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CASE STUDY

Environmental life cycle assessment of a commercial office building in Thailand

Oyeshola F. Kofoworola · Shabbir H. Gheewala

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Abstract
Background, aim, and scope To minimize the environmental impacts of construction and simultaneously move closer to sustainable development in the society, the life cycle assessment of buildings is essential. This article provides an environmental life cycle assessment (LCA) of a typical commercial office building in Thailand. Almost all commercial office buildings in Thailand follow a similar structural, envelope pattern as well as usage patterns. Likewise, almost every office building in Thailand operates on electricity, which is obtained from the national grid which limits variability. Therefore, the results of the single case study building are representative of commercial office buildings in Thailand. Target audiences are architects, building construction managers and environmental policy makers who are interested in the environmental impact of buildings.
Materials and methods In this work, a combination of input–output and process analysis was used in assessing the potential environmental impact associated with the system under study according to the ISO14040 methodology. The study covered the whole life cycle including material production, construction, occupation, maintenance, demolition, and disposal. The inventory data was simulated in an LCA model and the environmental impacts for each stage computed. Three environmental impact categories considered relevant to the Thailand context were evaluated, namely, global warming potential, acidification potential, and photo-oxidant formation potential. A 50-year service time was assumed for the building.
Results The results obtained showed that steel and concrete are the most significant materials both in terms of quantities used, and also for their associated environmental impacts at the manufacturing stage. They accounted for 24% and 47% of the global warming potential, respectively. In addition, of the total photo-oxidant formation potential, they accounted for approximately 41% and 30%; and, of the total acidification potential, 37% and 42%, respectively. Analysis also revealed that the life cycle environmental impacts of commercial buildings are dominated by the operation stage, which accounted for approximately 52% of the total global warming potential, about 66% of the total acidification potential, and about 71% of the total photo-oxidant formation potential, respectively. The results indicate that the principal contributor to the impact categories during the operation phase were emissions related to fossil fuel combustion, particularly for electricity production.
Discussion The life cycle environmental impacts of commercial buildings are dominated by the operation stage, especially electricity consumption. Significant reductions in the environmental impacts of buildings at this stage can be achieved through reducing their operating energy. The results obtained show that increasing the indoor set-point temperature of the building by 2°C, as well as the practice of load shedding, reduces the environmental burdens of buildings at the operation stage. On a national scale, the implementation of these simple no-cost energy conservation measures have the potential to achieve estimated reductions of 10.2% global warming potential, 5.3% acidification potential, and 0.21% photo-oxidant formation potential per year, respectively, in emissions from the power generation sector. Overall, the measures could reduce approximately 4% per year from the projected

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O. F. Kofoworola · S. H. Gheewala (✉)
Joint Graduate School of Energy and Environment,
King Mongkut's University of Technology Thonburi,
Bangkok, Thailand
e-mail: shabbir_g@jgsee.kmutt.ac.th

global warming potential of 211.51 Tg for the economy of Thailand.

Conclusions Operation phase has the highest energy and environmental impacts, followed by the manufacturing phase. At the operation phase, significant reductions in the energy consumption and environmental impacts can be achieved through the implementation of simple no-cost energy conservation as well as energy efficiency strategies. No-cost energy conservation policies, which minimize energy consumption in commercial buildings, should be encouraged in combination with already existing energy efficiency measures of the government.

Recommendations and perspectives In the long run, the environmental impacts of buildings will need to be addressed. Incorporation of environmental life cycle assessment into the current building code is proposed. It is difficult to conduct a full and rigorous life cycle assessment of an office building. A building consists of many materials and components. This study made an effort to access reliable data on all the life cycle stages considered. Nevertheless, there were a number of assumptions made in the study due to the unavailability of adequate data. In order for life cycle modeling to fulfill its potential, there is a need for detailed data on specific building systems and components in Thailand. This will enable designers to construct and customize LCAs during the design phase to enable the evaluation of performance and material tradeoffs across life cycles without the excessive burden of compiling an inventory. Further studies with more detailed, reliable, and Thailand-specific inventories for building materials are recommended.

Keywords Life cycle assessment · Embodied energy · Environmental impact · Primary energy consumption · Office building · Thailand

1 Introduction

Energy is an essential input to every production, transport, and communication process and is thus a driver for the economic as well as social development of any nation (Griffin and Steele 1980). The building construction industry consumes 40% of the materials entering the global economy and generates 40–50% of the global output of greenhouse gases and the agents of acid rain (California Integrated Waste Management Board 2000; Cheng et al. 2006; Uher 1999; Prasad and Hill, accessed 2006; Department of Trade and Industry 2006). Extraction or purification of materials from their natural ores is an activity that consumes energy, generates waste, and also contributes to environmental damage with negative impacts such as resource depletion, biological diversity losses, and other impacts such as global warming, acid rain, and smog (Cheng et al. 2006; Uher 1999; Prasad and Hill 2006; Department of Trade and Industry 2006). It is therefore evident that a connection exists between energy, environment, and development. To minimize the environmental impacts of construction and simultaneously move closer to sustainable development in the society, life cycle assessments of buildings are essential. Buildings are one of the areas in urban development that need to be assessed in terms of their environmental impacts. They provide the necessary infrastructure for many productive activities such as industries, services, commerce, and utilities, and thus satisfy a very basic human need. However, due to this very basic nature of buildings, stakeholders in development sometimes do not consider the environmental impacts of building, especially in developing economies. Life cycle assessment (LCA) is a very helpful tool in this regard as it not only provides an account of materials and energy involved in a product or system but also measures the associated environmental impacts (Earth Summit 2002; International Organization for Standardization 1997). LCA has been applied to develop eco-label criteria for hard floor coverings (Baldo et al. 2002), compare building insulation products (Schmidt et al. 2004a, b), assess the potential environmental impacts that might result from meeting energy demands in buildings (Osman and Ries 2007), as well as to the assessment of the CO_2 emissions reduction in the construction field through the selection of materials for houses of low environmental impact (Abeysundra et al. 2007). Researchers have also employed LCA as a tool to analyze energy consumption of processing construction components. Jonsson et al. (1998) compared concrete and steel building frames. Gunther and Langowski (1997) evaluated resilient floor coverings produced by 14 European manufacturers through their whole life cycles. Previous LCAs have generally focused on areas such as building materials; energy, water, and material use in operation and maintenance; construction and demolition waste management, etc (Beatriz et al. 2006; Nebell et al. 2006; Matsuno and Betz 2000; Petersen and Solberg 2005; Reddy and Jagadish 2003; Buchanan and Levine 2000); very few LCAs of complete buildings have been conducted (Hondo 2006; Oka et al. 1993; Treloar et al. 2000; Tucker and Treloar 1994; Thormark 2001; Mithraratne and Vale 2004). No life cycle environmental assessment of buildings has been carried out for Thailand, and none specifically of commercial office buildings. Many LCAs utilize either the process-based (Keoleian et al. 2001; Zapata and Gambatese 2005) or input–output techniques (Myer and Chaffee 1997; Miller and Blair 1985; Pan and Kraines 2001; Hetherington 1996; Lenzen 1998; Treloar 1997; Hendrickson et al. 1998). A hybrid LCA model that utilizes both process and input–output life cycle inventory methods to combine the strengths of both techniques has been utilized in this study. Thailand's economy is fast growing and its rate of construction and infrastructural development is very high. Social transformations and developments, especially in the real estate sector as well as the commercial and service sectors, have resulted in significant increases in the number of commercial buildings in Thailand (Bangkok Metropolitan Authority 2005; United Nations Centre for Human Settlements 1999). These have also contributed in no small measure to the increase in Thailand's energy intensity (Energy Information Agency 2005; Energy Policy and Planning Office 2005; Department of Alternative Energy Development and Efficiency 2004). The government has attempted to curb the rising energy intensity and also conserve and manage its energy resources through several measures. These include the implementation and enforcement of building codes, as well as energy conservation efforts for designated commercial and industrial buildings (Energy Policy and Planning Office 2005; Chirarattananon et al. 2004). However, thus far, no attempt has been made to assess the environmental impacts of commercial office buildings in Thailand. Consequently, there is limited quantitative information about their environmental impacts. Environmental assessments of office buildings can provide information necessary for a systematic and comprehensive reduction of environmental impacts from the building sector.

2 Goal and scope

The goal of this study is to estimate the environmental impacts of a typical commercial office building in Thailand. The office building stock was identified as being significantly important for study because it had the largest share of the commercial building stock in Thailand (Fig. 1) and also consumed the largest share of electricity (43.5%) in the commercial sector (Department of Alternative Energy Development and Efficiency 2004). It has been stated that energy is the single most important parameter for consideration when assessing the impacts of technical systems on the environment and that energy-related emissions are responsible for approximately 80% of air emissions, and are central to the most serious global environmental impacts

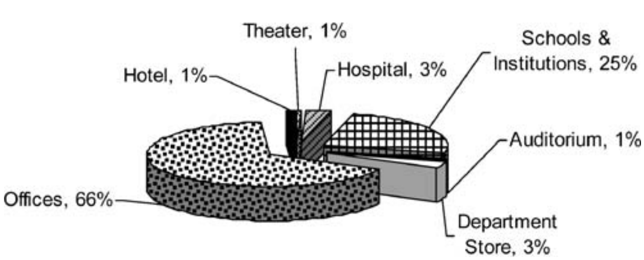


Fig. 1 Construction permission by type

Table 1 Basic parameters of case study commercial office building analyzed

Building parameters	Specifications
Office floors	38 floors above ground
Ceiling height	2.9 m ceiling height, acoustic ceiling tiles
Service life	50 years
Gross floor area	~60,000 m^2
Gross volume	~9,120,000 m^3
Structure	Concrete
Envelope	Brick and curtain wall combination
Foundation/ basement	Concrete foundation slab and walls
Walls (interior)	Brick
Walls (interior)	Brick and curtain wall combination (partially aluminum/glass curtain wall, partially concrete masonry unit/brick facing)
Floors	Cast-in place concrete
Flooring finish	Concrete; Concrete screed with three channels underfloor trucking: PVC tile, ceramic tiles
Roof	Flat roof, Concrete

and hazards, including climate change, acid deposition, smog, and particulates (International Energy Agency 2005). Consequently, any policies or research results, which might significantly reduce the energy consumption of Thailand's commercial building stock, would also have major impacts on the environmental quality of the country as well.

Office buildings are defined as buildings that have some part of it or all of it used for office purposes (Department of Alternative Energy Development and Efficiency 2004), and different types exist. It was found that almost all commercial office buildings in Thailand follow a similar structural as well as envelope pattern and thus the variables are limited. Hence, a representative sample could be studied. Therefore, a 'typical office building' based on information obtained by interviewing architects, cost consultants, facility managers, and building managers was defined. An office building, which followed the typical structural and envelope pattern in Thailand, was used as representative in this study. Its basic parameters are shown in (Table 1). The materials used for the building structure as well as the envelope are mostly reinforced concrete and curtain wall system. The results of the analysis are applicable to other commercial office buildings in the country.

2.1 System boundaries

The system studied includes the entire life cycle of the office building, including manufacturing of building materials, construction, operation, maintenance, and demolition

(Fig. 2). Transport for each life cycle stage was also included. Only the structure and envelope of the selected building are assessed. Excluded in the analysis are the potential of renewable energy use (on-site electricity generation with photovoltaic or solar hot water), indoor air quality issues (off-gassing from paints and flooring, and cleaning materials) during the use phase, water consumption and water effluents, and, future technological breakthroughs. The impact categories studied are global warming potential, acidification potential, and photo-oxidant formation potential. These categories were chosen as they are considered important and relevant to the geographical location of the study (Thailand), from an environmental and political point of view. The environmental impacts of the selected building were evaluated based on a service life of 50 years and major construction components such as concrete, structural steel, reinforcing steel, and bricks were considered.

2.2 Functional unit

The functional unit for this estimation was defined as 60,000 m^2 gross floor area of building. The case study building is a 38-story building in the central business district of Bangkok. Table 1 provides a list of the building characteristics. All lighting controls of the building are manual. The building is cooled by centrally located HVAC equipment. Electricity from the national grid is the only operating energy used by all systems in the building. The indoor operating set point temperature of the assessed building is 23–24°C.

2.3 Scope

The target product is a typical office building in Thailand. This analysis evaluates the environmental performance of an office building based on:

(a) Spatial context: an office building constructed, used, and demolished in Thailand.

(b) Temporal context: the life span of an office building is assumed to be 50 years.

(c) Technology: All the materials and transportation components (vehicles, infrastructure, and fuels) are assumed to be manufactured in Thailand, which enabled the use of the Thailand input–output (IO) table in the study.

2.4 Data origins and LCI analysis

All the data utilized for developing the input output model from which the emission intensities of building materials were computed were obtained from Thailand government databases (Department of Alternative Energy Development and Efficiency 2004; National Economic and Social Development Board 2006). The major sources of information about the types and quantities of materials and system components of the building were the priced bills of quantities, technical specifications, and relevant materials obtained from the building contractor. The electricity profile is of major importance as it broadly affects the environmental impacts assigned to energy-consuming steps. Thailand's electricity profile for the year 2004 was obtained from the Department of Alternative Energy Development and Efficiency (DEDE) of the Ministry of Energy (Department of Alternative Energy Development and Efficiency 2004). Electricity generation in Thailand is from mostly fossil fuels with an energy mix of 76% natural gas, coal and lignite 17%, diesel 3%, hydro 3%, fuel oil and others 1% (Department of Alternative Energy Development and Efficiency 2004). In addition, emission conversion factors based on the life cycle inventory of the Thailand electricity grid mix for the year 2000 (Lohsomboon 2002) as available in Table 2 were applied in this study.

2.5 Life cycle assessment methodology

The environmental effects of an office building in Thailand were evaluated and quantified by means of an LCA. There

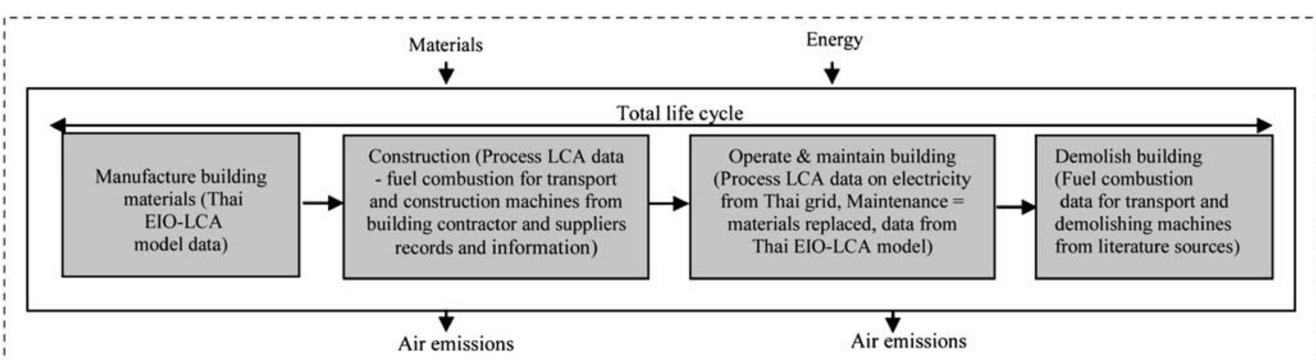


Fig. 2 System boundary of life cycle assessment

are primarily two LCA methodologies: a process-based LCA and the economic input–output analysis-based LCA (IO-LCA) (Facanha and Horvath 2006; Suh and Huppes 2005; Udo de Haes et al. 2004; Guinée 2002; Bullard and Herendeen 1975; Heijungs and Suh 2002). In a process-based LCA, the user maps all processes associated with all life-cycle phases of a product, and associates inputs (e.g., energy, water) and outputs (e.g., air emissions, noise, water discharges, accidents) with each process. By doing so, the total environmental load can be determined. Although this model enables very specific analyses, its heavy data requirements may make it time consuming and costly, especially when attempts are made to include suppliers upstream in the supply chain.

Due to great flexibility in designing system boundaries, the comparison of two LCAs of the same product is not always straightforward (Facanha and Horvath 2006). To overcome some of the limitations of a process-based LCA (e.g., data requirements, boundary selection), IO-LCA was created (Hendrickson et al. 1998). It couples environmental data with the economic IO model, and can determine the environmental load associated with the production of commodities (products and services). The model has the capability to provide comprehensive and industry-wide environmental analyses, but lacks the precision and detail found in a well-executed, process-based LCA, due to a high level of aggregation in industry or commodity (Suh and Huppes 2005; Udo de Haes et al. 2004).

Similar to the LCA of transportation (Facanha and Horvath 2006), a variety of issues arise when performing an LCA of an office building, the first one being that buildings are difficult to evaluate because they are large in scale, complex in materials and function, and temporally dynamic due to limited service life of building components and changing user requirements. The building production process is much less standardized than most manufactured goods because of the unique character of each building (Scheuer et al. 2003). Thus, the complexity of buildings justifies the use of a hybrid methodology. A hybrid LCA model combines the advantages of both process analysis and input-output analysis. Process-based LCA is more labor and time intensive, and also suffers from systematic truncation error due to the inclusion or exclusion of processes decided on the basis of subjective choices.

Similarly, the aggregation of economic sectors in IO-LCA enables its use for only a limited number of component analyses (Scheuer et al. 2003). IO-LCA can supply information for typical products or processes that are well represented by input–output categories, while the rest of the products or processes can be modeled by process analysis (Suh and Huppes 2005; Udo de Haes et al. 2004). Thus, for this study, a hybrid LCA model has been utilized. IO-LCA was used to account for only the production of building materials. The construction, operation, maintenance, and demolition phases in this study were accounted for separately by process-based LCA. Table 2 illustrates the methodology used for each phase of the building's life cycle. The pollutant emissions associated with transportation are added to the respective phase (e.g., construction, maintenance, demolition) in which it occurs. Classification and characterization factors were according to (Guinée 2002).

Table 2 Air emissions from power plants

Emissions	kg/kWh
CO_2	7.06E-01
SO_2	8.24E-04
NO_x	2.10E-03
CO	1.81E-04
N_2O	2.19E-05
NMVOC	3.42E-05
CH_4	1.92E-05
Dust	7.88E-05

Building materials manufacture The manufacture of building materials is composed of many sub-processes. The emissions associated with the manufacture of building materials was evaluated using IO-LCA model developed by the authors. All the data utilized for developing the IO-LCA model from which the emission intensities of building materials were computed were obtained from the Thailand government database. The IO-LCA model created for this study is based on Year 2000 data, requiring input–output data for Thailand's economy from the National Economic and Social Development Board of Thailand. The 180×180 sectors table was applied for the analysis. A matching energy input–output table (for 180×180 sectors) 1998, also from the same agency, was also utilized (National Economic and Social Development Board 2006).

Conversion factors for the various energy types (i.e., coal, natural gas, etc.) available in the energy input–output table were obtained from the Department of Alternative Energy Development and Efficiency (DEDE) of the Ministry of Energy, Thailand (Department of Alternative Energy Development and Efficiency 2004). Emission conversion factors based on the life cycle inventory of Thailand electricity grid mix (Lohsomboon 2002) were applied. Building material prices were obtained from the Thailand government Ministry of Commerce website (Ministry of Commerce 2006) and cross-checked with the price of the building materials as stated in the bill of materials obtained from the building contractors.

Input–output was originally used in the pioneering work of Bullard and Herendeen 1975. The method used in this study has been previously described by Limmeechokchai and Suksuntornsiri (2007) and Pullen (2000) and uses the energy and emission intensity contributions (in economic terms) to the relevant building material sectors. The input–

output analysis method was applied to determine the emissions resulting from the manufacture of building materials. The starting data available from the input–output table are in monetary terms per mass of material. Matrix analysis is used to derive emissions per monetary unit based on energy intensity of the sectors. The resulting numbers are then multiplied with mass of materials per economic unit to yield the emissions per unit mass of materials. Direct emissions were derived by the physical amount of each type of fossil energy directly combusted within a sector. The matrix of total energy content is

$$\mathbf{f} = [\mathbf{F}][\mathbf{I} - \mathbf{A}]^{-1}, \tag{1}$$

where

A is a square $n\times n$ matrix representing the inter-industrial transaction of n industries within the economy (transaction matrix).
I is an $n\times n$ unity matrix.
F The matrix F has a dimension of $k\times n$, where k is the number of fuel types.

Each element of the sectoral energy consumption matrix ($\mathbf{F}_{ki}$) is the direct consumption of fuel k in a physical unit by the monetary output of the economic sector i. The IO model was used for determining the fossil fuel or energy intensity for the production of goods and services based on a modified IO model to account for imports of goods and services (Miller and Blair 1985) as shown in Eq. 2.

$$\mathbf{f}^* = [\mathbf{F}]\left[\mathbf{I} - \mathbf{A}^{\mathrm{d}} - \mathbf{M}\right]^{-1} \tag{2}$$

Equation 2 represents the total energy content including effect of imported commodities to the economy. $[\mathbf{I} - \mathbf{A}^{\mathrm{d}} - \mathbf{M}]^{-1}$ represents the domestic purchase matrix. Imports of goods, represented by the import matrix **M**, required by local industry, are introduced into Eq. 1. Each element, $\mathbf{M}_{ij}$, is the monetary amount of imports supplied from the foreign industry i to the domestic industry j per total monetary-domestic industry output of j. This modification is based on the assumption that the rest of the world would have the same total energy intensities for 'equivalent' commodities as the economy of the country being studied according to Hetherington (1996). This is because the fossil fuel consumed by the rest of the world is not known, and calculating it would require global IO tables and fuel consumption data. It is therefore better to make this assumption than to assign zero emissions release to imports Hetherington, 1996. The matrix **F** has a dimension of $k\times n$, where k is the number of fuel types. Each element of the sectoral energy consumption matrix ($\mathbf{F}_{ki}$) is the direct consumption of fuel k in a physical unit by the monetary output of the economic sector i. The energy intensity (EI) is the multiplication of the transpose of the vector of conversion factor obtained from government agencies (Department of Alternative Energy Development and Efficiency 2004) and the total energy content f, i.e.,

$$\mathrm{EI}^{\mathrm{T}} = \left[\text{conversion factor}_{f\times 1}\right]^{\mathrm{T}} \times \left[\mathbf{f}_{f\times n}\right] \tag{3}$$

Each element of the energy intensity EI_i (i=1,…..,n) represents the energy intensity of sector i in the economy. An assumption made is that there is no disparity between different products from the same sector. To compute the sectoral emissions, the IPCC guideline for emissions estimation was applied. Thus, multiplying each element of **F** with the IPCC emission factors for estimation of CO_2 emission from combustion yielded a matrix of sectoral CO_2 emission, **B**, with elements of

$$\mathbf{B}_{ki} = \mathbf{F}_{ki} \times \mathrm{CF}_k \times \mathrm{CEF}_k \times \text{fraction of carbon oxidized}_k \times (44/12) \tag{4}$$

where

CF_k is a conversion factor $_k$ and
CEF is a carbon emission factor.

Different fuel types (k) have different carbon emission factors (Intergovernmental Panel on Climate Change 1996a, b, c). Therefore, a vector of total sectoral CO_2 emission factors that include infinite propagation of production chain of domestic or import commodities occurring in any economic sector is

$$\boldsymbol{b} = [\mathbf{B}][\mathbf{I} - \mathbf{A} - \mathbf{M}]^{-1} \tag{5}$$

Emission factors for non-CO_2 (e.g., CH_4 or N_2O) emissions rely on both fuel type and also activity, therefore each economic sector is assumed to be equal in activity. A matrix of sectoral non-CO_2 (e.g., CH_4 or N_2O) emissions, **B**, comprises elements of

$$\mathbf{B}_{ki} = \mathbf{F}_{ki} \times \text{conversion factor}_{ki} \tag{6}$$

and the total non-CO_2 (e.g., CH_4 or N_2O) emissions from combustion activity is

$$\boldsymbol{b}\mathrm{CO_2} = \mathrm{dCO_2}\left[\mathbf{I} - \mathbf{A}^{\mathrm{d}} - \mathbf{M}\right]^{-1} \tag{7}$$

$$\mathrm{bnon\text{–}CO_2} = \mathrm{dnon\text{–}CO_2}\left[\mathbf{I} - \mathbf{A}^{\mathrm{d}} - \mathbf{M}\right]^{-1} \tag{8}$$

The IPCC also gives emission factors for non-CO_2 (e.g., CH_4 or N_2O) emission based on fuel type and activity. The activities are located by the IO sectors. Generally, fuel is combusted in a sector, but sometimes it is also used in some particular processes for feedstock beyond the combustion to produce other goods and services. Therefore, overestimation of GHGs is avoided by using the matrix $\boldsymbol{F}$. The matrix $\boldsymbol{e}$ in a vector, containing $\boldsymbol{e}_{ki}$ elements as 1 for any fuel used for combustion and 0 for fuel used as feedstock in sector i has been previously introduced by Lenzen 1998 and Lenzen 2001. The overestimation of GHG emissions was reduced by introducing multiplier elements $\boldsymbol{e}_{ki}$ on every $\mathbf{F}_{ki}$ element.

$$\mathbf{F}^{*}_{ki}=\mathbf{F}_{ki}\cdot e_{ki} \tag{9}$$

The elements of matrix $\mathbf{F}$ are adjusted by Eq. 9, and then each element of $\mathbf{F}_{ki}$ in Eq. 4 is substituted with $\mathbf{F}^{*}_{ki}$, where $\boldsymbol{e}_{ki}$ is 1 if fuel type k is combusted in sector i and 0 if the fuel type k is used as feedstock in sector i. Direct GHG emissions from non-combustion activities were constructed as a vector, i.e., d′. The amounts of fugitive emissions from domestic fossil fuel production (solid, liquid and gases) have been evaluated (Limmeechokchai and Suksuntornsiri 2007). Research on local conditions and circumstances were unavailable; therefore, estimation of fugitive emissions by the global average method was applied as suggested in Limmeechokchai and Suksuntornsiri (2007). Taking into account the propagation of non-combustion activities in all sub-process chains, the total non-combustion emission of each GHG is $d'[\mathbf{I}-\mathbf{A}-\mathbf{M}]^{-1}$. Then, the total CO_2 emission is

$$\boldsymbol{b}CO_2= dCO_2\left[\mathbf{I}-\mathbf{A}^{d}-\mathbf{M}\right]^{-1}+d'CO_2\left[\mathbf{I}-\mathbf{A}^{d}-\mathbf{M}\right]^{-1} \tag{10}$$

Similarly, the total of non-CO_2, (i.e., CH_4, N_2O, NO_x, CO, and NMVOC) emissions were derived by

$$\text{bnon–}CO_2 = \text{dnon–}CO_2 \left[I - A^{d} - M\right]^{-1}+d'CO_2\left[I - A^{d} - M\right]^{-1} \tag{11}$$

These non-CO_2 emissions, similar to CO_2 emissions, are derived from activities associated with the conversion and combustion of feedstock for energy.

These sectoral emission intensity contributions (based on the impact categories assessed) were then multiplied by national average unit prices of different materials determined from the government database (Ministry of Commerce 2006) to generate the energy consumed as well as emissions in the production of a single unit. By multiplying the emissions with the total quantities of each material delivered to the construction site, the total emissions per material were quantified. CO_2 emissions for such non-energy processes such as cement manufacture were also considered in the analysis. About 600 kg of CO_2 is emitted per ton of cement during its production (Marland et al. 2006). For 30 MPa concrete, there is generally about 0.27 tons of cement per m^3 of concrete, therefore, the non-energy CO_2 emission rate for 30 MPa concrete is 162 kg of CO_2 per m^3. This CO_2 emission from cement manufacture was used for calculating the total CO_2 emissions for concrete at the manufacturing stage. Total emission intensities of building materials per monetary unit are shown in Table 3.

Building construction Construction includes burdens from electricity used for power tools and lighting, as well as diesel fuel used by heavy equipment at the construction site and associated transportation. Activities include site preparation, structural and envelope installation, mechanical, electrical equipment installation, and interior finishing (Scheuer et al. 2003). The availability of process-related data enabled the use of a process-based LCA for this stage. Data related to the construction process of the specific case study building site were obtained from the building contractor and supplier's records. These data are site specific and included data on those items which were part

Table 3 Total emission intensities of building materials

Material	t-CO_2 eq/Baht	t-SO_2 eq/Baht	t-C_2H_4 eq/Baht
Ceramic tile	1.2614E-05	7.06341E-07	1.24336E-08
Granite	2.1092E-05	4.86349E-07	9.59945E-09
Vinyl tile	1.1578E-05	6.26746E-07	1.74583E-08
Brick	2.8396E-05	7.49718E-07	1.79165E-08
Plaster	4.5044E-06	1.13819E-06	1.61232E-08
Gypsum	1.1248E-05	3.71803E-07	1.48949E-08
Aluminum	3.5433E-06	2.13622E-07	6.73871E-09
Paint	1.2293E-05	5.2572E-07	1.45153E-08
Wood	1.603E-06	2.88267E-07	5.61752E-09
Cement sand screed	1.1248E-05	3.71803E-07	1.48949E-08
Terrazzo	4.5044E-06	1.13819E-06	1.48949E-08
Precast concrete	4.5044E-06	1.13819E-06	1.61232E-08
Stainless steel	6.6398E-06	5.32445E-07	1.04928E-08
Glass	3.7137E-05	1.03293E-06	1.91681E-08
Ready mix concrete	0.0001951	3.25873E-06	3.85205E-08
Structural steel	2.5842E-05	1.44828E-06	2.63157E-08
Steel wire	8.055E-06	9.2302E-07	1.58452E-08
Steel reinforcement	2.5842E-05	1.44828E-06	2.63157E-08

of the contractors' final billing statement or bill of quantities. The main building elements which formed part of this bill included the building substructure, columns, floors, staircases, roof, walls, windows, and finishes. Items such as fitments, sanitary fixtures, appliances, plumbing, electrical and external items were not included due to the difficulty associated with obtaining this data. Other construction documents such as drawings, design specification sheets, and through on-site measurements and inquiries with subcontractors, manufacturers, were other sources of process data. All data relevant to construction machines and equipment used on site, and transportation distances of construction materials to the construction site were also obtained from the building contractor and supplier's records. The environmental flows associated with the construction stage were computed by accounting for the energy consumption of equipment used at the construction site. These were subsequently aggregated with emissions due to the energy consumption from the transportation of building materials to the construction site from their various points of purchase.

Building operation The operations phase activities consist of cooling and ventilating the building, lighting and equipment operation, and water supply. Only electricity was used in the studied building. Process-based LCA was applied in determining emissions during the operation stage. The operational energy consumption of the building was calculated based on the analysis of data on mechanical and electrical equipment design specifications as well as the anticipated usage pattern of the building (daily usage 8 h per day, 5 days a week). Actual electricity consumption records for the building exist only for a period of less than a year as the building was still new at the time of study. The calculated results showed a good correlation with the actual electricity consumption records, thus verifying the calculations. The results obtained agreed quite well with the average electricity consumption data obtained from electricity records. The analyzed energy consumption (electricity) results were converted into emissions by multiplying with emission conversion factors based on the life cycle inventory of Thailand electricity grid mix from Lohsomboon (2002).

Building maintenance Emissions from the maintenance stage were computed based on the life span of materials and followed the same procedure as that used for the manufacture of building materials.

Building end of life The last phase of a building's life entails demolition and decommissioning. The conventional demolition and decommissioning process often results in landfill disposal of the majority of materials (Scheuer et al. 2003). The emissions from the demolition stage are mainly due to the energy consumption of demolition machinery. All data on energy consumption of demolition machinery were obtained from literature (Winistorfer et al. 2005). Due to a lack of data on the energy requirement of the demolition process in Thailand, Thomas et al., 1996 was referred to for this study. Therein, 51.5 MJ/m^2 of energy as diesel fuel was needed to demolish a building typed as in situ concrete. It was also assumed that 0.845 t/m^2 of waste would be generated from the demolition of a non-residential building based on a previous study (Chini and Bruening 2003). The transportation distance for this study was assumed to be the distance from the central business district (CBD) of Bangkok where the studied building is located to the landfill site at the city outskirts of Nonthaburi measuring about 50 km (United Nations Economic and Social Commission for Asia and the Pacific 2003). The demolition materials were transported from the site via a diesel-powered dump truck. The energy for transportation is about 2.7 MJ/t km (Adalberth 1997a,b). This value was converted into emission using conversion factors.

3 Results and discussion

The results of the LCA based on the impact categories evaluated are presented in this section. The entire life cycle of the office building, including manufacturing of building materials, construction, operation, maintenance and demolition were assessed. The structure of the studied office building is of reinforced concrete (RC). Analysis of the manufacturing phase indicates that steel reinforcement and concrete are the most significant materials in terms of their associated environmental impacts as they accounted for about 17% and 64%, respectively, of the global warming potential originating from the production of materials utilized for the building (Fig. 3). In addition, of the total photo-oxidant formation potential they accounted for 42% and 30%, respectively, and, for 38% and 42% of the total acidification potential.

The dominance of these two materials could be attributed to their utilization in very large quantities as revealed by an analysis of the quantities of basic materials supplied for the construction of the office building (Fig. 4) Concrete accounted for about 80% of the material mass of the office building, followed closely by bricks with 13%. Steel was also significant as it made up 5.6% of the total material mass.

The total life cycle emissions according to each life cycle stage were determined. The results revealed that the operation stage activities account for about 52% of life cycle greenhouse gas emissions. The global warming potential at the manufacturing phase for energy related processes accounted for about 34% of the life cycle GWP. This closely matches life cycle energy distribution of the

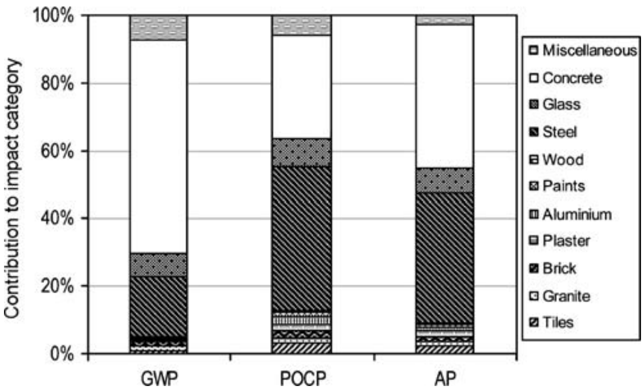


Fig. 3 Material percentage share of emissions (manufacturing phase)

building due to emission releases associated with fossil-based electricity generation. However, when CO_2 emissions for such a non-energy process as cement manufacture were also considered, the greenhouse gas emissions from the manufacturing stage were about 42% of the life cycle GWP. Of this, concrete and steel reinforcement accounted for 27% and 7.1%, respectively. The construction stage contributed 4%, whereas maintenance and demolition stages each had around 0.1% of the greenhouse gas emissions (Fig. 5). Analysis revealed that the air emission accounting for more than 98% of the total global warming potential was carbon dioxide.

Figure 6 presents the total life cycle acidifying gases emissions for each life cycle stage. The biggest contributor to this pollutant was again the operation stage at about 71%. SO_x and NO_x emissions (from grid electricity) accounted for 36% and 64%, respectively, of the total acidification potential for the office building during the operation stage. These emissions were released from grid supplied electricity generation. The manufacturing stage came second with 27.9%. The production of concrete and steel reinforcement in the manufacturing stage each accounted for about 11.7% and 10.3%, respectively, of total acidification potential. The construction, maintenance, and demolition phases each contributed about 0.4%, 0.8%, and 0.2%, respectively, to the total potential acidifying gas emissions.

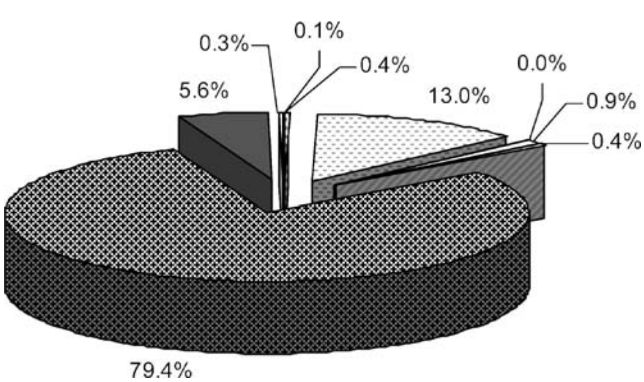


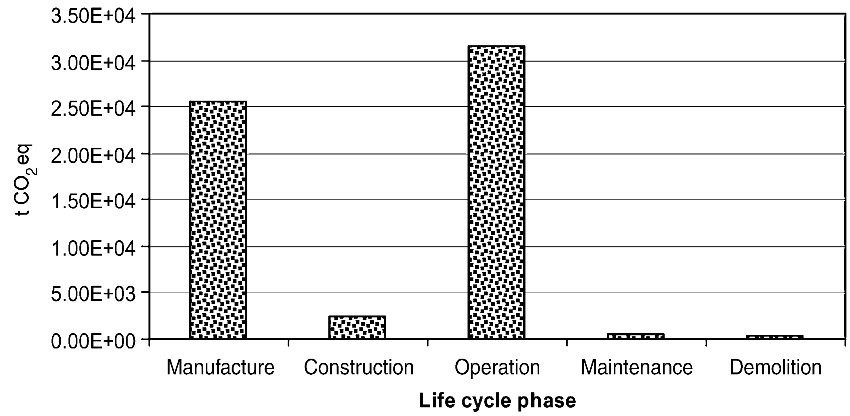
Fig. 4 Material percentage contribution by material mass. Granite: 0.4%, Brick: 13%, Aluminium: 0.0%, Tiles: 0.9%, Glass: 0.4%, Concrete: 79.4%, Steel: 5.6%, Plaster: 0.3%, Wood: 0.1%

The photo-oxidant formation potential of the assessed office building is shown in (Fig. 7). The manufacturing and operation stages together contributed more than 90% to this impact category. The operation stage constituted approximately 66% of the total photochemical ozone creation, which arose primarily from the use of electricity. The contribution to this impact category from the manufacturing stage (25%) was mainly from the production of concrete (7.5%) and steel reinforcement (10.1%). The environmental impact from the construction, maintenance, and demolition stages had marginal effects on the impact category. The most significant emissions of the total photochemical ozone creation potential category are the volatile organic compounds (VOC) responsible for over 90% of the impact category.

The results of the impact assessment of the office building reveals that lighting, air conditioning, office equipment, and other office appliances in the operational phase produced 40% or more of the overall impact in any given category. Lighting equipment produced around 15% and 11% of the impact both in the climate change and acidification categories and around 10% of the impact in the photochemical ozone formation category. The electricity used for air-conditioning accounted for approximately more than 40% in all the impact categories, producing around 54%, 40%, and about 40% of the impact in the climate change and acidification and photochemical ozone formation potential categories. Similarly, office equipment also accounted for about 16%, 12%, and 11%, respectively, of the impact in the climate change and acidification and photochemical ozone formation potential categories. The electricity consumption of the building as reflected by its energy index (238.71 kWh m^{-2} yr^{-1}) is higher than that for designated buildings in Thailand (102.9 kWh m^{-2} yr^{-1}). The high consumption and impact of electricity is mainly due to the building's central air-conditioning system. Additional factors contributing to the impact of electricity are high office equipment intensity and long operating hours. However, it must also be noted that the energy index compares well with data from other office buildings in Thailand as well as other South-East Asian countries (Department of Alternative Energy Development and Efficiency 2004). The contribution of each life-cycle phase to the overall environmental impact of the office building's life cycle is presented in (Fig. 8), which shows that the operating stage is clearly the life cycle phase that impacts on the environment the most.

In two of the three studied impact categories it alone produces more than 70% of the impact. The results indicate that the largest contributor to the impact categories were emissions related to fossil fuel combustion during the operations phase, particularly for electricity production. There was therefore a need to evaluate options for reducing emissions from the operation stage.

Fig. 5 Global warming potential by life cycle stage

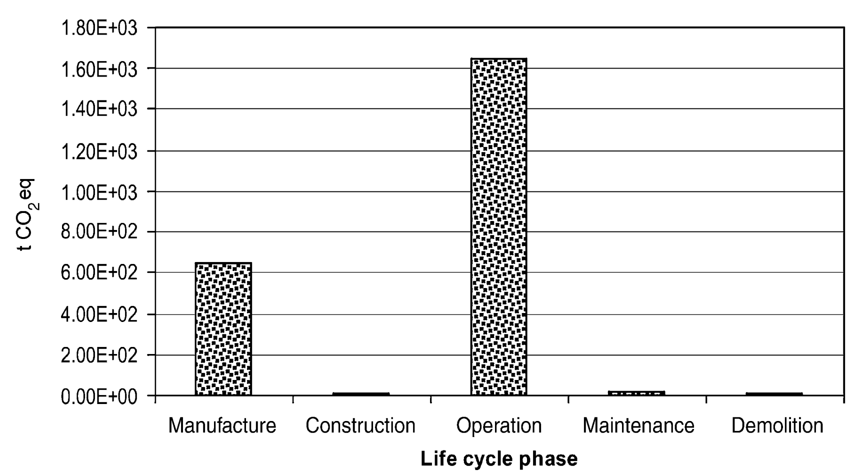


4 Environmental impact improvement assessment

The percentage share of the energy consumption of the analyzed building during its operational stage was further examined to determine the major contributors to this stage. The daily usage (8 h per day, 5 days a week) was found to be consistent with the general operational period for office buildings worldwide. It was found that although during off-office hours some energy consuming utilities (lifts, pumps) were operational, they did not contribute significantly to the energy profile of the building as their usage intensities are insignificant compared to that seen during normal working hours. In addition, an audit revealed that although the lighting systems installed in the building were energy efficient, the air-conditioning systems were central systems with no provisions for individual temperature control. Likewise, the set point temperature of the assessed building was as low as 23–24°C, even in summer. This is lower than the standard indoor air set-point temperature of 26°C (ASHRAE 2004). A similar pattern was also observed in other office buildings surveyed. The results of an assessment of energy (electricity) consumption by end-use appliances during the operation phase as depicted in Fig. 9, showed that air conditioning was the major load in the building, with lighting load coming second. This is in agreement with the results of some other studies (Chirarattananon et al. 2006; Department of Alternative Energy Development and Efficiency 2005; Aun 2004; Yang 2004; National University of Singapore 2006; Ayuni 2004).

The result of the assessment indicates that air-conditioning accounted for over 56% of the total operational energy use of the building. Evaluation and optimization of the building is therefore necessary to reduce emissions at the operational stage through a reduction in operational energy requirement. One relatively simple option considered to achieve this was to increase the set-point temperature of the air-conditioning system, which would induce a decrease in the energy requirement for cooling. The recommended standard indoor air set-point temperature is about 26°C (ASHRAE 2004). The results of analysis on increasing the indoor air set-point temperature indicate that a mean energy consumption reduction of about 7% can be achieved per 1°C increase in set point temperature. This result compares favorably with the mean energy consumption reduction potential of 6.14% obtained in Yamtraipat et al. 2006. A sample calculation revealed that 1.14×10^6 kWh/year of electric energy (electricity generated from power plants) would be saved if the set-point of room temperature is changed from 24°C to

Fig. 6 Acidification potential by life cycle stage



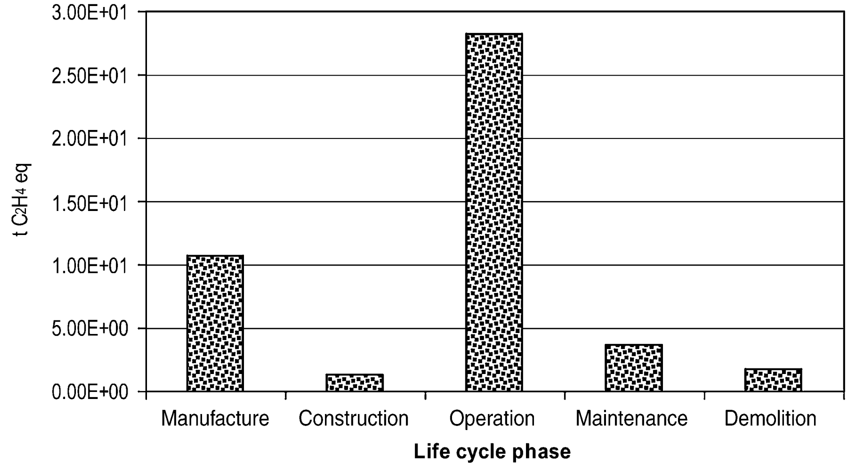


Fig. 7 Photo-oxidant formation potential by life cycle stage

26°C. Using emission factors per kilowatt hour for the Thai electricity grid mix (Lohsomboon 2002), it was calculated that this overall electric energy consumption saving can result in a corresponding reduction of 820 tons of CO_2 per year, 3.37 tons SO_2 per year, and 45 kg of C_2H_4 per year, respectively. The approach offered the possibility of determining the energy savings and the potential emission reductions from the office building stock of Thailand per year based on its electricity consumption balance of 12,350 GWh/year (Department of Alternative Energy Development and Efficiency 2004). Using the assumption that the indoor set-point room temperature is increased by 2°C for the entire office building stock, a similar calculation shows that an overall electric energy consumption saving of 978 GWh/year, with a corresponding reduction of 7.1×10^5 tons CO_2 per year, 2.9×10^3 tons SO_2 per year, and 7.7 tons of C_2H_4 per year. This energy saving is expected to contribute to estimated reductions of 0.85% GWP, 0.44% AP, and about 0.02% in the photo-oxidant formation potential from the power generation sector. Moreover, considering that global warming is becoming an increasingly important issue for the government of Thailand, it was essential to evaluate the effect of this simple energy efficiency strategy. The results obtained indicated that an approximate reduction of 0.33% per year from the projected global warming potential of 211.51 Tg (Zola and Lim 2000) for Thailand's economy could be achieved. Another relatively simple no-cost option assessed was the effect of implementing periodic building load reduction by switching off office equipment and lighting during lunch breaks, which usually have a duration of 1 h. It is expected that the air-conditioning system would not be operational during this period as well. This strategy does not compromise the occupants' thermal comfort nor does it impair their performance as the office is unoccupied at this period. As applying this strategy when the building is occupied could make energy cost in maintaining comfort, it is a small fraction of the loss when the work environment is not very comfortable. Shutting down the building systems for 1 h has been used in certain corporate offices in Thailand with the agreement of the occupants as an effective way of reducing energy consumption. Although many other options such as improved efficiency and occupancy sensors can be used to achieve the same objective, it should be noted that the main purpose of this scenario analysis was basically to determine the magnitude of energy and emissions reduction achievable through this scenario for the case study office building and Thailand's office building stock. By assuming that lighting, office equipment, and air-conditioning systems are switched off for 1 h during office hours throughout the year, it is possible to have a reduction of approximately 1.8×10^6 kWh/

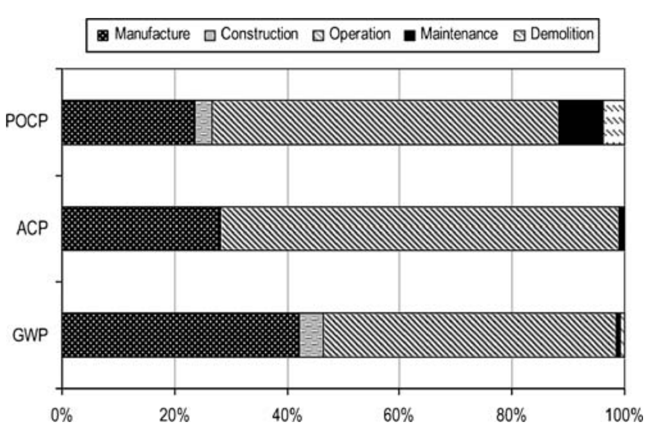


Fig. 8 The environmental impact contribution of an office building's life cycle phases

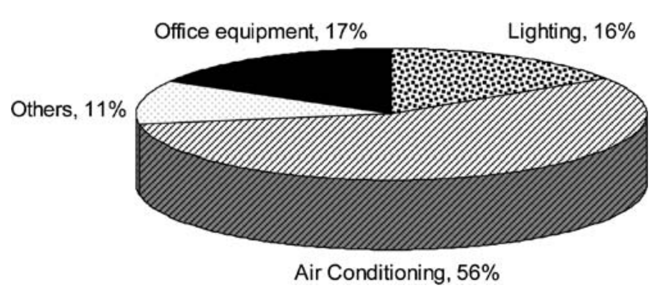


Fig. 9 Percentage end use electricity distribution (operation phase)

year with a corresponding reduction of 1.28×10^3 tons CO_2 per year, 4.1 tons SO_2 per year, and about 70 kg of C_2H_4 per year in the building's energy and environmental profile. On a national scale, this will contribute to reductions of about 7.8×10^6 tons CO_2 per year, 3.2×10^4 tons SO_2 per year and 424 tons C_2H_4 per year from Thailand's office building stock; and also to estimated reductions of 9.3% GWP, 4.9% AP and 0.2% C_2H_4, respectively, in emissions from the power generation sector. If combined, these simple no-cost energy conservation measures have the potential to achieve estimated reductions of 10.2% global warming potential, 5.3% acidification potential, and 0.21% photo-oxidant formation potential per year, respectively, in emissions from the power generation sector. Overall, the measures could reduce approximately 4% per year from the projected global warming potential of 211.51 Tg (Zola and Lim 2000) for the economy of Thailand.

5 Conclusions, recommendations, and perspectives

This study provides an estimate of the environmental impacts of a typical commercial office building in Thailand. The system studied included the entire life cycle of the office building, including manufacturing of building materials, construction, operation, maintenance, and demolition. Global warming potential, acidification potential, and photo-oxidant formation potential were determined. These categories were chosen as they are considered important and relevant to the geographical location of the study (Thailand), from an environmental and political point of view. The results indicated that the operation stage contributed most to the building's environmental impacts. Emissions for the impact categories considered (global warming potential, acidification potential, and photochemical ozone formation potential) at the operation phase also constituted the largest percentage of all releases to the atmosphere. At the manufacturing phase, steel reinforcement and concrete are the most significant materials both in terms of quantity, and also for their associated environmental impacts. The consideration of CO_2 emissions arising from non-energy process of cement manufacture can significantly increase the amount of greenhouse gas emissions from the manufacturing stage by about 8%. Life cycle distribution of environmental impacts is concentrated in the operational stage of the building. This correlates strongly with the energy requirement for operating the building. Consequently, significant reductions in the environmental impacts of buildings can be achieved through the practice of simple, no-cost energy conservation measures such as operating office building air-conditioning systems at set-point temperatures close to the standard indoor room set-point temperature of 26°C, and the practice of load shedding. The results obtained from this study indicated that implementation of these simple, no-cost energy conservation measures had the potential to achieve estimated reductions of 10.2% global warming potential, 5.3% acidification potential, and 0.21% photo-oxidant formation potential per year, respectively, in emissions from the power generation sector. Overall, the measures could reduce approximately 4% per year from the projected global warming potential of 211.51 Tg (Zola and Lim 2000) for the economy of Thailand. The government of Thailand has enacted policies to promote energy-efficiency in designated buildings. Existing building energy codes, utilized in combination with appliance standards, and labeling and information programs can reduce energy consumption and environmental burdens. New policies, for example policies which encourage building facilities managers to meet a recommended indoor set point temperature to minimize energy consumption for cooling in commercial buildings, could be introduced. In the long run, the environmental impacts of buildings will need to be addressed. Incorporation of environmental life cycle assessment into the current building code is proposed. It is difficult to conduct a full and rigorous life cycle assessment of an office building. A building consists of many materials and components. This study made an effort to access reliable data as quickly as possible on all the life cycle stages: manufacturing, construction, operation, maintenance, and demolition. Nevertheless, there were a number of assumptions made in the study due to the unavailability of adequate data. Further studies with more detailed, reliable, and Thailand-specific inventories for building materials end-of-life scenarios are recommended.

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