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Life cycle assessment: a multi-scenario case study of a low-energy industrial building in Thailand

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ABSTRACT

A life cycle assessment (LCA) is conducted on a low-energy industrial building under construction in Thailand. The building has a gross floor area of 14,938 m^2 and a 20-year lifetime. As energy-saving initiatives need to expand beyond the established domain of low-energy residential and commercial buildings, this study demonstrates the successful application of active and passive energy-saving measures to a large, energy-efficient industrial building—the first to be surveyed by an LCA. LED lighting, minimal air conditioning, and passive ventilation architecture reduce operation phase burdens. As a result, the manufacturing phase yields largest impacts in primary energy demand (71%), global warming potential (60%), and four other environmental impact categories. This is largely attributable to steel and concrete production and a higher embodied energy quantity per material. Additionally, four scenarios—a base case, recycling case, photovoltaic system scenario, and combined recycling/photovoltaic scenario—are simulated to evaluate strategies for further energy reduction. Analysis indicates that significant life cycle energy savings can be achieved through recycling (29%) and a rooftop PV system (64%). The combination of both enhancements compensates for all manufactured material embodied energies and results in a building with zero or sub-zero total life cycle energy demand. Buildings that are already low-energy can further reduce environmental impacts through inclusion of the aforementioned approaches in design and implementation.

1. Introduction

1.1. Background

Globally and nationally, building construction consumes significant amounts of energy and natural resources while contributing air emissions, solid waste, and other environmental burdens over the course of its life cycle. Invariably, buildings become a key focus for environmental betterment, as the sector accounts for up to 40% of energy consumption, 30% of raw material use, 25% of solid waste, and 33% of greenhouse gas (GHG) emissions worldwide [1,2].

In Thailand, industry comprised the largest share (37%) of energy consumption in 2013. At that time, 80% of electricity and 76% of total energy were derived from nonrenewable sources [3]. Despite state-sponsored targets directed at implementing stricter energy regulations in building codes, improving grid infrastructure, encouraging renewable generation, and cutting energy intensity 30% by 2036, the national energy generation requirement is expected to increase 58% from 2015 to 2035 [4]. Consumption from the industrial sector is expected to rise proportionately [4]. Manufacturing and industry today account for more than 42% of the Thai economy and, consequently, maintain a massive energy footprint [5].

Worldwide, there is a growing need for studies on buildings as well as a growing need for applicable case studies complete with techniques for improvement [1,6]. There has emerged a growing body of literature for LCA concerning optimization of life-cycle energy use; however, many case studies focus on developed

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countries [7–9], cool climates [10,11] and residential/commercial buildings [12–14]. The importance of the building's location in a hot climate is twofold: 1) its design will differ from that of buildings in cooler climates in order to accommodate for heat, and 2) it requires a higher cooling demand.

Additionally, while literature does exist concerning low-energy buildings [15–18], none focuses on industrial buildings. This study addresses multiple literature gaps and helps to provide a new perspective on established research by simulating a low-energy industrial building in an emerging nation with a warm climate.

1.2. Objectives

This study's primary purpose is to provide industrial managers, architects, energy consultants, and researchers in warm, emerging nations a feasible and effective path for implementation of additional sustainable measures. As the first German Sustainable Building Council (DGNB) certified factory (and only the third DGNB-certified building) in Thailand, it is an innovative example for companies that seek to lower energy expenses, market triple-bottom-line efforts, and pioneer environmental stewardship.

A set of core objectives for this LCA follows:

1. Simulate primary energy demand for each defined life cycle phase, with a focus on the dynamic relationship between embodied energy and operation energy.
2. Closely compare results with those of commercial and institutional buildings from literature to place results in context and highlight advantages of factory low-energy use.
3. Model the environmental burdens of each life cycle phase. Impact categories included are global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP).
4. Compare results from the "base case" scenario (assumes landfilling of all materials) to three additional impact reduction scenarios:
   - Scenario 2 considers recycling of all eligible building components. Alleviated energy and environmental impacts from virgin production are accounted for in the system.
   - Scenario 3 assesses the building client's stated interest in adding a 1 MW (7142 m2) rooftop PV system to the completed factory; embodied energy of the PV system and avoided emissions from non-renewable electricity production for the Thai grid are carefully considered. PV system is landfilled along with all building components.
   - Scenario 4 combines installation of a 1 MW system with recycling of all building materials and PV system components.

2. Methodology

Primary energy demand and environmental burdens of the material manufacturing and end-of-life phases were quantified using LCA software SimaPro 8 [19]. The majority of inventory data was taken from ecoinvent Version 3 (Ecoinvent) LCI database [20]. Ecoinvent is a comprehensive database used in many building LCAs, including Iqbal et al. [15,16]. It contains global market and infrastructure values for numerous manufactured materials, end-of-life processes, and others. In addition to ecoinvent, the European Sustainable Construction Database (ESUCO) [21] and Chinese Sustainable Construction Database (CHISUCO) [22] maintained by DGNB were consulted for environmental impact values of mechanical systems not available in ecoinvent, namely chillers and cold-water circulation pumps. Operation phase consumption was simulated using DesignBuilder Version 5 software [23].

2.1. Case study description

The industrial building under study is a low-energy factory currently under construction in eastern Thailand. The building is designed to achieve German Sustainable Building Council (DGNB) silver level certification, a green building benchmark for low-impact, affordable, and socially responsible sustainable design and operation [24]. In accordance with DGNB standards for industrial buildings, the factory was analyzed under a 20-year lifespan [24]. Gross floor area is 14,938 m^2 and net internal area, or usable floor space, is 14,772 m^2. Details concerning building ownership and factory operations are not included as part of this study to respect company privacy.

DGNB certification was selected by the client for its holistic approach, global adaptability, and distinct profile for industrial buildings. In contrast to LEED and TREES (local standard in Thailand), DGNB considers life cycle costs and life cycle assessment. Adaptations for the Thai context include use of a regional database as well as modification of building design parameters to fit a hot climate, namely the exclusion of thermal insulation and double-glazed windows [24]. The building utilizes passive architecture unconventional in factories in order to cool a large warehouse-type space of 198,875 m^3. Energy reduction measures include steel and fiberglass louvers for facilitating natural airflow, transparent roofing panels for daylighting, 100% LED lighting, and <5% air conditioned floor area. Building on these base measures required for certification, LCA is utilized to identify strategies for further energy reduction and avoided environmental impacts across the full life cycle. While this LCA is conducted during the building's construction, aspects could have been better controlled with LCA and thermal analysis before construction.

Industrial buildings consume energy throughout their entire life cycle both directly (i.e. electricity use during the operation phase) and indirectly (i.e. material extraction and upstream processes) [25]. Material boundaries include structural, architectural, electrical, and mechanical components. The framework, foundation, exterior and interior walls, roofing, flooring, doors, windows, chillers, and cold-water pumps are considered. A descriptive overview of the building system and specifications is shown in Table 1.

2.1.1. System boundaries

A cradle-to-grave life cycle of the industrial building, shown in Fig. 1, is used as the LCA system boundary. Life cycle phases include material manufacturing, construction, operation, and end of life. Inputs consist of raw materials, grid electricity, and fuels (such as diesel, oil, and hard coal), and outputs cover emissions to air, emissions to water, and solid waste. Raw material extraction and transportation distances leading up to the construction site are contained within the material manufacturing phase. Maintenance requirements for chillers, cold-water pumps, and paints are also grouped with material manufacturing. No other scheduled replacements are necessary given the relatively short building lifetime of 20 years [26]. This study focuses exclusively on the factory as a building system so that building performance may be evaluated independently from the energy intensity of any internal factory machinery. Given a wide potential in variation for machine energy demand, excluding factory machinery from the building impacts enables comparison between industrial buildings.

2.1.2. Electricity grid mix

For life cycle phases that require an input of electricity, the Thailand 2015 electricity mix is used. This mix is composed predominantly of natural gas (64%), bituminous coal (10%), and lignite (10%) with smaller sources of renewables (6.6%), hydroelectric power (6%), and biomass (4.4%) [27]. Electricity mix is assumed to

Table 1
Building system specifications.

Category	Specifications
Operation time	24 h, 7 days
Gross floor area	14,938 m^2
Floor plan	Ground floor: large, non-AC production area, AC offices, equipment room, printing, chemical storage room. 2nd floor: AC office and meeting areas joined by steel walkway
Structure	Driven concrete piles. Steel beam and steel truss bracing framework
Foundation	Cast in-place concrete slab base
External walls/facade	0.5 mm galvanized steel sheet siding, no thermal insulation. Steel and translucent fiberglass ventilation louvers
Roofing	0.5 mm galvanized steel sheet roof, 50 mm glass wool insulation. Translucent fiberglass skylight sections (for daylighting), 10% of roof area
Flooring	Cast in-place concrete floor with hardener, thickness 30 cm. Granite and ceramic tile finish in AC areas
Interior walls	Double-layered concrete masonry wall, thickness 70 mm. Autoclaved aerated concrete bricks, thickness 70 mm. Normal type gypsum board, non-insulated
Ceiling	Normal type 9 mm gypsum board and aluminum grill strip finish (in AC areas)
Lighting	205 recess luminaire LED tubes, 115 waterproof LED, 106 Phillips titanium LED bulb
Windows/Doors	Aluminum frame
Interior volume	198,875 m^3

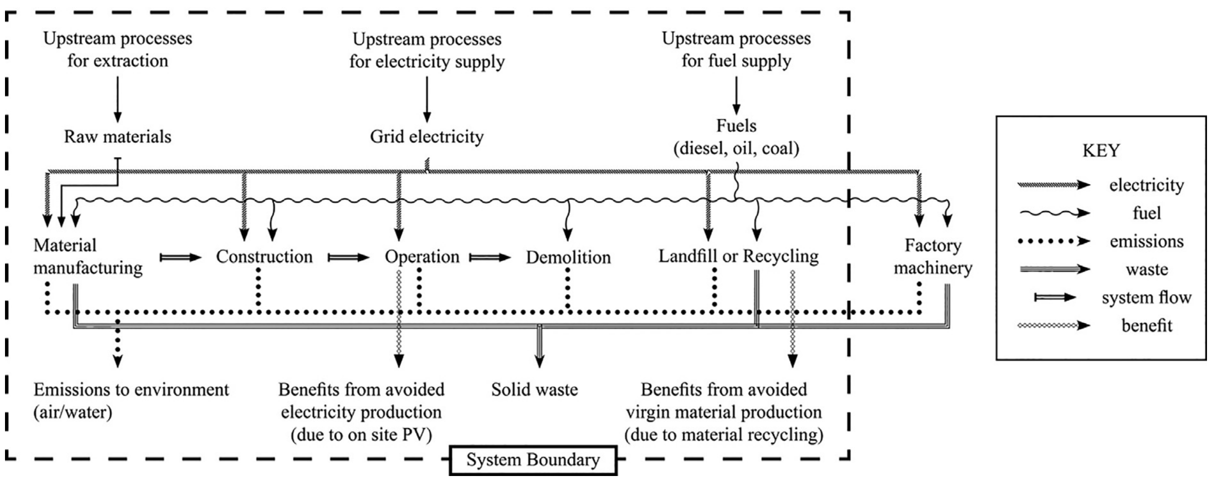

Fig. 1. System boundaries.

be static for the lifetime of the building as it is an extenuating circumstance beyond the building architects' and energy managers' ability to reduce environmental burdens.

2.2. Material manufacturing

Material manufacturing data was compiled from the bill of quantity provided by the contractor. Material specifications were sourced from architectural drawings and direct consultation with the energy consulting team working towards DGNB certification. Table 2 contains a full list of base-case material quantities, percent mass contribution, and embodied energy intensities. Embodied energy is the sum of cradle-to-gate sub-processes contained within the material manufacturing life cycle phase, from raw material extraction through transportation leading up to the construction site. Nearly all embodied energy and impact assessment values were taken from ecoinvent Version 3 (Ecoinvent) LCI database. Supplemental values were obtained from the European Sustainable Construction Database (ESUCO) and Chinese Sustainable Construction Database (CHISUCO) for multi-part mechanical systems, namely chillers and cold-water circulation pumps. Over 99.9% of material quantities by building mass are assessed.

Because buildings vary greatly in design, components, and function, the production processes of building materials are less standardized than most manufactured goods [6]; consequently, there exist variations in embodied energy methods and intensity values between studies [25]. Despite these variations, certain materials used in building construction such as steel, aluminum, copper, and PVC, embody high energy intensity because production requires numerous processes that span fully globalized industries, compounding energy requirements and transportation impacts [8].

2.3. Construction

The construction phase models electricity and diesel fuel consumption by on-site equipment. Construction is a significant consumer of non-renewable resources such as diesel fuel and is a large emitter of greenhouse gases [28,29]. Since records of equipment use and operation hours for construction are not available, a primary energy intensity for the construction phase was taken from a global industry average previously applied in other studies [30]. Scheuer et al. [31] approximated the primary energy requirement of construction to be 5% of total material embodied energy. Following Scheuer et al. [31], this 5% was allocated equally between electricity and diesel fuel to compute construction site fuel requirements. This approach is justified because the construction phase impact contribution is minimal, and construction processes do not vary greatly between countries [30].

2.4. Operation

In order to reduce the operation energy demand of a building, both passive and active measures should be implemented [32–35]. This factory utilizes several passive energy-saving measures, such as roof insulation, translucent skylights, and ventilation louvers, which effectively lower operation phase energy

Table 2
Life cycle mass and embodied energy intensity (EEI) of building materials.

Material	Tonnes	% by Mass	EEI (MJ/kg)	Material	Tonnes	% by Mass	EEI (MJ/kg)
Structural concrete slab	14,788	43%	0.9	Aluminum grill strip	11	0.03%	44.3
Concrete floor	10,067	29%	0.9	Non-shrink grouting	9.7	0.03%	3.9
Crushed sand grain	5149	15%	0.1	Aluminum door	8.9	0.03%	44.0
Driven concrete pile	1540	4%	0.8	Fire-, rust-proof paint	8.4	0.02%	99.5
Reinforcing steel	746	2%	22.7	Crushed gravel floor	5.4	0.02%	0.1
Concrete to roof slab	693	2%	2.0	Fiberglass panel	5.2	0.01%	69.8
Galvanized steel sheet	413	1%	26.5	Stainless steel sheet	4.8	0.01%	62.4
Steel pipe, roof truss	398	1%	22.4	Copper wire	4.1	0.01%	70.9
Aerated concrete bricks	260	0.7%	3.2	Polyethylene sheet	2.7	<0.01%	78.7
Steel beam	213	0.6%	19.0	Acrylic emulsion paint	2.1	<0.01%	98.8
PVC conduit and piping	162	0.5%	61.8	Bitumen binder sheet	1.8	<0.01%	45.5
Gypsum plaster	154	0.4%	1.9	Aluminum window	1.4	<0.01%	145.7
Chiller 1319 kW	35	0.1%	87.7	Alkyd internal paint	0.6	<0.01%	43.8
Gypsum wallboard	24	0.07%	221.3	Water pump 11 kW	0.5	<0.01%	5.2
Granite stone slab	23	0.07%	7.1	Anti-termite treatment	0.3	<0.01%	187.1
Glass wool insulation	12	0.03%	42.1	Polysulfide joint sealer	<0.01	<0.01%	30.7
Ceramic tile	12	0.03%	10.4				

Sources: ecoinvent, ESUCO, CHISUCO.

Table 3
DesignBuilder input parameters.

Lighting	Operation 24 h/day, 1.49 W/m^2
Occupancy	Building operates 24 h/day, 7 days/week Constant occupancy of 300 persons
Thermal capacitance of envelope materials	Galvanized steel external wall (7.2 W/m^2 K) Internal aerated concrete bricks (1.27 W/m^2 K) 50 mm metal roof with wool insulation (0.69 W/m^2 K) Steel louver (7.2 W/m^2 K) Fiberglass louver (6.121 W/m^2 K)
Air infiltration rate	0.15 h^{-1}
Mechanical ventilation rate	1.89 h^{-1}
HVAC coefficient of performance	5.5

requirements. Active measures include the use of LED lighting and an efficient chiller.

Energy is primarily consumed for the purposes of cooling, active mechanical ventilation, and lighting in the context of Thailand and other countries with warm climates. The factory is able to source all operation phase energy from the public electricity grid and does not generate any power on-site. DesignBuilder simulations take into account an expected continuous occupancy of 300 employees working 24 hours per day (three eight-hour shifts) throughout the year. Weather and ambient temperature data is compiled from International Weather for Energy Calculations (IWEC) using Bangkok area weather data. [15,36]. An annual temperature overview of Thailand is provided in Fig. A.1 in the Appendix. Operation phase building parameters used in DesignBuilder simulation software are specified in Table 3.

Only 5% of the factory (684 m^2 of non-production area) will be air-conditioned. Non-mechanical ventilation louvers and small gaps around doors and windows provide the necessary substitute cooling in non-air-conditioned building zones. Additionally, 50 mm-thick roofing insulation minimizes long-wave radiation heating.

2.5. End of life

The end-of-life phase consists of the energy required to demolish the building on-site and to dispose of materials. Demolition machinery is assumed to use diesel fuel exclusively and accounts for a very small percentage of energy use [30,31]. Due to a lack of data on demolition machinery and little variation in demolition processes among countries, a literature precedent from Kofoworola and Gheewala [30] was used to calculate the primary energy requirement of the demolition phase: 51.5 MJ of energy from diesel fuel "per square meter of gross floor area."

In the base case scenario, every material is assumed to be landfilled after demolition. The end-of-life phase includes transportation impacts from building site to sorting plant, electricity consumption by sorting machines, transportation from sorting plant to landfill, and diesel fuel consumption by landfill excavators. Transportation distance values are sourced from ecoinvent. The base case is a no-recycling reference point against which each additional scenario's relative magnitude of avoided energy impacts is compared. Recycling is the central point of scenarios 2 and 4; methodology for these approaches is discussed in Section 2.7.

2.6. Life cycle impact assessment

Standard ReCiPe hierarchist midpoint assessment is the LCIA method used in this study [37]. ReCiPe is selected because it is relatively updated, widely used, and employed elsewhere in the building LCA literature [30,38]. LCIA impact categories of global warming potential, ozone depletion potential, acidification potential, eutrophication potential, and photochemical ozone creation potential are selected for this analysis, consistent with recent building LCAs [10,11,34,38–43]. Additionally, these impact categories are the exact same ones required for DGNB certification, reflecting their relevance to the building sector. The scope of LCIA stops at characterization of impact categories; normalization was not used. Final characterization results, however, were converted to units of "per square meter per year."

2.7. Scenarios

In addition to the full LCA detailed above, this study expands upon the base case assessment to investigate three scenarios that further explore impact reduction via recycling and PV solar electricity. PV solar is investigated in part because of the building client's expressed interest in installation of a PV system post-construction. Additionally, Thailand's warm and sunny climate provides an ideal context for PV electricity generation. Table 4 provides descriptions for the scenarios analyzed.

Scenario 1, the base case described in the methodology above, assumes landfilling of all building materials for end of life. All electricity is supplied by the Thai energy grid.

Table 4
Scenario descriptions.

Scenario 1/Base case	Landfilling of all materials; all electricity taken from grid
Scenario 2	Recycling of all eligible materials; all electricity taken from grid
Scenario 3	1 MW PV system; landfilling of all materials
Scenario 4	1 MW PV system; recycling of all eligible materials, including PV system

Scenario 2 considers recycling of all eligible materials, namely those composed of steel, aluminum, polyethylene, or copper wire. All values for recycling impacts and benefits of alleviated virgin-production were obtained from relevant European Sustainable Construction and Chinese Sustainable Construction Database files because these provided material-specific end-of-life values not found in ecoinvent. Alleviated virgin-production impacts are subtracted only from life cycle totals. To prevent double-counting of benefits, manufactured materials in ecoinvent are selected to be virgin-production and not recycled. For the purpose of this study, incineration of PVC (recycling is not common practice) is included as an alternative end-of-life treatment and is considered part of "recycling" for the remainder of the paper. Materials that cannot be recycled or incinerated are landfilled.

Scenario 3 differs from Scenario 1 as it employs a 1-megawatt rooftop solar PV system. All building materials, including those in the PV system, are landfilled for end of life. Landfill disposal of PV is the only current option in Thailand. The photovoltaic solar system includes multi-Si wafer PV modules, steel frames, aluminum mounts, inverters, copper wires, and control panels. Environmental impacts from its manufacturing, construction, demolition, and landfilling are included in each respective life cycle phase calculation. Because a solar array has not yet been constructed, PV system material quantities are taken from literature for analogous rooftop and utility-scale systems [44,45].

Scenario 4 incorporates the PV system outlined in Scenario 3 as well as the recycling methodology presented in Scenario 2. Both the building and PV system recycle all eligible materials. All materials from the PV system are eligible in the recycling process with the exceptions of the control panel and inverter, which are not recycled and assume landfill impacts. Both the negative impacts of PV recycling and the benefits of alleviated virgin production are taken from Müller et al. [46] due to a lack of PV component recycling data in any of the databases surveyed.

A comparison of the building with and without PV installation demonstrates the net impact of installing large-scale rooftop solar on the factory. Implementation of active energy-saving methods is often at the expense of embodied energy due to the energy-intensive materials used in installation [15,47]. Through this comparison, the study will determine whether benefits from locally-produced renewable electricity outweigh the high embodied energy costs inherent in the installation of rooftop solar on an industrial building in Thailand.

3. Results and discussion

Sections 3.1 and 3.2 offer a breakdown of 1) primary energy demand by life cycle phase and 2) energy demand in the operation phase. Section 3.3 relates embodied and operation energy in low-energy buildings and includes a study validation comparing the factory to institutional and commercial buildings (because no industrial building LCAs exist) with similar concrete- and steel-based compositions. Section 3.4 details life cycle environmental burdens in five assessed categories. Section 3.5 discusses both energy and environmental impact results for the material manufacturing phase, the largest contributor to each. Section 3.6 provides an analysis of potential environmental impact and energy reduction scenarios, expanding upon base case results.

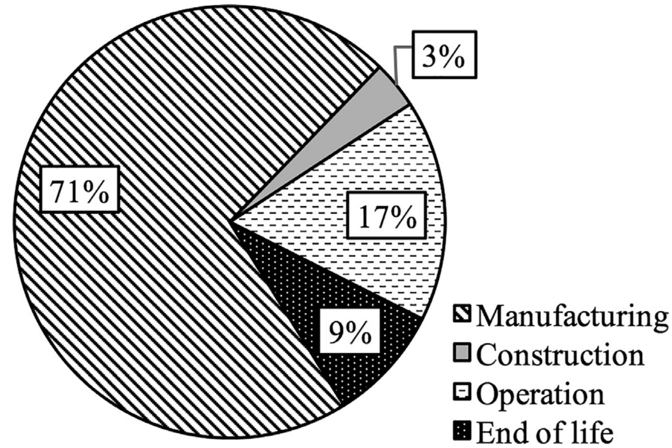

Fig. 2. Distribution of life cycle primary energy demand.

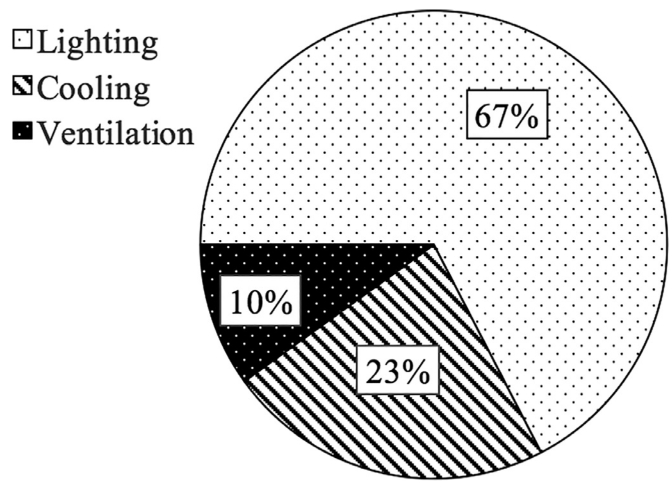

Fig. 3. Base case operation phase electricity consumption.

3.1. Life cycle energy contributions

Every stage of the life cycle contributes to primary energy demand, as shown in Fig. 2. Total primary energy comes predominantly from material manufacturing (71%), followed by operation (17%). In conventional buildings, the operation phase constitutes the vast majority (80–90%) of energy demand [9,48]. In low-energy buildings, however, operation phase impacts are minimal by design; thus, material manufacturing is expected to consume the largest share [15]. Fig. 2 illustrates how this finding also appears valid for low-energy industrial buildings. Reductions in operation demand are often accompanied by a small increase in embodied energy because energy-saving measures require energy-intensive materials [40,17,48]. This observation could explain the observed high embodied energy in comparison to operation energy demand; for example, 5161 kg of translucent fiberglass panels and louvers used in skylights to reduce lighting energy consumption have an embodied energy of 69.8 MJ/kg, one of the highest values of all materials considered.

3.2. Operation phase electricity consumption

The operation phase energy breakdown shown in Fig. 3 also differs substantially from conventional buildings. The passive

Table 5
Comparison of operation energy and embodied energy across studies.

	Operation energy (MJ/m^2/year)	Embodied energy (MJ/m^2)	Material mass (kg/m^2)	Building location	Energy source
Collinge et al. [11]	3920	5,080	1670	Pennsylvania, USA	Grid, natural gas
Scheuer et al. [31]	1500	6,250	2000	Michigan, USA	Grid, natural gas
Kofoworola & Gheewala [13]	860	6,800	2049	Bangkok, Thailand	Grid
This case study	408	6,090	2331	Eastern Thailand	Grid

architecture design shrinks cooling and ventilation demand to the point that LED lighting accounts for 67% of the total. Additionally, because the building utilizes active temperature conditioning for only 5% of its floor area, both cooling and overall demands are cut significantly. This suggests that material manufacturing, end of life, or external operation phase mechanisms—namely, solar PV—should be the focus of concerted energy efficiency efforts in industrial buildings. This comes in contrast to conventional concrete- and steel-composition buildings [30,31] and extends the success of passive architecture strategies in low-energy residential and commercial buildings into the industrial sector [12,17].

3.3. Study validation: embodied energy vs. operation energy

Table 5 places the case study in context by comparing material mass, embodied energy, and operation energy to other buildings in literature. No comprehensive studies of industrial buildings exist in the body of literature; therefore, buildings with similar concrete- and steel-based compositions were chosen. Collinge et al. [11] analyzes a 14-story university building along with an attached, two-story auditorium in Pennsylvania, USA. Scheuer et al. [31] looks at a six-story, 7300 m^2 university building in Michigan, USA. Kofoworola and Gheewala [13] considers a 38-story, 60,000 m^2 office building in Bangkok, Thailand, which shares the same climate as the case study. All studies chosen have similar material mass and embodied energy values. The material mass of the case study factory was estimated to be 2331 kg/m^2, material embodied energy to be 6090 MJ/m^2, and total annual operating energy to be 407.9 MJ/m^2. These results are compared with those of the other studies in Table 5.

According to Collinge et al. [11], small variations in normalized material mass, embodied energy, and operation energy are expected due to differences in construction method, definition of system boundaries, and use of different LCI databases. The low-energy industrial building, however, exhibits only a fraction of the operation energy of the conventional institutional and commercial buildings despite operating 24 h a day, seven days a week. Its simulated operation energy is half that of the Thai office building, one-fourth that of the Michigan university building, and one-tenth that of the Pennsylvania university building.

3.4. Environmental life cycle impact assessment

Fig. 4 demonstrates that material manufacturing, followed by operation, accounts for the greatest environmental impacts in nearly every category. This mirrors a trend identified in the analysis of primary energy demand and is a finding various building LCAs have observed [6,30,32,49]. Impact contributions from material manufacturing versus operation are as follows: global warming potential, 60% vs. 28%; ozone depletion potential, 75% vs. 9%; acidification potential, 56% vs. 26%; eutrophication potential, 47% vs. 42%; photochemical ozone creation potential, 58% vs. 16%. Impacts from manufacturing are at least double those of operation in every category but eutrophication potential.

*Categories from left to right are global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP).

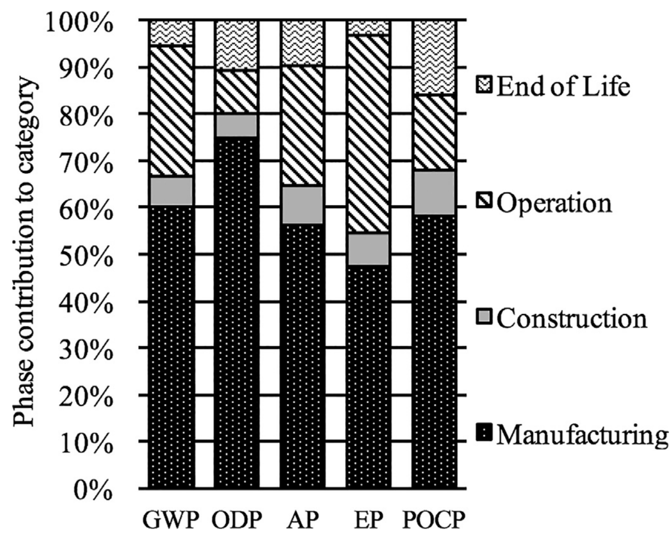

Fig. 4. Life cycle phase contribution analysis per impact category.

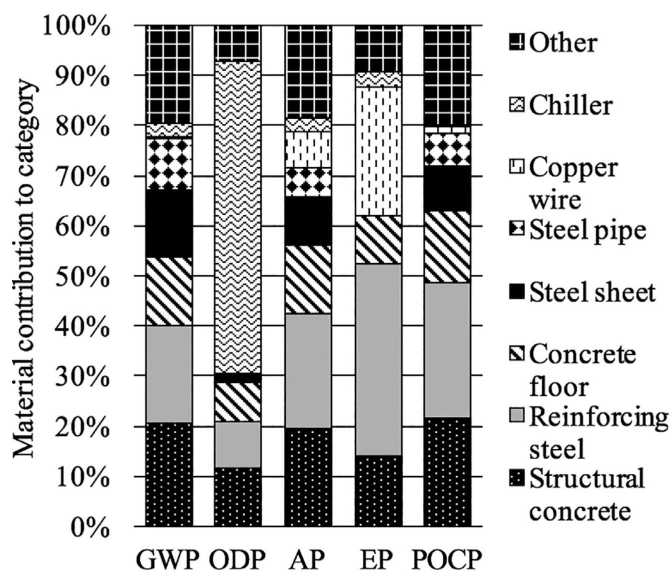

Fig. 5. Material contribution analysis by impact category.

3.5. Impacts from material manufacturing

Material manufacturing accounts for 71% of life cycle energy demand and contributes most to all environmental impact categories. Fig. 5 shows a material contribution analysis of the seven materials that together constitute more than 80% of impacts. The remaining 27 materials—which individually contribute less than 6% to all impacts—are categorized as "Other" in this representation and dis-

Table 6
Impacts by category for Scenarios 1–4 (per m^2, per year).

Scenario	Energy Demand (MJ)	Global Warming Potential (kg CO_2-eq)	Ozone Depletion Potential (kg CFC11-eq)	Acidification Potential (kg SO_2-eq)	Eutrophication Potential (kg PO_4-eq)	Photochemical Ozone Creation Potential (kg C_2H_4-eq)
(1) Base case	428	44	4.10E-06	0.16	0.017	0.14
(2) Recycling, no PV	302	35	4.00E-06	0.12	0.013	0.13
(3) No recycling, PV	153	−15	3.40E-06	−0.03	−0.017	0.05
(4) Recycling, PV	−20	−27	2.90E-06	−0.06	−0.033	0.04

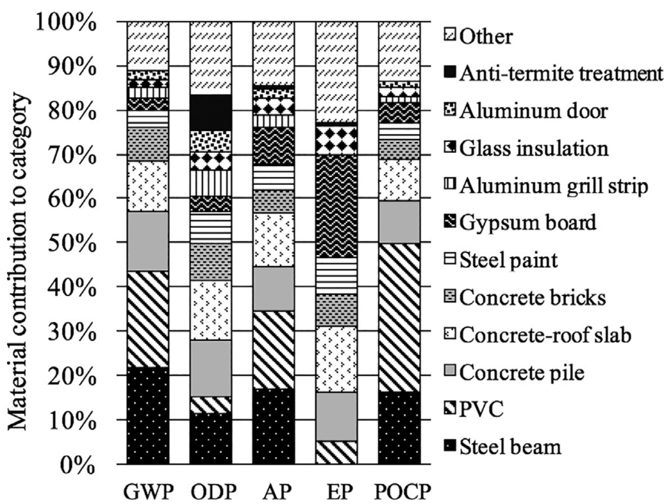

Fig. 6. Material contribution analysis of Fig. 5 "Other" materials by impact category.

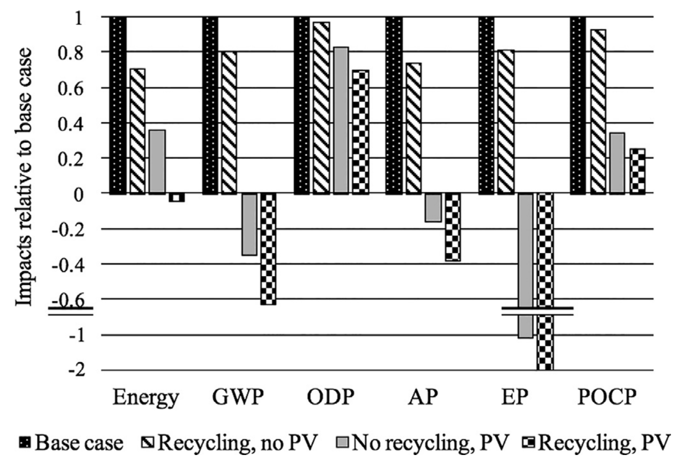

Fig. 7. Impacts by category for Scenarios 1–4, relative to base case. Categories from left to right are global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP).

played in Fig. 6. Concrete and steel, in various forms, collectively comprise 83% of building mass; by impact, they are responsible for 88% of global warming potential, 80% of acidification potential, 66% of eutrophication potential, and 87% of photochemical ozone creation potential. The remaining steel and concrete materials found in Fig. 6 are included in these totals. Individually, reinforcing steel is the largest contributor to acidification potential, eutrophication potential, and photochemical ozone creation potential due to its large material quantity and energy-intensive production processes. Manufacturing of chillers dominates ozone depletion potential in terms of contribution, accounting for 62% of the total environmental load. This may be because ozone-depleting refrigerants are still in production, and a large volume is necessary to operate the two 1319 kW mechanical systems [50]. Copper wire constitutes only 0.01% of building mass yet contributes to over 25% of eutrophication potential. This is likely due to upstream processes, such as ore extraction, which release phosphate equivalents and have a disproportionately damaging effect on water quality.

3.6. Discussion of scenarios

Material manufacturing is the largest but also the most difficult life cycle phase in which to achieve energy reduction in the case of industrial buildings. Low-energy material substitutes for durable envelope constituents such as a steel girder formwork, 30 cm concrete floor, and galvanized steel walls/roof have neither been applied successfully to industrial buildings nor implemented in Thailand or other hot climates [9]. Owing to an absence of low-energy substitutes (e.g. wooden beams, straw bale construction) in Thailand and stringent design constraints on industrial buildings, scenarios instead opt for a practical approach using established practices and technology.

Table 6 exhibits the final impact values for Scenarios 1–4 in terms of kg-equivalents per m^2 per year. A clear decline in environmental impacts is evident across categories as scenarios progress. Fig. 7 presents scenario primary energy demand and environmental impacts relative to the base case. Recycling in Scenario 2 reduces impacts in all categories, with primary energy declining 29% and acidification potential declining 26%. Major reductions achieved in Scenario 2 are attributed to the recycling of materials and components with high embodied energy, specifically steel, aluminum, polyethylene, PVC, copper wire, and chillers. Recycling is assumed to be closed-loop, and transportation within the recycling phase is included in impact values provided by ecoinvent. According to [9], up to 55% of embodied energy can be saved using recycled key materials. Although the reduction percentage in the present case study is only half the potential indicated in [9], considerable energy reduction is still achieved. It is suspected ozone depletion potential remains high because although the chiller can be recycled, its refrigerant input cannot. Photochemical ozone creation potential likely remained high because it is dominated by the manufacturing of concrete, which is not recycled. End-of-life transportation of recycled materials and sorting plant processes also augment photochemical ozone creation potential.

Scenario 3 varies from Scenario 1 with the inclusion of a 1 MW photovoltaic system, which provides further reductions in all impact categories. Implementation required additional materials be added to the building system—specifically 71,400 kg of Silicon multi-wafer modules, 180,000 kg of steel frame, four 500 kW DC-AC inverters, aluminum mounts, PVC conduits, copper wires, and a control panel [44]. These additions would increase total embodied energy by 33% from the base case, requiring assessment of whether an estimated $4.7*10^6$ MJ of annual photovoltaic energy generation would offset the system's own embodied energy.

The operation phase in Scenario 1 demands 71 MJ/m^2/year from the Thai grid, whereas Scenario 3 creates an energy surplus of 315 MJ/m^2/year. The PV system offsets its own embodied energy and largely offsets impact categories for the entire building. The Scenario 3 factory is a net-zero energy building; PV system electricity production surpasses operation phase energy demand by a factor of 5.4. This excess energy could be used in place of electricity from the Thai grid to power in-house factory machinery. Factory machinery is outside the scope of this study.

Global warming potential, acidification potential, and eutrophication potential are all sub-zero in this scenario, meaning that excess electricity production not only offsets environmental impacts but provides net benefits. This means that clean energy production compensates for the environmental loads accrued over the entire life cycle.

Of all scenarios considered, Scenario 4 shows the greatest reductions in energy and environmental impact categories. The combination of recycling and a 1 MW solar PV system results in a building that is a net exporter of energy over its life cycle. Life cycle energy is reduced to −4.7% of base case primary energy demand by recycling eligible photovoltaic parts—aluminum, silicon, and copper in PV modules as well as steel, aluminum, copper, and PVC in module support frames [45]. The Si-multicrystalline PV recycling method taken from Müller et al. [46] enabled the quantification of these benefits. From an energy and environmental standpoint, Scenario 4 is the best option for reducing life cycle burdens beyond the requirements of standard DGNB certification.

3.7. Recommendations

This case study highlights the successful application of operation phase passive and active measures, recycling, and rooftop PV to industrial buildings. Further steps can be taken by building architects and operators to reduce energy consumption during material sourcing, building operation, and disposal/recycling. For example, while the present building has a set point temperature of 24 °C, Kofoworola and Gheewala [30] suggest 26 °C for buildings in Thailand and warm climates. Another approach not considered in this study is employment of an automated sensor/timer system to dim LED lighting when daylight is sufficient for workers and production machinery to function.

Areas for improvement extend to the manufacturing and end-of-life phases as well. Steel and concrete make up 83% of total building mass and 78% of total embodied energy; it is suggested that architects and building contractors minimize their use of steel and concrete and seek low-energy material alternatives that recent studies have brought to light. In general, quantities of materials with large embodied energy (i.e. translucent fiberglass panels, gypsum wallboards, paints, etc.) should be reduced where possible. Sourcing of previously recycled materials for the manufacturing phase would lessen high embodied energy costs. Concrete is not often used for structural materials in its recycled state [51], although much of concrete may be recycled and mixed with virgin-produced concrete to be used for alternative purposes (i.e. sidewalks, asphalt, etc.). Future studies could determine benefits of recycling concrete, as this is by far the largest building component by mass and midpoint environmental impacts.

This study also recommends that LCAs become standard practice in industrial building design and construction to facilitate certification and data-driven decision making. Assessments conducted before building assembly will allow for environmentally-conscious modifications to be considered and implemented. Additionally, a more expansive body of literature on industrial buildings in warm climates would provide more accurate insight on the building sector and allow for more relevant comparisons between case studies. This study in particular could be expanded using an LCA complete with a dynamic energy mix that changes with the Thai grid over the lifetime of the building.

4. Conclusion

This study presents a comprehensive life cycle assessment of a low-energy industrial building in Thailand, poised to receive DGNB green-building certification. By maximizing natural airflow, minimizing cooling demand, and introducing efficient lighting, it will be the first industrial building in Thailand to receive this distinction. Three further energy-reducing pathways are constructed and tested: a factory which a) recycles its building materials (Scenario 2) b) installs rooftop PV solar (Scenario 3), and c) takes advantage of both recycling and PV (Scenario 4).

Base case results reveal that the material manufacturing phase constitutes 71% of the life cycle primary energy, the most of any phase. Despite manufacturing's disproportionate contribution, this paper finds a greater number of practical options for sustainable strategies related to building use (i.e. lighting, cooling, ventilation) and end of life (i.e. recycling).

When compared to the base case, Scenario 2 reduces total primary energy demand by 29% and acidification potential by 26% through the recycling of steel, aluminum, copper wire, polyethylene, PVC, and chillers– despite the fact that these materials constitute <6% of building mass.

By adding a rooftop PV system to the building in Scenario 3, reductions are achieved in all impact categories, with sub-zero impact results in three: global warming potential, acidification potential, and eutrophication potential. Despite the fact that a solar PV system augments material manufacturing phase impacts, PV-electricity production discounts those burdens.

The analysis ultimately shows that combined integration of an intelligently-designed base case, material recycling, and rooftop PV deployment on a large roof can turn a ~15,000 m^2 factory into a net-zero industrial building. The case study is a successful early exemplar of applying relatively new low-energy practices to the more complex and increasingly important context of industrial buildings. As energy-saving initiatives need to expand beyond the comfortable ground of residential and commercial buildings, the results of this study offer a bridge into a cleaner industrial sector while addressing a literature gap felt in emerging nations, particularly those with warm climates.

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Appendix

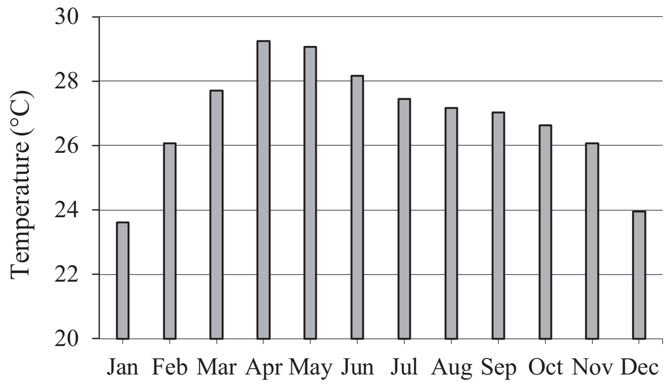

Fig. A.1. Average monthly temperature profile for Bangkok, Thailand (2010–2015). *Source:* World Bank Group [52].

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