Master's thesis

NTNU
Norwegian University of Science and Technology
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Department of Architecture and Technology

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Towards Zero Emission Neighbourhoods (ZEN) in a hot, tropical climate in Singapore

ZEN Research Center and ERI@N

Master's thesis in Sustainable Architecture
Supervisor: Aoife Houlihan Wiberg
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Abstract

This paper analyzes the potential of implementing Zero Emission Neighbourhood (ZEN) strategies for reduced environmental impact in warm climates, thorough the campus of Nanyang Technological University in Singapore.

The ZEN Center in Norway has started investigating an idea of distributing energy resources between interconnected buildings by creating synergies that balance out individual demands and achieve collective zero emissions. Valuable conclusions have already been drawn from several pilot projects in Norway, which motivates for further research in different climatic contexts. In parallel, an anticipated growth in conditioned floor area in South and Southeast Asia raises awareness of the increased energy consumption for cooling. The upsurge will consequently lead to higher Greenhouse Gas (GHG) emissions, which motivates the development of this paper aiming to induce a rapid decline and compensation for emissions from cooling.

The project analyzed six selected buildings on NTU's campus by evaluating them against a set of parameters including passive design strategies, existing campus ambitions for achieving zero energy, conditioned floor area and PV electricity generation. Additionally, each building's profile was quantified with GHG emissions from cooling. The calculation was obtained by multiplying energy consumption data of the chiller plants that maintain conditioned areas in the buildings and the grid emission factor for Singapore.

The results indicate that emission reduction can be achieved in the individual building profiles, but an emphasis is put on creating ZEN synergies that will neutralize GHG emissions for the connected buildings. An approximate calculation of the potential PV electricity generation by a building that is 98 per cent naturally ventilated demonstrated that it can generate a surplus of energy sufficient for

satisfying cooling demands of a building that is 100 per cent mechanically cooled. An even larger synergy can be beneficial for efficient management of peak loads in energy generation and could help to avoid constraints from inefficient energy storage with current technology. Moreover, synergies can transcend the physical connection and could be achieved with digital aid and transportation systems.

This paper potentiates the applicability of synergetic ZEN connections in warm climates and paves the road for future more detailed research in similar contexts. The concluding recommendations can be directly tested in a pilot project at NTU's campus.

Preface

This master thesis was written as part of the study program in Sustainable Architecture at the Norwegian University of Science and Technology (NTNU). The realization of this project was funded by the Zero Emission Neighbourhood (ZEN) Research Center in Trondheim that initiated a collaboration with the Energy Research Institute at Nanyang Technological University (ERI@N) in Singapore.

I would like to thank my supervisor Aoife Houlihan Wiberg, for giving me the opportunity to work on this research. For all the kindness, understanding, support, availability, guidance and encouragement in the challenging stages of my work. I would also like to thank Daniel Satola, for the patience to answer all my questions and for the ease of providing meticulous explanations. I am very thankful for the support from Yann Grynberg who provided me with the essential energy data for completing this project. And I am grateful for the entrusted responsibility and provided resources for tackling this complex problem to both the ZEN Research center and ERI@N. Thank you to all for showing me how exciting and fulfilling research can be.

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List of Abbreviations

BCA	Building Construction Authority
BREEAM	Building Research Establishment Environmental Assessment Method
BREEAM-NOR	BERAM - Norway
BM	Building Margin
CM	Combined Margin
EIA	Energy Information Administration
EMS	Energy Management System
ERI@N	Energy Research Institute at NTU
GHG	Greenhouse Gas
NTNU	Norwegian University of Science and Technology
NTU	Nanyang Technological University
OM	Operating Margin
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
SADS	School of Art Design and Media
SPMS	School of Physical and Mathematical Sciences
TAS	Thermal Array Sensor
TSV	Thermal Sensation Voting
ZEB	Zero Energy Building
ZEB	Zero Emission Building
ZEN	Zero Emission Neighbourhood

Introduction

1.1 Background

The U.S. Energy Information Administration (EIA) projects an increase of 65 per cent in energy consumption in the building sector by 2050, compared to the baseline of 2018. Most of this upsurge is a consequence of the strong economic growth in Asia (EIA, 2019) Even though current predictions are subject to variability, it is expected that the Asian contribution on increasing energy consumption will reach up to 89 per cent (Markham, 2018). The South Asian and Southeast Asian regions will have a significant impact on global GHG emissions, which makes them targets for decarbonization in order to align with the Paris Agreement's goal of limiting global temperature increase at no more than 2°C (Hutifilter et al, 2019). Additionally, climate change will have the largest impact in these regions, as the predictions demonstrate that global warming above 1.5°C will have a serious impact on local economic growth, health and biodiversity. The consequences include increased heat-related morbidity and mortality, increased poverty, compromised water supply and food security that can all ultimately lead to decreased regional security. (Raitzer, 2015)

The global status report of 2016 predicts a 100 per cent increase in building floor area in South Asia by 2050 (UN Environment and International Energy Agency, 2016). Consequently, efforts for reducing GHG emissions should focus on inducing a rapid decline in operational energy for cooling in the building sector, based on the expected increase in conditioned spaces. Research on this topic is mainly focused on cold climates which yields results that might not be suitable for different climatic contexts. However, international support has proven to be vital in decarbonizing processes, thus we need to intensify research in these areas and aid the achievement of GHG emissions reduction goals.

The Zero Emission Neighbourhood (ZEN) Center in Norway has started investigating an idea of distributing energy resources between interconnected buildings by creating synergies that balance out individual demands and achieve collective zero emissions. Valuable conclusions have already been drawn from several pilot projects in Norway, which motivated the development of this thesis. (Research center on ZEN in smart cities, 2018). The research project intends to provide an overall evaluation of ZEN applicability in a different climatic context and it is expected to stimulate international support processes for such regions.

Singapore, being the wealthiest economy in Southeast Asia, has been chosen as the ideal ground for testing the ZEN hypothesis, considering its increase in GHG emissions by 4 per cent in 2017 (UN Environment and International Energy Agency, 2017). The climatic context in which it is situated represents an extreme opposite of the cold, dry climate in Norway, where different conditions apply and a large portion of the building's total energy consumption falls off to cooling loads. Therefore, Singapore can be used as a testbed for investigating zero emission concepts in warm climates and showcasing a change in attitude towards reduced environmental impact in South and Southeast Asia.

The project will be based on the campus of Nanyang Technological University, which aims to become the greenest campus in the world. This makes it a solid base for investigating improvements that would advance its performance and bring it closer to achieving a net-zero emissions ambition at the neighbourhood scale.

1.2 Research questions

The main research questions expected to be answered within the scope of this topic are the following:

1. How to synergize a group of buildings with different energy profiles in the Singaporean context?
2. What are the main considerations for future research and implementation of ZEN principles in warm climates?

1.3 Research Method

The research will begin with a literature review on passive design strategies in warm climates with the purpose of compiling a catalogue of viable design considerations that contribute towards reducing energy demands.

The campus of Nanyang Technological University will be visited and evaluated for the purpose of selecting a set of buildings that represent different energy profiles. After the selection, energy consumption data[1] will be provided by the Energy Research Insitute at NTU (ERI@N). This will be used for calculating GHG emissions by applying the emission factor for the grid mix in Singapore to the annual consumed energy. Detailed energy profiles of the selected buildings will be developed by depicting each building's cooling method, conditioned area, GHG emissions from cooling and implemented passive strategies (based on the previously compiled catalogue). Additionally, the existing ambitions of NTU's campus for reducing energy demands will be analyzed and presented.

In the next step, each of the individual energy profiles will be evaluated and improved by proposing implementation of additional

[1] Operational energy for cooling based on electricity consumption of chiller plants for cooling the buildings.

strategies and ambitions for optimization of the design, operation and user's requirements. The main aim will be to reduce Energy Use Intensity (EUI) and maximize renewable energy production. The conclusions for possible optimization at the individual level will serve as guidelines for proposing synergies between the selected buildings.

1.4 Research Scope and Limitations

Analytical observation of the building's energy profiles will be conducted in relation to their function and design. Understanding the reasons for individual high cooling demands can then be further investigated, and reduction solutions can be proposed. After justifying and/or proposing reduction in cooling energy use, the project will converge to create a single entity which can synergize these buildings in the Eco-campus. The focus of the analysis will be to develop strategies for compensating high energy demands in some instances, with less demanding buildings, bringing the entity closer to achieving zero emissions.

There are a lot of variables that will hinder the generation of exact quantifiable measures, as there is limited data for some of the newer buildings. Additionally, the time for developing this topic is short and does not allow detailed simulations which will provide exact estimates for reducing cooling loads. Therefore, the emphasis will be on finding more efficient and architecturally integrated solutions that can balance operational energy use demands and reach zero emissions. Solutions such as PV's placement and electric autonomous vehicles transporting energy will be discussed. Obtained conclusions from this research will be aimed at inducing a shift in thinking towards reducing GHG emissions for cooling and implementing ZEN principles in warm climates. The discussion will strive to direct future research into accelerating these processes and increasing international support in research.

Theory

2.1 Norwegian Context

The Kingdom of Norway is located on the western and northermost part of the Scandinavian peninsula at a latitude of 60.4720°N and longitude 8.4689°E, which is around 3000 km from the North Pole. Norway is a highly developed country which has global influence on the economy, being ranked as the as the 1st on the UN Human Development Index in 2019 (International Monetary Fund, 2019). Also, it has the 4th highest GDP per capita in the word. (The World Bank, 2020)

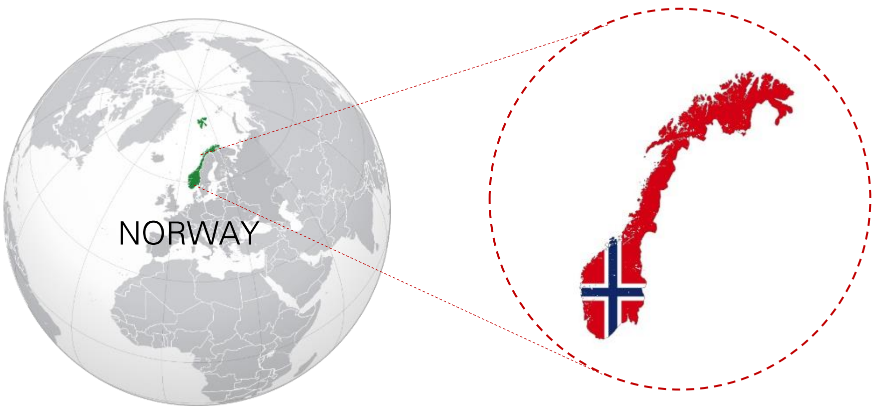


Figure 2.1 Norway is located at the western and northernmost part of the Scandinavian peninsula (left). Illustration of the mainland borders and flag with red white and blue colours (right).

2.1.1 Norwegian Climatic Context

According to the Köppen-Geiger climate classification Norway is denoted with several climate types (Figure 2.2), but we will observe the most dominant ones, which are the most important for the scope of this thesis considering that the ZEN Pilot projects (which we'll discuss in Chapter 2.1.2) are located in them (Figure 2.3) Figure 2.3 ZEN Pilot project locations in Norway. *Illustration obtained from* . They are: Cfb – Oceanic and Dfc – Subarctic. It is important to note that in recent years there is a shift in temperatures as a direct consequence of global warming, which is expected to influence some characteristics of the specified climate type compared to the classification from 1961-1990 (Meteorologisk Institut, 2012).

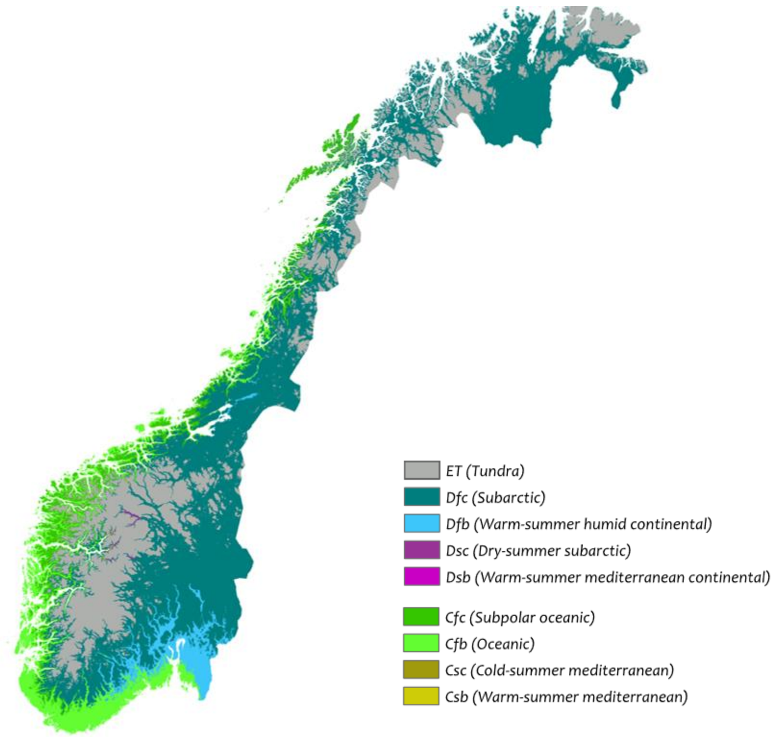


Figure 2.2 Köppen-Geiger climate classification map of Norway. *Illustration obtained from* (Peterson).

- Temperature

The climate in Norway is significantly milder compared to similar other countries with high latitudes. This comes as a consequence of the North Atlantic Current with the Norwegian Current that bring mild air onshore and raise the air temperatures. This results in milder winters on the coast where Oceanic climate is present. The coldest month averages above 0°C and the average diurnal change is between 10 to 15°C. At least four months have an average above 10°C. Inland, where the Subarctic climate is dominant the difference between the coldest and warmest month is significantly larger and reaches up to 30°C. In the coldest month the averages are below 0°C and there are 1-3 months with an average above 10°C. (Meteorologisk Institut, 2020)

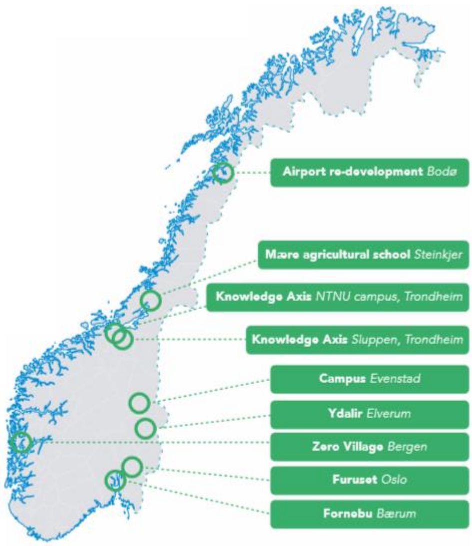


Figure 2.3 ZEN Pilot project locations in Norway. *Illustration obtained from* (Research Center on Zero Emission Neighbourhoods in Smart Cities, 2020)

In terms of design, the climatic context translates into an emphasis on the building's envelope with the aim of maximizing heat gains and minimizing heat loses.

- Precipitation

The coastal area is the wettest because of the wet mass carried by the Norwegian Current. Some mountain areas where the Oceanic climate is present are the wettest in Europe, exeeding annual percipitation of 5.000mm. The precipitation is heaviest in autumn and early winter, while the period from April to June is the driest. Inland, where the Subarctic climate prevails the precipitation is more dominant in summer and early autumn, leaving winter and spring relatively dry. Considering the size of the country there is a significant variation in number of days with rainfall above 3mm from 77 to 200 days. (Lippestad, Heidi, 2014)

- Wind

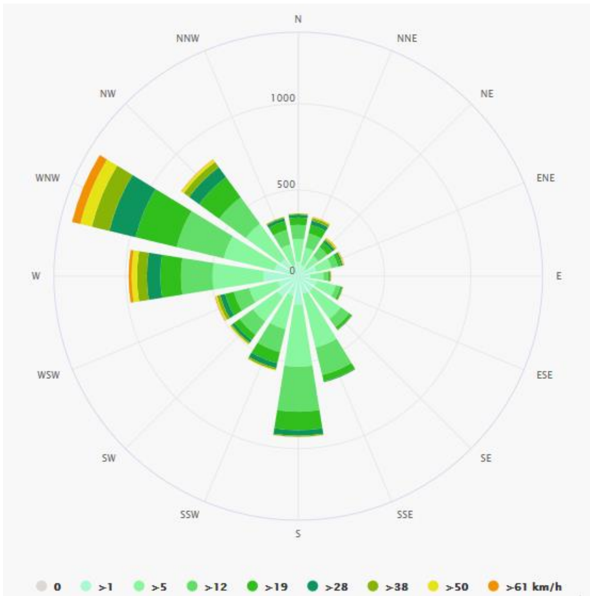


Figure 2.4 Wind rose indicating the number of hours per year (and speed) of wind blowing from the indicated directions. *Illustration obtained from* (Meteoblue, 2020)

The North Atlantic current generates prevailing winds from the NW direction with maximum speed reaching above 61km/h. The winds are dominant during autumn and winter periods, hence causing the increased percipitation, as ellaborated before.

2.1.2 Norwegian definition of Zero Emission and System Boundaries

According to the Research center on Zero Emission Buildings, a ZEB is defined as a building that "produces enough renewable energy to compensate for the building's greenhouse gas emissions over its life span." There are different levels of ZEBs that are based on the phases of building’s lifespan being accessed. Five main definitions exist depending on whether we consider only the emissions from operation, deducted energy for equipment, production of materials, construction and/or demolition/recycling. (Research Center on ZEB, 2016)

A Zero Emission Neighbourhood is defined in the ZEN report no.7 as “a group of interconnected buildings with associated infrastructure, located within a confined geographical area. A ZEN aims to reduce its direct and indirect greenhouse gas (GHG) emissions towards zero over the analysis period, in line with a chosen ambition level with respect to which life cycle modules and building and infrastructure elements to include”. The concept alludes to new, retrofitted or combined buildings on an infrastructure that can include grids and technologies for exchange, generation and storage of electricity, heat, sewage, waste, mobility, water and ICT. The analyses are based on the assumption that the service life for the buildings is 60 years and 100 years for the infrastructure. (Research center on ZEN in smart cities, 2018)

2.2 Singaporean context

The Republic of Singapore is a sovereign island city-state in Southeast Asia since 1965. It is located at the southern tip of the Malay Peninsula at a latitude of 1°22′N and longitude 103°59′E, which is 137 km north of the equator. Singapore is a highly developed country which has a global influence on the economy, being ranked as the 9th on the UN Human Development Index (International Monetary Fund, 2019). Also, it has the 7th highest GDP per capita in the world and has been highly ranked in the key social indicators as education, healthcare, quality of life, personal safety and housing (The Straits Times, 2019).

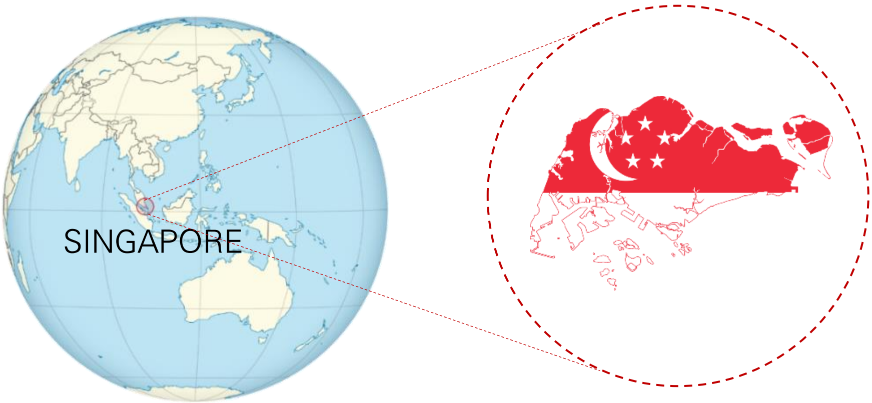


Figure 2.5 Singapore is located at the southernmost point of continental Asia (left). Illustration of the island borders and flag with red and white colours (right).

2.2.1 Singaporean Climatic Context

According to the Köppen-Geiger climate classification Singapore is denoted with - Af, which stands for a tropical rainforest climate defined by temperatures above 18°C in the coldest month and precipitation above 60mm in all months. The name is self-explanatory, as it indicates that in these regions there is no dry season and the rainfall is both heavy and frequent. Additionally, the diurnal temperature variation is larger than the average change in the monthly temperature (Figure 2.8), yielding no definite distinction between summer and winter seasons, since it is consistently hot and wet during the whole year. The Af climate type is usually found around the equator (Figure 2.6 Köppen-Geiger climate classification map (1980-2016). The tropical rainforest climate is predominantly located around the equator, including countries from all continents. *Illustration obtained from.*Figure 2.6), and so it is commonly known as the equatorial climate. However, there are several regions that are located further away and have dominant trade winds during the whole year. They are classified in a distinct subtype referred to as the tropical trade-wind rainforest climate (Godard, 1990).

Singapore's average annual solar irradiance of 1,580kWh/m^2/year is approximately 50% bigger than other countries with temperate climates, which makes it suitable for wider use of photovoltaic (PV) cells for energy generation.

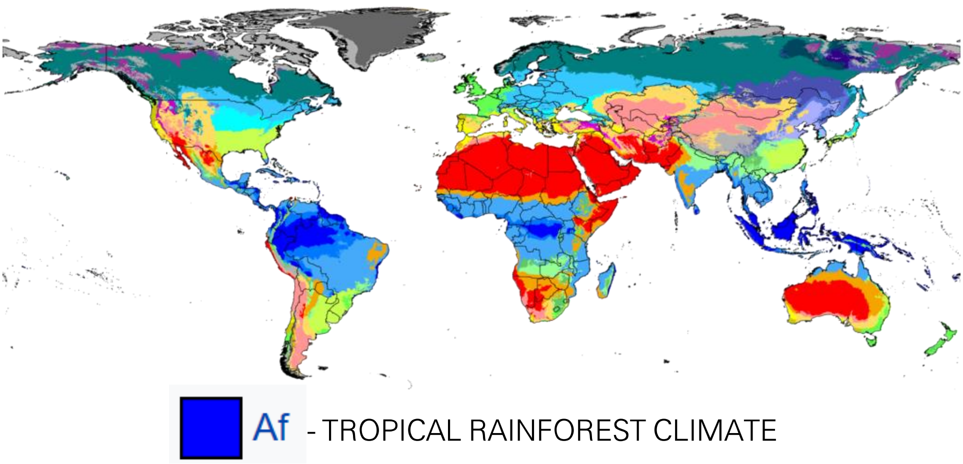


Figure 2.6 Köppen-Geiger climate classification map (1980-2016). The tropical rainforest climate is predominantly located around the equator, including countries from all continents. *Illustration obtained from* (Beck, 2016).

- ·Temperature

The average annual temperature in Singapore is 27.8 C. The warmest month, on average, is June with an average temperature of 28.9 C. The coolest month, on average, is December with an average temperature of 26.7 C. The highest recorded temperature at 34 C was measured in April, and the lowest recorded temperature of 21 C was measured in September. (Weatherbase, 2019)

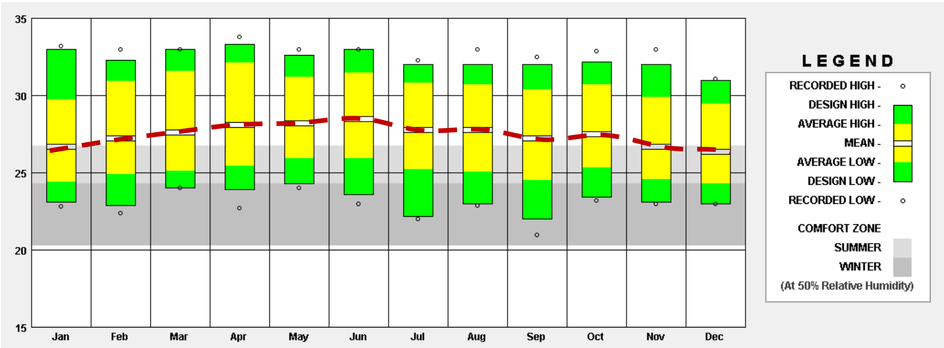


Figure 2.7 Monthly temperature range and average temperatures in Singapore. *Plot generated with ClimateConsultant® 6.0*

The diurnal temperature change in Singapore is more significant than the variation of the average monthly temperatures, which is typical for climates that are classified within the Af type (Figure 1.4). In Singapore, however, the proximity of the sea is a mitigating factor that moderates the influence on the climate and results in reduced diurnal variance. This comes from the fact that water has a higher heat capacity compared to earth, so a greater amount of heat is needed to increase the sea temperature. Such conditions alleviate the cooling process and result in reduced peak temperatures.

In terms of energy efficient design, the high average monthly temperatures translate into buildings aiming to reduce heat gains, as the cooling loads are dominant in the overall operational energy use. Additionally, the relatively constant average monthly temperatures inhibit the applicability of free-cooling systems for chilling fluids in air conditioning systems.

According to the Meteorological Service Singapore, the island has warmed up with a notable increase of average temperature in the mid-1970s due to accelerated urbanization. The statistics are based on continuous temperature records starting from 1948, which indicate that the mean surface air temperature has increased by 0.25 C per decade (Meteorological Service Singapore, 2011). In the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) it is stated that “it is extremely likely that more than

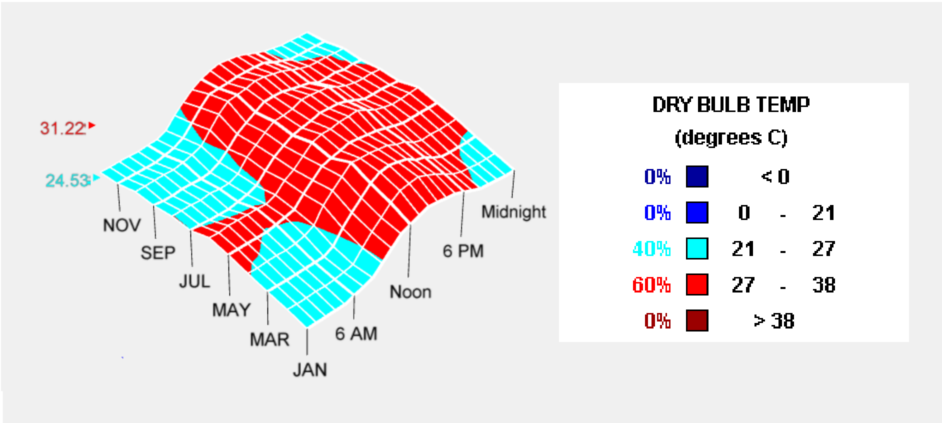


Figure 2.8 Hourly variation of temperature for each month.
Plot generated with ClimateConsultant® 6.0

half of the observed global trend was caused by anthropogenic (human-activity) increase in greenhouse gas concentrations and other anthropogenic forcings”. (IPCC, 2014) However, it must be noted that Singapore is experiencing a higher increase, considering that the ten warmest years have occurred in the last two decades. This could be a reliable indicator of the influence of the urbanization that could be additionally contributing to the elaborated effect. (Meteorological Service Singapore, 2019)

- Precipitation

The amount of precipitation in Singapore on average is 2270.8mm. December is identified as the month with the highest precipitation averaging 269.2mm, opposite to July when the precipitation average is the lowest at 149.9mm. The average number of days with precipitation is 218, with the most rain occurring in November (24 days) and the least rain in February (averaged at ten days) (Figure

2.9). (Weatherbase, 2019) There is a significant diurnal variation in rainfall because the rain is more dominantly occurring during the daytime, with higher frequency during the afternoons when the solar heating is at its peak. Related to the spatial distribution of the island, we can see on Figure 2.10 that the northern and western parts of

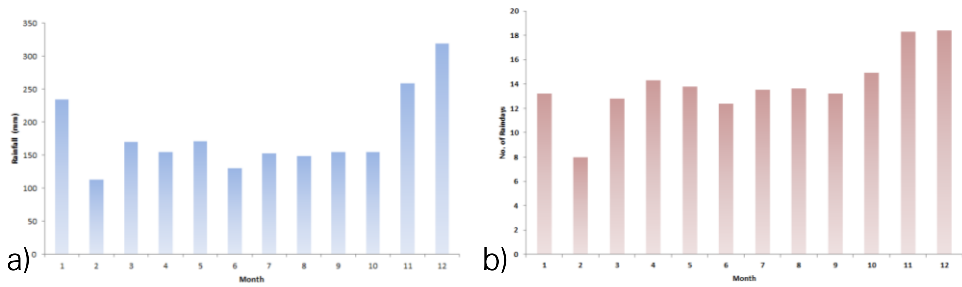


Figure 2.9 (a) Average number of days with rain per month and (b) monthly rainfall based on the measured period 1981-2010.
Graphs obtained from (MSS, 2019).

Singapore have higher rainfall compared to the eastern side. (MSS, 2019)

- Humidity

The relative humidity is also consistent during the whole year because there is no significant monthly variation. The diurnal

Figure 2.10 Average annual rainfall distribution on the island.
Graph obtained from (MSS, 2019).

humidity change is greater than the variation of the monthly average humidity. The mornings before the sunrise are usually attributed with 90% humidity, compared to 60% in the mid-afternoons in days when there is no rain (Figure 2.11). However, there are common situations when prolonged periods of rain induce 100%. The National Environment Agency reports an average relative humidity level of 83.9%. (National Environment Agency, 2018)

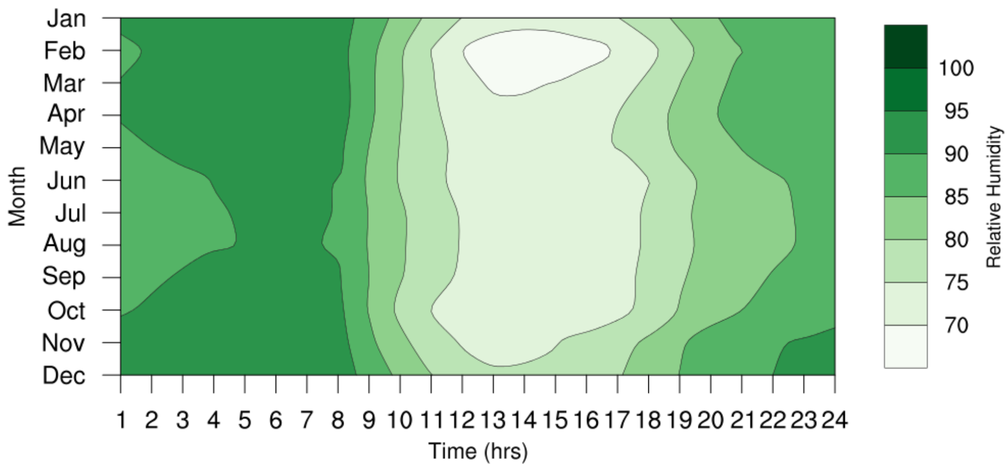


Figure 2.11 Variation in the relative humidity for every month based on records from 1981-2010. *Graph obtained from* (MSS, 2019).

Considering the high average monthly humidity, buildings in Singapore are facing an additional burden when it comes to dehumidification. Latent cooling loads have a significant impact on the overall energy consumption.

- Wind

Singapore has two main monsoon seasons: Southwest Monsoon Season which is from June to September and Northeast Monsoon Season from December to March. The strongest winds with mean speeds of 10m/s prevail during the Northeast Monsoon in January and February (Figure 2.13). There is a noticeable diurnal change in the wind speed in Singapore. Lighter winds are dominant at night, and they become stronger during the day. However, a general conclusion can be drawn that the winds are relatively light, with a mean surface speed less than 2.5m/s. This does not apply in thunderstorm downdraft conditions that produce gusts.

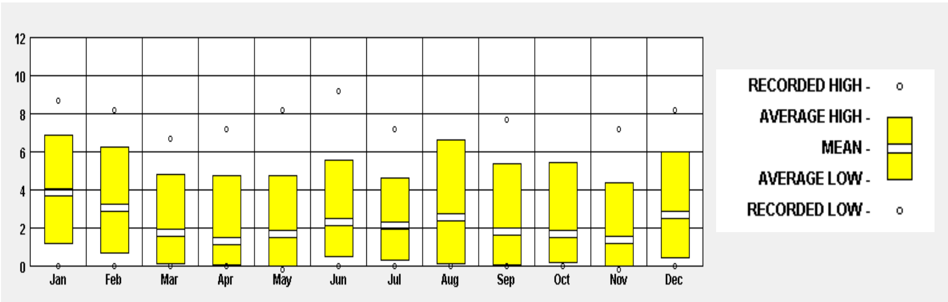


Figure 2.12 Monthly wind velocity range in m/s.
Plot generated with ClimateConsultant® 6.0

The main wind directions are from north and northeast during the Northeast Monsoon and south to southeast during the Southwest Monsoon. In the periods between the monsoons, there are lighter and more variable winds that gradually switch direction unless they are modified by terrain or weather systems (ex. sea breezes or showers).

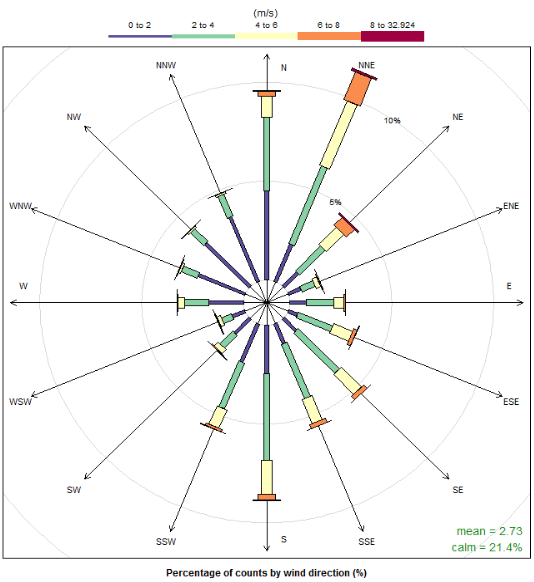


Figure 2.13 Annual wind rose based on data from 1981-2010.
Graph obtained from (MSS, 2019).

Singaporean wind conditions are suitable for implementing natural ventilation that contributes towards significant reduction in cooling loads. The mean surface speed allows for efficient cooling during the day, but can also be utilized during night for cooling down heated thermal masses.

2.2.1.1 The benefits of investigating ZEN strategies in the tropical rainforest climate

Current research on ZEN strategies is predominantly focused on the cold climatic context, which can be problematic when we want to implement the defined solutions in warmer climates. This invokes the need for detailed analyses on the adaptation of the strategies and investigation of new solutions that would be efficient for the different conditions. Norwegian climate is classified as temperate and continental, so an extreme opposite is a tropical climate, which makes Singapore one of the optimal choices for the topic. The conclusions that will be obtained based on this climate type can be easily implemented in the other tropical climate(A) types: tropical monsoon climate (Am) and the tropical wet and dry (savanna) climate (Aw/As). Additional minor variations and adjustments can improve their applicability in other warm climate types, such as:

- Desert climate (BW);
- Semi-arid (steppe) climate (BS);
- Humid sub-tropical climate (Cfa);
- Hot-summer Mediterranean climate (Csa);
- Warm-summer Mediterranean climate (Csb).

Such adaptability potentiates the benefit of the investigation, which will contribute towards a complete general overview of sustainability strategies and guidelines for further detailed research, not only for South and Southeast Asia, but also for all regions with similar climate types.

2.2.2 Singaporean Political Context

The Republic of Singapore has gained its independence on 9 August 1965 with the first prime minister Lee Kuan Yew. He is known for his politics focused on supporting business entrepreneurship and rapid economic growth with limitations on the democratic processes. Some activists and opposition politicians consider the regime to be authoritarian, as it induces strict regulation on political and media activities. However, such approach has contributed to efficient implementation of laws and policies and has produced an economic success. (McCarthy, 1999) Additional factors, such as the improved life quality and stability have progressed the Republic into a first world country (The Straits Times, 2015). This has been and continues to be a crucial element of Singaporean progression, as it attracts investors and highly qualified professionals to invest their resources and knowledge in the country. Today, Singapore is an important logistics and transportation hub and major tourist destination. (Lee Kuan Yew School of Public Policy, 2018)

The climatic conditions that we explained in Chapter 2.2.1 were not considered favorable during the progression of the country. Lee Kuan Yew addressed the need for air-conditioning all public spaces, which would alleviate the harshness and unpleasantness of the heat (The Straits Times, 2015). Today, the measure has been translated into the Singaporean Standard CP 13, which is a code of practice for mechanical ventilation and air-conditioning in building. According to the specification "a thermal comfort is achieved when the indoor temperature is maintained between 22.5°C and 25.5°C, with an average relative humidity not exceeding 70%". However, there is a pronounced inclination to cool down spaces at a temperature closer to the lower boundary of the standard. (The Straits Times, 2007)

As a highly developed country, Singapore is bound to align itself to global trends and join the sustainability movement. Nevertheless, such efforts date back to 1967 when the prime minister Lee initiated a vision for developing the country into a garden city with abundant lush greenery and clean environment (The Straits Times, 2015). The governmental awareness of environmental impacts from urbanization and rapid economic growth has resulted in setting the first environmental blueprint in 1992. Currently the Singapore Green Plan (SPG) 2012 and the Sustainable Singapore Blueprint (2030) are dictating the green policies of the nation by setting environmental targets that ensure sustainable development. They include measures for implementing water supply from non-conventional sources, reducing domestic water consumption, increasing waste-recycling rate, conserving nature, reducing ambient particle matter 2.5 etc. (Chew, 2016)

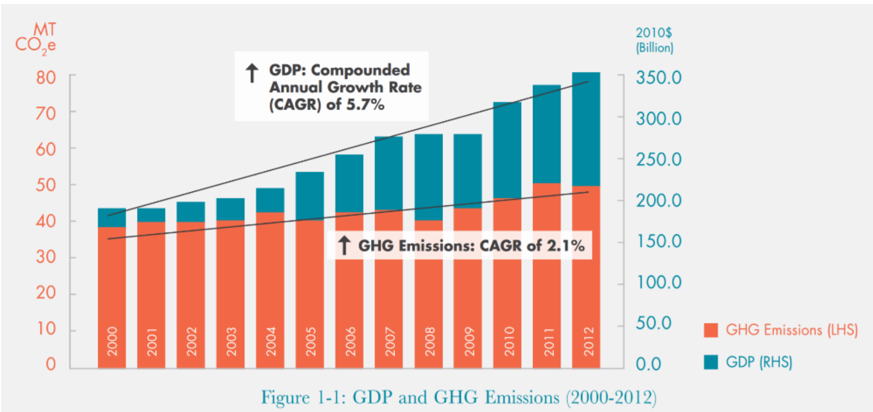


Figure 2.14 GDP and GHG emissions in Singapore (2000-2012)
Graph obtained from (Green House Design + Communications, 2016)

Even though Singapore's economy grew at an annual rate of 5.7 per cent, GHG emissions maintained slower growth at 2.1 per cent (Figure 2.14). However, the country still contributes to global GHG emissions with around 0.11 per cent. According to the Sustainable Singapore Blueprint (2030) emissions will be addressed by focusing on reducing PM 2.5 particles and SO_2, as well as PM 10 particles, CO, NO_2 and ground level ozone. The first group is predominantly targeted in reducing emissions from the industries by imposing SO_2 caps, real-time monitoring, legislating concentration standards etc. The second group of pollutants is besieged through emission reduction from vehicles. The strategies include tightened standards, enforced fuel quality regulations, encouraging purchase of new vehicles and turnover of old diesel cars. Still, the annual emissions for some of these gases have not been decreasing sufficiently (Figure 2.15 shows an increase in recent years), which potentiates the need for a more extensive approach that could include the building sector. (Ministry of Environment and Water Resources (Singapore), 2015)

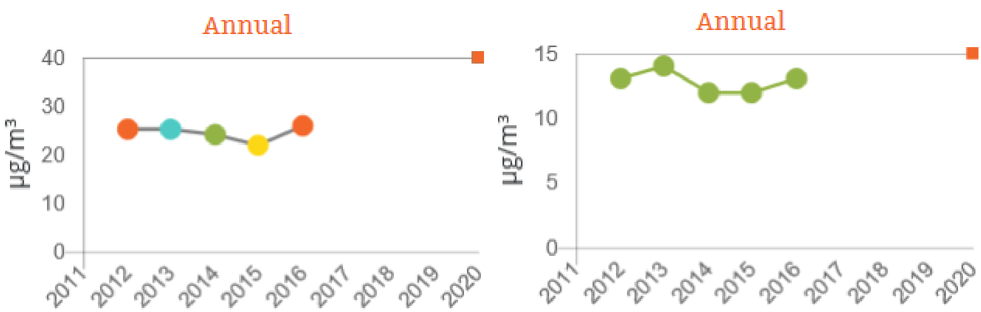


Figure 2.15 Annual Singaporean emissions of a) NO_2 and b) SO_2.
Graph obtained from (Ministry of Environment and Water Resources (Singapore), 2015).

2.2.3 Singaporean environmental performance benchmarking scheme - Green Mark

In recent years, the authorities have been focusing on new policies that are expected to reduce energy demands in the building sector. They are regulated and implemented by the Building Construction Authority (BCA) which is a statutory board under the Ministry of National development. It is anticipated that energy requirements will be lowered in new and retrofitted buildings, through the implementation of an environmental performance benchmarking scheme denoted as "Green mark"[2]. (Building Construction Authority, 2017) The main purpose of the rating is to reduce use of

[2] Closest analogy can be drawn to the BREEAM-NOR certification by the Norwegian Green Building Council (Grønn Byggallianse, 2015)

energy, water, resources and environmental impact, improve indoor environmental quality and provide clearer direction for improvement. A set of evaluation criteria are assessed giving the total number of points which indicate the rating of the building. The maximum obtainable points are 140, but a building that would be rated with the highest standard – "Green mark Platinum" needs only 90 points, whereas the lowest standard requires 50 points. (Building Construction Authority, 2016)

Requirements	Points
Climatic responsive design	30
Building energy performance	**30**
Resource stewardship	30
• **Materials**	**18**
Smart & Healthy building	30
• **Thermal Comfort**	**2**
• **Minimum Ventilation Rate**	**3**
Advanced Green efforts	20
• **Enhanced Performance**	**15**
Total	140
GHG reduction-related points	**68**
Green mark platinum rating	> 90

Figure 2.16 Sections of the Green mark benchmarking scheme with the total corresponding points and extracted points related to GHG emission reduction. The highest ranking – "Green mark platinum" requires a total of 90/140 points.

Figure 2.16 shows the main sections of the assessment and the total points for each, with selection of the points that can be related to reduction of greenhouse gas emissions. 68 points are related to GHG reduction, demonstrating that a building could easily be Green mark certified, or even Green mark Platinum rated even if no or very little GHG reduction is considered. The significant lack of focus on reducing GHG emissions from buildings, is an important topic that needs to be considered in the country's green ambitions.

2.2.4 Singaporean definition of Zero Energy and System Boundaries

In the Singaporean context the idea of a building with zero emissions is not developed yet, as it was explained in Chapter 2.2.2. The current ambition is to focus on Zero Energy Buildings that will mainly be retrofitted exiting constructions. The BCA defines a ZEB as "a building that is aiming to produce enough energy to run itself" by implementing "a combination of green building technology, clever building design that takes advantages of natural ventilation and lighting ('passive design'') and the harnessing of solar energy". (Building Construction Authority (Singapore), 2010)

The idea of a Zero Emission Neighbourhood is an obscure and far-fetched goal for the current political ambitions in Singapore. However, this does not obstruct the potential to implement ZEN strategies and demonstrate their benefit in the tropical context.

Materials and Methods

3.1 Passive strategies in tropical climates

Passive design strategies are an integral part in the process of increasing a building's energy efficiency. They are the first measure for reducing operational energy demands by reducing the cost of active design strategies. Cooling and heating loads can be decreased if the building is designed with appropriate passive strategies that embrace and utilize the climatic context. A comprehensive understanding and immersion into the topic are required in order to achieve maximum benefit from the implementation. The literature supporting different approaches applicable in tropical climates is dispersed and non-cohesive, so a clear overview had to be made for understanding the potential. Several sources have been consulted for compiling a list of optimal strategies relevant for the NTU campus:

- Design guidelines from Climate consultant®.
  The software generates guidelines based on different indoor comfort conditions based on the climatic context, which is describe quantitatively using EPW weather data files for Singapore from the EnergyPlus datasets. The proposals include the free online platform 2030 Palette, which is a resource for the design of zero net carbon, adaptable and resilient built environments worldwide. (Architecture 2030, 2018)

- "Sustainable building design for tropical climates: Principles and Applications for Eastern Africa" – UN Habitat.

A book dealing with the growth in energy consumption for air-conditioning that is exacerbated due to *inappropriate* architecture. A set of design strategies are analyzed in detail in attempts to explore the term sustainable architecture within the context of tropical climates. (Federico M. Butera, 2014)

- “Adapting zero carbon houses for tropical climates – passive cooling design in the Philippines” - Robert Wimmer.
  A paper that presents systematic approaches on applying passive cooling principles in the tropics with a practical example of a Zero Carbon building realized in the Philippines. (Wimmer, 2016)

- “Passive design in tropical zones” - Housing for health.
  A guide on passive strategies for residential buildings in Australia, with recommendations for reducing active cooling based on experimental projects. (Housing for health, 2017)

A catalogue of passive design strategies is composed on the following pages. It incorporates solutions that may be identified on some of the buildings at the NTU campus. They could have been used intentionally or as an indirect consequence of urban design (ex. a new building close to the existing one shadowing the west façade, hence protecting from overhearing and acting as a passive strategy). For the proposals that are not found on the campus, a further investigation in Chapter 4.2 will analyze their potential applicability.

Exterior wingwalls

Wind direction can be changed up to 45°C towards the building to capture natural ventilation with exterior wingwalls. With correcting placing the wingwalls can provide appropriate circulation inside and give efficient cooling by removing the hot humid air. This would decrease the required air conditioning for maintaining the appropriate temperature inside.

Window orientation

If windows are oriented towards prevailing breezes, good natural ventilation can be obtained. This would provide appropriate circulation inside and give efficient cooling by removing the hot humid air. This would reduce or eliminate the required air conditioning. In the context of NTU, the the annual prevailing breeze is from the north-east direction.

Long narrow floorplan

In hot humid climates cross ventilation can be maximized if long narrow building floorplan is utilized. In this case if possible door and window openings should be placed on opposite sides of the building with larger opening facing up-wind if possible. Lateral openings are suggested to be smaller or non-operable.

Jump ducts

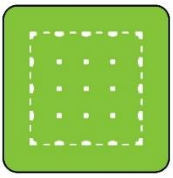
Jump ducts can promote natural cross ventilation if privacy is required, as they can substitute open floor plans or louvered doors for partitioning the space. They can be combined with fans to induce ventilation in cases of insufficient air flow.

Louvered openings

Windows that catch the breeze and can be left open in wet conditions, suchs as screenings, louvers, casements or awning windows can promote natural ventilation. Metal louvers can be used at low level to admit cool breezes and glass louvres can be used high above the windows to let out hot air and admit light above curtained or shaded areas.

Ceiling fans

On hot days ceiling fans or indoor air motion can make it seem cooler by 2.8°C or more, which reduces the required air conditioning for maintaining the temperature inside. They can promote natural ventilation and help the removal of hot air through the vented roof or high louvered windows.



Open plan interiors

Open plan interiors promote natural ventilation and eliminate obstacles and partitions that could compromise the ventilation. They are the optimal alternative to louvered openings and/or jump ducts when the function of the building does not require privacy and strict division of the plan.

Air inlet - outlet vertical difference

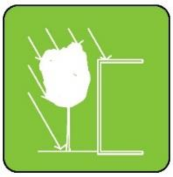
The vertical height difference between the air inlet and outlet should be maximized in order to produce stack ventilation, even when wind speeds are low. This can be achieved in open stairwells, two storey spaces or in rooms with high ceilings.

'Night flushing"

High-mass interior/exterior surfaces such as brick/concrete walls and floors and heat from the roof can be accumulated and stored during the day. This heat is then released at night and removed with ventilation. However the solution is not good for residential buildings, but buildings that are not occupied at night can benefit from it.

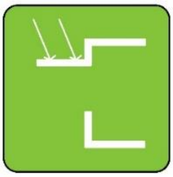
Shaded outdoor buffer zones

Shaded zones oriented at the prevailing winds can extend occupancy spaces in hot humid climates. If using high-mass exteriors the eastern and western walls should be shaded. This can be done with incorporated or separate elements depending on the architectural integrity of the building.



Trees

Spaced trees can provide shading and minimize heat-gains on the external walls and/or roof. They can be used to form a canopy above window level with little foliage at lower levels for optimal shading. The air will flow at the building level and the shade will cool it down before it is drawn inside. Dense planting should be avoided because it can block breezes.



Window overhangs

Window overhangs can reduce heat gains and the need for air conditioning. In tropical climates shading does not need to be operable and it can be an integrated element as the temperature and sun direction is approximately constant during the whole year.

Drawn openings

Providing elements which 'draw in' openings placed at the upper part of the wall helps to redirect and diffuse the light. Additionally, heat gains on the walls and floor inside are reduced due to the avoided direct exposure.

Hanging/ivy plants

In tropical climates the amount of rain supports native plant growth. This can be beneficial for placing hanging plants that minimize heat gains on external walls. Another option is to provide ivy-covered walls that grow from the bottom-up, but they are less efficient as they cannot be used for shading and can become breeding areas for mosquitoes and other pests.

Occupied basements

It is easier to maintain needed temperature in occupied basements and minimize air conditioning. This is due to reduced heat loads from the earth which stays near average annual temperature. However, appropriate drainage is required as tropical climates are characterized by heavy rains.

Low pitched roofs

Low pitched ventilated roofs with wide overhangs increase height and help natural ventilation. They are appropriate for humid climates as they provide improved drainage. The overhangs shade the external walls and reduce heat gains. In some cases the roof can be extended in order to create a shaded buffer zone.

Covered atria

Covered atria can provide shade for the enclosed spaces which helps to reduce temperatures inside and enforce night flushing by aiding natural ventilation during night. Covered external areas are always efficient for cooling the air and reducing heat gains on the external walls.

Atria

Internal courtyards are elements from the vernacular architecture that enhance natural ventilation and provide comfortable external spaces. They increase the natural lighting without increasing heat gains.

Evaporative cooling

The temperature around water surfaces can be reduced as a result of the evaporation which removes latent heat from the surface . Small basins can be placed outside the building to collect rainfall water and induce heat reduction.

Dominant north openings

Orient most of the opening to the north, shaded by vertical fins, in tropical climates because there are essentially no passive solar needs. North glazing balances daylight and it is expected not to be less than 5% of the floor area.

Reduced west openings

Minimize or eliminate west facing openings to reduce afternoon heat gains. The openings need to be shaded and louvered in order to gain from the wind direction.

Reflective roof surface

A radiant barrier (ex. shiny foil) will help reduce radiated heat gain through the roof as it will reflect a part of the heat. PVs can add to this benefit while providing energy and shading the area beneath them.

Vented roof

Well ventilated pitched roofs allow air to go through and cool the surface area which reduces heat transmission to lower levels and induces lower heat gains. They work well to shed rain and can be extended to protect entries and outdoor occupancy areas.

Green roof

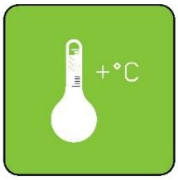
Using grass or ground covers rather than concrete or sealed surfaces helps the roof to behave as a thermal mass, by absorbing heat and re-radiating into the building during night.

Low wall-to-window ratio

Reducing the total area of the openings is beneficial for reducing heat gains during the day and promoting storage of heat in the exterior walls. This can be applied to buildings that are not expected to be occupied during the night, when 'night flushing' needs to take place.

Surface color

Use light/ more-reflective colored surfaces (with high emissivity) minimize conducted heat gains. The opposite applies to surfaces around the building, as they should not reflect the heat and light onto the building's exterior.



Raised thermostat setpoint

Raise the indoor comfort thermostat setpoint to reduce air conditioning energy consumption. This requires the users to be sensible to energy reduction and wear clothing appropriate to hot humid climates. Over-cooling results in low energy-efficiency of the building.

3.2 GHG emissions from cooling

In this thesis, the performance of the buildings is quantified through the estimated Greenhouse gas (GHG) emissions for cooling. The observations are focused on cooling loads as they represent 75% of the total electricity consumption in non-residential buildings in Singapore.[3] (Building and Construction Authority, 2018) This is to be expected, as cooling is the dominant requirement in warm climates where dry bulb temperatures are above comfort levels.

3.2.1 GHG emissions calculation

The calculations for the emissions are based on the energy consumption of the buildings and the electricity grid mix factor. The latter is defined as carbon intensity of electricity generation disaggregated by simple operating margin (OM) and build margin (BM) (in $kgCO_2/kWh$). The data for the margins in the Singaporean context is obtained from the Energy Market Authority (computed in accordance with UNFCCC[4]). (Energy Market Authority - Singapore, 2020)

Table 1: OM and BM for 2018 **(Energy Market Authority - Singapore, 2020)**

Electricity Grid Emission Factor / Year	2018
Average Operating Margin (OM) ($kgCO_2/kWh$)	0.4188
Build Margin (BM) ($kgCO_2/kWh$)	0.4031

[3] 15% of those fall off to mechanical ventilation, but the calculations are based this combination so the total percentage is considered relevant.
[4] United Nations Framework Convention on Climate Change

For the calculations the Combined Margin (CM) is obtained by combining the OM and BM, using the weighing: **50% OM; 50% BM**, which is based on firm electricity generation (ex. hydropower, geothermal and biomass). There is the possibility to consider variable electricity generation (ex. wind and solar PV) that would have implied the weighing **75% OM; 25% BM**, but this is not applicable for the current energy generation systems in Singapore. The used weighting is based on UNFCCC standards, but it is limiting to an extent, so in the future it is expected that weighting modifications could include additional factors, such as countries with high or low demand growth. (Asian Developmet Bank, 2017)

The following general equation is used for calculating the GHG emissions in this thesis:

$$GHG_{emissions} = EC \cdot E_{elec} \tag{3.1}$$

where:

EC - electricity consumption $[MWh/year]$

E_{elec} - electricity emission factor $[tCO_2/MWh]$. Considering that the electricity is from the grid, this refers to the grid emission factor that is quantified through the combined margin. Using the specified weighting, we obtain:

$$E_{elec} = 0.5 \cdot 0.4188 + 0.5 \cdot 0.4031 = 0.41095 \frac{tCO_2}{MWh} \tag{3.2}$$

- Calculation based on data for 12 months

Some of the obtained data is based on operational energy for cooling for several consecutive years. In those cases, the calculation of the emissions is based on the following equations:

$$EC = \frac{\sum_{20\mathrm{xx}}^{2019} \sum_{Jan}^{Dec} month}{\mathrm{Y}} \tag{3.3}$$

where Y is the number of years for which data is measured. The obtained value is in the units $[kWh/year]$.

Then using Equation (3.1) we obtain the emissions from operational energy. It is important to divide this value with the total conditioned area in the building (A) in order to define the emissions per square meter. This is essential for providing a comprehensible comparation between the performance of different buildings.

$$Emissions_{BUILDING\ X} = \frac{GHG_{emissions}}{A}; [\frac{kWh}{year \cdot m^2}] \quad 3.4$$

- Calculation based on data for 2 months

The buildings that are built recently do not have data on cooling operational energy for a longer period. At the point of obtaining the information on their energy performance, there were only two months of data available. Therefore, a viable approach had to be considered in the emission calculations in order to avoid unreliable conclusions.

The following graph shows the cooling loads in an academic building with a 12-month consumption data over three years. As expected, considering the 2.2ºC difference in average temperature between the warmest and coldest month (Chapter 2.2.1), there is no significant variation in the cooling loads.

Taking in consideration that the obtained data is for the months March and April, and comparing it against Figure 3.1 we can conclude that the calculation of the annual cooling loads should be based on the consumption in March. This is because in that month the consumption is closest to the average, in contrast to April, when most of the peaks are observed. Additionally, we would avoid Therefore, the equation for calculating the annual loads is not based on the average between the two months, because it is most likely to would give a false high demand.

$$EC_{BUILDING\ XX} = 12\left[\frac{\text{month}}{\text{year}}\right]\cdot \text{March [kWh]} \tag{3.5}$$

The emissions are calculated with Equation 3.1 and 3.4 accordingly.

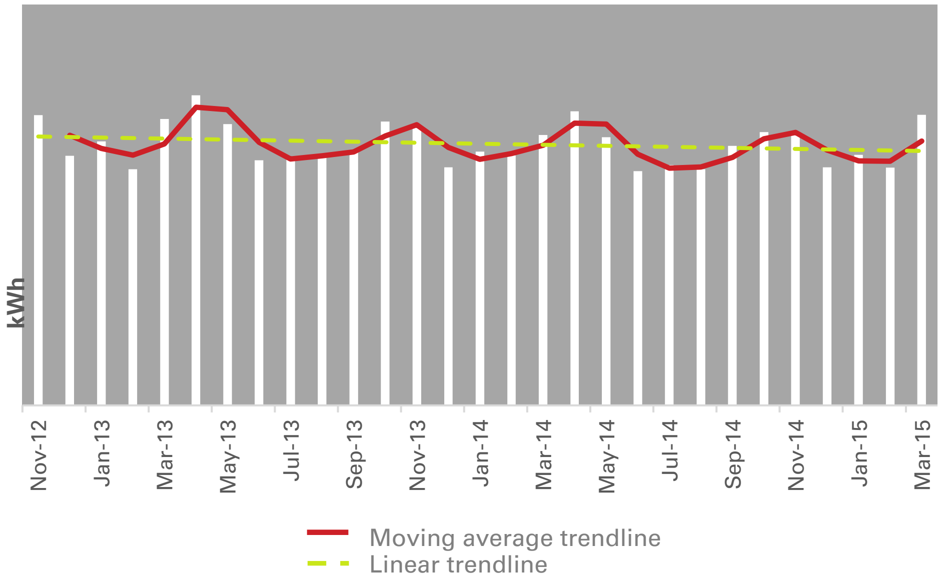


Figure 3.1 Cooling loads in an academic building with a 12-month consumption data over three years depicting the moving average and linear trendline.

In order to compare the results, the obtained values are normalized according to the highest demanding building, which yields a visual comparison.

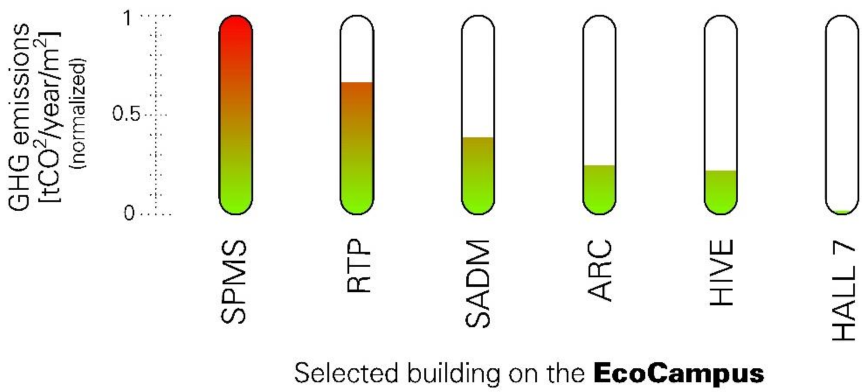


Figure 3.2 Normalized GHG emissions from cooling for selected buildings, based on the building with highest emissions.

3.3 NTU EcoCampus

Figure 3.3 Nanyang Technological University located near the west coast of the Singaporean island. *Image retrieved from Google maps.*

The main campus of the Nanyang Technological University is located near the west coast of the island and covers an area of $2km^2$ making it the largest university campus on the island of Singapore. A current initiative under the name "EcoCampus" by the Energy Research Institute (ERI@N) and Sustainable Earth Office at NTU aims to develop a novel sustainability framework with the objective to create the world's most eco-friendly campus. The means for achieving the goal have transformed the area into a test bed for research projects with cutting-edge technologies that are expected to reduce water, waste and energy consumption by 35% by 2020, compared to the baseline of 2011. To this date, the project has already reached a 20% decrease in water and energy consumption. (Nanyang Technological University, 2015) These ambitions make NTU's campus the ideal ground for implementing ZEN strategies and validating their applicability and required adjustments.

3.4 NTU *Existing* EcoCampus – Mapping of Existing Site level energy profiles and synergies

Map 1 shows the existing situation on the NTU campus, for a selected region of interest which encompasses the South- and North-spine academic buildings with a few administration buildings. The road is used as a boundary to define an area for implementing ZEN strategies. Some of the buildings are separated with distances longer than 300m, so students use covered pathways to walk between them in order to avoid exposure to the sun during the day. The map also depicts existing PV installations on the roofs, which form of the largest single PV system in Singapore (Nanyang Technological University, 2015). The current distribution of plants around the buildings is limited to certain areas and there are also patches of ground that are directly exposed to the sun.

map 02 SCALE 1:1000

EXISTING SITUATION

Nanyang Technological Univeristy - Ecocampus

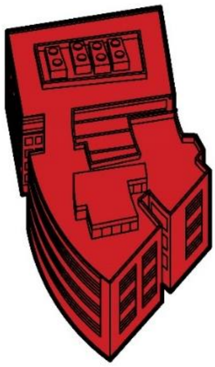
3.4.1 Profiles of selected buildings

A selection of six buildings is the base for proposing synergy in the aim to approach zero emissions. The choice is based on function, size, year of design and location. Every building is distinctive from the rest of the campus by at least one of the evaluated elements and has a function that imposes different energy demands compared to the other selected buildings. On Map 2 each of the buildings has been attributed with the identified passive strategies based on the catalogue from Chapter 3.1. Each building is assosiated with the appropriate energy profile, calculated with the method in Chapter 3.2.

The chosen buildings are:

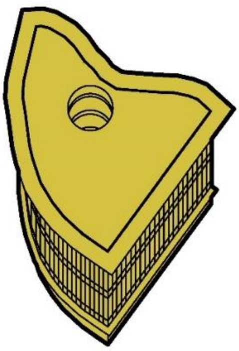
- School of Physical and Mathematical sciences
- Research Techno Plaza
- School of Art, design and media
- The Arc
- The Hive
- Hall of Residence 7

Each profile shows an isometric view of the building and an exploded isometric view of the conditioned floor area (in reference to the gross floor area). The general information section provides details about typology, year of constructon, capacity and a brief summary of the building. This is complemented with the identified passive strategies that have been incorporated in the design intentionally and/or spontaneously. The color of the building indicates the per cent of naturally ventilated area and the type of cooling system used: mechanical (red); mechanical + natural ventilation (orange) or natural ventialtion (green).



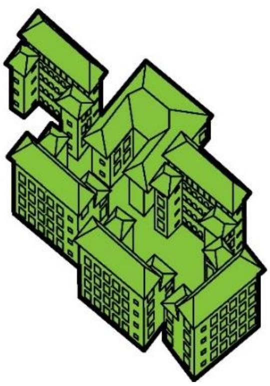
0-25% naturally ventilated

Dominantly mechanical cooling



25 - 80% naturally ventilated

Combined mechanical cooling
and natural ventilation



80 - 100% naturally ventilated

Dominantly natural ventilation

map 02 SCALE 1:1000

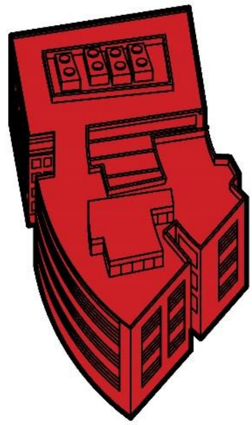
SELECTED BUILDINGS

Nanyang Technological Univeristy - Ecocampus

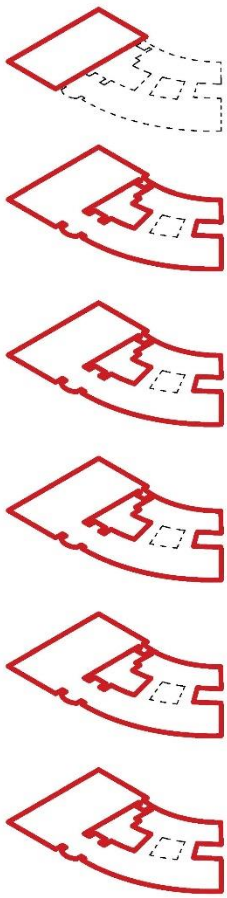
LOW HIGH

GHG EMISSIONS FROM COOLING **0.0734** $\frac{t\,CO_{2eq}}{m^2\,year}$

0% NATURALLY VENTILATED



ISOMETRIC VIEW



Conditioned Floor Area

Gross floor area

EXPLODED FLOOR ISOMETRIC

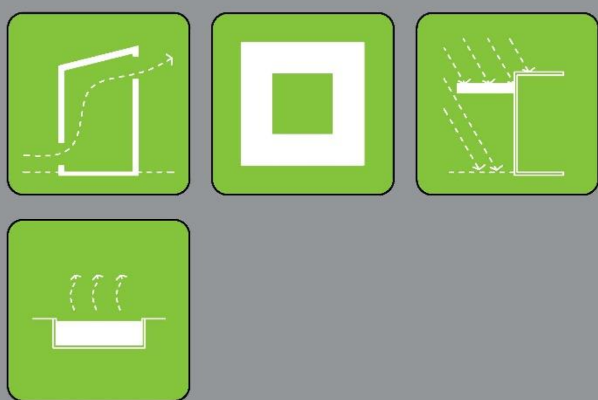
GENERAL INFO

SCHOOL OF PHYSICAL AND MATHEMATICAL SCIENCES (SPMS)

Function:	School
Gross floor area:	40.912m^2
Conditioned floor area:	40.500m^2
Floors:	6
Student capacity:	2350
Year of construction:	2009
Location:	21 Nanyang Link
Architect:	N/A

This scientific complex is designed from the ground up to provide a conducive environment for education and research. It houses three divisions: Chemistry and biological chemistry, Mathematical sciences and Physics and applied physics. Together they have over 100 faculty members, 250 full-time research staff, and 25 administrative staff for 2000 undergraduate students and 350 graduate students. The building has laboratories for each department that use equipment day and night due to the need for sustaining different subtsances and orgranisms. There are additional energy demands from cooling requiremnts for the clean laboratories bec of special regulations.

SUMMARY

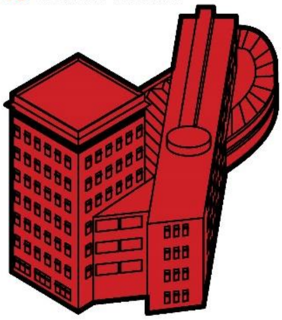


PASSIVE STRATEGIES

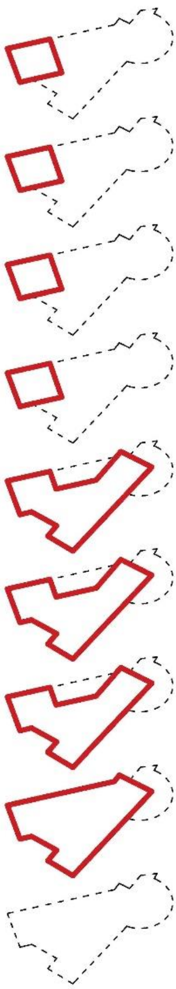
LOW HIGH

GHG EMISSIONS FROM COOLING **0.0484** $\frac{t\,CO_{2eq}}{m^2\,year}$

0% NATURALLY VENTILATED



ISOMETRIC VIEW



Conditioned Floor Area

Gross floor area

EXPLODED FLOOR ISOMETRIC

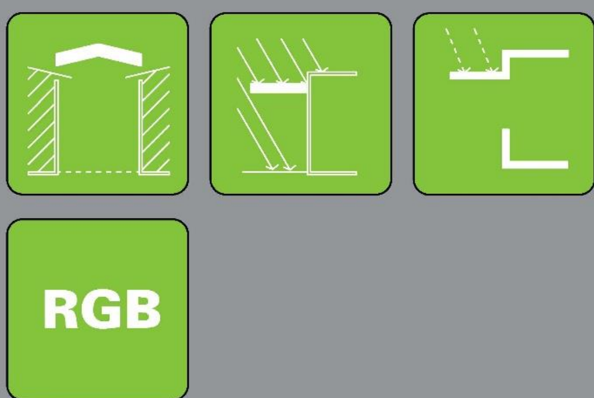
GENERAL INFO

RESEARCH TECHNO PLAZA

Function:	Research center
Gross floor area:	20.792 m^2
Conditioned floor area:	18.400 m^2
Floors:	8
Student capacity:	N/A
Year of construction:	2004
Location:	52 Nanyang Drive
Architect:	CPG Consultants

The building is made of four volumes: 4-storey atrium, 6-storey linear block, 9-sotrey tower block and an adjacent structure which houses the parking for staff and visitors to the center.. It houses ten research centers in different areas, with the aim to synergise them under one roof. There are 6 clean rooms, research and teaching laboratories, bio-engineering corridor, a broadband and wireless communication center, environmental research center, reality theatre, the Nanyang Technopreneurship Center, center for high performace embedded systems and Temasek Laboratoreis.

SUMMARY



PASSIVE STRATEGIES

LOW HIGH

GHG EMISSIONS FROM COOLING 0.0281 $\frac{t\,CO_{2eq}}{m^2\,year}$

0% NATURALLY VENTILATED

ISOMETRIC VIEW

GENERAL INFO

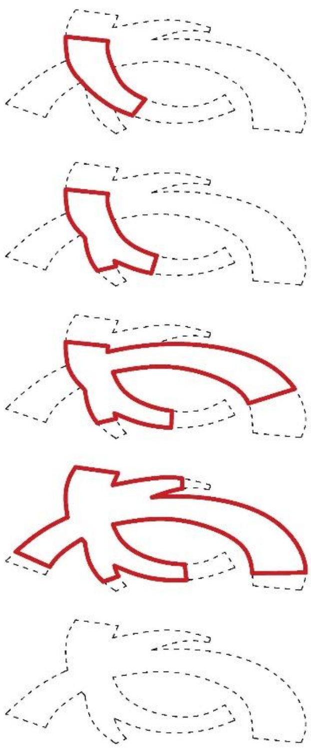
SCHOOL OF ART, DESIGN AND MEDIA

Function:	School
Gross floor area:	18.799 m^2
Conditioned floor area:	12.027 m^2
Floors:	2-5
Student capacity:	900
Year of construction:	2006
Location:	81 Nanyang Dr.
Architect:	CPG Consultants

The building is defind by a green roof made from two tapering arcs that slope at almost 45 angle, made from ribbed, reinforced concrete. They define three interwoven blocks of the school that enclose a sunken courtyard in a pleasant flow. The roof is an aesthetic feature that doubles as a scenic outdoor communal space that is also expected to reduce indoor temperature during the day by 2 C compared to conventional solutions.

The school is fitted with museum track lighting and climate-controls for safe preservation and presentation of valuable works of art, according to high international museum standards.

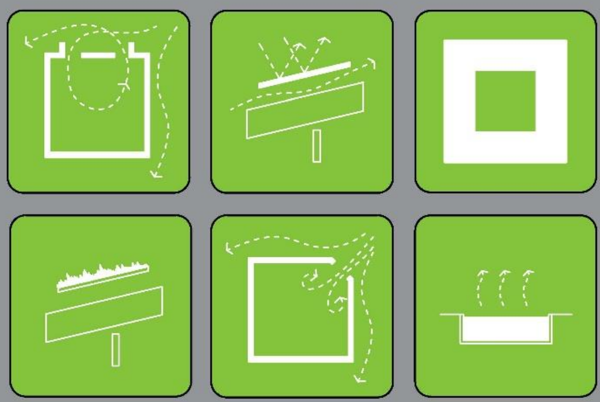
SUMMARY



Conditioned Floor Area

Gross floor area

EXPLODED FLOOR ISOMETRIC

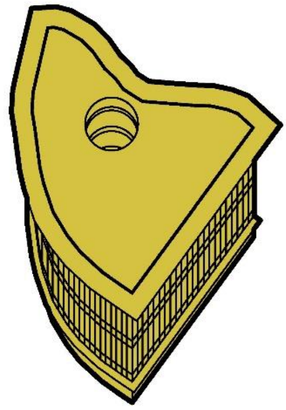


PASSIVE STRATEGIES

LOW HIGH

GHG EMISSIONS FROM COOLING **0.0179** $\frac{t\,CO_{2}\,eq}{m^{2}\,year}$

69% NATURALLY VENTILATED

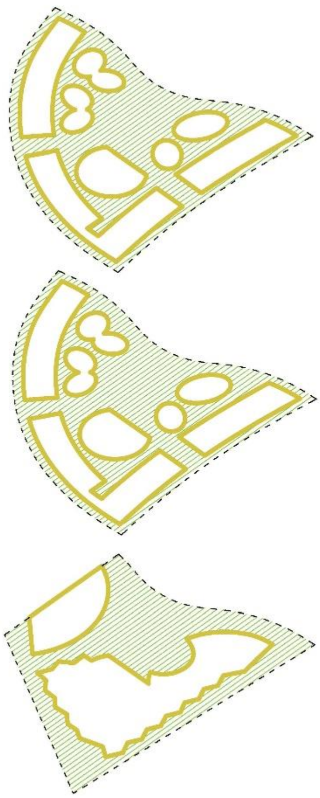


ISOMETRIC VIEW

GENERAL INFO

THE ARC

Function:	Learning hub
Gross floor area:	18.113 m2
Conditioned floor area:	12.679 m^2
Floors:	6
Student capacity:	1015
Year of construction:	2018
Location:	Western Water
Architect: Richard Kirk	architects / DCA

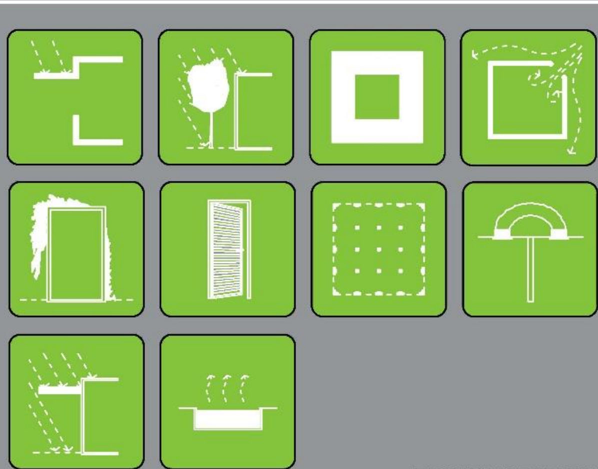


Conditioned Floor Area
Gross floor area
Naturally-ventilated area

EXPLODED FLOOR ISOMETRIC

The learning hub uses a novel approach for classrom clustering design in a layout with series of "learning platforms" which allow diversity and flexibility in learning patterns, modes and technologies. The building embraces new performative design technologies for the design to work passively with the tropical climate. The structure accelerates outside air thorugh its permeable facade and ensured natural vantilation for 30% of the floor area. Additionally, it houses NTU's Singapore Center for 3D Printing, which is researching novel smart technolgies.

SUMMARY

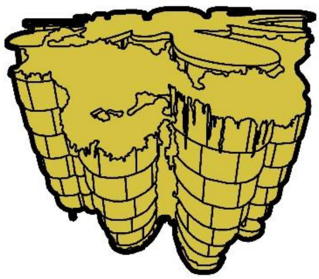


PASSIVE STRATEGIES

LOW HIGH

GHG EMISSIONS FROM COOLING **0.0187** $\frac{t\,CO_{2eq}}{m^2\,year}$

79% NATURALLY VENTILATED



ISOMETRIC VIEW

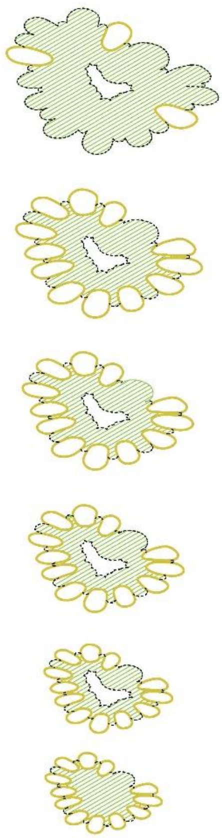
GENERAL INFO

THE HIVE

Function:	Learning hub
Gross floor area:	15.273 m2
Conditioned floor area:	12.218 m^2
Floors:	8
Student capacity:	1680
Year of construction:	2015
Location:	52 Nanyang Av.
Architect:	Thomas Heatherwick

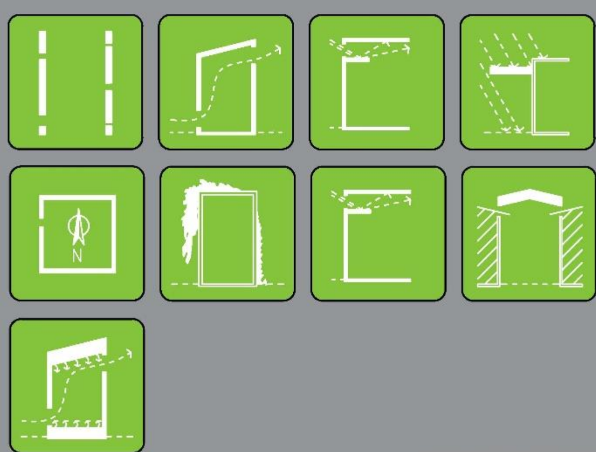
The learning hub uses a novel approach for classrom clustering design in a layout with series of “learning platforms” which allow diversity and flexibility in learning patterns, modes and technologies. The building embraces new performative design technologies for the design to work passively with the tropical climate. The structure accelerates outside air thorugh its permeable facade and ensured natural vantilation for 30% of the floor area. Additionally, it houses NTU’s Singapore Center for 3D Printing, which is researching novel smart technolgies.

SUMMARY



Conditioned Floor Area
Gross floor area
Naturally-ventilated area

EXPLODED FLOOR ISOMETRIC

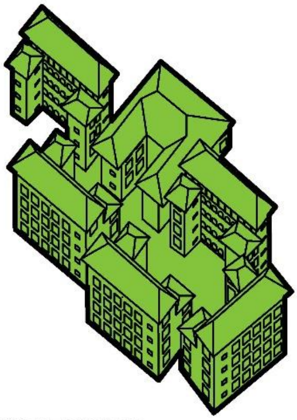


PASSIVE STRATEGIES

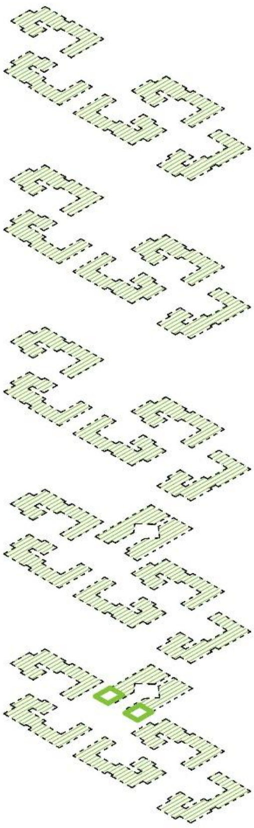
LOW HIGH

GHG EMISSIONS FROM COOLING **0.001** $\frac{t \cdot CO_{2eq}}{m^2 \cdot year}$

98% NATURALLY VENTILATED



ISOMETRIC VIEW



Conditioned Floor Area

Gross floor area

Naturally-ventilated area

EXPLODED FLOOR ISOMETRIC

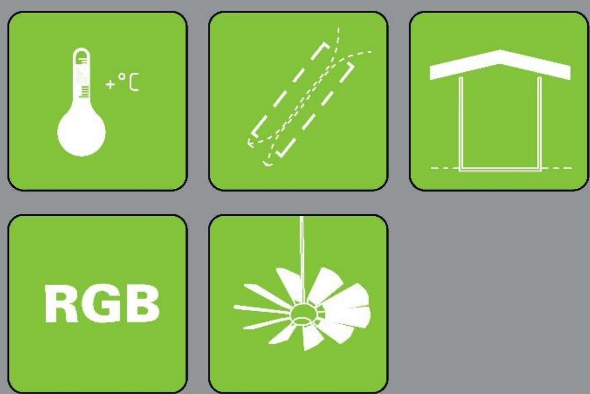
GENERAL INFO

HALL OF RESIDENCE 7

Function:	Dormitories
Gross floor area:	12.700m^2
Conditioned floor area:	70 m^2
Floors:	5
Student capacity:	500
Year of construction:	1990
Location:	30 Nanyang Link
Architect:	Kenzo Tange

This residential building is one of the older halls at NTU. It is located near the border of the campus at the southwest corner. The complex is made of five interconnected separate buildings, with wide open spaces and plenty of common areas for social gatherings and interactions. There is a variety of plants within and around the hall's compound. The complex has five lounges equipped with tables and chairs, a computer room with a printer, air-conditioned reading room and music room, a function hall for events and sport trainning, five pantries equiped with 2 induction cookers, 1 microwave and 1 hot water dispenser. There are also five laundry rooms with six washing machines at the first floor of each block.

SUMMARY



PASSIVE STRATEGIES

3.4.2 Summary findings of building profiles and site synergies

The calculated CO_2 emissions from cooling indicate that the SPMS building uses the highest amount of energy for cooling per square mater. In constrast, the Hall of Residence 7 has neglegible emissions from cooling as it only uses natural ventialtion (except for the reading and music room that are conditioned). The newest constructions that have been designed with respect to energy reduction demonstrate moderate to low emissions compared to the normalization value of the SPMS. The Research Techno Plaza, on the other hand, is a typical administrative building relying on mechanical cooling and resulting in high emissions for sustaining it's conditioned area. It is important to note that the building's typology has to be taken into consideration when evalating the cooling loads, because for example, some of the buildings require conditioned areas for safe laboratory work or functional operation of IT systems.

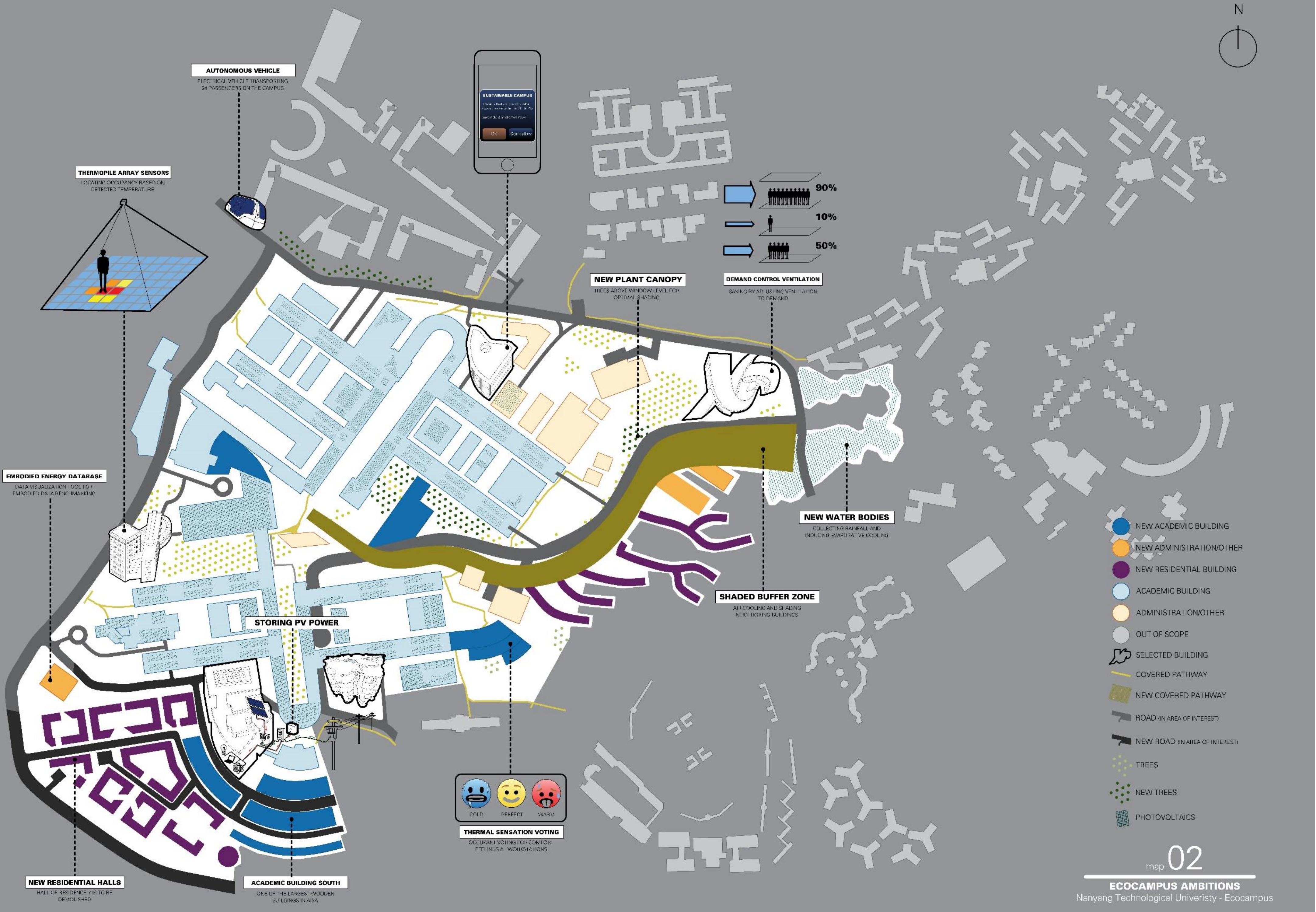
In terms of passive stategies, the new buildings demonstrate high degree of intentionally implemented measures that impact their performance. However, the buildings that date back to the period from 2004 to 2009, show the least amount of passive strategies and most of the attributed ones are spontaneous (withouth the direct aim to reduce energy consumption and/or emissions). In contrast, the Hall of Residence 7 as the oldest building shows some of the essential passive measures that are beneficial for warm climates.

3.5 NTU *Ambitions* EcoCampus – Mapping of Ambitions and Initiatives Site level energy profiles and synergies

The existing "EcoCampus" initiative is already considering several novel strategies that will contribute towards the goal of reducing energy consumption by 35% by 2020 compared to the baseline of 2011. (Nanyang Technological University, 2015) Map 2 shows an illustrative presentation of all ambitions that are being implemented or investigated for future implementation:

- Thermopile array sensors
- Sustainable campus apps
- Demand control ventilation
- Thermal sensation voting
- PV power storage
- Embodied energy database
- Autonomous vehicles

Detailed explanation for each with the corresponding reference needs to be elaborated in this part

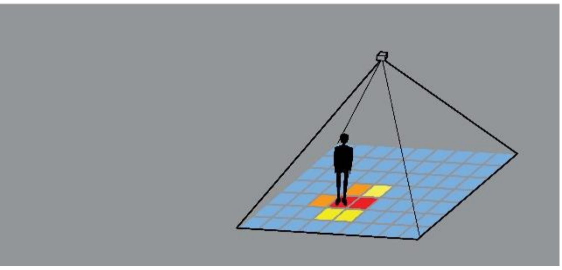


map 02

ECOCAMPUS AMBITIONS

Nanyang Technological Univeristy - Ecocampus

3.5.1 ·Thermopile Array Sensors (TAS)



Thermophile Array Sensors are an intelligent positioning system that detects the location of occupants, detetermines the required coolidng load and assigns the cooling in air-conditioned spaces. These sensors are a new generation of thermo-sensitive elements constituted of infraded (IR) sensor arrays. Figure 3.4 shows the working principles of TAS. A sensing area of 3x3 meters is divided in a 16x16 grid, where each element denotes the measured temperature in °C. In the example, an occupant is detected because of elevated temperature in several of the grid elements. (Azbil Corporation, 2019)

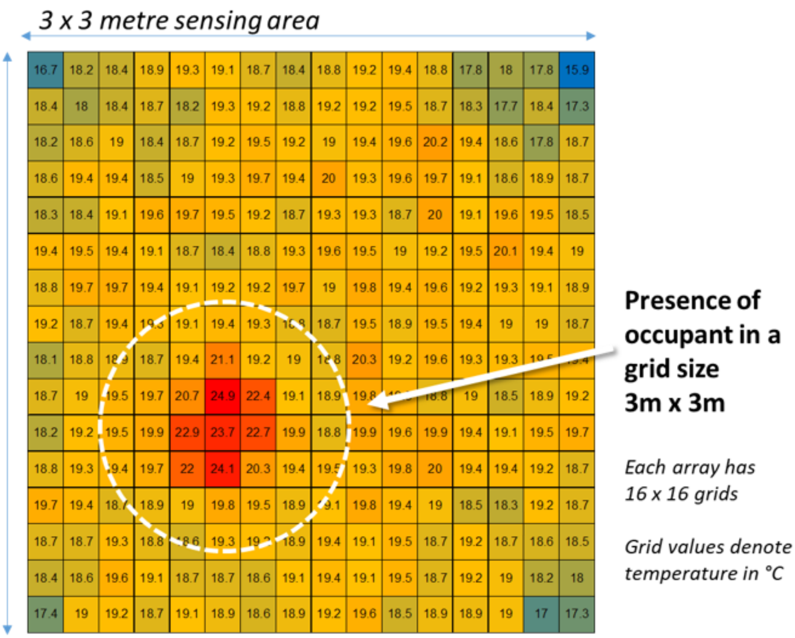


Figure 3.4 TAS working principle. An occupant is detected in elements within the grid where temperature is increased. (Azbil Corporation, 2019)

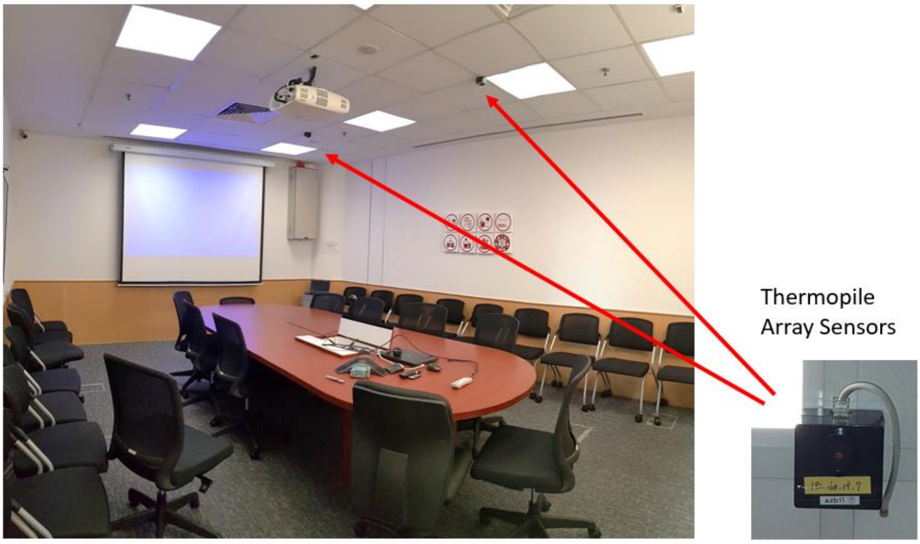
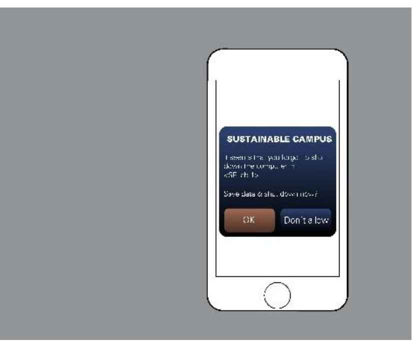


Figure 4: Meeting room test-bed space at RTP, Level 3.

Figure 3.5 Example implementation of TAS in The Research Techno Plaza building. (Azbil Corporation, 2019)

The implementation of TAS is based on machine learning algorithms that work by detecting the number of occupants and their location. Then using a set zone thermostat average of 23.5°C, the room is cooled in order to achieve a user-based set-point of 24.7°C. (Azbil Corporation, 2019)

3.5.2 ·Sustainable campus apps

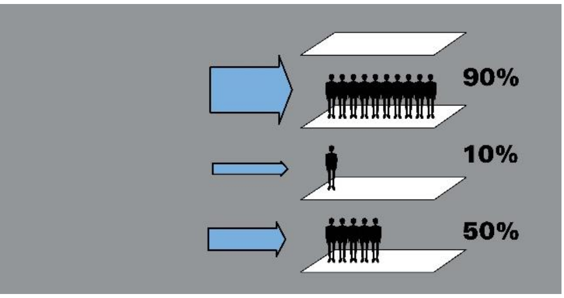


It is stated on NTU's website that «All first-year undergraduates take compulsory module in environmental science with focus on Asia (ephasizing the human dimensions in sustainability)» (Nanyang Technological University, 2015). Complimentary to this module, a smartphone app that stimulates energy-saving behaviour is used for interactive user engagement using the sociological concept of nudging and a gamification based approach. (ENGIE and ERI@N, 2020)

Figure 3.6 EcoGestures interface in a sustainability smartphone app that gamifies energy conservation behavior. (ENGIE and ERI@N, 2020)

The main objectives are focused on fostering sustainable behavior practices and raising awareness about energy consumption. The first version of the app has already been released and a sociological study has been conducted through face-to-face interviews, workshops and online surveys. The results indicate that the success of this approach depends on the gamification of energy conservation behaviors, which could save up to 5% of the total consumed energy. It has been concluded that users are attracted to features that offer tangible, immediate results while learning about measures for energy-saving behavior. In the future, upgrades on the existing software and new smartphone apps are expected to be an important milestone in reducing energy consumption. (ENGIE and ERI@N, 2020)

3.5.3 Demand control ventilation



This ambition is a promising approach with an expected average of 38% reduction in energy consumption. The system is based on sensors that are placed in various areas of the building for monitoring CO_2 levels in real time. The obtained information gives an estimate of actual occupancy, indicating that more users are present when CO_2 levels rise. The main characteristic of this type of ventilation is the controlled outside air intake. When CO_2 levels are adequate, intake is reduced, yielding a significant reduction in energy consumption. (Iota Communications, 2020)

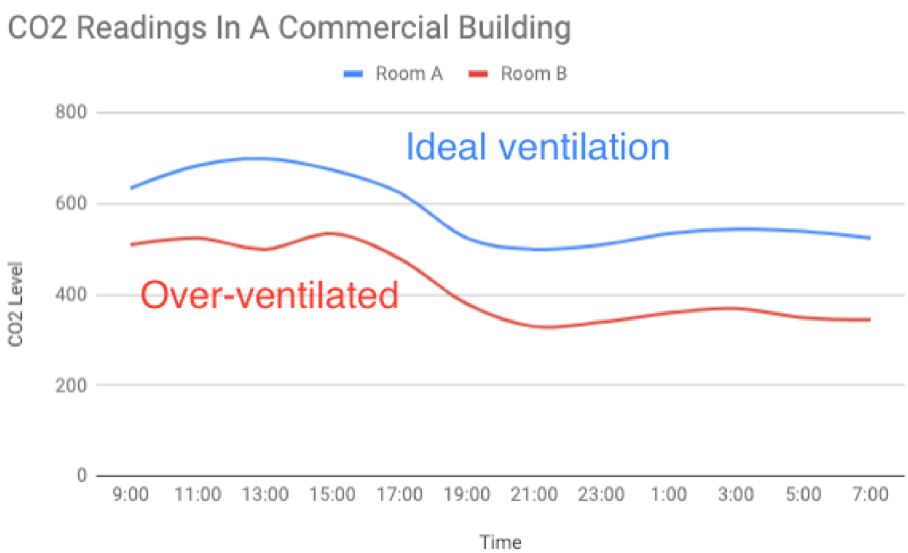
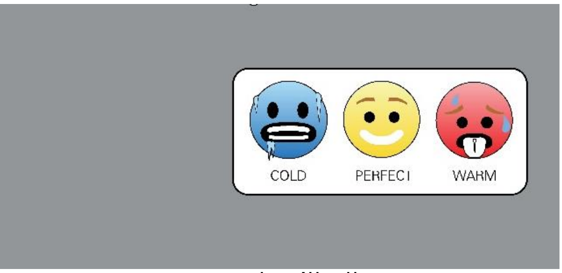


Figure 3.7 ASHRAE CO_2 readings from ventilation in two different areas of a building. One is over-ventilated because of using traditional methods; and the other ensures high-quality air without overworking the system by applying demand control ventilation. (Iota Communications, 2020)

3.5.4 Thermal sensation voting



Another ambition focuses on the user's thermal comfort as an important element for motivating energy consumption reduction. Thermal Sensation Voting (TSV) will be installed ar every occupant's workstation. The panel will allow users to vote for their comfort feelings. This induces adjustement and improvement of the zonal thermal comfort by modifying the temperature and relative humidity. Additionally, the results from the voting can be analysed and used for future adjustments of the system. (Azbil Corporation, 2019)

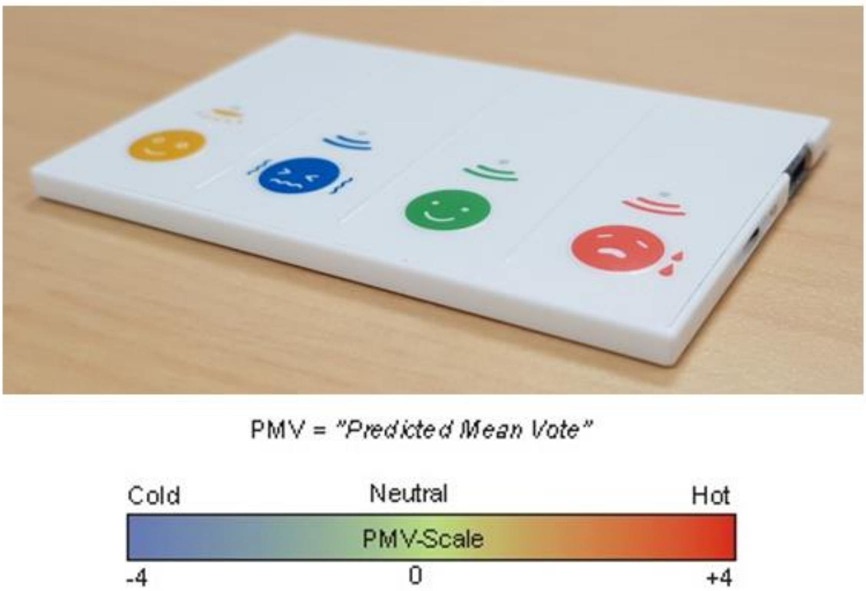
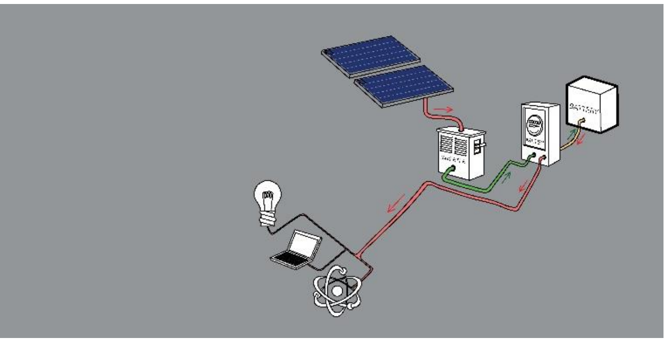


Figure 3.8 TSV panel for adjusting thermal conditions based on the occupant's comfort. (Azbil Corporation, 2019)

3.5.5 PV power storage



The Energy Management System (EMS) aims to reduce the amoutn of power used from the main gread, by utilizing PV power storage and other controllable devices. The main aim to is store power generated by the PV, so that it can be used during the night. Additionally, EMS looks for other controllable sources when PV or energy storage would not be able to meet the demand. (ERI@N, 2019)

3.5.6 Embodied energy database

In order to achieve its goals, the EcoCampus initiative is aware that it needs to focus on emobdied energy of the building materials. Using the Life Cycle Assessment tool, the Energy Research Institute is aiming at quantifying the environmental impact of the building materials on NTU's campus. The outcomes of this study are expected to raise awareness on the significance of building embodied energy on the overall carbon emissions and the results will be used for benchmarking and reference for assesing future NTU projects in terms of their carboon footrpint. Considering the current lack of an EPD database, the study will be using Building Information Modeling (BIM) software and data from the BCA Carbon Calculator. (ERI@N, 2020) Nevertheless, this initiative is a step in the right direction and should yield significant reslts in future constructions.

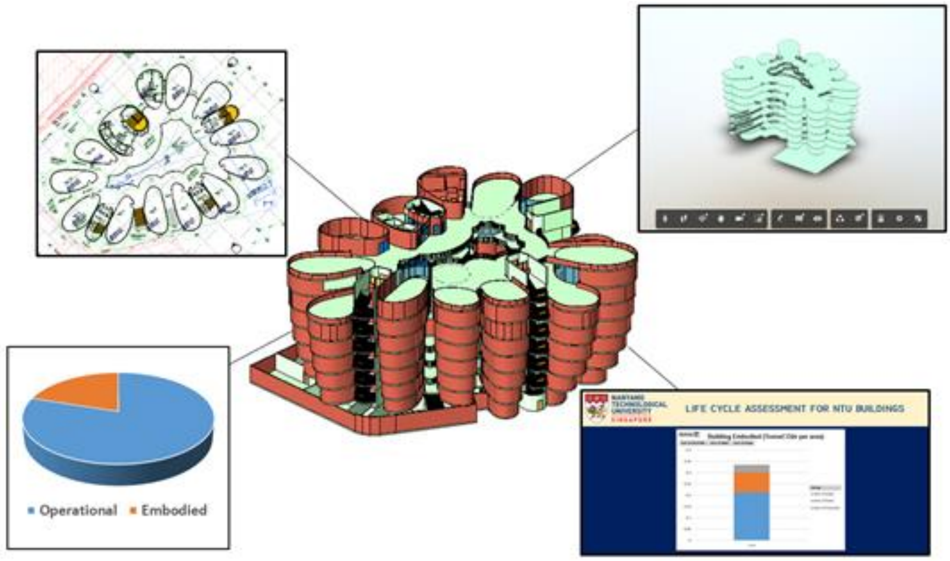
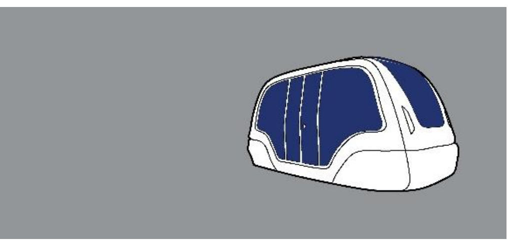


Figure 3.9 Energy assessment of The Hive based on BIM software simulations, depicting the percentage of embodied energy from building materials. (ERI@N, 2020)

3.5.7 Autonomous vehicles



Two types of autonomous vehicles that are based on 100% electric operation will be fully available on the campus:

- The quick charging autonomous shuttle vehicles for tropical urban cities produced by Navya will be tranporting up to 15 students on pre-defined routes around campus.

- 22-seater shuttle vehicles with full electric flash charging that takes only 20 seconds would be able to charge while users embark/disembark allowing for an efficient transport. A single charge can provide 2 km of transport, but the system would require a charging infrastructure with robotic arms that connect to the vehicle.

Results

4.1 NTU *ZEN* EcoCampus – Mapping of Optimized Site Level energy profiles and synergies

The existing situation of NTU's campus and the current ambitions provide detailed understanding of the prevailing efforts to reduce waste, water and energy consumption. However, there is a significant lack of interest in reducing GHG emissions on its built environment, which would decrease environmental impact and contribute to efforts for reducing global warming effects. This project set the task to identify buildings with different energy profiles on a selected area of interest and propose solutions for synergy between them, with the purpose of showcasing the potential of ZEN in warm climates.

4.1.1 Profiles of selected buildings

The most important changes need to focus on reducing Energy Use Intensity (EUI) and maximization of renewable energy production. EUI can be influenced through the optimization of the design, operation and user's requirements. Assessing the way each building works and optimizing the used technology can help us further reduce EUI. Based on these guidelines, the optimized building profiles showcase the potential for improvement on the individual level, for each building separately.

- Optimization of the design and operation

The catalogue of passive strategies from Chapter 3.1 is used as a base for assessing further optimization on the existing situation through implementation of additional cost-efficient passive design measures that would contribute towards reduction of cooling emissions.

The profiles are further analyzed by considering the current ambitions of the EcoCampus and assessing the anticipated technologies/strategies against each building. Although it can be tempting to assume that all of the ambitions are beneficial for the buildings, it is important to acknowledge that for some cases they are useful, and for some useless. Furthermore, the cost of implementing them in already optimized systems could prove to be inefficient. For example, the SPMS building that relies on mechanical cooling systems entirely, would have a significant reduction in emissions from cooling by implementing thermophile sensors, compared to The Arc that uses natural ventilation for more than 40% of its gross floor area. Even so, considering that the conditioned rooms in a learning hub like The Arc are used by booking a time slot, the ideal optimization could be easily achieved with cost effective programmed cooling, avoiding the costly installation of thermophile sensors. In the case of the Hive, on the other hand, these sensors would not be implementable at all, because the cooling system is completely different compared to a conventional building and would not allow focused cooling on smaller areas in the rooms.

An additional measure for optimization of the building's operation should take into account the occupancy of the buildings based on the academic year in the Singaporean formal education, which is defined with:

- Semester 1: August to December (Semester 1 vacations: 4-5 weeks)

- Semester 2: January to May (Semester 2 vacations: Usually 12-13 weeks). (World Education Network, 2020)

During vacation periods the occupancy is reduced, so the cooling loads should be reduced as well. The analyses on the obtained data showed that reduced cooling is not implemented in the buildings during the vacation period which totals four months. This assumption does not consider the occupancy of academic environments during exam preparation periods, when students are dominantly present in learning hubs. Nevertheless, even with exclusion of these periods it is possible to reduce cooling for two months and attain significant reduction in GHG emissions.

- Optimization of the user's requirements

A critical analysis on the current Singaporean Standard CP 13 described in Chapter 2.2 shows that the lower boundary for cooling down spaces (22.5 C) could be increased by at least one degree to reduce the emissions from cooling. Passive cooling strategies need to be complemented with active cooling equipment in most cases, but the amount of cooling needed could be substantially reduced with this change. Added to this point, a survey conducted on 424 participants in 2017 shows that "68 per cent of the respondents from Singapore often encountered excessive cooling of public places such as offices, shopping malls and cinemas" (Hill, 2017). Despite the results from the survey, it is still challenging to induce a behavioral change which would yield significant outcomes. It could be efficient to start implementing such changes with the students from NTU, because they are more likely to be open for accepting this shift. The proposal is to define a separate standard for cooling specifically for the campus, with a new lower boundary set at 23.5°C. The resulting energy demand reduction and consequent emission reduction could be analyzed and serve as a catalyst for change, by motivating other users and stakeholders to accept it. Taking this in consideration, each building is assessed based on its potential for introducing the separate standard. An example where this standard could not be implemented is the SPMS building, which houses conditioned laboratories required to sustain temperatures below a certain threshold. This inhibits the implementation of the standard in those areas, but still leaves room for improvement by incrasing the lower boundary to 23.5°C in other rooms.

- **Maximization of renewable energy production**

The optimization goal for maximizing renewable energy production is observed through the potential for increasing PV area on each of the buildings, based on the current level of utilization or design alterations. Even though the current PV installation on the EcoCampus is the biggest single installation in Singapore, it is important to consider a strategy for upgrading and expanding the current PV systems. The building's profiles aim to show the potential for PV paneling optimization in four areas:

- roof areas with existing PV panels that can be upgraded to a more efficient layout;

- roof areas where additional PV panles can be installed;

- roof areas where PV panels can be installed if an additional construction is added;

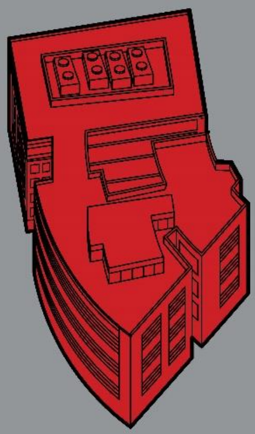
- facade areas where a potential for PV paneling is observed.[5]

It should be taken into consideration that combined photovoltaic and solar thermal systems (PV/T) could be a more efficient option for the suggested optimization. This is a hybrid system that combines components from both systems and generates both electricity and heat. A PV/T module is comprised of PV cells with a solar thermal collector that converts solar radiation to electricity and heat simultaneously. This increases the efficiency compared to using the two systems separately side-by-side, which is problematic if we consider the limited roof area at NTU. Additionally, the solar thermal collector cools down the PV module and increases efficiency. A simulation study of the ZEB model in Norway, has not indicated a clear benefit from the PV/T system in cold climates, but a conclusion has been drawn that the approach will be well-suited for warmer

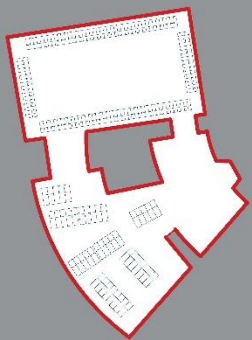
[5] The analysis is based on façade orientation and taking in consideration the architectural integrity of building.

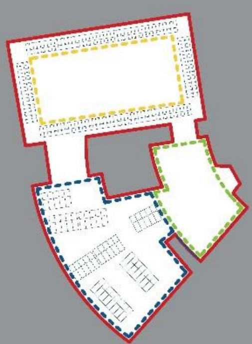
climates. (Good, 2016). This is an example for using research outcomes from cold climates for the benefit of intuitive implementation in warm contexts, that could provide significant benefits for GHG emission reduction in the tropics.

Following the guidelines for reducing EUI and optimizing the design, operation and user's requirements, while maximizing renewable energy production, the following pages present the proposed optimized profiles of the selected buidlings.



ISOMETRIC VIEW



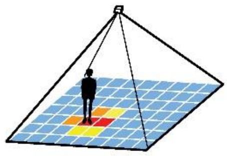


- Existing PVs
- Roof area
- Potential additional PV area
- More efficient PV distribution needed
- Additional construction for new PV

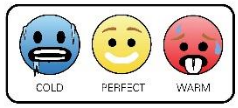
PV AREA IMPROVEMENT

AMBITIONS THAT COULD BE BENEFICIAL

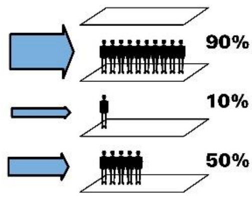
SCHOOL OF PHYSICAL AND MATHEMATICAL SCIENCES (SPMS)



THERMOPHILE ARRAY SENSORS



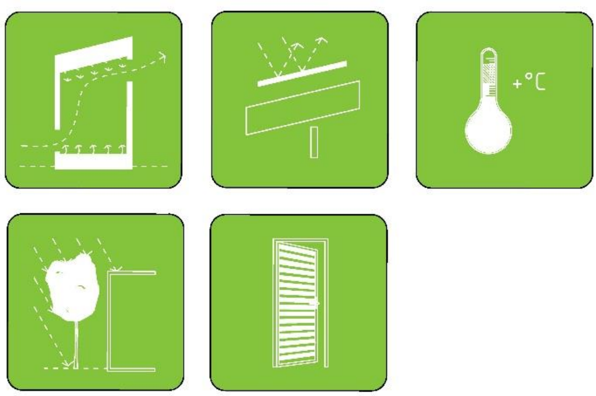
THERMAL SENSOR VOTING



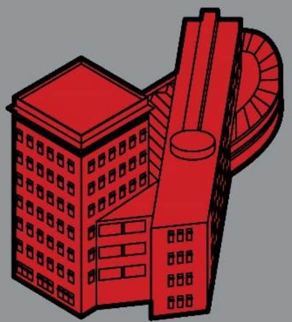
DEMAND CONTROL VENTILATION

SUSTAINABLE BEHAVIOR APPS

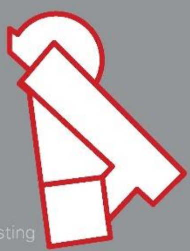
The implementation of additional passive stragies should be considered for reducing the cooling loads of SPMS. The ambitions are also expected to be beneficial for increasing the cooling efficiency of the building. However, the laboratories in the school will maintain the energy demand, so it is most important to neutralize the high emissions. It is advisable to generate a synergy with the neighbouring residencies from where energy can be obtained.



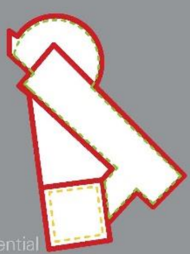
POTENTIAL ADDITIONAL PASSIVE STRATEGIES



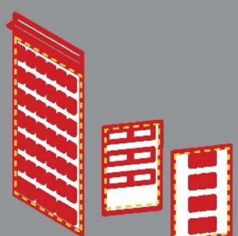
ISOMETRIC VIEW



Existing



Potential



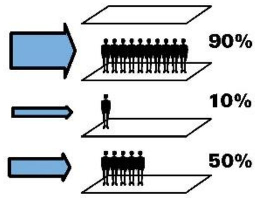
Potential

- Existing PVs
- Roof and wall area
- Potential additional PV area
- More efficient PV distribution needed
- Additional construction for new PV

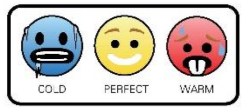
PV AREA IMPROVEMENT

AMBITIONS THAT COULD BE BENEFICIAL

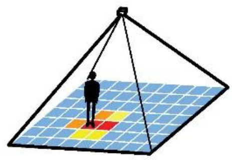
RESEARCH TECHNO PLAZA



DEMAND CONTROL VENTILATION



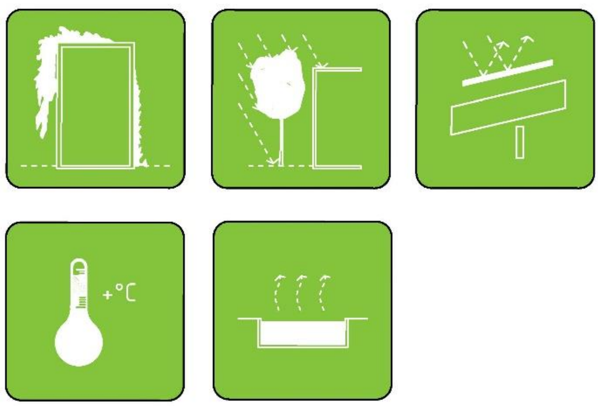
THERMAL SENSOR VOTING



THERMOPHILE ARRAY SENSORS

SUSTAINABLE BEHAVIOR APPS

The proposed additional passive strategies are expected to provide significant improvement in the building's performance in combination with the anticipated ambitions. Currently the building does not produce electricity, so if a PV roof construction is to be built, the impact of the construction will be reduced. However, considering the function and layout of the building it is highly likely that it will maintain its high GHG emissions from cooling. Therefore it is important to consider linking with another less energy demanding building to compensate for the cooling loads.



POTENTIAL ADDITIONAL PASSIVE STRATEGIES

ISOMETRIC VIEW

Existing

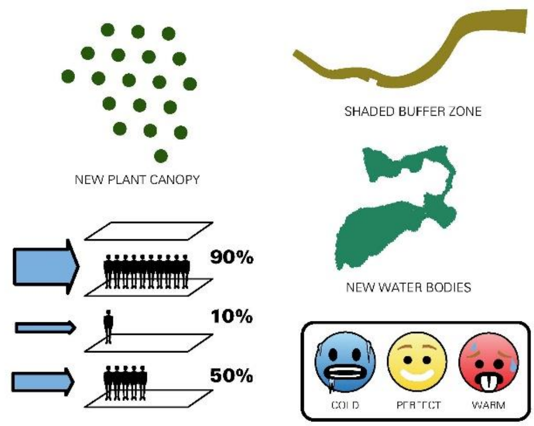
Potential

- Existing PVs
- Roof and wall area
- Potential additional PV area
- More efficient PV distribution needed
- Additional construction for new PV

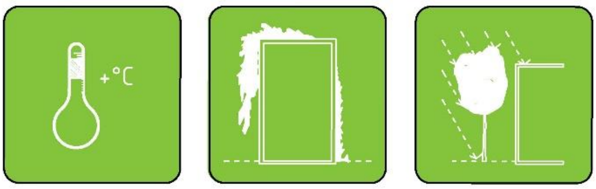
PV AREA IMPROVEMENT

AMBITIONS THAT COULD BE BENEFICIAL

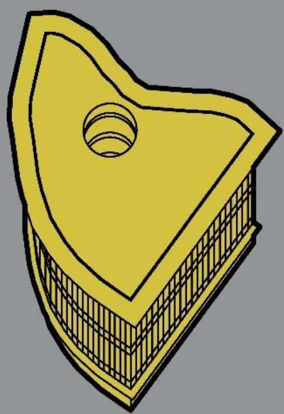
SCHOOL OF ART, DESIGN AND MEDIA



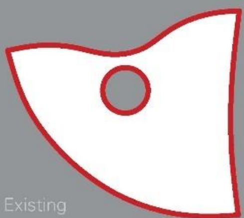
The distinctive appeal of this building complicates the implementation of additional passive strategies without affecting its architectural integrity. Therefore, it is not recommended to produce solar energy and the building needs to rely on the synergized network for obtaining energy in order to shift towards ZEN. Considerable strategies can be implemented around the building including the new water bodies that can provide air cooling and the new plant canopy nearby. Also the planned shaded buffer zone could provide shading on the south facade and reduce heat gains. Most of the existing ambitions are also not implementable on SADM, because of the volume distribution and specific layout of the building. Thermal sensor voting can provide informaton about the cooling efficiency, that could be optimized for reducing cooling loads.



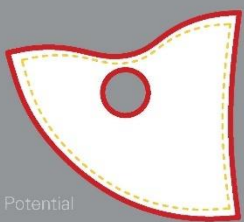
POTENTIAL ADDITIONAL PASSIVE STRATEGIES



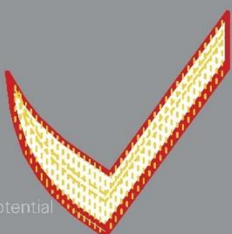
ISOMETRIC VIEW



Existing



Potential



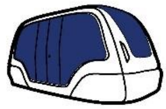
Potential

- Existing PVs
- Roof and wall area
- Potential additional PV area
- More efficient PV distribution needed
- Additional construction for new PV

PV AREA IMPROVEMENT

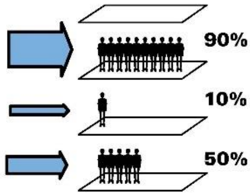
AMBITIONS THAT COULD BE BENEFICIAL

THE ARC

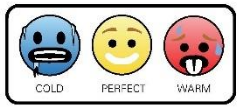


AUTONOMOUS VEHICLE CHARGING

SUSTAINABLE BEHAVIOR APPS

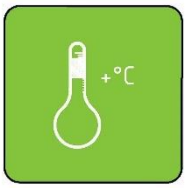


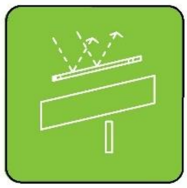
DEMAND CONTROL VENTILATION



THERMAL SENSOR VOTING

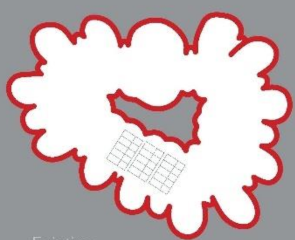
The building could benefit from additional strategies and amibitions that can potentially provide further reduction in the GHG emissions. Currently The Arc does not have a PV roof construction and it is advisable to consider the potential for energy generation. Additionally, the transparent facade could incorporate PV panels withouth affecting the existing outlook. However, this might not prove to be very efficient considering the proximity to neighbouring buildings and the overhang from the roof.
A simulation could provide more detailed report. If the building produces energy, it would become an important link towards achieving ZEN, as it could provide energy to the SADM during the peak hours. Considering the high-impact neighbouring buildings, this learning hub can serve as a charging station for the autonomous vehicles.



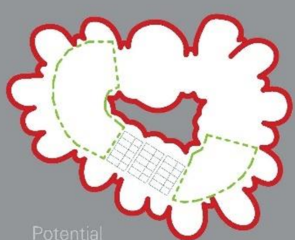


POTENTIAL ADDITIONAL PASSIVE STRATEGIES

ISOMETRIC VIEW



Existing



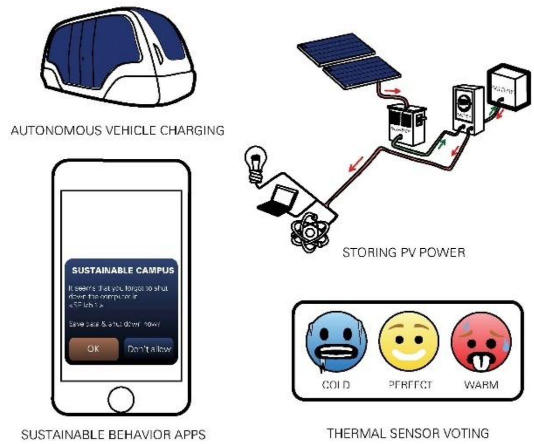
Potential

- Existing PVs
- Roof and wall area
- Potential additional PV area
- More efficient PV distribution needed
- Additional construction for new PV

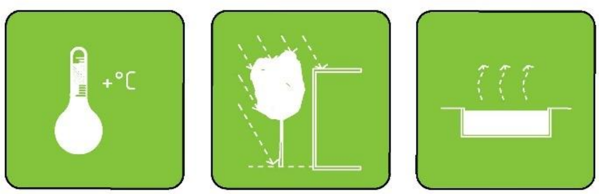
PV AREA IMPROVEMENT

AMBITIONS THAT COULD BE BENEFICIAL

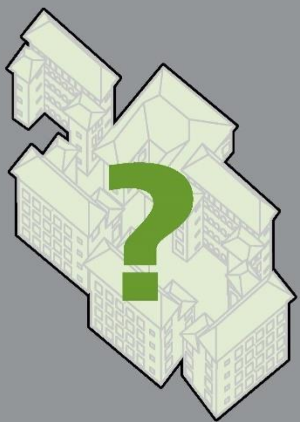
THE HIVE



This building has already consciously implemented several passive strategies that contribute to its efficient performance. However, it is important to consider the potential for further improvement by implementing ambitions that can be viable for the building. It could be possible to provide further reduction in GHG emissions from cooling. The existing roof PV construction can be increased (The facade and it's thermal mass properties, as well as the distinctive architectural character are not suitable for incorporating vertical PV panels. Additionally, The Hive can become a part of the synergized network that would share generated energy with the neighbouring high-demand buildings. A further synergy can be achieved if a part of the generated energy is used for charging the autonomous vehicles that would link to buildings that are futher away than the neighbouring ones.



POTENTIAL ADDITIONAL PASSIVE STRATEGIES



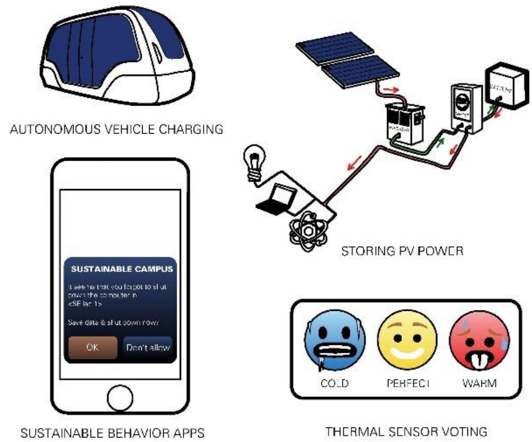
ISOMETRIC VIEW

- Existing PVs
- Roof and wall area
- Potential additional PV area
- More efficient PV distribution needed
- Additional construction for new PV

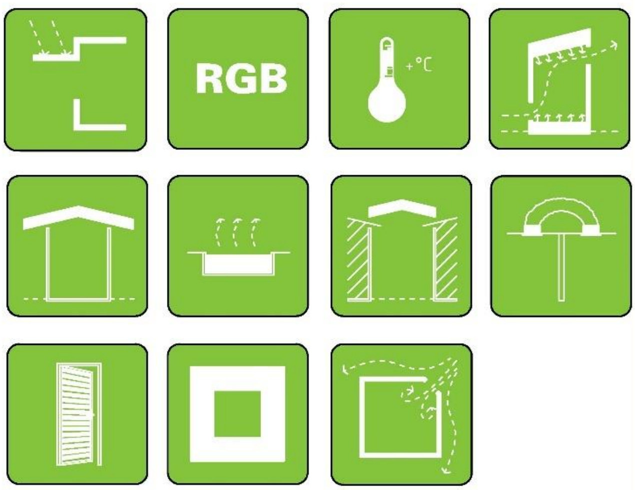
PV AREA

AMBITIONS THAT COULD BE BENEFICIAL

HALL OF RESIDENCE 7



A new complex is expected to be built, after demolishing the existing residencies. The new design should aim at implementing the suggested passive strategies and maximize the PV area. This is an opportunity to find appealing alternatives for integrating the PV panels into the facade. The strategies are expected to yield a surplus of generated energy that could be distributed to the SPMS, achieving a successful synergy.



POTENTIAL PASSIVE STRATEGIES

4.2 Energy synergies – Propolsals of linkage between the buildings

The proposal is to synergize the selected buildings with a smart energy management system that will balance energy consumption and generation. The main motivation for implementing this approach is caused by the temporal mismatch between onsite generation and loads at the hourly level[6]. The mismatch is expected to be considerable if we take into account that the predicted peak demands are uneven in terms of amount and period for each of the buildings, because of their different functions.

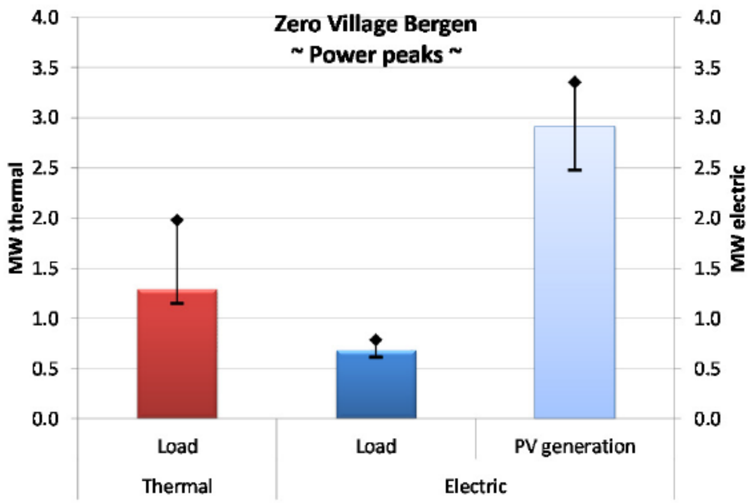


Figure 4.1 Figure indicating the potential magnitude of a mismatch between the thermal and electric loads and the PV generation, with min-max markers from sensitivity analysis on a ZEN pilot project – Zero Village Bergen.

Figure obtained from (Inger Andersen, 2016).

For example, PV generation peaks are in the central hours of the day for all buildings due to the geographical proximity, which results in an aggregated peak that needs to be handled either by exporting to

[6] We exclude temporal mismatches at the seasonal level, considering that the tropical climate has no distinctive seasons.

the grid (that could challenge the grid's limits) or by storage in a battery. (Anne Grete Hestness, 2017) In fact, as it was discussed in Chapter 3.5.5, one of the current ambitions of the "EcoCapmus" initiative is to provide PV power storage for each building. Nevertheless, this could be further developed into a synergized system where a centralized electric battery will provide redistribution of the energy produced by less demanding buildings to energy-intensive buildings. This could be justified by the findings that "long term onsite storage for energy with high energy quality i.e. electricity is not feasible due to lack of space and high cost with today's technology" (Voss, 2010). On the other hand, an energy exchange through synergy can help to avoid these constraints, while attaining the wanted results (Lund, 2014).

A direct example of this proposal can be observed with the School of Physical and Mathematical Sciences (SPMS) which showed the highest GHG emissions due to its cooling loads. This is partly induced by the lack of passive strategies in the design of the building, but mainly the cooling demands are generated by laboratories which require constantly maintainined low temperatures. Considering their importance for the academic environment, it is impossible to eliminate their consumption, so an alternative has to be found. A strategy for synergy with the neighbouring Hall of Residence 7, could provide compensation for the emissions. Currently the residencies produce almost zero emissions from cooling, and if the cooling demands are kept at low levels in the new construction the energy that they could potentially produce from a PV installation on the roof/façade can be fully distributed to the SPMS. This small network would have a big impact on the overall performance of the buildings and contribute towards the neutralization of the campus emissions. Using this approach, we can move closer to the zero emissions goal.

The following approximate calculations demonstrate the applicability of this system and its potential on the EcoCampus. Assuming that the new planned roof area for the Hall of Residence 7 (Chapter 4.1.1.6) will be approximately 5400 m^2 (predicting 90% coverage) and excluding additional PV placement on the selected façade, we can use the Equation 4.1 to calculate the average energy generation from the PV modules per year. These calculations consider the annual irradiation in Singapore ranging from 1580kWh/m^2 to 1620kWh/m^2. Hence the average daily generation is between 4.32 to 4.44 kWh/m^2. (On a sunny day the generation can peak up to 6.7 kWh/m^2, while on a rainy day it would be as low as 0.8 kWh/m^2). (SolarGy Pte Ltd, 2020)

$$E_{PV,annual} = A \cdot W \cdot 365 \frac{days}{year} = 8.514.720 \text{ kWh/year} \quad 5.1$$

where: A – area to be used for placing PV modules

W – solar capacity of PV cells per square meter.

Using Equation 3.1 we obtain the expected compensation for the GHG emissions based on the existing grid mix factor.

$$GHG_{emissions} = E_{PV,annual} \cdot 0.41095 \frac{tCO_{2eq}}{MWh} = 3.571.925 \ kgCO_{2eq}$$

Comparing this amount with the GHG emissions from cooling at the SPMS ($GHG_{SPMS} = 2.972.830 \ kgCO_2$) we observe a surplus of 17% that could compensate the building's operational energy demands and achieve net zero emissions for the proposed synergy. Moreover, in this comparation we do not include the anticipated reduction in cooling loads after implementation of additional passive strategies, incorporation of the ambitions and increase in the PV area at SPMS (Chapter 4.1.1.1). It is important to note that these calculations are approximate, and they do not include façades with optimal orientation that could add to the compensation in emission. In case of additional surplus that does not need to be used, the generated energy can be distributed to other buildings.

In the same way, it is expected that synergies among the other buildings would enhance this effect and contribute additionally towards reaching the ZEN goal. Based on the building selection in this thesis a full synergy can be achieved among the buildings. Considering the elaborated comparison, it is to be expected that the Zero Emission Neighbourhood will be successfully created, even if lower emission buildings like The Hive do not upgrade their PV installations and simply maintain low energy consumption.

The proposal of connecting these buildings can have additional benefits if the proposed strategy for reducing cooling loads during vacation periods is implemented. In those periods, most of the buildings could start producing surplus energy that does not necessarily need to be stored. That is because, there will still be buildings like The Research Techno Plaza which is an office building requiring cooling during the whole year. In this case, the synergy strategy would be very beneficial as the generated energy from neighbouring buildings can be distributed to this building. This would completely neutralize cooling emissions in the vacation period that will contribute towards achieving zero emissions.

4.2.1 Transportation System

Another point to consider when proposing the synergy strategies is based on the transportation system, which can link distant buildings without direct physical connection between them. The propose ambition of the EcoCampus initiative depicting autonomous vehicles can be upgraded if the transportation system is powered with energy generated from the buildings. In this case, the buildings which have the least GHG emissions can define the transportation system by serving as points for charging the electric vehicles. By doing so, the emissions from transportation can be neutralized.

On a futher note, when the storage of generated PV power becomes more efficient, some of the energy generated by buildings with surplus could be transported to high-impact buildings that would further optimize the compensation.

4.2.2 Digital technologies for synergy

It is important to stress the significance of digital aid in the process of achieving the zero emission neighbourhood goal. After all, users are the key link in accomplishing set targets, so the EcoCampus initiative should focus on motivating its users towards reducing emissions.

The current ambitions envision implementation of sustainability campus apps that will monitor some of the user's behavior and provide notifications for reducing energy consumption. Even though this idea could provide significant improvement, it is important to upgrade its goal into reducing emissions as well. This can be done through constant education with apps that are mandatory for each student on the campus. These could monitor the student's emission behavior and provide suggestions for improvement. Most importantly they should educate students on how their actions impact the environment. Additionally, certain activities can be awarded with vouchers that could provide supplementary motivation to the students.

Focusing on the synergy between buildings, digital aid can be helpful in the following example. If a student from the School of Physical and Mathematical Sciences has to spend three hours writing a report, he/she could find available working areas through a campus app. The algorithm of the app will focus on allocating places in the learning hubs, which will induce higher gravitation towards buildings where cooling demands and emissions are lower. In return, this action will result in alleviated occupancy in buildings with higher emissions. Such example would be beneficial for the SPMS building, because the student could spend three hours in The Hive, which means that the thermophile array sensors in the SPMS will not detect the student's presence and cooling will be reduced.

Following this pattern, the app could contribute towards significant reduction in emissions.

The following map shows the summary of optimized building's profiles, emphasizing the importance of synergy between the selected building. The discussed connection between SPMS and the new Hall of Residence 7 is presented.

map 03 SCALE 1:1000

PROPOSALS

Nanyang Technological Univeristy - EcoCampus

Discussion

5.1 Summary findings of building profiles and site synergies

The most important goal of this thesis is to induce a shift on the current perceptions about zero energy and potentiate the importance of synergy for the aim of reaching zero emissions. In the previous chapters we analyzed six individual buildings and evaluated their environmental impact in terms of GHG emissions from cooling. Then the possibility for improvement was presented for each building individually, based on the implementation of a set of additional passive strategies and incorporation of the anticipated ambitions of the EcoCapmus initiative. However, the results indicate that certain synergies between the analyzed buildings focused on optimizing their collaborative behavior could be essential for approaching the zero emissions goal.

The Norwegian ZEN pilot projects showcase the immense potential that could be attained from the implementation of similar synergies, where the whole neighbourhood works as a network of interconnected buildings that share resources and help to achieve overall zero emissions. In the tropical context, even though the climatic and political factors are different, the same principle remains. Some of the buildings have higher environmental impact as a direct result of their function and currently it is not possible to provide significant optimization that would neutralize their emissions. However, a linkage with the neighbouring buildings that have significant low emissions could help to alleviate the impact and provide improved overall environmental performance.

5.2 Challenges and limitations in the implementation

The broad scope and short time for analyses in this project induced several challenges and limitations that need to be considered. The oversimplified approximation due to lack of detailed data and appropriate simulations is expected to add a degree of uncertainty in the conclusions. Nevertheless, the main aim of the project is to evaluate the applicability of ZEN principles in warm climates and provide guidelines for future detailed research.

The Singaporean emissions grid mix factor used for the calculations of the GHG emissions from cooling based on the provided energy consumption from ERI@N, was the most recent estimate (published 2018) by the Singaporean Energy Market Authority. However, since the project aims to investigate future improvements for achieving zero emissions, the calculations could have been more relevant if future predictions on the value of the factor were available. Additionally, the calculation of the combined margin (CM) could not use the 75% OM, 25% BM weighting as the current system is based on firm electricity generation. The Solar Energy Research Institute (SERI) predicts two scenarios in which PV electricity generation will increase and contribute with 14%-30% in the total electricity demand by 2050 (**Error! Reference source not found.**)

Year	E1, 110 TWh	E2, 80 TWh	E3, 50 TWh
BAS, 7 TWh	6%	9%	14%
ACC, 15 TWh	14%	19%	30%

Figure 5.1 Two scenarios depicting the potential relative contribution of PV electricity to the electricity demand in 2050 in [%]. *Table obtained from* (Luther & Reindl, 2014).

Figure 5.2 Two scenarios depicting the potential relative contribution of PV electricity to the electricity demand in 2050 in [%]. *Table obtained from* (Luther & Reindl, 2014).

(Luther & Reindl, 2014).

That indicates that a more accurate prediction requires different weighting of the margins. This is expected to be developed in the future in alignment with UNFCCC standards.

The current calculations on energy consumption for the buildings where data is available for only two months are not very accurate and need to be considered with precaution. Future studies would have to reevaluate their performance and correct the obtained conclusions about their GHG emissions from cooling. Additionally, the future behavior of new buildings might be difficult to anticipate in the early stages of operation, as unexpected underperformance could impair the building's environmental impact.

The GHG emissions for each of the buildings are normalized based on the most emitting building. This does not necessarily need to be the case for future implementations of ZEN, but it is beneficial for referencing the other buildings and visualizing the potential for compensation of emissions among them.

The analyzed ambitions are based on current and future projects of the EcoCampus initiative. They were considered in this project as their implementation will directly influence future behavior of the buildings, but it is important to note that Chapter 3.5 does not provide an exhausted list of measures. Additional, different strategies could have the same or even bigger impact on operational performance but they are out of the scope of this thesis. Nonetheless, the EcoCampus initiative is a successful testbed for implementing novel technologies and it is notable that the ambitions consider the most recent technological development.

The calculations of the expected energy production by incorporation of PV modules on the new Hall of Residence 7 are approximate and cannot be implemented immediately as the demolition of the existing building is not scheduled yet. However, the importance of these assumptions is immense because they can serve as design goals in the planning process for the new residencies.

Future work and recommendations

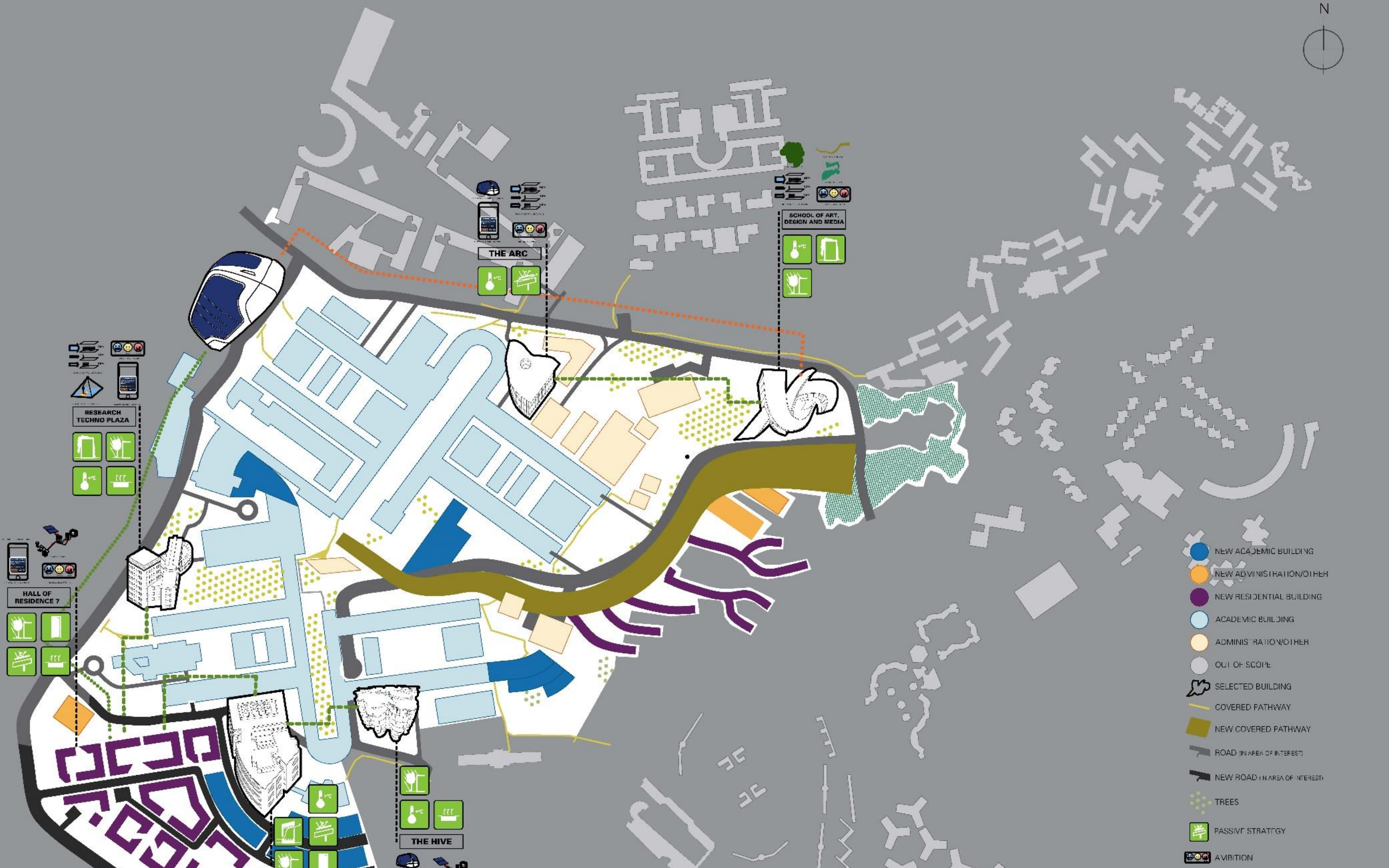
The evaluated implementation of ZEN strategies at the EcoCampus of Nanyang Technological University in Singapore results in conclusions that could become recommendations for future projects in warm climates as discussed in Chapter 1.1 and Chapter 2.2.1.1. Based on the development of this topic, a comprehensive overview of passive strategies was drawn and a set of existing ambitions that are part of the EcoCapmus initiative were evaluated against a set of selected buildings with different GHG emissions from cooling. Recommendations for upgrades on the PV system that is already the largest single installation in Singapore were suggested for the purpose of advancing the current goal of reaching zero energy into zero emissions.

The new construction at the place of the Hall of Residence 7 can become a perfect testbed for implementing the conclusions from this thesis. Chapter 4.1.1.6 summarizes the recommended passive strategies and ambitions that could significantly reduce operational energy use by reducing cooling loads and optimizing the performance of the building. In addition, the proposal of creating synergy between the campus buildings could be evaluated in a pilot project that will connect the School of Physical and Mathematical Sciences with the new residencies. An approximate estimate of the generated PV energy in Chapter 4.2 showed that a surplus of generated energy can compensate GHG emissions for cooling of the highly-demanding SPMS building. Furthermore, these calculations can be used in the future for designing the new building among with the recommended passive strategies and ambitions. The operational energy use should not be expected to produce more than $600.000 kgCO_{2eq}$, which translates into an energy demand of $260 \frac{kWh}{year \cdot m^2}$ based on the current Singaporean grid mix factor. This could be achieved if the design incorporates natural ventilation for more than 80% of the gross floor area, maintaining conditioned areas below 20%.

The research on this pilot project will be beneficial for testing and demonstrating the suitability of ZEN principles in the tropics. In the future, a successful completion of the project could lead to additional connections that can incorporate the other selected buildings. Based on the conclusion from the optimized building profiles the following map shows an image of the future using the proposed synergies. A single entity has been created along with the idea of using the transportation system as a connecting link for transferring energy between buildings.

Considering the transportation system and current implementation of autonomous electric vehicles on campus, a synergy between the buildings could become possible without direct physical connections. When technological advancement allows for efficient energy storage it could be possible for the vehicles to transport PV generated energy from buildings with surplus energy to buildings with insufficient energy. An optimized proposal might even lead to the generation of an energy positive neighbourhood. This is an immense possibility for connecting all of the buildings on campus and not only the selected few in this project. In this way, no physical connection is required and an enhanced synergy can be achieved as the energy distribution can be demand-controlled.

The conclusions from this project are not final and should not be implemented as imperatives. Moreover, the aim is to induce additional more detailed research that will produce valuable contribution towards reducing emissions in warm climates such as the South and Southeast Asian regions.



map 04 SCALE 1:1000

FUTURE SCENARIO

Nanyang Technological Univeristy - EcoCampus

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