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The challenges and opportunities to shift from Net Zero Energy Building to Net Zero Emission Building in a hot tropical climate in Singapore

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Abstract

The paper aims to investigate how a net zero energy building could be optimised in order to shift to net zero emission building by balancing greenhouse gas (GHG) emissions from the operational energy use and materials embodied emissions with those from onsite renewable energy in the tropical rainforest climate of Singapore.

The first net Zero Energy Building in Singapore, SDE4, is taken as the case study. Guided by Norwegian ZEB guideline, the principles of the Life cycle assessment (LCA) methodology are used to calculate the total GHG emissions profile of the case study, which focuses on operational emissions and materials embodied emissions. The system boundary for LCA includes the embodied emissions from materials for the transport of materials (A4) and replacement (B4) of new materials in addition to the production stage (A1-A3). These calculations provide an overview of the emissions profile of the Singaporean net zero energy building is provided, outlining the need to address the high embodied emissions. More importantly, the main emissions drivers, concrete and steel, are revealed from the results.

Based on the results, potential emissions reduction measures are discussed, and an emission-reduced scenario is proposed and calculated to demonstrate the improvement. The final result showed that, for the case study, on-site renewable energy generation could compensate for the operational emissions and materials embodied emissions if sufficient emissions reduction strategies have been adopted. In conclusion, the net zero energy building is possible to be shifted into net zero or low emission building with the implementation of emission-reducing design strategy, despite the rather challenging climate and situation in Singapore.

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Table of Contents

List of Figures

List of Tables

Abbreviations

BCA	Building and Construction Authority in Singapore
BIM	Building information model
EEI	Energy Efficiency Index
EPD	Environmental Product Declaration
ETTV	Envelope Thermal Value
GM SLE	Green Mark for Super Low Energy
GHG	Greenhouse gas emissions
GWP	Global warming potential
IMCSD	Inter-Ministerial Committee on Sustainable Development
IED	Integrated energy design
LCA	Life Cycle Assessment
MET	Mass Engineered Timber
NUS	National University of Singapore
RD&D	Research, Development and Demonstration
ZEB	Zero Energy Building or Zero Emission Building

1. Introduction

1.1 Background

Global level

To mitigate climate change, the global commitment had been reached for a deep cut on CO_2 emissions. This global movement has started a worldwide trend toward high energy efficiency, with measures on reducing energy consumption and increasing utilisation of renewable energy. Building and construction sector, as the contributor for more than 35% of global final energy use and nearly 40% of energy-related CO_2 emissions (UN Environment, 2017), plays a vital role in the climate change battle.

Hence the ambition to bring down carbon emission from buildings emerged worldwide, Zero Energy Building and Zero Emission Building (ZEB) have become a global trend as a strategy for a deep decarbonisation of the construction sector. Zero Energy concept focuses on reducing the energy use of the buildings and compensating the required operational energy by renewable energy sources. In contrast to differing methodologies to zero and nearly zero energy buildings, the net zero emission building (ZEB) design approach focuses more on environmental impact (in the form of GWP) caused by buildings during their entire lifespan.Geographically, the development of the ZEB concept differs because of the local climate context, region policy, technology advancement and energy system.

Europe, Norway

In Europe, the EU has committed to a long-term target of reducing greenhouse gas emissions by 80-95% by 2050 when compared to 1990 levels (European Council, 2009). As discussed in the Energy Roadmap 2050, to achieve these goals, significant investments need to be made in energy efficiency, new low-carbon technologies and renewable energy application (EU, 2012). In the building sector, the key to moving the whole industry towards decarbonisation would be focusing on the higher energy efficiency in existing and new buildings. Shortly, nearly zero energy buildings should be the norm and positive energy building should be the goal to chase.

In Norway, under the leading of the country's goal of reaching carbon neutrality by 2030, significant effort and achievement had been made by research centres and building industry. Instead of merely aiming at "nearly zero energy buildings", the national research centre of zero emission buildings (ZEB centre) has taken a step further to striving for a net zero balance considering greenhouse gas emission rather than energy over the lifetime of the building. The vision of ZEB centre is to eliminate the greenhouse gas emissions caused by buildings. The objective of ZEB is to achieve a target of zero emissions of greenhouse gases throughout its life span, including its production, operation and demolition.

The design strategies and technical package of ZEB are developed under the context of a cold climate dominated the Scandinavian area. For a decade, the research centre worked closely with their industry partners to develop state-of-art technologies and products for existing and new buildings that lead to the achievement of energy efficient zero-emission buildings. Thanks to the significant joint efforts from the ZEB centre and their industrial partners, nine ZEB pilot projects (Table.1) had been done and tested out by far.

ZEB pilot buildings	Type of building	Ambition level	Location
Haakonsvern	Office building	ZEB-O÷EQ	Bergen
Skarpnes	5 single-family houses	ZEB-O	Arendal
Zero Village Bergen	ca. 800 dwellings	ZEB-O	Bergen
Powerhouse Brattøra	Office building	ZEB-OM÷EQ	Trondheim
Powerhouse Kjørbo	Office building, renovation	ZEB-OM÷EQ	Sandvika
Multikomfort	Single family house	ZEB-OM	Larvik
Living Laboratory	Single family house	ZEB-OM	Trondheim
Heimdal VGS	Education	*	Heimdal
Campus Evenstad	Education and office	ZEB-COM	Hedmark

*In the Heimdal pilot project, the calculations included all the emissions from the materials (A1-A3) and in addition emissions from transport to building site (A4). However, the ambtion level is set to compensate only 20% of these emissions. (ZEB O20%M + A4)

Table 1. ZEB pilot projects. (source: A Norwegian ZEB Definition Guideline)

Currently, five ambition levels of zero emission buildings are defined, depending on how many phases of a building's lifespan that are counted in, namely ZEB-O, ZEB-O÷EQ, ZEB-OM, ZEB-COM, ZEB-COMPLETE. 100% of the pilot projects have achieved the ambition level of ZEB-O, which means renewable energy can compensate for the GHG emission from the operational stage within their system boundary. In terms of energy demand and generation, buildings with ambition level of ZEB-O can be considered as the zero energy buildings. In the current stage of development, the ambition level of ZEB-O is theoretically and technically available to be achieved based on the practical experience thanks to the climate-responsive passive design strategies and high-performance materials, components and energy system.

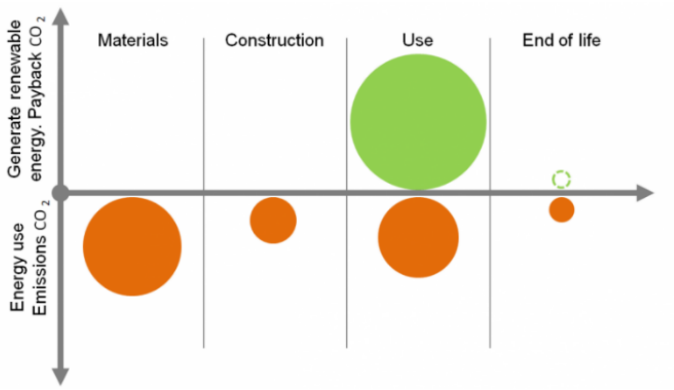

Figure 1. Illustration of the emissions balance of a zero emission building. The circles indicate the relative size of emission for each stage. (source: www.zeb.no)However, based on the experience from the pilot buildings, the emissions impact of materials use may exceed emissions related to the operational energy use in the process of increasing energy efficiency. As illustrated in Figure.1, the embodied emissions exceed the emission from the operational stage, becoming the biggest obstacle for a building towards zero emission. Thanks to the product innovation in terms of low emission initiated by the industry, around half of the projects have gained the ZEB-OM ambition level, which means both operational emission and embodied emission from the construction materials can be compensated by the renewable energy. Moreover, the highest ambition level has achieved by now is ZEB-COM, which is the pilot project in Campus Evenstad, the first ZEB-COM built in Norway. The ZEB-COM level indicates that the building's renewable energy production compensates for GHG emissions from the operation, construction and production of building materials (ZEB Centre).

The Nordic region has developed and adopted smart and sustainable solutions and policies to create environmental sustainability for decades. ZEB concept developed in Norway represents the state-of-art technologies and sustainable solutions to eliminate the carbon emission in the building sector in the context of Nordic cold climate. However, decarbonisation efforts should not just limit within a particular region.

Southeast Asia, Singapore

Actions on carbon emissions reduction need to be taken now, and actions need to cover all areas of the world. International support is vital for decarbonization in regions critical to the global climate (IPCC, 2014). The Asian region, as home to some of the most populated cities and fastest growing economies in the world, is no exception (Asian development bank, *Strategy 2030*, 2018). Large population and economic growth eventually link to subsequent massive carbon emissions. In 2015, Asia and Pacific accounted for almost half of total global carbon dioxide emissions (fig.2).

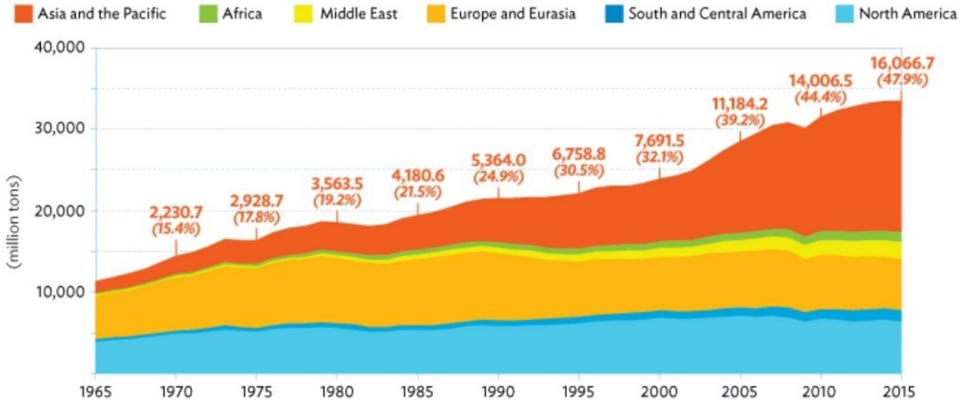

Figure 2. CO_2 emission share for the global region from 1965 to 2015. (Source: Asia Development Bank (ADB), *Key Indicators for Asia and the Pacific 2017*)

In particular, Southeast Asia is a growing source of GHG emissions and has an increasing influence on the global energy stage, accounting for 5% of total global demand (International Energy Agency, *Southeast Asia Energy Outlook 2017*, 2017). CO_2 emissions in Southeast Asia has been more rapid than in any other area the world (fig.3) in recent decades, at nearly 5% growth rate per year over the last two decades (Raitzer, 2015).

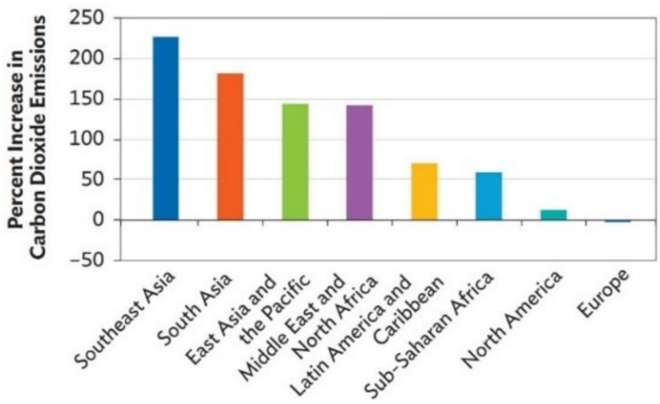

Figure 3. Increases in Total Carbon Dioxide Emissions in World Regions between 1990 and 2010. Note: Includes fossil fuels emissions only. (Source: World Bank. World Development Indicators. (accessed October 2015).)

The escalation of carbon emissions was a result of the rapid population and economic growth that boost by a fossil-fuel-based energy model (ADB, Key Indicators 2018). The ongoing rapid urbanisation in Asian area leads to a spread of metropolitan structures, following with a significant impact on the environmental system by the building industry. In addition, most of the population of Southeast Asia live in the tropic, and it is predicted that by 2050, half of the global population will reside in tropical regions (Wilkinson, 2014). This research prediction indicates that the influence of tropical regions is expected to grow in the coming decades. Therefore, studies on sustainable architecture in tropics, in the direction of zero energy building or zero emission building, would have a profound influence on the global progress in mitigating climate change. Smart design decisions and sustainable focus can help to control the carbon emission from expanding construction activities.

Within this region, Singapore plays an essential role in mitigating climate change and doing its part as a responsible global citizen, as its leading technologies and well-developed state system. As a developed country located in Southeast Asia, Singapore contributes around 0.11% of global emissions, and it ranks 26th out of 142 countries in terms of emissions per capita based on the latest IEA data in 2015 (NCCS). Currently, Singapore relies on a fossil-fuel energy model. In 2015, renewable energy consumption was only 0.8% of the city's total energy consumption (UNDP, 2018). With a deep understanding of its position and duty, Singapore has committed to reducing its GHG emissions intensity by 36% from 2005 levels by 2030. Singapore Government put in place the necessary policies, public investments, researches and support to assist the transition to lower emissions.

Buildings sector in Singapore, which is responsible for 27.6% (Household includes the energy use for building operation and construction activities) of the country's total electricity consumption (fig.4), plays a significant role in reducing carbon footprint to mitigate climate change.

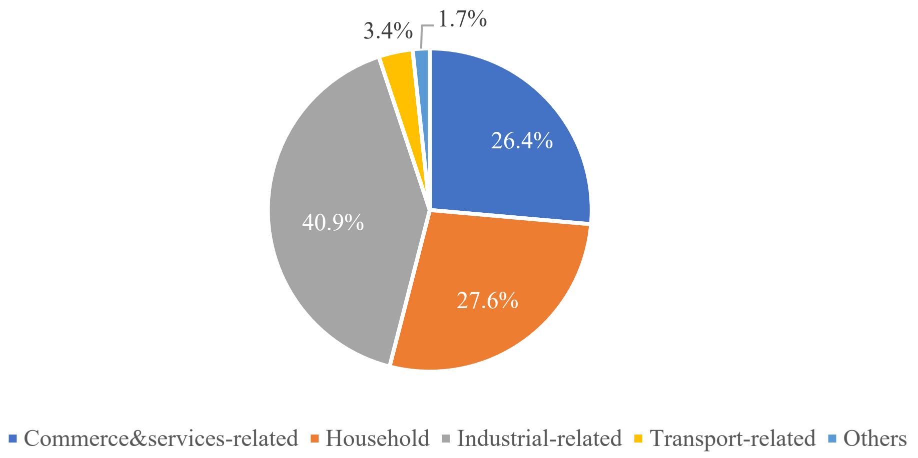

Figure 4. Singapore Electricity Consumption Landscape by Sector. (source: Energy Market Authority's Singapore Energy Statistics 2018)

Therefore, how to increase the energy efficiency of buildings becomes the first and essential problem to tackle in the Singaporean national sustainability agenda. To drive the advance of buildings' energy efficiency, Building and Construction Authority in Singapore (BCA) has been collaborating closely with the building industry to establish a certain framework and system.

BCA Green Mark

Green Mark Scheme was launched by BCA in January 2005 under the support of the Singapore Government. This initiative intends to promote sustainability in the built environment and raise environmental awareness among developers, designers and builders throughout the whole project period, design and construction. By encouraging the development of sustainable green buildings, BCA Green Mark plays a beneficial role in facilitating the movement of reducing the carbon footprint of the construction industry; also it is a leading green building rating system in the tropical and subtropical area.

In 2009, the 2nd Green Building Masterplan was launched in the association with the Inter-Ministerial Committee on Sustainable Development (IMCSD). IMCSD was established to formulate a national strategy for Singapore's sustainable development in the context of emerging domestic and global challenges. For the building industry, a sustainable development target has been set by IMCSD that is to achieve Green Mark Certification for 80% of all buildings by the year 2030 (BCA, *SLE Buildings Technology Roadmap*, 2015). Since Singapore began its green building journey in 2005, comprehensive initiatives and policies have been rolled out under the 1st and 2nd Green Building Masterplan. After the introduction of BCA Green Mark, long-term achievements have been documented that there were more than 3,300 buildings, equivalent to 36% (as at July 2018) of the total built-up areas in Singapore, had achieved Green Mark Standards, covering more than 100 million m^2 of gross floor area (BCA, *3rd Green Building Masterplan*, 2014). In the 3rd Green Building Masterplan, Singapore has set an ambitious vision to become *"a global leader in green buildings with special expertise in the tropics and sub-tropics, enabling sustainable development and quality living*". As a response to the vision, Green Mark Scheme has been updated to version 5 in 2015, which emphasised on developments in climatic-responsive passive design, smart building management system, greater resource efficacy, and an enhanced renewable energy adoption.

On the current stage, Singapore spearheaded the next significant step, to push the boundaries of building's energy efficiency, in green building movement. Efforts will be moved forward to put into setting industry standards with innovative solutions in term of attaining zero or net positive energy lowrise building and low energy highrise building. BCA has a long-term ambition to be able to achieve Super Low Energy for all buildings in Singapore and to accelerate the development of Zero Energy Buildings in the tropics. Globally, there is growing support for the movement towards Zero Energy Buildings. Hence, BCA introduced the *Green Mark for Super Low Energy* (GM SLE) during International Green Building Conference 2018. Targeting new and existing non-residential buildings such as offices, commercial, industrial and institutions, the BCA Super Low Energy Programme focuses on the energy efficiency and renewable solutions specifically in the building sector with the aim of pushing boundaries of sustainable building performance in tropical Singapore.

In Southeast Asia, the first Zero Energy Building, ZEB@BCA Academy, was built in 2009. An existing three-storey office building was retrofitted and is located within the BCA Academy, Singapore. The goal of zero-energy was achieved through a combination of green building technologies, passive design strategies that take advantages of natural ventilation and lighting, and the adoption of solar energy. This pilot project served as a test bed for application and integration of Green Building Technology in existing buildings, which can provide valuable and useful lessons-learnt and experience for future projects, especially the potential application of different available technologies.

Over the past eight years, ZEB@BCA Academy has a surplus of energy generation on an annual basis. The current ZEB-concept building has already been recognised as one of the most energy-efficient buildings in Singapore with outstanding energy efficiency 50% better than a code-compliant building (BCA, *SLE Buildings Technology Roadmap*, 2015). In this context, ZEB is gaining traction in Singapore following by several other ZEB demonstration projects, for example, the first new-built Net Zero Energy Building (NZEB@SDE4) in National University of Singapore (NUS) and Net Zero Energy building (SMU-X) in Singapore Management University. Since it is of importance to gain experience and learn from practices, both new-built Zero Energy Buildings, which served as living labs to test out the design strategies and technologies for new green buildings, containing a high value for researches.

In this paper, the first new-built Net Zero Energy Building (SDE4) in NUS campus has been chosen as the case study. Conceptualised by the NUS School of Design and Environment, the

ZEB@SDE4 is designed to be climate-responsive with an energy target of net-zero energy consumption. The institutional building features a series of innovative tropical green building approaches, such as harnessing solar energy, hybrid cooling system, natural ventilation and lighting.

Reflection on Background Situation

The net Zero Emission Building concept in Norway and Zero Energy Building in Singapore are both developed based on the same goal, to mitigate or even eliminate the impact on global warming from the building sector. The different local context and prerequisites determine their different starting points and the stage of development.

In Norway, the research has aimed further for zero-emission balance over the lifetime of a building instead of only focusing on the energy balance. As an argument, it is the greenhouse gas emission that is the primary reason when it comes to global warming. By now, all the pilot projects have obtained the basic ambition level on ZEB-O, and half of them reached ZEB-OM level. To achieve this advancement, several prerequisites are inevitable, such as the local low-emission energy system, industrial innovative technologies and products, advanced design approaches from the research centre, well-developed database and government-supportive policy.

Given the fact that hydropower is the mainstay of the Norwegian electricity system, the GHG emission from Norwegian energy production is relatively quite low. Also, the energy demand of the building operation has a significant reduction thanks to proper design strategies and innovative high-efficient components and building energy system. Therefore, carbon neutrality on operational stage is practically available since the emission from operational energy use can be balanced by the renewables generated onsite. With even more detailed design and the support from researches of low-emission materials and products, the renewables generated onsite can also compensate for the embodied emission from the materials, reaching the ZEB-OM level. As indicated in the ZEB balance, the impact of the embodied emissions from materials has exceeded the operational emissions ever since the operational energy demand has been deeply cut down compared with conventional buildings. Also, another reason that influents the ZEB balance can be the low value of the CO_2 factor of the electricity grid in Norway.

Besides, under the lead of the European Union and National goal, a nutritious environment has been created for ZEBs to grow. Specific building codes and various databases have been set up during the period of ZEB development. For example, the Environmental Product Declaration (EPD) databases have been established and worked as an indispensable part to conduct ZEB balance successfully. This movement initiated by the industry can be considered as its self-improvement responding to the need for the primary trend of sustainable development.

In Singapore, most of the researches and practical activities are focusing on reducing the building energy demand and increasing energy efficiency on the current stage. Research efforts and initiatives from government and industry are all aiming for development of the zero-energy or positive-energy buildings. The release of GM SLE building codes and research programmes would continue to boost the development of zero energy concept in the building sector. The concept of Zero Emission Building has not been bringing up on the table yet. Based on the current rapid development of zero energy building in Singapore, especially with the opening of the new-built NZEB@SDE4, it can be said that a solid foundation has been created, providing a proper starting point and study subject to make a transition from the zero energy concept to zero emission.

However, compared with the advantages and positive environment that Norway holds, to achieve zero emission ambition in Singapore might encounter several constraints imposed by current Singaporean building environment, which need to be developed further into emission-orientated. Firstly, the carbon emission profile of energy generation in Singapore is quite high because of the high reliance on fossil fuel. Secondly, now there is no available database contained information on greenhouse gas emission from materials and products. At last, there is a lack of useful researches on revealing the carbon emission profile of Singaporean buildings in the whole building lifetime, especially the materials embodied emissions.

To overcome these obstacles, it is essential to learn from successful global examples and seek technology integration in carbon reduction that can be achieved in Singapore's tropical context. Even though developed in the context of entirely different climates, the mindset and methodology of Norwegian ZEBs can still contribute to providing a guideline for solving challenges to achieve zero-emission in Singapore.

Necessity of Research

In the prime of the development of net zero energy building, net zero emission building inevitably would become the next step to embark in the journey towards an ultimate vision to eliminate carbon emission from buildings. According to the investigation, there is a lack of researches on the topic of zero emission building now in Singapore. It is the scarcity of researches on this topic and difficulty of conducting this study that makes it necessary and instructive. This study aims at investigating the potential to bring Zero Energy Building further into Zero Emission Building ambition in tropical rainforest climate like Singapore's. To design a zero-emission in hot humid tropical is quite different versus the temperate or cold climate regime. Singapore, as a country in the equatorial belt, owns the unique prerequisite to demonstrating the implementation of the zero-emission concept and particular climate-responsive technologies.

To reach this study target, anticipated results from this research work would include the revelation of the existing carbon emission balance of Singaporean buildings, indicating the influential emission contributors, and the proposal of basic strategies and direction to transform from zero-energy operation to zero-emission ambition. These research findings would become necessary materials to fill into the research vacancy on the topic of Zero Emission Building in Singapore. Therefore, the necessity of this research topic is self-evident based on the existing situation and background mentioned previously. Eventually, the findings from this study can work as a pathfinder on the way to zero emission.

Challenges and Opportunities

However, the aim to investigate the Zero Emission Building in Singapore would undoubtedly meet with challenges but also opportunities.

Firstly, Singapore sits in the tropical belt, where higher levels of temperature, ranges between 25°C to 33°C, and humidity with a mean annual value of 83.9% is constant throughout the year.

With this tropical climate context, the bulk of typical building total energy consumption, accounting for 56%, is related to space cooling demand provided by the air conditioning system (AC) in tropical countries, to provide optimal thermal comfort for occupants (Katili, 2015). The challenging building energy use from cooling demand all year long would be a great challenge on operational emission reduction. Effective strategies need to focus on the high-efficient AC system and passive cooling/ventilation methods, for example, maximise the utilisation of natural ventilation.

Secondly, the production of electricity in Singapore relies on fossil fuel. Even though now natural gas, the cleanest form of fossil fuel, has become the primary energy fuel, it still gives a carbon emission (430 gCO_2/kWh) about 10 times the amount higher than the one in Norway (40 gCO_2/kWh). Also, in Singapore, the natural resource is limited and most of its materials and products are relied on importation because of the small land area and island location. Lots of construction materials are shipped in internationally, which makes the materials embodied emission considerably high. For example, concrete and steel are mainly imported from Malaysia and China respectively. Therefore, a predictable high carbon emission profile of Singaporean building would set a challenge to compensate for the GHG emission by on-site renewables.

Lastly, there is inadequate information to serve the research on this topic, which leads to the challenges and limitations to proceed with the study successfully. For example, there is not an available database which storing the EPDs data of products now in Singapore, which makes the subsequent calculation of Life Cycle Assessment difficult. The EPD (Environmental Product Declaration) is a concise third-party verified and documented document with transparent and comparable information about product environmental performance throughout the life cycle.

As for the opportunity, there is an increasing number of researches and practices of zero energy buildings happening in Singapore. These developments were encouraged and supported by the BCA's ambition for Positive Energy, Zero Energy and Super Low Energy Buildings (BCA, *SLE Buildings Technology Roadmap*, 2015). Zero Energy building can be considered as the first step towards Zero Emission building. It eliminates the emission on the operational stage, which provides a solid foundation to continue the work. Notably, the construction of the first NZEB@SDE4 offers a reasonable basis for the collection of actual construction and performance data, also provide good foundation and study subject to optimise the design to shift to a zero-emission ambition.

Furthermore, technologies and design initiatives suitable for the tropics can be learnt from successful global experience. In this study, the existing Norwegian ZEB system would provide a guideline or experience on how to tailor the ZEB solution into the tropical-climate area, trying to derive a Singaporean Zero Emission Building system from existing Norwegian experience.

1.2 Research Questions

The objective of this research is to investigate the possibilities to achieve Zero Emissions Building in a tropical climate. The research process was leading by two main questions. First, what are the existing energy and emission profile of the case study? Second, how the design can be optimised based on the findings of the first question, in order to shift from the current net Zero Energy Building into future net Zero Emission Building in the Singaporean context? An overview of the current situation of SDE4's CO_{2eq} emissions gives direction and indicators to discuss the design alternative in terms of carbon emission further. Furthermore, the existing emissions profile of zero energy building SDE4 implies how far does it away from zero-emission and what efforts should put into the shift.

1.3 Research Method

The new ZEB@SDE4 Project in NUS campus is chosen as the case study. SDE4 is the first new-built Net Zero Energy Building in Singapore, which reaches zero energy balance for an operational year. When expanded into emissions, it means SDE4 reach carbon neutrality on its operational stage: the operational energy use can be compensated by the on-site renewable energy generation. The feature of zero energy consumption is the main reason why SDE4 is chosen as the case study in this research. It provides a reasonable starting point to further eliminate the GHG emission from material production, construction, replacement and even demolition.

For the first step, qualitative research into identifying what design strategies have been used in the current design of ZEB@SDE4 and how they influenced the result of energy use and embodied emissions of materials would be undertaken. In the same time, from the quantitative perspective, the general energy consumption together with the building emission profile would be presented. Energy consumption data would adopt energy simulation results, sourcing from the energy consultant for the design of SDE4. The emissions from operational energy would be calculated by applying the emission factor for the electricity grid mix in Singapore to the annual delivered energy data.

In addition to the emissions from the operation, as the second step, the embodied emissions would be calculated through Life Cycle Assessment (LCA), to reveal and evaluate the total embodied emission profile and the key drivers for the emissions in terms of an overall zero emissions balance. The introduction of LCA in the context of Singapore provides the opportunity to understand the current profile of the embodied emissions so that reduction approaches can be proposed. Due to the lack of EPD data in Singapore, the generic data obtained from Ecoinvent 3.1 database (GLO) would be used, which would be substituted for specific product data. As a result of this step, a ZEB balance would be presented and discussed.

The last step focuses on how the design can be optimised to achieve the transition to a Zero Emission Building ambition. Design alternative aimed to reduce emission, both from materials and operational stage, would be propounded and compared with the base case, to evaluate the effectiveness and impact of each design strategy on GHG emission reduction.

1.4 Anticipated Results

Firstly, the emission profile of the SDE4 along with the analytical results would be presented. Secondly, design improvement at the building level, as well as an overall concept to achieve Zero Emission Building, would be presented.

1.5 Scope and Limitations

Firstly, since the SDE4 just opened in January 2019, there is a lack of monitored data for the building operational energy use. It necessitates the use of simulated results for the calculation of the emission from the operational stage. Here exists a potential discrepancy between the monitored data with the simulated data. Because this research aims at getting a whole picture of the building performance, the accuracy of the data would not have a substantial impact on the analytical results.

Secondly, due to the lack of available accurate BIM model information and material inventory, a mock-up Revit model would be made from dimensioned drawings and onsite observation and thus gives a rough material inventory. This model would be a simplified model due to the lack of detailed construction information and the time-consuming of detailed modelling. Therefore, the materials quantity would have a discrepancy with the actual construction usage, also the material list may only encompass several main construction materials, cannot represent the whole detailed materials use situation of the case study. In addition, the on-site self-investigation and assumption would be the source of the information of types of building material, here might lead to a limitation of the accuracy of the material types and composition. Given these limitations on calculation data, the LCA result would only show the rough situation of the case study.

Lastly, for the fact that there is no EPD database in the Singaporean market, it necessitates the use of generic data as an alternative to replacing the specific EPD data. The generic data would be extracted from the Ecoinvent database.

Given the limitations listed above, the scope of the research would be limited into investigating the GHG emission from operational energy use (B6), materials product stage (A1-A3), materials transportation to the building site (A4), and the replacement of new materials (B4). Also, the building design would be fine-toned based on the findings from the LCA calculations so that to shift from net zero-energy to net zero-emission ambition.

2 Theory

2.1 Zero Emission Building System in Norway

2.1.1 Definition of Zero Emission Building

The definition of ZEB given by the Norwegian Research Centre on Zero Emission Buildings (ZEB Centre, www.zeb.no) is that *"A zero emission building produces enough renewable energy to compensate for the building's greenhouse gas emissions over its lifespan.",* which means building with zero emission of greenhouse gases related to its production, operation and demolition.

The zero emission building definition has been further expanded from net zero energy building by applying a life cycle perspective, whereby the primary energy used in the building during operation plus the embodied energy from materials, transport and construction and end of life energy demand from dismantling, transport and waste treatment etc. are included (S.M. Fufa et al, 2016).

In addition, instead of focusing on energy use in the operation and primary energy use like most of this previous work, ZEB centre has focused on CO_{2eq} emissions in a life-cycle perspective (Dokka Tor Helge et al., 2013).

Hence, the ZEB balance is measured in terms of associated greenhouse gas equivalent emissions during the lifetime of a building instead of on direct energy demand and generation.

2.1.2 ZEB Ambition Level Definition and System Boundaries

The ZEB centre has defined different levels of ambition for zero emission buildings depending on how many phases of the lifespan of a building that are counted in. Five most important definitions have been considered during the assessment of Norwegian ZEB pilot projects (fig.5).

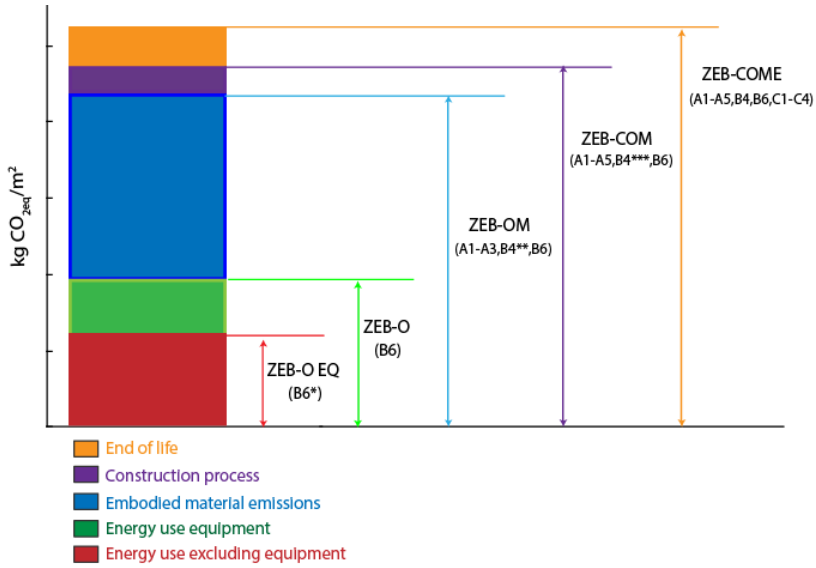

Figure 5. ZEB ambition levels. (source: *A Norwegian ZEB Definition Guideline*, 2016)

The "O" refers to emissions associated with Operational energy use. The “M” refers to embodied emissions associated with building construction Materials. Material embodied emissions refer to emissions that are released into the atmosphere during the production, construction, use and demolition of the materials. The "EQ" refers to operational emissions from technical EQuipment. The "C" refers to emissions associated with Construction and installation process, while the "E" refers to emissions associated with the End of life phase of the building.

The assessment of the Zero Emission building includes a life cycle perspective. According to standard NSEN 15978:2011, the life cycle of a building is divided into the following stages (Fufa et al., 2016):

Product Stage (A1 - A3): Cradle to gate processes for materials and services used in construction: raw material extraction and processing (A1), transport of raw materials to the manufacturer (A2), and manufacturing of products and packaging (A3).

Construction Process Stage (A4-A5): Transport of construction products to the construction site (A4), transport of ancillary products, energy and waste from the installation process (A5).

Use Stage (B1 - B7): Use of construction products and services, related to building components (B1 -B5) and operation of the building (B6 - B7), during the entire lifetime of the building. The maintenance (B2) repair (B3) and replacement (B4) lifecycles are related to the product's estimated service life (ESL).

End of Life Stage (C1 - C4): When the building is decommissioned and not intended to have any further use, the building is deconstructed or demolished (C1) and transported to waste treatment or disposal facilities (C2), whereby the waste is either processed (C3) and/or disposed of (C4).

Benefits and loads beyond the system boundary (D): This covers the benefits and loads arising from the reuse (D1), recovery (D2), recycling (D3), and exported energy/potential (D4) from end-of-waste state materials.

A detailed explanation of the ambition levels, including their related life cycle stage, is presented in Table2. The lifecycle stage presented in green is those included in each different ZEB ambition level.

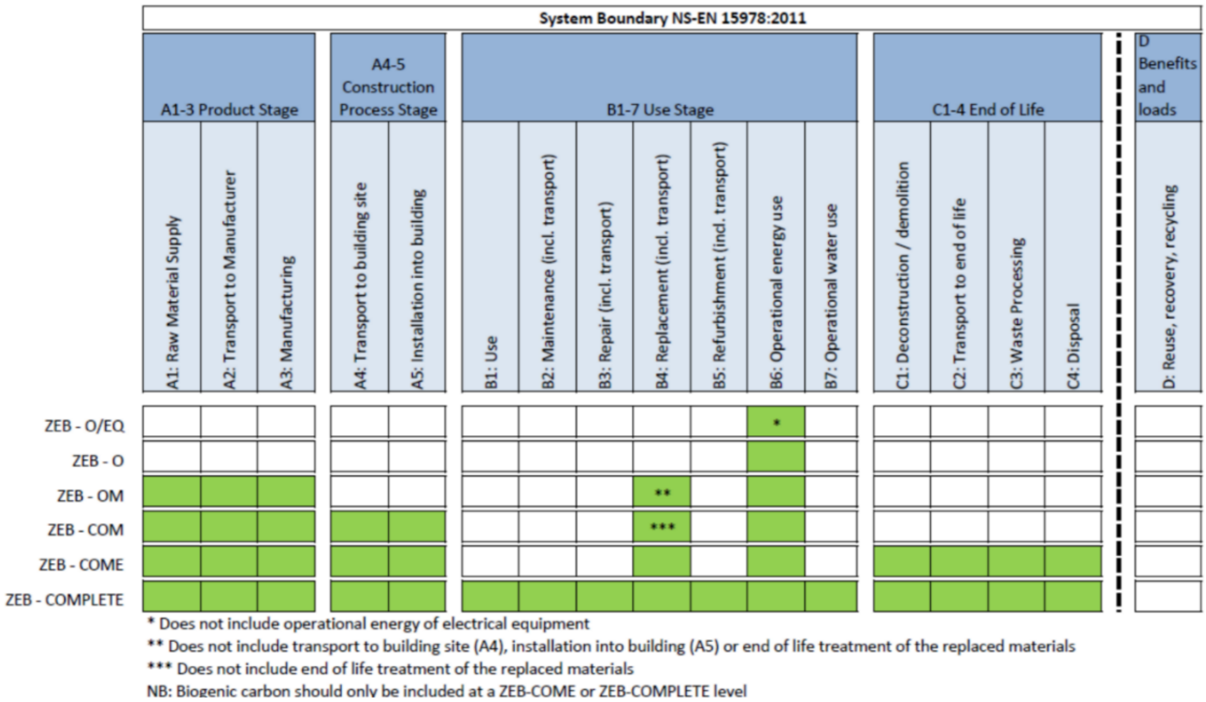

Table 2. Description of ZEB ambition levels according to NS-EN15978:2011. (source: *A Norwegian ZEB Definition Guideline*, 2016)

ZEB-O÷EQ: The building's renewable energy production compensates for greenhouse gas emissions from the operation of the building but excluding energy use for equipment and appliances (plug loads), covering the life cycle stage B6*. This is regarded as the lowest ambition level for ZEB pilot buildings.

ZEB-O: The building's renewable energy production compensates for greenhouse gas emissions from all operational energy use of the building (B6).

ZEB-OM: The building's renewable energy production compensates for greenhouse gas emissions from all operational energy (B6) and embodied emissions from its building materials production (A1-A3, B4**). Here the embodied emissions also include scenarios related to the production of materials used for the replacement phase according to NS-EN 15978: 2011.

ZEB-COM: The building's renewable energy production compensates for greenhouse gas emissions from construction (A4-A5), operation (B6) and production of building materials (A1-A3, B4***). Note that B4*** here also include the transportation (A4) and installation process (A5) of replaced materials.

ZEB-COME: The building's renewable energy production compensates for greenhouse gas emissions from construction (A4-A5), operation (B6), production of materials (A1-A3, B4) and end of life of the building (C1-C4). Here the B4 stage includes production, transportation, installation and end of life processes of replaced materials.

ZEB-COMPLETE: The building's renewable energy production compensates for greenhouse gas emissions from the entire lifespan of the building. Building materials production (A1-A3), construction (A4-A5), operation stage (B1-B7) and demolition/recycling (C1-C4). If relevant and available, benefits and loads beyond the system boundary (D) can be included as additional information, according to NS-EN15978: 2011.

2.2 Zero Energy Building System in Singapore

2.2.1 Definition of Zero Energy Building

Globally, there are many different definitions of the Zero Energy Building, mainly to address the practicality of achieving ZEB in the local context. Provided by BCA of Singapore, Zero Energy refers to energy self-sufficiency without the need to tap on the power supply from the grid at all. Specifically, Zero Energy Building in Singapore's context is defined as "*the best-in-class energy performing Green Mark building with all of its energy consumption, including* *plug load, supplied from renewable sources (both on-site and off-site)*" (Green Mark for Super Low Energy Buildings, 2018 by BCA).

It is noticeable that there is an expanded definition for ZEB in Singapore, i.e. Positive Energy, Zero Energy and Super Low Energy Buildings. As illustrated in Figure.6, Positive Energy building refers to building's renewable energy generation is more than or equal to 110% of energy consumption. While the Super Low Energy Buildings refer to '*the best-in-class energy performing Green Mark Building that achieves at least 60% energy savings through adopting energy efficient measures and onsite renewable energy based on 2005 building code level*'. The expansion to Super Low Energy took into consideration of the constraint of Singapore's high energy intensity and difficulty to refurbish the existing building into zero energy.

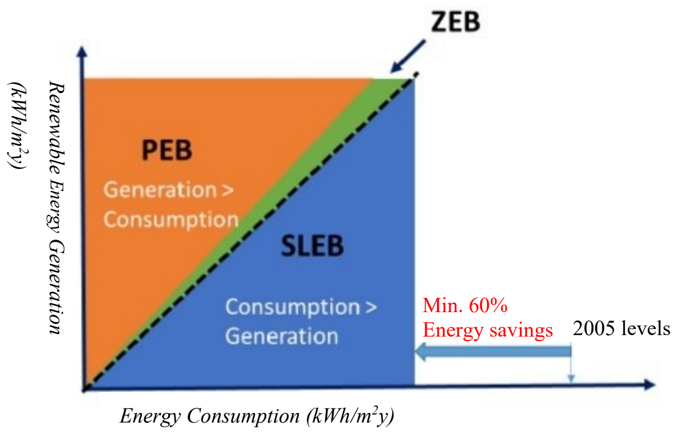

Figure 6. Graphical representation of PEB, ZEB & SLEB definitions (source: Super Low Energy Buildings Technology Roadmap, p19)

2.2.2 Green Mark for Super Low Energy System

This building certification programme set new performance benchmarks which aim to guide the future researches and practices toward zero-energy. In addition, it advocated the academia and industry professionals to take on the Super Low Energy (SLE) Challenge for taking the lead to develop future SLE projects. So far, over ten building owners and developers have pledged their commitments to accomplish at least one SLE project in future five years. Continue practices require increasing expertise on building energy efficiency so that to stimulate the growth of relevant research and improvement of the regulation system.

This certification framework for SLE buildings, adds on to the BCA Green Mark scheme, aims to support the zero energy aspiration in the tropical and subtropical region. There are two buildings categories under GM SLE certification system, Super Low Energy buildings and Zero Energy buildings, both equal to Green Mark Platinum in GM ratings.

To address the challenges and seize opportunities provided by SLE programme, the *Super Low Energy Buildings Technology Roadmap* (BCA, 2018) was developed by BCA in partnership with industry and academia and launched to help achieve the ambitious goal of up to 80% energy efficiency improvement over 2005 levels by 2030.

In SLEB Technology Roadmap, SLE ambition has been quantified into recommended Energy Efficiency Index (EEI) targets. Table.3 illustrates the corresponding EEI for office buildings, showing improvements in the EEI by 60% over 2005 industry levels by 2018 and 80% by the year 2030.

	EEI (kWh/m^2/year)					
Year	2005 Levels	2018	2020	2025	2030	Improvement over 2005 by 2030
SLE Roadmap Target	244	100	85	60	50	80%

Table 3. SLE Roadmap Target for Office Buildings. (source: BCA, Super Low Energy Building Technology Roadmap, 2018)

In order to push the energy efficiency boundaries further, a Research, Development and Demonstration (RD&D) Initiative has been funding by the government to set up researches and innovation programmes, which aim to accelerate the development and application of expertise in terms of promoting green building. Besides these researches, pilot projects served as test beds are crucial to examine various experimental technologies in actual building environment and receive effective feedback.

As the key findings stated in the Roadmap, achieving SLE with a target of 60% energy saving over 2005 level is technically feasible with existing advanced technologies. However, further technological advancements and research development would be needed to reach an improvement of 80% energy efficiency, to make SLE both technically feasible and economically viable for mainstream adoption by 2030. It is worth noting that lowrise institutional buildings have the potential to achieve zero or positive energy target first.

3 Methodology

3.1 SDE4 Building Design as Case Study

This new project, named as SDE4, locates in Singapore, which is a new addition to the existing buildings of the NUS School of Design and Environment (SDE). This six-story building, with a gross floor area of around 8588 m², houses a mix of research laboratories, design studios, library, as well as teaching and common learning space. It also includes staff offices, social plaza and exhibition area. The building is meant to hold around 500 students when it opens in January 2019 and functions as a living laboratory to promote creative and collaborative learning and research process on sustainable development. The key information for SED4 is summarised in Table 4. Figure.7 illustrates the cross sections of SDE4.

Table 4. Building information. (Source:1. Wolfgang Kessling, 2016, Net Zero by Design, Transsolar Klimaengineering. 2. Nirmal Kishnani, The power of Zero-energy and comfort in tropical Singapore, NUS)

Building Information	
Location	4 Architecture Drive, Singapore (Latitude 1.29 N, Longitude 103.77E)
Building Type	Education (School of Design and Environment)
Project Type	New construction
Size	6 levels
Gross Floor Area	8588 m²
Site Area	1300 m²
Site Coverage	0.526
Main Functions	Design Studios/Research Centres/Laboratories/Workshops/Library NUS-CDL Smart Green Home/Staff Offices/Social Plaza and Exhibition Area
Completion	Early 2019
Energy Efficiency Ambition	≤75 kWh/m²/year
IED Team	
Owner/Developer	National University of Singapore
Architects	Serie and Multiply Architects
Energy consultant	Transsolar Energietechnik Gmbh
Executive Architect, Engineer	Surbana Jurong Consultants Pte. Ltd.

Figure 7. Cross Section of Building SDE4. (source: https://www.dezeen.com/2016/11/07/national-university-singapore-building-zero-energy-design-school/)

The building structure adopts the typical reinforced concrete frame structure, using cast-in-place columns, beams and floors to give flexibilities. Proper shading envelope is adopted to mitigate the impact of intense solar radiation. As the main energy-efficient strategy, an innovative hybrid cooling system is applied to reduce the reliance on fully air-conditioning and provide occupants with adaptive thermal comfort.

SDE4 is a prototype of net-zero-energy and sustainable design thinking in the tropics. There are four main strategies of SED4 for the design approach, namely energy, well-being, process and design. SDE4 is designed to be net-zero energy, system and space aimed at improving the well-being of occupants and integrated design process was adopted. SDE4 is classified as type A, which means consuming as much as energy as it produces within the building footprint. Also, it has been awarded a Green Mark Platinum certificate.

3.1.1 Climate Conditions in Singapore

In order to better understand the design strategies adopted by SDE4, the climate in Singapore has been analysed. Singapore is located near the equator and features a typically tropical climate, with abundant rainfall, high and uniform temperature and humidity all year long. Unlike temperate climate zone, climate variables in Singapore, such as temperature and relative humidity, are dominated by hour-to-hour daily variations instead of month-to-month variation, indicating the solar radiation has a strong influence on the local climate.

The daily temperature ranges from mean minimum 23-25ºC during the night and mean maximum 31-33ºC during the day.

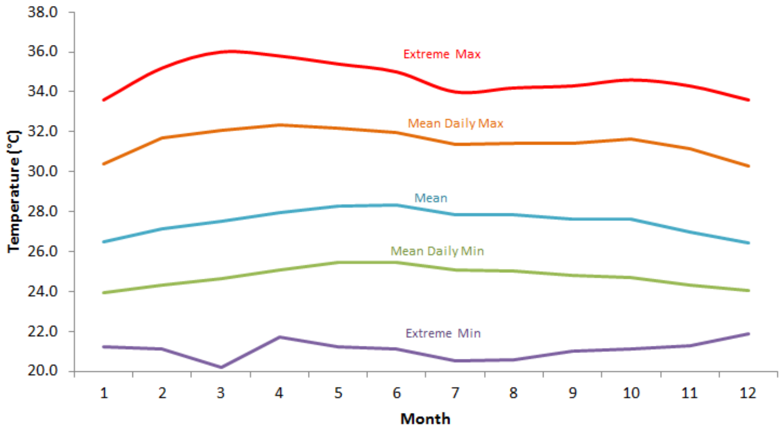

Figure 8. Mean monthly temperature variation (ºC) (1981-2010). (Source: Meteorological Service Singapore, http://www.weather.gov.sg/climate-climate-of-singapore/)

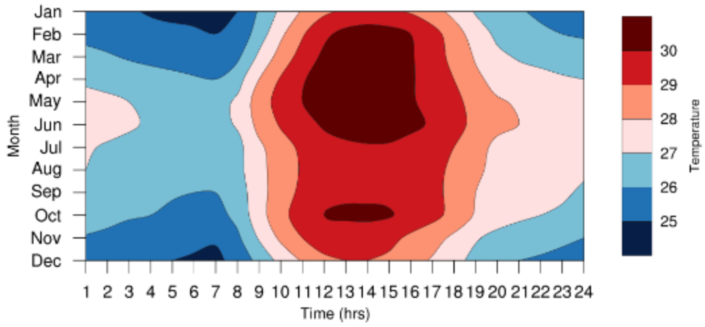

Figure 9. Hourly variation of temperature for each month (1981-2010). (Source: Meteorological Service Singapore, http://www.weather.gov.sg/climate-climate-of-singapore/)

The mean annual relative humidity in Singapore is considerably high as 83.9%. It is fairly uniform throughout the year but varies on a daily basis. As recorded, the relative humidity is usually over 90% in the morning just before sunrise and falling to around 60% in the mid-afternoon on sunny days.

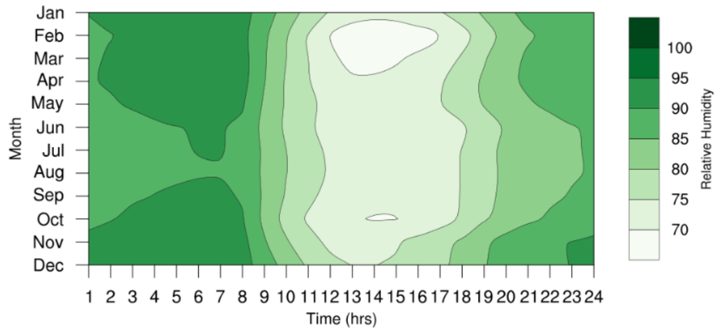

Figure 10. Hourly variation of relative humidity for each month (1981-2010). (Source: Meteorological Service Singapore, http://www.weather.gov.sg/climate-climate-of-singapore/)

The sunshine duration in Singapore is four to five hours from September to December and about six to seven hours during the rest of the year. An average annual solar irradiance of 1580 kWh/m^{2}yr and about 50% more solar radiation than temperate countries.

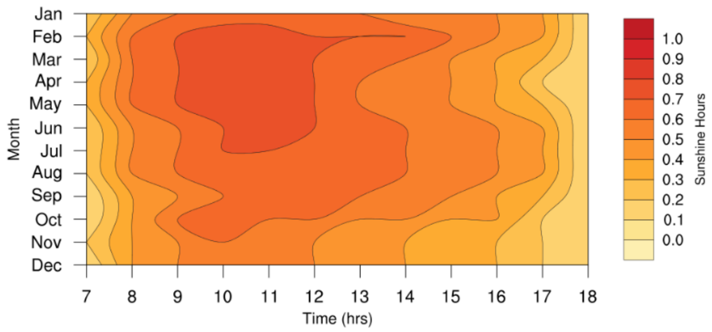

Figure 11. Hourly variation of sunshine hours for each month. (Source: Meteorological Service Singapore, http://www.weather.gov.sg/climate-climate-of-singapore/)

3.1.2 Energy-saving Design Strategies

High temperature and humidity are the outstanding features of the tropical climate. These specific climate conditions lead to the fact that buildings need to find their way to mitigate the impact of the intense solar radiation. Also, high temperature all year round results in a situation that air conditioning is responsible for the biggest bulk of energy consumption in tropical buildings. For a typical office building, 60% of electrical consumption is attributed to space cooling system, following by lighting (15%) and mechanical ventilation (10%). Another active source of energy use is plug loads, which may consume up to 25% of the total building energy consumption (BCA, Super Low Energy Building Technology Roadmap, 2018).

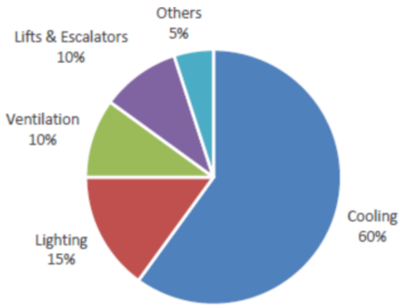

Figure 12. Typical Office Building Energy Usages. (Source: BCA, Super Low Energy Building Technology Roadmap, 2018)

High demand for air conditioning due to the local climate in Singapore makes the net-zero-energy vision challenging. With limited roof space for onsite renewable energy, the balance between “How much energy can be produced on-site?” and “how efficiently can energy be consumed?” is the crucial question for this big-scale tropical project during the whole design process.

Therefore, during the design process of SDE4, the most demanding design requirements are listed below:

1. Reduction of energy use intensity (EUI) with optimisation of design, operation and users’ requirements
2. Reduction of EUI by optimising system and technology
3. Maximisation of renewable energy production

Strategies adopted by SDE4 are a combination of maximum passive and optimal active design strategies, responsible for static and dynamic system of the building respectively. Here, the focus has been put on the energy-saving related strategies. In this respect, static system would include building configuration and envelope. Dynamic system, on the other hand, would include ventilation, cooling and lighting. In the following chapters, strategies responsible for static and dynamic system respectively have elaborated into details.

3.1.2.1 Static System: Building Configuration and Envelope

In order to provide desired indoor thermal comfort and reduce energy use, the challenge for tropical building design is essentially mitigation of the force of the sun. For this reason, vernacular architecture in tropics has some architectural features like open platform, big roof, open interior space with minimal partitions (V.Bezemer, 2008). The platforms and roof can create shade for the building from the sun. Also, the lack of emphasis on solid walls facilitates natural ventilation. Therefore, instead of creating a sealed environment with heavy reliance on air conditioning, as many of Singapore's commercial buildings, the architects took inspiration from traditional tropical architecture to have a climatic-responsive design.

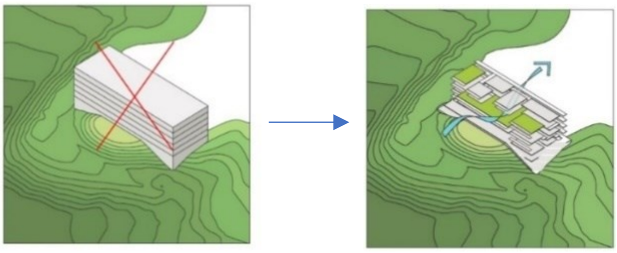

Figure 13. Building Configuration Strategy. (Source: Wolfgang Kessling, 2016, Net Zero by Design, Transsolar Klimaengineering.)

The proposal of the building configuration is based on a series of platforms and boxes. First, the building mass is broken down into smaller volumes to create a porous structure which has better penetration for the daylight and natural breezes. With this layout strategy, the plan has a shallow depth compared to the typical deep commercial floor plan. Also, each level has its communal terraces on three sides which integrate with the vegetation to provide the pleasant outdoor working environment, also to cool down the natural breezes a bit before coming indoors. This building form sets a solid foundation by maximising the capacity of shading and the possibility of natural lighting and ventilation, also embracing the potential of plants and landscape into the building, which distinguishes itself from a sealed fully-conditioned conventional design.

When it comes to the building envelope, a passive rule for the tropics has been applied, which is to allow good quality light and natural ventilation into the interior while reducing the heat transmittance. In SDE4, it is achieved by using some important elements, like a large overhanging roof together with shading devices on the eastern and western façades, to shade the whole building from the intense solar radiation so that to provide a cooler interior. In the meantime, the porous configuration combined with occupant-controlled windows, allows the building to make use of natural ventilation further.

Figure 14. Building Shading Strategy. (Source: Wolfgang Kessling, 2016, Net Zero by Design, Transsolar Klimaengineering.)

The large overhanging roof prevents the south façade from the intensive incident solar load. All the glazing on south façade can be entirely shaded by the overhang. Besides this, the east and west façades are assembled with perforated aluminium panels that protect the inner glass envelope from direct solar radiation in the morning and the late afternoon. These two passive approaches are effective and common in tropics because the sun rises from the east, goes down to west with a very high solar angle during the noon, resulting in the massive solar radiation hitting not only the south façade/rooftop but also the east/west façades.

Further, a study of detailed shading design for south façade is also conducted. In this study, the performance of different scenarios have been compared by changing parameters: have overhang/shading or not, the distance of overhang, the type of shading, the type of glazing. A trade-off among the optimisation of thermal comfort, daylight and glare must be made to reach a desirable performance.

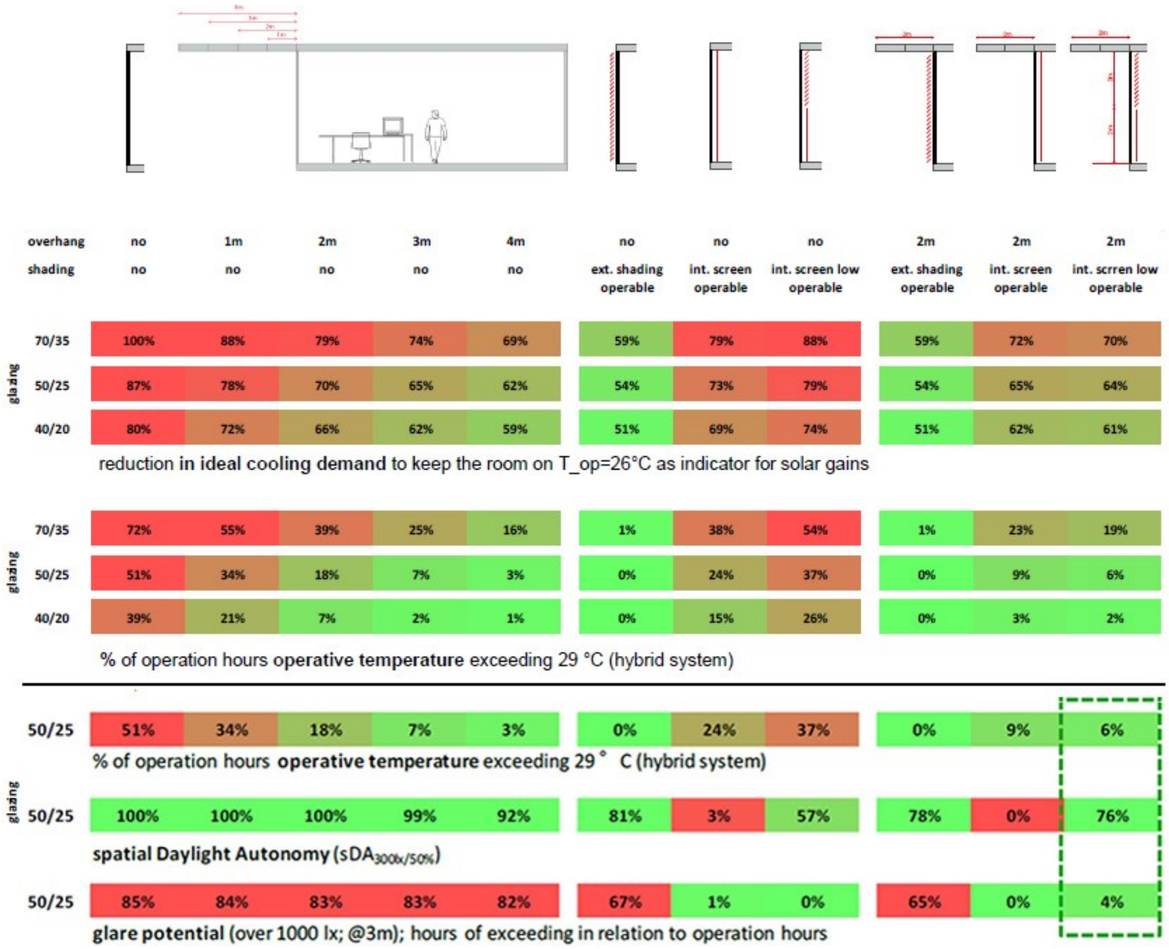

Figure 15. Research on façade shading combined approaches. (Source: Nirmal Kishnani, The power of Zero-energy and comfort in tropical Singapore, NUS.)

As illustrated in the diagram above, the efficiency of reduction of cooling demand decreases while the distance of the overhang increases. Also, among three types of shading: operable external shading, operable internal screen and operable internal low screen, the first one performs the best on the aspect of solar control. However, when combined the overhang and the shading, no more reduction occurs for the external shading scenario after adding the overhang, in contrast, the operable internal low screen scenario has a considerable reduction, although it still performs worse than the external shading scenario. Besides this, the thermal performance gets better when using the glazing with a lower transmittance and g-value.

After the first round comparison, the glazing 50/25 (light transmission/g-value) is chosen for the next comparison for its moderate performance on both aspects of thermal and the daylight performance. The reason for it to beat the glazing 40/20 is that the latter has a considerable reduction on daylight condition while both of them have a relatively similar thermal performance.

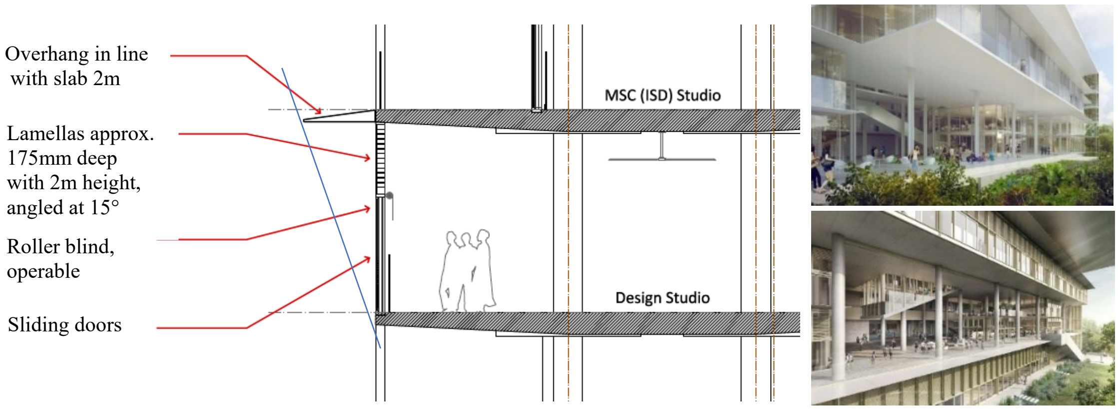

Figure 16. South Façade Shading Design. (Source: Nirmal Kishnani, The power of Zero-energy and comfort in tropical Singapore, NUS)

In the final comparison, the external shading and the internal screen perform unsatisfied on glare potential and spatial daylight autonomy respectively. Hence, the scenario with the internal low screen, which is comprised of lamellas on the upper part and an operable roller blind on the lower part, and the 2-meter overhang is chosen based on the trade-off between thermal comfort, daylight and glare.

To sum up the performance of the strategies for the static system, the overall Envelope Thermal Value (ETTV), representing the thermal performance of the whole envelope, was ultimately quantified at less than 40W/m^2. It has a significant improvement compared to the value of 50 W/m^2, the maximum permissible ETTV (BCA, *Code on envelope thermal performance for* *building*, 2008), set by BCA for energy conservation. More importantly, it results in a 25% saving of total energy use compared to the reference case (Kessling, 2016).

3.1.2.2 Dynamic System: Ventilation, Cooling and Lighting

Mixed Ventilation Mode Allows for Flexibility of Use

Commonly in tropical countries, about 60% of the total energy load consumes by the air-conditioning system, which means improving the efficiency of the usage of AC system is a considerably effective strategy to reduce energy use. Moreover, there is *"…a trend in many tropical countries is to design air-conditioned buildings that operate at 22.5 +/-1 °C all year, to meet the stringent specifications outlined in the Thermal Comfort Standards... These buildings are designed as sealed and do not take advantage of favourable outdoor conditions available"* (Kessling et al., 2015). Evidence from field studies (Sekhar, 2016) suggests that there is indeed an issue of overcooling in tropical buildings, which caused by inappropriate design and operation of the HVAC system and occupants are forced to adapt to this cold discomfort through increased clothing insulation.

Critical to solving these problems is to rethink of and re-define the model of indoor thermal comfort, which would have its impact on the adjustment of the air conditioning system thus influent the energy use. Also, it is important to make efficient and effective use of the favourable outdoor environmental elements, for example, the pleasant natural breezes, to have the ability to employ a variety of cooling options, avoiding the stiff operational mode in the conventional sealed-cooling building. In other words, the usage of the air-conditioning should be limited to necessary situations and adopt a smarter way, which can be considered as the maximisation of energy efficiency.

Based on these critical thinkings, SDE4 adopts a hybrid cooling system, which on the one hand takes the maximum advantage of the passive cooling (natural ventilation) when available, on the other hand, adopts an innovative mechanical system to provide adaptive thermal comfort. The design approached mixed-mode ventilation which combining natural ventilation (52%), mechanical ventilation (4%), air-conditioning (10%), and a new hybrid cooling system supplying tempered fresh air augmented by ceiling fans (34%) (NUS, *SDE Zero*, 2018). The air conditioning is limited in areas where indoor thermal conditions needed to be controlled. All the circulation, toilets, lobbies and staircases are naturally ventilated.

The aim to make maximum use of natural ventilation is bear in the designer's mind from the very beginning. Built form and shading strategy built up the foundation to boost the maximal feasibility of natural ventilation. Social plaza, interaction spaces, modelling space, workshops and all corridors and services areas are naturally ventilated. These spaces are well-shaded to lower ambient temperature and located to catch prevailing winds running predominantly along north-northeast and south-southeast.

For the fact that SDE4 is located on the hillock facing the southern coastline of Singapore, a constant breeze is blowing through the building thanks to the cross-ventilation-friendly design. Besides, in order to enhance the effectiveness of the natural ventilation, two solar wind towers are installed at the roof above the main staircase, which helps to suck warm indoor air through chimney then draws cool ambient air through the façade into the interior using buoyancy effect. As a reference case, solar wind tower is proved as effective in project ZEB@BAC Academy in Singapore, the sensation of thermal comfort shifted from "much too warm" to "comfortably warm" based on predicted mean vote and occupant survey during the operational time (Stephen Wittkope, 2015).

With reasonable thermal zoning and only used the air conditioning when it needed, 25% of operational energy can be saved based on the simulation result (Kessling, 2016).

Hybrid Cooling System: Design for Adaptive Thermal Comfort

a. Fundamental Theory for Hybrid Cooling Method

Apart from releasing the building from a conventional sealed fully-cooled mode, a significant and innovative approach in SDE4, known as the Hybrid Cooling, has also made a significant contribution in the aspect of increasing energy efficiency and thermal comfort.

The hybrid tempered method built on the theory of adaptive thermal comfort, which suggests a human connection to the outdoors and control over the immediate environment allows them to adapt to and even prefer a wider range of thermal conditions that are generally considered comfortable ("Adaptive Thermal Comfort…", n.d.). Hence, adaptive thermal comfort can deliver the same comfort as conventional cooling but with lower reliance on mechanical systems thus leading to the possibility to increase energy-efficiency. Contrary to the conventional cooling which is based on strictly controlled conditions, the adaptive comfort approach is taking into account thermal perception and behaviour of the users, requiring users to take active roles in controlling the indoor environment ("what is adaptive comfort," 2009).

Moreover, the innovative part of the hybrid cooling system is to take benefit out of the elevated airspeed, using ceiling fans to work with the air conditioning to circulate the cooled air. The definition of thermal comfort in tropical and subtropical regime suggests that a higher level of temperature and humidity are acceptable when combined with elevated air speed. That is because of the positive effect of air movement on both convective and evaporative heat losses from the human body and thus influence thermal comfort sensation. Research in the use of fans in tropical climates showed that tropically acclimatised people prefer slightly higher levels of air movement (Yang et al., 2015). Also, another theoretical analysis (Nicol, 2004) suggested that with the air velocity increases, the allowance of comfort temperature also increases (fig.17). Several field studies and environmental chamber studies in tropics provided evidence for occupants' preference for a warmer temperature with adaptive methods such as elevated air speeds (Sekhar, 2016). Therefore, the method of elevated air speed has long been proved and used in practice as a means to off-setting higher temperatures.

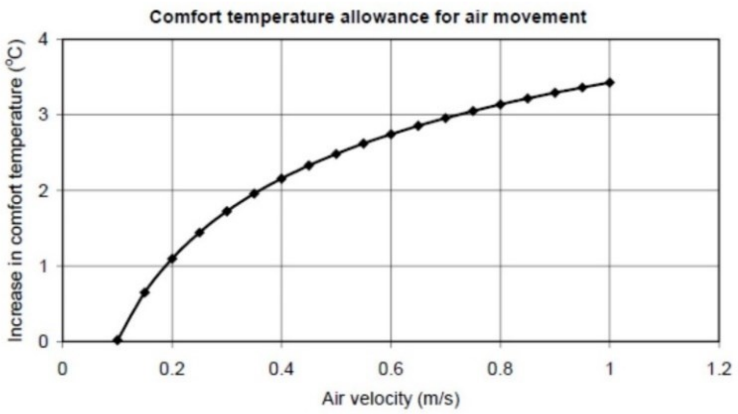

Figure 17. The Increase in Comfort Temperature for Different Air Speed. (Source: F. Nicol /Energy and Buildings 36 (2004) 628-637)

The hybrid cooling system in SDE4 has been carried out by adapting the Predicted Mean Vote thermal comfort model. Predicted Mean Vote (PMV) is critical for the design of SDE4 because it includes all the environmental parameters in a holistic way which define thermal comforts, such as air temperature, relative humidity, air velocity and radiant environment, together with two personal parameters, metabolic rate and clothing insulation. Updated in 2013, the ASHRAE Standard 55 includes a procedure for evaluating the cooling effect of elevated air speed using the Predicted Mean Vote for elevated air speed (PMVeas).

ASHRAE 55 thermal comfort chart (ANSI/ASHRAE Standard 55-2013) for elevated air speed showed that an operative temperature (a simplified measure of human thermal comfort derived from air temperature, mean radiant temperature and airspeed) up to 30ºC with an airspeed of 0.8m/s is possible for occupants feeling thermal comfortable, instead of 25ºC operative temperature at 0.1m/s airspeed. At an airspeed of 0.8m/s, the chart predicts comfort conditions at an operative temperature of 26.9ºC to 30.2ºC as presented in Figure.18, based on a summer clothing insulation value of 0.5clo (typical summer indoor clothing). Air speeds below 0.8m/s are allowed without local control, and 1.2m/s is possible with local control. However, some studies revealed that occupants' acceptable range of airspeed could exceed the upper limit denoted in the chart under high temperature.

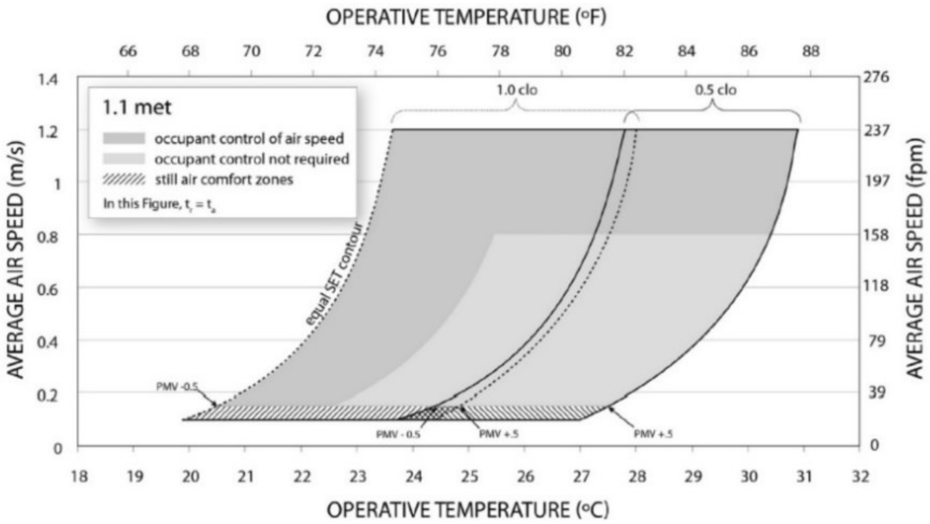

Figure 18. Acceptable Range of Operative Temperature and Average Air Speed for the 1.0 and 0.5 clo, at humidity ratio 0.01. (Source: ANSI/ASHRAE Standard 55-2013)

b. Comparison between Conventional System and Hybrid Cooling System

The conventional system in a tropical climate is that a sealed environment depends on air conditioning with ducted air supply and return system. It supplies rooms with pre-cooled air at around 14ºC to bring the indoor conditions down to 23-25ºC with about 55% relative humidity, which is very energy-consuming and typically accounts for up to 60% of a building's total energy load in a tropical country like Singapore. In addition, the conventional approach neglects the outdoor environmental conditions and reduces the indoor human comfort levels to only a single variable, setpoint temperature for the air conditioning. Obviously, the conventional way is against the target of climate-responsive net-zero energy.

Therefore, as a result of rethinking the use of air conditioning in tropics, the innovative hybrid cooling system adopted in SDE4 is a way in which the indoor conditions can be managed adaptively, taking into account various environmental paraments. Also, the hybrid cooling system is related to the idea of how to deliver higher comfort while consuming less energy. Therefore, the hybrid system is intended to work with the local climate to ensure that rooms would not be overly chilled, which accomplished through using air conditioning with elevated air speed from ceiling fans.

The system is designed as a single-pass system with no recirculated air as it continuously supplies fresh air to occupants. Cooled air at a higher temperature and humidity level than the conventional system would be supplied to rooms through ceiling-mounted ducts, which is augmented with elevated air speed from ceiling fans to reach to the “pleasantly cool” thermal comfort sensation (Kessling el at, 2015).

As for the technical details, the hybrid cooling system supplies rooms with pre-cooled air at 18^{0}C, 4^{0}C higher than the conventional system, to temper the indoor conditions into 27-28^{0}C operative temperature with 65% relative humidity. Elevated airspeed from ceiling fans can be controlled locally, from 0.7m/s up to 1.2m/s. Air temperature and humidity levels set higher than a standard air-conditioning system results in a less cooling load. Compared to the conventional air-conditioning system, the hybrid cooling system has a significant impact on EUI reduction.

During the design process, CBE Thermal Comfort Tool for ASHRAE Standard 55-2017 (Tyler, 2017) developed by Center for the Built Environment, University of California Berkeley has been used to test out the effectiveness of the method and its setting. An example model of the design studio, facing south with an occupant density of 4m^2 per person, has been used for the test.

In the conventional AC system, with an airspeed of 0.1m/s, humidity 55%, clothing level 0.5clo and metabolic rate 1.1met, the neutral temperature is found at around 25°C (fig.19) for the sedentary status. To reach the operative temperature of 25°C so that indoor conditions can move into the range of +/− 0.50 (PMVeas), representing an acceptable comfort level for more than 80% of occupants. The AC system has to cool down the air about 4°C, from air temperature 27°C to 23°C in the operational time. The cooling process of the conventional AC system demonstrates in Figure.20.

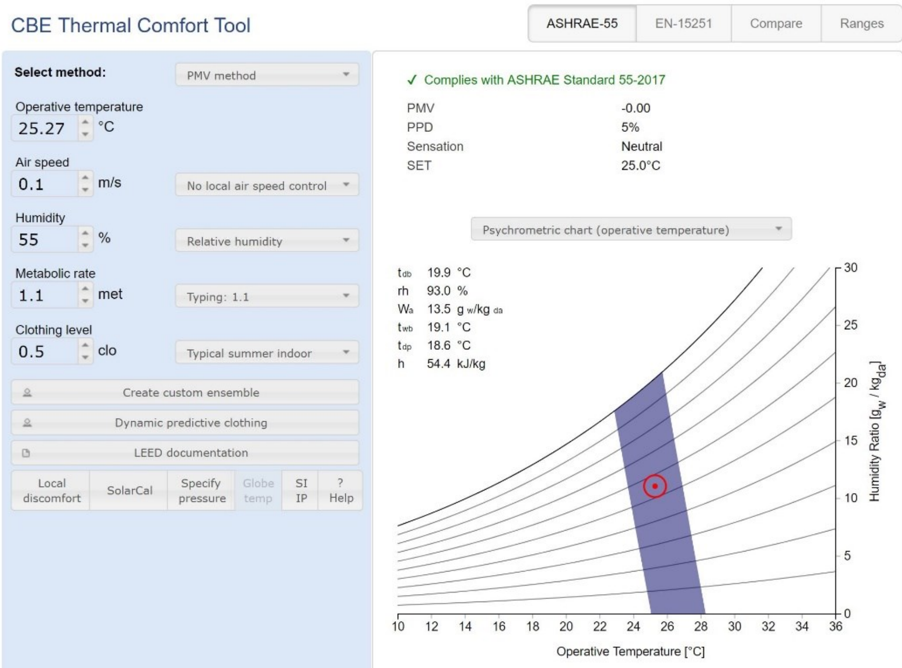

Figure 19. Environment Parameters for Conventional System in ASHRAE Standard 55. (CBE Thermal Comfort Tool for ASHRAE Standard 55, available at http://comfort.cbe.berkeley.edu/)

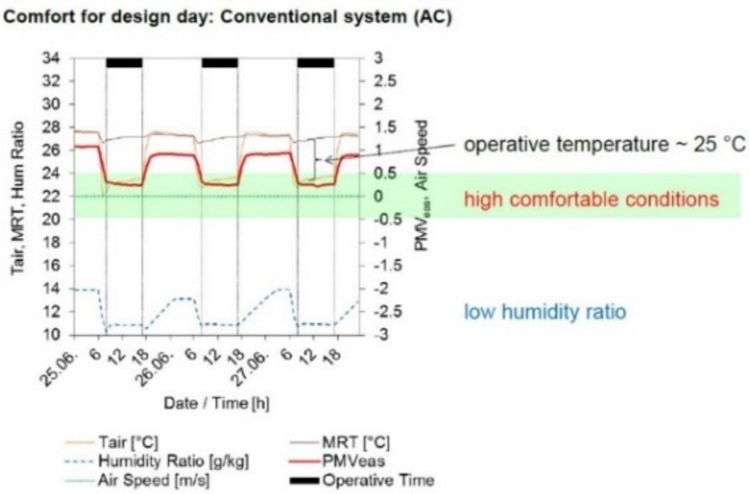

Figure 20. Cooling Process of the Conventional AC System. (Source: Wolfgang Kessling, 2016, Net Zero by Design, Transsolar Klimaengineering)

While when the experimental operative temperature is set at 28°C, the indoor thermal condition falls beyond the comfort zone with “still air” (0.1m/s) and humidity 65% as shown in Figure.21. However, without lower the operative temperature, the indoor thermal condition can move into the comfort zone (fig.22-23) by only increasing the airspeed to minimum 0.3m/s to maximum 0.8m/s (without local airspeed control). The cooling process of the hybrid system (fig.24) indicates that with the elevated air speed 0.7m/s, the air-conditioning system only need to cool down the air about 1°C to reach the range of -0.50/+0.50 (PMVeas). Compared with the conventional AC system, a significant amount of energy can be reduced by minimising the cooling load. Provided by the energy simulation result, by using the hybrid cooling system, around 36% to 56% reduction of energy use occurred (Kessling el at., 2016).

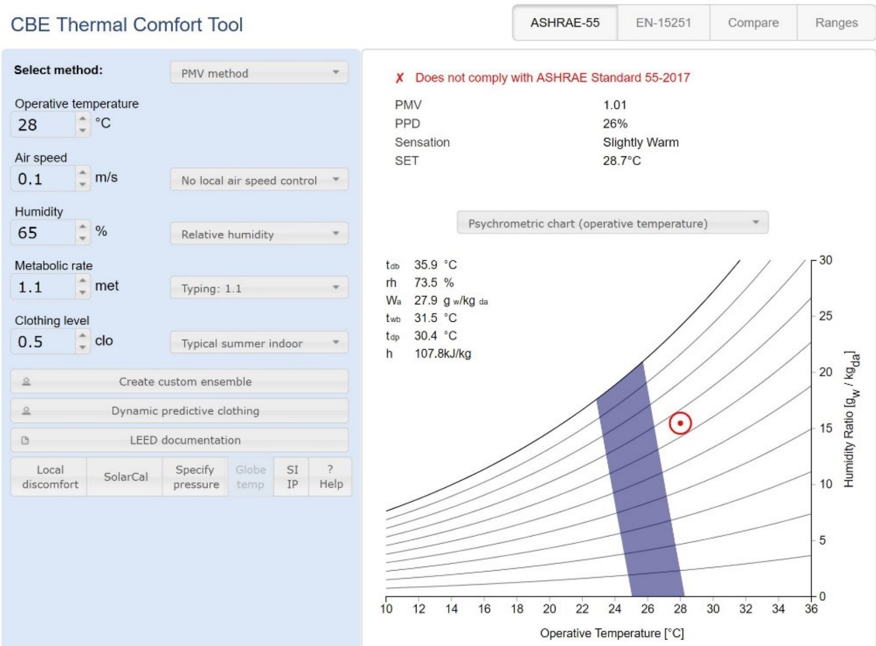

Figure 21. Testing Environment Parameters for Hybrid Cooling System in ASHRAE Standard 55. (CBE Thermal Comfort Tool for ASHRAE Standard 55, available at http://comfort.cbe.berkeley.edu/)

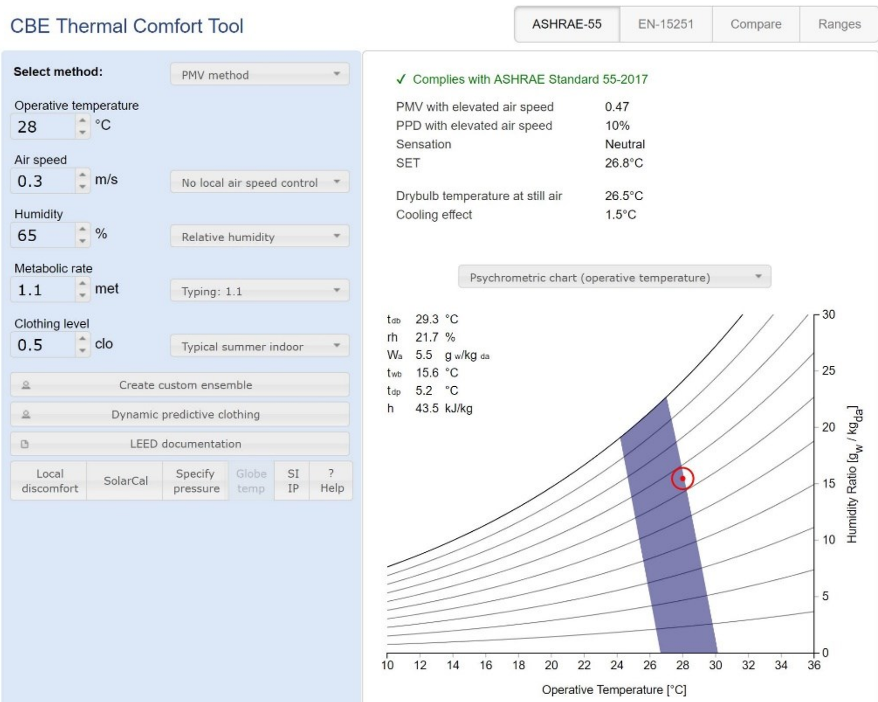

Figure 22. Testing Environment Parameters for Hybrid Cooling System in ASHRAE Standard 55. (CBE Thermal Comfort Tool for ASHRAE Standard 55, available at http://comfort.cbe.berkeley.edu/)

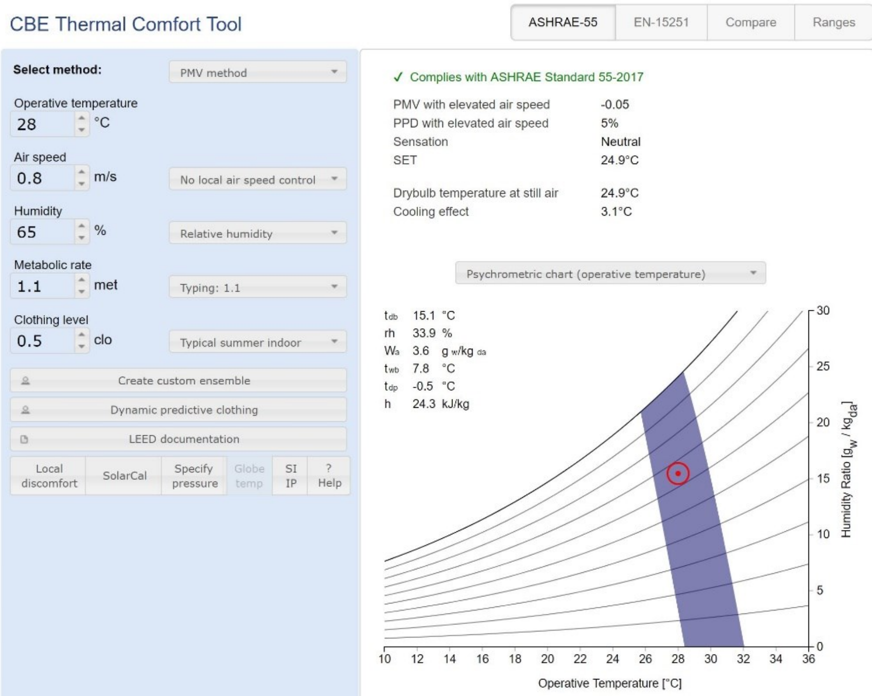

Figure 23. Testing Environment Parameters for Hybrid Cooling System in ASHRAE Standard 55. (CBE Thermal Comfort Tool for ASHRAE Standard 55, available at http://comfort.cbe.berkeley.edu/)

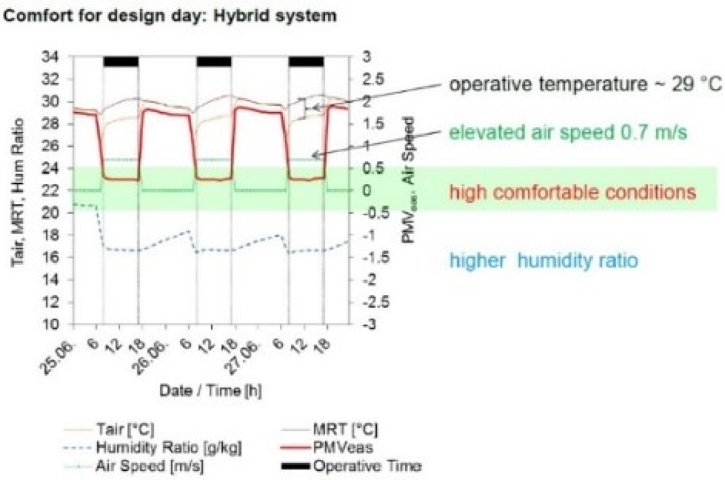

Figure 24. Cooling Process of the Hybrid Cooling System. (Source: Wolfgang Kessling, 2016, Net Zero by Design, Transsolar Klimaengineering)

Subjective studies with users in SDE4 were conducted to examine the impact of air movement and temperature on the aspect of thermal comfort under hot and humid condition. Preliminary results showed high levels of users acceptance for conditions where the temperature ranges between 26-28°C with a relative humidity of 60-65% (NUS, *SDE Zero*, 2018). Not just in SDE4, elevated air speed method also has been proved by other researches. For example, a laboratory-based study (Chow, 2010) conducted in Hong Kong evaluated the thermal sensation of people with elevated air speed, temperature, and humidity in the air-conditioned environment, they noted that thermal comfort was possible for the entire range of 25–30°C and relative humidity of 50-85% with bodily airspeeds in the range of 0.5-3m/s. In this respect, combining air velocity with a higher room temperature may provide a global energy-efficient solution (Schiavon & Melikov, 2008).

c. Indoor Thermal Climate and Thermal Comfort

Providing control over the indoor environment to users is another key factor to approach adaptive thermal comfort. Also, it reflects the belief of designers, which a building need not deliver the same conditions all day to everyone.

Research indicated that the presence of user control is widely accepted to affect the occupant's satisfaction (Hellwig, 2014). The more transparent, simpler and responsive the ventilation system, the better the occupant feels through adaptive comfort. Occupants who enjoy more control of their environment may tolerate a wider range of indoor temperature. Moreover, adaptive comfort requires educated occupants with the awareness of controlling their environment and less strict dress code for occupants to adjust themselves to indoor conditions. Therefore, occupants in SDE4 not only are able to control the air velocity by adjusting the fan speed, but also have control over the indoor illuminance level by adjusting roller blinds and artificial lighting, air temperature via thermostat, radiant temperature by adjusting the louvre screens and roller blinds, and natural ventilation via operable windows.

Lighting System

The building is designed to maximise natural daylighting so that to minimise the energy use for artificial lighting. As such, light shelves and shading devices located on the south side of the building together with fritted glazing permit most of the rooms to be lit sufficiently without the artificial light on sunny days. Moreover, light tubes are utilised to further light up the top floor. On the other hand, intelligent controls over artificial lighting are adapted to reach optimal management of the lighting system. An array of devices such as sensors, meters and controllers have embedded in SDE4. Daylight sensors are installed to monitor natural daylight and automatically dim or switch the artificial lighting whenever needed based on the environmental light level. Occupancy sensors override the lighting system with automatic setbacks when rooms are unoccupied.

3.1.3 Material Choices

The main building components and materials used in the SDE4 is summarized in Table.5. One of the key features of SDE4 is the intended use of the raw and natural characteristics of the materials, which expressed in the use of exposed concrete, steel and perforated metal. All materials are left as raw, delicate, and pure as possible. Columns are cast in place with 100% recyclable light-weight formworks made of spiral bands of Kraft paper, aluminium and polyethene.

Table 5. The main building components and materials used in SDE4.

Building Parts	Building Materials
Foundations	Isolated pile foundation reinforced concrete
Superstructure	cast-in-place reinforced concrete framework, 600mm diameter round column, rectangle concrete beam and part of the area used thicken floor slab, the flat slab structure, to replace the usage of beams
Outer Wall	Perforated aluminium shading panels on East and West side, partly North side. Glass curtain wall on south side (solar control low-E glass)
Inner Wall	Glass curtain wall for teaching area, 100/200mm concrete wall for auxiliary rooms
Floor Structure	300/400/500mm thickness concrete floor slab
Roof	Light concrete slab
Technical Equipment	Ductwork for cooling, ventilation and water, FCU units, lighting and electrical system, CHP unit, roof-mounted photovoltaic, elevator

The foundations are estimated to be designed with isolated reinforced concrete pile foundation. It should be noted that the amount of steel rebar in the reinforced concrete is based on estimation followed by the norms of structure design.

The superstructure adopted the reinforced concrete framework, building up by round concrete columns with rectangle concrete beams for some area like auxiliary area. While in some open area like studios and plaza, it adopted the flat slab structure in order to keep a clean appearance, which omitted the use of beams by thickening the floor slab.

The walls are characterised predominantly by the glass curtain walls, whilst thin concrete walls are used for axillary area and technical shafts. Considered the hot-humid climate in Singapore, there is no insulation material needed in the building envelope.

The floor structure is characterised by concrete slabs with simple screed, and no additional flooring is applied. The roof structure is also constructed with concrete and has the PV system installed on the top.

3.2 Operational Energy Use and Related Emissions

A target was set for SDE4 to be a net zero energy building with total energy use of not more than 75 kWh/m^{2}y (Kessling, 2016). Target has been achieved by introducing a range of energy efficiency measures explained in chapter 3.1, including climate-responsive building configuration and envelope, hybrid cooling system and intelligent building management system.

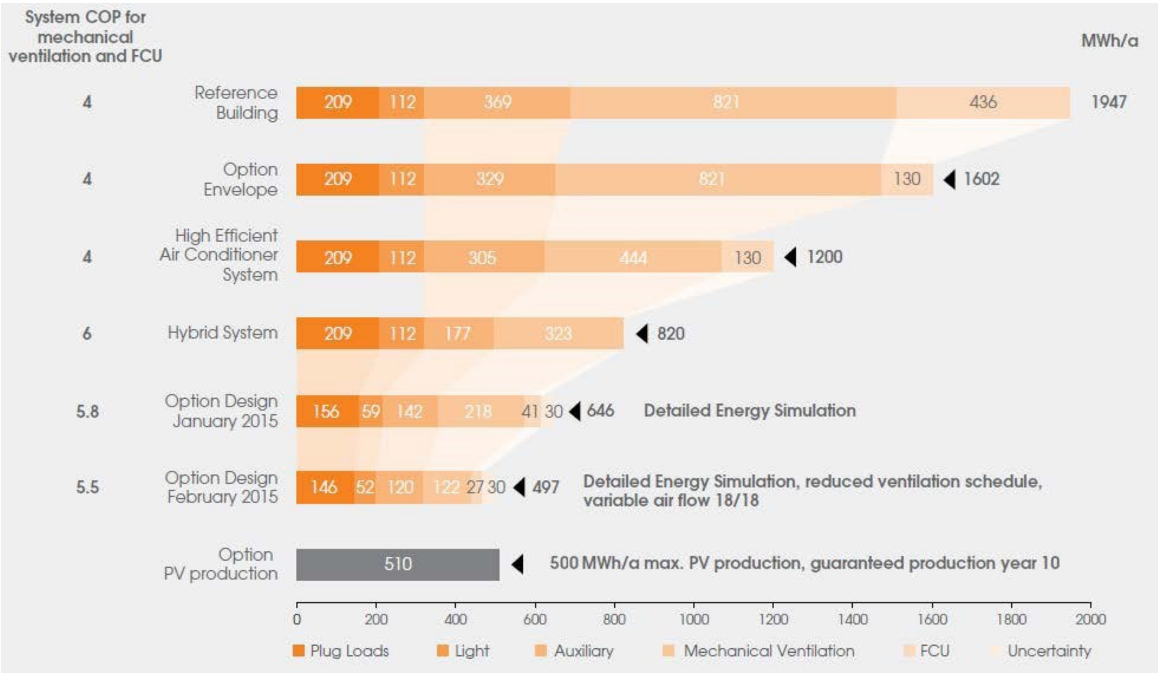

Figure 25. Step-by-step Reduction on Energy Consumption. (Source: Wolfgang Kessling, 2016, Net Zero by Design, Transsolar Klimaengineering)

Figure.25 presents the energy reduction step by step thanks to different energy-saving approaches (Kessling et al., 2016):

1. Benchmarking against a reference building

2. Optimizing the building envelope: selective façade glazing and optimized shading system

3. Optimizing air conditioning system: high-efficient supply and return air system with sensible and latent heat recovery

4. Adopting hybrid cooling system for adaptive thermal comfort with elevated air speed

5. Detailed modelling of thermal zones, optimized daylight and artificial lighting

6. Optimized operation concepts: increased operation with natural ventilation, VAV 18/18, reduced plug loads, invest in high-efficient chiller with total system COP > 5.5

3.2.1 Energy Demand

Energy demand for different building services in SDE4 (heated floor area of 8588m^2) is presented in Table.6. The energy demand represents the annual net energy need of the building operation. Since SDE4 just opened in January 2019, there is a lack of measured data for annual energy consumption. Therefore, in this study, the annual delivered energy to the building adopted the theoretical results of energy demand assessed by the dynamic energy simulation tool. Detailed values are obtained from the public domain, a publication from NUS and SDE4's energy consultant Transsolor Energietechnik.

The total calculated annual energy demand of SDE4 is 497 MWh/yr or 57.9 kWh/m^{2}y, where plug loads and ventilation/cooling account for the largest amount of energy demand.

Table 6. Energy Consumption in SDE4.

SED4 (BRA= 8588 m²)	**Energy demand**	
	MWh/yr	**kWh/m²yr**
Plug Loads	146	17
Lighting	52	6
Auxiliary	120	14
Mechanical Ventilation	122	14.2
Fan Coil Unit	27	3.1
Uncertainty	30	3.5
Total	**497**	**57.9**

3.2.2 Energy Supply System

To meet demand with on-site energy production, SDE4 mainly relies on the extensive roof-mounted solar photovoltaic (PV) system, consisting of 1225 PV panels (2090m^2) installed on its horizontal roof. In the calculation of the energy production from the PV system, 16.6% PV efficiency for guaranteed ten production years is used. Combined with local solar radiation data (the horizontal solar radiation in Singapore is about 1650 kWh/m²y), about 239 kWh of renewable energy can be produced by every square meter of PV panels per year. Therefore, the on-site horizontal roof-top PV system is capable of generating around 500 MWh/a (499,510 kWh/yr or 58.16 kWh/m^{2}y) of electricity every year (Kessling, 2016).

SDE4 is also connected to the University's utility grid, with which it exchanges electrical power when there is a surplus or deficit of energy demand. When there is insufficient solar energy, the building will draw energy from the power grid. Based on the simulation, SDE4 not only has the ability to meet its own energy needs for the next 20 years, but it will also generate an energy surplus in the first ten years.

3.2.3 CO_2 factor for Grid Electricity in Singapore

Singapore, for a long time, relies heavily on an energy model powered by imported fossil fuel. A majority of GHG emissions was generated from the combustion of fossil fuels for energy production in Singapore. Electricity Grid Emission Factor, which measures emissions per unit of electricity generated, is used to indicate the carbon intensity of electricity generation. In order to reduce the GHG emission from energy production, since 2000, Singapore has gradually shifted its energy model from carbon-intensive fuel oil to natural gas, the cleanest form of fossil fuel, which has lower carbon content per unit of electricity generated. However, there are limits to having a continuous reduction in the future by only cutting down the use of fossil oil since natural gas already constitutes more than 95% of the fuel mix for electricity generation today. For this reason, there is a need to put a conscious effort into increasing renewable energy production. Among the alternative energy options available today, solar energy offers the most promising opportunity for Singapore. By launching the SolarNova programme, solar power generation has increased and the total installed solar PV capacity in Singapore is currently about 47-megawatt peak for both residential and non-residential areas (NCCS, 2017).

As illustrated in Figure.26, grid emission factor in Singapore occurred a reduction in the recent decade and remained relatively constant at 0.42 kgCO_2/kWh in 2017 under years' effort (Singapore: Ministry of Trade and Industry, 2018). Since the renewable energy generation was only 0.8% of the total energy generation capacity in 2018 (EMA, Singapore Energy Statistic 2018), the CO_2 factor for electricity can be expected to have a continuous reduction in the future with the increasing renewables production area and technology.

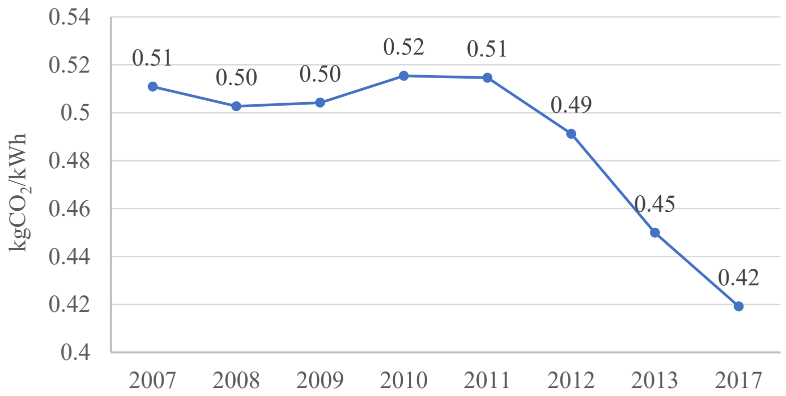

Figure 26. Carbon Intensity of Electricity Generation in Singapore. (source: DATA.GOV.SG)

Compared with the Norwegian grid mix of electricity, around 0.04 kgCO_2/kWh, Singapore's electricity production produces 10 times more GHG emission than that in Norway.

On the basis of currently available information mentioned above, the emission factor of 0.42 kgCO_2/kWh is adopted in the calculation of the emission from the operation stage using electricity from the electric grid, also the calculation of the 'negative' (balancing) emission generated by the PV system in the operational stage.

3.2.4 CO_2 Emissions from Operational Energy Use

The carbon emissions from the operational stage are calculated by using the operational energy use, energy produced by the PV system and CO_2 factor for the grid mix. Locally produced electricity from the PV system is considered to replace electricity imported from the grid, and it is used to offset the total CO_{2eq} emissions.

Given the emission factor of 0.42 kgCO_2/kWh for electricity in Singapore, the total amount of operational CO_2 emission is the total annual energy demand (57.8 kWh/m^{2}y) multiplies by the emission factor, which gives the value of 24.3 kgCO_2/m^{2}y. While CO_2 emission for onsite PV energy production can be calculated by the PV production (58.1kWh/m^{2}y) multiplies by the "negative" emission factor, which gives the value of −24.4 kgCO_2/m^{2}y.

3.3 Embodied Emissions

The calculation of embodied emissions from materials in SDE4 has been conducted and presented in this chapter. The calculations are based on the principle of life cycle assessment analysis.

The goal of the calculation for the original design is to evaluate and thus provide an overview of the embodied emission in materials. Also, key contributors to the CO_{2eq} emissions can be revealed from the results, which provides sufficient basis to propose design alternative aimed for minimising the CO_{2eq} emissions thus to reach zero emission balance.

The embodied emissions calculations of SDE4 are performed using the LCA online software, One Click LCA together with the ZEB tool, an Excel-based tool developed by the Norwegian ZEB research centre for life cycle GHG emissions calculations. One Click LCA developed by Bionova Ltd. is third-party verified by the Building Research Institute against EN 15978, ISO 21931-1, ISO 21929-1, EN 15804, EN 15942 and ISO 21930 standards. Also, the software licenses more than 10,000 construction datasets from all around the world, including the Ecoinvent database.

3.3.1 Functional Unit and System Boundary

The functional unit of this calculation is 1m^2 of heated floor area over the 60 years estimated lifetime of the building. The results are presented on an annual basis, where the total amount of emission for 1m^2 functional unit is divided by 60 years. The impact assessment is the global warming potential for the 100-year perspective indicator (GWP100) calculated in $kgCO_{2eq}$ (Methodology IPCC 2013). The system boundary for this study is limited to the material product stage (A1-A3), including the transportation of materials to the building site (A4). Also, the replacement of new materials over the lifetime of the building (B4) has been included. The related life cycle stages included in this study of SDE4 are shown in Figure.27.

System Boundary NS-EN 15978:2011																
A1-3 Product Stage			A4-5 Construction Process Stage		B1-7 Use Stage							C1-4 End of Life				D Benefits and loads
A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to building site	A5: Installation into building	B1: Use	B2: Maintenance (incl. transport)	B3: Repair (incl. transport)	B4: Replacement (incl. transport)	B5: Refurbishment (incl. transport)	B6: Operational energy use	B7: Operational water use	C1: Deconstruction / demolition	C2: Transport to end of life	C3: Waste Processing	C4: Disposal	D: Reuse, recovery, recycling
x	x	x	x					x								

Figure 27. System boundary, x indicated modules included in the embodied emission calculation.

Considered that Singapore relies on imported materials resources from the international market, the emissions from materials transportation to the building site (A4) are expected as an influential factor to the complete GHG emissions balance which made it meaningful to be included in the study. In addition, because the calculations are conducted for a 60-years lifetime, there would be a certain amount of materials that need to be replaced. Hence it is also reasonable to include emissions from replacement (B4) to show the whole picture of Singaporean building GHG emission profile.

The building elements included in the calculations (table.7) are comprised of building envelope, building services such as ventilation/cooling and lighting, energy generation system and other installation like elevators.

Table 7. Building components included in the calculation.

Building parts	Building envelope	Building services	Power supply	Other Installations
Building components	21 Groundwork and foundation	36 Ventilation and air conditioning	49 PV system	62 Passenger and goods transport
	22 Superstructure	44 Lighting		
	23&24 Walls			
	25 Floor structure			
	26 Outer roofs			
	28 Stairs and Balconies			

3.3.2 Life Cycle Inventory Data

Life cycle inventory contains the types and the quantity of material inputs for LCA calculation. For the building SDE4, there is, unfortunately, no available detailed material inventory. Hence, the approach took here is to build a mock-up REVIT model from dimensioned drawings (retrieved from Serie Architects.) then obtain the quantity of materials from material takeoffs. The material types are referenced with on-site observations.

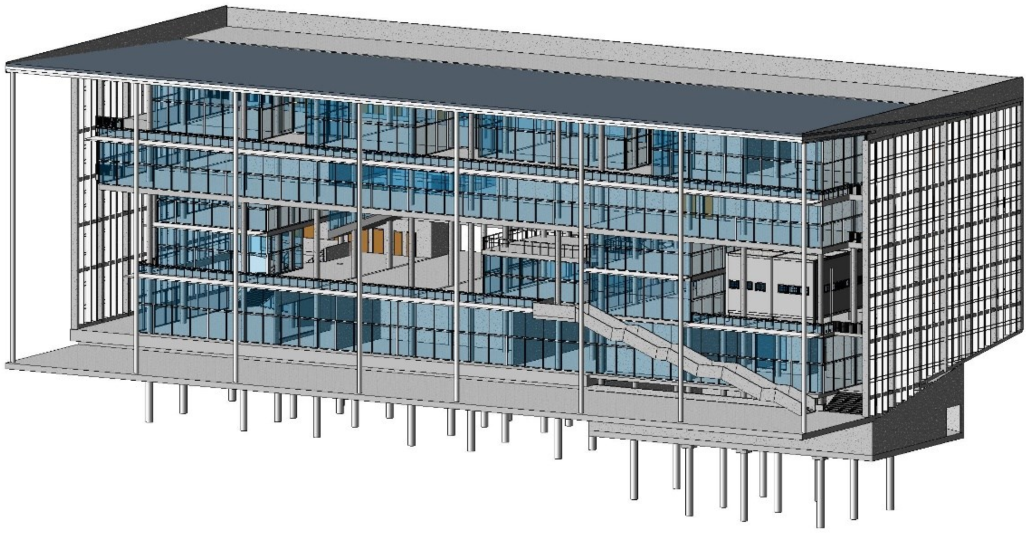

Figure 28. Mock-up Revit Model of SDE4.(Drawing source: Serie Architects, retrieved from https://www.serie.co.uk/projects/8/school-of-design-environment#13)

Area or volume of the construction materials, including foundation, structure, walls, floors and roof, have been exported from the REVIT model to Excel and then these data have been used in the calculation of the embodied emissions. The whole life cycle inventory tables can be found in Appendix 2. A summary of the building components and materials can be found in Table 5.

It should be noted that, because of the limitation on available data, the materials inventory extracted from the mock-up REVIT model only represents the main construction of the original SDE4, and lots of detailed construction information are missing. For instance, there is no available information on the foundation so that the typical type of foundation, the isolated pile foundation, has adopted in the Revit model for SDE4's construction situation. Also, the roof construction has been simplified due to lacking information. Only the structural concrete layer is included in the calculation. The roofing membrane and drainage layer are not considered.

For the technical system, part of the technical equipment and ductworks for ventilation/cooling, lights and fans are included in the material inventory. The data are obtained from onsite observation thanks to part of the technical equipment is installed on the exposed ceiling. The length and diameters of the duct have been drawn down and then calculated the material quantity. Also, the quantity of the lights and fans in studios and classrooms has been counted on site. However, the current data only represent a portion of the complete technical material inputs because some part of the technical system is hidden, and rooms like offices, labs are inaccessible.

The renewable energy system, a large area of photovoltaic panels on the roof, also contributes lots of material inputs and embodied emissions. Because there is no information to specify the type of PV panels used in SDE4 directly, the PV type is estimated by its efficiency and power (Doshi,2017 & Luther, 2013). Hence, the monocrystalline silicon cell type with high nominal efficiency around 14-21.5% is chosen. The generic value of GHG emissions for the mono-si PV panel is around 210 kgCO_{2eq}/m^2. In addition, the amount of materials and emissions from the inverter and mounting system are estimated based on related researches. The emissions from the inverter can be estimated from the total power of 500kW that it needs to handle, and this gives a value of 14400 kgCO_{2eq}/unit. For mounting system, Kristjansdottir et al. (2016) presented that the simplest PV mounting system showed the emission of around 10 kgCO_{2eq}/m^2, whilst the more complex systems showed emissions from around 20 to 25 kg CO_{2eq}/m^2. In this calculation, the median value of 17.5 kgCO_{2eq}/m^2 is adopted.

Because specific product information is not available, generic data are adopted in order to calculate the embodied emissions from materials (A1-A3), which sourced from the EcoInvent v.3.1 database and has been accessed via ZEB tool and LCA software, One Click LCA.

To calculate emissions from materials transportation (A4), it is needed to identify the place of production since most of the raw materials in Singapore are imported from the international market. For example, data updated in 2016 showed that 48.6% of the concrete is imported from Malaysia, 14% from China and 11.4% from Japan. Relevant data are retrieved from the global trading platform, Tridge (available at www.tridge.com). The places where the main construction materials sourced from are summarized in Table.8, together with the transportation mode and travelled distance. The travelled distance has been calculated using Google Maps and Sea Rates. Among multiple locations of the manufacturers and freight ports, the closest ones to Singapore are chosen. For those materials cannot identify the place of production, a standard 500km estimate of travelled distance is adopted.

Table 8. Data inputs for the calculation of transportation emission (A4).

Material	Country imported from	Distance to site (km)	Transportation mode
Concrete	Malaysia	60	Lorry
steel bar	China	2767	Ship
Galvanised steel	China	2767	Ship
Aluminium	Malaysia	50	Lorry
Glass for curtain wall	United States	18738	Ship
Technical system	-	500	Truck

In addition, the amount of replacement of materials (B4) over the life cycle of the building can be calculated using the following formula introduced in Norwegian ZEB guideline (Fufa et al., 2016):

Number of replacements of product (j) = E [ReqSL/ESL(j) -1].

Whereby, *ReqSL* is the required service life of the building, *ESL* is the estimated service life, *j* is the product, *E* rounds the factor to the nearest whole integer. Here, the number of replacement of products used in the calculation are without rounding up to a higher integer.

Because most of the building components lacked specific product type, the estimated service life of each component is based on average values referred to typical life spans recommendation for building components sourcing from UK RICS Carbon Statement and Preventive Maintenance Guidebook by Lawrence J. Schoen, P.E., Fellow ASHRAE. Detailed data are presented in life cycle inventory table in Appendix 2.

For the replacement scenario (B4) of PV modules, a 50% reduction of the environmental impacts relative to the A1-A3 impacts is used (Fufa et al., 2016). Referred to Norwegian ZEB definition guideline, this approach is connected to the expected reduction of materials use and increase in PV module efficiency. It is believed that a continuous development of the new technology in terms of emissions reduction will occur in the PV industry (NREL, 2016).

3.3.3 Results

The embodied emissions calculations are performed and presented for SDE4 in this chapter. The embodied emissions for life cycle stages (A1-A4, B4) and building component category are shown in Table.9.

Table 9. Embodied emissions for A1-3, B4 life cycle stage and building elements.

Scope	
Databases Used	EPDs, Ecoinvent v3.1, One Click LCA
Lifetime of Construction (years)	60
Heated floor area - BRA (m^2)	8588
Functional Unit	$1m^2$ over a lifetime of 60 years
Building Site	Singapore

	A1 - A3 (tonne CO_{2eq})	**A4 (tonne CO_{2eq})**	**B4 (tonne CO_{2eq})**	**Total (tonne CO_{2eq})**	**$kgCO_{2eq}/m^2y$**	**Contribution**
20 Building, general						
21 Groundwork and Foundations	852	32	0	884	1.71	14.2 %
22 Superstructure	799	14	0	813	1.58	13 %
23/24 Walls	558	56	212	826	1.6	13.2 %
25 Floor Structure	1913	61	0	1974	3.83	31.6 %
26 Outer Roof	161	10	0	172	0.33	2.8 %
28 Stairs and Balconies	22	1	0	23	0.04	0.4 %
30 Heating, Ventilation and Sanitation, general						
36 Ventilation and Air Conditioning	244	1	244	489	0.95	7.8 %
40 Electric Power, general						
44 Lighting	44	0.2	89	133	0.26	2.1%
49 PV system	541	0.3	350	891	1.73	14.3 %
60 Other Installation, general						
62 Passenger and Goods Transport	16	0.2	16	32	0.06	0.5 %
tonne CO_{2eq}	5150	176	911	**6237**	**12.1**	
tonne CO_{2eq}/yr	86	3	15			
$kgCO_{2eq}/m^2$	599.7	20.6	106			
kgCO2eq/m2y	**9.99**	**0.34**	**1.77**			
Contribution	**82.6 %**	**2.8 %**	**14.6 %**			

The total embodied emissions from A1-A4 and B4 of SDE4 is 6237 tonne CO_{2eq} for the whole building with a 60-year lifetime or 12.1 $kgCO_{2eq}/m^2y$. However, since the material inventory is incomplete, it can be predicted that the total embodied emissions would be higher for the realistic case. The majority of the emissions come from initial material inputs (A1-A3), accounting for 82.6% of the total embodied emissions. 14.6% of emissions come from the use phase replacements (B4), while 2.8% of the emissions are contributed by transporting the materials to the building site (A4).

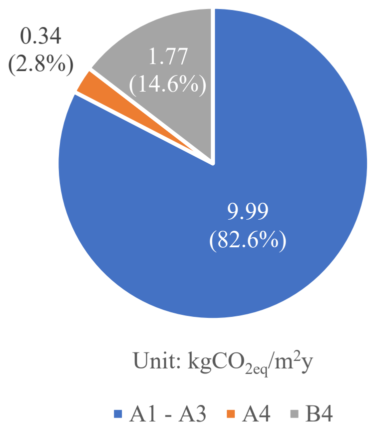

Figure 29. The ratio between embodied emissions from stage A1-A3, A4 and B4 in SDE4.

Sourced from a study done by Wiik et al. (2018), the average emissions from transportation (A4) in ZEB pilot buildings is around 0.183 $kgCO_{2eq}/m^2y$. Compared with SDE4, the transportation emissions from SDE4 is about 1.86 times more than Norwegian ZEB projects, with a value of 0.34 $kgCO_{2eq}/m^2y$.

Moreover, the embodied emissions from each building component category are illustrated in Figure.30. The results show that the floor structure is the most important contributor to GHG emissions (31.6%) followed by PV energy system (14.3%), foundation (14.2%), walls (13.2%), superstructure (13%), ventilation and air conditioning (7.8%), roof (2.8%), lighting (2.1%) and stairs, elevators (<1%). It is interesting to note that the floor structure contributes to the largest amount of emissions because SDE4 adopted Flat Slab structure, thickened the floor slab in order to omit beams. It can be considered that floor structure is part of superstructure in this case. As the second largest emissions contributor, about 40% of the emissions from the PV system is due to the replacement of the PV panels.

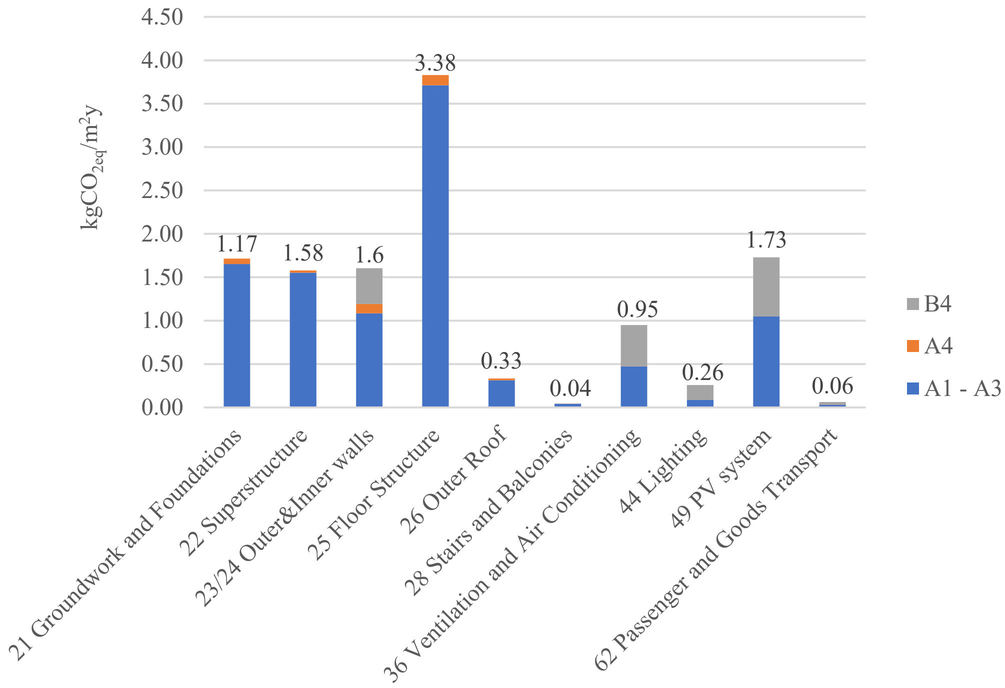

Figure 30. Embodied emissions from building elements.

In Figure.31, the emissions from the main material inputs and technical installations are shown. The results demonstrate that the concrete (34.5%), steel (27.1%) and PV system (14.2%) are the key drivers for the embodied material emissions and also the critical design drivers for reducing the material embodied emissions.

It is noted that the concrete and glass curtain wall has significant emissions from transport to site (A4), with 74% and 19.5% of total transport to site (A4) emissions, respectively. High transportation emissions from the glass curtain wall are because the glass panels are sourced from a producer in the United States.

In the replacement (B4) stage, the largest contribution of emissions come from the PV system (38%), following by ventilation system (26.5%), glass curtain walls (17.3%) and other technical equipment. The estimated service life for a PV panel is 30 years so that they would be replaced once in the lifetime of the building (60 years). It should be noted that here adopts the assumption that the panels would have a 50% reduction in its environmental impact in the future 30 years' time. While the inverters have a 25-year service life and would be replaced twice during the lifetime of the building.

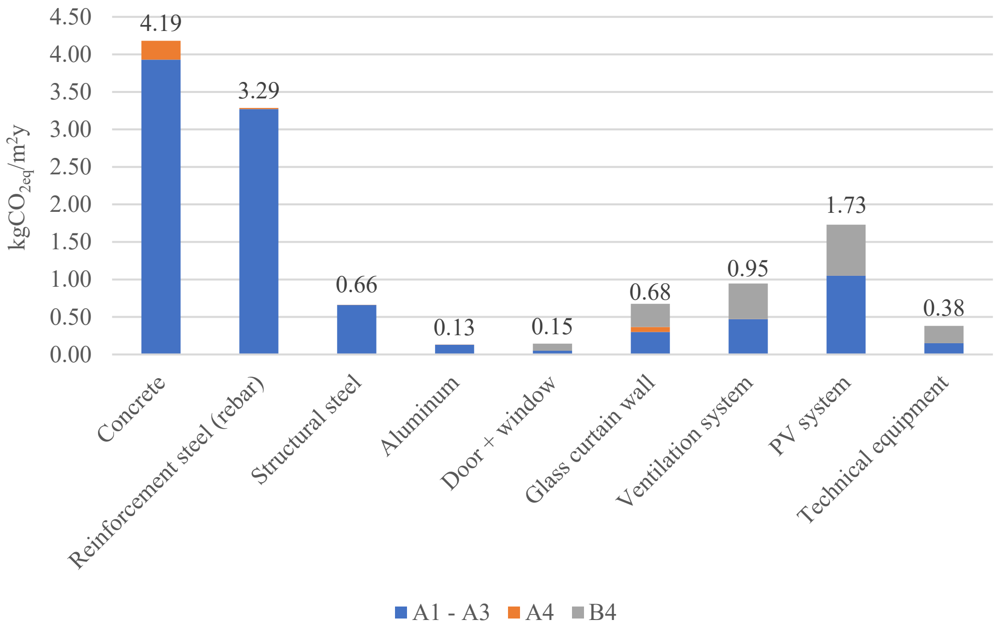

Figure 31. Distribution of carbon dioxide emissions from materials.

3.4 ZEB Balance

The definition of ZEB balance is about whether the greenhouse gas emission from the operational energy and materials (or also other lifecycle stages depending on the ambition level) in the lifetime of the building can be compensated with the renewable energy production. If the sum of ZEB balance is zero or negative, it represents the building has reached a ZEB balance. Its related GHG emissions have been compensated with the production of renewable energy. Otherwise, the building has failed to reach the ZEB balance with a positive sum. The ZEB balance has been calculated using the symmetric weighting approach (Sartori, 2012), which means that the same CO_2 factor is applied for both export and import of electricity.

Figure.32 presents the ZEB balance of total emissions and on-site energy production from the PV system for SDE4. The bar chart shows that operational emissions (B6) could be covered by onsite PV energy production. However, it also shows that the on-site PV energy production is far from enough to compensate for the materials embodied emissions. A ZEB balance with system boundary of operational emissions and materials embodied emissions is failed to reach for SDE4.

Table 10. ZEB balance for SDE4.

	$kgCO_{2eq}/yr$	$kgCO_{2eq}/m^2y$
Operational energy use emission	208342	24.26
Material embodied emission	103944	12.1
Local energy production (PV)	-209600	-24.41
ZEB balance	**102686**	**11.95**

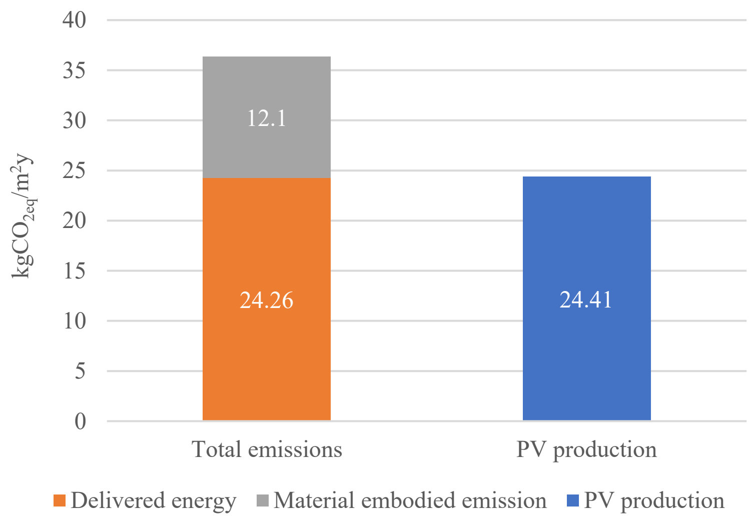

Figure 32. ZEB balance of SDE4.

Based on the calculation shown in Table.10, there is a need of 49% more renewable energy production to successfully cover the material embodied emissions so that to reach a ZEB-OM balance. To generate enough renewable energy to compensate for the materials embodied emission together with operational emissions, a total of 3164 m^2 of PV panels is required, which means around 1074 m^2 additional PV panels need to be installed onsite. Here it should be noted that the area is calculated based on the same background data as the horizontal rooftop PV panels. Larger area would be required for a vertical position like the façade area because of the angle and the incident radiation difference. Also, the additional material emissions from the additional PV panels and the mounting system did not account for.

Compared between different lifecycle stage, results show that the operational stage contributes the largest amount of the emission during the building's lifetime, accounts for about 66.7% of the total GHG emissions. While the embodied emission from materials only accounts for 33.3%.

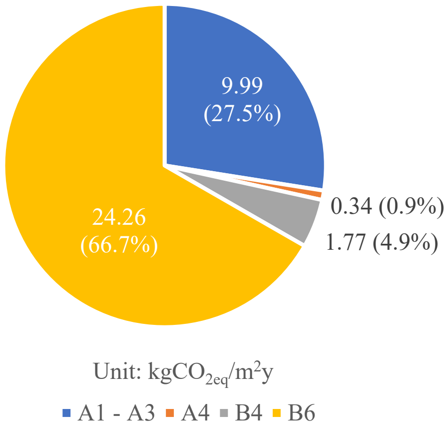

Figure 33. The ratio between embodied emissions and operational emissions.

On the contrary, in a study of Norwegian zero emission building case studies (Wiik et al., 2018) shown that the embodied emissions associated with the production and replacement of materials (A1-A3 and B4) is the largest contributor to total life cycle carbon emissions, contributing approximately 60-75% to total emissions, while the operational stage only contributes around 35-40%.

The reason for this different situation for the ratio between embodied emissions and operational emissions is because the GHG emissions from electricity in Singapore is much higher than the one in Norway. Experience from Norwegian study shown that the grid emissions of electricity have a significant effect on the share of embodied emissions and operational emissions.

Here a sensitivity analysis of the grid emissions factor for use stage is undertaken. The current grid mix in Singapore was recorded as 0.42 $kgCO_2/kWh$. Calculated with this value, the ratio of operational emissions to material embodied emissions is 66.7%: 33.3%. If a lower gird mix is applied, for example, the default CO_2 factors of 0.132 $kgCO_2/kWh$ employed by ZEB Research Centre, the ratio of operational emissions to material embodied emissions then changed to 38.7%: 61.3%. The result agreed with the general ratio appeared in ZEB pilot projects. It indicates that for very energy-efficient buildings and ZEBs, embodied emissions constitute a significant or even dominant share of total GHG emissions. Also, it highlights the importance of addressing the material embodied emissions.

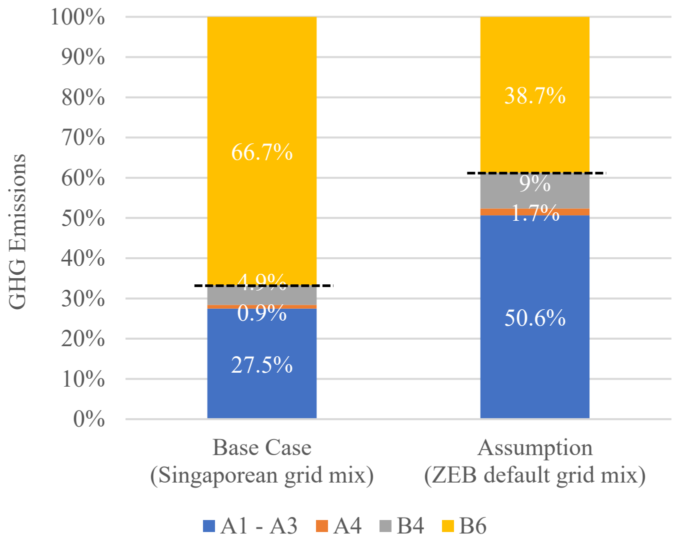

Figure 34. The ratio of operational emissions to material embodied emissions applied Singaporean grid mix and ZEB default grid mix. (The dotted line indicates the proportion of emissions that belong to the material embodied emissions)

This ZEB balance highlights that further measures are required to reduce the material emissions, to improve the efficiency of energy use and to increase onsite renewable energy production, in order to reach a zero-emission balance. Especially for Singapore, the emissions from materials need to be addressed together when increasing the energy use efficiency.

4 Findings

In this chapter, potential strategies aimed for improving the building sustainability in terms of GHG emissions are discussed. Strategies including energy efficiency improvement, materials embodied emissions reduction and renewable energy production increment are presented.

Thereinto, the main focus of this research is on reducing embodied emissions from materials. Firstly, even though the largest share of GHG emissions is contributed by operational energy use, SDE4 still represents a high-efficient building in terms of energy use in tropics. The energy-efficient design approaches initiated in SDE4 have already set an example and provided experience to future projects. Hence, in the case of SDE4, the impact of improvement for reducing the embodied emissions from materials would be much more significant compared to operational emissions. Secondly, the operational emissions are largely affected by the local grid emissions. Lastly, currently in Singapore there is no consideration for material choices in terms of embodied emissions during the early design phase, which makes it interesting to find out what would be the environmental impact of the materials if it were taken into consideration.

4.1 Strategies for Optimised Net Zero Emission Design in Tropics

4.1.1 Improve the Energy Efficiency of Building Operation

Referred to the EEI target set in the SLE roadmap by BCA, buildings are expected to reach improvements in the EEI by 80% over 2005 industry levels by 2030. For an office building, the specific target is the energy use should equal or less than 50 kWh/m^2/yr (BCA, *Super Low Energy Building Technology Roadmap*, 2018). And the average energy use of office buildings is around 221 kWh/m^2/yr. Compared to the EEI target, SDE4 has almost reached the SLE roadmap target set for 2030 with the EEI of 57 kWh/m^2/yr. Also, SDE4 achieved a 74% of energy reduction compared to conventional buildings in 2018 levels. It indicated that SDE4 currently represents a high standard in terms of building energy efficiency in Singapore.

As a zero-energy building, the practical energy-efficient approaches adopted by SDE4, such as the hybrid cooling system, provided a successful example for follow-up projects.

Besides the approaches already applied in SDE4, there are several technologies supported by researches to improve air conditioning in tropics. For instances, separate dehumidification and cooling functions; develop highly effective desiccant membrane to remove humidity in air conditioning with less energy. These innovations could achieve more than 40% of the energy savings on air conditioning (BCA, SLEB roadmap, 2018).

Moreover, a significant impact on electric consumption is strongly connected to user behaviour (Paone, 2018). Effective user education on building operation can help to improve the efficiency of energy use. Especially in NZEB buildings, the education level (their understanding on sustainability and how the building concept works) of the occupants has an increasing impact on if buildings can function in the way like it has been designed to. Therefore, getting occupants on board would be a smart way to help reducing building energy use.

Furthermore, the electric plug load also needs to be addressed for its increasingly significant impact. For example, artificial lighting could also be optimised using efficient installations and sensor control, as well as by promoting daylighting.

4.1.2 Optimised Material Choices

With the original design, SDE4 has been labelled as a net-zero energy building. The onsite-produced renewable energy, by only using the flat roof for the PV system, is just enough to compensate for the operational emissions in an entire year. When the embodied emissions from materials are also considered, it is challenging to reach a zero ZEB balance with the current level of renewable energy production and high embodied emissions profile.

Hence, it entailes more attention to the material choice and embodied emissions reduction approach. According to the study of Jelle et al. (2017), multiple strategies can be implemented for reducing the materials embodied emissions, as listed below:

1. Reduce the amount of materials used
2. Reuse and recycle materials
3. Select materials with low embodied emissions
4. Source local materials
5. Choose durable materials

Combined these general strategies with the result analysis of the material embodied emissions from SDE4, specific potential approaches suited for the current situation in Singapore are discussed.

To understand the impacts of the new material choices or design optimisations, sensitivity analyses are undertaken for the material embodied emissions. Improvements are quantified by showing the comparison of embodied emissions with the base case.

4.1.2.1 Select the Low Carbon Concrete or Precast Elements

The LCA assessment of SDE4 shows that 34% of the total embodied emissions are contributed by concrete, and 27.2% comes from the steel rebar for concrete. As the main construction material in Singapore, the high carbon emissions from concrete needs to be addressed in order to mitigate the total emissions from the building sector.

Since the manufacture of cement contributes the majority of the GHG emissions from concrete production, a new strategy used supplementary cementitious materials to partially replace cement so that to reduce the total emissions, i.e. so-called low carbon concrete. The concrete structure design may be further optimized by adopting low carbon concrete.

The type of concrete chose in the calculation for the base case is conventional concrete with high embodied emissions (range from 238 $kgCO_2/m^3$ to 386 $kgCO_2/m^3$ based on different strength levels). To investigate the impact of adopting low carbon concrete, a sensitivity analysis is undertaken and presented in Figure.35.

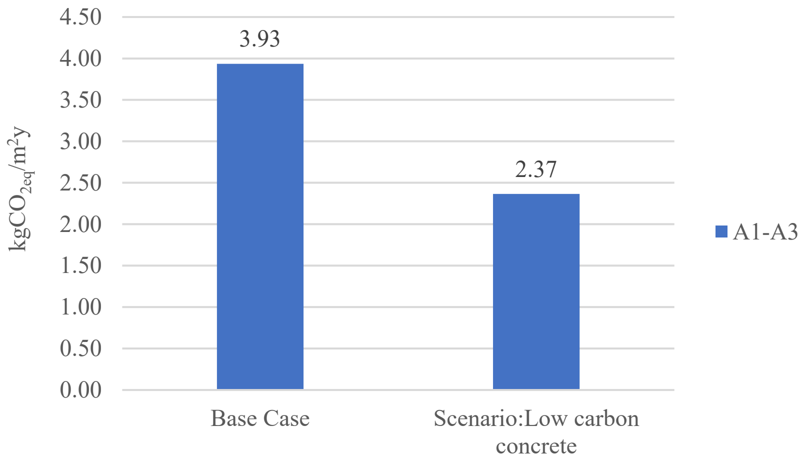

Figure 35. Comparison of embodied emissions from A1-A3 for different concrete choice.

The result shows that by using low carbon concrete, 39.9% of embodied emissions (A1-A3) from the use of concrete could be reduced. Here the low carbon concrete chose the type with 50% recycled materials partly substituted cement, with embodied emissions ranged from 135 $kgCO_2/m^3$ to 231 $kgCO_2/m^3$ based on different strength levels. Also, it is assumed that they are sourced from the same production place in Malaysia.

The impact of using low carbon concrete on ZEB balance is presented in Figure.36. It showed that 4.3% of the total embodied emissions could be reduced.

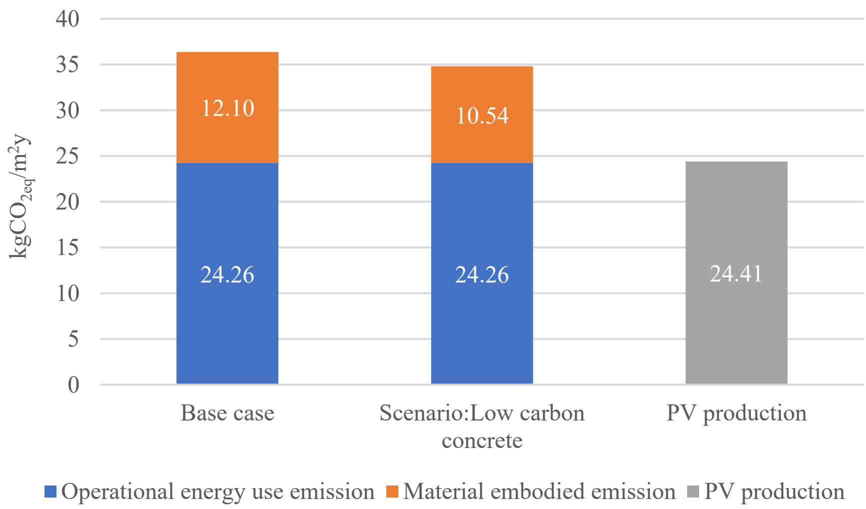

Figure 36. ZEB Balance compared for different concrete choice.

Besides the use of low carbon concrete, precast concrete elements can be considered to replace the cast-in-place concrete. A study conducted in Hong Kong (Wong & Tang, 2012) compared the precast and cast-in-situ concrete with the system boundary from 'cradle to site' (A1-A4) and concluded that precast method could reduce carbon emissions. It presented that for a typical residential housing comprised of six 40-storey building blocks in Hong Kong, prefabrication elements can reduce 71.8% of the GHG emission compared with in-situ elements. It also shows benefits on the construction stage, saving workforce and material used for formwork.

4.1.2.2 Select Recycled Metal for Rebar and Structure Steel

The GHG emissions from the steel rebar accounted for the second largest share of the total embodied emissions. Products manufactured from recycled materials usually contain less embodied emissions. The GHG emissions from regular steel rebar and structural steel made of only virgin materials are ranging from 2.89 $kgCO_2/kg$ to 3.21 $kgCO_2/kg$ (data sourced from One Click LCA database), while the GHG emissions from rebar and structural steel made of recycled content are reduced to around 0.5-0.74 $kgCO_2/kg$. For calculation, rebar with 97% recycled content, structural hollow steel sections with 30 % recycled content and structural steel profiles with 90% recycled content are chosen. Also, it is assumed that they are sourced from the same production place in China. Sensitivity analysis is done with regular steel and recycled steel for embodied emissions.

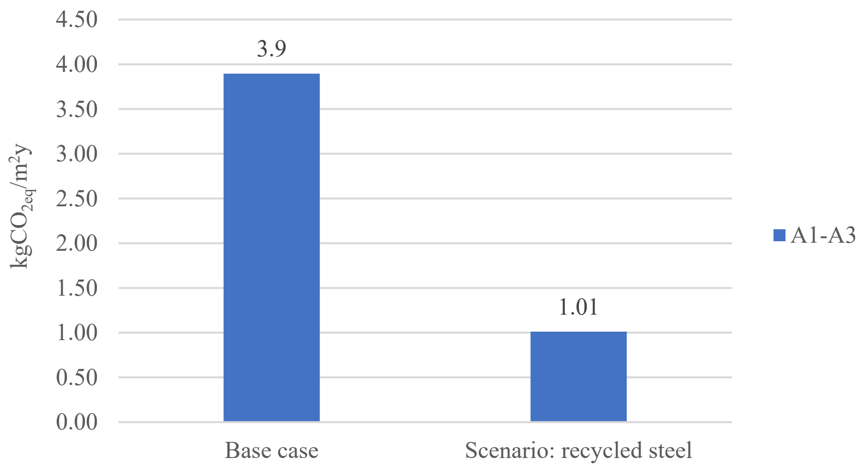

Figure 37. Comparison of embodied emissions from A1-A3 for different steel type choice.

The result shows that by adopting recycled steel, 74% of embodied emissions (A1-A3) from the use of steel products can be reduced. Also, the impact of adopting recycled steel on ZEB balance is presented in Figure.38. It showed that 8% of the total embodied emissions could be reduced.

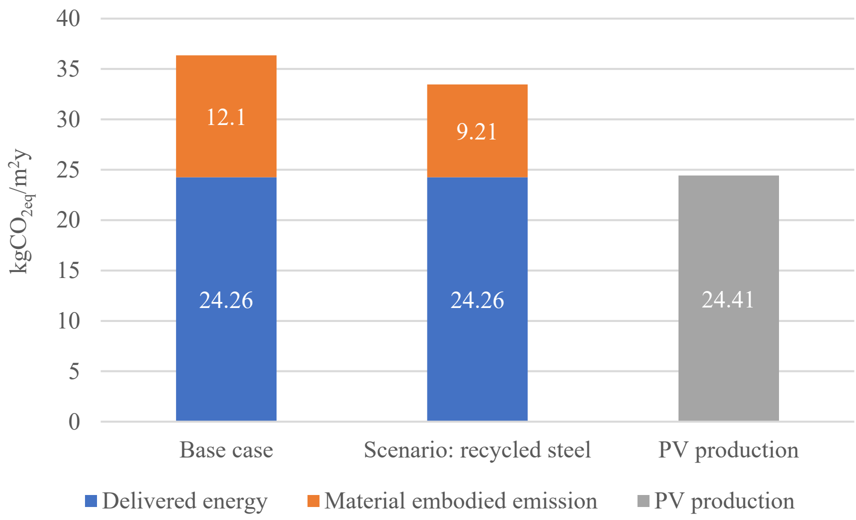

Figure 38. ZEB Balance compared between different steel type choice.

4.1.2.3 Reduce the Use of High-emission Concrete by Adopting Timber Structure

For the past few years, the Singaporean built sector has embarked on the productivity and sustainability journey and finally started the adaption of Mass Engineered Timber (MET) construction method. By now, four local projects have been built in MET construction, showing the feasibility to adopt timber construction in Singapore. Thereinto, the new six-storey educational building, located on the campus of Nanyang Technological University (NTU) in Singapore, has used the MET construction and would become Asia's largest wooden building. This project, named as Academic Building South (ABS), would house Nanyang Business School with over 40000 m^2, which would be completed in 2021.

The building type and building height of ABS are both similar to SDE4, which provides a real example and inspiration to propose a timber structure alternative for SDE4.

Figure 39. ABS design illustrations.

To produce mass engineered timber, layers of timber panels are glued together for strength and structural stability. Then, they are cut to specific dimensions in factories before being shipped off for onsite assembly. Typical products include Cross Laminated Timber (CLT) and Glued Laminated Timber (Glulam).

Regarding the conventional structures and construction methods adopted in the built timber projects in Singapore, slabs on the first storey are remained constructed using reinforced concrete to prevent termite infestation. Subsequent storey slabs are constructed using CLT, and the beams and columns are constructed using Glulam. Steel connections have been used between the load-bearing beams and columns (BCA, 2017).

Based on the experience from built projects, there are several advantages that the MET construction showed. MET has a load-bearing capacity similar to that of concrete but is 80% lighter, which means less timber is needed to support the same weight compared with concrete. Also, the foundation would shrink in size and material used for a building constructed with MET because it will not have to bear as much weight. Besides the structural properties, MET is also fire-resistant and can be protected against moisture and termites so that to acclimatize to the humid tropical conditions with special treatment. Another benefit took out from timber construction in tropics is that it provides five times better heat insulation than concrete (Lim, 2014). In terms of sustainability, timber is renewable and requires the lowest energy and water consumption of any building material in the construction stage. Also, it can be recycled after the demolishment of the building.

However, currently engineered timber used in Singapore has been sourced from Europe and North America, and mainly from Austrian suppliers (BCA,2017). All the MET elements are manufactured off-site and shipped to Singapore. It can be predicted that a considerable large amount of emissions would generate by materials transportation.

Timber structure scenario

In the original design, the building used a concrete structure, which consists of concrete beams and columns, floors and walls. While in the timber alternative, all these concrete components are replaced by timber. The timber case of SDE4 has been constructed with CLT floors and walls with a structure of Glulam beams and columns. For the area with auxiliary rooms, CLT walls ware used as the main load-bearing elements. Compared with the original concrete structure, this alternative only changed the material choice for the components mentioned above. No change has been made to the building layout and programme. Also, it should be noted that for structural reasons, the elevator shaft and foundation are kept as concrete components. However, the foundation would be reduced in size since the timber structure is lighter than the traditional concrete structure.

a. Dimensioning of the timber components

In order to make a realistic design model with a performance as much as possible as the base case, the components are dimensioned on simple load analysis followed conventional timber structure rules.

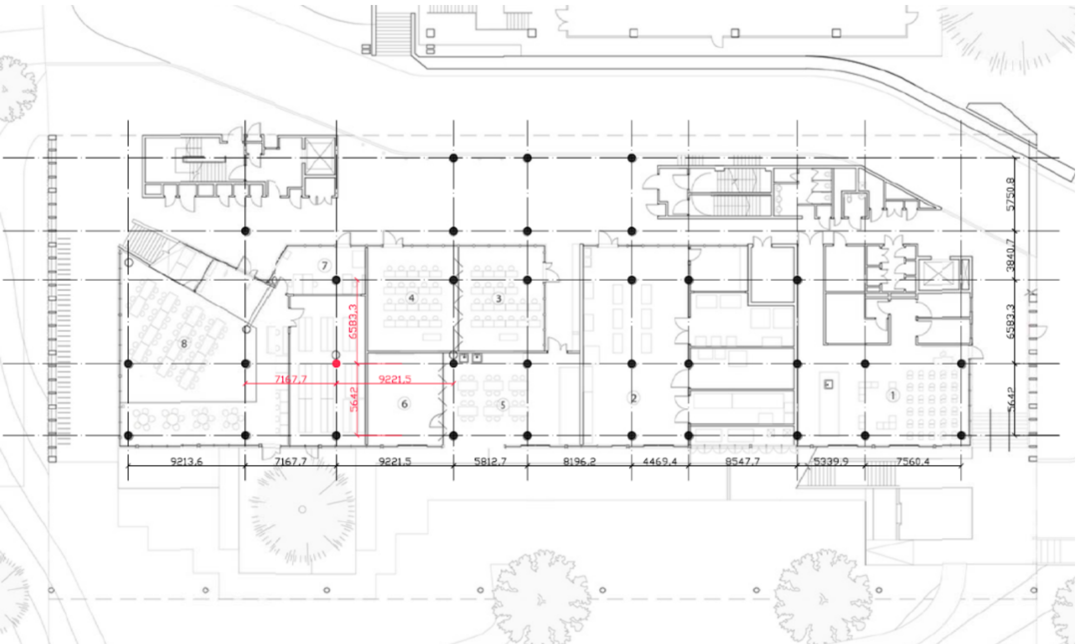

Figure 40. The dimension of the column grid in SDE4.

As shown in Figure.40, the span of the original structure ranged from 4.5m to maximum 9.3m. The column grid of the base case has been kept. To dimension the columns, the worst case column (marked as red in fig.40), which is supposed to bear the most load in the building, has been chosen to calculate the design column size.

The Euler's critical load formula and the building permanent and live loads have been used to roughly dimension the column. The technical details of the CLT and Glulam material are sourced from product brochures by Austrian producers, KLH for CLT and Binderholz for Glulam. The dead load from the structure itself, including floor slab and beam, has been calculated roughly by material volume and its structure analysis weight and multiply by the floor numbers. The live load of the building has also been considered, sourced from a public resource. The floor heights in SDE4 are different from each floor and considered a bit high for timber structure, the minimum is 4m and the maximum is 8m for some double-height area. Therefore, the dimension of the column needs to be corrected by the slenderness ratio less than 50 and then verified by load calculation.

The Glulam column with strength class GL 24C is chosen and finally dimensioned as 380mm ×3800mm for the regular case, and 550mm × 550mm for the double-height column. As a rule of thumb, for timber beam span to depth ratios of 10-15 are recommended (Smith, 2012), which is *h=l/10-15, h* is the depth of the beam, and *l* is the span. Considered the largest span is 9.3m, the depth of the beam would be 9300mm/12.5≈ 740 mm. For the beam, the same type of Glulam as the column is chosen. Since the span on X-axis direction is a bit larger than the Y-axis, the X-axis direction beams are used to bear the floor load to shorten the span thus to reduce the thickness of the floor panels. Therefore, guided by the structure pre-analysis tables for CLT panel sourced from KLH, 250mm thickness with 7 layers CLT panel is qualified for the largest span around 6.5m.

For exterior walls, 100mm thickness with 5-layer structure panels is chosen. It is a single-sided fire exposure CLT panels with fire resistance class R60. For interior walls, the 7-layer 180mm thickness double-sided fire exposure panel with fire resistance class R60 is chosen. As the original design with exposed concrete, there is also no finishing or cladding for the timber structure.

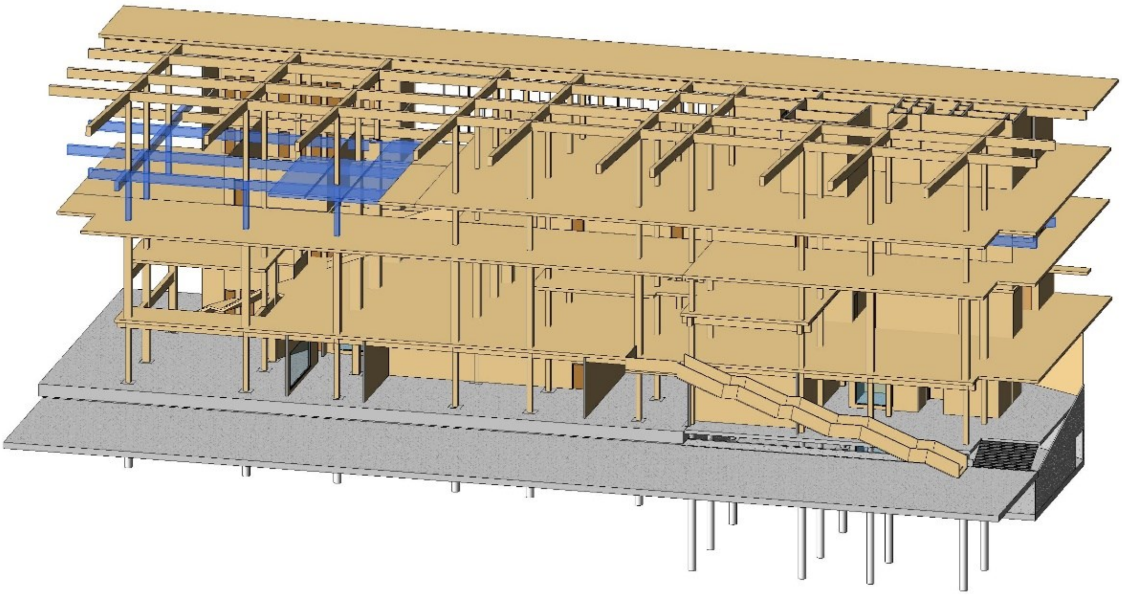

Figure 41. Alternative- Timber Structure Revit model.

b. Material inventory data

The whole life cycle inventory tables can be found in Appendix 3. The calculated building elements are the same as the base case.

Since the CLT/Glulam structure can be 80% lighter than concrete structure, the size and material use of the foundation has been reduced when adopted timber structure. Referred to research done by Hofmeister (2015) showed that the amount of concrete used in foundation to hold the timber structure could be reduced into 30%. Hence, this value has been adopted for estimating the foundation in this scenario.

The EPD data for CLT and Glulam are chosen the generic data from Europe because currently construction timber in Singapore has been sourced from Europe, mostly Austria. The embodied GHG emissions from CLT panel is about 303.96 $kgCO_2/m^3$ and that from Glulam element is about 238 $kgCO_2/m^3$, sourced from the Ecoinvent v 3.1 database.

It should be noted that timber treatments, additional bracing, metal connections and fasteners have not been included in the inventory. The timber which would be suitable for use in a tropical environment is expected to have some special treatment in order to protect the timber from termites and excessive moisture. Therefore, additional emissions from the treatment process can be anticipated.

According to the ZEB Definition Guideline (Fufa et al., 2016), the biogenic carbon content ($kgCO_{2eq}$) of wood is not considered in the calculation since the system boundary of this study does not cover the whole life cycle of the building.

$CO2_{eq}$ emissions compared to the base case

Compared to the base case, the amount of concrete shows a significant reduction, around 66%, by replacing most of the structure, walls and floors with timber elements.

Table 11. Estimated material quantities for the base case and Timber case structure.

Material	Base case	Timber case	Unit	Reduction
Concrete	7249	1498	m^3	*-66%*
in foundation	1748	545	m^3	*-52%*
in walls	1263	311	m^3	*-61%*
in slabs	3584	497	m^3	*-76%*
in columns/beams	600	123	m^3	*-66%*
Reinforcement steel (rebar)	582077	118087	kg	*-66%*
Structural steel	92944	92944	kg	-
Aluminium	12130	12130	kg	-
Glass panels	3359	3359	m^2	-
Glulam beam/column	0	607	m^3	*+100%*
CLT panel	0	3462	m^3	*+100%*

A comparison of the emissions from the component categories shows that the reduction in the emissions from the foundation is more significant since the timber structure is around 80% lighter than concrete even though they served the same load-bearing structure purpose. Emissions from columns and beams are reduced by about 21.5% when the switch is made to timber even for the same structural load. CLT walls result in slightly higher emissions mainly because more volume of wooden panel is used for the interior wall panels which are thicker than concrete walls. The technical system is ignored here because no change is made for the timber case.

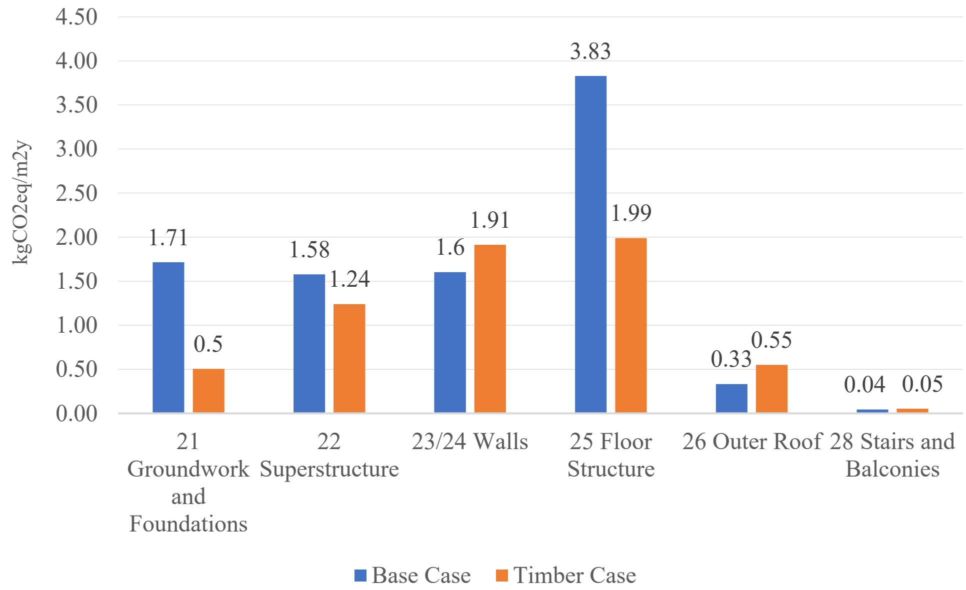

Figure 42. Embodied emissions from building elements (comparison between concrete structure and timber structure).

Compared the emissions from each material, a large amount of emissions is saved from reducing the use of reinforced concrete. Moreover, although a large amount of timber is adopted, the total emissions from timber elements are still lower than concrete because of its low-emission property.

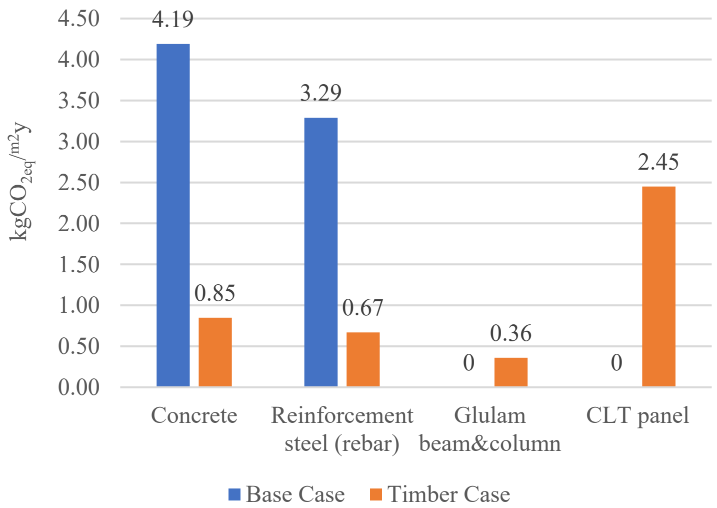

Figure 43. Distribution of carbon dioxide emissions from materials (comparison between concrete structure and timber structure)

The results of total embodied emissions from the comparison between the base case and timber case are summarised in Table.12, showing that an embodied emissions reduction of about 23.6% is obtained by adopting timber as the main construction material. Since the generic data is used in the calculation, it can be predicted that the total embodied emissions from the timber case can be lower if used specific data. However, GHG emissions from transportation to the site for the timber case has increased 1.66 times than the base case due to the long travel distance.

Table 12. Embodied emissions comparison between the base case and timber case.

	A1-A3		**A4**		**Total (A1-A4, B4)**
	tonne CO_{2eq}	$kgCO_{2eq}/m^2y$	tonne CO_{2eq}	$kgCO_{2eq}/m^2y$	$kgCO_{2eq}/m^2y$
Base case	5150	9.99	177	0.34	12.1
Timber case	3385	6.57	471	0.91	9.25
Difference	-1765	-3.42	294	0.57	-2.85
Total reduction	34.3%	34.2%	166.6%	166.6%	**23.6%**

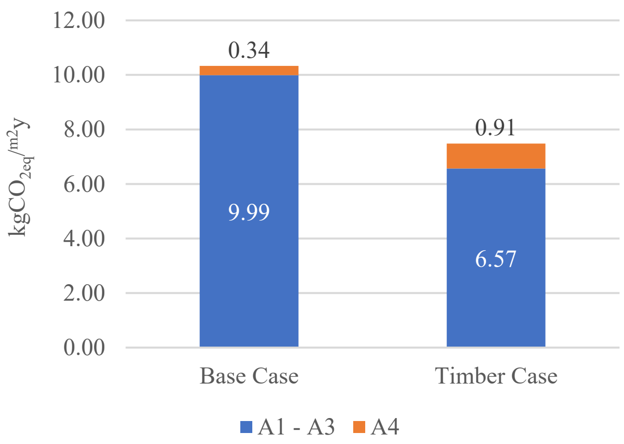

Figure 44. Embodied emission from A1-A3, A4 comparison for base case and timber case.

When taking a look at the percentage took by each lifecycle stage, the embodied emissions from A1-A3 in timber case has reduced to 19.6% from 27.5% in the base case. The share of the transportation emissions rose from 0.9% to 2.7% of total GHG emissions. The long travel distance from Europe to Singapore decreased the emission benefit when switching to the low-emissions timber construction.

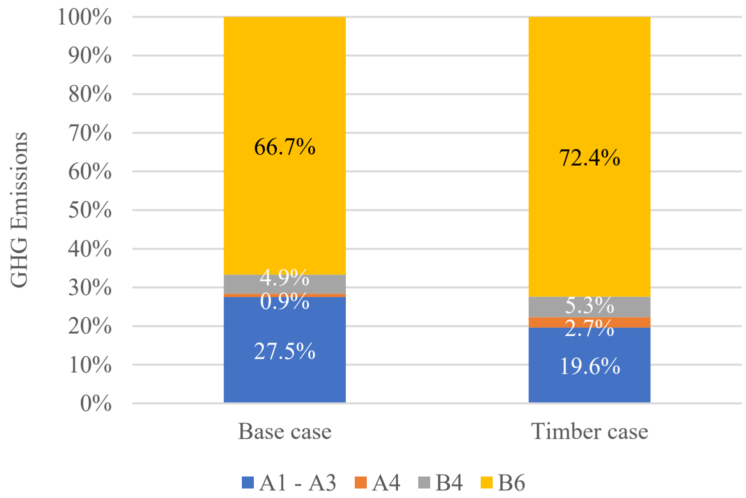

Figure 45. Comparison of the percentage of each lifecycle stage in base case and timber case.

4.1.2.4 Source Materials from Neighbour Countries

Sourcing materials from neighbouring countries can reduce the materials transportation distances and associated GHG emissions from the transportation stage (A4), especially when Singapore is highly reliant on importing materials from outside Singapore.

Based on the results, a large amount of GHG emissions comes from the transport of the engineered timber from Europe and glass panels from the United States. Region-wise, Europe dominates the total global production of CLT with Austria being the largest producer. Timber projects in Singapore were all sourced from the European market. In order to reduce the emissions from transportation in future timber projects, engineered timber from the Asian-Pacific market, such as producers from Japan and Australia, should be considered as alternatives. The travel distance from Japan to Singapore is estimated to be 4430 km if the engineering timber is sourced from Japan, and 6117 km from Australia, which are shorter than sourcing from Europe (about 12080 km). Approximately, 63% of the transportation emissions can be reduced by sourcing material in a location closer to Singapore, particularly in the case of timber.

4.1.3 ZEB Balance for Optimised Design

By combined the embodied emissions reduction measures above, a hypothetical scenario for optimising the design of SDE4 in terms of materials choice and embodied emissions is proposed and assessed. Measures included the adoption of low carbon concrete, recycled steel, timber construction and closer suppliers.

The results of the assessment for embodied emissions shows a reduction of 52.5% by applying related reduction measures. Although the GHG emissions from transportation are slightly higher in the new scenario, a significant reduction occurs in the material production stage (A1-A3). The result indicates the effectiveness of the discussed approaches.

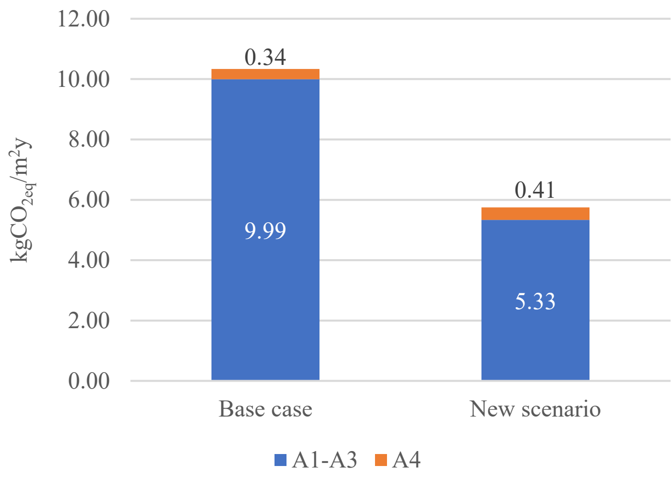

Figure 46. Comparison of the embodied emissions of the base case and new scenario.

Table.13 shows the comparison of the ZEB balance of the base case and the new scenario. In the new scenario, the resultant ZEB balance is reduced from 11.95$kgCO_{2eq}/m^2y$ to 5.6$kgCO_{2eq}/m^2y$, which indicated a higher possibility for the on-site PV energy production to balance the total emissions so that to reach a zero ZEB balance.

Table 13. ZEB balance: scenarios comparison

	Base Case	**New Scenario**
	$kgCO_{2eq}/m^2y$	$kgCO_{2eq}/m^2y$
Operational energy use emission	24.26	24.26
Material embodied emission	12.1	5.75
Local energy production (PV)	-24.41	-24.41
ZEB balance	**11.95**	**5.6**

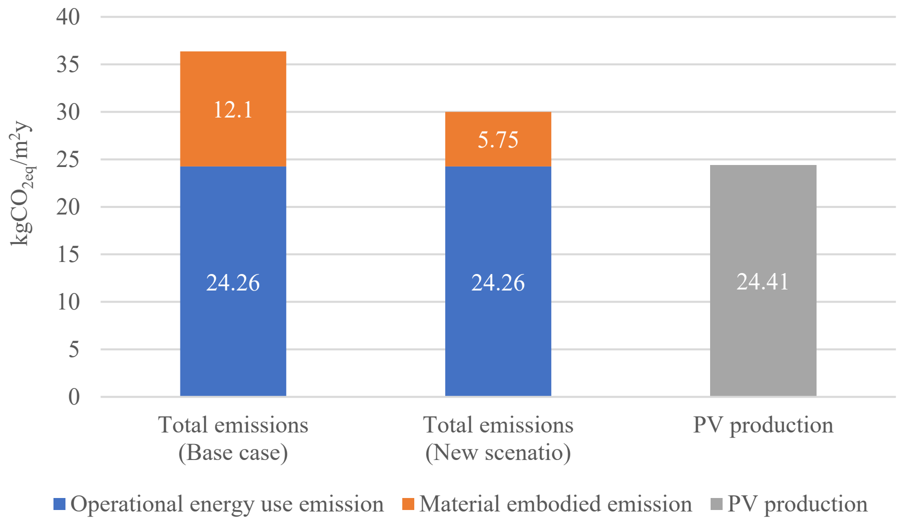

Figure 47. Comparison of ZEB balance of Base case and New scenario.

To generate enough renewable energy to compensate for the total GHG emissions in the new scenario, an addition of 487 m^2 PV panels need to be installed on site. Compared with the base case (1074 m^2), around 55% less area of the PV panels is need to be installed. It should be noted that the needed PV area is calculated based on the same background data as the horizontal rooftop PV panels. Larger area would be required for a vertical position like the façade area because of the angle and the incident radiation difference. Also, the additional material emissions from the additional PV panels and the mounting system did not account for.

4.1.4 Increasing Renewable Energy Production

Because of its geographic and resource constraints, Singapore has limited options for implementing renewable energy sources. The wind turbine has low efficiency because of the low local wind speed. Hydropower is not available as Singapore does not have a fast-flow river system. Also, resourced-limitation makes biofuel challenging to grow as a sophisticated domestic resource.

Solar photovoltaic energy is considered as the best way to approach since Singapore has a high average annual solar irradiation of about 1500 kWh/m^2. Although Singapore has limited available land for the large scale solar farm, the deployment of the PV system can find its way in integrating with building design.

Beside installed PV system on the roof, part of the south-facing facades can be used for PV production, also the east and west façades. It provides extra benefit by reducing the use of shading devices when increasing PV production.

Increasing on-site PV production

Given that there are existing vertical west and east solar shading screens, to increase on-site PV energy production in SDE4, it can consider replacing shading panels with PV panels. In this case, the PV modules are used as part of the building envelope, saving the materials from the aluminium shading panels. The available façade area is around 1200 m^2 in total.

Around the building there is no other building obstruction on the west side, while there are some trees located on the east side of the building and the lower part of the east façade might be shadowed by the building behind during morning.

The anticipated PV energy production on the east-west façades is calculated through simulation software, Polysun PV. By applied Singapore local weather data and considered the obstruction situation onsite, the mono-si PV panels with similar efficiency as the existing PV system are chose and calculated to have a capability to the production of 143485 kWh/y or 16.7 kWh/m^2y.

By increasing the onsite renewable energy production from additional vertical PV system, the final ZEB balance for the new scenario is calculated and presented below. It should be noted that the additional embodied emissions from the vertical PV system have also been included to offer a more realistic situation.

Table 14. ZEB balance for the new scenario.

	kgCO_{2eq}/y	**kgCO_{2eq}/m^2y**
Operational energy use emission	208342	24.26
Material embodied emission	58656	6.83
Local energy production (PV)	-269749	-31.41
ZEB balance	**-2751**	**-0.32**

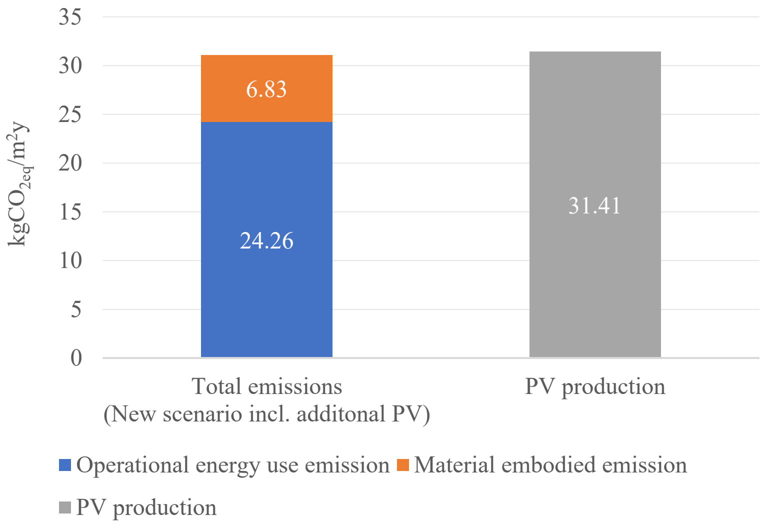

Figure 48. ZEB balance of the new scenario with PV production improvement.

The result shows that after applying the embodied emissions reduction approaches together with PV production increment, the ZEB balance is achieved with a negative sum value of -0.32 $kgCO_{2eq}/m^2y$. This result shows that the onsite renewable energy production can compensate for the operational emissions and materials embodied emissions. Although the calculation results show that the ZEB balance had been achieved under the conditions set by the hypothetical design scenario, it is anticipated that the real GHG emissions profile would be higher due to the limitations of this study, including data scarcity and subjective assumptions. However, the results indicate that it is possible to shift from net zero energy building into zero or low emission building in a hot, tropical climate in an urban environment like Singapore.

5 Discussion

The goal of this paper is to reveal the existing GHG emissions profile of the net-zero energy building in Singapore in order to investigate the possibilities to achieve a shift to Zero Emissions Building in a tropical climate in Singapore. The results of the life cycle assessment show that the key drivers for high embodied GHG emissions in SDE4 come from using carbonised construction materials with a high carbon content, such as concrete and steel. Also, the operational emissions are considerably high because of the high carbon emissions from electricity production in Singapore, even though SDE4 can be considered as an energy-efficient building.

In the original SDE4 design, In terms of the balance of GHG emissions, the onsite PV energy production can only balance the emissions from the operational stage. The embodied emissions from materials are too high to be balanced by the PV. This result is largely as a result of the fact that the environmental impact of the different materials choice was not considered nor calculated during the design process. The results show that only approximately 60% of the embodied emissions of the materials used in the SDE4 base case can be covered by the onsite renewables even after adding the additional PV production from the vertical façades. Therefore, the choice of materials is as important as the operation energy reduction when it comes to mitigating the total GHG emissions from buildings. More attention ought to be paid to the choice of building materials in low energy or net zero energy building.

Despite the fact that SDE4 has a high existing GHG emissions profile in the base case, the results show the potential for the design to be optimised and further improved to reach a target of low carbon emissions. The total GHG emissions profile can be improved by following a holistic approach which should simultaneously promote energy-efficiency measures, minimise of embodied emissions as well as increase renewable energy production. Especially materials embodied emissions should be indeed further reduced in the case of buildings in Singapore.

Based on the results of the sensitivity analyses with different design parameters, a significant reduction in the materials embodied emissions can be achieved by adopting effective emissions reduction strategies, including reducing materials used and adopting low-emission materials etc. Moreover, the calculation results show that the ZEB balance has been achieved in the new scenario.

Even though the calculated GHG emissions profile has been underestimated due to the research limitations already specified, this case study still provides a strategy to show that it is possible to shift from net zero energy building into low or net zero emissions building in the tropical climate of Singapore.

However, it should be noted that the ZEB balance is achieved on the basis of the high carbon content and associated high CO_2 factor of electricity production. The higher the CO_{2eq} factor for electricity during operation, the easier it is to counterbalance embodied emissions (Georges, 2015). It is because the same CO_{2eq} factor is used in calculating the avoided emissions from electricity exported from the PV system. Therefore, if the grid mix in Singapore decreases in the future, the ZEB balance achieved now in this research would not be the case in the future even with the same GHG emissions profile.

Considered the fact that Singapore has been aimed to increase its renewable energy uptake, it can be anticipated that there will be a decrease in the CO_2 factor of the electricity production in Singapore over time. Then, based on the changed in electricity grid mix, the emissions from the production, construction and replacement of building materials are anticipated to gradually contribute the more and more significant part of the total GHG emissions.

The embodied emissions from materials should always be optimised where feasible and reduction measures should be implemented in the early design phases, together with energy-saving and reduced operational design.

The design principles of optimised SDE4 provide valuable lessons for net zero emission design strategies in dense urban environments where typically high energy demand is commonplace. These design strategies of developing net zero emission building are especially valuable for the Asian area. This is particularly timely since Asia is now in a critical period of its development and consequently, low or net zero emission design would have a significant impact on reducing GHG emissions related to its expanding urbanisation construction activities due to growing economies and populations. The building industry can be transformed if the benefits of net zero energy or emission designs are readily understood.

6 Limitations

The main limitation of this work lies in the uncertainties connected with completing embodied carbon emissions calculations, including data collection, data source and data quality.

The CO_2 factor of electricity production in Singapore used in this study represents the carbon intensity, namely, the CO_2 gas emitted from electricity generation. Hence the GWP impact from electricity generation might be underestimated when excluding the impact of other greenhouse gases.

Incomplete material inventory

The results of embodied emissions calculations are highly dependent on the level of detail recorded in the life cycle materilas inventory. Due to the lack of detailed information, the material inventory used for calculation in this study should be considered as a limitation and are likely to be underestimated. It is anticpated the embodied emissions contribution for materials would be significantly higher when a more detail materials inventory would be included in the calculations.

The material inventory used in this study was extracted from the BIM model which was built by the author. Since the model was built based on limited access to architectural drawings, the model is expected to lack some details or to differ somewhat from the exact original design slightly. For example, the detailing of the roof construction was simplified because of inadequate information. Only the primary concrete layer was kept, and no additional materials were considered.

Also, assumptions are made for some data due to the absence of specific information. For example, the foundation, is found to take up to 6% of the total embodied emission of materials. However, these results are based on the type of foundation and the amount of materials were assumed based on a typical design situation and may not necessarily be representative of the real situation in SDE4. In addition, the strength of the foundation could be underestimated which would led to a lower amount of of concrete and steel quantities being used in the calculations which would result in lower emission results for this component. The amount of steel rebar in reinforced concrete was estimated based on the norms of structure design and the amount of reinforcing steel (rebar) was calculated as a percentage in the concrete structure. Therefore, it is assumed that the amount of rebar is underestimated by using the conventional value instead of the specific amount in the SDE4's structure.

The largest data deficiency is from the building technical system. For example, information about what type and how much technical equipment has been installed in the building was unavailable to obtain, except for a small part of the ductwork which could be observed from the exposed ceiling.

As a result of the lack of available data and architectural drawings, the material types used in SDE4 were largely identified based on onsite observations which is a key limitation. It is possible that the material type assumptions used in these calculations are different from the specific materials in the real case.

EPD sources

There was also limited detailed information available about the exact products to be used. Due to a lack of EPDs in general in Singapore, generic data had to be used which was extracted from Ecoinvent database. Generic data is often found to be higher in global warming potential than their specific counterparts found in the EPDs (Houlihan Wiberg, 2015). Nevertheless, using generic data can provide an overview of the emissions profile which would be representative of the general situation for buildings in Singapore. Also, for the transportation stage, the places of production of materials were chosen based on the trading market share, which would not reflect the real situation from the case study but a general situation in Singapore.

Design alternative

For the proposed timber structure design, limitation lied on the assumption of the dimension of the building components because it directly affects the material inventory used for subsequent GHG emissions calculations. A deviation might occur due to oversize or undersize the structure. Also, calculations excluded the consideration for the material inputs of structure connections and potential additional structural supports. It results in an underestimation on the embodied emissions from the timber structure alternative.

Moreover, the proposed scenario mainly focus on the materials optimisations, neglecting the detailed design problem might occur for adopting new materials. For instance, the grid of the column might need to change slightly to adapt to the timber structure. Also, the artistic perspective of the building for the proposed scenario is not considered.

7 Conclusions

This research involved an assessment of the GHG emissions of the case study, the net-zero energy building in Singapore, and offered an overview of its total emissions profile together with the identification of the key embodied emissions drivers.

Even though SDE4 could be considered as a high-efficient building, it was found that the operational GHG emissions contributed about almost 70% of the total emissions because of the high current emissions from electricity production in Singapore. By way of contrast in Norway, the results from the ZEB pilot buildings were shown to contribute 30 to 40% of the total (Wiik et al., 2018). The embodied emissions profile of the construction materials was calculated and found to be considerably higher with a value of 12 $kgCO_{2eq}/m^2y$. By way of contrast, the emissions from materials in the ZEB pilots was found to be around half this value. The findings of this research show that a ZEB balance was failed to be reached in the original SDE4 design.

The aim of this research was to investigate the possibility of optimising the design to acheive a shift from a net zero energy building to net zero emission Building design in Singapore. To achieve this, the original SDE4 design has been optimised in terms of material choices.

The new scenario involved the use of timber as the main construction materials, as well as, subsituting the high-emission concrete and steel used in the foundation, slab on the ground and technical shafts with low carbon concrete and recycled steel. This optimisation in materials resulted in a significant reduction in embodied emissions. Also, onsite PV electricity production has been increased in the new scenario by installing additional PV panels on the vertical facades. A ZEB balance for the new and optimised scenario has been calculated and the results show that this has been achieved. This result shows that with sufficient emissions reduction measures, a low or net zero emissions building can be achieved based on the foundation of a high-efficient operation in tropics Singapore.

Currently, the concept of net zero emission buildings has not been widely discussed in the building sector in Singapore. The main focus has been on how to decrease the operational energy use during the design process, without considering the importance of the construction materials. The findings of this Research point out the need to reduce the GHG emissions from energy generation in Singapore. More Research is needed on the adoption of renewable energy in order to mitigate the building operational emissions in the long term. Furthermore, the significant impact of the embodied impact from materials has been identified, which also necessitates further research in the environmental impact assessment of materials and components in furture net zero emission buildings in Singapore.

It also should be pointed out that the knowledge and experience gained from achieving net zero emission in Singapore, can be beneficial for Asian tropical and subtropical region, encouraging the adaptation of emission-orientated building design.

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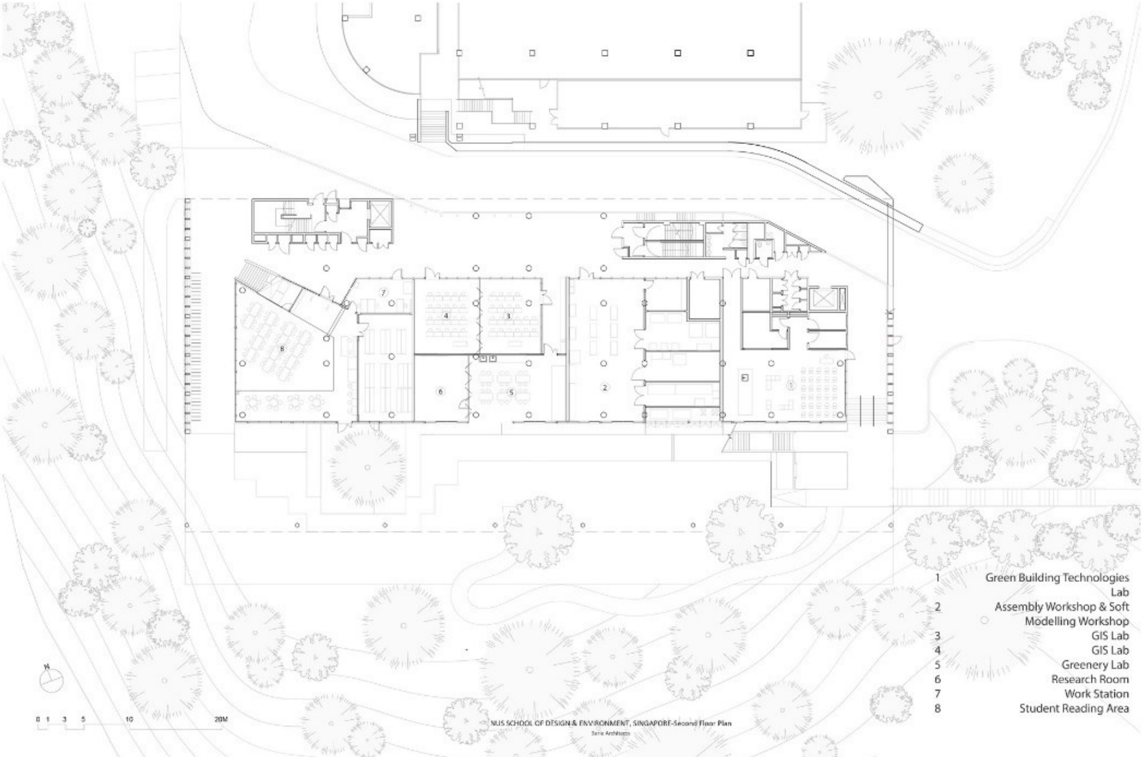
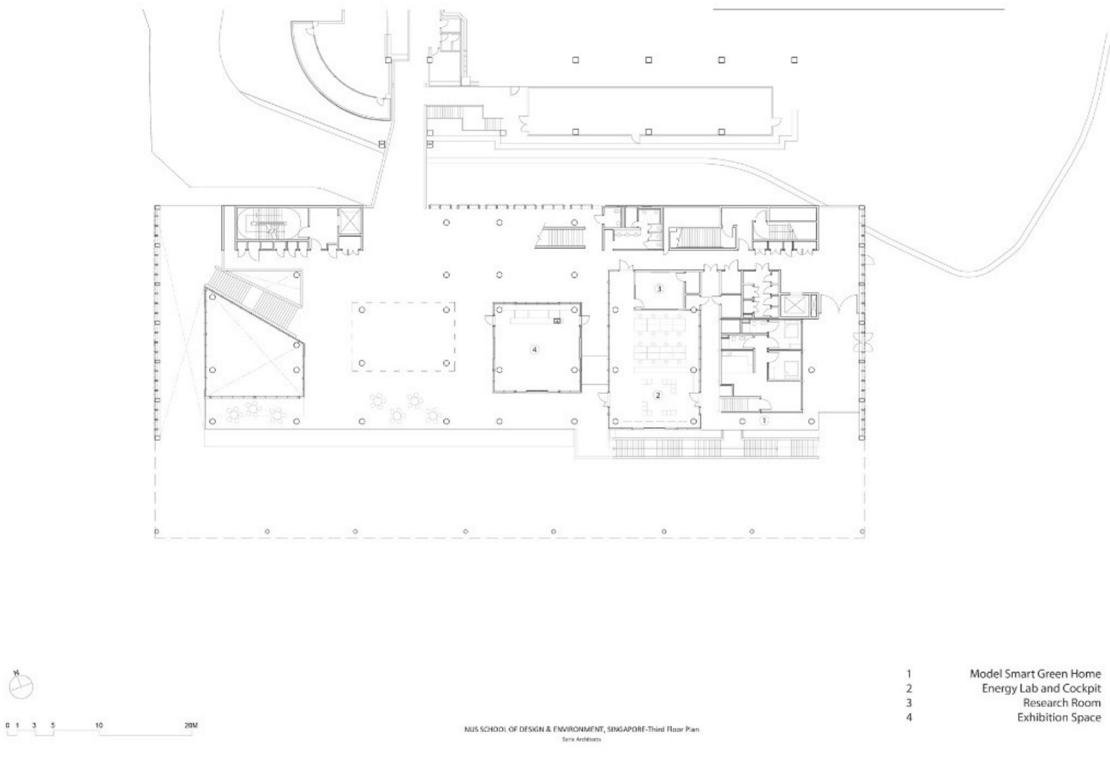
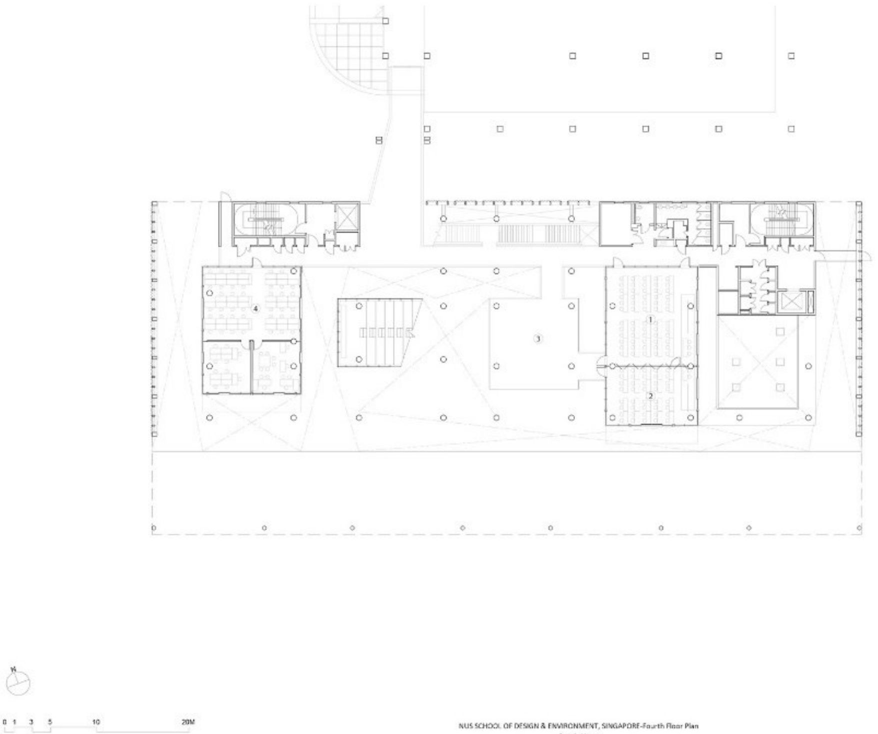
Appendix 1: Technical Drawings of SDE4

(Source: Retrieved from Serie Architects, https://www.serie.co.uk/projects/8/school-of-design-environment#1)

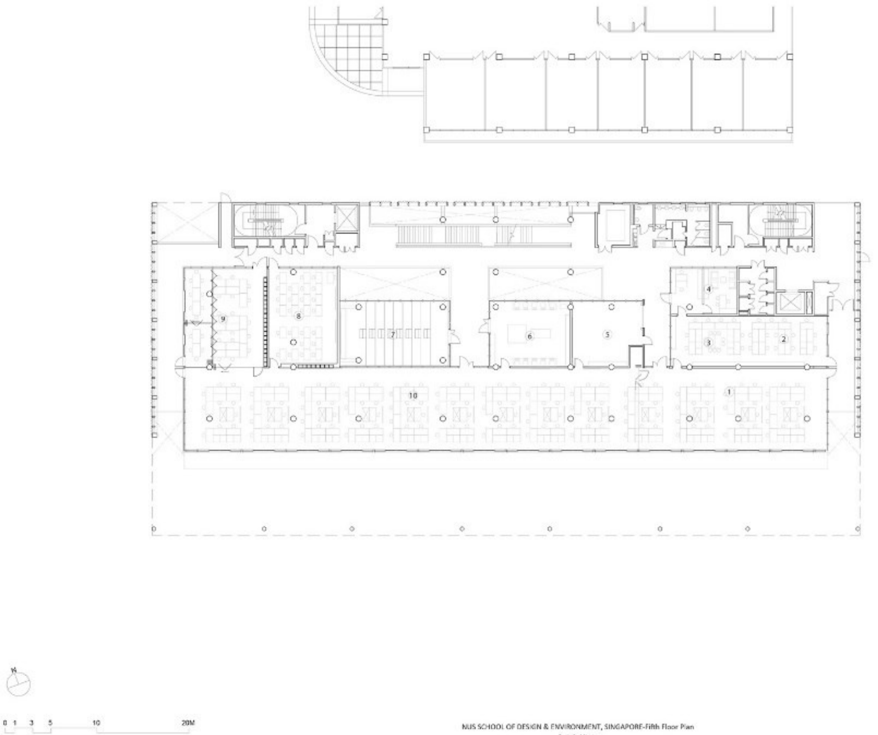






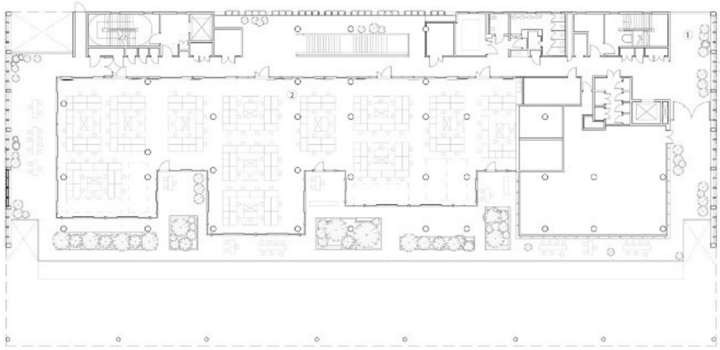
1	Executive Room
2	Executive Room
3	Landscape Terrace
4	Architecture Studio 2

NUS SCHOOL OF DESIGN & ENVIRONMENT, SINGAPORE-Fourth Floor Plan
Serie Architects



1	Design Studios
2	MA ID Studio
3	ID Programme E&P Office
4	ID Programme - Head's Office
5	3D Scanning Lab
6	Prototyping Lab
7	Forum
8	Computer Lab
9	Design Incubation Centre
10	Design Studio 1

NUS SCHOOL OF DESIGN & ENVIRONMENT, SINGAPORE-Fifth Floor Plan
Serie Architects



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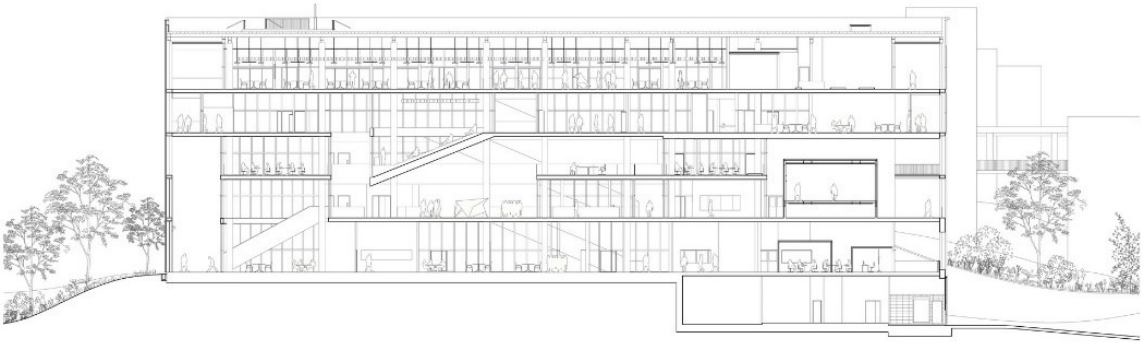
NUS SCHOOL OF DESIGN & ENVIRONMENT, SINGAPORE-Sixth Floor Plan
Serie Architects

1 Test Bed Area
2 Architecture Year 1 Studio



NUS SCHOOL OF DESIGN & ENVIRONMENT, SINGAPORE-Long Section
Serie Architects

NUS SCHOOL OF DESIGN & ENVIRONMENT, SINGAPORE-Short Section
Serie Architects

Appendix 2: SDE4 life cycle inventory table

Building parts	*Family and type*	*Material input*	*Amount*	*Unit*	*Service life*
21 Groundwork and foundation					
Foundation Slab	Foundation Slab	Concrete	1621.94	m^3	Life of Building
		Steel rebar (1%)	137864.9	kg	
Isolated foundation	M_Pile Cap-1 Pile: 1000 x 1000 x 900mm	Concrete	33.3	m^3	
	Pile-reinforcement Pipe: 600mm Diameter	Concrete	62.66	m^3	
		Steel rebar (1.65%)	12474.8	kg	
	Retaining wall	Concrete	30.26	m^3	
22 Superstructure					
Columns	Concrete-Round-Column: 12"	Concrete	171.15	m^3	Life of Building
		Steel rebar (3.27%)	43,985.55	kg	
	M_Concrete-Rectangular-Column: 350 x 550mm	Concrete	60.37	m^3	
		Steel rebar (0.8%)	3791.236	kg	
	CHS-Circular Hollow Section-Column: 406.4x6.3CHS	Steel	12717	kg	
	RHS-Rectangular Hollow Section-Column: 200x100x8RHS	Steel	12952.5	kg	
	RHS-Rectangular Hollow Section-Column: 500x100	Steel	56834	kg	
	UBP-Universal Bearing Pile-Column: 200x200x174UBP	Steel	4788.5	kg	
Beams	M_Concrete-Rectangular Beam: 300 x300mm/300x500mm/300 x600mm	Concrete	184.19	m^3	
		Steel rebar (2%)	27628.5	kg	
	UBP-Universal Bearing Pile: 203x203x45UBP	Steel	5652	kg	
23 Outer walls & 24 Inner Walls					
Solid wall	Basic Wall: 100/200mm exterior Concrete wall	Concrete	212.98	m^3	
	Basic Wall: 100/200mm Concrete wall	Concrete	1049.55	m^3	
	Gypsum wall board	Gypsum	6.87	m^3	29

Glass curtain wall	Mullion	Rectangular Mullion: 2.5" x 5" rectangular (cross-section: 0.000377m²)	Aluminium (2700kg/m³)	4420.37	kg	50
	Glass panel	System Panel: Glazed (12mm thickness)	Glass	3358.61	m²	
Solar shading	Perforated Aluminium panel	1129.38 area with 32% perforated, 2mm thickness	Aluminium	4,147.09	kg	
	Connect bar	Square Bars	Aluminium	2781	kg	
Windows		Operable window			pc	30
		window louvres		18	pc	
Doors		Internal glass door		47	pc	30
		Fireproof door		110	pc	
25 Floor structure						
Floor slab		Floor: Generic	Concrete	3,035.91	m³	
			Steel rebar (1.5%)	349129.65	kg	
Ceiling buffer			Aluminium	781.55	kg	
26 Outer roofs						
Primary construction		Basic Roof: Generic - 0.3m	Concrete	190	m³	
		Basic Roof: Generic - 0.1m	Concrete	358.25	m³	
28 Stairs and Balconies						
Stairs		Cast-In-Place Stair: Monolithic Stair	Concrete	54.32	m³	
			Steel rebar (0.8%)	3411.296	kg	
36 Ventilation and air conditioning						
Ventilation ducts		PCD/EAD/FAD duct	Aluminium	4725	kg	30
		CHWS/CHWR pile	plastic	0.88922	m³	30
Equipment		-				15
Ceiling fan		0.45 radius		89	pc	
44 Lighting						
light tube		0.8m length		318	pc	20
downlight		0.1m radius		193	pc	
49 Energy supply systems						
PV system	PV mounting structure		Aluminium	-		
	PV panel module	mono-crystalline silicon		2090	m²	25
	Electric installations	inverter and cabling		-		
62 Passenger and goods transport						
Lifts		Elevator		2	pc	35

Appendix 3: Timber alternative life cycle inventory table (material change highlighted in red)

Building parts	***Family and type***	***Material input***	***Amount***	***Unit***	***Service life***
21 Groundwork and foundation					
Foundation Slab	Foundation Slab	Concrete	**485.582**	m^3	Life of Building
		Steel rebar (1%)	**41359.47**	kg	
Isolated foundation	M_Pile Cap-1 Pile: 1000 x 1000 x 900mm	Concrete	**9.99**	m^3	
	Pile-reinforcement Pipe: 600mm Diameter	Concrete	**18.798**	m^3	
		Steel rebar (1.65%)	**3742.44**	kg	
	Retaining wall	Concrete	30.26	m^3	
22 Superstructure					
Columns	Concrete-Round-Column	Concrete	**8.13**	m^3	Life of Building
		Steel rebar (3.27%)	**2,089.41**	kg	
	M_Concrete-Rectangular-Column: 350 x 550mm	Concrete	60.37	m^3	
		Steel rebar (0.8%)	3791.236	kg	
	M_Glulam-Southern Pine-Column: 380x380/ 550x550/830X830	**wood: spruce**	**162.27**	m^3	
	CHS-Circular Hollow Section-Column: 406.4x6.3CHS	Steel	12717	kg	
	RHS-Rectangular Hollow Section-Column: 200x100x8RHS	Steel	12952.5	kg	
	RHS-Rectangular Hollow Section-Column: 500x100	Steel	56834	kg	
	UBP-Universal Bearing Pile-Column: 200x200x174UBP	Steel	4788.5	kg	
Beams	M_Concrete-Rectangular Beam: 300 x300mm/300x500mm	Concrete	**54.19**	m^3	
		Steel rebar (2%)	**8507.83**	kg	
	M_Glulam-Southern Pine: 740X380	**wood: spruce**	**444.63**	m^3	
	UBP-Universal Bearing Pile: 203x203x45UBP	Steel	5652	kg	
23 Outer walls & 24 Inner Walls					

Solid wall		Basic Wall: 100/200mm Concrete wall	Concrete	**310.8**	m^3	
		Basic Wall: CLT wall	**wood: spruce**	**986.68**	m^3	
		Gypsum wall board	Gypsum	**6.87**	m^3	29
Glass curtain wall	Mullion	Rectangular Mullion: 2.5" x 5" rectangular (cross-section: 0.000377m²)	Aluminium (2700kg/m³)	4420.37	kg	50
	Glass panel	System Panel: Glazed (12mm thickness)	Glass	3358.61	m^2	
Solar shading	Perforated Aluminium panel	1129.38 area with 32% perforated, 2mm thickness	Aluminium	4,147.09	kg	
	Connect bar	Square Bars	Aluminium	2781	kg	
Windows		Operable window			pc	30
		window louvres		18	pc	
Doors		Internal glass door		47	pc	30
		Fireproof door		110	pc	
25 Floor structure						
Floor slab		**Floor: CLT floor**	**wood: spruce**	**1726**	m^3	
Concrete Slab on ground		Floor: Generic - 0.5	Concrete	**496.53**	m^3	
			Steel rebar (1.5%)	**57100.95**	kg	
Ceiling buffer			Aluminium	781.55	kg	
26 Outer roofs						
Primary construction		**Basic Roof: CLT**	**wood: spruce**	**159.21**	m^3	
		Basic Roof: CLT	**wood: spruce**	**545.976**	m^3	
28 Stairs and Balconies						
Stairs		Cast-In-Place Stair: Monolithic Stair	Concrete	**23.82**	m^3	
			Steel rebar (0.8%)	**1495.896**	kg	
		Wooden stairs	**wood: spruce**	**43.99**	m^3	
36 Ventilation and air conditioning						
Ventilation ducts		PCD/EAD/FAD duct	Aluminium	4725	kg	30
		CHWS/CHWR pile	plastic	0.88922	m^3	30
Equipment		-				
Ceiling fan		0.45 radius		89	pc	
44 Lighting						
light tube		0.8m length		318	pc	20

downlight		0.1m radius		193	pc	
49 Energy supply systems						
PV system	PV mounting structure		Aluminium	-		
	PV panel module	mono-crystalline silicon		2090	m²	25
	electric installations	inverter and cabling		-		
62 Passenger and goods transport						
Lifts		Elevator		2	pc	35

Appendix 4: Ceiling plan drawing

(Source: Bertrand Lasternas. (2019). Hybrid System School of Design and Environment SDE4. National University of Singapore)