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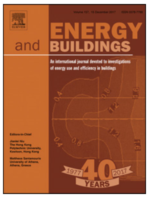

Life cycle assessment: a multi-scenario case study of a low-energy industrial building in Thailand

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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