Life Cycle Energy Assessment of University Buildings in Tropical Climate

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Abstract: In recent years, there is a strong emphasis on embodied energy due to its significance in all buildings life cycle stages. Previous studies on embodied energy showed that building embodied energy ranges between 2% and 80% of total building energy. Singapore's Nanyang Technological University (NTU) has committed to achieve the vision of being the world greenest campus through various green initiatives. These include technological implementations on campus buildings to reduce its operational energy intensity. With improvement in operational energy intensity, the share of embodied energy increases. This study focused on the life cycle energy assessment of NTU's 22 academic buildings, making NTU the first university campus in Singapore and the Asia Pacific to conduct a large-scale life cycle energy investigation. Based on an assumed lifetime of 40 years, the average embodied energy for material, construction, transportation, maintenance and end of life stages constitute 1179.5 kWh/m^2 or 29.5 kWh/m^2 per year. The average operational energy is 11033.4 kWh/m^2 or 276 kWh/m^2 per year. Operational energy constitutes 90% of total life cycle energy while the remaining 10% is from embodied energy. The results provide suggestions to building professionals on ways to reduce the share of building embodied energy. These suggestions include material reusing and recycling, importing building materials from neighbouring countries and use of low carbon building materials.

Keywords: Embodied Energy, Life Cycle Assessment, University Building, Tropical Climate

1. Introduction

Rising level of greenhouse gases (GHG) has intensified global effort and researches to reduce the carbon emissions from human activities. Most research studies on building energy focused on improving operational energy intensity, which include electricity, heating, ventilation and air conditioning (HVAC). However, for the last few years, embodied energy or "gray" energy has become a hot research topic in the field of sustainable environment. Hence, it is imperative to reduce both operational and embodied carbon emissions to reduce GHG emissions. International Energy Agency (IEA) Annex 57 report has indicated that the embodied energy and embodied GHG emissions from the construction sectors account for around 20% of the world energy consumption and GHG emissions (Cheng et al., 2008; International Energy Agency, 2016). In particular, the embodied energy and GHG emissions from the manufacturing and construction sectors for developed countries like Singapore makes up 5% to 10% of the global CO2 emissions (International Energy Agency, 2016).

Embodied energy is the energy needed for the whole life cycle of a particular material. In buildings, embodied energy exists at nearly all life stages, which include the material, construction, transportation, maintenance and end of life stages (International Energy Agency, 2016). Based on most case studies on life cycle energy of buildings, operational energy usually constitutes a significant proportion of the whole life cycle energy (between 80% and 90% of total building energy) as compared to embodied energy (10% to 20%) (Kua and Wong, 2012; RICS, 2012). According to consolidated results of multiple studies on the building life cycle energy, embodied energy varies between 2% to 80%. These values differ based on various factors, which include building types, research boundaries and climate (Ibn-Mohammed et al., 2013). The results of the embodied energy range from numerous studies are shown in Figure 1. For example, the embodied energy percentage of a Zero Energy Building (ZEB) is usually more than 90%. A study by Takano et al. showed that embodied energy could contribute up to 46% of the total life cycle energy for low energy buildings and up to 38% for conventional buildings (Takano et al., 2015). Based on a lifetime of 50 years, Thormark highlighted the embodied energy of a low energy Swedish dwelling is around 45% of total energy used (Thormark, 2002). Pacheco-Torgal et al also emphasized as the operational energy improves with better insulation, the relative share of embodied energy will be greater in the energy equation (Pacheco Torgal et al., 2016). Another study by M Cellura et al. proved that the embodied energy impact of tropical buildings is significantly higher than the buildings in cold climate. The reason is tropical buildings like in Singapore do not have energy demand for heating. Hence, this reduces the building's operational energy (Cellura et al., 2014). Overall, the above examples highlighted the significance of embodied energy throughout the building lifetime especially for buildings in the tropical climate.

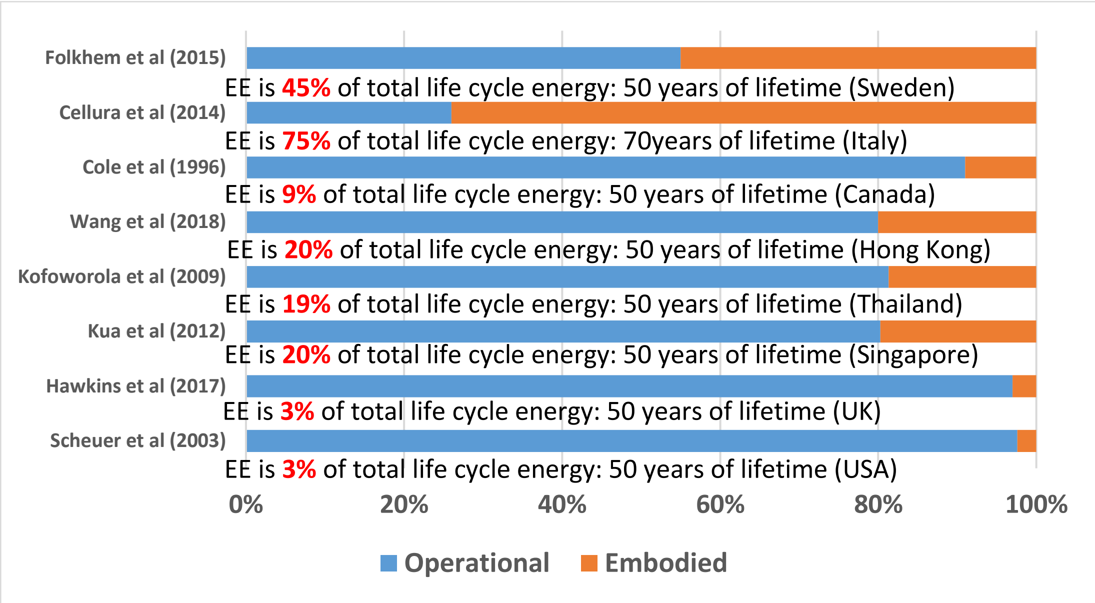

Figure 1 The range of embodied energy (EE) as part of the whole building life cycle energy from different studies

Multiple countries have implemented numerous plans to reduce the relative share of embodied carbon or energy of buildings through policies and programmes. There are several existing policies and building energy guidelines on embodied energy mainly from European countries. In contrast, there is a lack of embodied energy policies and guidelines in Asian countries. For example, in Switzerland, Life Cycle Assessment (LCA) of buildings is required for all government buildings in major Swiss cities like Zurich. Besides that, the city of Zurich has also launched "2000 Watt Society" campaign to encourage public participation in achieving 2000 Watt per capita. Under this initiative, the 2000 Watt per capita includes both operational and embodied GHG emissions. In the Netherlands, it is mandatory for new residential and office buildings with Gross Floor Area (GFA) greater than 100 m^2 to report their embodied carbon during the application of building permit (Zizzo et al., 2017). Regarding the embodied carbon policy in Singapore, Singapore Building Construction Authority (BCA) has included assessment of embodied carbon of building materials as part of the Green Mark Scheme (GMS), which is US LEED equivalent (BCA Singapore, 2010).

In recent years, Singapore has poured in huge resources in developing and implementing sustainable initiatives to reduce its carbon footprint. These include shifting to clean energy resources like solar and wind power, zero energy building and electric vehicles. Since 2005, Singapore BCA has implemented Singapore Green Mark Scheme (GMS), which aims to encourage buildings owners to reduce building carbon footprint via BCA recommended guidelines (BCA Singapore, 2010) as the construction sector contributes a significant amount of GHG emissions.

Aligned with Singapore's goal to reduce carbon emissions, Nanyang Technological University (NTU), a world-class institution aims to be one of the greenest campuses in the world through the implementation of various green initiatives. NTU spearheads the effort in Singapore to reduce greenhouse gas emissions in order to meet its commitments under the Paris Agreement. NTU has also set a vision to achieve a 35% reduction in energy, water and waste intensity by the year 2020. Some initiatives include high-energy performance material for tropical building envelope, use of chilled ceiling and new generation thermal insulation film (EcoCampus NTU, 2018). All other projects to reduce NTU campus operational energy intensity could be found in EcoCampus NTU. As the largest university campus in Singapore, NTU houses more than 200 buildings with the highest Green Mark Certification in Singapore. This shows NTU commitment in incorporating sustainability in its operations. Recent technological implementations (infrastructure and systems) in NTU are aimed to reduce the operational energy intensity, which are evident with the implementation of new technologies like smart sensors, energy information analytics and solar panels. Although building operational energy contributes significantly towards building carbon emissions, the embodied energy within the buildings should not be neglected. On top of that, there are no efforts or projects to address the impact of embodied energy for NTU buildings. Therefore, there is a need to investigate NTU's embodied carbon footprint to evaluate NTU impact on global warming.

Although there are several embodied energy studies of academic buildings, the number of such studies is still lower than the number of embodied energy studies on commercial and residential buildings. Some studies on academic buildings include a case study of five academic buildings in University College London. The investigation revealed that the average embodied energy of the five buildings was 250 kWh/ m^2 (Hawkins and Mumovic, 2017). Another study at the University of Michigan, United States showed that a six-storey academic building had an overall embodied energy of 7 GJ/ m^2. This is equivalent to 1950 kWh/m^2 of embodied energy intensity (Scheuer et al., 2003). Buchanan Building at the University of British Columbia, Canada recorded a global warming potential of 32.46kgCO2e/kg (Cortese 2009). Other examples include the LCA assessment of a university building's renovation based on conventional and Passivhaus standard (ENERPHIT) in Spain. Based on a 50-year lifetime, the energy savings achieved using ENERGPHIT renovation (9.6 x10^7 MJ) is 30% more than conventional renovation (7.3 x10^7 MJ). This is despite the embodied energy of ENERGPHIT renovation is much higher (Sierra-Pérez et al., 2018). In Singapore, there is no published study of embodied energy for academic buildings. However, there are embodied energy studies on other types of buildings. Kua et al. study on the embodied energy of a Singapore commercial building indicated that the building had an average material embodied energy of 27,900 MJ or 150 MWh/ m^2 (Kua and Wong, 2012).

1.2 Objective

The primary objective of this project was to conduct a detailed life cycle assessment of buildings in NTU. All life cycle stages were taken into account. The stages include the material, construction, transportation, operational, maintenance and end of life stages. Besides that, based on the results, some recommendations were made on how to reduce the relative share of embodied energy impact in buildings. The results will serve as a benchmark for future embodied energy studies in NTU and act as a guideline for future building development in NTU and Singapore.

2. Project Scope and Methodology

2.1 Case Study Description

22 buildings in Nanyang Technological University (NTU) were selected as the case study buildings in this study. In this study, the selected buildings are academic buildings with laboratories and classrooms. These buildings are mainly reinforced concrete buildings. Out of the 22 buildings, 20 buildings have concrete faced while only two buildings have glass curtain wall as main façade. The total Gross Floor Area (GFA) of all studied buildings is around 440,000 m^2 with an average GFA of 20,000 m^2. The number of floors for all case study buildings is between 5 floors to 9 floors. As all buildings differ in GFA, the embodied energy value were calculated in kWh per GFA (kWh/m^2). The lifetime of all buildings was assumed at 40 years. This assumption is similar to an embodied carbon study in Singapore that assumed a 30-year building lifetime (Kua and Wong, 2012).

2.2 Study Scopes, References and Methodology

According to Singapore BCA Carbon Calculator for embodied carbon calculation (BCA Singapore, 2017), it is compulsory to declare the amount of concrete, steel and glass used for non-residential buildings. The declaration is needed to earn points under the Green Mark Scheme especially for Green Mark Platinum (Highest Green Mark certification). This requirement reflects that the key contributors of building embodied carbon footprint are concrete, steel and glass. Hence, the research team put the focus on the three building materials and other building materials in which the data were available. Besides that, based on Wang et al. study, it was found that concrete, steel and glass usually constitute the largest percentage in embodied energy impact (Wang et al., 2018). Based on a report from the Royal Institute of Chartered Surveyors, it is highly recommended for studies to focus only high-embodied energy impact materials for embodied energy calculation. The reason is many building components have negligible environmental impacts that provide restricted opportunity to achieve embodied energy savings (RICS, 2012).

In this study, the following boundaries were made

Boundaries

1. The scope of this study encompassed the following phases which is illustrated in Figure 2

- Material Phase (EEm)
- Construction Phase (EEc)
- Transportation Phase (EEt)
- Use Phase (Operational) (OE)
- Use Phase (Maintenance) (EEr)
- End of Life (EEeol)

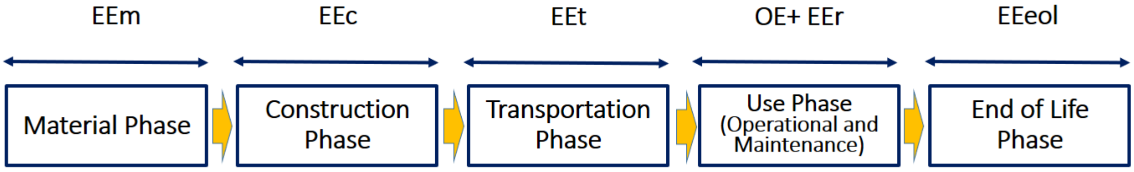

Figure 2 Life Cycle Boundaries for NTU Study

2. Only major building materials were include in this study, which include concrete (Not including foundation, steel (Including reinforcement bar) and glass. External structures like building foundation

were estimated based on previous LCA studies on building foundation (Lotteau et al., 2017; Meneghelli, 2018). The analysis on building foundation will be included at a separate section.

3. Other building materials like carpet, wood, plaster and aluminium were included in this study. For the calculation of recurring embodied energy in the maintenance phase, the focus was on building facades and finishes.

4. Boundaries set for wall classification include

External wall were assumed as concrete

Walls around lifts, stairs and toilets were assumed as concrete.

One of the main references for building LCA is the ISO for Life Cycle Assessment (ISO 14040 and 14044) (ISO 2006a, 2006b). Based on both guidelines, LCA researches for embodied energy should include: defining scope and goal, inclusion of life cycle inventory, life cycle impact assessment and results analysis. Therefore, it is imperative to define the scopes and boundaries for embodied energy studies. Different studies have different results due to use of different scopes, boundaries and embodied energy coefficients. Besides ISO, another reference is the EN15978 Sustainability for Construction Works-Assessment of environmental performance of buildings-Calculation method (CEN 2011b). According to BS EN 15978, the system boundaries include all life cycle stages: Product (Modules A1-A3), Construction Process (Modules A4-A5), Use (Modules B1-B7), End of Life (Modules C1-C4), and benefits and loads beyond system boundary (Module D) (BSI, 2011). Based on this standard. Information from the product stage should be derived from the Environmental Product Declaration (EPD) or other data sets that are in line with EN 15804 (Achenbach et al., 2017).

In this study, Building Information Modelling (BIM) was mainly used for quantification of building materials. For building materials that cannot be extracted from BIM, other data sources like architectural plans and Concrete Usage Index (CUI) were used.

Based on previous embodied energy studies, Building Information Modelling (BIM) is regarded as one of the most innovative approaches to quantify building materials. The reason is that there is no need for manual calculation that is costly, laborious and time-consuming.

In general, there are three main methods to analyse embodied energy, which include process-based analysis, input-output analysis and hybrid input-output analysis (Hong et al., 2016). The process-based analysis was used in this study in which the embodied energy coefficients were mainly derived from UK Inventory of Carbon and Energy (ICE), Singapore BCA Carbon Calculator dataset, ecoinvent and other sources. The reason is that Singapore does not have a database on the environmental impact of its building materials. One example is steel in which Singapore imports steel mainly from China, Australia, Indonesia and other countries. The global average data for the embodied energy of steel from various sources (Hammond and Jones, 2011; ecoinvent, 2018) ranges from 7.2 MJ/kg to 35 MJ.kg. Due to no local embodied energy data of steel, the project team assumed the embodied energy of secondary steel to be around 12 MJ/kg. Similarly for concrete, the embodied energy of concrete was assumed to be 1 MJ/kg, which is similar to Kua et al and ICE database (Hammond and Jones, 2011; Kua and Maghimai, 2016). Although the ICE database is based on statistics in the United Kingdom, ICE remains one of the most comprehensive embodied energy data sources up to date (Hammond and Jones, 2011). In most embodied energy studies, the functional unit of embodied energy is expressed in MJ. The value on MJ could be converted to kWh using the equation of 1 kWh = 3.6MJ.

2.3 Data Sources

In this study, there were three data sources for building materials quantification

a. Revit models (Building Information Modelling)

Revit models of 22 academic buildings were analysed to find out the total volume of concrete, steel and glass used. Through creating "Material Take Off" schedule in Revit, individual volume of different building materials could be determined. The data was consolidated and the material weight was calculated using the density formula. More details are further elaborated in Section 3.

b. Architectural plans and on-site measurement

Architectural plans were referred to check the accuracy of BIM data on building structures volume like wall, slab and beam, Various on-site measurements were conducted to countercheck with the information in the architectural plans and also to determine other parameters like floor height.

c. Concrete Usage Index (CUI)

According to Building Construction Authority (BCA) Green Mark Scheme (BCA Singapore, 2010), BCA requires all Green Mark certified building owners to calculate the building CUI values for Green Mark certification. This method allowed the team to calculate the total volume of concrete accurately. However, only the CUI values for newer buildings were available.

The embodied energy of each building material was based on the following databases.

1. University of Bath Inventory of Carbon and Energy (ICE) (Hammond and Jones, 2011)

2. Singapore Building Construction Authority (BCA) Carbon Calculator (BCA Singapore, 2017), which is based on data from University of Bath, World Steel Association and other related sources.

3. ecoinvent (ecoinvent, 2018)

Table 1. Embodied Energy of Selected Building Materials

Materials	Embodied Energy (MJ/kg)	Reference
Concrete (32/40MPa)	1.03	(Hammond and Jones, 2011; BCA Singapore, 2017)
Steel (Virgin)	35.3	(Hammond and Jones, 2011; BCA Singapore, 2017; Kua and Maghimai, 2016)
Steel(Recycled)	12	(Hammond and Jones, 2011; BCA Singapore, 2017)
Glass	28	(Hammond and Jones, 2011)
Aluminium	220	(Hammond and Jones, 2011; BCA Singapore, 2017)
Aluminium(Recycled)	10	(Hammond and Jones, 2011; BCA Singapore, 2017)
Plasterboard	6.75	(BCA Singapore, 2017)
Bricks	3	(Hammond and Jones, 2011; BCA Singapore, 2017)
Wood	15	(BCA Singapore, 2017)

3. Life Cycle Inventory for NTU buildings

3.1 Material Phase (EEm)

The embodied energy during the material phase (EEm) is divided into energy required to extract raw materials, manufacturing process and transportation. However, only the former two processes are usually considered due to the insignificance of transportation from the extraction site to manufacturing site. According to two case studies in tropical countries (Singapore and Thailand) (Kofoworola and Gheewala, 2009; Kua and Wong, 2012), the authors found that concrete and steel accounted more than 70% of the total embodied energy emissions. This clearly reflects concrete and steel are the key contributors of building's material embodied energy. The process analysis methodology by Kua et al. was employed in this study to investigate the embodied energy during materials, construction and transportation stages (Kua and Wong, 2012). All embodied coefficients were based on the sources mentioned in Section 2.2. As the information of steel are not available in the BIM models, the assumption of 110kg of reinforcement steel in 1m^3 of concrete was used. The assumption was based on the previous studies in Singapore and also from other references. The range from these studies is between 100kg and 130kg of reinforcement steel in 1m^3 of concrete (Kua and Maghimai, 2016; Ong and Lee, 1997). The research team also found some flaws in the BIM models in which various BIM models do not have the beam components. To overcome this problem, the Concrete Usage Index (CUI) of a similar NTU academic building was calculated. The results showed that the beam volume is around 80% to 95% of the slab volume (Almost equal to the slab volume) (NTU Office of Development and Facilities Management (2016). Other related studies also displayed similar results (Mahamid 2017; Guerra et al., 2019). Hence, the aforementioned assumption was used to fill the missing beam information for various NTU buildings.

The embodied energy during the material phase (EEm) can be expressed (in MJ) as

$$EEm = Vm \times \rho \times EEC \qquad (1)$$

Vm: Volume of materials (m^3)

ρ: Density of materials (kg/m^3)

EEC: Embodied Energy Coefficient (MJ/kg)

For the calculation of material embodied energy, as most steel products in Singapore are usually in the form of secondary steel, the embodied energy coefficient of secondary steel was used in this study. Another reason of choosing the EE coefficient of secondary steel is the 91% recycling rate of steel based on Singapore NatSteel data. The same source also indicates that the high proportion of secondary steel in new steel products (Kua and Maghimai, 2016).

3.2 Construction and Transportation Phase (EEc and EEt)

Due to lack of information on the construction energy, the study assumed a construction energy of 120 MJ/m^2 (Cole and Kernan, 1996). The construction energy (EEc) for buildings can be expressed as

$$EEc = 120(MJ/m^2) \times \text{Gross Floor Area (GFA)} (m^2) \quad (2)$$

Singapore mostly imports building materials from other countries due to its lack of natural resources and spaces for manufacturing (Gursel and Ostertag, 2016). In this study, it was assumed that all materials were imported from other countries. One example is concrete which mainly consists of cement, sand and aggregates. Each of the components usually originates from different countries. As the information on the origin of materials was not available, the countries of origin for each building materials were selected based on United Nations commodity trade statistics database for Singapore (Gursel and Ostertag, 2016) and also (Atlas.media.mit.edu, 2017). The database provides information on Singapore's materials import volume from different countries. Using the example of concrete, based on Kua's research, 1 kg of concrete block is assumed to have 1 part of Ordinary Portland Cement, 2 parts of sand and 3 parts of gravel. Hence, for each component, the assumption of the countries of origin was based on the UN commodity trade database (Kua and Maghimai, 2016) and Atlas.media.mit.edu. The energy from the transportation stage (EEt) largely depends on the mass of building materials, the distance between the manufacturing site and construction site, and also the transportation energy for different transportation modes. The functional unit for transportation mode is in MJ/tonne.km in which each mode of transport has different embodied energy impact. In this study, the assumed transportation modes were 35-tonne trucks for land transport and diesel-driven ship vessels for deep sea transport (Cannon Design, 2012). The distances of land and sea transport were calculated based on https://sea-distances.org/ and google maps (Sea-Distances.org, 2018). The fossil fuel energy is 0.94MJ/tonne.km and 0.16 MJ/tonne.km for 35-tonne truck and ocean shipping respectively (Cannon Design, 2012).

Overall, the energy for transportation (EEt) is the multiple of material mass, transportation distance and embodied energy for a particular mode of transport. Therefore, the energy from transportation (EEt) can be expressed (in MJ) as follows.

$$EEt = Mi \times Di \times EEC\ transport \quad (3)$$

Mi: Mass of transported materials

Di: Distance between Singapore and countries of origin (km)

EEC transport: Fossil fuel energy for a particular mode of transportation (MJ/tonne.km)

3.3 Use Phase (Operational) (OE)

NTU buildings' operational energy was based on real-time data in which the daily real operational energy use was obtained from the existing Building Metering System (BMS) on campus. The operational energy include electricity for cooling, lighting, electrical appliances and plug loads. The data was collected from NTU Financial Year 2012 to 2017. The BMS system collects monthly data for electricity consumption for each building via sub-metering.

3.4 Use Phase (Maintenance) (EEr)

The recurring embodied energy is defined as the embodied energy needed for retrofitting and maintenance of building materials, facades, finishes and other materials. According to Junnila et al., the recurring embodied energy could constitute 5% to 10% of the total life cycle energy (Junnila et al, 2006). According to Dixit et al., the recurring embodied energy strongly correlates with the lifetime of the buildings as the number of retrofitting and maintenance highly depends on the building lifetime (K.Dixit et al., 2014).. Based on Cole's study of different building lifetimes (25, 50 and 100 years), the recurring embodied energy was 1.3, 3.2 and 7.3 times of the embodied energy during the material, construction and transportation stages (Cole and Kernan, 1996). In this study, due to data limitation, only the main building materials and finishes were included for calculation of recurring embodied energy. The lifetime of the buildings was assumed at 40 years. Based on references on building materials lifespan (Carbon Leadership Forum, 2018), the replacement frequency was calculated according to the average lifespan of the materials. The information is shown in Table 2.

Table 2. Life expectancy and replacement frequency of studied building materials and finishes

Materials	**Lifetime (Years)**	**Replacement frequency (For 40 years)**
Concrete	50+ (Throughout building lifetime)	0
Steel	80+ (Throughout building lifetime)	0
Glass	50 (Throughout building lifetime)	0
Carpet	11	3
Plaster	10	3
Paint	5 -7	5
Flax insulation	20	1
Tiles	50+ (Throughout building lifetime)	0
Aluminium (Frame)	35-50	0
Wood Vinyl	20-30	1

Hence the recurring embodied energy (EEr) can be expressed (in MJ) as follows.

$$EEr = Vm \times \rho \times EEC \times RF \quad (4)$$

Vm: Volume of materials (m^3)

ρ: Density of materials (kg/m^3)

EEC: Embodied Energy Coefficient (MJ/kg)

RF: Replacement frequency within building lifetime

3.5 End of Life Phase (EEeol)

In general, the end of life phase (EEeol) is categorized into demolition, transportation of waste materials, recycling and waste landfill/incineration. As the recycling benefits specifically for steel had already accounted during the calculation of material embodied energy (EEm), only the energy needed for recycling and waste sorting was taken into account in this phase. Based on multiple studies on Life Cycle Assessment of buildings, most studies excluded the end of life phase from the analysis of building life cycle energy (Meneghelli, 2018; Wang et al., 2018). This is due to the insignificance of demolition or disposal energy as compared to the whole life cycle energy. Studies have shown that demolition energy usually constitutes less than 1% of overall life cycle energy (Meneghelli, 2018). However, there are also studies that highlight the importance of end of life stage. This is evident especially with the potential energy savings from reusing and recycling of demolished building materials. For example, Thormark (Thormark, 2002) in his study stated approximately 37%-42% of embodied energy could be saved through recycling of building materials.

There was no available data to calculate the demolition energy, which include demolition schedule or types of machinery used for demolition. Therefore, assumptions on demolition energy were made based on Cole's study and report from the US Advisory Council on History Preservation (Cole and Kernan, 1996; US Advisory Council on History Preservation, 1979). The energy for demolition was assumed at 90 MJ/m2, which was based on the Cole's study.

For energy of waste transportation, the distance between buildings and sorting centre was assumed based on Kua's study. The study accounted for the distance of a sorting centre at the northwestern part of Singapore and the buildings to be 35km (Kua and Wong, 2012) Under the same circumstance, it was also assumed that the trucks were transporting the waste at full loads.

There are multiples scenarios for waste management, which include landfill, incineration and recycling. In this study, the most common end of life scenarios (average values) for concrete and glass was based on various studies (Steelconstruction.info, 2019; Zero Waste SG, 2014). For other building materials, it was assumed that these materials would be sent to landfill. The details of the waste management for both concrete and glass is shown in Table 3.

Table 3 End of Life Scenarios for Concrete and Glass

Materials	Current End of Life Scenario
Concrete	20% sent to landfill 80% for recycling
Glass	80% sent to landfill 20% for recycling

The energy needed for each waste management method was mainly obtained from Ecoinvent (ecoinvent, 2018).

3.6 Life Cycle Energy

The life cycle energy of buildings is the sum of all energy at each life cycle stage which include embodied energy and operational energy. All values in MJ are converted to kWh using the equation of 1kWh =3.6 MJ.

The overall life cycle energy can be expressed as

Life Cycle Energy (kWh or kWh/m2) = EEm +EEt + EEc +OE + EEr + EEeol

where EEm is material embodied energy

EEt is transportation energy

EEc is construction energy

OE is operational energy

EEr is recurring embodied energy (Maintenance)

EEeol is embodied energy for end of life

4. Results and Discussion

4.1 Main results and discussion (Base Case)

This section provides the results of the life cycle energy of 22 academic buildings in NTU. To make comparison with operational energy, embodied energy of all buildings are expressed in kWh/m^2. The material embodied energy and GFA of all studied buildings is shown in Table 4. The embodied energy of building foundation will be included in Section 4.2. Only buildings with very high research activity intensity (buildings with high number of wet laboratories) are indicated in Table 4 as buildings with wet laboratories have very high-energy consuming equipment like fume hood and refrigeration.

Table 4. Material Embodied Energy and Case Buildings Specifications

(GFA, Façade and Roof Type and research activity intensity)

Buildings	**Material Embodied Energy (kWh/m²)**	**Operational Energy (kWh/m²)**	**Gross Floor Area (m²)**	**Façade Type**	**Roof Type**	**Research Activity Intensity**
1	596	6,121	25,394	Concrete	Concrete	-
2	810	17,740	19,282	Concrete	Concrete	High
3	730	12,960	11,706	Concrete	Concrete	-
4	869	11,127	15,484	Concrete	Concrete	-
5	563	4,904	21,157	Concrete	Concrete	-
6	758	18,185	14,552	Concrete	Concrete	High
7	799	4,629	14,686	Concrete	Concrete	-
8	607	8,489	22,535	Concrete	Concrete	-
9	739	20,468	12,325	Concrete	Concrete	High
10	903	11,918	20,792	Concrete	Concrete	-
11	650	15,000	22,206	Concrete	Concrete	High
12	671	3,553	20,590	Concrete	Concrete	-
13	620	18,972	17,235	Concrete	Concrete	High

14	689	3,666	19,000	Concrete	Concrete	-
15	581	15,815	7,173	Concrete	Concrete	-
16	627	3,750	7,485	Concrete	Concrete	-
17	663	10,200	18,687	Concrete	Concrete	-
18	988	6,615	18,854	Glass	Concrete	-
19	723	16,890	38,872	Concrete	Concrete	High
20	851	4,703	15,538	Glass	Concrete	High
21	709	25,134	44,311	Concrete	Concrete	-
22	613	1,895	29,578	Concrete	Concrete	High

The average material embodied energy (EEm) of NTU buildings is 716 kWh/m^2 with a range between 563 and 988 kWh/m^2. The average EEm per year is equivalent to 18 kWh/m^2 .yr for a lifetime of 40 years. The building with the highest material embodied energy is Building 18 (988 kWh/m^2 or 25 kWh/m^2.yr) and the building with the lowest material embodied energy is Building 5 (563 kWh/m^2 or 14 kWh/m^2 .yr). These values are much lower as compared to other studies due to the exclusion of other building materials, substructures and building foundation. However, if only consider the embodied energy from concrete, steel and glass, the average embodied energy of NTU buildings is 586 kWh/m^2. NTU value is quite similar to the material embodied energy of concrete, steel and glass of the studied building in Scheuer' study, which is 752 kWh/m^2. Besides that, result from this case study is also similar to the result from the Carbon Leadership Network (Carbon Leadership Forum, 2016). The website recorded an average material embodied energy of 240 kgCO2e/m^2 or 562 kWh/m^2. Based on another study by Junnila, considering only the embodied energy of concrete, steel and glass, the material embodied energy of the building is 628 kWh/m^2 (Junnila et al., 2006) The material embodied energy of all case buildings in NTU is illustrated in Figure 3.

Due to huge difference in Gross Floor Area (GFA), the buildings were categorized into buildings with large GFA (more than 20,000m^2) and buildings with small GFA (Less than 20,000m^2). The material embodied energy of buildings with large and small GFA are shown in Figures 4 and 5.

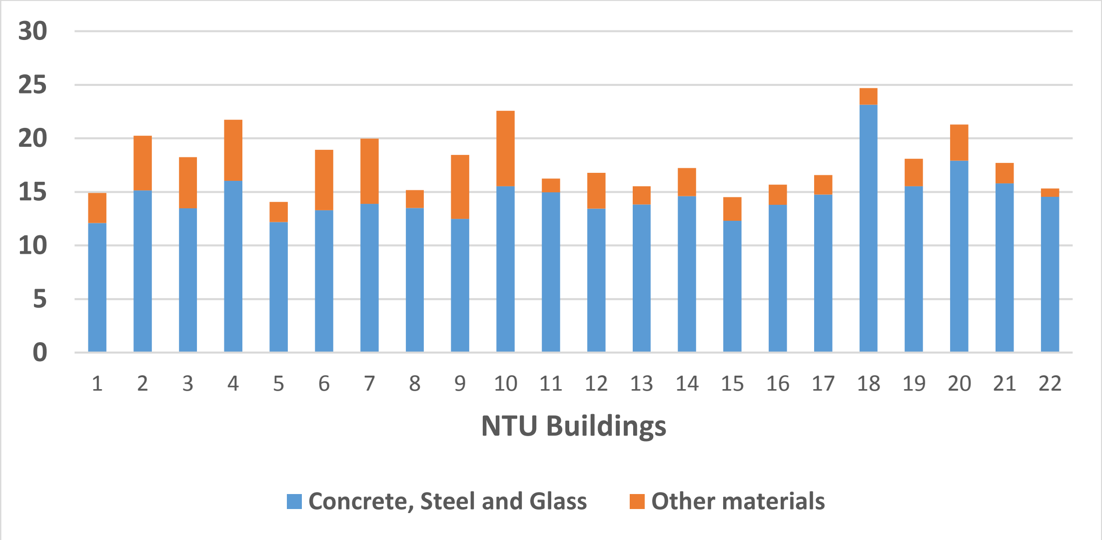

Figure 3 Material Embodied Energy per year (kWh/m^2.yr) of NTU Case Study Buildings

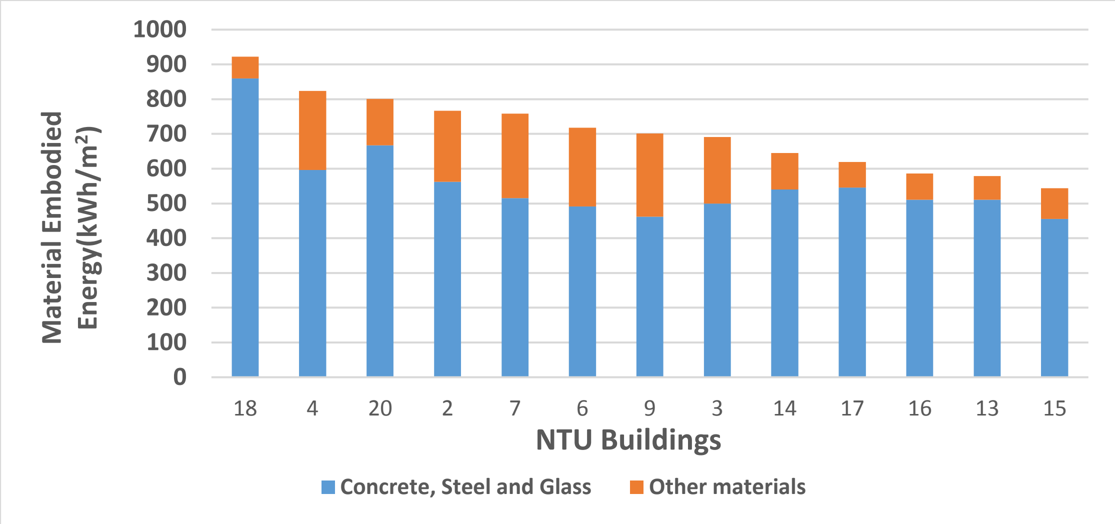

Figure 4 Material Embodied Energy for Buildings with GFA **< 20,000 m^2**

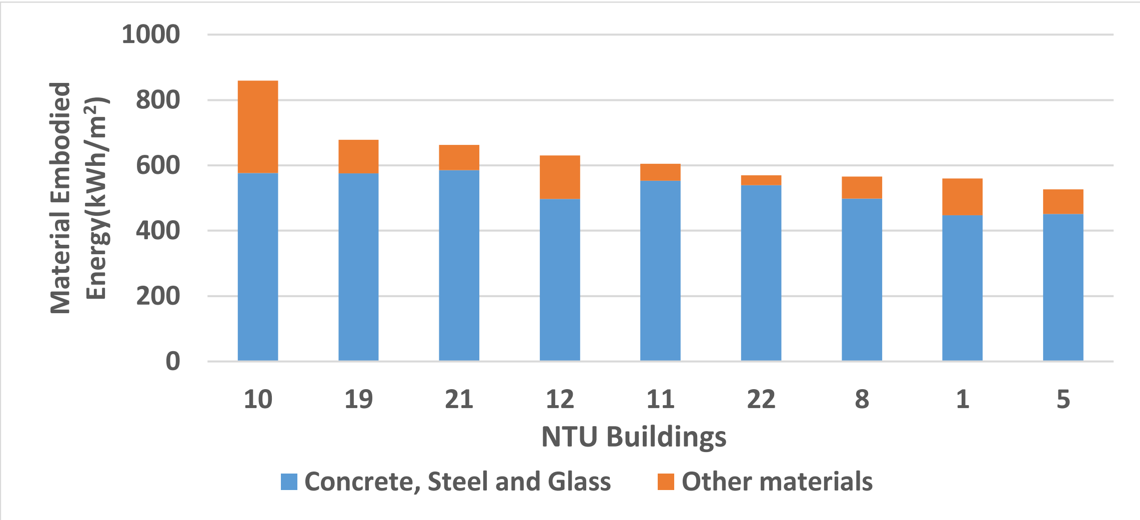

Figure 5 Material Embodied Energy for Buildings with GFA **⩾ 20,000 m^2**

A study has shown that the share of material embodied energy of buildings usually increases with the increase in GFA or building size. In that study, the life cycle energy is sub-linearly correlated with the house size (Stephan and Crawford, 2016). However, in this study, there is no strong correlation between Gross Floor Area (GFA) and material embodied energy. For example, despite Building 18 has the highest material embodied energy of 988 kWh/m^2, the building GFA is not the highest (18,800 m^2). Another example is Building 10 that has the second highest material embodied energy (903 kWh/m^2) although its GFA is not very high. The main reason is that building 18 has a much higher glass volume as compared to other buildings that have a higher concrete volume. As the embodied energy of glass is at least 20 times higher than concrete, this results in much higher embodied energy percentage for building 18. On the hand, the main reason of the high embodied energy in building 10 is the use of aluminium façade which has a relatively high embodied energy as compared to other façade materials.

Among all building materials, concrete has the most significant proportion of material embodied energy (41% to 59%) despite concrete has a relatively low embodied energy (1.03MJ/kg) than other materials like secondary steel (9.5MJ/kg). The reason is concrete is usually required in huge quantity regardless of buildings type. In this study, it is also found that around 23% to 33% of material embodied energy is from steel. However, in this study, all results had included the recycling benefits of steel. If the recycling benefit of steel is not considered, the share of steel embodied energy will increase by 45%. This will increase the overall share of building embodied energy with the same percentage.

Construction energy (EEc) only accounts for 0.3% of total life cycle energy for NTU buildings. This is equivalent to an average 3% of the total embodied energy. The construction energy was calculated based on the assumption of 33kWh construction energy for every $1m^2$ of building gross floor area (Cole and Kernan, 1996). The transportation energy (EEt) is 102 kWh/m^2, in which EEt contributes an average of 9% of the total embodied energy. Overall, the transportation energy (EEt) is equivalent to 1% of total life cycle energy. Although the impact of transportation energy is not as significant as the material embodied energy, there is enormous embodied energy saving potential that could be achieved by importing materials from nearby countries. For example, importing 100kg of steel from China will save at least 45% of transportation energy as compared to importing the same weight of steel from South Korea.

Due to a large sample size of buildings, the operational energy (OE) of all case study buildings is in the range of 1895 kWh/m^2 to 25134 kWh/m^2. This is equivalent to an Energy Use Intensity (EUI) of 47 kWh/m^2/year to 628 kWh/m^2/year. According to Singapore BCA, the Energy Use Intensity (EUI) is the electricity used in a building for a year, which measures the energy efficiency of the building. The mean operational energy intensity is 11021 kWh/m^2 or an EUI of 276 kWh/m^2 for a year. The result corresponds to Singapore BCA Benchmarking Report for university buildings which have an average EUI of 395 kWh/m^2.year (BCA Singapore, 2018). The large difference in operational energy is due to difference in building usage. For example, Buildings 6,9,13, 19 and 21 have high number of laboratories compared to other buildings. These buildings typically have fume hoods that require high electricity usage. On the other hand, other buildings like buildings 12, 16 and 22 mostly consist of office spaces and classrooms. Figure 6 illustrates the EUI of NTU buildings.

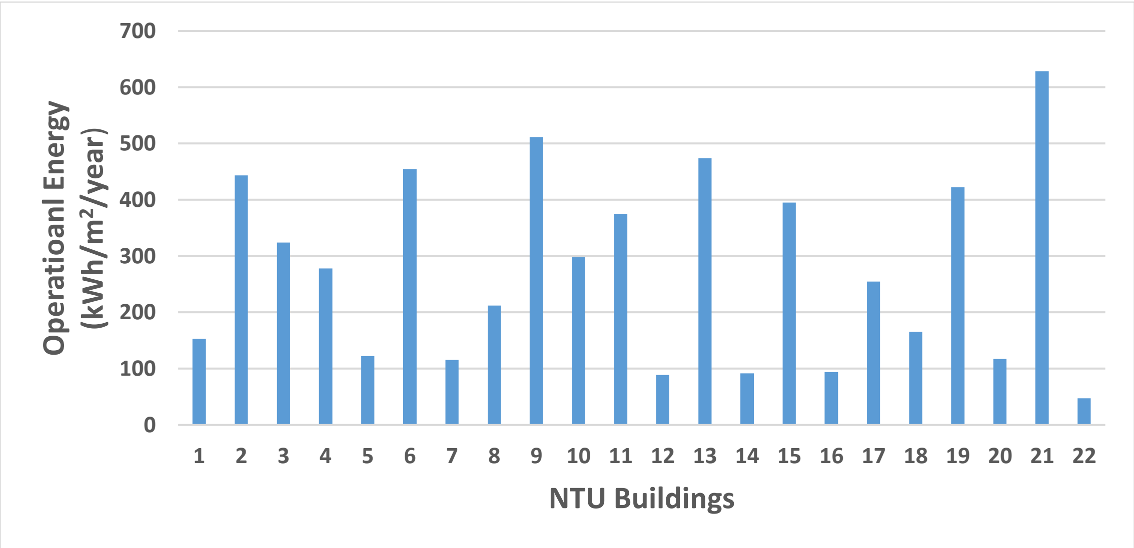

Figure 6 Energy Usage Index (EUI) of NTU buildings

The recurring embodied energy during the maintenance stage constitutes 2.4% of the total life cycle energy. Due to the short lifetime of the buildings, there is no contribution of recurring embodied energy from the structural systems like concrete and steel, and also other building finishes with a longer lifespan. Among all the studied materials, two building finishes that constitutes the most for the recurring embodied energy are carpet and plaster. This is due to the relatively high replacement rate and these two materials have relatively large embodied energy coefficient. The energy during the end of life phase includes demolition energy, waste transportation energy from NTU to disposal site and the energy for waste management (landfill/recycling). It can be concluded that the energy during the end of life phase only constitutes an average of 0.3% for the whole life cycle energy of buildings in NTU. This is equal to 3% of the total embodied energy.

The total life cycle energy of all case study buildings is in the range of 2811 kWh/m^2 to 26376 kWh/m^2 with a mean value of 12213 kWh/m^2. This encompasses embodied energy during the material, construction, transportation and end of life stages, and also the operational energy during the use stage.

Figure 7 displays the percentage breakdown of embodied energy at various life cycle stages. Considering only the embodied energy, the material embodied energy (Em) constitutes the highest percentage in which Em varies between 51% and 71% of total embodied energy. This highlights the significance of the material stage in this case study. The second highest contributor of embodied energy is the maintenance energy (EEr) which contributes an average 24% of total embodied energy. This is equivalent to 2.4% of the whole life cycle energy. The construction, transportation and end of life stages only constitute an average of 3%, 9% and 3% of the overall embodied energy respectively. This is equivalent to an average of 0.3%. 1% and 0.3% of the overall life cycle energy.

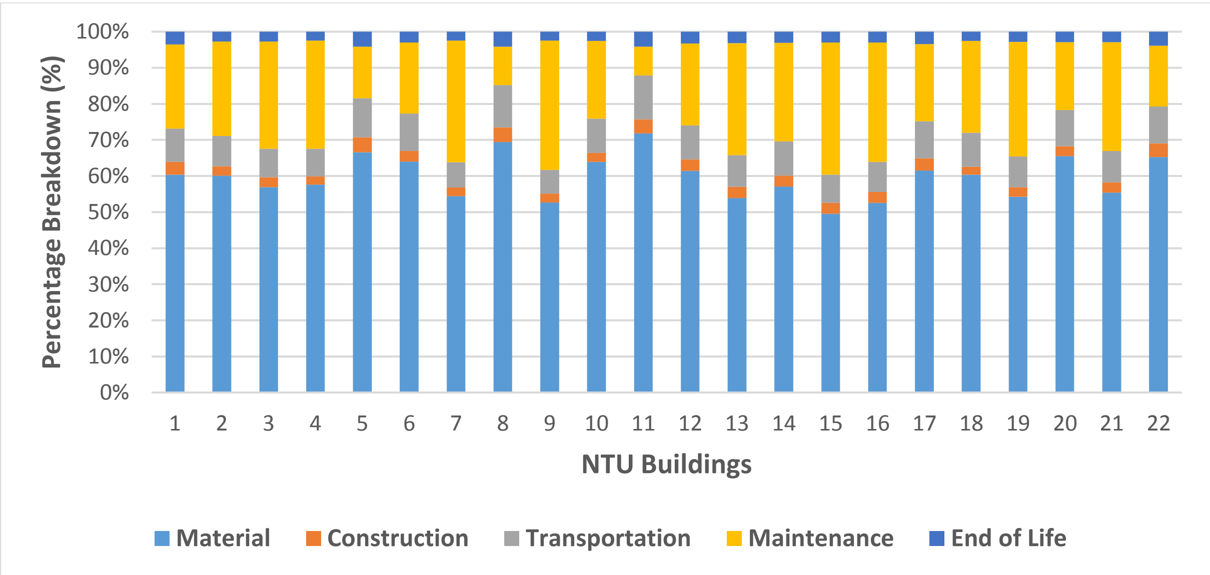

Figure 7. Percentage breakdown of embodied energy for NTU Case Study Buildings

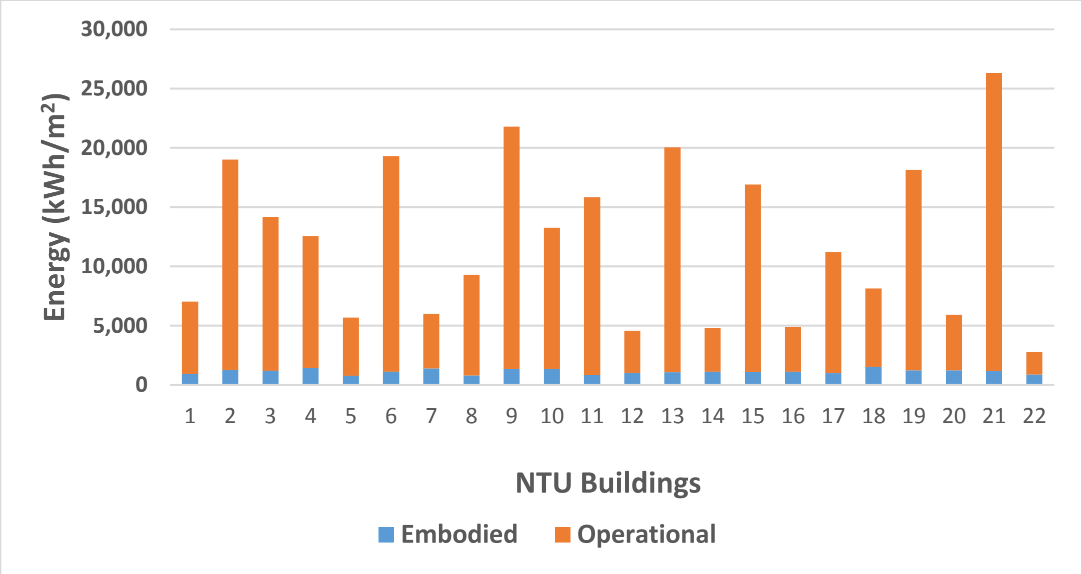

Figure 8. Embodied Energy vs Operational Energy of NTU Case Study Buildings

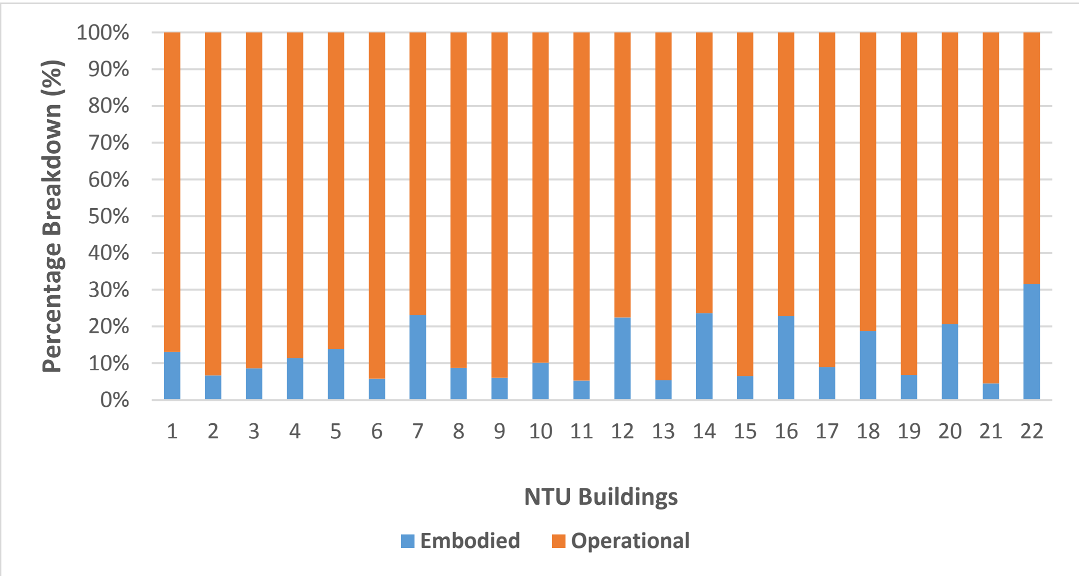

Figure 9. NTU Case Study Buildings: Overall percentage breakdown between embodied energy and operational energy

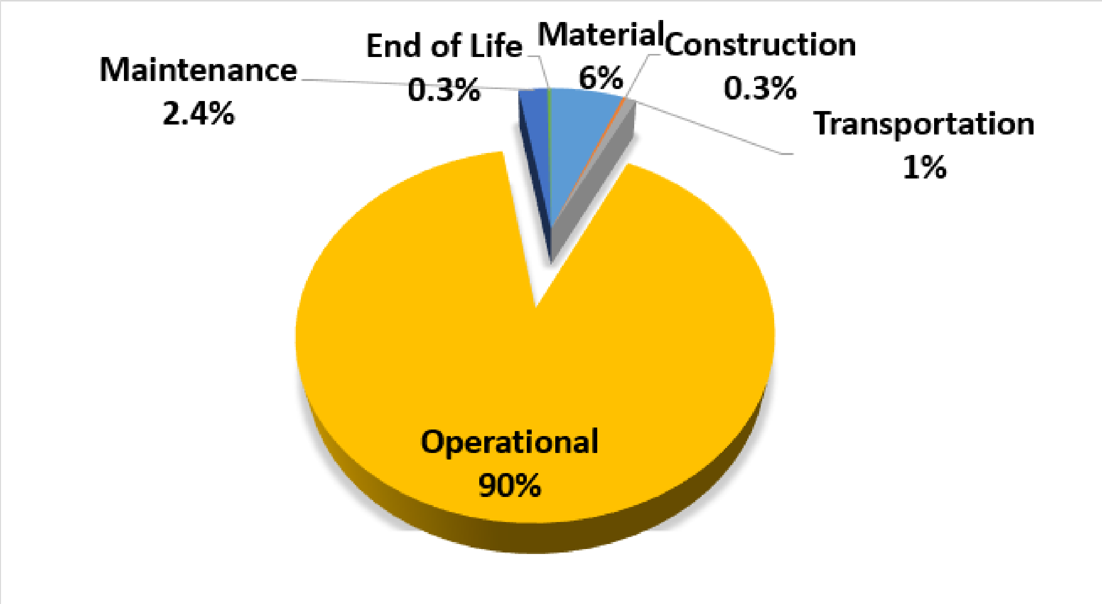

Figure 10 Percentage breakdown of life cycle energy of NTU Campus buildings

(Based on 22 academic buildings)

As shown in Figure 8 and Figure 9, operational energy dominates the whole life cycle energy of all buildings. About 63% to 95% is from operational energy. The remaining 5% to 37% is from embodied energy. Building 21 shows the highest life cycle energy demand of 26376 kWh/m^2. On the other hand, the building with the lowest life cycle energy is building 22. Building 22 only has a life cycle energy of 2811 kWh/m^2, which is approximately 10 times lesser compared to Building 21. One of the possible reason is the large number of laboratories in building 21 than other NTU buildings. This implies that building 21 requires a relatively higher operational energy demand than other NTU buildings. On the other hand, building 22 has various existing green features which help in saving operational energy. These include passive displacement ventilation, the use of low emissivity glass and other energy savings initiatives. Building 22 also been awarded the Singapore highest Green Mark certification for its various energy savings initiatives. On top of that, the building is also considered as one of the low energy buildings in Singapore. The aforementioned reasons explained the relatively low operational energy intensity of building 22.

In short, based on the results of 22 academic buildings in NTU, operational energy constitutes the dominant share of 90% while the remaining 10% is from embodied energy, Out of the 10%, the percentage breakdown of embodied energy of the whole life cycle energy are as follow: Material embodied energy (6%), recurring embodied energy (2.4%), construction (0.3%), transportation (1 %) and end of life (0.3%). The overall percentage breakdown is illustrated in Figure 10.

4.2 Inclusion of building foundation

With the inclusion of building foundation, the significant impact is on the material embodied energy. The building foundation was estimated based on the assumption of 280kg of concrete for each 1m^2 of gross floor area (GFA) (Lotteau et al., 2017; Meneghelli, 2018). The increase in material embodied energy of NTU buildings is around 13% to 39%. The embodied energy impact of building foundation for other life cycle stages is minimal as compared to the material production stage. Figure 11 shows the material embodied energy (Material EE) for scenario without building foundation and also the material EE of the building foundation.

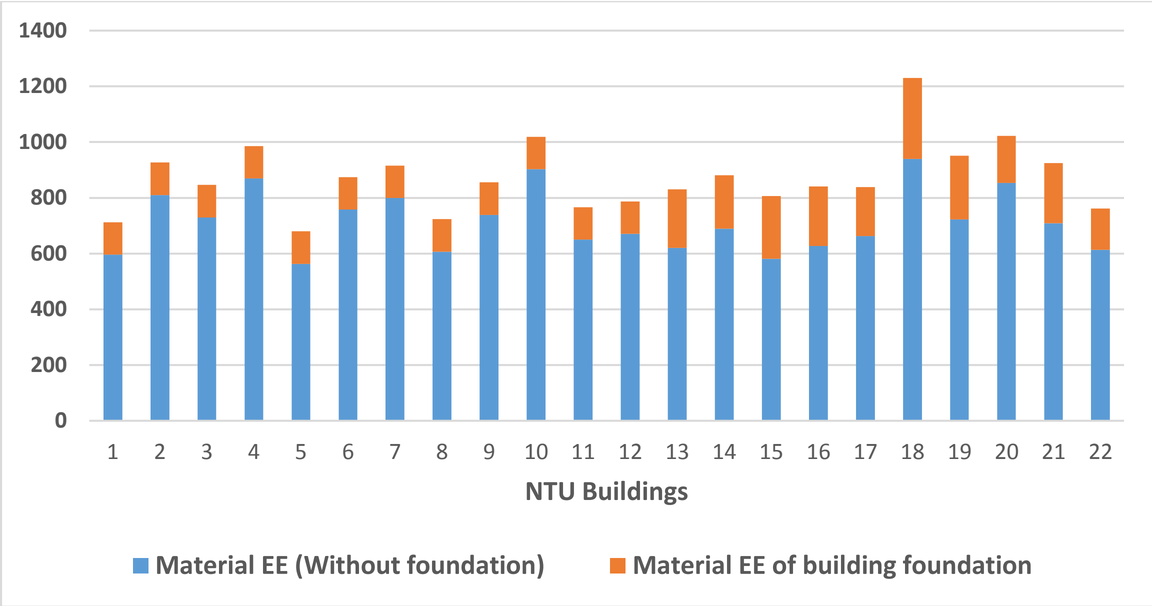

Figure 11 Material embodied energy (kWh/m²) without foundation and material EE of building foundation

Overall, with the inclusion of building foundation, the share of material embodied energy increases by 1% while the contribution of operational energy is reduced by 1%. The percentage breakdown of other life stages remained unchanged. The overall percentage breakdown with inclusion of building foundation is shown in Figure 12.

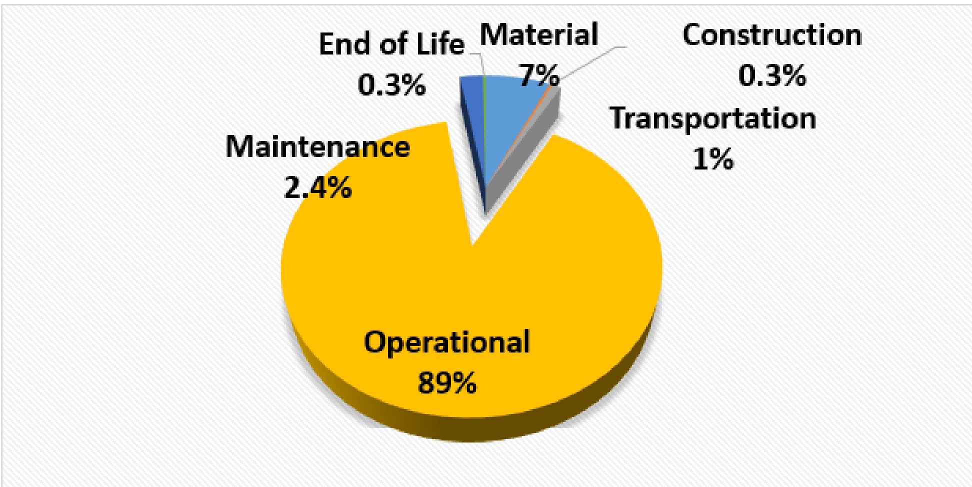

Figure 12 Percentage breakdown of life cycle energy of NTU Campus buildings

(Based on 22 academic buildings with inclusion of building foundation)

4.3 Strategies to achieve embodied energy savings

As mentioned in the “Introduction”, there have been previous and ongoing efforts in NTU to reduce the campus’ operational energy intensity. NTU EcoCampus initiative pioneered the effort, which aims to achieve 35% reduction in energy, waste and water by year 2020 in NTU (EcoCampus NTU, 2018). Some projects include the use of high performance building façade, demand control ventilation and new generation thermal insulation film. However, there are no initiatives to address the embodied energy of buildings in NTU. Besides that, with the expected further improvement in operational energy in NTU for the coming years, the relative share of embodied energy will definitely increase.

To investigate and understand ways to reduce the share of building embodied energy, this study has included two multi-scenario case studies on the transportation and selection of low embodied energy impact building materials. Various studies had included similar scenarios based analysis to understand further ways to reduce the relative share of embodied energy.

a) Importing from neighbouring countries

Based on most studies on embodied energy, the impact of transportation energy is minimal due to the transportation of building materials within the same country. However, this is different for countries which depend heavily on imports like Singapore. A study on a North American LEED-certified library has shown that LEED projects usually choose manufacturers within a short distance from the manufacturing site to the project site (Meneghelli, 2018). This is because the impact of transportation energy is significantly reduced for importing building materials from nearby manufacturing sites or countries. The above example implies that the importance of selection of building materials from nearby manufacturing sites to reduce the embodied energy impact. Similar to Singapore, Hong Kong also mainly imports products from China and other neighbouring countries. An embodied energy study in Hong Kong showed that the average transportation energy of the studied buildings was 0.58 GJ/ m^2, which represents 6% of the total embodied energy (Wang et al., 2018). Besides that, another study in Hong Kong by Yan et al. also calculated that transportation energy accounted for 6.1%-8.4% of total embodied energy (Yan et al., 2010). The aforementioned studies clearly shown that cities like Singapore and Hong Kong could have a greater share of transport energy use as these cities rely on other countries for materials. This is in contrast to countries which do not heavily depend on imported materials like China, South Korea and USA. The studies in China and South Korea reflected a relatively low amount of transportation energy. The results include a 4% transportation energy for an academic building in China and a 1% transportation energy for a South Korean residential building (Wang et al., 2018).

To evaluate the impact of transportation distance on the embodied energy of NTU buildings, the following scenarios were presented in Table 5. The transportation scenarios for the each building material were based on the United Nations commodity trade statistics database for Singapore (Gursel and Ostertag, 2016) and also (Atlas.edia.mit.edu, 2017). The chosen building for this case study is Building 8.

Table 5. Summary of importing scenarios for building materials

Material	**Scenario 1 (Nearer countries)**	**Scenario 2 (Countries which are further away)**
Cement	Import from Malaysia (418km from NTU, Singapore)	Import from Japan (5908 km from NTU, Singapore)
Steel	Import from China (3443 km from NTU, Singapore)	Import from South Korea (6065 km from NTU, Singapore)

The countries of origin for other concrete components (Sand and aggregate) and glass were assumed the same.

Both scenarios assumed that sand and aggregate were imported from Indonesia and glass was imported from Malaysia. Based on the Scenario 1 which assumed importing cement from Malaysia and importing steel from China, the overall energy for transportation is 1,352,443.15 kWh. On the other hand, the transportation energy in Scenario 2 (Countries which are further away) is 3,522,356.24 kWh. There is a significant embodied energy savings of 62%. The reason is due to the difference in transportation distance (Malaysia vs Japan) and (China vs South Korea). Port in Japan is at least 14 times much further from Singapore than Kuantan port in Malaysia. The same reason also applies to steel transportation as Pohang port, South Korea is approximately 2 times further away from Singapore than Guangzhou port in China.

The case scenario of importing from nearer countries has saved a total transportation energy of 2,169,913 kWh. This is equivalent to 83kWh/m^2.

Table 6. Comparison of transportation energy between both scenarios

Importing Scenarios	Transportation Energy/kWh
Neighbouring/Nearer countries	1,352,443.15
Countries further away from Singapore	3,522,356.24
% Embodied Energy Savings	62%

b) Choose environmentally sustainable products/Products with high recycling potential

Using building materials with high recycling or reusing potential is regarded as one of the initiatives to achieve an overall reduction in embodied energy impact. Several studies have shown that the use of recycled and reused materials can greatly reduce the overall life cycle energy demand of buildings. A study in Hong Kong showed that using recycled materials as building materials could help to achieve more than 5% of embodied energy savings (Yan et al., 2010). This is due to the avoidance of energy for extraction of materials which can encompass a high percentage of the material embodied energy.

The recycling potential is evident especially for ferrous and non-ferrous metals like steel and aluminium. One of the examples is steel. Based on the Life Cycle Assessment of Steel from the World Steel Association, 50% of the steel production goes to the construction and infrastructure sectors (World Steel Association, 2018). Therefore, based on the aforementioned statistics, it is imperative to consider the recycling of metals to help in reducing building GHG emissions.

On the other hand, there is a recommendation from Singapore BCA to use green concrete, which is environmentally friendly. Green concrete has components like fly ash in which at least 50% of the total aggregate mass are being replaced with recycled materials. The main recycled materials in green concrete are recycled concrete aggregates (RCA) and washed copper slag (WCS) (BCA Singapore, 2012). However, there is a maximum percentage of recycled aggregates that can be used for structural components as green concrete is usually used for non-structural components (BCA Singapore, 2012).

In this case study, the benefits of using recycled building materials was assessed using two scenarios. Scenario 1 considered the use of 100% virgin concrete while scenario 2 considered the mix use of virgin concrete and green concrete (10% of total concrete). The case study building is building 8. Only concrete (35/40MPa) was considered for this case study. As the benefit of steel recycling had been considered at the earlier part of this study, the focus of this multi-scenario case study was on concrete.

Table 7. Comparison of material embodied energy between two scenarios

Building Waste Management Scenarios	**Embodied Energy(kWh/m^2)**
Scenario 1: Virgin concrete (100%)	464
Scenario 2: Mix of virgin and green concrete (10%)	265
% Embodied Energy Savings	43%

From Table 7, the embodied energy in Scenario 2 is 43% lesser than the scenario of using virgin concrete for building construction. The embodied energy savings is 4,324,222 kWh or 199 kWh/m^2.

5. Conclusions

This paper assessed the life cycle energy of 22 academic buildings in NTU, Singapore with the focus on embodied energy. Various conclusions are drawn from this paper. First, operational energy makes up the majority of life cycle energy for all buildings. Based on an assumed lifetime of 40 years, the range of operational energy is between 63% and 95% while the remaining 5% to 37% is from embodied energy. In short, the average life cycle energy of NTU buildings is 12212.9 kWh/m^2 or 305 kWh/m^2 per year. The next conclusion is that there is no strong correlation between building GFA and embodied energy intensity. Building embodied energy still mainly depends on the type and weight of materials used. In this study, it is noticeable that concrete encompasses more than 95% of total building mass and contributes 61% of overall embodied energy. Third, there are various ways to reduce the share of embodied energy, which include recycling and reusing of buildings materials and opting for low carbon building materials life green concrete.

Based on the results from this study, there are some recommendations for future embodied energy studies in Singapore and tropical climate. First, the scope of future studies should expand to other types of buildings in NTU, which include non-academic buildings and student residential buildings. Such studies could provide a better overview of overall campus embodied carbon emissions. Another recommendation is to include more building materials for embodied energy analysis. This is to provide a better understanding of the buildings overall embodied energy impact. On the other hand, there is an urgent need to establish Singapore embodied energy and carbon database for major building materials. As different countries have different electricity mixes, having a local database will ensure higher accuracy for future embodied energy studies. There is also a need to conduct other comprehensive methods of analysis. Some examples include hybrid input-output analysis (I-O) analysis that combines the strengths of both I-O analysis and process-based analysis. Overall, this study outlined the life cycle energy demand of academic buildings in a tropical university campus. The results are expected to support future researches on life cycle energy of buildings in Singapore and across the region.

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