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Life Cycle Energy and CO2 Analysis of a Student Residential Building in Ningbo, China.

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Master in Industrial Ecology
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MASTER THESIS

for

Student
Francisco Javier Medel Jimenez

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Life cycle energy and CO_2 analysis for a student residential building in Ningbo, China
Livsløpsanalyse for energibruk og CO_2-utslipp for et studentbolighus i Ningbo, Kina

Background and objective

In recent years the installation of photovoltaic (PV) systems into Chinese buildings have become more popular. The reason for this is that buildings with installed PV systems tend to consume less energy and create less overall emissions and environmental damage, however these PV systems also can generate a significant amount of indirect energy consumption, emissions and environmental impacts during their manufacturing and installation. This fact has urged the building sector to find methods to quantify the life cycle energy and environmental performance of buildings before and after PV systems are installed.

Life cycle energy assessment (LCEA) is a tool that can help to quantify the use of direct and indirect (embodied) energy of a product or a system, which is also input to the assessment of the associated life cycle environmental impacts. It helps to analyse what processes or activities make a high contribution to the energy demand of the building. It can also help to identify key parameters related to the characteristics of the building or the PV system and to analyse the sensitivity of different variables and assumptions with respect to the overall energy and environmental performance.

The objective of this MSc thesis is to carry out an analysis of the life cycle energy demand and CO_2 emissions for a student residential building in a university campus in Ningbo, China. The aim is to compare the building as it has actually been built with an alternative design where a PV system is used for onsite energy generation, and include all scope 1, 2 and 3 CO_2-emissions for the two concepts, including a contribution analysis and sensitivity analysis. The study should contribute to provide recommendations on the use and benefits of PV for such a type of building.

The work is a follow-up of a previous study carried out in co-operation with Professor Wu Deng at the University of Nottingham in Ningbo, China.

The following tasks are to be considered:

1. Carry out a literature study on life cycle energy use and CO_2-emissions from buildings relevant to the objective of this work.
2. Provide a description of the case study in Ningbo, and collect the data and information needed to perform energy and CO_2 analysis of scenarios you decide to study, for all main elements of the building system with and without PV installations.

3. Develop a model for operational energy demand (by use of Energy Plus) and for the overall life cycle energy use and CO_2 emissions (scope 1, 2 and 3) according to state-of-the-art life cycle principles. Run the model for given scenarios and assumptions.
4. Report results as well as a contribution analysis, including a sensitivity analysis to assess the effects of uncertainties in your model variables.
5. Discuss the overall findings of the study, agreement with literature, strengths and weaknesses of the methods, and its implications for practical policy and further research.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 1th September 2016

Olav Bolland
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ABSTRACT

Buildings with installed photovoltaic power systems tend to consume less energy and create less environmental damage. However, these photovoltaic power systems also can generate a significant amount of energy and environmental impacts during their manufacturing and installation processes. There are numerous life cycle assessment studies evaluating the amount of energy and carbon emissions that photovoltaic systems generate, but normally the system boundaries of these assessments are limited to the photovoltaic system excluding the building. The purpose of this thesis was to perform a comparative life cycle energy analysis of a student dormitory building in Ningbo, China with and without using a photovoltaic energy generator in its operational phase and to evaluate the efficiency of the photovoltaic system in terms of carbon emissions and energy performance. An energy contribution analysis and sensitivity analysis was also executed.

The research was conducted using a life cycle energy assessment method in which two separate assessments were performed: one for the student dormitory building and one for a solar panel. Construction, operation, and demolition life cycle phases of the building and the photovoltaic power system were included. Data was obtained from the original drawings of the case study building, and data from literature review was used for the solar panel. An energy and carbon emission contribution analysis was done before the installation of the photovoltaic system in the building. Later, a bigger energy model was created by combining the life cycle energy assessment of the building and the photovoltaic system. This model helped to complete a scenario and sensitive analysis so that the effects of modifying key input parameters and/or processes could be analyzed.

The results show that the total amount of energy consumed and carbon dioxide emissions generated during the life cycle of the dormitory was 5,907 kWh/m^2 and 6 ton CO_2-eq./m^2 per 50 years. The HVAC system in the building emits more carbon dioxide and consumes more electricity than any other process. Total amount of energy consumed and carbon dioxide emissions generated during the life span of the photovoltaic power system was 1,277 kWh/m^2 total usable area, and 2 ton CO_2-eq./m^2 usable area. The conversion of upgrading metallurgical silicon (UMG-Si) into solar grade silicon (SoG-Si) was the process consuming more energy and emitting more carbon dioxide. The installation of the photovoltaic system in the dormitory can reduce its direct energy by 15.63% and carbon emissions by 15.65% during its 50 years' life span. In the case of the building's total life cycle energy consumption (direct and indirect energy), this reduction is 8.7% in terms of energy and 10.43% in the case of carbon emissions.

Result also revealed that using renewable energy as the energy supply of electricity generation for the manufacturing of solar panels and throughout the life cycle of the dormitory can help to enhance the benefits of installing photovoltaic systems. Using hydropower as energy supply 83.8% of carbon emissions reduction is obtained compare to the original 10.43%.

The installation of the photovoltaic power system helps to mitigate carbon dioxide and reduce energy consumption in the student dormitory. The system has more effects on the direct energy consumed by the building, although a precise and holistic amount of energy and carbon emission reduction is given by the building's total life cycle energy consumption (direct and indirect energy). The results presented here can assist to identify critical processes and to make changes that can help to improve the overall energy and carbon emission performance of the life cycle of the building and the photovoltaic system. The combined life cycle energy assessment model created in this thesis can be used as a tool to assess solar panel installation in buildings, as a tool to improve the production technology of photovoltaic systems and construction materials, as a reference for policy making, and as a benchmark for future research.

ACKNOWLEDGMENTS

This thesis was completed in two different universities as part of the fulfillment of the master thesis for the degree of MSc in Industrial Ecology.

The first part of this thesis was accomplished at the University of Nottingham in Ningbo, China. I would like to express my sincere gratitude to my supervisor Dr. Wu Deng, for all his support during my staying in Ningbo. His flexibility, quality of the advice, and the data he provided me have made possible to complete this thesis. I also would like to thank Jin Yan for sharing the drawings and material information, for her translations and support. Thank you Jin Yan!

The second part of this research was partially done in NTNU and in Hong Kong. I feel extremely grateful to my main supervisor Helge Brattebø. Thank you for your flexibility, for trusting my work, and for your wise insight about the direction of this thesis. I also want to say thank you to my work superior Mark S.C. Hsu from Hong Kong. Thank you for your flexibility and for your conviction.

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Trondheim, 8.2.2017

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GLOSSARY OF SYMBOLS

AC	Alternating current
ACC	Autoclaved aerated concrete
ASHREA	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BOS	Balance of systems
C	Carbon
CdTePVs	Cadmium tellurium photovoltaics
CH_4	Methane
CLCD	Chinese life cycle database
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxide equivalent
DC	Direct current electricity
EJ	Exajoules
EE	Embodied energy
EEPBT	Embodied energy payback period
EPBT	Energy payback time
ESP	Extruded polystyrene insulation foam
EVA	Ethylene vinyl acetate
GJ	Gigajoule
GJ/m^2	Gigajoule per square meter
GPBT	Green-house gasses payback time
GWe	Gigawatt-electric

GWP	Global warming potential
HVAC	Heating, ventilation, and air conditioner
ICE V2.0	Inventory of carbon and energy for building materials version 2.0
ISO	International organization for standardization
IPCC	Intergovernmental panel on climate change
kg	Kilogram
km	Kilometer
kg CO_2	Kilogram of carbon dioxide equivalent
kWh	Kilowatt hour
kWp	Kilowatts peak
kWh/Wp	Kilowatts hour per watts' peak
kWh/ kg	Kilowatts hour per kilogram
l	Liter
LCA	Life cycle assessment
LCEA	Life cycle energy assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
m	Meter
m^2	Square meter
m^3	Cubic meter
m^3/m^2	Cubic meter per square meter
MJ	Mega joule
MJ/kg	Mega joule per kilogram

MJ/liter	Mega joule per liter
MJ/m^2	Mega joule per square meter
MJ/m^3	Mega joule per cubic meter
ms-Si	Multi-crystalline silicon
MSW	Municipal Solid Waste
NaOH	Sodium hydroxide
O_3	Ozone
PBTs	Payback times
PV	Photo-voltaic
PVC	Polyvinyl chloride
Si	Silicon
SiO_2	Silicon dioxide
SoG-Si	Solar grade silicon
Total EE	Total embodied energy
t-waste	Metric ton waste
ton/m^2	Metric ton per square meter
ton-CO_2 eq.	Metric ton of equivalent carbon dioxide
UMG-Si	Upgraded metallurgical-grade silicon
Wh/m^2	Watt-hour per square meter
yrs	Years
XPS	Extruded polystyrene board

Chapter I INTRODUCTION

China is the economy with the biggest changes in energy demand in residential buildings. Urban areas in China are expected to grow by 20 million every year follow it by an increase in the demand for residential housing (Zhou et al. 2009). According to Zhou and colleagues, it is expected a construction of 2 billion squares meter of buildings by 2020 in China (Zhou et al. 2009). As a consequence of this, the energy use in buildings is expected to double by the same year, passing from 6.6 EJ in 2000 to 15.9 EJ by 2020 (Zhou et al. 2009). Greenhouse gas emissions and environmental stressors are some of the consequences resulting from the increasing demand of energy in residential housing in China; for this reason, Chinese buildings have an extraordinary opportunity to apply renewable energies and new technologies in their structures. Solar photovoltaic energy technology can be an excellent alternative (Li et al. 2007).

In recent years, the installation of photovoltaic (PV) systems into Chinese buildings have become more popular. In 2012 PV solar rooftops in commercial and residential buildings generated 1.4GWe out of 20GWe of the installed solar PV capacity in China (International Renewable Energy and Agency 2014). The reason behind this popularity is because buildings with installed PV systems tend to consume less energy and create less environmental damage. However, these PV systems also can generate a significant amount of energy and environmental impacts during their manufacturing and installation. This fact has urged the building sector to find a tool to quantify the energy and environmental performance of PV systems before and after they are installed. The embodied and consumed energy from manufacturing, use, and demolition of the building along with the energy consumed in the production and installation of the PV solar system need to be quantified when assessing environmental impacts.

Life cycle energy assessment (LCEA) is a tool that can help to quantify the use of energy and the embodied energy of a product or a system and the environmental impacts generated from that (Lu and Yang 2010). In this research paper, a comparison life cycle energy assessment of a Chinese student residential building will be performed with and without installing a rooftop PV energy system. This paper will be structured in the following parts:

In chapter 2 the motivation and research aims will be discussed, research questions to be answered by this study are presented here.

In chapter 3 the concepts and theory behind life cycle energy assessment, life cycle assessment, and photovoltaic solar systems will be defined.

In chapter 4 literature review of previous LCA studies will be critically evaluated. In this chapter, the methodology of previous studies will be compared to the methodology implemented during this thesis.

In chapter 5 the student residential building to be analyzed will be presented. In this chapter research methodology, data acquisition, and LCEA calculations are included.

In chapter 6 the results of the LCEA of the case study building are presented. In this chapter, a process contribution analysis and an analytical presentation of results are also included.

In chapter 7 the case study solar panel and the research methodology will be presented. Data acquisition approach and calculations are included in this chapter too.

In chapter 8 the results of the LCEA of the case study PV system are shown. In this chapter, a process contribution analysis and an analytical presentation of results are also included.

In chapter 9 an energy contribution analysis with and without the installation of the PV system in the building is calculated. In this chapter results from chapter 8 and 6 are combined to analyze the benefits of installing solar panels in the student dormitory.

In chapter 10 the scope of the scenarios to be analyzed in the next chapter is created. A visual representation of the scenarios is illustrated in this chapter.

In chapter 11 a sensitivity and uncertainty analysis of selected scenario is calculated.

In chapter 12 a discussion of the main findings along with the limitations of the study and recommendations for future research are given.

In chapter 13 the conclusions of this master thesis are written

Chapter II OBJECTIVE AND RESEARCH QUESTIONS

2.1 Objective

The purpose of this research project is to performed an analysis of the life cycle energy demand and carbon emissions for a student residential building in a university campus in Ningbo, China. The purpose is to compare the building as it has been built with an alternative design where a PV system is used for onsite energy generation, and include all scope, 1, 2, and 3 carbon emissions for the two concepts, including a contribution analysis and sensitivity analysis. The study will provide recommendations on the use and benefits of installing a PV in the building in terms of energy and carbon emissions.

2.2 Research questions

Several questions need to be answered to make the analysis and provide recommendations:

1. How much energy and carbon emissions are generated during the entire life cycle of the student dormitory and what processes consume more energy?
2. How much energy and carbon emissions are generated during the entire life cycle of the photovoltaic solar system and what processes consume more energy?
3. How much energy and carbon emission is reduced by installing the PV system in the student dormitory?

Research questions one and two can be addressed by performing two different life cycle energy assessments, one for the residential building and one for the photovoltaic solar panel.

To address the third question, the results from the LCEA of the solar panel need to be added to the results of the building. By doing this a comparison analysis can be completed.

Chapter III DEFINITIONS AND THEORY

It is important to have a clear understanding of the concepts and definitions that this research paper presents. For the same reason, in this segment an overall review of key concepts on how to perform a LCEA (especially for building and PV systems) will be given. Concepts such as direct and indirect energy, LCA, LCEA, and PV energy systems are presented.

3.1 Energy Classification

Energy can be classified into different concepts: primary, secondary, direct, indirect, embodied etc. This classification depends on the production, conversion, and the final use of energy (Grubler et al. 2012). The energy that is found in natural resources e.g. coal, crude oil, natural gas, wind etc. and that has not been converted to become usable energy is called primary energy (Frischknecht et al. 2015). Secondary energy is the energy that has undergone a conversion process in order to deliver a service of consumption. This form of energy it is also known as energy carrier, e.g. coal or natural gas is transformed to produce electricity (Frischknecht et al. 2015). Commonly direct energy is the energy that flows in form of primary and secondary energy (Grubler et al. 2012)

The embodied energy of a product or process refers to the total accumulative secondary energy that is consumed during its entire life cycle (Lippke et al. 2004). This embodied energy is also known as indirect energy (Grubler et al. 2012). Both forms of energy, direct and indirect can be quantified and a common tool to do this is by performing a Life Cycle Energy Analysis (LCEA).

3.2 Life Cycle Energy Analysis (LCEA)

Life Cycle Energy Analysis (LCEA) is a method that quantifies all the energy inputs to a building during its entire life cycle. This energy includes the initial and recurring embodied energy, the operational, and the demolition energy of the building (Ramesh et al. 2010).

The initial embodied energy is the energy content in each of the materials needed to construct the building. Energy content represents the energy consumed during the extraction of raw materials, manufacturing, and transportation of the materials to the site. This equation represents the initial embodied energy: (Ramesh et al. 2010).

$$EE_i = \sum m_i + M_i + E_C$$

Where:

EE_i = initial embodied energy

m_i = quantity of building material

M_i = energy content of material (i) per unit quantity

E_C = energy used at site to construct the building

The energy incurred in the maintenance and rehabilitation of the building is called the recurring embodied energy. The embodied energy of the materials to be replaced and the energy used during its maintenance are measured here: (Ramesh et al. 2010).

$$EE_r = \sum m_i \, M_i \, [\,(L_b + L_{mi}) - 1]$$

Where:

EE_r= recurring embodied energy

L_b = life span of the building

L_{mi} = life span of the material (i)

The energy required to operate the daily comfort inside a building is called operational energy. HVAC (heating, ventilation and air conditioning), lighting, water heating, and energy for running appliances are considered here. The amount of energy consume depends on factors such a climate, building design, operational schedules, etc. (Ramesh et al. 2010).

$$OE = E_{OA} * L_B$$

Where:

OE = operational energy

E_{OA} = annual operating energy

L_B = life span of a building

The demolition energy is the energy needed during the demolition of the building and the one needed to transport the waste material to landfills or recycling centers (Ramesh et al. 2010).

$$DE = E_D + E_T$$

Where:

$DE =$ demolition energy

E_D= energy used for the demolition

E_T = energy used for the transportation of waste materials

The sum of all the three energies is the life cycle energy consumption of a building, we can express it as:

$$LCE = EE_i + EE_r + OE + DE$$

Performing a life cycle energy analysis is a strategy that can help to track and to evaluate the energy use in buildings, it could be possible to quantify the necessary amount of primary energy use and give us an indication of the greenhouse gasses emitted, however for a deep quantification of environmental impacts a life cycle assessment needs to be performed (Ramesh et al. 2010).

3.3 Life Cycle Analysis (LCA)

Life cycle assessment (LCA) is a tool that quantifies and evaluate potential environmental aspects and impacts associated with the whole life of a product or process (IEA Annex 31 2001). Commonly LCA studies track the necessary materials and energy flows that a process or a product needs during their whole life cycle. Performing a life cycle energy assessment (LCEA) refers to quantify the energy flows, primary and embodied, from the materials and/or process to later assess their environmental impacts.

According to international standards an LCA consist of four phases: Definition of goal and scope, inventory analysis, impacts assessment, and interpretation and results (International Organization for Standardization 1997). In the first step, the goal and the scope of the study are defined. Here the functional units, system boundaries, and critical review process are established. The inventory analysis happens in the second step, here the data collection occurs in order to quantify the inputs and outputs in terms of energy and materials (IEA Annex 31 2001). In the impact assessment stage the flow of materials and energy are classified into one of the environmental impact categories, later these categories can be grouped into one of the main characterization factors (Cabeza et al. 2014). Finally, the last step deals with the interpretation, evaluation, and recommendations based on the results (Ortiz et al. 2009). Figure 1.0 shows the LCA framework methodology.

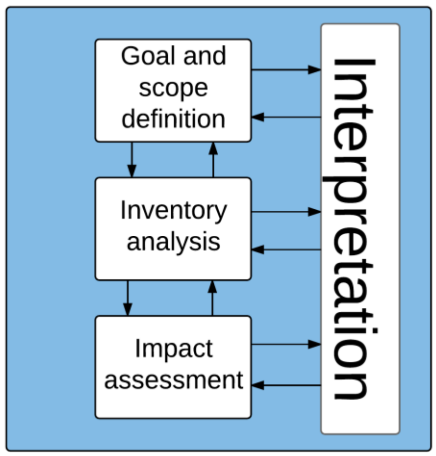


Figure 1.0 LCA framework methodology (International Organization for Standardization 1997; Baharwani et al. 2014).

Fava along with Taborianski and colleagues have quoted that LCA has been used since 1990 in the building sector and it is an important tool for assessing buildings (as cited in Ortiz et. al 2009). Nowadays residential buildings are in need to change their construction practices, LCA can be an objective tool to evaluate and quantify environmental stressors. In this study, a LCEA method was chosen as the best alternative to evaluate the environmental performance of the building to study. The motivation of this study will be discussed later in this section.

3.4 Photovoltaic (PV) energy systems

Photovoltaic (PV) energy systems are considered a clean and sustainable way of energy generation. They use solar cells to capture the sun rays to storage and produce energy (Solarenergy.net). However, despite the fact that PV energy systems do not produce any environmental impacts or consume energy during their operation, they can consume a significant amount of energy during their manufacturing, installation, transportation, maintenance, and recycling process (Lu and Yang 2010). At the same time manufacturing of different other components, known as the balance of system (BOS), is required to operate and install PV systems. These components include: wires, panels, mounting systems, battery (stand-alone system), electrical components, switches, solar converter, etc. (Lu and Yang 2010)

It is important to have a clear understanding of the life cycle of PV systems in order to quantify the total energy use in each of the life cycle phases. The acquisition of raw materials (cradle) is the first step of the life cycle of a PV system, in this stage some minerals are extracted from the ground: quartz sand for silicon PVs and copper, iron, and zinc ore for CdTePVs (Frischknecht et al. 2015). The following stage is processing and purifying these minerals until they reach a solar grade purity. A Siemens process is needed at this stage, which in turns generates a huge amount of energy. After these minerals reach a high level of purity they can be transformed into cells. The manufacturing process is divided into several steps: wafer, cell, and module. Here silicon ingots are sliced, then a p-n junction is formed and finally the cells are connected. (Frischknecht et al. 2015). During the installation process, PV systems are mounted along with other components such as cables and modules. The final stage is the treatment or disposal (grave), in this stage some components can be recycled and recovered for future use (cradle) (Frischknecht et al. 2015). Figure 2.0 shows the entire manufacturing process of a PV energy system.

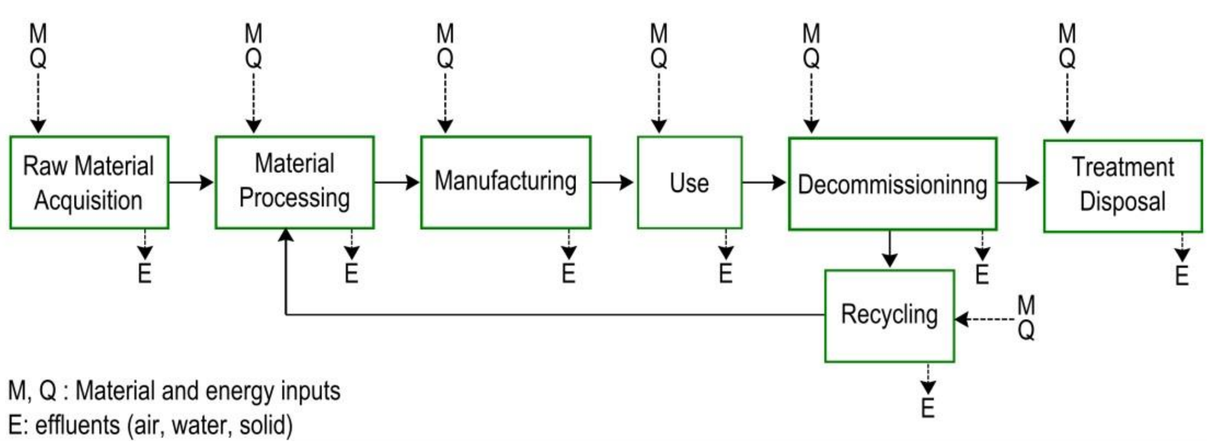


Figure 2.0 Life Cycle of a Photovoltaic System (Frischknecht et al. 2015)

Generally, the most common method to evaluate the life cycle performance of PV systems in terms of energy consumed is using the energy payback time equation. Energy payback time (EPBT) is a metric analysis to determine the energy sustainability of renewable energies, it is the time that takes the PV to generate the equivalent amount of energy used to produce it. As Kanapp and Jester mentioned in their analogy, it is the equivalent to the financial payback but in terms of energy (Knapp and Jester 2002). EPBT is determined by two parameters: how the PV is produced it and how it is installed. The first one refers to the direct energy used by the manufacturer and the embodied energy in the components, the second refers to the energy output of the PV based on the solar insolation (Knapp and Jester 2002). These parameters can be extended to reflect the energy used in the BOS, transportation, and the end-of-life management of the PV system. The energy payback time is calculated from:

EPBT = (Specific Energy)/ (Energy Generation Rate)

(Knapp and Jester 2002)

Numerous PV LCA studies have been performed based on the EPBT metric analysis. However, none of them have included the life cycle of the building together with the PV system in their research methodologies and objectives. Kannan and colleagues for instance performed an LCA study in terms of EPBT for a 2.7 kWp grid-connected mono-crystalline solar PV system operating in a building in Singapore (Kannan et al. 2006), at the same time Corrado and Battisti did another LCA study in terms of EPBT for a grid-connected multi-crystalline silicon (mc-Si) PV system in a roof in Rome (Battisti and Corrado 2005). Other LCA studies have included the components of the PV system in conjunction with the components of the building. Nevertheless, the approach of these studies is based on the design of the building (having established the use of solar energy since their design stage). A more critical analysis of these studies will be discussing in the literature review section.

Chapter IV LITERATURE REVIEW

Residential buildings can generate a significant amount of greenhouse gas emissions (e.g. CO_2, O_3, CH_4, etc.) because of the energy consumption during their construction, operation, and demolition. Nowadays residential buildings are installing PV energy generators in their structures to reduce energy consumption during their operation. However, the manufacturing and installation of PV energy system into buildings can also consume an immense amount of energy and resources. LCEA studies of PV energy systems are beneficial in calculating their energy efficiency, but generally these studies are given in terms of energy payback time (EPBT) and greenhouse-gas payback time (GPBT) and do not include buildings in their models. Nevertheless, it is important to expand the system boundaries of the study and not only include the PV system, but also include the residential building into one LCEA study. By doing this, a realistic comparison (in terms of energy and environmental stressors) regarding the performance of PV modules in their application to buildings can be calculated.

This literature review will address the methodology of previous LCA studies regarding of buildings that have included PV energy systems into their models. The comparison and relevance of the literature review will be based on the amount of life cycle phases (of both the building and the PV system) included in the LCA study and the extension of the LCA system boundaries in order to include the building and the PV system simultaneously. The literature review is separated into three areas: in the first section, LCA studies using the EPBT energy measurement will be covered. In the second section, there will be a discussion of some LCA studies that have included PV energy systems into the design stage of the building. Finally, the importance and significance to the field of this research paper in comparison to previous studies will be discussed.

One of the most common methods to calculate the efficiency of a PV solar energy system is the EPBT. This method calculates the time that is required for the solar PV system to generate the same amount of energy used during its manufacturing process (Kannan et al. 2006). A wide variation in EPBT measurement can be found in the literature (Kannan et al. 2006), but normally the BOS, installation, and the disposal of the PV phases are included in the calculations. Many LCA studies have used this metric to determine the energy efficiency of PV systems in buildings. However, when using the EPBT method there is always the limitation of excluding the energy consumption of the entire life cycle of the building. The system boundaries of the EPBT method normally only includes the life cycle phases of the PV system and the authors determine what phases to include. The next two LCA studies were chosen as a comparison of previous LCA studies that have used the EPBT method. They were selected based on the number of the life cycle phases included in the study (of both the PV system and the building), and the extension of the system boundaries in order to include the solar panel and the building simultaneously.

Battisti and Corrado (2005) performed an LCA study to investigate a complete environmental and energy profile of PV systems, the results of their study were presented in energy and environmental PBTs. They analyzed a multi-crystalline silicon (mc-Si) photovoltaic system, which was grid-connected and retrofitted on a tilted roof in Rome, Italy. To calculate the EPBT they estimated the time period needed for the benefits in energy savings obtained in the operational stage of the building to be equal to the whole life impacts of the PV. The benefits were calculated from the amount of conventional energy (from the Italian electricity mix) and the emitted greenhouse gases that the PV system was replacing. The results showed that the EPBT was 3.3 yrs., while the CO_{2eq}. PBT was 4.1 yrs. (Battisti and Corrado 2005). The cumulative energy demand indicator used to calculate the impact assessment and EPBT in this LCA study offers a clear measurement of the PV's energy efficiency. However, there is an evident limitation in the calculation of the EPBT. The benefits in the cumulative energy of replacing the conventional electricity mix with the PV system is calculated only for the operational phase of the building. Therefore, the energy consumed during the other life cycle phases were not calculated because they were not replaced by the PV system even though there was a significant amount of energy consumed (in forms of the embodied energy). It is important to include the energy consumed during the construction and demolition of the building in the EPBT calculations because this gives a more realistic total energy payback time.

However, Wilson and Young (1996) included the total embodied energy of a building together with the embodied energy of the PV system. They calculated the embodied energy payback period (EEPBT) of PV panels installed in two hypothetical buildings in London. First, they quantified the amount of embodied energy that would be accounted for by the PV installation into the building and the percentage of annual energy consumption that the PV system would save. Their results showed an increase of 17.3% of the life cycle embodied energy in both buildings with the installation of the PV panels, and an increase of 32.8% in a building A and 35.5% in a building B of embodied carbon emissions (this assumed a 60 yrs. life time for the buildings and 20 yrs. for the modules in their first scenario). The reason for this increase is that the embodied energy of the PV panel was included in the embodied energy of the building. To calculate the EEPBT and energy savings they took into consideration the module and system energy conversion efficiency, energy loss, and sunlight availability. To obtain the payback period they divided the embodied energy content in PV modules by the annual savings produced. In their results an EEPBT of 12.1 yrs. for buildings A and 7.4 yrs. for building B was shown (Wilson and Young 1996).

Compare to the study of Battisti and Corrado the results in this study showed a bigger EPBT; one of the reasons behind this is the difference in extension of the system boundaries in both studies (the main reason with bigger influence is the solar radiation but this factor is not considered for purpose of this literature review). Wilson and Young included the embodied energy of the PV modules plus the building, whereas Battisti and Corrado only included the PV system. Therefore, the method used by Wilson and Young to calculate the EPBT followed a more inclusive and realistic way, this because the energy to be replaced by the PV panel was not only the embodied energy of the PV if not also the embodied energy of the building. However, the embodied energy of the building and the PV system was the primary energy consumed during their manufacturing and operational phases excluding other phases. In this study the demolition phase of the building with the PV installed was excluded whereas in the study of Battisti and Corrado all the life cycle phases were omitted.

Many other LCA studies such as the one performed by Knapp and Jester (2002) in California, Kannan et al. (2006) in Singapore, and Lu and Yang (2010) in Hong Kong have used the EPBT as a metric to calculate the efficiency of PV systems in buildings. However, the EPBT method does not always include the building in its calculations (normally authors determined which life cycle phases to include and the extension of the system boundaries in their studies) which in turns can affect the real energy payback time results. Nevertheless, a new approach to include PV energy systems into buildings (in order to reduce energy during their operational phase) has become more popular in recent years. This method consists in the inclusion of renewable technologies from the stage of building design.

Further LCA studies have included the PV energy systems in their boundaries from the design stage of the building. These LCAs can establish how much energy could be saved with the installation of PV energy generators. Commonly these studies already have a predetermined energy reduction that the building needs to achieve and it is during the architectural design stage that this is established. Net zero buildings, low energy consumption buildings, passive houses and self-sufficient houses are an example of new sustainable designs.

A comparison LCEA of a low-energy house, a passive house, and a self-sufficient house completed by Fiest (1997) shows how PV energy systems have been included in the building's design regulations and the effect that they can have. Fiest compared six different buildings complying with six different design ordinances and their total cumulative energy inputs. He used as a reference a mid-terrace house complying with the 1984 German thermal insulation regulations. The cumulative energy input was a sum of total electricity consumption, natural gas for heating consumption, natural gas consumption for domestic hot water, primary energy input for building construction, and replacement primary energy input. The results showed that the cumulative energy input of the reference house was the biggest, followed by the low energy house and then the low energy house with electricity efficiency (Figure 3.0)

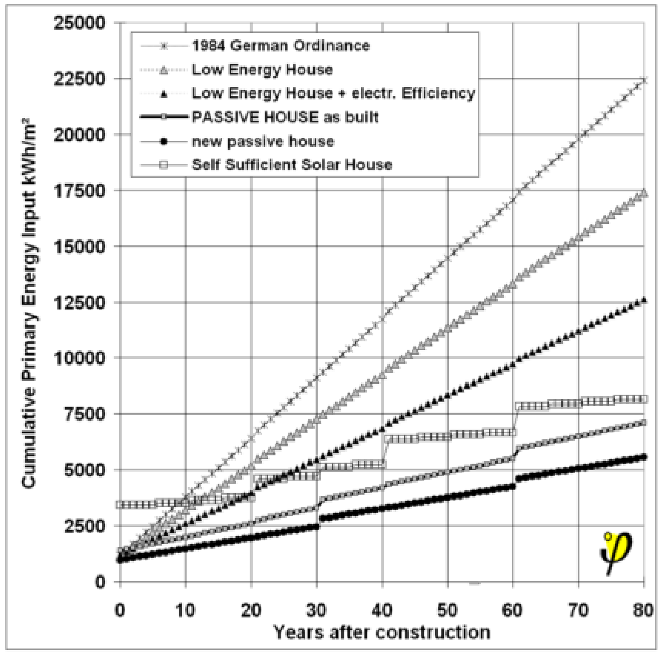


Figure 3.0 Cumulative primary energy input of six different houses (Feist 1997)

Surprisingly the results of the self-sufficient solar house were worse than the passive house and the future passive house, though the house was off the grid. The reason behind the results is that the primary energy input for the building construction and the replacement was significant high due to the need for the exchange of some technical components, including PV modules every 20 yrs. (Feist 1997). The purpose of his study was only to compare the cumulative energy by the different design regulations through an LCEA perspective excluding environmental stressors. However, Thiers and Peuportier (2011) in another building design LCA research included various environmental stressors.

Thiers and Peuportier (2011) performed an LCA research of two high energy performance buildings in France. These high-energy performance buildings were defined as “Net Zero Energy Buildings”, which are buildings that produce the same amount of primary energy that they would consume in a year. The purpose of the study was to determine the energy performance of Net Zero Buildings and to complete an LCA. The reference buildings were originally designed as passive houses but transformed into high energy performance buildings. To accomplish this, additional devices were added to the buildings. PV modules were installed to cover most of the roof to generate heat and electricity. The results showed that the construction materials and equipment can influence the energy and environmental performance of a building. For example, the production of PV panels generated a significant contribution to six environmental stressors (ecotoxicity, odor, primary energy, abiotic resources, and acidification). Their results also showed that high energy performance buildings tend to have better environmental and energy results than low energy performance buildings (Thiers and Peuportier 2012).

The LCA studies by Fiest and Thiers and Peuportier, demonstrate how PV energy systems have been incorporated into the design stage of a building. The incorporation of these solar panels in sustainable designs normally reduces the amount of energy consumption. However, few LCA studies have shown the implications of manufacturing, installation, maintenance and disposal of these systems. Performing LCA studies of buildings with and without installed PV systems can help to make responsible choices to include PV energy technology during the early design stage of a building.

The studies that have tested the efficiency of PV energy panels installed in buildings have some limitations and do not always include the embodied energy of the building in their calculations. As cited in the literature, the most common method to determine the energy efficiency of PV installed in buildings is calculating the EPBT. However, these studies do not include the energy consumed in the life cycle of the building making their system boundaries limited to the PV. This approach was taken by Battisti and Corrado (2005) that performed an LCA based only on a PV panel in Rome. Some other authors such as Wilson and Young (1996) included the total embodied energy of a building together with the embodied energy of the PV system, but in their case they did not take into account all the phases of the building and PV. Including the photovoltaic system early in the design stage of the building or performing a building's retrofitting is another method that has made possible to determine the energy efficiency of a PV system. Fiest (1997) showed how PV energy systems have been included in the building's design regulations and the effect that these systems had in the accumulative energy consumed. At the same time, Thiers and Peuportier (2011) performed an LCA research of two high energy performance buildings in France and showed the effects in six environmental stressors that the installation of PV panels had in these buildings.

It is essential to mention that each author is responsible for establishing his/her system boundaries when performing an LCA. They can justify the inclusion or exclusion of the building and the PV in their methodologies base on the goal, scope, and data availability to perform the LCA. However, having a broad system boundary when calculating the efficiency of PV systems installed in buildings (not only by using the EPBT), can give a more realistic result in terms of energy savings and the generation of environmental stressors. These results can have a significant impact on consumers, property developers, and environmental policy makers when facing the choice of installing PV energy systems in their buildings.

The evident limitations of previous LCA studies have motivated the performance of this thesis. The methodology of this research thesis differs from previous LCA studies in four different ways:

1. The manufacturing, operation, and demolition life cycle phases of both: the building and PV solar panel are included.

2. The system boundary of this study is expanded to include the life cycle phases of the building and the solar panel at the same time. Figure 4.0 represents these boundaries

3. An energy model is designed for quantifying the building's operational energy demand by use of an energy simulator software (in this case EnergyPlus).

4. A broad life cycle energy model is created by combining the results of the life cycle energy assessments of the building and the PV simultaneously. A sensitivity and scenario simulation in this new model can be performed to show the effects (in terms of energy and carbon emissions) on changing some critical parameters in one of these models.

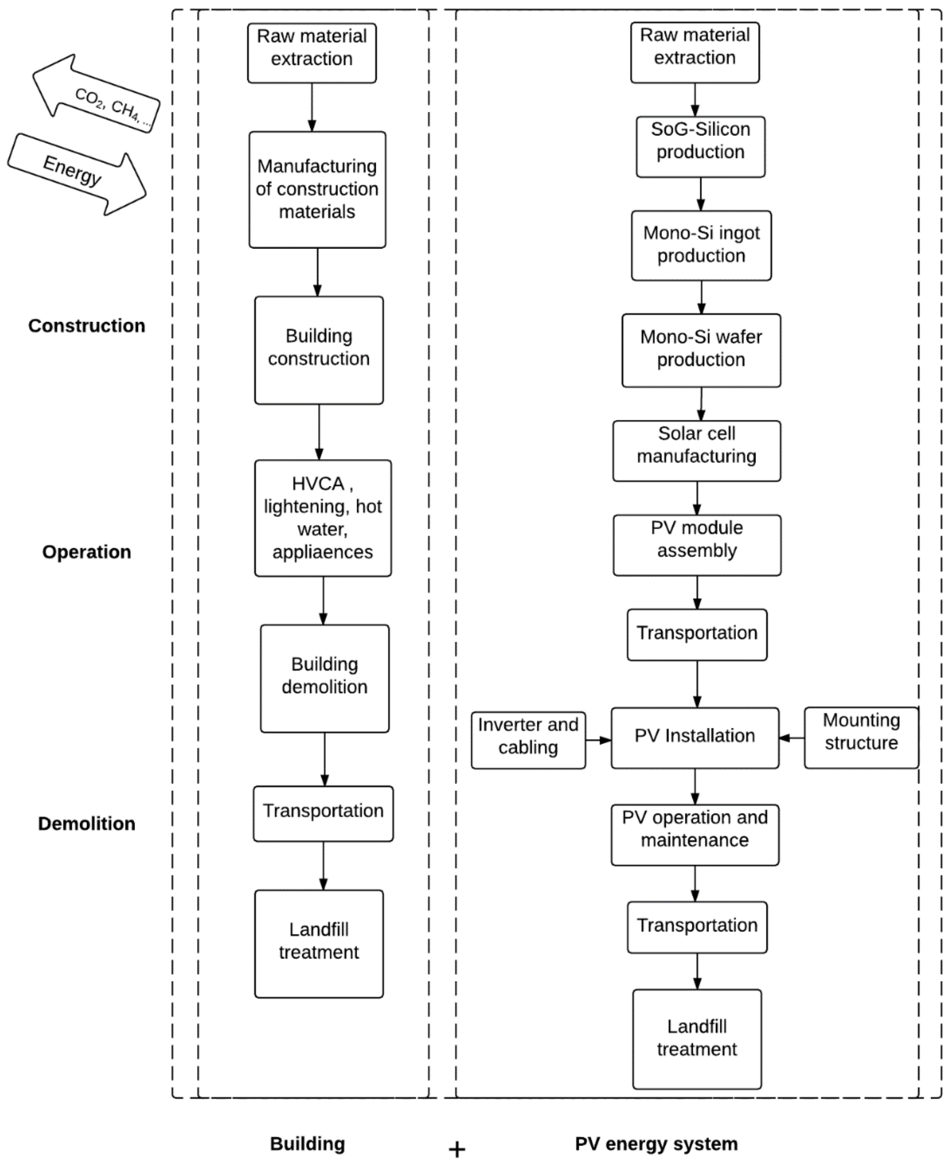


Figure 4.0 System boundaries including the life cycle phases of the building and the solar panel

Chapter V LCEA OF THE CASE STUDY BUILDING

5.1 Building information

The International Residence Building No. 18 is located inside the campus of the University of Nottingham in Ningbo, China. The residence building has been selected because of the data availability for purpose of this thesis. The building was built in 2012 and it is now occupied by international students.

Residence Building No. 18	
Location	Ningbo, China
Year of built	2012
Functionality	International student residence
Floor area	7,792 m^2
Planned life time	50 yrs.
Height	31.3 m
Number of floors	9
Number of units	68 (four units for ground floor and eight units for other floors)
Occupation	272 (four people per unit)

Each unit in this residential building has the same design. A common area is shared by four residents together with two toilets, a washroom, and a shower room. Each unit has four private bedrooms and there is also a balcony that can be accessed through the common area. Except for the first floor that has four units, there are eight units per floor (Figure A.1)

The ground floor has a lobby, a laundry room (with six washing machines), and three storage rooms. There is also an open parking lot at the end point of the corridor (Figure A.2)

5.2 Case study methodology

Data collection methodology for calculating the energy consumption by the different life cycle phases of the student residential building is represented in the flowchart below.

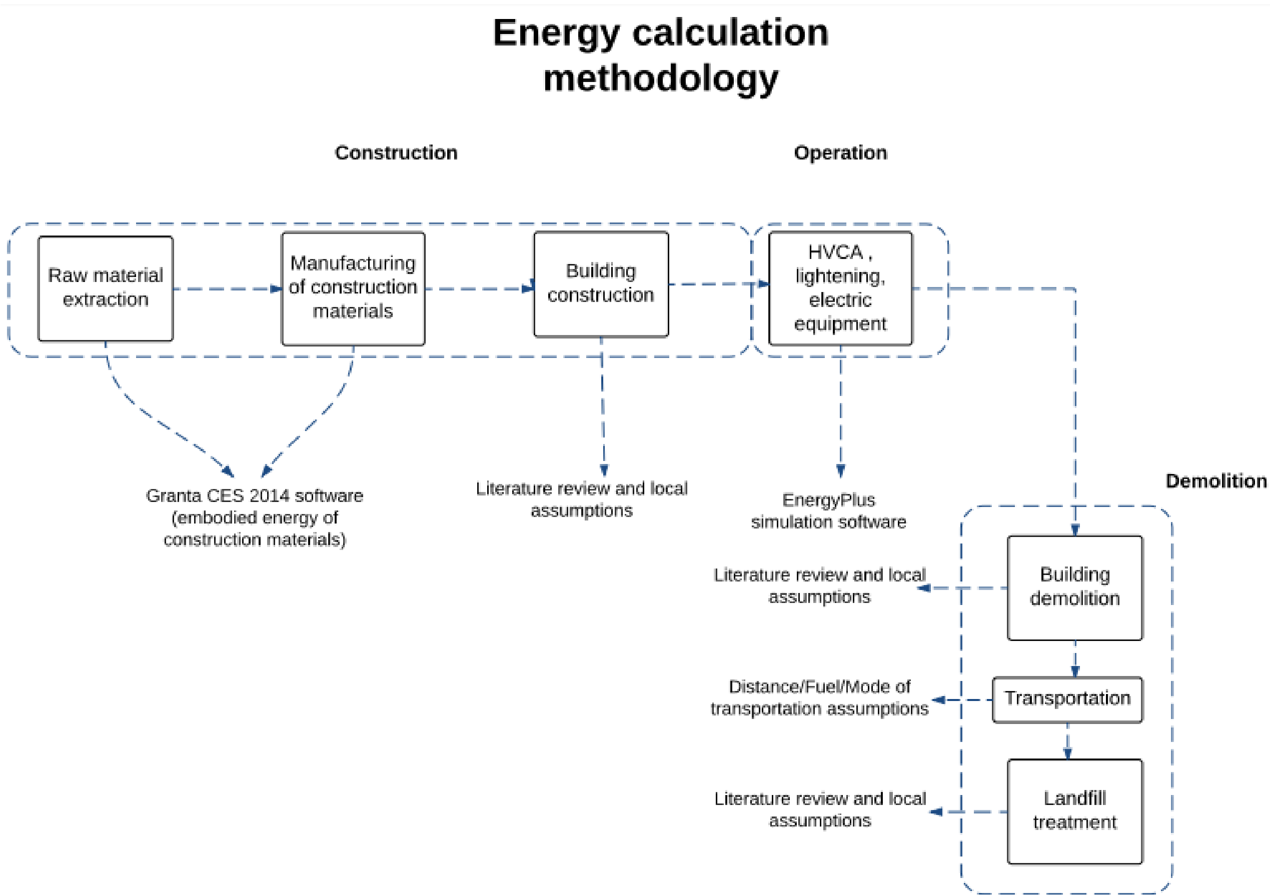


Figure 5.0 Energy calculations methodology

5.3 Construction process

To calculate the total amount of energy consumed and carbon footprint during the construction stage of the building three steps need to be performed. The first step is to quantify primary construction materials (in kilograms) consumed during the construction of the building. The second step is to calculate the total amount of embodied energy and carbon dioxide in those materials, and the last step is to calculate the energy and carbon emissions coming from the activities related to the construction of the residential building.

In this study, primary construction materials were obtained from the original drawings of the building. The elements included in this research are the envelope (internal and external walls, doors, windows, floors, and ceilings), structural elements (columns, piles, beams, wall, and girders), and interior elements (ceramic tile as the only interior element to be calculated). To reduce complexity in this LCEA model, this research only focusses on six primary construction materials: concrete, cement mortar, steel, glass, timber, and ceramic tile.

The lifespan of these materials was obtained from a study made by Chau and colleagues in 2007 about materials for commercial buildings in Hong Kong (Chau et al. 2007) and from another case study of a residential building in Hong Kong (Chen et al. 2001). The table below shows the life expectancy of the chosen construction materials obtained from the mentioned studies.

Table 1.0 Life expectancy of selected construction materials

	Concrete	Steel	Timber (doors)	Tiles	Glass
Life expectancy in years	50	50	38	10	45

Source: (Chau et al. 2007), (Chen et al. 2001)

Embodied energy intensities of the selected construction materials were obtained from two different sources: literature review and from Granta CES EduPack, a material database software. Granta CES is a software created by the Department of Engineering at the University Cambridge, the software presents the properties of a great variety of construction materials, these properties include the embodied energy and the carbon footprints of materials (Ashby and Cebon 1994). Embodied energy calculations from this software comprise the energy of the primary material production, material processing, and material recycling. To get the total amount of embodied energy these three energy intensities (primary material production, material processing, and material recycling) were added together.

The narrow information about the embodied energy of Chinese construction materials has made this research to rely on the software mentioned above. However, Wu Deng and colleges cited a study performed by Tsinghua University in 2003 in which the embodied energy intensities and carbon emissions of Chinese construction materials such as cement, and steel were calculated (as cited in Yang, 2003, pg. 86). The results of their study were used in this research. The embodied energy of the rest of the materials (ceramic tile, glass, and concrete) was taken from the material database software already cited (Table 2.0)

Table 2.0 Embodied energy intensities of selected construction materials

	Cement	Steel	Tile	Glass	Concrete	Timber
Embodied Energy (MJ/kg)	10.2	38.6	16.1	15	0.94	15
CO_2 emission (kg/MJ)	1.594	6.778	.590	.85	0.14	1.10

Source: Tsinghua University study (Yang 2003, pg. 86) and Granta CES material database software (Ashby and Cebon 1994)

Transportation of raw materials to the building site is a crucial factor when calculating the embodied energy of a building. Nevertheless, it is extremely difficult to track the origin of these materials since some of them are imported from different regions or countries. (Chen et al. 2001) This study does not take into consideration the embodied energy consumption on transportation from the manufacturer to the construction site. However, it does take into consideration the direct energy consumption of the processes and activities necessary to erect and to demolish the building.

Activities such as excavating and removing soil, drying concrete elements, lifting materials, smoothing the soil, etc. are activities that require energy. Energy use by these activities needs to be counted as part of the embodied energy. In this study the embodied energy of such activities was allocated in the construction and demolition stages. Primary energy intensities of these processes have been obtained from a research conducted by Adalberth in 1997. To calculate the carbon emissions related to these activities an emission factor was used.

According to Yang an emission factor of .3170 kg per one MJ of electricity Chinese production and 3.1720 kg CO_2 emissions per 1 liter of petrol production in China is suggested (Yang 2003, pg.136) (Table 3.0)

Table 3.0 Primary energy use by activities/processes during the construction and demolition of a building.

Types of processes	Energy intensity
Drying of concrete element	. 900 MJ/kg
Drying of standard concrete on building site	.158 MJ/kg
Excavation and removal of soil	115.2 MJ/m^3
Smoothing of soil	.011 MJ/kg
Crane lifting	7.2 MJ/m^2
Lighting of construction objects[a]	93.6 MJ/m^2
Heating of construction objects[a]	93.6 MJ/m^2
Heating of sheds[a]	50.4 MJ/m^2

Source: (as cited in Adalberth 1997)

[a] Measured in units per usable floor area

5.3.1 Construction phase calculations

Summary of the data and calculations needed to qualify embodied energy coming from selected construction materials is represented in Table 4.0

Table 4.0 Summary of calculations corresponding to the construction phase of the building

	Cement	Steel	Timber	Tile	Concrete	Glass
Material amount (m^3)[a]	-	58[b]	43,482	171	-	43
Density (kg/m^3)[c]	-	7,850	-	2,225	-	2,600
Total amount (kg)[d]	365,844	452,003	43,482	379,407	10,762,069	112,502
EE intensity (MJ/kg)[e]	10.2	38.6	15	16.1	0.94	15
Total EE (MJ)[f]	3,731,609	17,447,316	652,224	6,108,453	10,116,345	1,687,530
CO_2 intensity (kg / MJ)[g]	1.6	6.8	1.10	0.6	0.14	0.9
Total carbon emissions (ton)[h]	13,122	3,064	48	224	1,507	96

[a] Total amount of material in cubic meters (m^3) was obtained from the original drawings. Total amount of materials consumed by each of the elements of the building (envelope, structure, and interior elements) were counted

[b] Total amount of steel was obtained from a previous research project on a similar residential building inside the campus. The calculation was based on the total steel needed per square meter (m^2) area (Zhang 2015)

[c] Density values were obtained from various sources: 2009 ASHRAE Handbook fundamentals, Granta CES material database software, (Engineeringtoolbox.com 2015) and (HKEPD 2010). An average density was calculated if a discrepancy in values was presented

[d] Total amount given in kilograms (kg) was calculated by multiplying the total amount of the material in cubic meter (m^3) times the average density of the material

[e] Embodied energy intensity (EE) value was obtained from several resources as cited in section 6.3

[f] The total embodied energy calculation (Total EE) was calculated by multiplying the total amount of the material in cubic meter (m^3) times the embodied intensity value

[g] Carbon emission intensity value was obtained from several resources as cited in section 6.3

[h] Total carbon emissions were calculated by multiplying the emission intensity times the total amount of the material in kilograms

The method to calculate energy consumed by processes/activates during the construction of the building is represented in the tables 5.0 and table 6.0. Construction activities were separated into two phases: *a* and *b*. Construction phase *a* activities are activities that the energy intensity value is measured based on the total area of the construction site, whereas construction phase *b* activities are measured based on the amount of the construction material.

Table 5.0 Summary of calculations of the construction phase *a* activities

Type of process	Energy intensity	Total area (m^2)	Total energy used (MJ)	CO_2 emission (ton)
Crane lifting	7.2 MJ/m^2	1,042	7502 [a]	2[b]
Lighting of construction object	93.6 MJ/m^2 [c]	7,797[d]	729,799[a]	231[b]
Heating of construction object	93.6 MJ/m^2 [c]	7,797[d]	729,799[a]	231[b]

[a] Total energy consumed was calculated by multiplying the energy intensity times the total construction area

[b] Total amount of carbon emission was calculated multiplying total energy consumed in MJ by the emission factor suggested by Yang of .317 kg of CO_2 for 1 MJ electricity production (Yang, 2003, p136). The result is later converted to metric ton

[c] Measured in units per usable floor area

[d] Total amount of usable floor area of the student residential building

Table 6.0 Summary of calculations of construction phase *b* activities

Type of process	Energy intensity	Total amount (kg)	Total energy used (MJ)	CO_2 emission (ton)
Drying of concrete element	.900 MJ/kg	10,762,069	9,685,862[a]	960[b]
Drying of standard concrete on site	.158 MJ/kg	734,285	116,017[c]	11[b]
Excavation and removal of soil	115.2 MJ/m^3	694 [d]	79,953[e]	8[b]
Smoothing of soil	.011 MJ/kg	888,320	9,771[f]	1[b]

[a] Energy consumed by drying the concrete was calculated by multiplying the total amount of concrete consumed during the construction of the envelope (excluding the concrete consumed by the structure construction) times the energy intensity

[b] Total amount of carbon emission was calculated dividing total energy consumed in MJ by the energy intensity of petrol, 32 MJ/liters. This result in liters of petrol later was multiplied times the emission factor suggested by Yang of 3.1720 kg CO_2 emissions per 1 liter of petrol production. (Yang, 2003, p136). The result is converted to metric ton

[c] Energy consumed by drying of standard concrete on building site was calculated by multiplying the total amount of concrete consumed during the construction of the structure (excluding the concrete consumed by the envelope construction) times the energy intensity

[d] Amount in m^3

[e] Energy consumed by the excavation and removal of the soil was calculated by multiplying the total amount of removed soil during the construction stage times the energy intensity. The amount of removed soil was assumed to be 694 m^3

[f] Energy consumed by smoothing the soil was calculated by multiplying the total amount of smoothed soil during the construction of the building times the energy intensity. The amount of smoothed soil was assumed to be 888,320 kg

5.4 Operational process

Energy consumption during the operational phase of a building is the energy that is used for space and water heating, and for electricity. (Adalberth 1997). An energy modeling of the building case study was created to quantify the energy consumption during its operational phase. In this case, the OpenStudio plug-in for the SketchUp modeling software was used. It is important to mention that OpenStudio is used as an interface of the EnergyPlus modeling software. EnergyPlus is an energy modeling simulation software created by the U.S. Department of Energy. The aim of this software is to quantify the energy consumption of a building and water use. EnergyPlus considers parameter such as luminaire intensities, air, and energy movement between zones, fenestration, and hourly HVAC loads, etc. (U.S. Department of Energy 2015)

5.4.1 Energy modeling with EnergyPlus

5.4.1.1 Geometry, Spaces, and Thermal Zones

The energy modeling process starts with the building geometry, space definition, and thermal zones assignments. In this case, the building geometry was drawn using the original building drawings. SketchUp was the software used to model the building envelope (Figure A3)

According to the International Building Performance Simulation Association when modeling a thermal zone an air mass heating balance needs to be constant in the zone (International Building Performance Simulation Association - USA Affiliate (IBPSA-USA) 2012). The criteria that the association suggests when modeling a zone is based on usage, temperature control, solar gains, perimeter or interior location, and distribution system type (IBPSA-USA 2012). Following this criterion, the building was divided into three different thermal zones per floor (Figure A4), therefore thermal zones were selected based on their usage and similitudes in internal loads.

The first zone was assigned to the entire unit place, this unit place comprises four private bedrooms, two toilets and washroom spaces, showers, common area, and storage rooms. The second zone corresponds to the corridor and the elevator spaces, and the third zone to the stairs and terraces. In this case, the similitude in the usage of the room and internal loads (thermostats set points, solar gains, schedules, light intensity, occupancy, etc.) were the factors when assigning the thermal zones.

Space definitions were selected base on similar energy loads and operations in the thermal zones (Figure A5). It is important to mention that OpenStudio has a predetermine space selection option in which internal loads are based on the parameters and usage of each space type. In this case, two predetermine OpenStudio templates with similar internal loads and schedules in the zones were used. Midrise apartment and the small hotel templates (U.S. Department of Energy 2016) were implemented in the entire model to assigned spaces and loads to the thermals zones.

5.4.1.2 Operation and Internal Loads

To model the internal loads of the thermal zones four key factors were considered: occupancy, lights, electric equipment, and infiltration. Some of the predetermine attributes of these key factors were modified from the original templates.

The occupancy definition value was modified to show the number of people sharing the same thermal zone in each of the floors, therefore the internal loads per zone requirements. The new value in people per space floor area was calculated dividing the number of people per floor using the same type of space over the total floor area of that particular space (Table B1).

In the case of loads coming from electric equipment, the predetermine values were not modified because these loads are difficult to model without having the precise description of electric equipment and their usage (Table B2). The values in energy per space floor of light were also not modified due to the lack of information about the lightning power in each of the thermal zones (Table B3).

OpenStudio uses the geometry of the entire model to assign values in infiltration. Infiltration is the induction of air inside a thermal zone through a door or a window. In this model doors and windows were drawn based on details from the original drawings (Figure A1)

5.4.1.3 Construction Materials

The materials used in the construction of exterior and interior walls, floors, roofs, windows, and doors were taken from the original building's drawings (Table B4). From these drawings, a new set of construction materials was created for each of the components of the building. The properties of these materials were taken from the original data (Table B5).

Autoclaved aerated concrete (ACC) blocks were used as the principal material for the exterior and interior walls. For insulation, extruded polystyrene board (XPS) and thermal polymer mortar were used in both cases. For the general floor and general ground, plain cement concrete, tile, and mortar were the principal components during the construction.

Some of the predetermine materials in the outside layers were modified to reflect the original data. Some properties of the new materials were changed (Figure B1).

There are four windows and a balcony per unit. All the interior windows inside the units are PVC double glazed windows, exterior doors are also PVC double glazed doors. There are also two fire doors per floor (stairs).

5.4.1.4 Climate analysis

Climate is the most important factor when modeling the energy performance of a building. It can be defined as the prevalent conditions of the weather in a certain region (Yang 2015). There are some key variables in the weather that can have an impact on the energy consumption of one building. These variables are: temperature, humidity, solar irradiance, sunshine duration, sky conditions, and precipitation (Yang 2015) (Table C1)

Temperature and humidity can have a direct effect on the heat exchange between the building and the exterior. This heat exchange can cause an increase or decrease in the usage of HVAC inside the building. Solar heat gains affected by the solar irradiance, sunshine hours, and sky condition variables also can influence the heat balance exchanges. Low or high energy radiation through windows means more or less energy gains. These gains can have a direct effect on space's heat balance, thus also in the usage of HVAC and electronic equipment. The use of internal luminance can also be influenced by solar irradiance, sunshine hours, and sky condition variables. Weather conditions are determined by the location of the building to analyze.

This building is located in the city of Ningbo, China. However, this building was modeled with weather data from Hangzhou. Hangzhou is located 153 km North West of Ningbo, it lays on the 30° 03' 55'' N latitude and 102° 11' 43'' E longitude coordinates (Coutsoukis 2009).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHREA) has classified Hangzhou as having a warm – humid 3A weather type (ASHRAE 2006). This weather is characterized by having hot summers and cold winters. The main weather variables are presented in the table below (Table 7.0)

Table 7.0 Weather characteristics of Hangzhou, Zhejiang in China

Weather variable	
Temperature	36°C max to - 2.20°C min
Humidity	75.3 %
Solar irradiance	2,189 Wh/m^2 average per day
Sunshine duration	-
Sky conditions	-
Precipitation	1141 mm per year

(Liggeti and Milne 2008)

5.4.2 Results

Table 8.0 Energy and carbon emissions generation during the operational phase of the building

	Total amount of energy (kWh/50 yrs.)[a]	Total CO_2 emissions (ton/50 yrs.)	Total amount of energy (kWh /m^2 /50 yrs.)[b]	Total CO_2 emissions (ton/m^2 /50 yrs.)[c]
Operation	31,430,556	35,869[d]	4,031	5

[a] EnergyPlus gives the amount in GJ per year basis. The result was converted to kWh and multiplied by 50

[b] Total energy in kWh / 50 yrs. is divided by 7,797 m^2 which is the total floor area of the building

[c] Total carbon emission in ton / 50 yrs. is divided by 7,797 m^2 which is the total floor area of the building

[d] Total amount of carbon emission was calculated converting the total amount of energy from GJ to MJ. The result was multiplied by the emission rate of energy production in China suggested by Yang. et al. (Yang., 2003, pg. 136) of .317 kg CO_2 eq. per 1 MJ of Chinese electricity production

5.5 Demolition process

The end of the life cycle of the building is the demolition phase. In this stage, the building is demolished and all the waste material is taken to the landfill (Chang et al. 2013). Energy use in this stage can be substantially high due the heavy machinery use to demolish the building and to transport the material to the landfill facility. There is not data about energy intensities generated during the demolition of buildings in China; for this reason, the energy intensities coming from the activities and processes completed during the demolition were taken from the previously mentioned study by Adalberth in 1997.

To calculate the total amount of energy consumption during the transportation of the waste material to the nearest municipal solid waste facility (MSW) several assumptions were made. It was assumed that construction and demolition debris were transported to the municipal solid waste in Beilun, Ningbo, located 38 km from the construction site (calculated from google maps) and that five trucks were assigned to complete the task.

The mode of transportation was assumed to be a Chinese manufacturer construction dump truck fueled by diesel oil, HOWO dump truck 6X4 engine with a load capacity of 30,000 kg (howotruck.org 2016). Information regarding fuel consumption for this truck was not found. However, an average consumption rate of gasoline for this kind of heavy trucks was obtained from a study realized by The Transportation Research Board and National Research Council in the United States, the rate is .4895 liters per km (Harrington and Krupnick 2012).

The amount of debris generated by the building was calculated using rate of a waste generation found by Poon and colleagues in 2014. In their research, a general waste generation rate was calculated based on visual inspections, truckload records, and tape measurements (Poon et al. 2004). Their results showed a general waste rate generation of $0.176m^3/m^2$ per gross floor area (Poon et al. 2004). In this study concrete will be the primary construction material of the building, therefore the density of the concrete will be used in this calculation.

Material recovery and recycling are not considered in this study. However, energy consumed by the MSW landfilling facility is included in the system boundary. To calculate the energy consumed by this facility an energy intensity rate was obtained from an LCA research. In this research, an environmental impact assessment of a MSW facility in China was studied.

Construction and operation phases were included in the cited LCA. The results show a consumption of 1.2620 liters of diesel per t-waste-^{1} and .173 kWh per t-waste^{-1} for electricity (Yang et al. 2014). This result includes diesel consumed by the transportation vehicles during the operation and construction of the facility.

All the above-mentioned processes/activities were included in the final calculations to show the energy consumed by the building during its demolition. In the next section calculations are shown.

5.5.1 Demolition phase calculations

Demolition phase calculations were separated into three different categories: activities and processes, transportation, and landfilling. The sum of the three is the total amount of energy consume during the demolition stage of the case study building.

5.5.1.1 Activities and processes

Table 9.0 Summary of calculations of activities during the demolition phase

Type of process	Energy intensity	Total area (m^2)	Total energy used (MJ)	CO_2 emission (ton)
Crane lifting	7.2 MJ/m^2	1,042	7502 [a]	2[b]
Lighting of construction object	93.6 MJ/m^2 [c]	7,797[d]	729,799[a]	231[b]
Heating of construction object	93.6 MJ/m^2 [c]	7,797[d]	729,799[a]	231[b]

[a] Total energy consumed was calculated by multiplying the energy intensity times the total construction area

[b] Total amount of carbon emission was calculated multiplying total energy consumed in MJ by the emission factor suggested by Yang of .317 kg of CO_2 for 1 MJ electricity production (Yang, 2003, pg.136). The result is later converted to metric ton

[c] Measured in units per usable floor area

[d] Total amount of usable floor area of the student residential building

5.5.1.2 Transportation

Table 10.0 Summary of calculations due to transportation during the demolition phase

Total waste (kg)	Number of trips per truck	Diesel used per truck (l)	Total amount of diesel (l)	Total energy used (MJ)	Total CO_2 emission (ton)
1,097,817.6[a]	15[b]	279[c]	1,395[d]	44,640[e]	4[f]

[a] Total amount of waste material was calculated by multiplying the net gross floor area (7,797 m^2) times the waste generation 0.176 m^3/m^2, times the density of autoclaved aerated concrete block used in this building (800 kg/m^3)

[b] Number of trips per truck was calculated dividing total waste (1,097,817.6.6 kg) by load capacity per truck (30,000 kg), and then by number of trucks which is five. The result 7.31 of trucks was multiply by two since each truck needs to return to the demolition site to pick more debris, this gives a result of 14.683 (15 trips per truck)

[c] Diesel consumed by one garbage truck was calculated by multiplying the trips per truck (15 trips), times the distance (38 km) times the consumption rate of .4895 liters per km

[d] Total amount of diesel consumed by the trucks was calculated multiplying the amount of diesel consumed by one truck (279 liters), times the total amount of dump trucks (5)

[e] Total energy consumed was calculated by multiplying the energy intensity of petrol 32 MJ/liters times the total amount of diesel consumed by the trucks (1,395 liters)

[f] Total carbon emission was calculated multiplying the total number of liters of diesel (1,395 liters) times the emission rate of petrol 3.172 kg per 1 liter of petrol (Yang, 2003, pg. 136)

5.5.1.3 Landfilling

Table 11.0 Summary of calculations due to landfilling during the demolition phase

Total waste (kg)	Total diesel consumed (MJ)	Total electricity consumed (MJ)	Total energy used (MJ)	Total CO_2 emission (ton)
1,097,817.6[a]	44,334[b]	684[c]	45,018[d]	141[e]

[a] Total amount of waste material was calculated by multiplying the net gross floor area (7,797 m^2) times the waste generation 0.176 m^3/m^2, times the density of autoclaved aerated concrete block used in this building (800 kg/m^3)

[b] Total energy consumed coming from diesel was obtained by multiplying total amount of diesel consumed, calculated by multiplying the rate of liters per waste in $tones^{-1}$ (1.2620 liters) times the total amount of waste in $tones^{-1}$ (1,097.8176 ton), times the energy intensity of petrol 32 MJ/liters

[c] Amount of total of electricity consumed by the MSW was calculated by multiplying the total waste in $tones^{-1}$ (1,097.8176 ton) times the .173 kWh rate per total waste in $tones^{-1}$. The result (189.922 kWh) was converted to MJ.

[d] Total energy consumed is given by summing total electricity consumed (684 MJ) plus total energy consumed in diesel (44,334 MJ)

[e] Total carbon emission was calculated multiplying the total number of liters of diesel (44,334 liters) times the emission rate of petrol 3.172 kg per 1 liter of petrol plus the total amount of electricity (684 MJ) times the emission rate of .317 kg CO_2 per MJ electricity generation in China

Chapter VI ENERGY CONTRIBUTION ANALYSIS OF THE BUILDING

The first part of this thesis quantifies the energy and CO_2 emissions generated during the lifespan of a student dormitory building in Ningbo, China. The results of this first part reveal that the total amount of energy consumed by the student dormitory building during all its lifespan is 5,907 kWh/m^2. Construction, operation, and demolition phases are included in these calculations. The total amount of carbon emissions generated by the building is 6 ton/m^2. Table 12.0 shows the results.

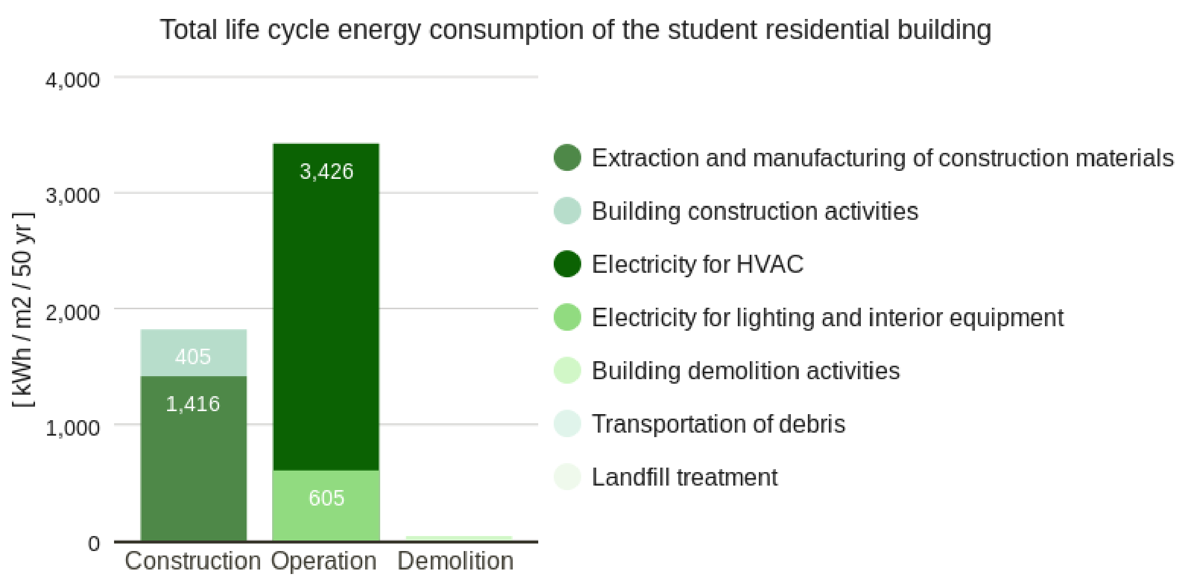
Table 12.0 Energy consumption and carbon emissions generated by the student dormitory

	Total energy consumption (kWh/ 50 yrs.)	**Total CO_2 emissions (ton/ 50 yrs.)**	**Total energy consumption (kWh /m^2 /50 yrs.)**	**Total CO_2 emissions (ton/m^2 /50 yrs.)**
Construction	14,195,050	6,966	1,821	1
Operation	31,430,550	35,850	4,031	5
Demolition	432,473	611	55	0
Total	46,058,078	43,445	5,907	6

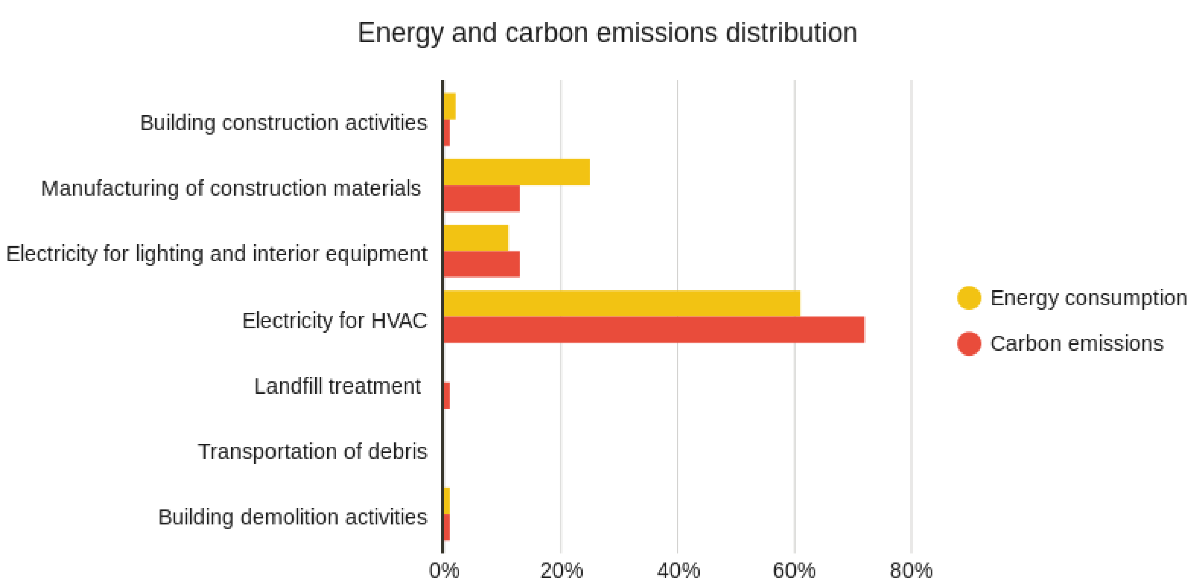
These LCEA results demonstrate that it is during the operational phase of the building when energy consumption is higher and not during its construction or demolition phases; 68% of the total energy consumption was consumed during the operational stage, 31% during the construction phase and only 1% during the demolition stage. The energy, carbon distribution and breakdown by stages and processes it is represented in Graph 1.0 and Graph 2.0 below.

The vast amount of energy consumed during the operational phase of the dormitory is attributed to the electricity used for HVAC, this process alone counts for 57% of the building's total energy consumption. Electricity for lighting and interior equipment also has a high-energy contribution with 10% of the total energy consumed. Graph 3.0 shows the distribution of the electricity consumed during the operational phase.

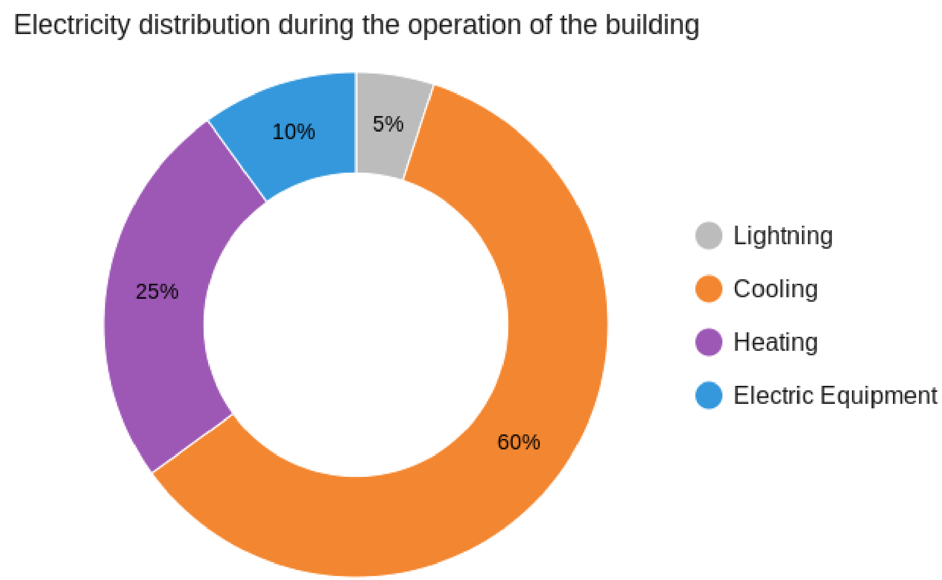
Graph 1.0 Energy consumption by different stages and processes during the life cycle of the student residential building



Graph 2.0 Energy and carbon emissions percentage distribution by different processes



Graph 3.0 Electricity distribution during the operation of the building

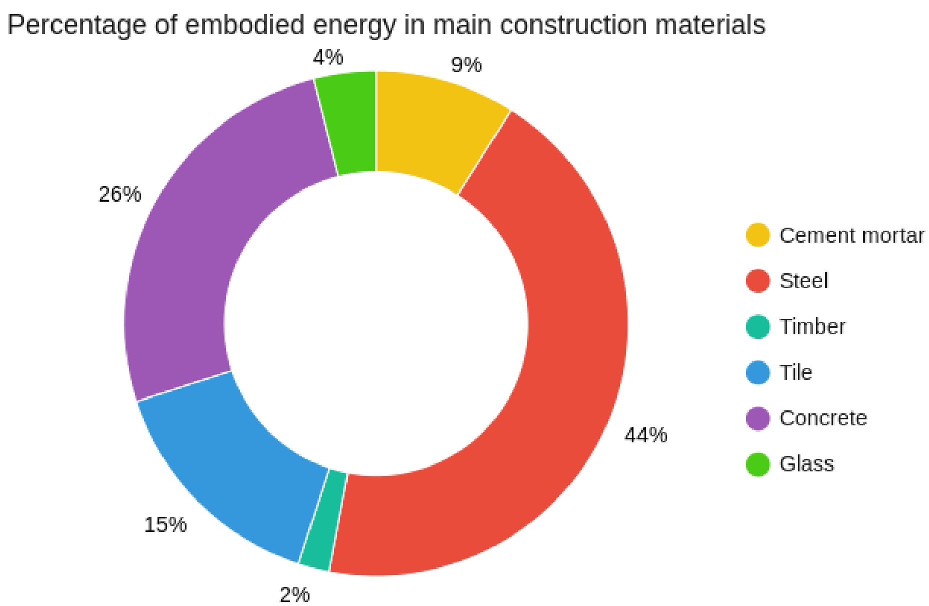


The results also show that most of the energy and carbon emissions produced during the construction phase of the dormitory have been caused by construction materials. The total amount of embodied energy generated by these materials counts for 78% of the total energy used in the construction phase and 24% of the total energy consumed in the total life cycle of the dormitory. Among these materials steel and concrete are the materials that contribute the most to the total embodied energy, the reason behind these results is the huge amount of concrete (including cement mortar) and steel that is needed to erect the building. The embodied energy intensity of steel is another factor affecting this result. Virgin steel has the highest embodied energy intensity factor among the selected materials, 38.6 MJ of embodied energy per kg of steel, tile has second highest with 16.1 MJ per kg of tile. Graph 4.0 shows the percentage of embodied energy generated by construction materials.

Embodied energy in construction materials along with the energy consumed by the activities to construct and demolish the building are classified as indirect energy, direct energy is the energy use only to operate the building. Graph 5.0 shows a comparison between direct and indirect energy and carbon emissions during the life cycle of the building.

Direct carbon emissions are eight times higher than indirect emissions. The reason behind this result is the vast amount of energy consumed for HVAC and the high carbon emission intensity for electricity production in China. Chinese electricity production comes from coal, around 60% (China Energy Group at Lawrence Berkeley National Laboratory 2014), which is considered one of the dirtiest energy supplies.

Graph 4.0 Percentage of embodied energy generated by construction materials



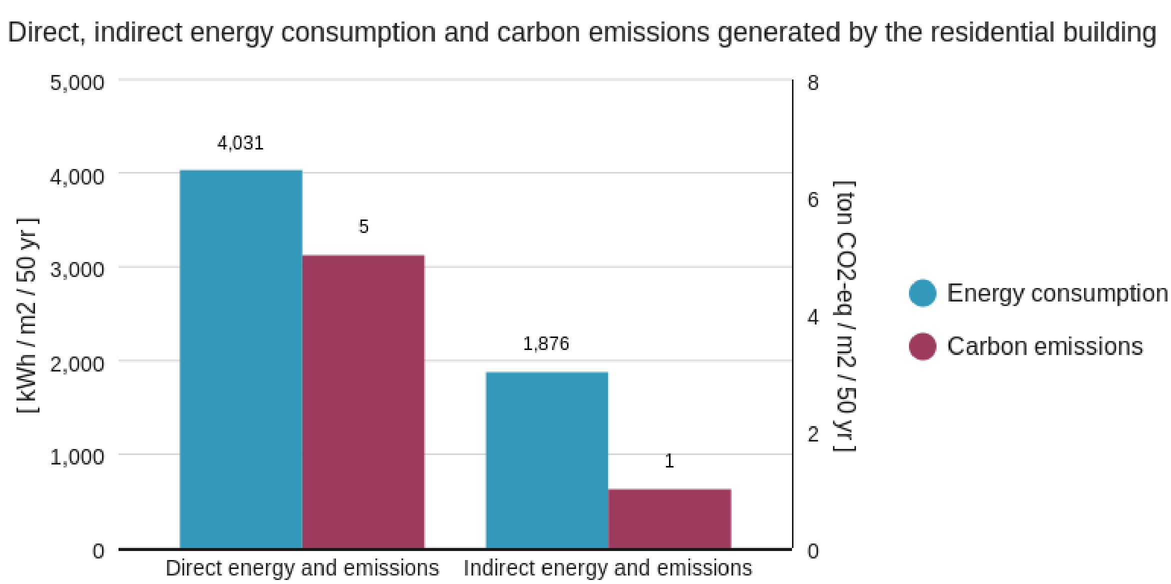
The results of this life cycle energy analysis can be compared to other dissertation and studies. See for example (Ge et al. 2009), who in their study simulated the annual energy consumption of a residential building in Hangzhou (the same location of the building as the one assessed in this study), and found similar results. Their simulation showed a 90.79 kWh/m^2/yr. operational energy consumption, compare to the 80.62 kWh/m^2/yr. found in this study.

A previous dissertation in which a life cycle energy assessment of two different student dormitories on the same campus was also examined. (Zhang 2015) calculated the energy and carbon emissions for buildings 20 and 22. In his calculation, he included the construction of the building (embodied energy of construction materials, decoration, and maintenance), operational energy, and the energy consumed by the residents due to their transportation habits. He excluded all the activities related to the demolition of the building. His results showed a total energy use of 243,664 GJ by Building 20 and 238,187 GJ by Building 22

(Zhang 2015). The discrepancy between his results and this study can be attributed to the amount of processes/activities, data collection, the inclusion of inputs and outputs, and methodology that both studies achieved. However, in both studies operational stage represents the biggest contributor to the total amount of energy consumed by the building, followed by the activities related to the construction.

In addition to the dissertation of Zhang Yu (2015), several other energy assessments of buildings have been performed. These studies have revealed that operational energy constituted 80-90% of the building' total life cycle energy demand and embodied energy around 10-20% (Ramesh et al. 2010). Although these percentages can differ depending on the method to model the energy assessment, the relationship between operational energy and life cycle energy will be constant (Ramesh et al. 2010); being the operational energy the highest contributor to the energy demand of the building.

Graph 5.0 Direct, indirect energy consumption and carbon emission generated during the life cycle of the student residential building



7.1 Solar panel information

For purpose of this thesis, a Chinese-manufactured solar panel was evaluated. A local manufacturer of solar cells and panels was selected as the supplier. Characteristics such as model, brand, and silicon purity were chosen based on data availability and information from the merchant.

Solar Panel Specifications	
Manufacturer	Nbsolar
Location	Ningbo, China
Model	TDB156x156-72-P
Cell type	Multi-crystalline
Number of cells	72
Cell dimension	156 x 156 mm
Rate power at STC[a] (Pmax)	290W
Rate voltage (Vmp)	35.2V
Rate current (lmp)	8.24A
Open-circuit Voltage (Voc)	44.2V
Short-circuit current (lsc)	8.59A
Maximum system voltage	DC 600V
Module efficiency	14.9%
Module dimension	1958 x 992 x 46 mm
Weight	23.5 kg
Operating temperature	-40°C to +85 °C
Planned life time	25 yrs.

(nbsolar.com 2011)

[a] STC: irradiance 1000W/m^2; module temperature 25 °C; AM = 1.5

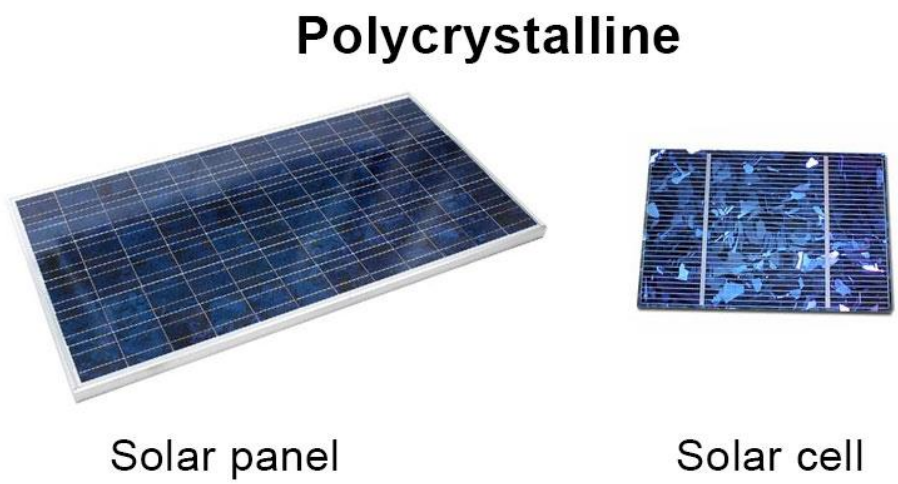


Figure 6.0 Polycrystalline solar panel case study (Arthur 2014)

7.2 Case study methodology

The direct and indirect energy involved in the production of the solar-grade silicon, wafers, ingots, cells, modules, and the balance-of-systems were obtained from previous studies. An extensive literature review was performed to attain the most accurate, precise, and updated results about the production of PV energy systems in China. Table 13.0 represents these studies.

Table 13.0 Previous studies related to the manufacturing of crystalline PV systems in China

Author/year	Origin	Cell type	UMG-Si production	SoG-Si production	Ingot casting	Wafer slicing	Cell production	Module assembly	Total energy
(Hou et al. 2016)	China	Multi /Mono	0.093 kWh/W_p	0.687 kWh/W_p	0.042 kWh/W_p	0.109 kWh/W_p	0.204 kWh/W_p	0.204 kWh/W_p	1.339 kWh/W_p
(Li and Chang 2012)	China	Multi	-	2287.25 MJ	157.54 MJ	24.01 MJ	686.69 MJ	72.00 MJ	3237.9 MJ
(Alsema 2000)	-	Multi	450 MJ/m^2	1800 MJ/m^2	750 MJ/m^2	250 MJ/m^2	600 MJ/m^2	350 MJ/m^2	4200 MJ/m^2
(Peng and Lu 2013)	China	Multi	-	-	-	-	-	-	2952 MJ/m^2
(Zhang et al. 2012)	China	Multi	-	175 kWh/kg	55 kWh/kW_p	15 kWh/kW_p	200 kWh/kW	150 kWh/kW	-
(Yang et al. 2015)	China	Multi	.07 kWh/kg	13 kWh/kg	118 kWh/kg	118 kWh/kg	175 kWh/kg	25 kWh/kg	449.07 kWh/kg
(Alsema 2000)	-	Mono	450 MJ/m^2	1800 MJ/m^2	2300 MJ/m^2	250 MJ/m^2	550 MJ/m^2	350 MJ/m^2	5700 MJ/m^2
(Peng and Lu 2013)	China	Mono	-	-	-	-	-	-	3775 MJ/m^2

Notes:

UMG= Upgraded metallurgical-grade silicon; SoG= Solar grade silicon;

Although these LCA studies were created for a Chinese manufactured PV system – (Alsema 2000) does not mention the manufacturing country of origin – there is still a significant difference between results. Factors such as time, technology, and data acquisition could influence on these results. For example, (Peng and Lu 2013) and (Alsema 2000) made estimations to calculate the entire life cycle energy requirements of the solar panel based on literature review and previous studies. In contrast (Hou et al. 2016), (Yang et al. 2015), and (Li and Chang 2012) acquired the data from a combination of surveys made to PV enterprises, literature review, and reports.

The exclusion of processes and system boundaries delimitation were also a key factor in the difference between results. For instance, (Li and Chang 2012) and (Zhang et al. 2012) did not include the production of upgraded metallurgical-grade silicon, (Peng and Lu 2013) did not breakdown the manufacturing processes of the PV system, whereas (Yang et al. 2015) included the imported materials from abroad in their system boundaries. In the case of process parameters, aspects such as wafer thickness, wafering losses, silicon purification and the crystallization process also had an influence on final results (Alsema 2000).

Based on the comparison between the methodologies of the different LCA studies – including only those of multi-crystalline silicon grade –, the results from Yang. et al. are the most adequate for the purpose of this research. Their results have shown an accurate, precise, and updated information about PV system manufacturing in China. According to the authors, the data source of Chinese PV technology was acquired from surveys and environmental impact assessment reports from relevant factories in China. The researchers also performed an extensive literature review in order to get the necessary data on the industrial silicon manufacturing (Yang et al. 2015)

7.3 Life cycle energy output of solar system

Before calculating the energy consumption during the entire life cycle of the PV system it is fundamental to quantify the number of solar panels that need to be installed to provide the electricity demand of the case study building.

To calculate the array of solar panels that are needed is important to consider these factors: electricity demand of the building, energy output during the life cycle of the solar panel, and the roof's usable surface area (DeBono 2015). It is assumed that the solar system is grid-connected, therefore the partial amount of the electricity demand will be supplied by the PV system. The energy output per solar panel needs to be calculated and multiplied by the number of solar panels that can be installed on the roof. It is important to note that degradation of solar cells over time has not been considered in this study.

The amount of energy output of the solar panel during its life is calculated using this equation:

$$E_O = A * \ r * \ H * \ PR * lt$$

E_o= energy output of the solar panel (kWh)

A = solar panel area (m^2)

r = solar panel yield efficiency (%)

H= annual solar radiation (NASA 2016)

PR = performance ratio (default.75)

lt = life time of solar panel (default 25 years)

Therefore,

$$E_O = 1.942 \ m^2 * \ 14.9\% * \ 1310 \ kWh/m^2 * .75 * 25 \text{ yrs.} = 7107.35 \text{ kWh}$$

The number of solar panels to be installed on the building depends on the roof's usable surface area. The building has a roof's usable surface area of 704.7 m^2, then 704.7 m^2 ÷1.942m^2 = 362.8. The array is approximately composed of 362 solar panels.

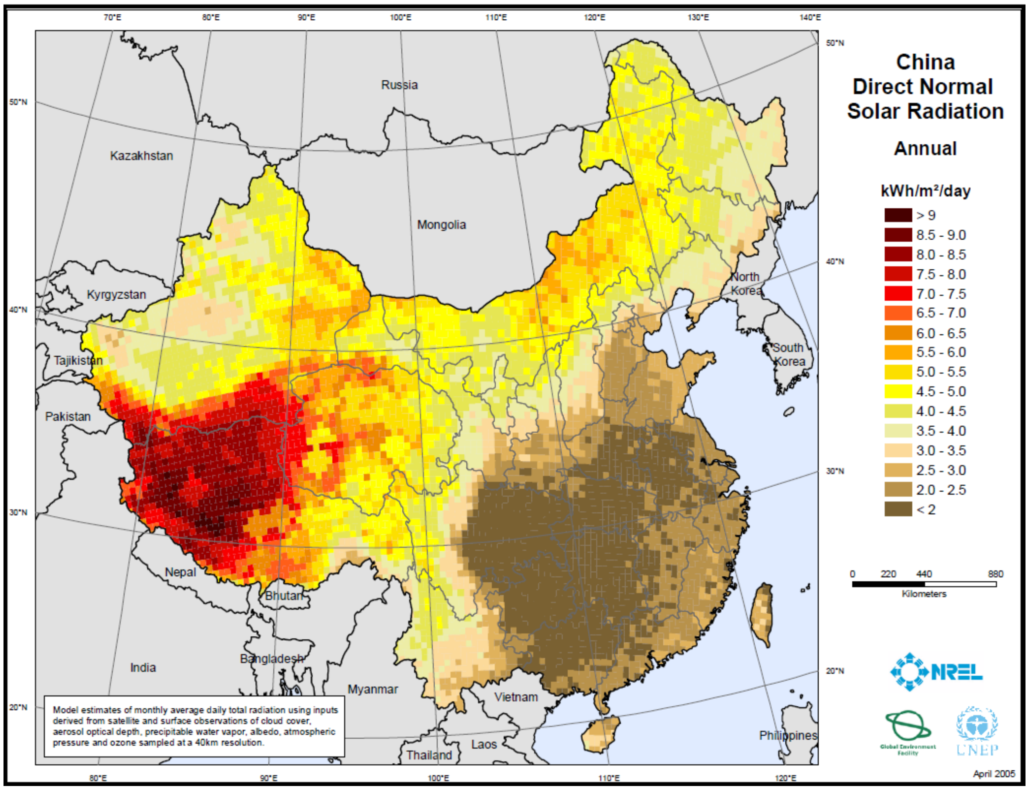


Figure 7.0 Solar direct radiation in China (National Renewable Energy Laboratory 2005)

A partial amount of the energy output of the PV system can be lost during the transmission of energy to the grid. The average loss ratio of grid transmission in China during 2010 was 6.53% (Lu et al. 2013). Therefore 95.47% of the PV energy output is for final use. The amount of electricity that the PV solar system can provide during its life cycle – assuming a 25 years' life span of each solar panel with a one-time replacement – is resumed in the table below.

Table 14.0 Energy and carbon reductions of the photovoltaic solar panel during its life time

Energy output per solar panel (kWh/ 50 yrs.)	Number of solar panels	Total energy output of the PV system (kWh/ 50 yrs.)	Total CO_2 reductions (ton/ 50 yrs.)
13,570.78	362	4,912,623.99[a]	5,606.28[b]

a The result of multiplying the energy output per panel times the number of solar panels

b Carbon emission reduction was calculated multiplying total energy output in MJ times the emission factor suggested by Yang of .317 kg of CO_2 for 1 MJ electricity production (Yang, 2003, pg. 136). The result is later converted to metric ton

In the next section, a brief description of the manufacturing processes involved in the production of the entire PV energy system along with their corresponding calculations are going to be presented. Energy intensities from the study of Yang. et al. are going to be applied for calculation purposes.

7.4 Manufacturing process

Manufacturing calculations were separated into three different categories: manufacturing of the solar panel, transportation, and manufacturing of the balance-of-system. The sum of these three categories is the total amount of energy consume during the manufacturing stage of the case study PV system.

7.4.1 Manufacturing of solar panel

7.4.1.1 Raw material extraction and metallurgical-grade silicon production (UMG-Si)

Mining quartz and the extraction of silicon from silica is the first step in the manufacturing process of a PV system. Silica is made out from sand, but the transformation to silicon requires pulverized quartz and a mixture of coal. This process requires a significant amount of energy since an electric arc is necessary for the reaction. The final result is metallurgical-grade silicon (UMG-Si) (Stoppato 2008).

$SiO_2 + 2C \rightarrow Si + 2CO$.

7.4.1.2 Solar grade silicon production (SoG-Si)

Solar cells silica must have a 99.9999% grade of purity in order to reach a semiconductor grade transmitter (Francis 2013). To reach this grade of purity metallurgical-grade silicon needs to be transformed into solar grade silicon. There are many methods to do this, but the most common method the one created in the late seventies by the Union Carbide Corporation (UCC) (Phylipsen and Alsema 1995). In this technology, mg-Si is hydrogenated in a fluidized-bed reactor at 500°C with a copper based catalyst (Breneman et al. 1978)(Lutwack 1980)

7.4.1.3 Ingot casting and wafer slicing

The next step in manufacturing PV solar systems is the ingot casting and wafer slicing. In this process, high purity silicon feedstock is melted and converted into multicrystalline ingots. A crucial task in this process is removing the impurities and grain boundaries of the multicrystalline ingots. Ingots must have a semiconductor grade of purity, because of this reason contouring the outer part of the ingots can help to remove impurities. Once the ingots are out of impurities they are sawed into smaller blocks. Later, these smaller blocks are sliced into thin wafers by using a multi-wire saw and a slurry (Phylipsen and Alsema 1995).

7.4.1.4 Cell production

Solar cell production involves various stages. First, it is necessary to remove the slicing damage that occurred in the previous process by pouring sodium hydroxide (NaOH) (Overstraeten and Mertens 1986). Later these wafers need to be rinsed with water and concentrated sulphuric acid (Phylipsen and Alsema 1995). In the next step, the n-type emitter layer is formed and metallized in the wafer. This is normally done by in-diffusion of phosphorous atoms and by pasting a layer of aluminum and silver in the back of the cell. The last step in this process is the bulk passivation, here hydrogen atoms created in a plasma (normally a film) are used in order to reduce impurities and grain boundaries (Phylipsen and Alsema 1995).

7.4.1.5 Module assembly

This is the last step in the manufacturing of a solar panel. In this process, solar cells are tested and inserted into a module matrix – the normal configuration module matrix is 4 x 9 cells –. The cells are connected using copper strips cover by tin. In the following phase, the matrix is protected by two sheets of ethylene vinyl acetate (EVA) foil and laminated at a temperature of 120-150^{o}C. The module is later washed and dried (Phylipsen and Alsema 1995).

7.4.1.6 Total energy consumption during the manufacturing process of the solar panel

Results of the total energy consumed by the manufacturing process of the case study panel are presented in table 15.0 Results are based on the characteristics of the solar panel and the energy intensities presented by Yang et al.

Table 15.0 Breakdown of energy consumption in the manufacturing process of the solar panels

Silicon ore mining (kWh/m^2)	UMG-Si production[a] (kWh/m^2)	SoG-Si production[b] (kWh/m^2)	Wafer slicing (kWh/m^2)	Cell production (kWh/m^2)	Module assembly (kWh/m^2)	Total energy[c] (kWh/m^2)	CO_2 emissions[d] (ton/m^2)
0.09	8.7	425.33	60.75	90.11	13.1302	598.13	.68

[a] Refers to upgraded metallurgical-grade silicon

[b] Refers to solar grade silicon production

[c] Results show the production of 362 solar panels. Energy intensities from the study of Yang et al. are multiplied by the material requirements and total number of solar panels

[d] Total carbon emission was calculated multiplying the total amount of electricity (598.13 kWh /m^2) times the emission rate of .317 kg CO_2 per MJ electricity generation in China

7.4.2 Transportation of the solar panel

To calculate the total amount of energy consumption during the transportation of the solar panels to the building several assumptions were made. It was assumed that the solar panels were completely manufactured in the Nbsolar facilities in Ningbo and transported to the University of Nottingham campus, which is located 15 km from the factory site (calculated from google maps).

The mode of transportation was assumed to be a Chinese manufacturer cargo truck fueled by diesel oil, HOWO sinotruck 4X2 cargo truck 6-cylinder engine with a load capacity of 7.845 m^3 (howotruck.org 2016) Information regarding fuel consumption for this truck was not found. However, an average consumption rate of gasoline for this kind of heavy truck was obtained from a study realized by The Transportation Research Board and National Research Council in the United States, the rate is .4895 liters per km (Harrington and Krupnick 2012).

Solar panels are assumed to be packaged on pallets of 30, therefore 8 pallets containing 240 solar panels per trip are expected. A round trip from the factory to campus is also assumed.

Table 16.0 Energy consumption due to the transportation of solar panels to the building

Number of trips	Distance to building (km)	Consumption of diesel (l/km)	Total amount of diesel (l)	Total energy consumed(MJ)	Total CO_2 emissions (to)
4	60	.4895	29.37[a]	939.84[b]	.0931[c]

[a] Total amount of diesel consumed by the truck was calculated multiplying the distance (60 km) times the consumption rate of .4895 l/km

[b] Total energy consumed was calculated by multiplying the energy intensity of petrol 32 MJ/liters times the total amount of diesel consumed by the truck (29.37 liters)

[c] Total carbon emission was calculated multiplying the total number of liters of diesel (29.37 liters) times the emission rate of petrol 3.172 kg per 1 liter of petrol (Yang., 2003, pg. 136)

7.4.3 Manufacturing of balance-of-system

To install and operate a PV solar panel additional components are needed. These additional components are known as a balance-of-system (BOS). They help to conduct and transform solar energy from the solar panels to electricity – to be used directly or stored for future use – (U.S. Department of Energy). Based on the installation method, rooftop or ground-mounted, solar panels can demand less or more BOS. The most common BOS equipment are junctions boxes, inverters, cables, connectors, and mounting system (Fthenakis et al. 2011).

The solar panel studied in this research is planned to be mounted on the rooftop of the university building. The required BOS for the installation included in this study are mounting system, frames, inverters, and cabling. A brief description of each element is presented below.

7.4.3.1 Mounting system and frames.

Solar panels need a structural support when they are installed. Frames and mounting systems normally help to fix solar panels on the rooftop or on the ground. Frames or rails cover solar panels around the edges, while at the same time these – frames – are fixed to a mounting tube or pipe made of steel or aluminum. The structure gives support, and it also secures solar panels to the ground or floor.

7.4.3.2 Inverters

Inverters are designed to reverse the direct current electricity (DC) coming from the solar panel into alternating current (AC), which is the current used by household appliances (Zipp 2013). Inverters can vary and they need to be chosen carefully based on the size of PV array, module, orientation, pitch, location, and potential shadings (Hutchens 2011).

7.4.3.3 Cabling

Electric cables assist in placing the entire PV system together. They connect junction boxes – on the back side of each panel – to the inverter and/or to the grid.

The amount of cable needed for the installation of PV systems can vary depending on the size of the building and the distance between the PV panels and the electric grid (Jungbluth N., Stucki M, Frischknecht R. 2010).

7.4.3.4 Total energy consumption during the manufacturing of balance-of-system

Because of the limited amount of LCA studies of balance-of-system the results of Hou et al. are taken for calculations. The authors included energy consumed by controllers, inverters, cables, etc. in their calculations. They estimated a 0.255 kWh/W_p energy consumption during the system integration and construction – including the manufacturing of balance-of-system – Tables 17.0 shows the total kWh of energy requirements for the manufacturing of the balance-of-system.

Table 17.0 Energy consumption for the manufacturing of the balance-of-system

Energy consumption for PV system integration (kWh/W_p)	Total energy consumed (kWh)	Total CO_2 emissions (ton)[a]
0.255	27,693	31.603

[a] Total amount of carbon emission was calculated multiplying the total energy consumed times the emission factor suggested by Yang of .317 kg of CO_2 per 1 MJ electricity production (approximately 0.278 kWh) (Yang, 2003, pg. 136)

7.4.4 Total amount of energy consumed during the manufacturing stage of the case study PV system.

As cited before, the total amount of energy utilized during the manufacturing stage of the PV system is the sum of the energy consumption during the production of the solar panel, transportation, and fabrication of the balance-of-system. Table 18.0 shows the sum of these three processes.

Table 18.0 Total energy consumption during the manufacturing stage of the solar system

Solar panels manufacturing (kWh/ m^2)	Solar panels transportation (kWh/ m^2)	BOS manufacturing (kWh/ m^2)	Total energy consumed (kWh/ m^2)	Total CO_2 emissions (ton/m^2)
598.13	.37	39.39	637.89	.72

Notes:

kWh / m^2 array total area

7.5 Operation and maintenance of PV system

PV energy systems convert solar energy into electricity, it is presumed that this same energy is consumed during their operation. Therefore, there is no need to generate extra energy during the operation of the system. However, during the lifetime of the PV system, replacement of solar panels, cables, junction boxes, or inverters are expected (Hou et al. 2016). For purpose of this study, only the replacement of solar panels is considered.

Solar panels have a usable lifespan of 25 years. A replacement would be needed to supply the building's energy demand during its 50 years of life expectancy. Therefore, energy consume in this phase is assumed to be the same as the manufacturing process. Table 11 represents this energy consumption.

7.6 PV system decommissioning

The last stage of the PV system life cycle is the decommissioning of the components of the system. This stage includes dismantling solar panels and BOS, transportation of debris to the waste management facility, and/or recycling of the pieces.

Material recovery and recycling are not considered in this study. However, energy consumed by the MSW landfilling facility and the transportation are included in the system boundary.

7.6.1 Transportation of the solar panel to the MSW facility

To calculate the total amount of energy consumption during the transportation of the PV system to the nearest municipal solid waste facility (MSW) several assumptions were made. It was assumed that solar panels and BOS were transported to the municipal solid waste in Beilun, Ningbo, located 38 km from the building (calculated from google maps) and that one truck was assigned to complete the task.

The mode of transportation was assumed to be a Chinese manufacturer construction dump truck fueled by diesel oil, HOWO dump truck 6X4 engine with a load capacity of 30,000 kg (the same truck chosen to transport waste material during the demolition of the building) (howotruck.org 2016). Information regarding fuel consumption for this truck was not found. However, an average consumption rate of gasoline for this kind of heavy truck was obtained from a study realized by The Transportation Research Board and National Research Council in the United States, the rate is .4895 liters per km (Harrington and Krupnick 2012).

Based on the trucks' load capacity it is assumed that three loads of debris are needed to transport all the components to the MSW facility. It is also assumed a round trip from the factory to campus. Table 10.0 summarizes the results.

Table 19.0 Energy consumption due to the transportation of solar panels to the MSW facility

Number of trips	Distance to building(km)	Consumption of diesel (l/km)	Total amount of diesel (l)	Total energy consumed(MJ)	Total CO_2 emissions (ton)
6	228	.4895	111.606[a]	3571.392[b]	.354[c]

[a] Total amount of diesel consumed by the truck was calculated multiplying the distance (228 km) times the consumption rate of .4895 l/km

[b] Total energy consumed was calculated by multiplying the energy intensity of petrol 32 MJ/liters times the total amount of diesel consumed times the truck (111.606 liters)

[c] Total carbon emission was calculated multiplying the total number of liters of diesel (111.606 liters) times the emission rate of petrol 3.172 kg per 1 liter of petrol (Yang., 2003, pg. 136)

7.6.2 Energy consumption during the landfill treatment of the PV system

To calculate the energy consumed by the MSW landfill treatment an energy intensity rate was obtained from a previous LCA research. The results of an environmental impact assessment of a MSW landfill facility in China realized by Yang et. al in 2014 were used. These results indicate a consumption of 1.2620 liters of diesel per t-waste-^{1} and .173 kWh per t-waste^{-1} for electricity during the landfilling treatment process (Yang et al. 2014). Table 20.0 shows calculations and results.

Table 20.0 Energy consumption during the landfill treatment of the PV system

Total waste (kg)	Total diesel consumed (MJ)	Total electricity consumed (MJ)	Total energy consumed (MJ)	Total CO_2 emission (ton)
9,607[a]	387.96[b]	5.983[c]	393.943[d]	.0403[e]

[a] Total amount of waste material is the total net weight of the 362 solar panels (8,507 kg), plus the estimated weight of the BOS and frames (1,100 kg)

[b] Total energy consumed coming from diesel was obtained by multiplying total amount of diesel consumed, calculated by multiplying the rate of liters per waste in tones^{-1} (1.2620 liters) times the total amount of waste in tones^{-1} (9.607 ton), times the energy intensity of petrol 32 MJ/liters

[c] Amount of total of electricity consumed by the MSW was calculated by multiplying the total waste in tones^{-1} (9.607 ton) times the .173 kWh rate per total waste in tones^{-1}. The result (1.662 kWh) was converted to MJ

[d] Total energy consumed is given by summing total electricity consumed (5.983 MJ) plus total energy consumed in diesel (387.96 MJ)

[e] Total carbon emission was calculated multiplying the total number of liters of diesel (12.12 liters) times the emission rate of petrol 3.172 kg per 1 liter of petrol plus the total amount of electricity (5.983 MJ) times the emission rate of .317 kg CO_2 per MJ electricity generation in China

7.6.3 Total amount of energy consumed during the decommissioning stage of the case study PV system.

Energy consumed during the transportation of the solar panels to the municipal landfill and during the treatment of these panels in the landfill is the total amount of energy consumed during the decommissioning stage.

As mentioned before in the maintenance and operational section, the PV system has a lifespan of 25 years, for the same reason it is necessary to replace the system. Therefore, the results in this section are multiply by two. Table 21.0 shows results.

Table 21.0 Total energy consumption during the decommissioning stage of the PV system

PV system transportation (kWh/ m^2)	Landfill treatment (kWh/ m^2)	Total energy consumed (kWh/ m^2)	Total CO_2 emissions (ton/m^2)
2.82	.31	3.13	.001

Notes:

kWh / m^2 array total area

Chapter VIII ENERGY CONTRIBUTION ANALYSIS OF THE PV SYSTEM

The second part of this thesis quantifies the energy and carbon emissions generate during the lifespan of a roof-mounted PV solar system. The results of this second part revealed that the total amount of energy consumed by the PV energy system during its entire life cycle is 899,097 kWh. Manufacturing, operation, and decommissioning phases are included in these calculations. The total amount of CO_2 generated during the lifespan of the PV system is 1,024 metric tons. Table 21.0 shows the results.

Table 21.0 Life cycle energy consumption and CO_2 emissions generated by the PV energy system

	Total energy consumption (kWh)	**Total CO_2 emissions (ton)**	**Total energy consumption (kWh/m^2)**	**Total CO_2 emissions (ton/m^2)**
Manufacturing	448,447	512	637	1
Operation and maintenance	448,447	512	637	1
Dismantling	2,203	0	3	0
Total	899,097	1,024	1,277	2

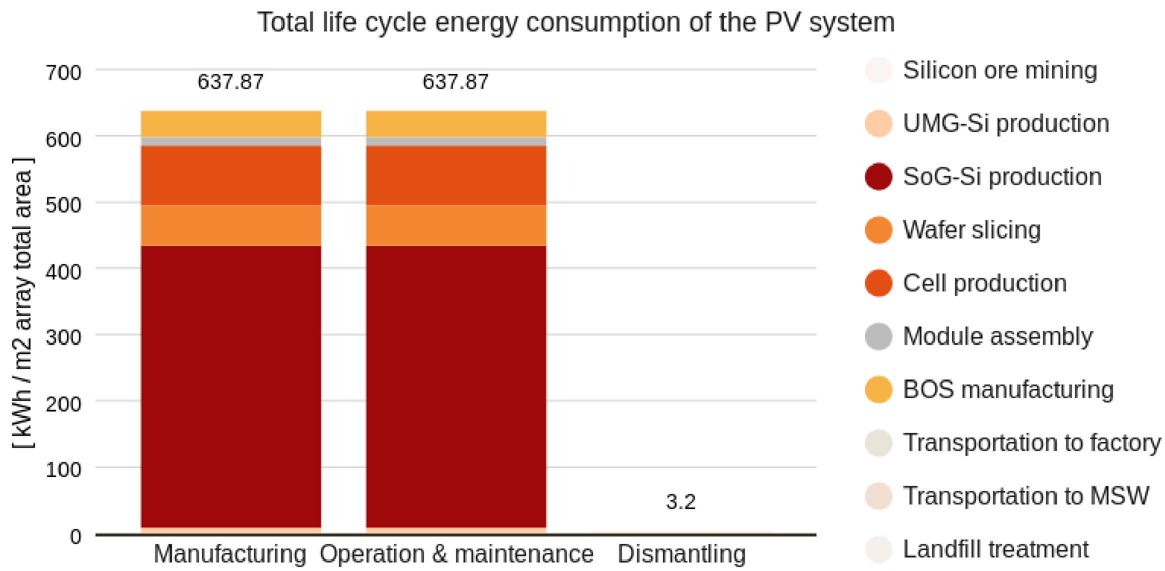
Notes:

kWh / m^2 array total area. Total array land area is = 704 m^{2,} equivalent to fit 362 solar panels.

Results show that energy consumption during the manufacturing of PV solar systems is higher than dismantling the system. The operation of the PV system is assumed to have a neutral role in the energy consumption. But, since it is necessary to replace the PV system after 25 years, the energy consumed during its manufacturing process is aggregated to the maintenance and operation stage.

During the module manufacturing phase, some processes consumed and emitted more energy and emissions than others. Graph 6.0 shows energy consumed by different processes/stages.

Graph 6.0 Energy consumption by different stages and processes during the life cycle of the PV system



The process that consumes more energy during the manufacturing stage of the solar panel is the conversion of the upgraded metallurgical silicon (UMG-Si) into solar grade silicon (SoG-Si), 67% of the total energy is consumed here. The reason behind this is that the Siemens process needed for upgrading the purity of the metallurgical silicon into solar silicon consumes a vast amount of electricity. Many other studies have shown this before, see for example (Jiao et al. 2011) and (Stoppato 2008).

The second biggest contributor to the energy consumption of the PV system is manufacturing solar cells, around 14% of the total energy is consumed in this process. Producing solar cells involves various stages (Phylipsen and Alsema 1995). It is unclear to know the processes that consume more energy when producing solar cells; there is a big discrepancy in the results of studies since every cell manufacturing process is different. However, according to Alsema and Phylipsen major factors affecting energy consumption in this process can be attributed to the operational hours of the manufacturing solar cells plants (24 hours or less) and the solar cell batch size (Phylipsen and Alsema 1995).

In the next section, the energy payback time and energy contribution analysis with and without the PV system will be presented.

8.1 EPBT

The energy payback time, which is the time that takes the PV system to generate the equivalent amount of energy consumed to produce it can be calculated with this equation:

$$EPBT = E_i \;/\; E_s$$

Where:

E_i = Energy consumed during the life cycle of the PV system (manufacturing and decommissioning)

E_s = Annual energy saved due to energy generated by the PV system

$$EPBT = 449{,}548.23 \text{ kWh} \;/\; 98252.5 \text{ kWh/yr.} = 4.6 \text{ years}$$

It will take 4.6 years to the PV system to generate the equivalent amount of energy that was consumed to produce it. It is relevant to indicate that this result does not include the replacement at 25 years. Since it will be necessary to replace solar panels during the lifespan of the building, the energy payback time then will be increased to 9.2 years.

It is well known that the EPBT of a solar system depends on key factors such the annual solar radiation, sunshine hours, the yield efficiency and performance ratio of solar panels and BOS (Lu and Yang 2010), the type of solar cell, and the usable area of the system. For this reason, a wide variation in the results of previous studies can be found in the literature.

It is important to compare EPBT studies with similarities in their input data. Geographical data, panel characteristics, and manufacturing process information need to be comparable to make a fair comparison between investigations.

There are few Chinese studies assessing the EPBT of solar panels located in Zhejiang province with the same characteristics as the one assessed here. The study of (Fu et al. 2015) is the only one found in the literature. They performed a LCA of a PV solar system in China with similar characteristics as the one assessed here. They evaluated the EPBT of the PV system located in different regions in China. Their result showed a 3.36 to 4 years EPBT for the region corresponding to this study.

Chapter IX ENERGY CONTRIBUTION ANALYSIS OF THE BUILDING WITH AND WITHOUT THE INSTALLATION OF THE PV SYSTEM

Net energy consumed during the operational stage of the building is given by the equation below. In this equation, the energy savings due to the installation of the photovoltaic systems is considered.

$$NEo = OE_B - E_{PV}$$

Where:

NEo = net direct energy consumed during the operation of the student residential building with a PV installed

$OE_B =$ operational energy consumed by the student residential building during 50 yrs.

E_{PV} = energy output generated by the PV system during its life span, 50 yrs.

$$NE = \text{4,031 kWh / m}^2 - \text{630 kWh / m}^2 = \text{3,401 kWh / m}^2$$

The result shows a 15% reduction in the direct energy due to the installation of solar panels on the rooftop. However, the indirect or embodied energy to produce the PV array is not included in this result.

If the previous equation is modified to include the total life cycle energy consumption of the PV system together with the indirect embodied energy of the building, then the original equation can be written as follow:

$$NEE = EE_B + EE_{PV}$$

Where:

NEE = net indirect embodied energy of the student residential building with the PV system

$EE_B =$ embodied energy of the student residential building

EE_{PV} = embodied energy of the PV system

$$NE = \text{1,876 kWh / m}^2 + \text{116 kWh/ m}^2 = \text{1,992 kWh / m}^2$$

The embodied energy of the PV system is added to the initial embodied energy of the building; the result shows an increase of 6.1% due to the extra energy require to produce the photovoltaic system.

It is essential to include the total amount of energy inputs during the life cycle of the PV system and the building to get a more holistic and legitimate approach, by doing this it would be possible to know what are the real savings generated by the solar array. The equation below represents the total life cycle energy consumption by the student residential building with a PV system installed on the rooftop. Embodied energy of the PV system is included on the building's initial embodied energy, energy savings during the operation is also included.

$$TLCE = NEc + NEo + NEd$$

Where:

$TLCE =$ total life cycle energy required (direct and indirect) by the student residential building with PV system

$NEc =$ net construction energy of the student residential building with a PV installed

NEo = net operational energy of the student residential building with a PV installed

NEd = net demolition energy of the student residential building with a PV installed

$$TLCE = 1{,}937 \text{ kWh / m}^2 + 3{,}401 \text{ kWh / m}^2 + 55 \text{ kWh / m}^2 = 5{,}393.1 \text{ kWh / m}^2$$

The result represents the net total direct and indirect energy required to build, operate, and demolish the residential building together with the PV energy system. Energy savings due the installation of a PV system into the rooftop have been deducted in the operational phase. An overall 9.13% decrease in energy demand and carbon emissions can be attributed to the solar energy system. Table 22.0, table 23.0, and table 24.0 show the energy contribution analysis in terms of energy and carbon emissions due to the installation of the PV system.

Table 22.0 Indirect energy and carbon emissions of the student dormitory with and without a PV solar system

	Total energy consumption (kWh / m^2 / 50 yrs.)	Total carbon emissions (ton CO_2-eq. / m^2 / 50 yrs.)
Building's embodied energy and carbon emissions w/o PV system[a]	1,876[b]	0.97[c]
Building's embodied energy and carbon emissions w/ PV system[d]	1,992[e]	1.10[f]
Increase (%)	6.18	13.40

[a] Building's embodied energy, or indirect energy, refers to energy consumed during the building's construction and demolition stages

[b] Total amount is the sum of indirect energy consumed during the building construction (1,821 kWh/ m^2 /50 yrs.) and the demolition (55 kWh/ m^2 / 50 yrs.)

[c] Total amount is the sum of indirect carbon emissions during the building construction (.89 ton/ m^2 /50 yrs.) and the demolition (.078 ton/ m^2 / 50 yrs.) of the building

[d] Building's embodied energy w/ PV system, or indirect energy, refers to energy consumed during the construction and demolition stages of the building plus the energy consumed during the manufacturing, maintenance, and dismantling of the PV system

[e] Total amount is the sum of indirect energy consumed during the building construction (1,821 kWh/ m^2 /50 yrs.) and the demolition (55 kWh/ m^2 / 50 yrs.) plus PV manufacturing (57 kWh/ m^2 /50 yrs.), maintenance (57 kWh/ m^2 /50 yrs.), and dismantling (.28 kWh/ m^2 /50 yrs.)

[f] Total amount is the sum of indirect carbon emissions during the building construction (.89 ton/ m^2 /50 yrs.) and the demolition (.078 ton/ m^2 / 50 yrs.) plus PV manufacturing (.065 ton/ m^2 /50 yrs.), maintenance (.065 ton/ m^2 /50 yrs.), and dismantling (.00 ton/ m^2 /50 yrs.)

Table 23.0 Direct energy and carbon emissions of the student dormitory with and without a PV solar system

	Total energy consumption (kWh / m^2 / 50 yrs.)	Total carbon emissions (ton CO_2-eq. / m^2 / 50 yrs.)
Building's direct operational energy and carbon emissions w/o PV system [a]	4,031[b]	4.60[c]
Building's direct operational energy and carbon emissions w/ PV system[d]	3,401[e]	3.88[f]
Reduction (%)	15.63	15.65

[a] Building's net operational energy, or direct energy, refers to energy consumed during the operational phase of the building

[b] Building's operational energy, was modelled and obtained from EnegyPlus. Please refer to section 6.4 for more details

[c] Total amount of carbon emission was calculated converting the total amount of the building's operational energy w/o PV system from GJ to MJ. The result was multiplied times the emission rate of energy production in China suggested by Yang (Yang, 2003, pg. 136) of .317 kg CO_2 eq. per 1 MJ of Chinese electricity production

[d] Building's net operational energy with PV system, or direct energy, refers to energy consumed during the operational phase of the building minus the energy output coming from the PV system during 50 yrs.

[e] Total amount of the building's operational energy w/ PV is the building's direct energy (4,031 kWh/m2 /50 yrs.) minus the PV system energy output (630 kWh/m^2/50 yrs.)

[f] Total amount of carbon emission was calculated converting the total amount of the building's operational energy w/ PV system from GJ to MJ. The result was multiplied times the emission rate of energy production in China suggested by Yang (Yang, 2003, pg. 136) of .317 kg CO_2 eq. per 1 MJ of Chinese electricity production

Table 24.0 Total life cycle energy consumption and carbon emissions of the student dormitory with and without a PV solar system

	Total energy consumption (kWh / m^2 / 50 yrs.)	Total carbon emissions (ton CO_2-eq. / m^2 / 50 yrs.)
Building's total life cycle energy use and carbon emissions w/o PV system[a]	5,907.1[b]	5.56[c]
Building's total life cycle energy use and carbon emissions w/ PV system[d]	5,392.4[e]	4.98[f]
Reduction (%)	8.7	10.43

[a] Building's total life cycle energy consumption w/o PV system includes energy consumed by all phases of the building (construction, manufacturing, and demolition)

[b] Total life cycle energy consumption w/o PV system is the sum of building' direct energy (4,031 kWh/m^2 /50 yrs.) plus indirect energy (1,876.1 kWh/m^2 /50 yrs.)

[c] Total amount of carbon emission was calculated converting the total amount of the building's life cycle energy consumption w/o PV system from GJ to MJ. The result was multiplied times the emission rate of energy production in China suggested by Yang (Yang, 2003, pg. 136) of .317 kg CO_2 eq. per 1 MJ of Chinese electricity production

[d] Building's total life cycle energy consumption w/ PV system includes energy consumed by all phases of the building (construction, manufacturing, and demolition) plus energy consumed by all phases of the PV system (manufacturing, maintenance, and dismantling) minus the PV system energy output produced during its life span

[e] Total life cycle energy consumption w/ PV system is the sum of building' total life cycle energy consumption (5,907 kWh/m^2 /50 yrs.) plus the PV system's total life cycle energy consumption (116 kWh/m^2 /50 yrs.) minus the energy output produced by the photovoltaic system (630 kWh/m^2/50 yrs.)

[f] Total amount of carbon emission was calculated converting the total amount of the building's life cycle energy consumption w/ PV system from GJ to MJ. The result was multiplied times the emission rate of energy production in China suggested by Yang (Yang, 2003, pg. 136) of .317 kg CO_2 eq. per 1 MJ of Chinese electricity production

In order to present the results showing the benefits of installing a PV system on the rooftop of the student dormitory, it was necessary to performed two separate LCEAs: one for the building and one for the PV system. The already disclosed results show a 6.18% increase in the building indirect energy and 13.40% of indirect carbon emissions due to the installation of solar panels on the rooftop. This increase corresponds to the energy consumed for manufacturing, maintaining, and dismantling the PV system and added to the building's embodied energy. Energy output produced by the solar panels during their life span is not included in these results. However, energy savings due to the solar panels are included in the building's direct energy consumption results. Direct energy consumed by the building during its 50 yrs. life span is being reduced by 15.63% and carbon emissions by 15.65% as the benefit of mounting these solar panels.

If the direct and indirect energy of the building and the PV system is summed up and the energy output of the solar panels is reduced, the original building's total life cycle energy consumption can be decreased by 8.7% and the carbon emissions by 10.43%.

The results of this master thesis revealed that installing a photovoltaic solar system on the rooftop of the student dormitory can be beneficial in the mid and long-term. As cited in section 8.2 the EPBT of the solar system is 9.2 years, meaning that energy and carbon emissions benefits are going to be collected after 9 years. There is limitless literature assessing PV system in terms of EPBT, but few studies have evaluated the LCEA of the building and the PV system separately and added up together (see literature review for more details).

Among studies that have evaluated the benefits of PV system in term of direct, indirect, and building's total life cycle energy demand is the one performed by (Ramesh et al. 2013). They performed a life cycle energy analysis of a multifamily residential building in India in which the embodied energy of the building increased by 20% due to the PV installation, but a 37% decrease in the overall life cycle energy (primary) was reached. In their research methodology was not mention the origin of the solar module embodied energy. It is ambiguous to know the PV's system boundary and the effects that could have on the overall results.

Another study that has included the total embodied energy of a building together with the embodied energy of the PV system is the one performed by Wilson and Young in 1996. They calculated the embodied energy payback period (EEPBT) of PV panels installed in two hypothetical buildings in London. Their results showed an increase of 12.1% in the life cycle embodied energy in building A, and 11.6% in building B with the installation of the PV panels, and an increase of 21.9% in a building A and 23.8% in a building B of embodied carbon emissions (this assumed a 60 yrs. life time for the buildings and 30 yrs. for the modules coming from their second scenario). Their results showed a higher percentage increase in the building's indirect energy (due to the solar panels) compare to the 6.18% energy and 13.40% carbon increase showed in this study.

Clearly, the discrepancy in results in the mentioned studies can be attributed to many factors. For example life time and type of building, materials, method of construction, location and time of the study, materials included in the calculation of initial embodied energy, the lifespan of solar panels, replacements, etc.

In addition to these factors, the lack of information in the research of (Ramesh et al. 2013) makes impossible to perform a comparison analysis between studies. In the case of the results presented by Wilson and Young it is evident that the big difference (although, the already mentioned factors have a big impact) affecting this discrepancy is the difference in solar panel's embodied energy. They used 2,496 kWh/m^2 for the embodied energy content of the PV module, against the 1,277 kWh/m^2 used in this study. It is clear that the energy consumption during the manufacturing of the solar panels is different, and that the system boundaries in both studies also differ.

The installation of the solar panels on the rooftop of the dormitory can bring energy and environmental benefits. Both LCEA models have been developed and analyzed in this research thesis. In previous chapters (see chapter VII and VIII) the processes and parameters that contributed the most to the total energy demand of the building and PV system were identified. In the next section, these parameters and/or energy processes of both models are going to be modified to construct a scenario and uncertainty analysis.

It is relevant to mention that this thesis has used a factual student dormitory and a factual solar panel as case studies, neither the attributes of the building or the solar panel have been modified. Factual weather data was also used in the methodology of this study. In the next section, some of these attributes are also going to be modified.

Chapter X SCENARIO CONSTRUCTION

In this chapter, the scope of the scenarios to be discussed and analyzed are going to be presented. It is not possible to assess the complete LCEAs models due to the amount of life cycle phases and input parameters in both studies. However, three scopes were selected to construct and analyze the desired scenarios.

Scope number one covers the electricity energy source that supplies the entire model. The energy supply that represents the base case scenario is based on the current energy supply that is delivered to the student dormitory inside the campus, which is coal. Electricity energy supply use in the solar panel manufacturing plant is also assumed to be coal since 60% of the Chinese electricity production comes from coal (China Energy Group at Lawrence Berkeley National Laboratory 2014). Different energy supplies scenarios under this scope are going to be presented and analyzed in the next section.

Scope number two covers solar panel characteristics and manufacturing process efficiency. Results in chapter VIII showed critical processes that are the greatest energy consumers during the solar panel production process. The process to change in this scenario is the conversion of the upgraded metallurgical silicon (UMG-Si) into solar grade silicon (SoG-Si) – 67% of the total energy consumed in the manufacturing of a solar panel is consumed here –. At the same time the yield efficiency, the performance ratio, and the usable area (m^2) of the solar panel are going to be changed.

Scope number three covers changes in material efficiency, specifically the embodied energy that comes from selected materials (steel, concrete, timber, glass, tiles, and cement). Results in chapter VII showed that total amount of embodied energy generated by these materials counts for 78% of the total energy used in the construction phase and 24% of the total energy consumed in the total life cycle of the dormitory. Among these materials, steel and concrete are the materials that contribute the most to the total embodied energy. The reason behind these results is the huge amount of concrete (including cement mortar) and steel that is needed to erect the building. Changing the original quantity of materials does not seem practical and it doesn't induce to any energy process improvement, for this reason instead of changing the original amount of construction materials the embodied energy intensities of producing steel, cement, and concrete are going to be changed.

A representation of scope number one, two, and three can be appreciated in the figure below.

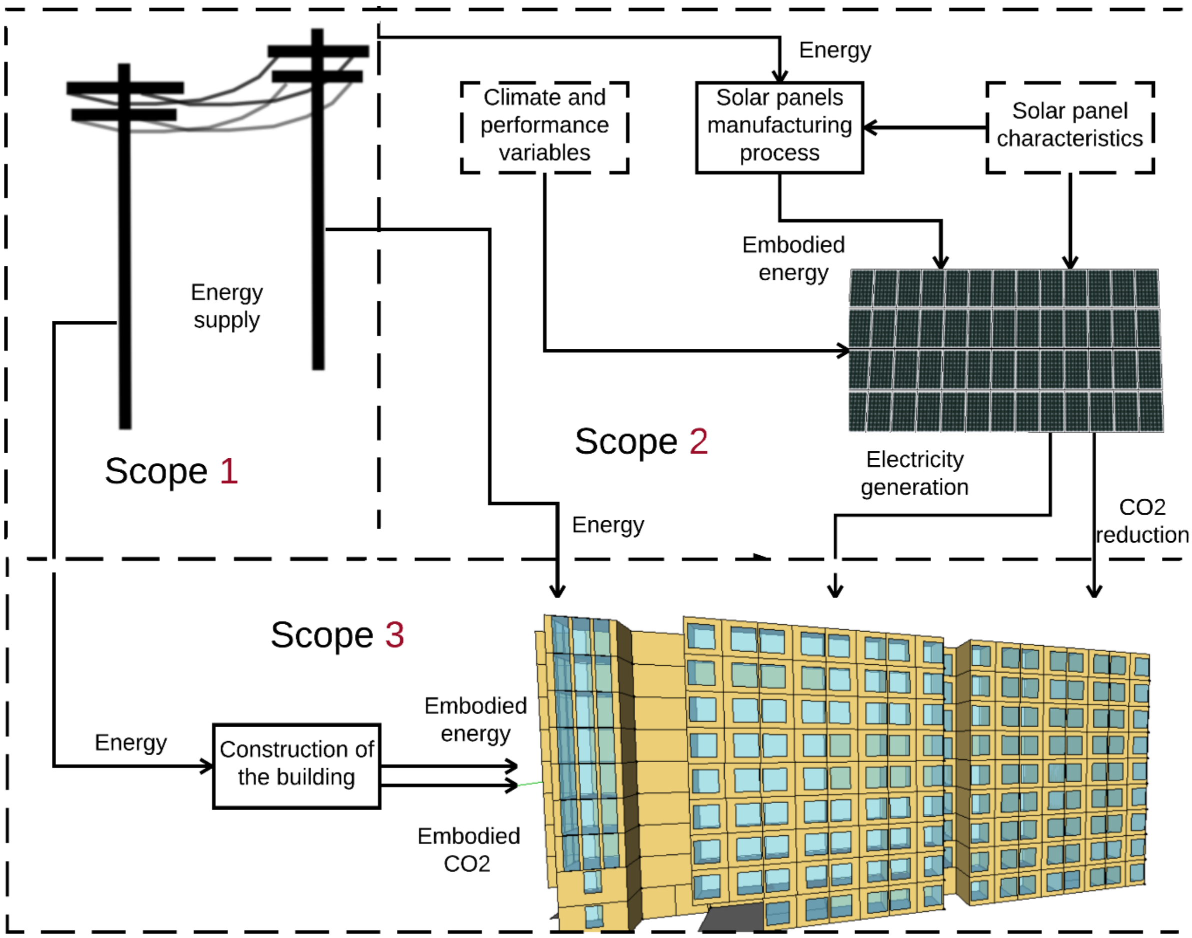


Figure 8.0 Visual representation of the scopes for scenario construction

Chapter XI SENSITIVITY AND SCENARIO ANALYSIS

In this chapter a scenario analysis combined with a sensitivity and uncertainty analysis is going to be performed. The scope of the scenarios has already been mentioned in the previous section. In this part more details about the scenarios and the sensitivity analysis is discussed.

11.1 Scenario number one

In the first scenario, the electricity energy production of the entire system is changed. Coal is used as the source of producing electricity in the base case scenario. For comparison four other electricity energy supplies were used in this scenario: natural gas, biomass, nuclear power, and hydropower.

The input parameter to change in this scenario is the emission factor coming from the different energy supplies when producing electricity in China. A visual representation of scenario number one and the input parameters to be changed is represented in figure 9.0.

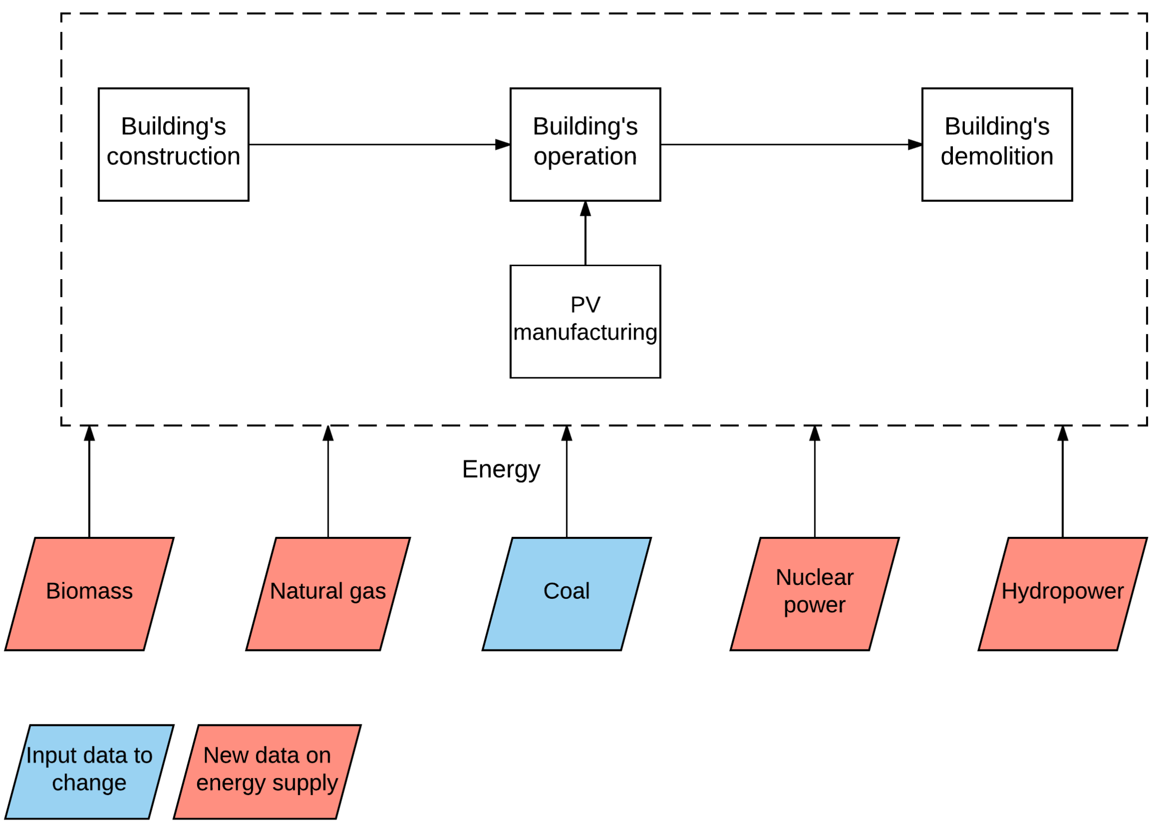


Figure 9.0 Visual representation of scenario one and input parameters to change

Emission factors coming from different Chinese energy supplies were taken from an LCA study performed by (Feng et al. 2014). In this study, the authors modeled a hybrid LCA with the help of the Chinese input-output economic tables to found the emission intensities of the energy supplies. Researchers in the same study also performed an insensitive literature review with different emission factors of energy supplies coming from other countries in other to deal with data uncertainty in their model. The results of Feng at al. were used as the mean energy supply emission factor in this scenario (except for coal, the emission factor suggested by Yang (Yang, 2003, pg. 136) of .317 kg CO_2 eq. per 1 MJ of Chinese electricity production was used). The emission factors with the highest and lowest intensities from previous global studies were also used to deal with uncertainties in this scenario (these studies were also taken from the literature review executed by the same authors.). Table 25.0 summarized the sensitivity and uncertainty analysis for scenario one.

Table 25.0 Sensitivity and uncertainty analysis under different energy supply scenarios

Process	Parameter (emission factor)	Literature[a]	Carbon emissions [ton CO_2-eq./m^2/50 yrs.]	Carbon emissions reduction[b]	Variation in total emissions[c]
Energy supply	Coal	High	5.39	3.1%	8.2%
		Mean	4.98	10.5%	0%
		Low	3.30	40.7%	-33.7%
Energy supply	Natural gas	High	4.26	23.5%	7.8%
		Mean	3.95	29.1%	0%
		Low	2.07	62.7%	-47.6%
Energy supply	Biomass	High	1.49	73.1%	24.2%
		Mean	1.20	78.4%	0%
		Low	0.97	82.4%	-19.2%
Energy supply	Nuclear power	High	1.15	79.2%	26.4%
		Mean	0.91	83.6%	0%
		Low	0.86	84.4%	-5.5%
Energy supply	Hydropower	High	1.12	79.9%	24.4%
		Mean	0.90	83.8%	0%
		Low	0.87	84.3%	-3.3%

[a] Mean emission factor coming from the study of (Feng et al. 2014) applied specifically for China. Highest and lowest emission factors are from global case studies.

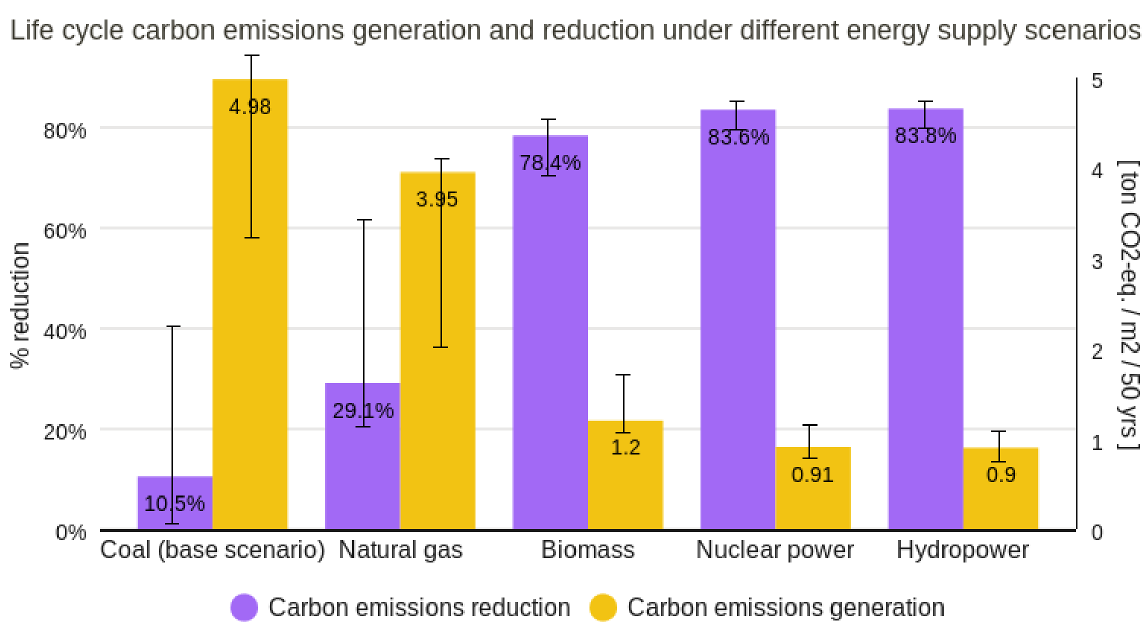
[b] Refers to the building's total life cycle carbon emissions reduction w/ PV system.

[c] Variation with respect to total emissions using the mean emission factor

Results show that using renewable energy as the energy supply for the electricity consumed during the manufacturing of solar panels and throughout the life cycle of the dormitory can reduce more carbon emissions than using conventional energy. The installation of a PV system using coal as an energy supply in the entire model can reduce up to 10.5% carbon emissions during the life span of the student dormitory. However, if natural gas is used instead of coal 29.1% or carbon reduction can be attained. In the case of using biomass and nuclear power, 78.4% and 83.6% carbon emissions reduction can be reached. Using hydropower for electricity production can help to minimize more emissions than any other energy supplies; in this case, 83.8% carbon reduction can be reached.

Error bar graph 7.0 shows uncertainties of emission factors based on the variation in the results. Uncertainty on natural gas' emission intensity presents the highest variation, here results using the lowest input emission factor varies 47.6% with respect to the mean value. Coal's emission intensities are the second highest uncertain inputs with a variation of 33.7% and 8.2% with respect to the mean value. In contrast, hydropower's emission factors are the most accurate since the variation between the highest and the lowest inputs with respect to the mean is less. Graph 7.0 presents carbon emission results and an error bar that shows results' variations.

Graph 7.0 Life cycle carbon emission generation under different energy supply scenarios



11.2 Scenario number two

In the second scenario, the characteristics of the solar panel along with its manufacturing process are changed. These characteristics are the yield efficiency, passing from an original 14.9% to 16%, the performance ratio changing from .75 to .80, and the usable array area (m^2) which will be the double from the original area. In the case of the manufacturing process, this change is the conversion of the upgraded metallurgical silicon (UMG-Si) into solar grade silicon (SoG-Si), with a 50% energy consumption reduction. Table 26.0 summarized these changes and assumptions for each condition

Table 26.0 Changes in solar panel characteristics and manufacturing process under different conditions

	Base scenario	Condition 1	Condition 2	Condition 3
SoG-Si production energy consumption (kWh/ m^2)*	425.33	212.66	N/A	212.66
Module performance ratio	.75	N/A	.80	.80
Module efficiency (%)	14.9%	N/A	16%	16%
Usable module area (m^2)	704.7 m^2	N/A	1,409.4 m^2	1,409.4 m^2

Notes:

*kWh / m^2 array total area. Total array land area is = 704 $m^{2,}$ equivalent to fit 362 solar panels.

Under this scenario, three different conditions are evaluated. Under condition one only the conversion of the upgraded metallurgical silicon (UMG-Si) into solar grade silicon (SoG-Si), with a 50% energy consumption reduction is assessed. Under condition two, the yield efficiency, the performance ratio, and the usable array area (m^2) are changed. And finally, under condition three the conversion of the upgraded metallurgical silicon (UMG-Si) into solar grade silicon (SoG-Si) with a 50% energy consumption reduction and the solar panel characterize are changed. A visual representation of scenario number two and input parameters to be changed is represented in figure 10.0

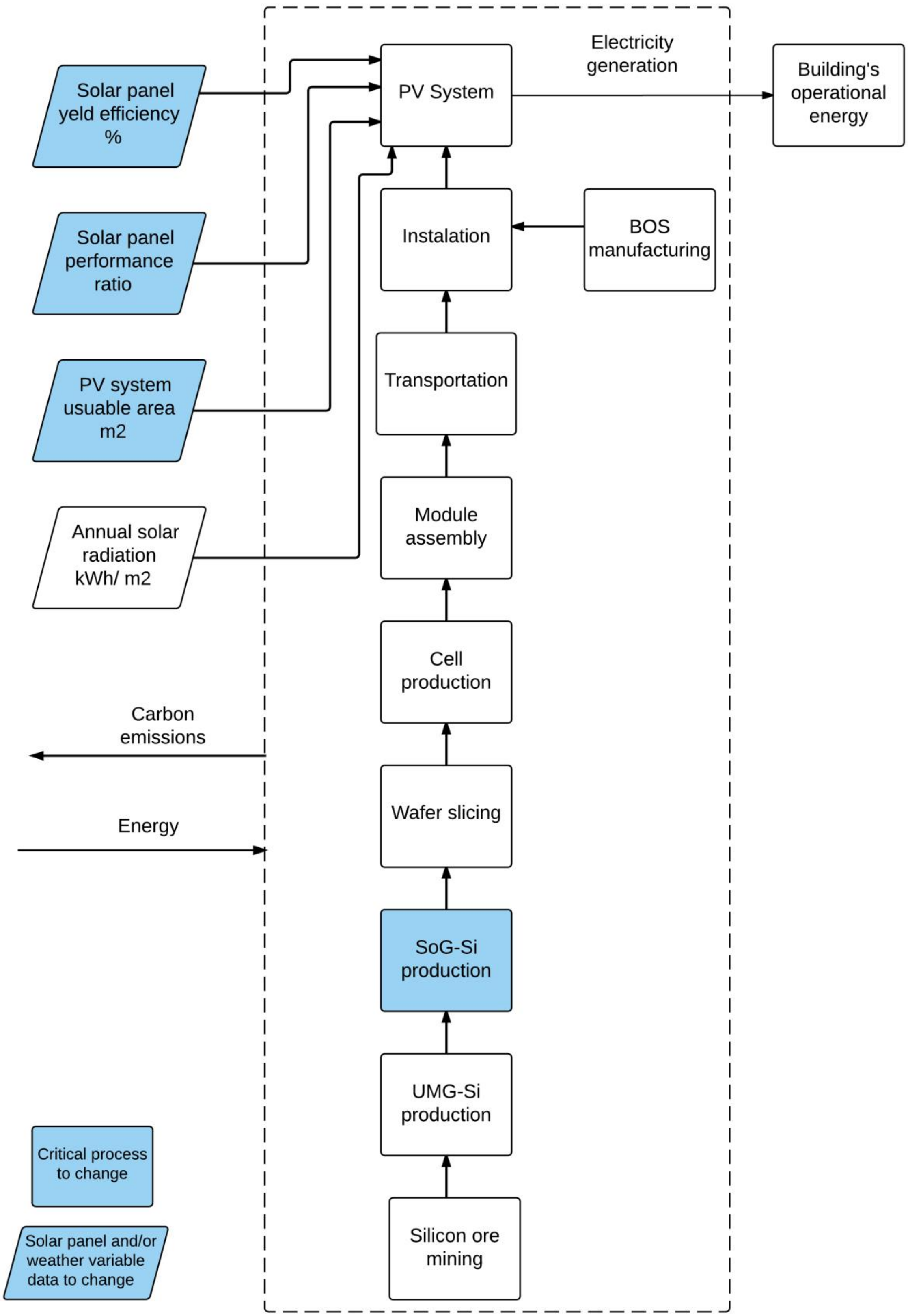
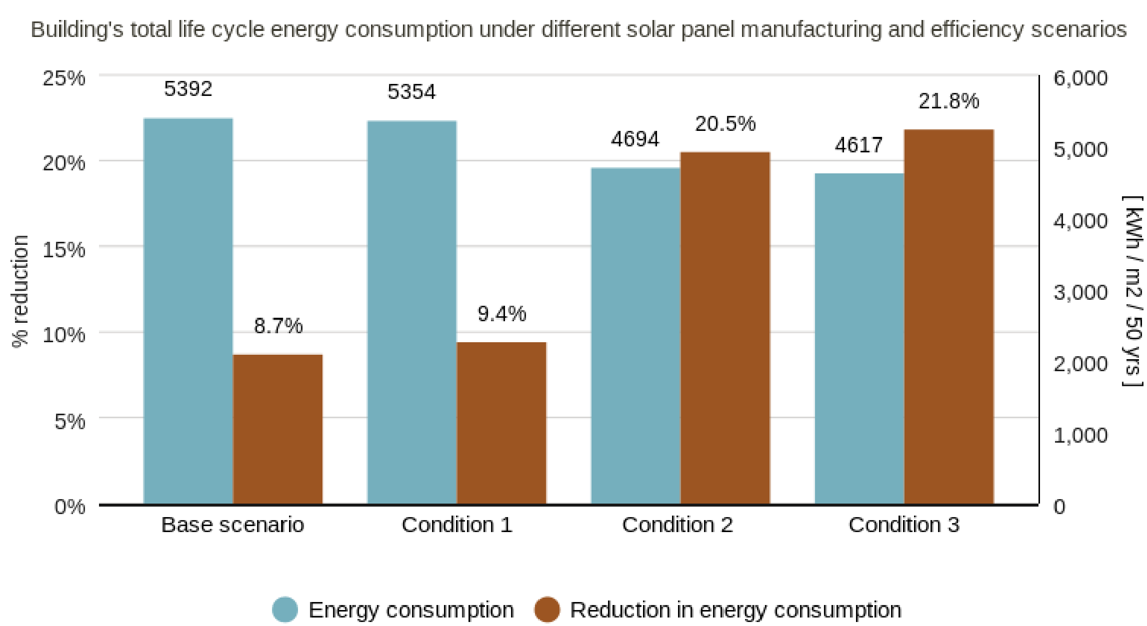


Figure 10.0 Visual representation of scenario two and input parameters to change

Results show that changing the energy consumption in the critical process of upgrading metallurgical silicon (UMG-Si) into solar grade silicon (SoG-Si) by 50% (condition number one) a 9.4% reduction in the building's total life cycle energy consumption with PV system, and an 11.3% carbon emission reduction can be achieved. Direct energy to produce the solar panel is reduced by 33% by changing this critical process, hence the embodied energy of the building with the PV system installed is also reduced.

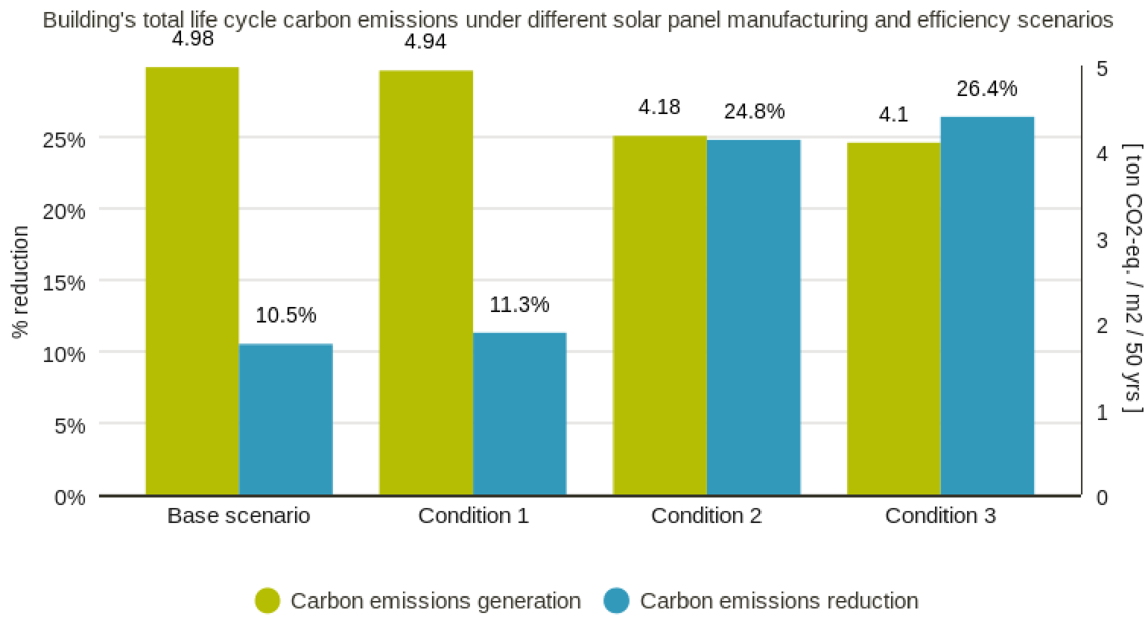
If the characteristics of the solar panel are changed and the array usable area too (condition two), the building's total life cycle energy consumption with the installed PV system can be reduced by 20.5% compare to the only 8.7% reduction of having the original panel features and usable array area. Since the array usable area in m^2 is being double it will be necessary to produce twice the number of solar panels. In this case, the energy to produce them will be also duplicated, but the energy output generated by the panels will be also the double amount. In terms of carbon emission, this reduction can reach 24.8% compare to the 10.5% presented in the original case. Graph 8.0 and 9.0 illustrates these results

Graph 8.0 Building's total life cycle energy consumption under different solar panel manufacturing and characteristics conditions



If the already mentioned characteristics of the solar panel are changed, the array usable area is double, and the energy consumption in the critical process is reduced (condition number three) is when major energy and carbon emission benefits can be perceived. In this condition, the results show an overall 21.8% reduction in the building's total life cycle energy consumption, and a 26.4% carbon emission reduction.

Graph 9.0 Building's total life cycle carbon emissions under different solar panel manufacturing and characteristics conditions



11.3 Scenario number three

In the last scenario to analyze the embodied energy of critical construction materials is going to be modified. Energy intensities of cement, steel, and concrete are being modified. Figure 11.0 shows the visual representation of scenario three and critical process to alter.

In the base case scenario embodied energy intensities taken from Granta CES material database and from the Tsinghua University study (refer to section 6.3 for more details) are being used. Intensities from two other databases are going to be used to extract the new embodied energy intensities, ICE V2.0 and CLCD.

ICE V2.0 or The Inventory of Carbon and Energy for building materials is a database created by the University of Bath. This database was created in 2004 and contains the carbon and energy footprints of over 200 construction materials, it covers the UK and European construction materials (Circularecology.com 2016). The CLCD or the Chinese Life Cycle Database is an inventory database created by Sichuan University and IKE Environmental Technology Co. Ltd, it covers 600 datasets from different sectors and industries in China (Ike-global.com).

By changing the inputs of energy and carbon intensities of the selected materials a new output in the building's total life cycle energy and carbon demand is produced. Data uncertainty can also be assessed by evaluating the variation of results using the two different databases (due to the lack of information of energy and carbon footprints of Chinese construction materials it was not possible to gather more embodied energy intensities). Table 27.0 summarized the results, it also includes a sensitivity and uncertainty analysis for this scenario.

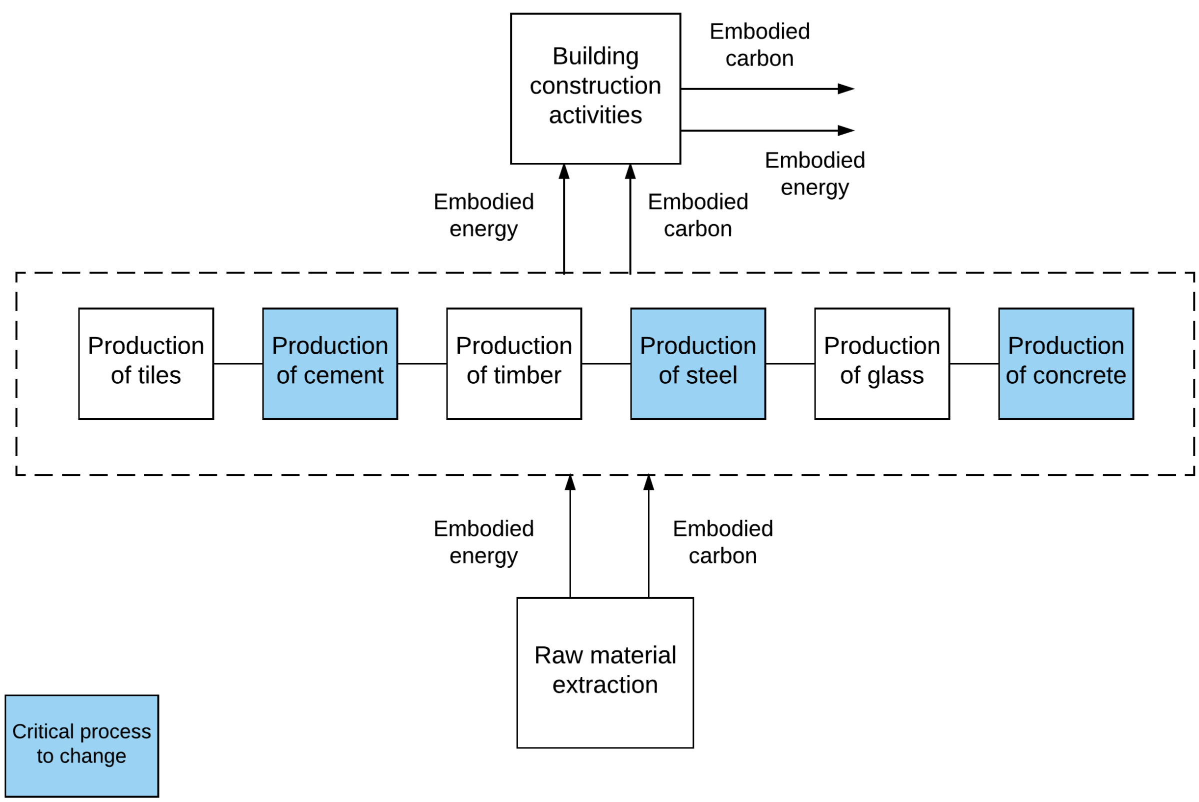


Figure 11.0 Visual representation of scenario three and critical processes to change

Table 27.0 Sensitivity and uncertainty analysis using different embodied energy intensities in selected construction materials

Process	Parameter (EE factor)	Database	Total energy consumption[a] [kWh/m²/50 yrs.]	Reduction in energy[b]	Variation[c]	Carbon emissions [ton CO2-eq./ m²/50 yrs.][d]	Reduction	Variation
Production of cement	Embodied energy and carbon	Base scenario[e]	5,392	8.7%	0%	4.98	10.5%	0%
		ICE V2.0[f]	5,318	8.8%	1.1%	4.94	11.3%	7.6%
		CLCD[g]	5,330	8.8%	1.1%	4.91	11.8%	12.3%
Production of concrete	Embodied energy and carbon	Base scenario[e]	5,392	8.7%	0%	4.98	10.5%	0%
		ICE V2.0[f]	5,308	8.8%	1.1%	4.91	11.8%	12.3%
		CLCD[g]	5,402	8.7%	0%	4.93	11.5%	9.5%
Production of steel	Embodied energy and carbon	Base scenario[e]	5,392	8.7%	0%	4.98	10.5%	0%
		ICE V2.0[f]	5,184	9.0%	3.4%	4.70	15.6%	48.5%
		CLCD[g]	5,486	8.6%	-1.1%	4.62	16.9%	60.9%

[a] Total building's life cycle energy consumption with the PV system installed

[b] Reduction in total building's life cycle energy consumption due to the PV installation

[c] Variation in the reduction results due to change the embodied energy intensity input

[d] Total building's life cycle carbon emissions with PV system installed

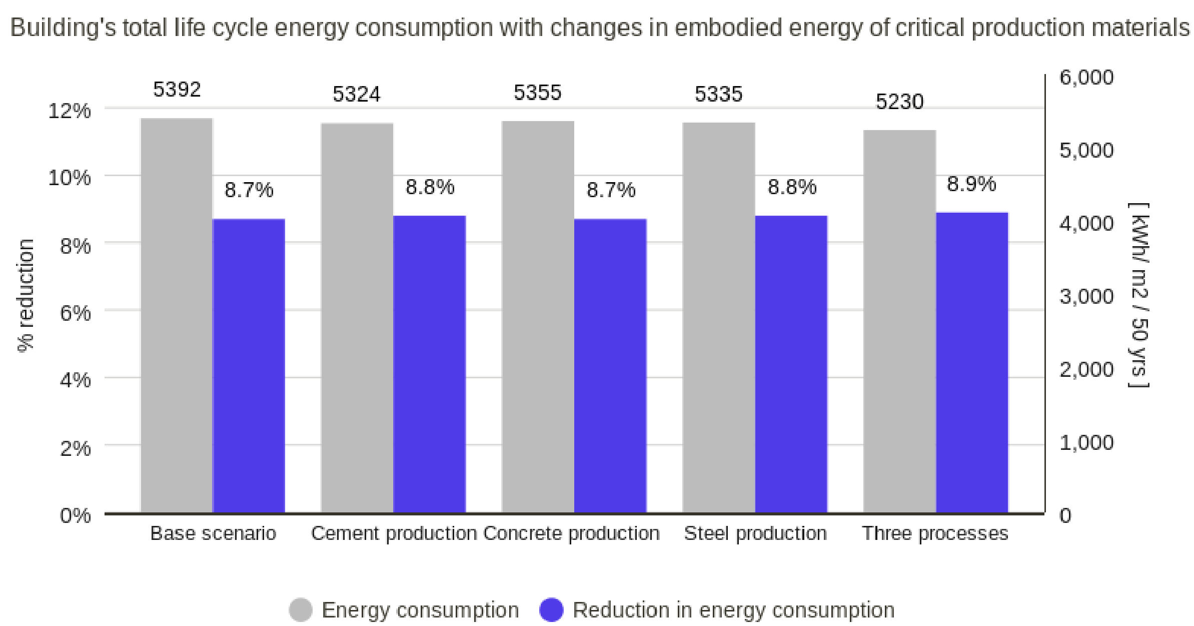
[e] Embodied energy and carbon intensities were taken from Granta CES material database (for tile, glass, and concrete) and from the study of Yang, 2003 (for cement, timber and steel).

[f] ICE V2.0 refers to The Inventory of Carbon and Energy for building materials database created by University of Bath

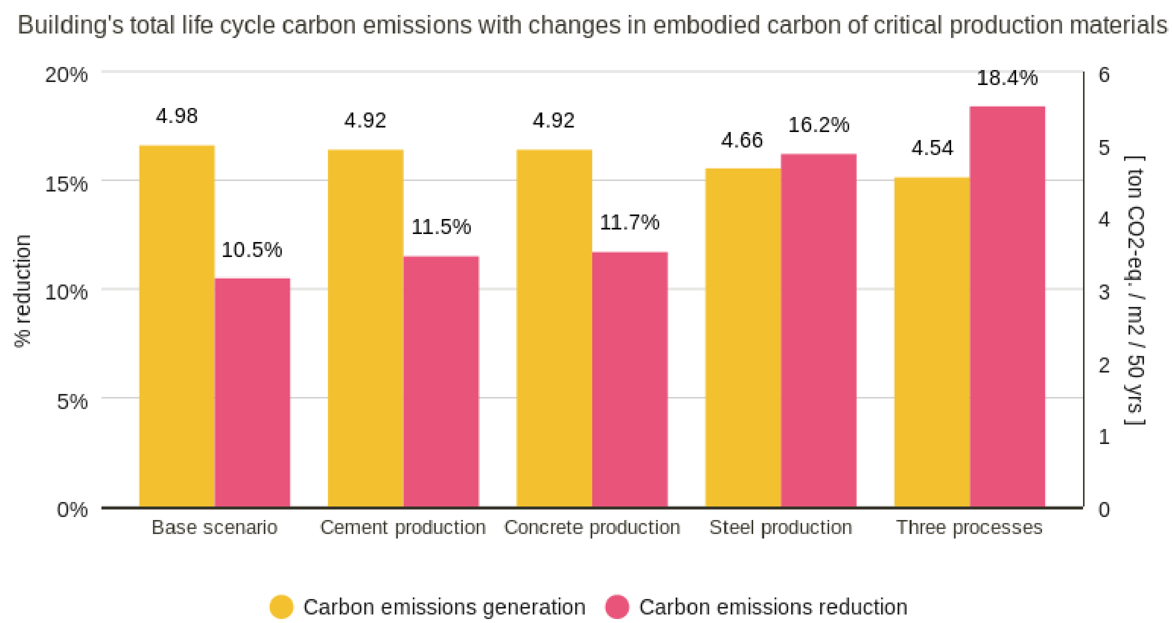
[g] CLCD refers to the Chinese Life Cycle Database created by the Sichuan University and IKE Environmental Technology Co. Ltd

Results are represented in graph 10.0 and 11.0. Average embodied energy intensities given by both databases, ICE V2.0 and CLCD, were used to illustrate results. Variation in embodied energy intensities was minimal between the three different sources, but the embodied carbon emission intensity was substantially different in these sources. However, it is not indispensable to illustrates the variation in results due to low uncertainties presented in embodied energy and carbon emission intensities.

Graph 10.0 Building's total life cycle energy consumption with changes in embodied energy of critical construction material



Graph 11.0 Building's total life cycle carbon emissions with changes in embodied carbon intensity of critical construction material



Results in this scenario have revealed that changing the energy intensities of the construction materials with higher embodied energies (cement, steel, and concrete) has a minimal effect on the building' total life cycle energy consumption. However, changing embodied carbon intensities of the already mentioned materials has more effects on the carbon dioxide emissions.

Steel is the material that presents the highest impact on carbon emission reduction when changes in embodied carbon intensities are made. A 16.2% overall reduction in the building's life cycle carbon emissions can be achieved compare with the original 10.5% if the embodied carbon in this material (steel) is changed. Concrete is the second material with the highest impact on carbon emission reduction in this scenario. Original embodied carbon intensities of these critical materials were reduced by around 10%. The variation on the building's total carbon emissions reduction (being 10.5% reduction the base case scenario) was about 50% using the new steel's embodied energy intensity, and about 11% using the new concrete's carbon emission intensity.

Graphs 10.0 and 11.0 also show that if changes in the production of cement, steel, and concrete occur at the same time the benefits in energy and carbon emission would be higher. In this case, an 8.9% energy reduction and 18.4% carbon reduction can be reached.

Chapter XII DISCUSSION

Results and relevant findings from this research are going to be presented and discussed in this chapter. These results are presented in the same chronological way as they were obtained. Limitations of this study and recommendation for future research is also presented in this section.

12.1 Relevant findings

12.1.1 LCEA of the student dormitory

The total amount of energy consumed and carbon dioxide emissions generated during the life cycle of a student dormitory inside a university campus in Ningbo, China was 5,907 kWh/m^2 and 6 ton CO_2-eq./m^2 per 50 years. The construction, operation, and demolition life cycle phases of the student dormitory were included.

The process that consumed more energy and emitted more carbon emissions during the life cycle of the building was the space heating and cooling process, occurring during the operational stage of the building. The amount of electricity consumed by the HVAC system in the building represents 57% of the total life cycle energy consumption. This process (HVAC systems for space heating and cooling) is also responsible for emitting more carbon dioxide than any other process, generating 82.5% of the building's total carbon footprint.

12.1.2 LCEA of the PV system

In the case of the PV energy system, the total amount of energy consumed and carbon dioxide emissions generated during its entire life cycle was 1,277 kWh/m^2 total array area, and 2 ton CO_2-eq./m^2 total array area. The production, maintenance, and dismantling life cycle phases of the PV system were included. The replacement of the system after 25 years of use was counted and added in the maintenance phase.

The process that consumed more energy and emitted more carbon emissions during the life cycle of the PV system was the conversion of upgrading metallurgical silicon (UMG-Si) into solar grade silicon (SoG-Si), this process generates 67% of the total energy consumption and carbon footprint.

12.1.3 Energy contribution analysis of the student dormitory with and without the installation of a PV energy system

If the PV system is installed on the rooftop of the student dormitory the direct energy consumed by the building during its 50 years' lifespan can be reduced by 15.63% and carbon emissions by 15.65%. In the case of the building's total life cycle energy consumption (direct and indirect energy) this reduction can be reached 8.7% in terms of energy, and 10.43% in the case of carbon emissions.

12.1.4 Scenario and uncertainty analysis

Scenario and uncertainty analysis number one revealed that using renewable energy as the energy supply of electricity generation for the manufacturing of solar panels and throughout the life cycle of the dormitory can be more carbon effective than using conventional energy. The installation of a PV system using coal as an energy supply in the entire model can reduce up to 10.43% carbon emissions during the life span of the student dormitory. However, if biomass or nuclear power is used 78.4% or 83.6% carbon emissions reduction can be reached. Using hydropower for electricity production can help to minimize more emissions than any other energy supplies; in this case, 83.8% carbon reduction can be achieved.

Results in scenario number two concluded that if the yield efficiency, performance ratio, and the usable array area of the solar panels are modified, and the manufacturing process of upgrading metallurgical silicon (UMG-Si) into solar grade silicon (SoG-Si) is reduced by 50%, an overall 21.8% reduction in the building's total life cycle energy consumption, and a 26.4% carbon emission reduction can be attained.

Major findings in the last scenario revealed that changing the energy intensities of the construction materials with higher embodied energies (cement, steel, and concrete) has a low impact on the building' total life cycle energy consumption. But, a noticeable change can be perceived on the reduction of carbon dioxide emissions if the embodied carbon intensities are changed. In this case, by changing the steel's embodied carbon factor a 16.2% overall reduction in the building's life cycle carbon emissions was achieved compare with the original 10.43%. Nevertheless, if changes in embodied energy and carbon intensities of these three materials (cement, concrete, and steel) occur at the same time, an 8.9% energy reduction and 18.4% carbon emissions reduction is possible.

12.2 Comparison with other studies

The results of this thesis have demonstrated the energy and environmental benefits of installing PV system in buildings. Numerous LCA studies have shown these benefits before, see for example (Battisti and Corrado 2005), (Knapp and Jester 2002), (Lu and Yang 2010), and (Kannan et al. 2006) in this studies the benefits were calculated using the EPBT and GPBT of solar panels. However, the EPTB approach was not implemented in the methodology of this study. The practical and innovative methodology implemented in this study differs from previous research papers.

In chapter I and II (literature review) was mentioned that a more practical, realistic, and inclusive methodology was going to be implemented. For the same reason, there were found limited studies showing similar results and methodologies as the one presented in this thesis.

Among studies that have quantified the benefits of PV system in terms of direct, indirect, and building's total life cycle energy demand and carbon emissions is the one performed by Wilson and Young in 1996. Their results showed a higher percentage increase in the building's indirect energy (due to the installation of solar panels) compare to the results of this study (Refer to chapter IX for more details). Another study using a very similar methodology as the one used here was the life cycle energy analysis of a multifamily residential building in India performed by (Ramesh et al. 2013). In this study, direct and indirect energy was quantified before and after the installation of solar panels on the rooftop, nevertheless this research did not perform the life cycle energy analysis of the solar panels.

Results in both studies significantly differ from the results of this thesis. As mentioned in chapter IX, this discrepancy can be attributed to many factors. For example the life time and type of building, materials, method of constructing, location, systems boundaries and phases included in the calculations, the lifespan of solar panels, the inclusion of replacements, the source of energy generation etc. (See results in chapter IX for a complete analysis).

In the case of the scenario and sensitivity analysis other studies has shown similar results as this research. In a comparative life cycle assessment of PV solar systems performed by Bekkelund in 2013 revealed that using renewable energies instead of conventional energy as the energy supply during the manufacturing process of solar panels could significantly reduce the GWP (Global Warming Potential). The study showed that using hydropower for electricity supply reduced more the GWP than any other energy supply. In the same thesis, Bekkelund showed that improving the energy efficiency, electricity in that case, of the solar panel manufacturing process could also reduce the GWP result. She showed that an improvement of 20% in energy efficiency could bring a 7% average reduction in GWP for mc-Si panels (Bekkelund 2013). Her sensitivity analysis findings show similar results as the one presented here. However, Bekkenlud compared only the PV solar system without considering the life cycle of a building. There is not documentation of any other sensitivity analyses study in where an energy supply, electricity efficiency, and material efficiency and the simultaneously effects on the PV solar system installed in a building.

12.3 Recommendations and implications

Based on the findings of this research some practical recommendations are suggested:

- It is recommended the installation of the solar panels in the student dormitory. Based on this research 362 solar panels will be needed for setting up the entire PV system. By doing this, the building's lifetime operational energy will be reduced by 15.63% and carbon emission reduced by 15.65%. The building's total life cycle energy demand, in which all life cycle phases are included not only the operational phase, can be reduced by 8.7% and the total carbon emissions by 10.43%.
- It is recommended to install locally manufactured solar panels with high efficiency, at least 16%, and high-performance ratio, .80. It is also recommended to increase the usable surface area (m^2) for installing more solar panels. Ningbo has a low annual solar insolation, 1,310 kWh/ m^2, therefore more solar panels would be needed to generate more onsite energy (Refer to scenario number two in section 11.2)

- It is highly recommended to change the energy supply for electricity generation in the student dormitory. Using renewable energies for onsite electricity generation can have significant impacts on energy demand and carbon reductions (refer to scenario number one in section 11.1). The expected energy generation produced by the solar panels can be used to cover the on-site energy demand.
- It is highly recommended to use passive cooling and heating techniques to reduce the energy consumption for HVAC. Space heating and cooling have more negative impacts than any other process in the entire model (refer to chapter VI).

In addition to the practical recommendations of installing solar panels in the student dormitory, it is also important to connect the results of this thesis to a broad social and environmental context. These results can have a significant impact on consumers, property developers, and environmental policy makers when facing the choice of installing PV energy systems in their buildings.

Consumers can perceive these benefits by lowering their electricity bills in the mid and long term, although a significant initial investment would be needed to purchase the system. Property developers can opt to install solar panels in their buildings in order to comply with local environmental regulations and carbon taxes (China has announced to implement a nationwide emission trading system and carbon tax by the end of 2016 (Swartz 2016)). In addition, the solar panels to install by these developers should have a high-efficiency yield and performance ratio, they also need be locally manufactured to obtain more energy and environmental benefits (scenario analysis number two has demonstrated this conclusion)

The impacts of installing PV systems on consumers and property developers is conventional, and results of this thesis have shown that. However, implications of these results for the local environmental regulations and policies can be significant.

Environmental policy makers should be aware of the implications of the manufacturing process of solar panels. As shown in this study some processes consume more energy than others. Regulations may be implemented to induce companies to reduce their energy and environmental footprints. Incentives to manufacturing companies to do more research and improve their manufacturing process (especially in the critical processes) can be an energy and carbon-effective regulation. These regulations and incentives can be also used in the manufacturing an extraction of the building's constructions materials. As shown in this research some materials have high embodied energies (steel, concrete, tile), their production process can also be improved in terms of energy performance.

Policy makers should be also informed about the implications of the energy supply of electricity generation to be consumed by the solar panels' manufacturers in their plants. As shown in this study, solar panel's carbon emissions can be minimized when the energy supply of electricity generation comes from renewables energies. Knowing this, Chinese environmental regulators can provide incentives to manufacturers to change their energy supply.

12.4 Limitation of the study and recommendations for future research

Although the data collected to model the life cycle energy assessment of the building was obtained from original drawings, the data used to model the operational life cycle phase of the building did not come from a real source. To model the building's operational energy the simulation software EnergyPlus was used. Energy intensities given by the model were modified but a high degree of uncertainty is still presented. It was not possible to obtain the energy utility bills from the student dormitory to calibrate the results. A recommendation for future researchers following this methodology:

- *Obtain the energy utility bills (the last twelve) of the building to analyze (or any other with similar use and characteristics). Calibrate your result using EnergyPlus, and/or perform an uncertainty analysis.*

Embodied energy and carbon intensities of construction materials were taken from various sources in this study. Some studies referred to data applicable to only certain countries. It is important to gather, compare, and cite data from the same country with same production characteristics. A recommendation for future researchers following this methodology:

- *Collect embodied energy intensities of construction materials (it is applicable for all emission and energy intensity factors) from country specific databases. If data is not available, try to use data that resembles the production process in that specific place.*

The lack of a standard and practical method to quantify energy and environmental emissions of PV systems was a motivation to perform this research. However, the methodology presented in this research is not illustrated as a framework to follow, there should be a general framework to faculties the comparison of buildings with and without PV energy systems (in a life cycle perspective). To achieve this:

- *Develop a general LCEA framework model for the building and for the PV system. Give details about what to include in the system boundaries and in the calculations.*

Chapter XIII CONCLUSIONS

The installation of a photovoltaic system in a student dormitory in China can reduce its energy consumption and bring environmental benefits. Life cycle energy assessment is the instrument that quantifies and gives a clear and precise amount of carbon dioxide and energy reduction that the student dormitory is receiving from the installation of solar panels on its rooftop.

Performing a life cycle energy assessment of the student dormitory and the solar panel helps to construct a model in where both assessments are combined, having a system boundaries expansion. Expanding the system boundaries to include the PV system and the building gives a holistic and clear amount of energy and carbon reductions produced by the installation of solar systems. It also helps to identify critical processes and to make changes that can help to improve the overall energy and environmental performance of the life cycle of the building and the photovoltaic system.

The model created in this research can have a significant impact on consumers and property developers at the time of deciding whether installing PV energy systems in their buildings or not. It also has an impact on manufacturers of solar panels, building constructors, and material producers because they can use the model as a tool to research and improve the energy intensities in their manufacturing processes. However, among all the beneficiaries the most important impact can be obtained by Chinese citizens.

Chinese policy makers can make use of life cycle energy models as a decision tool for policy and environmental regulations, in this case PV system installation. China is facing a huge environmental crisis, any decision tool that helps to tackle the problem is a winning for its citizens, but to world.

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Appendix: A

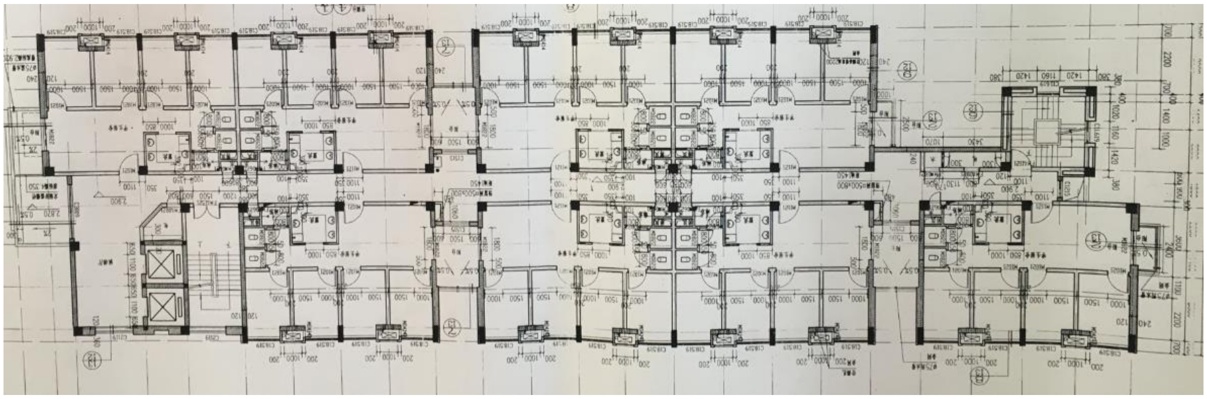

Figure A1: each unit in this residential building has the same layout

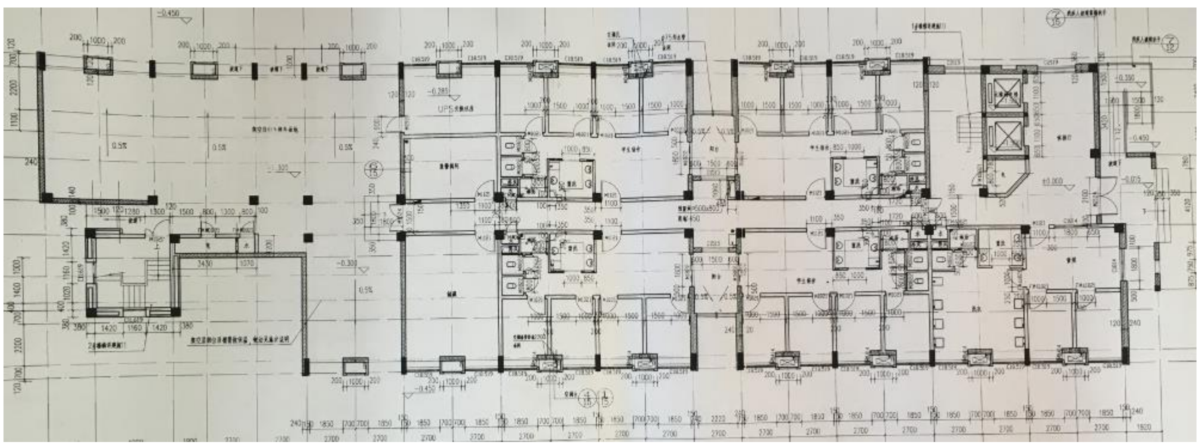

Figure A2: layout of the ground floor

Figure A3: building geometry

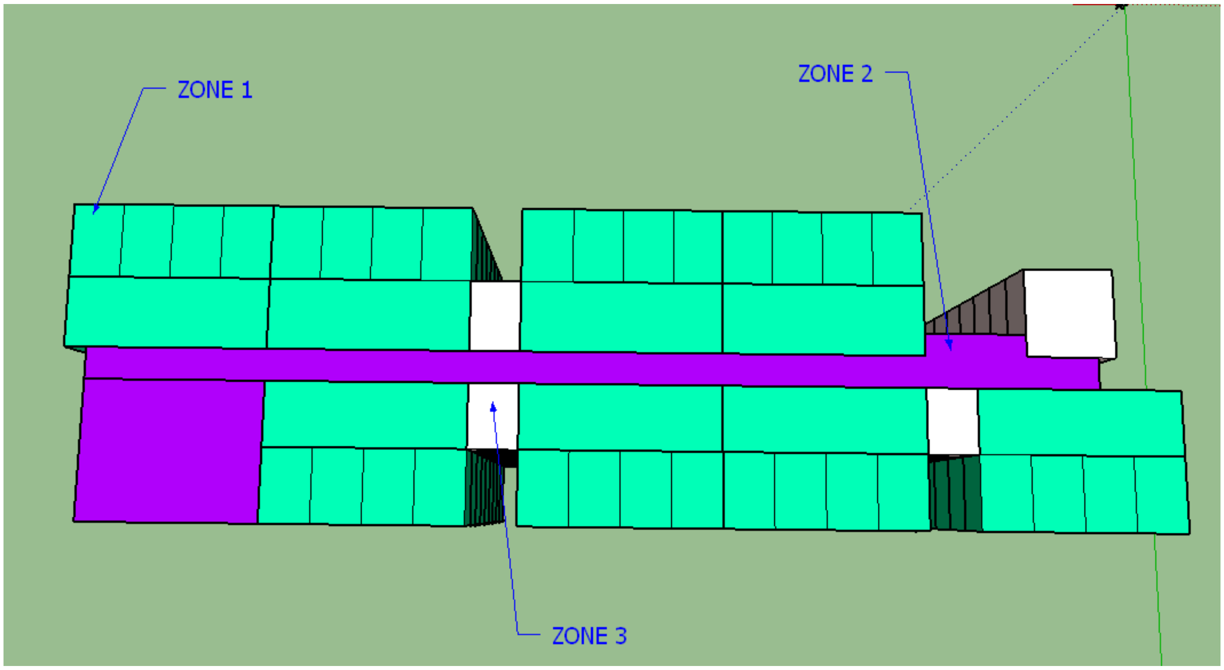

Figure A4: the building was divided into three different thermal zones per floor

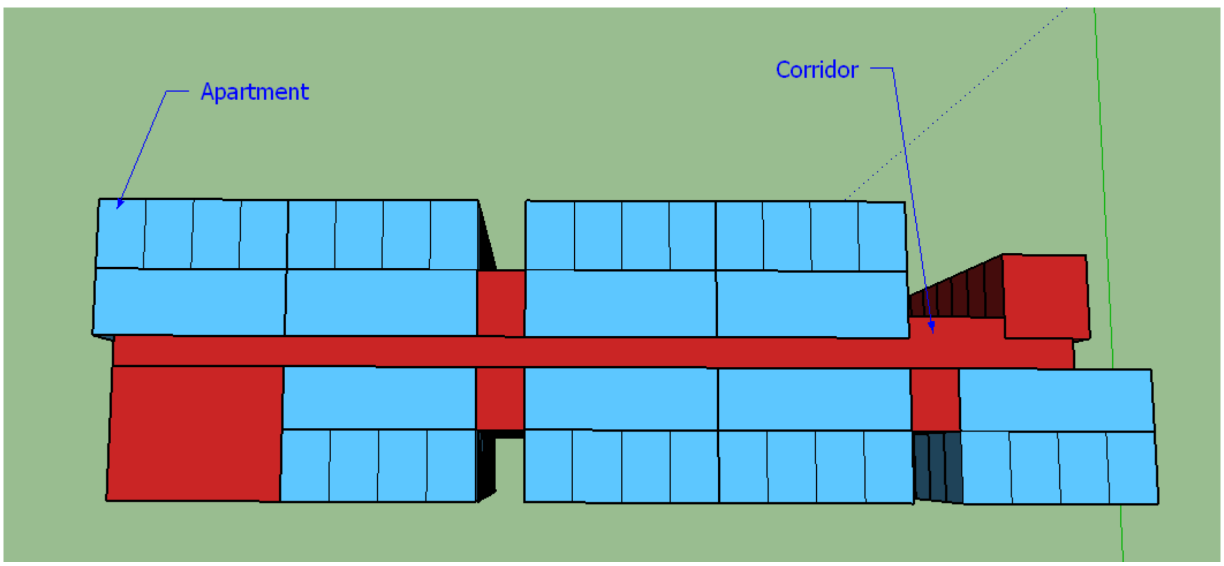

Figure A5: building space division

Appendix B

Table B1: Internal loads per zone requirements

Thermal Zone	EnergyPlus Space Type	People per Floor	Area (m2)	People per Space Floor Area
1	Midrise Apartment - Apartment	272	689	0.394860427
2	Midrise Apartment - Corridor	272	171	1.590643275
3	Midrise Apartment - Corridor	272	10	27.2

Table B2: Energy per space floor are coming from electric equipment

Usage	EnergyPlus Space Type	Energy Per Space Floor Area (W/ft^2) for Electric Equipment
Apartment unit	Midrise Apartment - Apartment	0.76
Corridor	Midrise Apartment - Corridor	0
Stairs and terrace	Midrise Apartment - Corridor	0

Table B3: Energy per space floor area coming from lighting

Usage	EnergyPlus Space Type	Energy Per Space Floor Area (W/ft^2) (Lights)
Apartment unit	Midrise Apartment - Apartment	0.37
Corridor	Midrise Apartment - Corridor	0.209
Stairs and terrace	Midrise Apartment - Corridor	0.209

Table B4: original construction materials

Component	Material
Exterior Wall	Autoclaved aerated concrete block
	Thermal insulation mortar
	Extruded polystyrene board (XPS)
Internal Wall	Autoclaved aerated concrete block
	Thermal insulation mortar
	Extruded polystyrene board (XPS)
General Floor	Polished concrete tile
	Mortar
	Plain cement concrete (portland)
	Cast-in-place slab
Ground Floor	Polished concrete tile
	Mortar
	Plain cement concrete (portland)
	C15 plain concrete
	Gravel cushion
	Stone block
	Mixture of weathered stone and soil compactor
Roof	C25 fine concrete
	Extruded polystyrene board (XPS)
	Asphalt waterproof coating
	Mortar
Windows	PVC double glazed window
Interior door	Wood
Exterior door	PCV plastic door

Table B5: properties of the construction materials

Component	Material	Thickness	Conductivity (W/m K)
Exterior Wall	Autoclaved aerated concrete block	480/360/240 mm	0.147
	Thermal insulation mortar	20 mm	0.085
	Extruded polystyrene board (XPS)	30 mm	0.03
Internal Wall	Autoclaved aerated concrete block	200 /100 mm	0.147
	Thermal insulation mortar	20 mm	0.085
	Extruded polystyrene board (XPS)	30 mm	0.03
General Floor	Polished concrete tile	No details	No details
	Mortar	No details	1.73
	Plain cement concrete (portland)	No details	0.29
	Cast-in-place slab	No details	No details
Ground Floor	Polished concrete tile	No details	No details
	Mortar	25 mm	1.73
	Plain cement concrete (portland)	No details	0.29
	C15 plain concrete	No details	No details
	Gravel cushion	50 mm	No details
	Stone block	200 mm	No details
	Mixture of weathered stone and soil compactor	No details	No details
Roof	C25 fine concrete	40 mm	No details
	Extruded polystyrene board (XPS)	30 mm	0.03
	Asphalt waterproof coating	No details	No details
	Mortar	20 mm	No details
Windows	PVC double glazed window	No details	0.19
Interior door	Wood	No details	0.15
Exterior door	PCV plastic door	No details	0.19

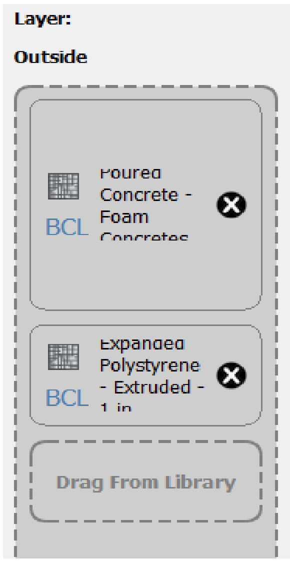

Figure B1: exterior wall layer construction properties

Appendix C

Table C1: Weather variables and effects on energy consumption (Yang, 2015)

Weather variable	Definition	Effect on the building's energy consumption.
Temperature	The amount of heat that is contained in a object (place in this case) for comparison purposes. (oxforddictionaries.com)	Low or high energy convention and infiltration through the building means more or less usage of HVCA and electronic equipments.
Humidity	Amount of water vapor in the atmosphere (oxforddictionaries.com)	Low or high energy convention and infiltration through the building means more or less usage of HVCA and electronic equipments.
Solar irradiance	Amount of radiant energy per unit area produced by the Sun	Low or high energy radiation through windows means more or less energy gains. These gains can have a direct effec in the space's heat balance, thus also in the usage of HVAC and electronic equipments. Use of internal lightning can increase/reduce. Energy coming from solar panels can be drastically impacted.
Sunshine duration	Amount of sunlight produced in a certain time	More or less time of energy radiation trough windows means more or less energy gains. These gains can have a direct effect in the space's heat balance, thus also in the usage of HVAC and electronic equipments. Use of internal lightning can increase/reduce. Energy coming from solar panels can be drastically impacted.
Sky conditions	Refers to cloud cover and probability of precipitation.	Use of internal lightning can increase/reduce. Energy coming from solar panels can be drastically impacted.
Precipitation	Amount of rain, snow, hail or sleet that falls to the ground in an area and certain time	Low or high energy conduction due to the moisture on exterior surfaces means more or less usage of HVCA and electronic equipments.