Energy & Buildings 190 (2019) 172–182

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

A multi-scenario life cycle impact comparison of operational energy supply techniques for an office building in Thailand

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ARTICLE INFO

Article history:
Received 24 September 2018
Revised 2 February 2019
Accepted 24 February 2019
Available online 26 February 2019

Keywords:
Life cycle assessment
Environmental impact
Energy intensity
Office building
Thailand
Solar energy
Lithium-ion battery
Thermal energy storage

ABSTRACT

This study provides a life cycle assessment (LCA) of a sustainably designed office building to be built in Thailand. The building has a gross floor area of 6300 m^2 and a lifetime of 50 years. An analysis of four different energy supply scenarios was performed to evaluate methods for reducing grid electricity demand with the goal of optimizing renewable energy usage and minimizing environmental impacts. The scenarios included: (1) the conventional, grid-dependent building, followed by (2) the addition of a rooftop photovoltaic (PV) system, (3) a PV system with lithium-ion battery storage, and (4) a PV system with an ice storage system. Scenarios 3 and 4 were included in this study as 16% of the electricity from PV was overproduced during the weekends when the building was unoccupied. The results show that scenarios 2, 3, and 4 reduced operational grid consumption by 33%, 37.8%, and 37.9% but increased metal depletion potential by 23.9%, 34.4%, and 29.0%, respectively. Ice storage led to the greatest reduction in lifetime environmental impacts. Efficient production and utilization of renewable energy in buildings is vital to reducing nonrenewable fuel dependence; however, it is necessary to minimize metal depletion in the implementation of such technologies.

1. Introduction

Faced with the finite nature of the planet's nonrenewable energy supply, Thailand's Ministry of Energy has implemented the Alternative Energy Development Plan to curb the environmental impacts from the country's growing energy consumption. The energy goals include reducing greenhouse gas emissions by 25%, increasing renewable energy dependence to 30%, and diversifying Thailand's grid mix overall [1]. To reach these energy savings goals, Thailand must look to its commercial business sector, which comprised an average of 21.2% of national annual energy consumption over the period 2002–2017 [39]. The environmental burdens of existing and future commercial buildings can be reduced by implementing energy efficient improvements such as sustainable design or renewable energy integration. Tropical regions with year-round sunlight such as Thailand have the potential to replace grid demand with solar energy [4]. Bangkok, Thailand experiences a daily average irradiation of 19 MJ/m^2 and the potential for solar energy is relatively high [4]. However, many renewable energy sources share the problem of intermittency, or irregularity in availability, which can lead to the failure to take full advantage of available energy without storage. Many countries circumvent this problem with a feed-in tariff which offers financial incentives for selling overproduced renewable energy to the grid, encouraging renewable energy reliance [27]. However, Thailand has no publicly accessible net energy metering or residential feed-in tariff, and as a result excess renewable energy goes unused [39]. Energy storage can potentially solve the problem of intermittency by making excess renewable energy usable.

As previous life cycle assessment (LCA) studies exist regarding either the benefits of sustainable design in commercial buildings or the practicality of rooftop photovoltaic (PV) to curb grid demand and decrease environmental impacts, only studies regarding residential housing or industrial buildings have sought to combine the two principles in a comparative LCA [4,9,13,40]. Similarly, independent LCA studies exist focusing on energy storage for renewable energy in the form of Li-ion batteries or ice storage, yet none present a comparison between the two storage technologies nor are they in the context of a sustainably designed commercial office building [11,13,14].

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https://doi.org/10.1016/j.enbuild.2019.02.038
0378-7788/

Nomenclature

AP	acidification potential
EPD	equipment power density
HT	human toxicity
LED	light-emitting diode
LPD	lighting power density
NLT	natural land transformation
PE	primary energy
PV	photovoltaic
EP	eutrophication potential
GWP	global warming potential
HVAC	heating, ventilation, and air conditioning
LCA	life cycle assessment
MD	metal depletion
ODP	ozone depletion potential
POCP	photochemical ozone creation potential
WD	water depletion

This study presents an analysis of multiple energy supply scenarios in the context of a sustainably designed office building in order to compare and optimize grid demand reduction methods. Given the baseline case of a typical commercial office building in Thailand with full grid electricity dependence, the scenarios considered include the conventional, grid-dependent building, the building with the installation of an on-site PV system, and the separate addition of two energy storage systems to the solar power system. The objective of this study is to identify and quantify the lifetime environmental impacts and offsets of a commercial office building as a result of implementing sustainable building design and employing state-of-the-art energy supply methods.

2. Methodology

2.1. Goal

The purpose of this study is to compare the environmental impacts, offsets, and energy savings resulting from multiple energy supply scenarios of a sustainable office building planned for construction in Bangkok, Thailand. This study will be used to (1) highlight key features of the base case building which contribute to its lower energy intensity compared to typical existing buildings in Thailand, and (2) determine the potential environmental impact offsets and energy savings of the building over its 50-year lifetime when different energy supply scenarios are employed. The results of this study are relevant to office buildings in climates with solar irradiation levels similar to Thailand, 18–22 MJ/m^2, office buildings equipped with PV panels, and regions lacking a feed-in tariff or net metering policy. This study is not intended for office buildings with energy demand patterns substantially deviating from that of the base case building, such as residential buildings or buildings located outside of a tropical climate. The results will inform energy consultants, architects, designers, policy makers, and businesses of key design aspects which influence the building's energy efficiency and overall environmental impact. The data used are generally from the best technology known. The results of this study are specific to geographical regions with climates similar to Thailand for a period of approximately 10 years.

2.2. Commercial office building case study

The case study building is a six-story sustainable office building to be built in Bangkok, Thailand (Fig. 1). The building will have a total gross floor area of approximately 6300 m^2, of which 4790 m^2 will be air conditioned. The building's energy will be supplied by the public electricity grid. Additional parameters of the building are listed in Table 1 below. The intention of sustainable design is to eliminate environmental impacts through thoughtful design choices that reduce water and electricity consumption. Commonly, sustainable design manifests in the use of low impact materials, energy efficient products, renewable energy sources, and energy efficient design which have a combined effect to reduce the product's impact throughout its lifetime [24]. This building employs sustainable design to reduce energy demand from cooling and lighting, which typically accounts for 70% of a building's operational energy demand [32].

Fig. 1. Perspective drawing of the building provided by architect.

To reduce cooling demand, natural ventilation measures, double-glazed windows, and external façades were implemented. To cool 20% of the building via natural ventilation some measures include: louver windows, windows with horizontal slats designed to allow air to flow in and out while blocking rain, and large ceiling fans which facilitate air circulation throughout the atriums. Reducing heat transmission through windows is two-fold. The windows themselves are double-glazed (lower heat transfer value) and external façades shade the glass paneling on the east and west faces of the building. The west face has a Polytetrafluoroethylene (PTFE)-coated tensile fabric façade which deflects heat, disperses sunlight for a natural atmosphere in the building, and cools air for natural ventilation. The east wall façade is a green wall which provides shading, radiant cooling, and a green atmosphere by incorporating plants into the structure to improve occupant comfort [17,23].

Reduced lighting demand can be attributed to extensive natural lighting measures and minimal electrical lighting infrastructure. In addition to glass paneling which allows direct sunlight to enter the building, solar tubes, a variant of skylights, redirect daylight to areas with insufficient natural lighting. To meet the lighting demand,

Table 1
Base case building characteristics.

Parameter	Characteristics
Office floors	Six above ground, one basement
Service life	50 years
Gross floor area	~6300 m^2
Floor	Cast-in-place and reinforced concrete
Floor finishes	Concrete screed, polished concrete
Ceiling	3.2 m height, suspended, gypsum plasterboard
Structure	Reinforced concrete
Envelope	Concrete brick, curtain wall, exterior textile facade
Foundation	Concrete slab
Walls (interior)	Concrete brick, curtain wall, gypsum plasterboard
Roof	Flat concrete

Table 2
Scenario descriptions.

Scenario 1/Base case	Sustainable office building, unmodified
Scenario 2	Office building with PV
Scenario 3	Office building with PV and Li-ion battery
Scenario 4	Office building with PV and ice storage

highly efficient local area network-connected light-emitting diode (LED) lights, which achieve illumination requirements while maintaining low energy consumption, were employed [26]. Although the building itself is more energy efficient and sustainable than a typical office building in Thailand, further improvements can be made to the building's operational phase to further reduce grid energy reliance [20]. The following section presents scenarios which transition the building's energy supply towards renewables.

2.3. Energy supply scenarios

The four energy supply scenarios to be compared are listed in Table 2.

Scenario 1, referred to as the "base case" sustainable office building described in the case study above, represents the building with no renewable energy production or storage technologies. The electricity demand of the building is met with the Thai electricity grid.

Scenario 2 considers the base case office building with the addition of 724 m^2 (327 panels) of 330W-capacity multicrystalline PV rooftop panels with an average lifetime efficiency of 15% accounting for 1% annual degradation, a typical rate for PV cells [15]. Each panel is mounted and fixed with a set of 4 25000W-rated inverters. For 6 h each day, the solar panels produce renewable energy which is immediately consumed during the building's operational hours. Due to the building's expected operation schedule, the building's energy demand decreases on the weekends and approximately 590 kWh of solar energy is overproduced each weekend.

Scenario 3 builds upon Scenario 2 with the addition of a Li-ion battery with 100% charge efficiency and 90% discharge efficiency. The battery has a capacity of 370 kWh and contains a $LiFePO_4$ cathode. A Li-ion battery was studied as this technology represents the future of battery storage due to its modernized cathode and anode materials, increasing efficiency, dropping Li-ion battery prices, greater specific energy, and longer lifetime as compared to a typical lead acid battery [6,18].

Similarly, Scenario 4 builds upon Scenario 2 with the utilization of thermal energy storage (TES) in the form of external melt ice-on-coil ice storage with a system efficiency of 90%. This system integrates with the building's existing chiller and uses overproduced solar energy to cool refrigerant and store energy in the form of ice. When cooling is needed, melted ice runs through the structure's fan coil units to provide cooling. This system was included in this study as it is a proven energy-conservation technology due to its high rated efficiency, environmentally benign impacts during operation, and easy integration into a building's existing chiller [30].

2.4. Scope

The system studied is a cradle-to-grave assessment and includes the entire life cycle of the commercial building, including manufacturing of building materials, construction, operation, maintenance, demolition and end of life (Fig. 2). Transportation for each life cycle stage is included as built-in transportation distances, energy consumption values, and environmental impact values based on the availability of the data in existing databases. The structure, envelope, lighting, and HVAC system are assessed within this study. Excluded from this study are operational water use, indoor air quality issues during the operational phase, and kitchen and sanitary fittings. Inputs consist of raw materials, electricity from the Thai grid, and diesel fuel while outputs include emissions to air, water, and soil. Both inputs and outputs contribute to a range of environmental issues. Inventory data originated from the Ecoinvent 3 software database, accessed through SimaPro 8 LCA software [29]. Manufacturing and assembly of the building, PV, and all parts of each storage technology were calculated manually in SimaPro based on market manufacturing and infrastructure data specific to Thailand when available, and global data otherwise, as global data represents averaged values for material manufacture, transportation, and end of life. Manufacture, construction, replacement, and end of life impacts associated with PV and each storage technology were summed with the base case office building to produce the operational module of each corresponding scenario. Materials for all scenarios were assumed to be manufactured, constructed, used, demolished, and disposed of in Thailand. The functional unit is defined as 6300 m^2 gross floor space of a commercial office building, of which 4790 m^2 will be cooled through central heating, ventilation, and air conditioning (HVAC), over a 50-year period.

The ReCiPe Hierarchist midpoint method, a comprehensive LCA methodology that combines Eco-indicator 99′ and CML 2002 with up-to-date impact categories, was used for life cycle impact assessment including the following impact categories: global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), natural land transformation (NLT), water depletion (WD), human toxicity (HT), and metal depletion (MD). An analysis of primary energy (PE) was also included within this study [12]. The impacts for analysis were selected based on their relevance to the environmental concerns associated with grid energy usage and manufacturing processes. The ReCiPe Hierarchist method of analysis is utilized as it is capable of calculating impacts for both regional and global scales, it provides a balance between individualist and egalitarian weighting perspectives, and it is used in modern building LCA studies [7,40].

2.5. Manufacturing

Base Case: The manufacturing phase of the building includes environmental impacts associated with building materials as well as energy used for the construction of the building. As the building is still in the design phase, a partial Bill of Materials was provided by the architectural design company to serve as a basis for the final building inventory. Literature values were used for the inventories of the HVAC system and elevator, while the fan inventory originated from the manufacturer [3,10,33]. Impacts for the façade originated from literature [28,37].

Energy Supply Scenarios: Inventory for the solar panels (Table A.1) and the Li-ion battery (Table A.2) were derived from literature and assumed virgin production of all input materials [21,44]. Material inventory of the solar panels was based on the specification of 327 PV panels (2m^2 surface area per panel) with a maximum power of 330 W and included mounters and inverters. To store an average of 590 kWh_{th} of excess electrical energy each weekend, it was determined the battery would need to charge a maximum of 295 kWh of energy per day on both Saturday and Sunday, and discharge at 90% efficiency a net 265 kWh per day of use. To size the battery, a typical maximum depth of discharge of 80% and average specific energy of 110 Wh/kg were used to calculate the total capacity (370 kWh) and weight of the battery [6,31,36,41,42,44]. Ice storage inventory was provided by a manufacturer in Thailand (Table A.3). In order to house 590 kWh of thermal energy, 25 m^3 of ice storage was used as the basis for the siz-

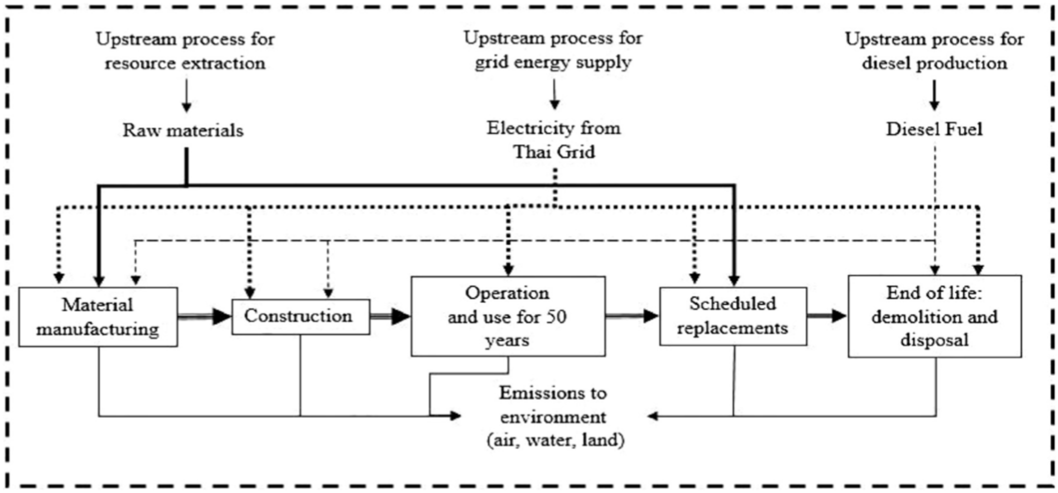

Fig. 2. System boundaries diagram.

ing of the storage tanks. The embodied energy of manufacture and assembly of the components in terms of kWh as well as the primary energy in the replacement phase and end-of-life are shown in Table A.4.

2.6. Construction

The building construction encompasses the grid electricity, diesel fuel, and associated combustion emissions from machinery required to construct the building. Energy is needed for lighting, power tools, and construction machinery for site preparation, structural and envelope installation, mechanical and electrical equipment installation, and interior finishing [34]. As the building is still in the design phase, the primary energy intensity for the construction of the building was determined using an approximation from a previous study in which the energy was determined to be 5% of the total embodied energy of manufacturing materials, allocated equally between electricity and diesel fuel [34]. This approximation has been employed in similar LCA studies [19,40].

2.7. Building operation

The activities in the use phase simulation included cooling and ventilating the building, as well as lighting and office equipment operation. From the anticipated weekly usage pattern of the office building (Table 3), the operational energy consumption was simulated through the Transient System Simulation Tool (TRNSYS) developed by the University of Madison Wisconsin [[38] Transient Systems Simulation Program, 2017]. Since operational energy use by custodial service on weekends is both negligible in comparison to the building's scheduled operational periods during weekdays and difficult to quantify, this study adopted the approach of similar LCA studies of office buildings in which energy consumption of the building during the weekends for lighting and HVAC was not taken into consideration [19,20,35,43].

Table 3
Base case building operation schedule.

Time Frame	Demand (kW)		
	Cooling	Lighting	Plug
Weekday			
Operation: 9:00–18:00	30–90	24	58
Non-operation: 1:00–9:00 and 18:00–24:00	0	0	24
Weekend			
Non-operation	0	0	24

The simulations were generated based on the following assumptions during weekday operational hours: occupancy rate of 0.04 persons per m^2, set temperature range of 25 - 27 °C [2], and a chiller coefficient of performance of 3.5. Artificial weather data for Bangkok was created from an approximation of Bangkok's weather patterns and sunlight irradiation over the last 20 years using United States Department of Energy weather database. TRNSYS simulations were conducted for a time span of one year (8760 h) and used to calculate the building's hourly electricity demand measured in kWh. Impact data for 1 kWh Thai grid mix are presented in Table A.5.

Base Case: all electricity demands were supplied by Thailand's electricity grid.

Energy Supply Scenarios: In Scenario 2, the building is supplied with both electricity from the grid, and electricity produced from the solar panels during the building's operation. In Scenarios 3 and 4, energy demand is fulfilled from the Thai grid, the direct electricity from solar panels, and energy stored in the form of electricity for the battery or energy stored thermally in the form of ice for the ice storage system. Reductions to grid demand due to replacement by renewable energy production or storage is considered an offset to the environmental impacts originating from the operational use phase in each scenario.

2.8. Maintenance and replacements

Base Case: Emissions from the maintenance stage were computed based on the expected material lifetimes provided by the architectural design company (Table A.5) and followed similar procedure as that used for the manufacturing of building materials. The impacts associated with replacement end of life, including disposal and transportation, were included within this phase of the building.

Energy Supply Scenarios: The PV cells have a replacement time of 25 years, the Li-ion battery has a lifetime of approximately 13 years, and the ice storage system has a lifetime of 15 years resulting in 1, 3, and 2 replacements during the building's 50-year life span, respectively [8]. All renewable energy supply scenarios assume no expected maintenance.

2.9. End of life - demolition and disposal

The final phase of the building's life encompasses the building demolition and the disposal of materials. To determine the impacts associated with the demolition and deconstruction of the building, the impacts associated with the production and combustion of diesel fuel used to power heavy machinery were calculated by adopting a literature value of 51.5 MJ/m^2 used in similar LCAs [19,40].

Base Case: For this study, all steel, aluminum, and polyethylene piping were assumed to undergo recycling as waste disposal, and impacts and offsets associated with such processes were extracted from the database. The remaining building materials were assumed to be landfilled at the end of life, aligning with the waste treatment results of similar studies [22,34].

Energy Supply Scenarios: End of life for the solar panels assumed recycling for the frame, composed of aluminum and plastic, and landfilling for the remaining components. End of life for the battery assumed landfilling for all materials as Li-ion battery recycling facilities do not exist in Thailand and lithium iron phosphate cathode recycling is not yet commercially available [16]. For the ice storage system, steel and polyethylene piping were assumed to be recycled, the insulating foam to be landfilled, water undergoing wastewater treatment, and ethylene glycol undergoing hazardous waste treatment for spent antifreeze.

3. Results and discussion

3.1. Base case office building

3.1.1. Life cycle impacts by building phase

Impacts originated predominantly from the use phase of the unmodified office building in several categories, including GWP, AP, POCP, NLT, and PE (Fig. 3). The results of the previously mentioned categories align with similar studies [19,32]. The use phase contribution to these categories is 85.4%, 69.7%, 82.3%, 89.8%, and 68.6%, respectively. The non-use phases (the combined impacts of manufacturing, construction, replacement, and end of life) contributed primarily to the impact categories of ODP, EP, WD, HT, and MD, comprising over 96% of each of these categories. Non-use phase impacts originate primarily from manufacture and replacement phases; in each impact category, there is a marginal offset to the overall impact resulting from end of life recycling processes. Minimizing use phase impacts in the alternate energy supply scenarios therefore has the potential to be substantially beneficial in five of the ten of the analyzed environmental impact categories and marginally beneficial to the remaining categories.

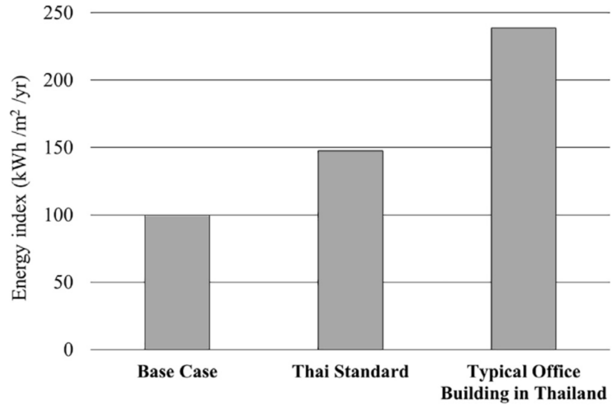

Fig. 4. Annual energy consumption per floor area.

3.1.2. Operational phase energy analysis

Operational energy demand of this building was compared to others based on the building energy index. Fig. 4 illustrates the literature value for the energy index of a typical office building in Thailand, found to be 238.7 kWh/m^2/yr [20].

The Thai Standard for electricity consumption in designated buildings (DBs), Thai buildings audited on the basis of energy use, was found to be 146.4 kWh/m^2/yr [5]. The building in this study was found to have an energy index of 99.8 kWh/m^2/yr, less than half that of the typical office building and roughly 68% of the Thai Standard value. Simulations were used to examine energy demand and usage patterns in the building and identify causes of its low energy index. Results are shown in Table 4; values for the Thai Standard originate from the Thailand New Building Energy Code for DBs [5].

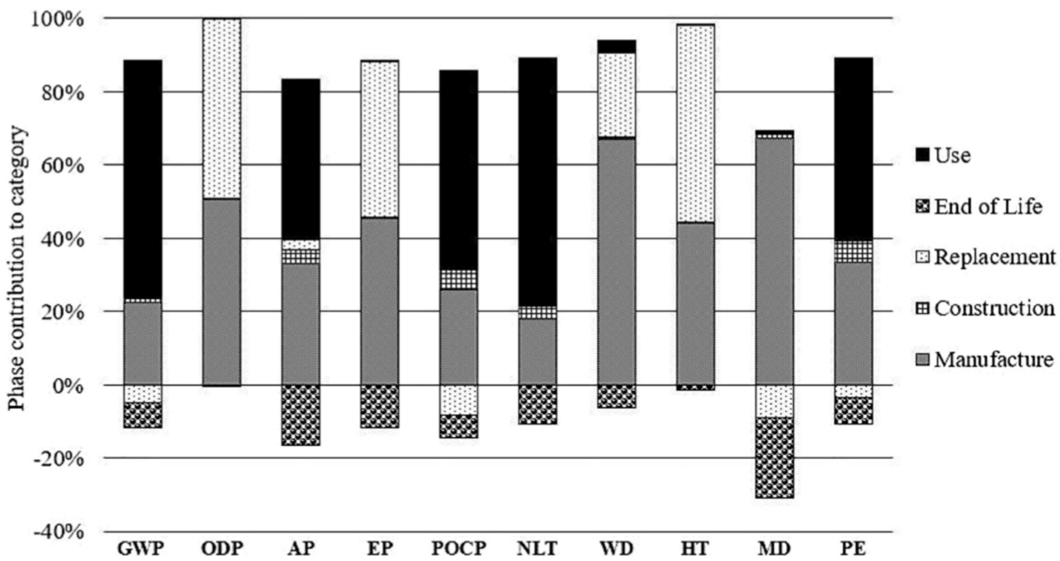

Fig. 3. Impact contribution of each life cycle phase of the base case office building.

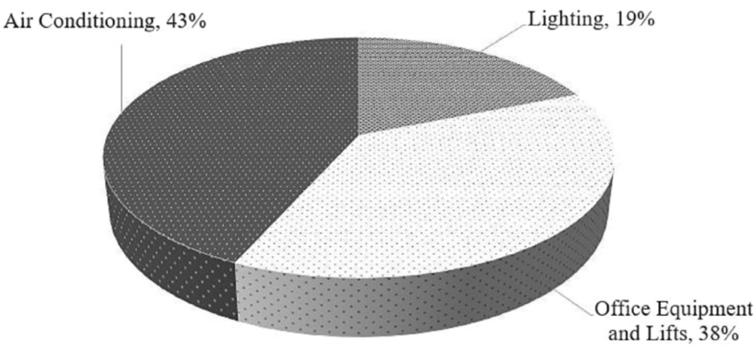

Fig. 5. Composition of operational energy consumption.

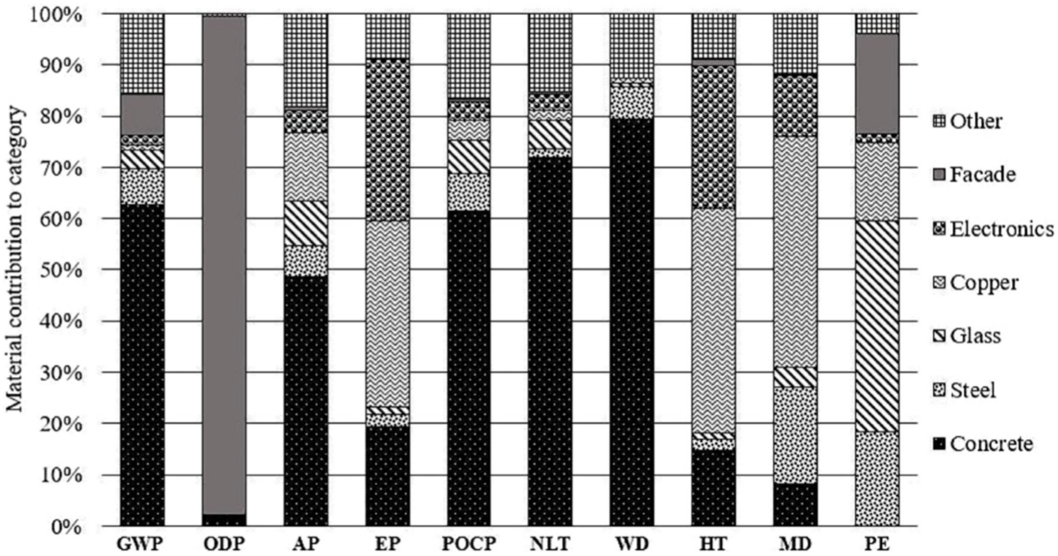

Fig. 6. Material contribution to each impact category of base case scenario.

Table 4
Energy index comparison of base case and Thai Standard office building.

Parameter (W/m^2)	Thai standard	Base case building
Overall Thermal Transfer Value (OTTV)	50	33.13
Roof Thermal Transfer Value (RTTV)	15	3.23
Lighting Power Density (LPD)	14	10.5

OTTV and RTTV are a measure of energy consumption of a building's envelope and rooftop, respectively, and thus the below-standard values for OTTV and RTTV in this building indicate it is designed to efficiently avoid excess heat absorption and subsequently has a lower HVAC demand. The LPD value is a standard for the mechanical illumination of the building, and the low LPD value of the base case building can be attributed to its natural lighting design incorporation. Equipment Power Density (EPD) includes office equipment, elevator operation, and other electrical usage in the building. The allocation of energy consumption by LPD (lighting) demand, EPD (office equipment) demand, and HVAC (air conditioning) demand are further broken down in Fig. 5. The daily usage period was based on the building's intended operational schedule (10 h per day, 5 days a week). Air conditioning represents a majority of the building's electricity demand, followed by equipment.

This distribution of the operational energy demand differs from that of another comprehensive study which details the typical energy distribution of eight separate countries; the typical percentage of air conditioning demand is closer to 55%, followed by lighting demand [32]. Air conditioning and lighting both occupy a below-average fraction of the total energy usage compared to building standards, and all categories have a lower power density than Thai Standard values, due to environmentally conscious components of the building design leading to its lower overall energy index even in a fully grid-dependent scenario.

3.1.3. Impacts from material manufacturing

Life cycle impacts tend to be dominated by the use phase, which diminishes the importance of the manufacturing phase; however, as energy efficiency improves and nonrenewable energy is phased out, the manufacturing phase will grow to be the largest contributor to many impact categories. For this reason, a breakdown of the material manufacturing phase of the building unequipped with PV or energy storage was evaluated. Fig. 6 shows the manufacturing phase impact contributions, representing the unmodified building's structurally embodied environmental burdens.

The listed materials constitute 80% of each impact category, while the 'Other' category accounts for 11 additional materials which constitute less than 20% of any impact category. Other materials include: concrete screed, insulation, aluminum, glazing, finishes, timber, gypsum, bricks, lights, iron, and plastic. Concrete comprises 92% of the building's total mass and contributes the majority of manufacturing phase impacts in six of the ten impact categories analyzed. The PTFE façade is the single largest contributor to ODP. Although it comprises only 0.01% of the building's total

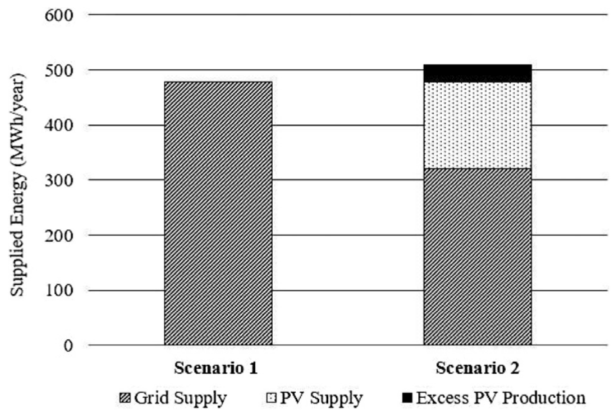

Fig. 7. Composition of operation energy supply.

mass, the façade comprises 98% of the entire ODP impact category for the manufacturing phase. This is due to the façade's high impact intensity coating material, PTFE, which contributes not only 99.99% of the impacts of the façade itself, but 94% of the ozone depletion category for the manufacturing phase. Copper, found in the elevator and HVAC system, accounts for 0.04% of the building's mass, but constitutes a majority of the manufacturing phase EP, HT, and MD; 36%, 44%, and 45%, respectively. Electronic components constitute only 0.001% of the building's mass; however, its impacts constitute 34% of manufacturing EP, 28% of manufacturing HT, and 12% of manufacturing MD. The environmental burdens from copper and electronics can be attributed to upstream processes such as mining, concentration, purification, and refining of mined metals [25].

3.2. Office building with rooftop PV system

3.2.1. Energy supply

Fig. 7 depicts the energy grid supply composition in Scenarios 1 and 2. Due to the solar power provided by the rooftop PV system in Scenario 2, annual energy consumption from the grid was reduced from 478.2 MWh to 320.3 MWh. The offset of 157.9 MWh is equivalent to 33% of the building's use phase energy; however, the actual production of the rooftop PV system was 188.6 MWh. 16% of total solar energy generated, 30.7 MWh, was produced during non-operational building hours and thus went unused. The solar power production had the potential to meet up to 40% of the building's energy demand if used in entirety. The offset of environmental burdens resulting from the 33% grid electricity reduction were subtracted from the use phase impacts in Scenario 2, and the resulting net lifetime impacts, including all non-use phase PV impacts.

Fig. 8 exhibits the impact changes associated with the addition of PV cells throughout the building's lifetime relative to the base case scenario of the building LCA. Accounting for both non-use phase impacts and use phase offsets, Scenario 2 reduced the building's net total energy consumption by 21%. Similar reduction trends were observed in the following impact categories: GWP (28%), AP (20%), POCP (26%), and NLT (29%). Scenario 2 resulted in a net increase in EP, WD, and HT by 6%, 4%, and 5%, respectively. A substantial increase of 24% for MD was observed. This dramatic increase can be attributed to the large embodied metal depletion values of the following metals within the PV system: Aluminum (2.0 kg Fe-eq/kg), Silver (1477 kg Fe-eq/kg), Copper (50.52 kg Fe-eq/kg), Tin (1513 kg Fe-eq/kg), and Lead (1.72 kg Fe-eq/kg).

3.3. Office building with PV system and energy storage system

Results for the breakdown of energy supply to the building in Scenarios 1–4, seen in Fig. 9, show that the addition of energy storage in Scenarios 3 and 4 offset approximately 7% of the electricity supplied by the grid; the Li-ion battery and ice storage system supplied an additional 22,931 kWh and 23,422 kWh respectively, equating to a 0.15% larger grid offset annually by ice storage. The closeness of these results was expected, as both storage technologies operated at the same efficiency, and both were sized to hold 590 kWh of energy per weekend, the average amount of PV overproduction. The 0.15% difference in grid reduction potential is marginal and thus it is assumed that the impact reductions resulting from the operational phase of the building are effectively the same. Therefore, the differences in the percent change of each impact category between Scenarios 3 and 4 in the context of Scenario 2 (building with PV) as seen below are a consequence of the en-

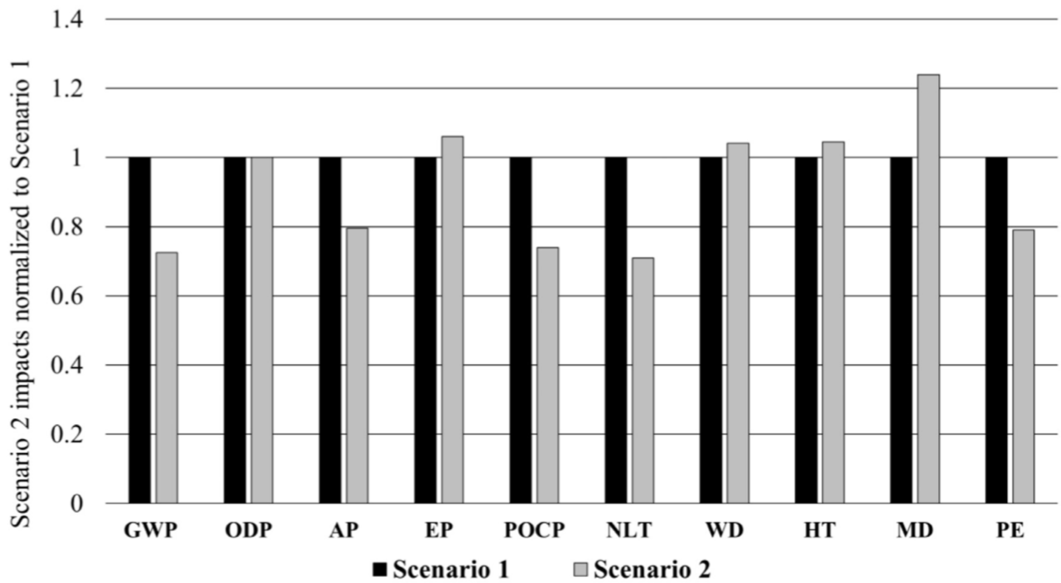

Fig. 8. Normalized impacts of Scenario 2 to Scenario 1.

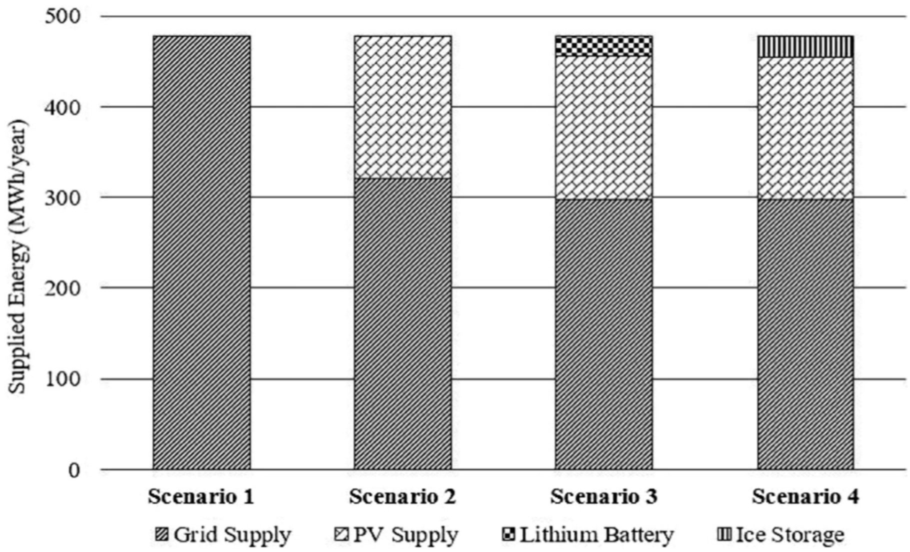

Fig. 9. Composition of operational energy supply per scenario.

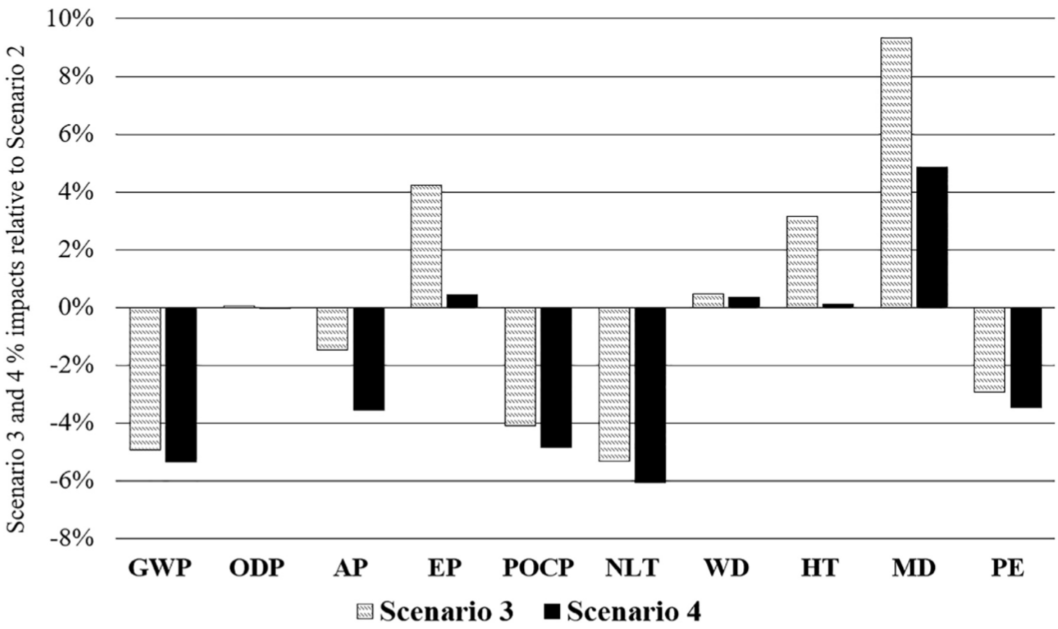

Fig. 10. Comparison of percent reductions to the building from energy storage.

vironmental burdens associated with the non-use phases of each storage technology.

Fig. 10 shows the percent impacts accrued by Scenario 2 when either Li-ion battery (Scenario 3) or the ice storage system (Scenario 4) are added to the building. Positive percent changes indicate increased impact burdens, while negative percent changes indicate impact reductions. The simulated results as well as the non-use phase impacts, consisting of each storage system's material manufacturing, the total lifetime replacements, and the end of life treatment, demonstrate that Scenario 4 outperforms Scenario 3 in all impact categories, including lifetime primary energy demand. The non-use impacts for Scenario 3 are primarily a result of the production of the battery's electronics including copper, manufacturing of the $LiFePO_4$ cathode, and landfilling of the battery. In Scenario 4, the combined impacts of the production and waste process of ethylene glycol account for 62–82% of the impacts across all impact categories, while impacts from the production of steel contribute 20–42% across all impact categories, excluding water depletion.

For impact categories concerning GWP, ODP, POCP, NLT, and WD, Scenarios 3 and 4 had similar lifetime impact reductions. The greatest differences were seen in the remaining five impact categories. For AP, Scenario 4 reduced the building's burdens 2.1% more than Scenario 3 due to fewer non-use phase inputs. In terms of EP and HT, Scenario 3 increased the building's impacts by 3.8% and 3%, respectively, while Scenario 4 increased impacts by only 0.4% and 0.1%, respectively. This drastic increase in impacts for Scenario 3 is due to the quantity and highly impact-intensive materials needed for the Li-ion battery.

Metal depletion differed the most between the two storage scenarios; Scenario 3 increased burdens by 4.4% more than Scenario 4, which can be attributed to characteristics of ice storage such

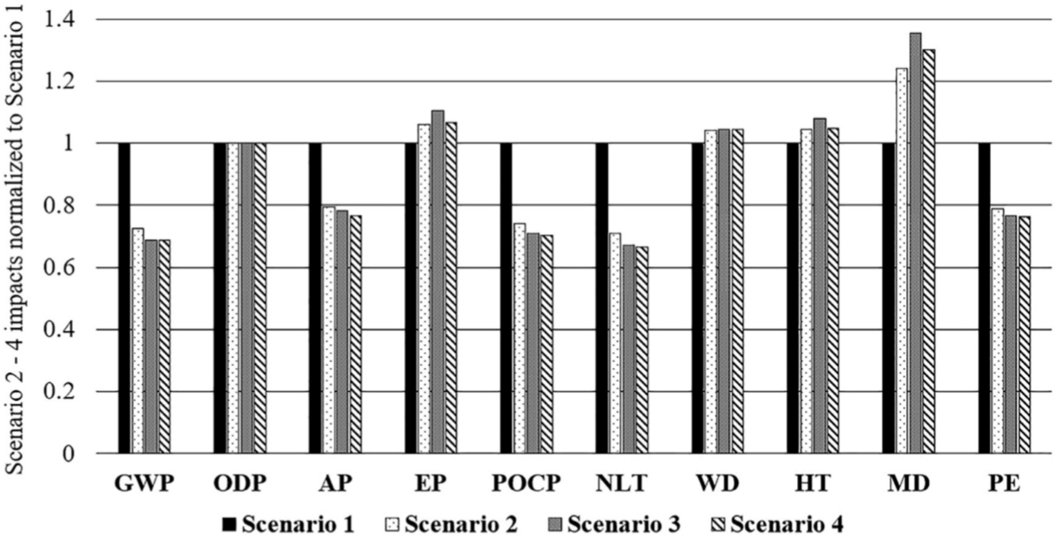

Fig. 11. Summary of impacts from Scenarios 2–4 normalized to Scenario 1.

as fewer replacements, lower total metal mass, less impact intensive materials, and end of life recycling. Due to the different lifetimes of the energy storage technologies, 13 years for Li-ion battery and 15 years for ice storage, the Li-ion battery incurs an additional replacement over the building's 50-year lifetime which leads to greater non-use phase impacts. In terms of total metal mass per technology, the Li-ion battery requires almost 5000 kgs more metal than the ice storage system throughout the building's lifetime. Additionally, the Li-ion battery requires four impact-intensive materials (Copper: 50.52 kg Fe-eq/kg; Aluminum:1.45 kg Fe-eq/kg; Electronics:32.44 kg Fe-eq/kg; and $LiFePO_4$:0.71 kg Fe-eq/kg), whereas the ice storage system requires only one (Stainless steel: 9.03 kg Fe-eq/kg). When assessing end of life treatment, the stainless steel used in the ice storage system is recycled, whereas the Li-ion battery assumes landfilling for all materials; this results in additional impact offsets in the non-use phase for the ice storage system [44].

Overall, the results consistently showed lifetime environmental advantages to implementing renewable energy usage as an alternative to full grid dependence (Fig. 11). Use phase impacts were initially substantially offset by the installation of solar power, and both storage scenarios subsequently affected the offsets in each category by an additional amount varying from −9% to +6%. It is important to note that Scenarios 2–4 drastically increased the building's metal depletion impacts as these technologies were primarily composed of a variety of metals.

4. Conclusions and recommendations

This study sought to minimize lifetime environmental burdens in a sustainably designed office building through alternative energy supply scenarios reducing grid electricity consumption in favor of renewable energy. Each of the energy supply scenarios was analyzed for its ability to reduce grid demand and minimize lifetime environmental impacts relative to the base case scenario. The ice storage system provided the greatest reductions to building lifetime impacts, reducing the primary energy demand of the building by an additional 3.5% compared to the building with PV and no energy storage. Scenario 4 consistently outperformed both Scenario 2 and Scenario 3 in lifetime reductions to each impact category.

The baseline of the building began at an advantage due to design elements that reduced cooling and lighting demands in the use phase, which reduced overall energy demand for studied energy supply methods. For a building lacking similar features, a larger capacity would be required from the grid or from any renewable energy utilizing technology; however, the trends of results would be no different. Future studies could consider substituting high impact materials like concrete and the PTFE façade for alternative materials when possible. Furthermore, impacts arising in the use phase constituted a majority of four of the analyzed impact categories as well as primary energy demand. Thus, reducing operational impacts was determined to be the best approach to reducing lifetime impacts. The optimization of solar power utilization with the use of technologies that allow for the recapture of excess energy production lead to a reduction in grid dependence; however, a holistic perspective in the form of an LCIA was used in order to more accurately represent the lifetime environmental benefits of each storage technology as it also considered the burdens embodied by the storage system itself, which were compensated by the grid avoidance in some, but not all, impact categories.

Storage technology implementation may pragmatically depend on a number of factors, including cost, a building's requisite discharge schedule and energy demand distribution, and the value of marginal increased impact savings compared to the implementation of solar power without storage. From a purely environmental standpoint, ice storage is ideal in this case study, but is limited in application by actual building cooling demand in various climates. The results of this study are therefore dependent on geographical location and climate. Because ice storage can offset only thermal demand and not electrical demand, only warm climates with year-round cooling demand would find maximum benefit from this system, and so for seasonal climates with seasonal cooling demand, the Li-ion battery is better suited due to its capacity to meet any form of electrical demand. As the results from this study are not conclusive as to which storage option would be best to optimize excess electricity from PV in non-tropical climates, it is recommended that future LCAs comparing energy storage systems be conducted to determine the extent of their benefits in different building sectors as well as different environments. Similarly, it is recommended that a comparative Life Cycle Cost analysis be performed for the energy technologies in order to provide a more holistic view for the application of these technologies.

Acknowledgments

The authors would like to thank EGS-Plan: Krittima Santiwattana for conducting the operation phase simulations and providing data and technical expertise pertaining to the operation phase, and Thanyatorn Khumpairoj, Karun Pantong, and Paveen Rojchanavisart for their assistance with the building's blueprints, architectural drawings, and a bill of quantity. Additionally, the authors would like to thank Prof. Richard Kamens for his support and guidance.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit-sectors.

Declarations of interest

None.

Appendix

A.1. Photovoltaic system inventory

Table A.1
Photovoltaic system inventory.

Component	Material	% Weight	Weight (kg)
Glass	Glass	76.22	6469
Encapsulant	EVA	5.75	486
Backsheet	PET	3.77	324
Frame	Aluminum	7.82	659
Cells and Ribbons			
	Silicon	4.70	400
	Silver	0.04	4
	Copper	0.74	63
	Tin	0.07	6
	Lead	0.04	4
Sealant	PIB, TPT	0.85	72
Inverter			61
Total		100	8548

A.2. Lithium ion battery inventory

Table A.2
Li-Ion battery inventory.

Material	% Weight	Weight (kg)
Cathode		
LiFePO4	43.76	1472.46
Aluminum Foil	1.97	66.30
Carbon Black	2.80	94.21
Styrene Acrylate Latex	3.63	122.12
Electrolyte		
Ethylene glycol dimethyl ether	16.29	547.81
Lithium Chloride	2.90	97.70
Separator		
Polypropylene	0.93	31.40
Polyethylene	0.93	31.40
Electronics		
Insulated gate bipolar transistor	1.04	34.90
Resistor, auxiliaries and energy	1.04	34.90
Anode		
Graphite	17.53	589.68
Carbon Black	0.52	17.45
Copper	4.77	160.51
Styrene Butadiene Latex	0.62	20.94
Packaging of Cell		
Polypropylene	0.52	17.45
Aluminum foil	0.73	24.42
Module packaging and electronics		
Polypropylene		336.36
Electronics		125.74
Totals	100	3825.74

A.3. Ice Storage inventory

Table A.3
Ice Storage inventory.

Component	Material	Amount
Inner storage	Stainless steel	517 kg
Outer storage	Stainless steel	326 kg
Insulation	High-density PU foam	212 kg
Piping	Polyethylene	120 kg
Phase changing liquid	Water	20.2 m^3
Circulating liquid	Water, 30% ethylene glycol	1.92 m^3

A.4. Non-Use Phase Energy Consumption in kWh

Table A.4
Non-Use Phase Energy Consumption in kWh.

Phase	PV System	Li-Ion Battery	Ice Storage
Manufacture + Assembly	284,184	93,636	52,450
Replacements	338,560	228,426	142,378
End of life	−54,605	20,567	19,287

A.5. Thailand electricity grid mix impacts for 1 kWh

Table A.5
Thailand electricity grid mix for 1 kWh.

Impact	Unit	Amount
Climate change	kg CO_2 eq	0.61872
Ozone depletion	kg CFC-11 eq	0.00000
Terrestrial acidification	kg SO_2 eq	0.00111
Freshwater eutrophication	kg P eq	0.00155
Photochemical oxidant formation	kg NMVOC	0.00155
Natural land transformation	m^2	0.00013
Water depletion	m^3	0.00011
Human toxicity	kg 1,4-DB eq	0.00142
Metal depletion	kg Fe eq	0.00062

A.6. Expected material lifetimes provided by the architecture company

Material lifetimes included in supplementary PDF titled: "Material Lifetimes".

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.02.038.

References

[1] Y Achawangkul, UNESCAP, Department of alternative energy development and efficiency (DEDE) ministry of energy, Thailand, 2 Mar. 2017 Last accessed 22 August 2018. www.unescap.org/sites/default/files/MoE%20_%20AE%20policies.pdf.
[2] ANSI/ASHRAE/IES Standard 90.1-2010, Performance Rating Method Reference Manual (Rep. No. PNNL-25130), 2016 Retrieved July 2018, from https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25130.pdf.
[3] S. Chen, System Dynamics Based Models for Selecting HVAC Systems for Office Buildings: A Life Cycle Assessment from Carbon Emissions Perspective (2011) RMIT University.

[4] N. Chimres, S. Wongwises, Critical review of the current status of solar energy in Thailand, Renew. Sustain. Energy Rev. 58 (2016) 198–207.

[5] S. Chirarattananon, P. Chaiwiwatworakul, V.D. Hien, P. Rugkwamsuk, & K. Kubaha. Revised Building Energy Code of Thailand: Potential Energy and Power Demand Savings (2006).

[6] K.C. Divya, J. Østergaard, Battery energy storage technology for power systems—an overview, Electric Power Syst. Res. 79 (4) (2009) 511–520.

[7] Y.H. Dong, S.T. Ng, Comparing the midpoint and endpoint approaches based on ReCiPe—a study of commercial buildings in Hong Kong, Int. J. Life Cycle Assess. 19 (7) (2014) 1409–1423.

[8] R. Dufo-López, J.M. Lujano-Rojas, J.L. Bernal-Agustín, Comparison of different lead–acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems, Appl. Energy 115 (2014) 242–253.

[9] J. Eskew, M. Ratledge, M. Wallace, S.H. Gheewala, P. Rakkwamsuk, An environmental Life Cycle Assessment of rooftop solar in Bangkok, Thailand, Renew. Energy 123 (2018) 781–792.

[10] Essence Technical Specifications (Rep.), 2017. Retrieved July 24, 2018, from Big Ass Fans website Last accessed 24 July 2018 https://www.bigassfans.com/docs/essence/cutsheet-essence.pdf.

[11] J. Heier, C. Bales, V. Martin, Combining thermal energy storage with buildings–a review, Renew. Sustain. Energy Rev. 42 (2015) 1305–1325.

[12] International Reference Life Cycle Data System (ILCD) Handbook, General Guide for Life Cycle Assessment—detailed guidance, first ed., European Commission, 2010 EUR 24708, JRC.

[13] M.I. Iqbal, R. Himmler, S.H. Gheewala, Potential life cycle energy savings through a transition from typical to energy plus households: a case study from Thailand, Energy Build. 134 (2017) 295–305.

[14] A. Jaiswal, Lithium-ion battery based renewable energy solution for off-grid electricity: a techno-economic analysis, Renew. Sustain. Energy Rev. 72 (2017) 922–934.

[15] D.C. Jordan, S.R. Kurtz, Photovoltaic degradation rates — an analytical review, Natl. Renew. Energy Lab. 21 (June) (2012) 12–29. US Department of Energy www.nrel.gov/docs/fy12osti/51664.pdf.

[16] P. Kerdlap, S.H. Gheewala, Electric motorcycles in Thailand: A life cycle perspective, J. Ind. Ecol. 20 (2016) 1399–1411.

[17] A.A. Khadra, N. Chalfoun, Development of an integrated passive cooling façade technology for office buildings in hot arid regions, WIT Trans. Ecol. Environ. 190 (2014) 521–533.

[18] S.M. Knufer, R. Hensely, P. Hertzke, P. Schaufuss, N. Laverty, N. Kramer, Electrifying insights: How automakers can drive electrified vehicle sales and profitability (Rep.), (January) 2017 Retrieved July 22, 2018, from McKinsey & Company website https://www.scribd.com/document/337911353/How-Automakers-Can-Drive-Electrified-Vehicle-Sales-and-Profitability-McK#download&from_embed Last accessed July 22 2018.

[19] O.F. Kofoworola, S.H. Gheewala, Environmental life cycle assessment of a commercial office building in Thailand, Int. J. Life Cycle Assess. 13 (2008) 498–511, doi:10.1007/s11367-008-0012-1.

[20] O.F. Kofoworola, S.H. Gheewala, Life cycle energy assessment of a typical office building in Thailand, Energy Build. 41 (10) (2009) 1076–1083.

[21] Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe, 2017 Rep. No. IEA-PVPS T12-12:2017.

[22] C.M. Mah, T. Fujiwara, C.S. Ho, Construction and demolition waste generation rates for high-rise buildings in Malaysia, Waste Manag. Res. 34 (12) (2016) 1224–1230.

[23] M. Manso, J. Castro-Gomes, Green wall systems: a review of their characteristics, Renew. Sustain. Energy Rev. 41 (2015) 863–871.

[24] J.F. McLennan, The Philosophy of Sustainable Design, EcoTone, Kansas City, MO, 2006.

[25] P. Nuss, M.J. Eckelman, Life cycle assessment of metals: a scientific synthesis, PLoS One 9 (7) (2014) e101298.

[26] A. Pandharipande, D. Caicedo, Smart indoor lighting systems with luminaire-based sensing: A review of lighting control approaches, Energy Build. 104 (2015) 369–377.

[27] Pembina Institute, How Feed-In Tariffs Maximize the Benefits of Renewable Energy, Sustainable Energy Solutions, 2017 www.pembina.org/re.

[28] PTFE Group of Companies, *Safety Data Sheet: fluorofab PTFE coated glass fabric with silicone adhesive* [Brochure], 2016. Author. Retrieved July 22, 2018, from Last accessed 22 July 2018 https://greenbelting.com/uploads/tx_rkdownloads/Silicone_Adhesive_PTFE_Coated_Glass_Fabrics_01.16.pdf.

[29] PRé Sustainability, Simapro, Software to Measure and Improve the Impact of Your Product Life Cycle, 2017 [Online], Available: pre-sustainability.com/simapro (accessed 13.06).

[30] B. Rismanchi, R. Saidur, H.H. Masjuki, T.M.I. Mahlia, Thermodynamic evaluation of utilizing different ice thermal energy storage systems for cooling application in office buildings in Malaysia, Energy Build. 53 (2012) 117–126.

[31] C.J. Rydh, B.A. Sandén, Energy analysis of batteries in photovoltaic systems. Part I: performance and energy requirements, Energy Convers. Manage. 46 (11–12) (2005) 1957–1979.

[32] R. Saidur, Energy consumption, energy savings, and emission analysis in Malaysian office buildings, Energy Policy 37 (10) (2009) 4104–4113.

[33] S. Salmelin, S. Vatanen, H. Tonteri, Life Cycle Assessment of an Elevator, 2002 Publication https://www.irbnet.de/daten/iconda/CIB2765.pdf Last accessed 22 July 2018.

[34] C. Scheuer, G.A. Keoleian, P. Reppe, Life cycle energy and environmental performance of a new university building: modeling challenges and design implications, Energy Build. 35 (10) (2003) 1049–1064.

[35] D. Shi, Y. Gao, R. Guo, R. Levinson, Z. Sun, B. Li, Life cycle assessment of white roof and sedum-tray garden roof for office buildings in China, Sustain. Cities Soc. 46 (2018) 101390.

[36] C. Spanos, D.E. Turney, V. Fthenakis, Life-cycle analysis of flow-assisted nickel zinc-, manganese dioxide-, and valve-regulated lead-acid batteries designed for demand-charge reduction, Renew. Sustain. Energy Rev. 43 (2015) 478–494.

[37] *Tensile Roof Fabric Structures: PTFE Coated Glass Cloth* (Rep.), 2010. Retrieved July 22, 2018, from Architen Landrell Associates Limited website Last accessed July 22 2018 http://pdfs.findtheneedle.co.uk/20406..pdf.

[38] The University of Wisconsin Madison, Transient Systems Simulation Program (Version 18) [Computer software]. 2017 (March). Retrieved September 23, 2018, from http://sel.me.wisc.edu/trnsys/.

[39] Thailand Ministry of Energy, Energy policy and planning office. Thailand Energy Statistics, Annual Report: Electricity Consumption for the Whole Country Classified by Sector (Table 5.3-4), 2017 Retrieved from http://www.eppo.go.th/index.php/en/en-energystatistics/electricity-statistic?orders[publishUp]=publishUp&issearch=1 Last accessed January 7 2019.

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

[41] L. Unterreiner, V. Jülch, S. Reith, Recycling of battery technologies–ecological impact analysis using life cycle assessment (LCA), Energy Procedia 99 (2016) 229–234.

[42] P. Van den Bossche, F. Vergels, J. Van Mierlo, J. Matheys, W. Van Autenboer, SUBAT: an assessment of sustainable battery technology, J. Power Sources 162 (2) (2006) 913–919.

[43] H.J. Wu, Z.W. Yuan, L. Zhang, J. Bi, Life cycle energy consumption and CO 2 emission of an office building in China, The Int. J. Life Cycle Assess. 17 (2) (2012) 105–118.

[44] M. Zackrisson, L. Avellán, J. Orlenius, Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles–Critical issues, J. Cleaner Prod. 18 (15) (2010) 1519–1529.