materials and devices, so called retrofits. The latter is the profile of electricity grid [19-31]. Generally, when a building is supplied by fossil-fuel based grid and is not equipped with any retrofits, the operational emissions (OEs) will accumulate and overtime surpass the embodied emissions (EEs). Thus, the operational phase becomes the hotspot of buildings [7, 8, 19-31]. However, Table 1 shows that the replacement of fossil fuels by renewable energies in grid profile can reduce the amount of carbon emitted per kWh electricity generated. This thereby results in reduction of the OEs and total life cycle emissions (TLEs). Likewise, Table 2 illustrates that the use of retrofits can make buildings less energy intensive. This in turn reduces the OEs and TLEs, despite the additional EEs associated with the retrofits. Nonetheless, success in reducing the OEs leads to the embodied phase becoming significant, and in some cases become the hotspot of buildings. This issue is shown in Table 1 and 2, where the share of EEs-to-TLEs increases when the OEs are cut. For Thailand, the 2021 national grid profile comprised of 55% natural gas, 18% coal & lignite, 14% imported electricity, 12% renewable energy, and 0.4% oil [1]. This profile caused the grid to emit about 0.442 kg of carbon per kWh electricity generated. Nonetheless, by 2037, Thailand's Ministry of Energy aims to reduce the carbon emitted per electricity generated to 0.271 kg via reduction of fossil fuels to 11% and increasing the renewable energy up to 30%, whereas the natural gas will remain about the same [17]. This suggests that Thailand's grid is moving toward a more sustainable composition; and thus, the importance of the embodied and operational phases will incline and decline simultaneously and respectively [28-31]. With this regard, it is advisable for designers to not only consider the OEs, but also the EEs whilst designing buildings. This is because the retrofits will become less effective as the grid is decarbonized; thus, an excessive use of the retrofits can intensify the EEs and can potentially increase the TLEs [23, 29, 31]. For example, Table 3 shows that in a lesser sustainable grid, the use of PV and heat-pump reduces the OEs by 85%; and reduces the TLEs by almost half. Meanwhile, the same devices provide 86% reduction for the OEs in a more sustainable grid, but they only provide 23% reduction for the TLEs. This example demonstrates that the embodied phase plays an important role in a decarbonized grid and without consideration of both the OEs and EEs while designing buildings, one could potentially end up using retrofits such that the add-on EEs are larger than the reduced OEs resulting in larger TLEs for the buildings. It is thereby necessary for designers especially in Thailand where the grid is being decarbonized [17], to consider the EEs and OEs during the design stage. Doing so will improve the designers' decisions on the choice of retrofit, ultimately helping the designers to obtain truly GHG-less building.

Table 1 Influence of grid-profile variation on EEs, OEs, and TLEs

Reference	Country	Type & Area (m^2)	System Boundary	Use phase (years)	Electricity Grid Supply	EEs ($kgCO_2$ eq/m^2)	OEs	TLEs	% of EEs to TLEs
[20]	New Zealand	Office 5,841	Cradle-to-Grave	50	FF 34% , RE 66%	1,000	37,500	38,500	2.6%
					FF 26% , RE 74%	1,000	35,000	36,000	2.8%
					FF 19% , RE 81%	1,000	27,500	28,500	3.5%
[21]	Northern Ireland	Resident 187.1	Cradle-to-Grave	60	FF 59% , RE 41%	354	2,077	2,431	15%
					FF 40% , RE 60%	354	1,628	1,982	18%
					FF 30% , RE 70%	354	1,571	1,925	18.4%
					FF 20% , RE 80%	354	1,540	1,894	19%
[22]	Singapore	Office 420	Cradle-to-Grave	20	NG 77% , PP 20%	51	1,155	1205	4.2%
					NG 84% , PP 13%	51	1,046	1097	4.6%
					NG 95% , PP 1%	51	913	964	5.3%

Note. This table represents buildings subjected to the variations of electricity grid mix under a fixed retrofit scenario (the least retrofit). Abbreviations are Cradle: raw-material extraction, Grave: Disposal, FF: Fossil Fuel, RE: Renewable Energy, PP: Petroleum Products, NG: Natural Gas (more environmentally friendly compared to PP), EEs: Embodied Emissions, OEs: Operational Emissions, TLEs: Total Life Cycle Emissions

Table 2 Influence of energy-saving retrofits variation on EEs, OEs, and TLEs

Reference	Country / Type of Building /Areas	Use Phase (years)/ System Boundary	Grid Supply	Retrofit Scenarios	EEs ($kgCO_2$ eq/m^2)	OEs	TLEs	% of EEs to TLEs
[20]	New Zealand Office , 5841 m^2	50 Cradle-to-Grave	FF 34% , RE 66%	S:1 Baseline	1,000	37,500	38,500	3%
				S2: improved Enve, HVAC	7,000	15,500	22,500	31%
[21]	Northern Ireland Resident 187.1 m^2	60 Cradle-to-Grave	FF 59% RE 41%	S1: Baseline	354	2,077	2,431	15%
				S2: floor insulation, PV	430	1,750	2,180	20%
				S3: improve Enve, HVAC	351	1,362	1,713	21%
				S4: improve Enve, HVAC, DHW	366	1,017	1,383	26%
[22]	Singapore Office , 420 m^2	20 Cradle-to-Grave	NG 77% , PP 20%	S1: Baseline	51	1,155	1,205	4.2%
				S2: improve HVAC	53	757	811	6.6%

Note: This table represents buildings subjected to the variations of energy-saving retrofits under a fixed electricity-grid scenario (the most fossil fuels). Abbreviations are Cradle: raw-material extraction, Grave: Disposal, FF: Fossil Fuel, RE: Renewable Energy, PP: Petroleum Products, NG: Natural Gas (more environmentally friendly compared to PP), Enve: Building Envelope, HVAC: Heating /Ventilation / Air-Condition, DHW: Domestic Hot Water, PV: photovoltaic (solar-cell) panels, EEs: Embodied Emissions, OEs: Operational emissions, TLEs: Total Life cycle Emissions

Table 3 Influence of grid-profile and energy-saving variation on EEs, OEs, and TLEs

Reference	Country / Type of Building /Areas	Use Phase (years)/ System Boundary	Grid Supply	Retrofit Scenarios	EEs ($kgCO_2$ eq/m^2)	OEs	TLEs	Different in TLEs
[23]	Spain Office , 2782 m^2	50 Cradle-to-Grave	FF 61% RE 39%	S1: Baseline (improve Enve)	220	780	1,00 0	-
				S2: Baseline , improve HVAC, PV	440	110	550	45%
			FF 26% RE 74%	S1: Baseline (improve Enve)	220	430	650	-
				S2: Baseline , improve HVAC, PV	440	60	500	23%

Note. This table represents buildings subjected to the variations of energy-saving retrofits and electricity-grid mix. Abbreviations are Cradle: raw-material extraction, Grave: Disposal, FF: Fossil Fuel, RE: Renewable Energy , Enve: Building Envelope, HVAC: Heating / Ventilation / Air-Condition, PV: photovoltaic (solar-cell) panels, EEs: Embodied Emissions, OEs: Operational emissions, TLEs: Total Life cycle Emissions

Design strategies and their effectiveness to mitigate the life cycle GHG emissions

1. Substitution of carbon-intensive materials with low-carbon materials

Substitution of carbon-intensive materials with low-carbon materials is a strategy advised by [11]. According to Table 4, the substitution of concrete and steel with timber helps to mitigate the EEs of buildings. This mitigation occurs because timber is a natural resource which can be regarded either as low-carbon materials [32-34], carbon-neutral materials [32, 35-39], or carbon-storage materials [40]. Moreover, timber residues and wastes from the production and End-Of-Life (EOL) stages can also be employed in energy generation instead of fossil fuels. This ultimately results in further drop of EEs in buildings [34, 36, 38, 41, 47]. Besides timber, Table 4 shows that composite and innovative materials could be substituted for concrete and steel. This approach yields reduction in EEs

Table 4 Substitution of carbon-intensive materials with timber, composite, and novel materials

Reference	Country	type	Area (m^2)	Cast Studies	System Boundary	EE	Difference in EEs
[32]	USA	Parking Garage	13,300	Steel (0% recycle)	Cradle-to-Gate	107	-
			13,300	Steel (93% recycle)		41	-62%
			12,300	PC (0%SCM)		80	-25%
			12,300	PC (50%SCM)		52	-51%
			19,900	Timber (CN)		37	-65%
			19,900	Timber (LC)		67	-47%
[33]	UK	Residential	2,250	Steel Frame	Cradle-to-Grave	486	-
				Concrete Frame		420	-14%
				Timber (LC)		178	-63%
[34]	Australia	Residential	603	Concrete (concrete landfill, steel recycle)	Cradle-to-Grave	312	-
				Steel (recycle)		237	-24%
				Mature Hardwood (LC, energy recovery)		80	-74%
[35]	EU, China, North America, Australia	Resident, Office, Commercials, Parking Lots	1,140 - 29,100	RC	Cradle-to-Gate	average difference of 216	
				Timber (CN)			
[36]	UK	Not Specified	Not Specified	Steel (recycle)	Cradle-to-Grave	228	-
				RC (landfill & recycle steel bar)		185	-19%
				Timber (CN / landfill)		119	-48%
[37]	Portugal	House	56	Concrete	Cradle-to-Gate	7143	-
				Steel		5714	-20%
				Timber (CN)		4464	-38%
[38]	U.S	Office	10,702	Concrete building	Cradle-to-Site	450	-
				Hybrid CLT with fireproofing (CN)		333	-26%
[39]	Switzerland	Residential	1,100	Concrete Hollow Block	Cradle-to-Site	160	-
				Bamboo (CN)		80	-50%
[40]	China	Nursing Home	4,297	Concrete Frame	Cradle-to-Grave	360	-
				Timber Frame (CS)		215	-40%
[41]	Thailand	Residential	112	Steel Modular (recycle where possible)	Cradle-to-Grave	641	-
				Timber Modular (recycle where possible)		381	-41%
[42]	Australia	Commercial	50,000	Concrete Slab	Cradle-to-Grave	29.4	-
				Concrete with SCMs slab		25	-15%
				Timber-Concrete slab		29	-1%
				Steel-Concrete slab		37	+26%
[43]	China	residential	357	RC Frame	Cradle-to-Grave	535	-
				Steel-Bamboo composite Frame		482	-10%
[44]	Malaysia	residential	119	block system	Cradle-to-Grave	273	-
				precast system		102	-63%
				steel system		203	-26%
				timber system		17	-94%
				Glued laminated timber & steel supports		53	-81%
				laminated veneer lumber & steel supports		49	-82%
[45]	China	residential	3,248	Bricks Structure	Cradle-to-Grave	628	-
				RC block masonry structure		506	-19%
[46]	Potugal	residential	N.S.	Brick	Cradle-to-Gate	29	-
				Glass fiber - insulation - glass fiber		11.65	-60%

Note. This table extracts only embodied emissions. Also, if there are multiple scenarios representing timber buildings with the same assumption, this table only considers the scenario with the largest EEs (the worst performance by timber). The abbreviations are: Cradle: raw-material extraction, Gate: manufacturing process, Site: construction activities, Grave: disposal, CN: Carbon Neutral materials, LC: Low Carbon emitted materials, CS: Carbon Storage Materials, RC: Reinforce Concrete, PC: Precast Concrete, SCM: Supplementary Cement Materials, EEs: Embodied Emissions ($kgCO_2$ eq/m^2). The negative and positive signs represent the reduction and increase in EEs relative to the baseline case respectively.

because it allows designers to not only develop composite materials by combining traditional carbon-intensive materials with traditional low-carbon materials [38, 42-46], but also to develop greener solutions from novel materials [46]. Apart from substituting alternative materials for concrete and steel, another approach that can reduce the EEs embedded within concrete and steel is to use low-carbon ingredients in their productions. To produce concrete, various industrial byproducts, so called Supplementary Cement Materials (SCMs) can be used to reduce the cement content required in concrete mixes [48-52]. Likewise, steel scraps could be employed as a raw material for the production of steel. Doing so will avoid the need for virgin materials and their associated processes; hence, a corresponded reduction in embodied energy and emissions [32]. Despite the aforesaid benefits, designers are tasked to assure that the proposed solutions are structurally viable [11] and the TLEs of the proposed solutions are lower than the TLEs of the baseline solution [11, 42]. The former can be assured through ASTM test or equivalent [11]. Meanwhile, the latter can be assured through LCA tool [11]; the assessment which tasks designers to consider the OEs and TLEs of the buildings. For example, [42] shows that although the concrete-steel composite slab provides highest EEs among all solutions, this solution offers the least heat transfer through the slab during building's operation. This thereby yields a substantially low OEs which later-on leads the solution to provide a lower TLEs compared to baseline (concrete) slab.

2. Improvement of materials' structural performances

Improvement of materials' structural performances is suggested to lessen the need of materials required in buildings, whilst ensuring that buildings still perform at the same level of structural service [11, 12]. Doing so will subsequentially dematerialize the buildings; thus, reducing the needs for natural and carbon-intensive resources and preventing wastes associated with buildings' lifecycle [11, 12]. This results in a drop of the EEs ultimately. According to Table 5, this strategy could be executed by three main techniques. The first is to develop and use lightweight materials such as hollow floor. The advantageous characteristic of these materials is its lightness, as it allows designer to downsize the dimensions of the corresponded support elements; hence, a drop in the EEs [53-55]. The second is to develop and use high-strength materials such as high-strength concrete, and concrete reinforced with carbon fiber reinforced polymer. Although high-strength materials are more carbon intensive during their production compared to normal-strength materials, the durability associated with the high-strength materials allows designers to cutdown materials required in building designs to an extent that the carbon induced during materials' production are offset by the cut-off carbon from the reduction of required materials [56, 57]. Nonetheless, it is essential for designers to assure that the carbon induced are offset by the carbon cut-off, or else, the overall EEs will increase as shown in [56]. The third is to adjust the structural design of buildings in a way that the buildings require smaller amount of materials but have sufficiently structural performance. This technique could be achieved by various methods such as reducing thickness of structural elements, rearranging the structural configurations, and choosing systems that requires minimal carbon-intensive materials and construction equipment [58-61]. By applying such methods, designers are allowed to cutdown materials required in buildings which subsequentially reduces the needs for raw-materials extraction, transportation, construction activities, construction equipment, and wastes generated throughout the lifecycle of buildings. This third technique, thus, results in a reduction of the EEs correspondingly.

Table 5 Improvement of materials' structural performances

Reference	Country	Type	Area (m^2)	Case Studies	System boundary	EEs	Difference in EEs
[53]	Spain	Housing project	500	CIP RC slab with insulation slab	Cradle-to-Grave	230	-
				CIP RC slab		223	-3%
				Prestress hollow RC slab		136	-41%
				Precast hollow RC slab		179	-22%
[54]	South Korea	Commercial	13,487	RC slab with beams	Cradle -to-Site	242	-
				RC flat slab		234	-3%
				RC voided slab		218	-10%
[55]	South Korea	Commercial	N.S.	RC slab with beams	Cradle-to-Site	196	-
				RC voided slab		171	-13%
[56]	Brazil	Office	3,600	Slab built from RC25	Cradle-to-Grave	100%	-
				Slab built from RC50		91%	-9%
				Slab built from RC75		98%	-2%
[57]	Germany	Bridge	45	Reinforce Concrete	Cradle-to-Gate	150%	-
				Steel Bridge		150%	0%
				Carbon Fiber Reinforced Polymer Concrete		100%	-33%
[58]	Hong Kong	Apartment	39,501	Hybrid CIP and Precast system	Cradle -to-Site	561	-
				Increase Precast rate by 35%		553	-1.4%
				Reduce thickness of walls		551	-2%
[59]	Not Specify	Not Specify	3,600	Outrigger Steel	Cradle -to-Site	30	-
				Diagrid Steel		23	-23
				Braced Tube Steel		28	-7
				Braced Tube Concrete		15	-50
				Tube-in-Tube Concrete		18	-40
[60]	U.K.	Residential	4,356	Slab thickness of 0.275m, 12 Columns with the size of 0.2mx0.8m Column Grid-X (m): 7.33, 7.33, 7.33 Column Grid-y (m): 7.33, 7.33, 7.33	Cradle -to-Site	210	-
				Slab thickness of 0.25m, 14 Columns with the size of 1.2m x0.35m Column Grid-X (m): 5,6,5,6 Column Grid-y (m): 7,7,8		183	-12%
[61]	Hong Kong	Residential	310,000	CIP system	Cradle -to-Site	92.7*	-
				Increase Precast rate by 35%		74.9*	-19%

Note. This table extracts only the embodied emissions. The abbreviations are Cradle: raw-material extraction, Gate: manufacturing process, Site: construction activities, Grave: disposal, EE: Embodied Emissions (kgCO_2 eq/m^2), CIP: Cast-In-Place, RC: Reinforce Concrete. The negative sign represents the reduction in EEs relative to the baseline case. * represents that the unit is endpoint.

3. Adaptation of design-for-disassembly (DfD) and sustainable waste management

Table 6 portrays that adaptation of DfD principle in buildings, suggested by [11, 12, 62], can reduce the EEs of buildings. This reduction occurs considering that the principle allows parts of buildings to be disassembled and reused at the building's EOL [63-67]. Reflecting on the results shown in [65], one can observe that reusing the materials can offset the additional EEs associated with the DfD structure. Moreover, [66-68] show that reusing and recycling the construction wastes can improve the environmental performance of building compared to landfilling. This reflection agrees with [69] which suggests one to sustainably manage the wastes via reusing (applicable for steel and timber), recycling (applicable for concrete, steel, and timber), and energy recovery (applicable for timber). To summarize, the DfD design principle and the sustainable waste management can lessen the demands for virgin materials and for material productions, hence enhancing the circularity for the buildings whilst decreasing the EEs simultaneously.

Table 6 Adaptation of DfD principle, reusing, and recycling strategies

Reference	Country	Type	Area (m^2)	Cast Studies	System Boundary	EEs	Difference in EEs
[63]	Denmark	Residential	150	Conventional Built House	Cradle-to-Grave	800	-
				DfD Built House		667	-17%
[64]	Denmark	Office	37,839	Reinforce Concrete	Cradle-to-Grave	226	-
				PC Concrete built with DfD (reused 1 time)		190	-16%
				PC Concrete built with DfD (reused 2 times)		180	-20%
[65]	USA	N.S.	N.S.	Steel-Concrete Composite Floor	Cradle-to-Grave	125	-
				PC DfD Floor with Mechanical Connectors (reuse 0)		140	+12%
				PC DfD Floor with Mechanical Connectors (reuse 1)		75	-40%
				PC DfD Floor with Mechanical Connectors (reuse 2)		50	-60%
				PC DfD Floor with Mechanical Connectors (reuse 3)		40	-68%
[66]	Brazil	Pavilion	4133	DfD steel: 1st life, 100% recycle, Disposal	Cradle-to-Grave	1,621	-
				DfD steel: 1st life, 64%recycle & 36%reuse, 2nd life, Disposal		1,354	-16%
				DfD steel: 1st life, 100%reuse, 2nd life, Disposal		1,016	-37%
[67]	Italy	Residential	130	CIP Concrete (99% recycle, 1% landfill)	Cradle-to-Grave	1,250	-
				Steel Modular (87.5% recycle, 12.5% landfill)		1,213	-3%
				CIP Concrete (99% recycle, 0.8% reuse, 0.2% landfill)		853	-32%
				Steel Modular (79.3% recycle, 16.3% reuse, 2.5% landfill)		512	-59%
[68]	Thailand	Industrial	14,938	Landfill all materials	Cradle-to-Grave	616	-
				Recycle all materials that are eligible		436	29%

Note. This table only extracts the embodied emissions. The abbreviation is EEs: Embodied Emissions (kg CO2/ m^2), Cradle: raw-material extraction, Grave: Disposal, DfD: Design-for-Disassembly, PC: Precast Concrete, CIP: Cast-In-Place. The negative and positive signs represent the reduction and increase in EEs relative to the baseline case respectively.

4. Use of passive and active measures

Table 7 shows that the use of passive and active measures, suggested by [11-14], contributes to mitigation in GHGs, despite the additional EEs associated with employment of retrofits. The table also depicts that the use of active measures results in greater mitigation of the OEs and TLEs compared to the practice of passive measures [68, 70-79]. The main reason behind this is: the active principle involves the use of advanced technologies (such as photovoltaic PV solar-cell panels, LEDs, improving HVAC, etc.) to produce and distribute the energy required for the occupants' thermal and lighting comforts; whereas, the passive principle aims to improve and maximize the properties of building envelopes (such as the use of insulation, the reduction in Window-to-Wall Ratio, etc.) as a means to achieve thermal and lighting comforts for occupants.

Evaluation of the strategies' adequacies on reaching net-zero GHGs emission goal

The previous section indicates that the EEs can be reduced by substituting low-carbon materials for carbon-intensive materials, by improving structural performance of the materials, and by increasing the circularity of buildings. Nonetheless, the EEs cannot be cut to an absolute zero due to the limitations presented in Table 8. Apart from the EEs, the previous section also shows that the use of passive and active measures can result in reduction of OEs for the buildings. Furthermore, the use of PV solar-cell panels is a unique design strategy because it is capable of reducing and compensating the OEs and EEs, whereas the other strategies are only capable of reducing either OEs or EEs. In depth details, [68, 70, 76] demonstrate that the PV solar-cell panels can diminish the demands for the national grid electricity and can provide electricity surplus which can be fed to the national grid. This in turn results in the buildings to gain negative OEs that can compensate for the EEs. As a result of the compensation, the buildings then achieve the net-zero GHGs emission ultimately. The described performance of PV solar-cell is illustrated in Figure 2. Through the figure, one can find that the use of PV solar-cells not only reduces the OEs to zero [70], but also provides negative OEs that can compensate for the EEs; thus, leading to the TLEs of buildings to achieve net-zero and net-negative emissions [68,76]. Due to the described performance, one can thus safely accept, based on the life cycle principle, that the use of PV solar-cell panels is the key for buildings to achieve the net-zero emission, whereas the use of the other strategies helps to accelerate the performance of PV and shortens the time for buildings to achieve net-zero GHGs emissions by cutting-down the EEs and OEs. From this finding and based on the life cycle principle, the study concludes that: in theory, the presented design strategies demonstrate great potential on leading Thailand's building sector towards the net-zero GHG emissions goal given the condition that all buildings in Thailand are equipped with renewable energy-based on-site electricity self-generator (such as PV solar panels) on a large scale. However, this conclusion is theoretical, idealized, and solely based on the principle of life cycle. In reality, there is a wide range of practical limitations that prevents PV solar-cell panels from being used extensively such as financial viability of the building owners [18], locations of the buildings, available spaces for the PV installation, the electricity fed-back limit [17], etc. Thus, these limitations prevent Thailand's building sector to attain the net-zero emissions through the use of the design strategies. This finding thus calls for action from the supply side (such as a decarbonization of grid, an implementation of financial incentive policies, etc.) [9, 17, 18], and the demand side which are to: improve and deploy energy-saving materials and devices together with other design strategies [18]. In response to the need of the latter, this study highlights five possible research improvements and one management strategy as means to add practical values for the design strategies and to promote Thailand's building sector towards the net-zero emissions goal.

Table 7 Embodied and operational emissions via the use of passive and active measures

Reference	Country / Type/ Area	SB / use-phase	Scenario	EEs	OEs	TLEs	Difference in TLEs
				(kgCO$_2$ eq/m^2)			
[68]	Thailand, Industrial 14,938 m^2	Cradle-to-Grave 20 years	S1: Baseline (lighting, natural airflow)	616	264	880	-
			S2: improved PV	871	-1171	-300	-134%
[70]	Norway Office 2,940 m^2	Cradle-to-Grave 60 years	S1: Baseline	311	1021	1,332	-
			S2: slightly improved Enve , baseline HVAC	362	323	685	-49%
			S3: slightly improved Enve , improved HVAC	350	283	633	-52%
			S4: largely improved Enve , baseline HVAC	373.8	327	700	-47%
			S5: largely improved Enve , improved HVAC	358	277	635	-52%
			S6: largely improved Enve , improved HVAC, PV	416.7	0	416.7	-69%
[71]	London Residential 123.2 m^2	Cradle-to-Use 60 years	S1: Baseline	0	4,623	4,623	-
			S2: slightly improved Enve , HVAC , DHW	15	2,541	2,556	-45%
			S3: medium improved Enve , HVAC , DHW	79	1,513	1,592	-66%
			S4: deeply improved Enve, HVAC, DWH , PV	175	896	1,071	-77%
[72]	USA University 130,993 m^2	Cradle-to-Grave 100 years	S1: Baseline	496	305	802	-83%
			S2: improved HVAC	504	229	733	-84%
			S3: improved HVAC, lighting	504	191	695	-85%
			S4: improved HVAC, lighting, Enve	573	76	649	-86%
[73]	Portugal Residential 100 m^2	Cradle-to-Use 30 years	S1: Baseline , gas boiler for DHW	0	271,800	271,800	-
			S2: improved Enve , HVAC, solar collector for DHW	1,000	137,900	138,900	-49%
			S3: improved Enve , HVAC, VTC for DHW	1,200	42,600	43,800	-84%
			S4: improved Enve , HVAC, VTC for DHW, PV	3,500	12,910	16,410	-94%
[74]	Sweden Residential 2822 m^2	Cradle-to-Grave 50 years	S1: Baseline , baseline HVAC temp setting at 22.7	65	298	363	-
			S2: improved Enve , baseline HVAC	104	223	327	-10%
			S3: improved Enve , improved HVAC temp at 21	118	181	299	-18%
			S4: improved HVAC temp at 21	72	230	302	-17%
			S5: improved HVAC temp at 22.7	72	255	327	-10%
[75]	Turkey Residential 573 m^2	Cradle-to-Use 30 years	S1: Baseline	100%	100%	100%	-
			S2: improved Enve , PV	105%	70%	81%	-19%
[76]	Thailand Residential 141.4 m^2	Cradle-to-Grave 50 years	S1: Baseline	406	3,119	3,525	-
			S2: improve Enve , HVAC , DHW , PV 30 m^2	578	654	1,232	-65%
			S3: improve Enve , HVAC , DHW , PV 44 m^2	612	47	659	-82%
			S4: improve Enve , HVAC , DHW , PV 85 m^2	733	-1,763	-1,030	-129%

Note. [71,73] assumed that the model building is already existant; hence, the baseline EEs are zero, and the EEs in improved scenarios represent additional EEs associated with introduced retrofits. The abbreviation is SB: System Boundary, EEs: Embodied Emissions, OEs: Operational Emissions, TLEs: Total Life cycle Emissions, Cradle: raw-material extraction, Use: Operation, Grave: Disposal, Enve: Building Envelope, HVAC: Heating /Ventilation / Air-Condition, VTC: Vacuum Tube Collector, DHW: Domestic Hot Water, PV: photovoltaic (solar-cell) panels. The negative sign represents the reduction in TLEs relative to the baseline case.

Table 8 Limitations of design strategies used to cut the EEs

Embodied Strategies	Description
The Use of Timber	There are three sources of EEs associated with timber. The first is transportation. The second is timber's production process. The third is the carbon associated within the material itself, as it could be regarded as negative-, neutral-, or low- carbon materials. However, [35] reports that the emissions associated with the timber can vary depending on assumptions on biogenic carbon (the carbon stored with the timbers [32]) and on forest management; for example, under a condition where the biogenic carbon is assumed to be large and forest is assumed to be unsustainably managed, using timber will contribute a large number of GHG emissions.
The use of composite and innovative materials	There are three sources of EEs associated with the alternative materials. The first is transportation [61]. The second is the materials' production. The third is the recycle processes [69].
SCMs usage	There are two sources of EEs associated with SCMs. The first is transportation [50-52]. The second is allowable portion of cement used in concrete mix, as [15] states that fly ash, natural pozzolans, ground granulated blast-furnace slag, and silica fume are prohibited to be used over 35%, 20%, 70%, and 15% respectively.
The improvement of materials	There are still GHG emissions from materials' production processes, despite its reduction of material usage as shown in Table 5.
Design-for-Disassembly	There are three sources of EEs associated with these structures. The first is transportation. The second is materials' production process [61]. The third is materials' recycle processes [69].
Steel and Timber's Recycle	There are still GHG emissions present during the recycling process of steel and timber [69]. This is because steel and timber's recycling processes still involve the use of fossil fuels, despite the removal of demands for virgin materials. Furthermore, the recycle rates of steel and timber in Thailand are 55% and less than 50% respectively [16]. These portions are considered as relatively low [16].

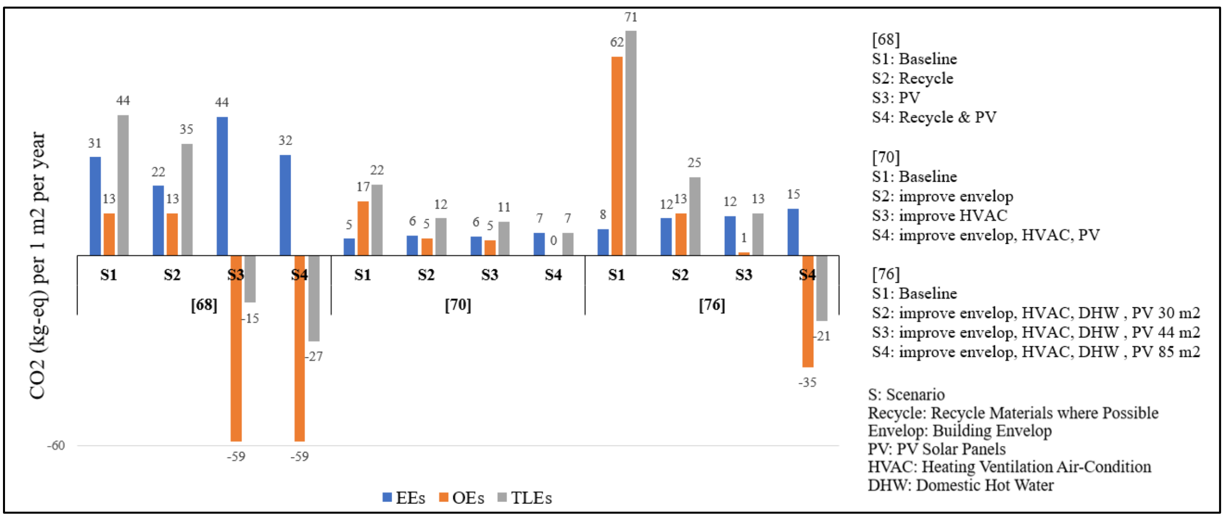

Figure 2 Life cycle emissions of buildings with and without PV solar-cell panels

The first is to develop a novel method for designing buildings with lightweight structural elements such as hollow concrete beams and columns, beams with web opening, etc. Doing so will reduce the demands for raw materials while providing the same structural services whilst reducing the EEs. The second is to develop a novel method for designing buildings with the sole use of SCMs. This suggestion is not only drawn based on its improvable structural property, but also based on its environmental performances which contribute to lower GHG emissions compared to ordinary cement [48-50]. The third is to study the structural properties of various industrial wastes and bio-based materials, or their by-products (such as used glasses, used plastics, construction wastes, agricultural by-products, etc.) and develop them as (or as part of) structural load-bearing elements. Doing so will reduce the demand for carbon-intensive materials, transform the building from being linear to circular, and lessen the EEs of buildings subsequentially. The fourth is to study the thermal properties of various industrial wastes and bio-based materials, or their by-products, to develop them as (or as part of) building envelops such as insulations, wall&roof materials, etc. Doing so will lessen the demand for chemical-based insulations whilst maximizing the occupants' thermal comfort. Thus, the building is subjected to unnoticeable EEs and is able to reduce the OEs in the long-run. The fifth is to develop combination of design strategies that can provide the maximum EEs and OEs mitigation. For example, the efficiency of PV solar-cell panels could be maximized by placing them where the solar radian is at maximum [74], using them together with building insulation [76], and with other commercial gadgets (such as thin film, batteries), and recycling them when possible. Doing so will keep the total emissions of buildings at its minimum and provide a greater chance for the building to achieve net-zero GHG emissions. Besides the research improvements, designers can apply management strategy during the design stage [80]. This strategy consists of four main steps: (1) set environmental targets for the buildings, (2) design the building applying the presented and suggested design strategies, (3) assess the environmental performance of the buildings via LCA and other tools preferably Circularity Indicator (a decision-making tool for designers that assess the circularity of a product) [62], and (4) adjust the building till it satisfies the targets.

Conclusions

The embodied and operational phases have equal chances of being the hotspot for buildings as the emissions in each phase depends on the choice of material, the choice of energy-saving retrofits, and the electricity grid profile. In this study, five design strategies were reviewed: to substitute low-carbon materials for carbon-intensive materials, to improve structural performance of carbon-intensive materials, to increase the circularity of buildings; as well as to use passive and active measures. It was found that, in theory, the design strategies demonstrate great potential on leading Thailand's building sector to net-zero GHG emissions goal given an ideal condition that all buildings use renewable energy-based on-site electricity generator such as PV solar-cell panels on a large scale. Nonetheless, there are various limitations preventing this ideal situation to arise. Thus, this study highlights five possible research improvements and a hands-on management strategy to push forward Thailand's building sector toward the net-zero emissions goal ultimately.

References

[1] Energy Policy and Planning Office. 2021. Energy Statistic of Thailand 2021. Thailand's Ministry of Energy.

[2] Iqbal, M. I., Himmler, R., & Gheewala, S. H. 2017. Potential life cycle energy savings through a transition from typical to energy plus households: A case study from Thailand. Energy and Buildings, 134: 295-305.

[3] EPPO, Thailand's Energy Policy and Planning Office. 2015. Energy Efficiency Plan; EEP 2015. Thailand's Ministry of Energy.

[4] DEDE, Department of Alternative Energy Development and Efficiency. 2018. Energy Efficiency Plan 2018 - 2037. Thailand's Ministry of Energy.

[5] Ministry of Natural Resources and Environment. 2020. Thailand Third Biennial Update Report. United Nation Climate Change.

[6] UNGCNT, United Nation Global Compact Network Thailand. 2021. Thailand's Long-term Greenhouse Gas Emission Development Strategy, presented at COP26, Thailand Pavilion.

[7] EN 15978:2011. 2011. Sustainability of Construction Works. Assessment of Environmental Performance of Buildings-Calculation method.

[8] ISO 21931-1:2010. 2010. Sustainability in Building Construction—Framework for Methods of Assessment of the Environmental Performance of Construction Works - Part 1: Buildings, International Organization for Standardization, Geneva.

[9] Thailand's Office of Natural Resources and Environmental Policy and Planning. 2019. Master Key Plan for Climate Change between 2015 and 2050.

[10] Ministry of Higher Education, Science, Research and Innovation. 2020.

Strategies to drive forward Thailand by Bio-Circular-Green Economic Model (BCG) 2021 - 2027.
[11] U.S. Green Building Council. 2021. LEED v4.1 Building Design and Construction. [Accessed March, 2022]. Available from: https://www.usgbc.org/leed/v41#bdc
[12] European Commission. 2020. Circular economy principle for building design. [Accessed March, 2022]. Available from: https://ec.europa.eu/growth/content/designing-buildings-context-circular-economy_en
[13] Thai Green Building Institute. 2017. TREES for new construction and major renovation. [Accessed March, 2022]. Available from: https://www.tgbi.or.th/uploads/trees/2017_03_TREES-NC-Eng.pdf
[14] DEDE, Department of Alternative Energy Development and Efficiency. 2017. Building Energy Code by Department of Alternative Energy Development and Efficiency.
[15] American Concrete Institute. 2002. Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91). [Accessed March, 2022]. Available from: https://kashanu.ac.ir/Files/aci%20211_1_91.pdf
[16] Piyapanphong, S. 2018. Country Report (Kingdom of Thailand). Eighth Regional 3R Forum in Asia and the Pacific "Achieving Clean Water, Clean Land and Clean Air through 3R and Resource Efficiency- A 21st Century Vision for Asia-pacific Communities," India. [Accessed March, 2022]. Available from: uncrd.or.jp/content/documents/5857Thailand_Country%20Report.pdf
[17] EPPO, Thailand's Energy Policy and Planning Office. 2018. Power Development Plan (PDP).
[18] Rajbhandari, S., & Limmeechokchai, B. 2020. Assessment of greenhouse gas mitigation pathways for Thailand towards achievement of the 2°C and 1.5°C Paris Agreement targets. Climate Policy, 21(4): 492-513.
[19] Hasik, V., Ororbia, M., Warn, G. P., & Bilec, M. M. 2019. Whole building life cycle environmental impacts and costs: A sensitivity study of design and service decisions. Building and Environment, 163: 106316.
[20] Ghose, A., McLaren, S. J., Dowdell, D., & Phipps, R. 2017. Environmental assessment of deep energy refurbishment for energy efficiency-case study of an office building in New Zealand. Building and Environment, 117: 274-287.
[21] Norouzi, M., Colclough, S., Jiménez, L., Gavaldà, J., & Boer, D. 2022. Low-energy buildings in combination with grid decarbonization, life cycle assessment of passive house buildings in Northern Ireland. Energy and Buildings, 261: 111936.
[22] Liu, S., Schulz, U. W., Sapar, M. H., & Qian, S. 2016. Evaluation of the environmental performance of the chilled ceiling system using life cycle assessment (LCA): A case study in Singapore. Building and Environment, 102: 207-216.
[23] González-Prieto, D., Fernández-Nava, Y., Marañón, E., & Prieto, M. M. 2021. Environmental life cycle assessment based on the retrofitting of a twentieth-century heritage building in Spain, with electricity decarbonization scenarios. Building Research & Information, 49(8): 859-877.
[24] Raugei, M., Keena, N., Novelli, N., Aly Etman, M., & Dyson, A. 2021. Life cycle assessment of an ecological living module equipped with conventional rooftop or integrated concentrating photovoltaics. Journal of Industrial Ecology, 25(5): 1207-1221.
[25] Burek, J., & Nutter, D. 2018. Life cycle assessment of grocery, perishable, and general merchandise multi-facility distribution center networks. Energy and Buildings, 174: 388-401.
[26] Nematchoua, M. K., Asadi, S., Obonyo, E., & Reiter, S. 2021. Environmental analysis of health damages coming from a residential neighborhood built in 150 countries. Journal of Housing and the Built Environment.
[27] Chastas, P., Theodosiou, T., Kontoleon, K. J., & Bikas, D. 2018. Normalising and assessing carbon emissions in the building sector: A review on the embodied CO2 emissions of residential buildings. Building and Environment, 130: 212-226.

[28] Kiss, B., & Szalay, Z. 2022. Sensitivity of buildings' carbon footprint to electricity decarbonization: a life cycle–based multi-objective optimization approach. The International Journal of Life Cycle Assessment.

[29] de Oliveira Fernandes, M. A., Keijzer, E., van Leeuwen, S., Kuindersma, P., Melo, L., Hinkema, M., & Gonçalves Gutierrez, K. 2021. Material-versus energy-related impacts: Analysing environmental trade-offs in building retrofit scenarios in the Netherlands. Energy and Buildings, 231: 110650.

[30] Lausselet, C., Ellingsen, L. A., Strømman, A. H., & Brattebø, H. 2019. A life-cycle assessment model for zero emission neighborhoods. Journal of Industrial Ecology, 24(3): 500-516.

[31] Ramírez-Villegas, R., Eriksson, O., & Olofsson, T. 2019. Environmental Payback of Renovation Strategies in a Northern Climate—the Impact of Nuclear Power and Fossil Fuels in the Electricity Supply. Energies, 13(1): 80.

[32] Zeitz, A., Griffin, C., & Dusicka, P. 2019. Comparing the embodied carbon and energy of a mass timber structure system to typical steel and concrete alternatives for parking garages. Energy and Buildings, 199: 126-133.

[33] Moncaster, A., Pomponi, F., Symons, K., & Guthrie, P. 2018. Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system. Energy and Buildings, 173: 389-398.

[34] Lu, H. R., el Hanandeh, A., & Gilbert, B. P. 2017. A comparative life cycle study of alternative materials for Australian multi-storey apartment building frame constructions: Environmental and economic perspective. Journal of Cleaner Production, 166: 458-473.

[35] Himes, A., & Busby, G. 2020. Wood buildings as a climate solution. Developments in the Built Environment, 4: 100030.

[36] Hart, J., D'Amico, B., & Pomponi, F. 2021. Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. Journal of Industrial Ecology, 25(2): 403-418.

[37] Tavares, V., Lacerda, N., & Freire, F. 2019. Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The "Moby" case study. Journal of Cleaner Production, 212: 1044-1053.

[38] Pierobon, F., Huang, M., Simonen, K., & Ganguly, I. 2019. Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest. Journal of Building Engineering, 26: 100862.

[39] Escamilla, E. Z., Habert, G., Daza, J. C., Archilla, H., Fernández, J. C., & Trujillo, D. 2018. Industrial or Traditional Bamboo Construction? Comparative Life Cycle Assessment (LCA) of Bamboo-Based Buildings. Sustainability, 10(9): 3096.

[40] Yang, X., Zhang, S., & Wang, K. 2021. Quantitative study of life cycle carbon emissions from 7 timber buildings in China. The International Journal of Life Cycle Assessment, 26(9): 1721-1734.

[41] Bukoski, J. J., Chaiwiwatworakul, P., & Gheewala, S. H. 2016. The Life Cycle Assessment of an Energy-Positive Peri-Urban Residence in a Tropical Regime. Journal of Industrial Ecology, 21(5): 1115-1127.

[42] Hahnel, G., Whyte, A., & Biswas, W. K. 2021. A comparative life cycle assessment of structural flooring systems in Western Australia. Journal of Building Engineering, 35: 102109.

[43] Zhang, X., Xu, J., Zhang, X., & Li, Y. 2021. Life cycle carbon emission reduction potential of a new steel-bamboo composite frame structure for residential houses. Journal of Building Engineering, 39: 102295.

[44] Balasbaneh, A. T., & bin Marsono, A. K. 2017. Strategies for reducing greenhouse gas emissions from residential sector by proposing new building structures in hot and humid climatic conditions. Building and Environment, 124: 357-368.

[45] Zhang, X., & Wang, F. 2015. Life-cycle assessment and control measures for carbon emissions of typical buildings in China. Building and Environment, 86: 89-97.

[46] Samani, P., Mendes, A., Leal, V., Guedes, J. M., & Correia, N. 2015. A sustainability assessment of advanced materials for novel housing solutions. Building and Environment, 92: 182-191.

[47] Dong, Y., Ng, S. T., & Liu, P. 2021. A comprehensive analysis towards benchmarking of life cycle assessment of buildings based on systematic review. Building and Environment, 204: 108162.

[48] Zhao, J., Tong, L., Li, B., Chen, T., Wang, C., Yang, G., & Zheng, Y. 2021. Eco-friendly geopolymer materials: A review of performance improvement, potential application and sustainability assessment. Journal of Cleaner Production, 307: 127085.

[49] Xiao, R., Ma, Y., Jiang, X., Zhang, M., Zhang, Y., Wang, Y., et. al. 2020. Strength, microstructure, efflorescence behavior and environmental impacts of waste glass geopolymers cured at ambient temperature. Journal of Cleaner Production, 252; 119610.

[50] Dollente, I. J. R., Tan, R. R., Promentilla, M. A. B. 2021. Life Cycle Assessment of Precast Geopolymer Products. Chemical Engineering Transactions, 88: 799-804.

[51] Lovecchio, N., Shaikh, F., Rosano, M., Ceravolo, R., & Biswas, W. 2020. Environmental assessment of supplementary cementitious materials and engineered nanomaterials concrete. AIMS Environmental Science, 7(1): 13-30.

[52] Nath, P., Sarker, P. K., & Biswas, W. K. 2018. Effect of fly ash on the service life, carbon footprint and embodied energy of high strength concrete in the marine environment. Energy and Buildings, 158: 1694-1702.

[53] Valencia-Barba, Y. E., Gómez-Soberón, J. M., Gómez-Soberón, M. C., & López-Gayarre, F. 2020. An Epitome of Building Floor Systems by Means of LCA Criteria. Sustainability, 12(13): 5442.

[54] Paik, I., & Na, S. 2019. Evaluation of Carbon Dioxide Emissions amongst Alternative Slab Systems during the Construction Phase in a Building Project. Applied Sciences, 9(20): 4333.

[55] Na, & Paik. 2019. Reducing Greenhouse Gas Emissions and Costs with the Alternative Structural System for Slab: A Comparative Analysis of South Korea Cases. Sustainability, 11(19): 5238.

[56] Garcez, M. R., Rohden, A. B., & Graupner De Godoy, L. G. 2018. The role of concrete compressive strength on the service life and life cycle of a RC structure: Case study. Journal of Cleaner Production, 172: 27-38.

[57] Stoiber, N., Hammerl, M., & Kromoser, B. 2021. Cradle-to-gate life cycle assessment of CFRP reinforcement for concrete structures: Calculation basis and exemplary application. Journal of Cleaner Production, 280: 124300.

[58] Teng, Y., & Pan, W. 2019. Systematic embodied carbon assessment and reduction of prefabricated high-rise public residential buildings in Hong Kong. Journal of Cleaner Production, 238: 117791.

[59] Mavrokapnidis, D., Mitropoulou, C. C., & Lagaros, N. D. 2019. Environmental assessment of cost optimized structural systems in tall buildings. Journal of Building Engineering, 24: 100730.

[60] Eleftheriadis, S., Duffour, P., & Mumovic, D. 2018. BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives. Energy and Buildings, 173: 587-600.

[61] Dong, Y. H., & Ng, S. T. 2015. A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong. Building and Environment, 89: 183-191.

[62] Ellen MacArthur Foundation. 2015. Circularity Indicators An approach to measuring circularity. [Accessed March, 2022]. Available from: https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o

[63] Rasmussen, F. N., Birkved, M., & Birgisdóttir, H. 2020. Low- carbon design strategies for new residential buildings – lessons from architectural practice. Architectural Engineering and Design Management, 16(5): 374-390.

[64] Eberhardt, L. C. M., Birgisdóttir, H., & Birkved, M. 2018. Life cycle assessment of a Danish office building designed

for disassembly. Building Research & Information, 47(6): 666-680.

[65] Eckelman, M. J., Brown, C., Troup, L. N., Wang, L., Webster, M. D., & Hajjar, J. F. 2018. Life cycle energy and environmental benefits of novel design-for-deconstruction structural systems in steel buildings. Building and Environment, 143: 421-430.

[66] Arrigoni, A., Zucchinelli, M., Collatina, D., & Dotelli, G. 2018. Life cycle environmental benefits of a forward-thinking design phase for buildings: the case study of a temporary pavilion built for an international exhibition. Journal of Cleaner Production, 187: 974-983.

[67] Vitale, P., Spagnuolo, A., Lubritto, C., & Arena, U. 2018. Environmental performances of residential buildings with a structure in cold formed steel or reinforced concrete. Journal of Cleaner Production, 189: 839-852.

[68] Tulevech, S. M., Hage, D. J., Jorgensen, S. K., Guensler, C. L., Himmler, R., & Gheewala, S. H. 2018. Life cycle assessment: a multi-scenario case study of a low-energy industrial building in Thailand. Energy and Buildings, 168: 191-200.

[69] U.S. Environmental Protection Agency. 2020. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM).

[70] Rabani, M., Madessa, H. B., Ljungström, M., Aamodt, L., Løvvold, S., & Nord, N. 2021. Life cycle analysis of GHG emissions from the building retrofitting: The case of a Norwegian office building. Building and Environment, 204: 108159.

[71] Vavanou, A., Schwartz, Y., & Mumovic, D. 2021. The life cycle impact of refurbishment packages on residential buildings with different initial thermal conditions. Journal of Housing and the Built Environment.

[72] Hu, M. 2019. Life-cycle environmental assessment of energy-retrofit strategies on a campus scale. Building Research & Information, 48(6): 659-680.

[73] Mateus, R., Silva, S. M., & de Almeida, M. G. 2019. Environmental and cost life cycle analysis of the impact of using solar systems in energy renovation of Southern European single-family buildings. Renewable Energy, 137: 82-92.

[74] Ramírez-Villegas, R., Eriksson, O., & Olofsson, T. 2019. Life Cycle Assessment of Building Renovation Measures–Trade-off between Building Materials and Energy. Energies, 12(3): 344.

[75] Mangan, S. D., & Oral, G. K. 2016. Assessment of residential building performances for the different climate zones of Turkey in terms of life cycle energy and cost efficiency. Energy and Buildings, 110: 362-376.

[76] Iqbal, M. I., Himmler, R., & Gheewala, S. H. 2018. Environmental impacts reduction potential through a PV based transition from typical to energy plus houses in Thailand: A life cycle perspective. Sustainable Cities and Society, 37: 307-322.

[77] Cubi, E., Zibin, N. F., Thompson, S. J., & Bergerson, J. 2015. Sustainability of Rooftop Technologies in Cold Climates: Comparative Life Cycle Assessment of White Roofs, Green Roofs, and Photovoltaic Panels. Journal of Industrial Ecology, 20(2): 249-262.

[78] Lawania, K. K., & Biswas, W. K. 2016. Cost-effective GHG mitigation strategies for Western Australia's housing sector: a life cycle management approach. Clean Technologies and Environmental Policy, 18(8): 2419-2428.

[79] Pombo, O., Allacker, K., Rivela, B., & Neila, J. 2016. Sustainability assessment of energy saving measures: A multi-criteria approach for residential buildings retrofitting—A case study of the Spanish housing stock. Energy and Buildings, 116: 384-394.

[80] Saadé, M., Erradhouani, B., Pawlak, S., Appendino, F., Peuportier, B., & Roux, C. 2022. Combining circular and LCA indicators for the early design of urban projects. The International Journal of Life Cycle Assessment, 27(1): 1-19.