RAC Facades

Retrofit Active Cooling Façade System for Tropical High-rise Residential Buildings

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Acknowledgement

My interest in architectural space cooling for buildings grew from both my personal experience living in the tropics and my interest in architecture and design. This motivation has led me towards an education in TU Delft specializing in building technology, where I gained knowledge in façade design, among many other things.

For my Master thesis, I chose to research into active cooling technology for built high-rise residential buildings in tropical areas. I believe that as designers, it is our duty to shape a world where our existence and actions do not harm the world itself to the point where future generations must solve the problems we create. During this journey, I have managed to utilize skills I have acquired from academia, including façade design and detailing, energy and cost calculations, simulations and parametric optimization. I have gained insight into how HVAC systems are designed, and how they play a role in not just indoor comfort but also possibly the architectural expression of the building.

I would like to take this opportunity to thank my mentors Alejandro and Christien for patiently guiding me through this graduation thesis by encouraging critical thinking and open-mindedness. I thank my friends Natchai and Prethvi for our discussions over energy calculations and cooling technologies.

Lastly, I want to thank Xin Ying and my family for their encouragement during my time in TU Delft, and their support in my pursuit for learning opportunities based on my interests rather than social norms. Most of all, I dedicate this project to my parents.

4 July 2019

Benjamin Yong Zhen Hui

Abstract

The aim of this paper is to design a retrofit façade-integrated cooling system for built high-rise residential public housing buildings in the tropical climate and evaluate its feasibility.

Literature research into the climate, building design, cooling technologies and case studies of façade-integrated systems were important factors that led to the conceptual designs.

Energy calculations and parametric optimization through Rhinoceros + Grasshopper were conducted to develop the façade concepts to suit the cooling load of the chosen building. Material and component costs were calculated to evaluate which façade concept proposal was more suitable and what design constraints were introduced by the limited available physical space.

With a chosen façade concept, minor tweaks were made to account for additional issues such as conduction heat loss and the oversizing of components. Façade details with respect to structural elements, moving parts, system operation and maintenance procedures were developed. The overall implications and limitations of the design were discussed with the aid of daylighting simulations and extrapolative calculations to paint a broader picture of its overall feasibility and what it takes to be realized.

Contents

1 Introduction

Residential buildings should provide comfort and ease of living to its inhabitants, regardless of weather conditions. This occasionally involves additional cooling or heating systems to maintain comfortable indoor temperatures. This paper thus discusses a possible alternative cooling system and its facade retrofitting strategies on a high-rise residential building in a hot and humid climate.

1.1 Problem Statement

According to the International Energy Agency, the growing use of air conditioners in homes and offices around the world will be one of the top drivers of global electricity demand over the next three decades. (IEA, 2018) The growth in global human population is accompanied with rising thermal comfort needs. At present, energy used to provide indoor thermal comfort accounts for 50% of a building's energy consumption on average.

In Southeast Asia alone, cooling technologies such as refrigeration and air conditioning could account for 40% of the region's electricity demand by 2040. (Fleming, 2018) Typical air conditioning systems utilise the vapour compression cycle, which adopts the use of refrigerants detrimental to the environment. (Australian Department of the Environment and Energy, 2011) While efforts are being made to further increase the efficiencies of such systems, space cooling remains a growing problem, with its energy use and greenhouse effects projected to skyrocket amidst increasing cooling demands.

Singapore is one of the few developed countries in Asia. Its successful economic growth over the past few decades has brought about better living standards, but with higher affinity also comes higher consumption of resources. It sits about 1.35° North of the Equator, placing it within the realms of a tropical rainforest biome. Its purchasing power and location on the world map both contribute to the increasing prevalence of the use of air conditioning in its society. Ownership of household air conditioning systems has been on a steady rise for the past few decades, with 76.1% of all households owning such a system in 2013. (Singapore Department of statistics, 2018) Due to sparse land area in the country, 94% of residents stay in high-rise apartments. (Singapore Department of statistics, 2018) As of 2018, 81% of residents live in public high-rise apartments, (HDB, 2018) which account for 58.8% of all electricity consumption of all housing units. (Energy Market Authority Singapore, 2018) On average, air conditioning accounts for about 24% of energy usage of each household, (National Environmental Agency, 2017) and up to 40% of the household electricity bill. (Hill, 2018)

This trend is set to continue in the coming years, inevitably resulting in a further rise in energy consumption for space cooling. Efforts have been made to reduce cooling needs by introducing passive cooling strategies in the design of these public housing buildings. (HDB, 2012) These methods, while effective, are still insufficient in providing adequate thermal comfort nor cooling demands. (Wong et al., 2002) Air conditioning systems thus bridge this gap, albeit with high energy consumption and at the cost of the environment.

Traditional air conditioning utilises vapour compression cycles, where a refrigerant is cycled back and forth to carry heat from one space to another. (Hoffman, 2006) These refrigerants have been known to be detrimental to the environment. Over the past few decades, the Montreal Protocol has spurred a successful decline in the use of refrigerants harmful to the ozone and pushing the air conditioning industry towards refrigerants with lower Global Warming Potential (GWP). (Jindal & Low, 2016) However, even at present, refrigerants with a GWP more than a thousand times that of Carbon Dioxide are still widely in use, with the Montreal Protocol dictating that its use decrease by 85% over the next 25 years. While there are indeed refrigerants with much lower GWP values, these same refrigerants spark concerns with toxicity and flammability. As such, there is a need for more alternatives. (Jindal & Low, 2016)

Research has been done on alternative cooling strategies to vapour compression. Desiccant cooling is one of them and fits well within the tropical environment of Singapore where dehumidification and cooling are paramount. (Chua, Chou, Yang, & Yan, 2013) A desiccant coated heat exchanger system can supply dehumidified air efficiently whilst serving as a fresh air ventilation system. When coupled with other subsystems, further improvements to the overall system efficiency and energy consumption can be achieved. (Vivekh, Kumja, Bui, & Chua, 2018) However, currently more research and development into this cooling technology is needed for it to surpass the capabilities of traditional household vapour compression air conditioners, in terms of running costs and system efficiencies. Government incentives for further research would also help to speed up the process and encourage the development of such environmentally friendly cooling technologies for space cooling purposes, but there have not been any. Desiccant cooling heat exchanger systems are thus left stagnant in a state of research.

Cooling systems of office buildings are often centralised for cost and maintenance purposes. (EMSD, 2018) However, residential buildings pose a different problem as occupants prefer being in control of the thermal environment of their dwellings. Decentralised cooling systems are therefore viable because they can promote better user comfort and control by catering to the users individually. (Gruner, 2012) Unnecessary cooling is reduced because not everyone desires the same amount of cooling. On top of that, decentralised systems have been shown to have a generally higher energy efficiency than centralised counterparts. (Gruner, 2012) The building façade is deemed as the most appropriate area for the integration of a decentralised cooling system because façade integration does not consume floor area nor require extra ceiling height. (Heating and ventilating review, 2010) Interior ventilation ducts can be minimised. This paper thus aims to explore a **desiccant-coated heat exchanger system integrated as a retrofit façade for existing high-rise public housing buildings.**

1.2 Main Objectives

The following research objectives are derived from the above problem statement and serves to guide the focus of the research.

- Understand the climate of Singapore and the current situation of its public housing buildings with regards to its existing passive climate design strategies, facade design aspects, indoor thermal comfort, user behaviour and cooling load.
- Establish why desiccant cooling is an appropriate cooling strategy for the given climate, how a desiccant coated heat exchanger system works, and what additional subsystems can be integrated with it to further improve its energy performance.
- Explore the different possibilities of how desiccant cooling can be integrated as a retrofit façade system whilst producing sufficient cooling power, and determine which way is the most appropriate.
- Explore how such this façade system integrates into society and determine if it is feasible based on its implications and limitations.

1.3 Boundary Conditions

In this project, where the focus is on developing an energy friendly desiccant cooling façade system on an existing building, there are a few boundary conditions considered during the research phase:

- The use of refrigerants is avoided at all costs on the grounds of pushing as much as possible towards a system with better environmental consideration.
- Physical measurements and facade system prototyping are not possible with the given timeframe of the thesis.

1.4 Research Question

"How feasible is a retrofit façade-integrated desiccant cooling system for high-rise public housing in a hot and humid tropical climate?"

1.5 Sub Questions

In order to answer the main research question, additional sub questions must be answered first:

Context

- What are the requirements of a cooling method for a tropical rainforest climate?

- What are the current design aspects, user behaviour and cooling loads in a typical public housing building?

Strategy

- What is an appropriate active cooling strategy and how can additional subsystems be integrated to it to improve its energy performance?
- What are the design parameters of this system and its components that influence their performance?

Design

- What are the different ways in which this cooling strategy can be integrated as a façade system, and which one is more cost-effective?
- What implications and limitations does the façade system have?

1.6 Approach and Methodology

The research is divided into two main parts; literature research and retrofit façade system design. In literature research, the climate condition of Singapore will first be introduced, bringing into discussion the requirements of a cooling strategy in this climate. An understanding of the state of the art of current high-rise public housing buildings and air conditioning systems is necessary to know further technical and spatial requirements of the cooling system to be designed later. A real building is then chosen as a representative case of a typical public housing building in Singapore on which the retrofit façade system will be designed for. Research into a possible and appropriate cooling strategy is then undertaken, along with current innovations and improvements made possible by integrating the system with additional features to boost performance. Design parameters of the system and its components which affect its cooling performance are taken into account.

Case studies of façade integrated systems are introduced as examples of how HVAC systems can be architecturally integrated as a facade. Different facade integration concepts for the chosen building are explored and designed. Calculations and design simulations are conducted to verify the workability of these concepts. They are evaluated based on how cost-effective they are relative to each other, and a final one is chosen among them to be further developed in depth and details. Further analysis of the energy consumption, implications on the society, its limitations and its future prospects are discussed to provide a clearer picture of the feasibility of its concept.

1.7 Thesis Scheme

Figure 1.1 below illustrates the outline of the research, based on the sub questions. The contextual knowledge is first discussed. After which, an understanding on the cooling strategy is established. Different ways of integrating the cooling strategy as a façade system are then explored and compared. Design-related questions are then answered with the development of a final retrofit façade system.

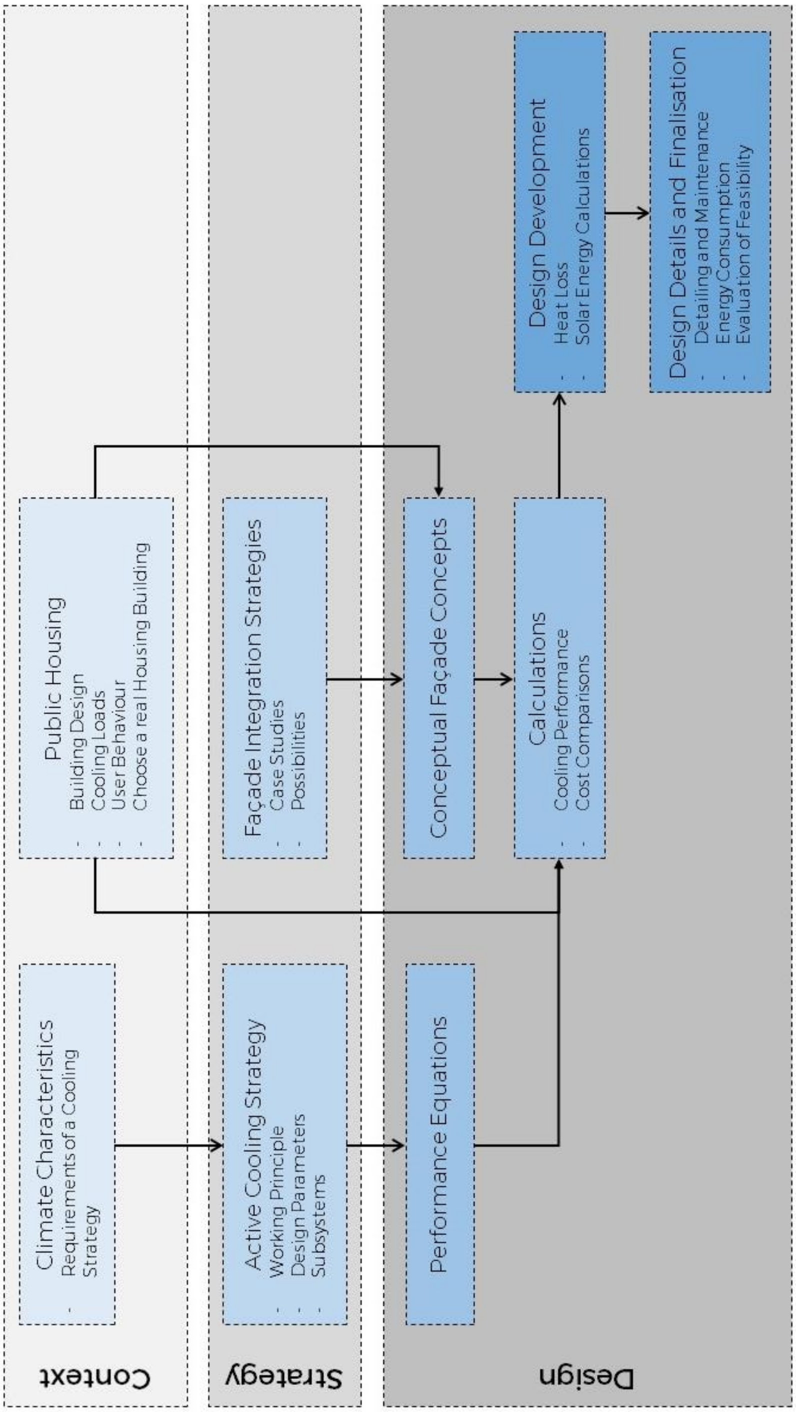


Figure 1.1: Scheme of Thesis.

Table 1.1 below is the time plan or the entire research. The main tasks are listed and organised according to when time is allocated for it.

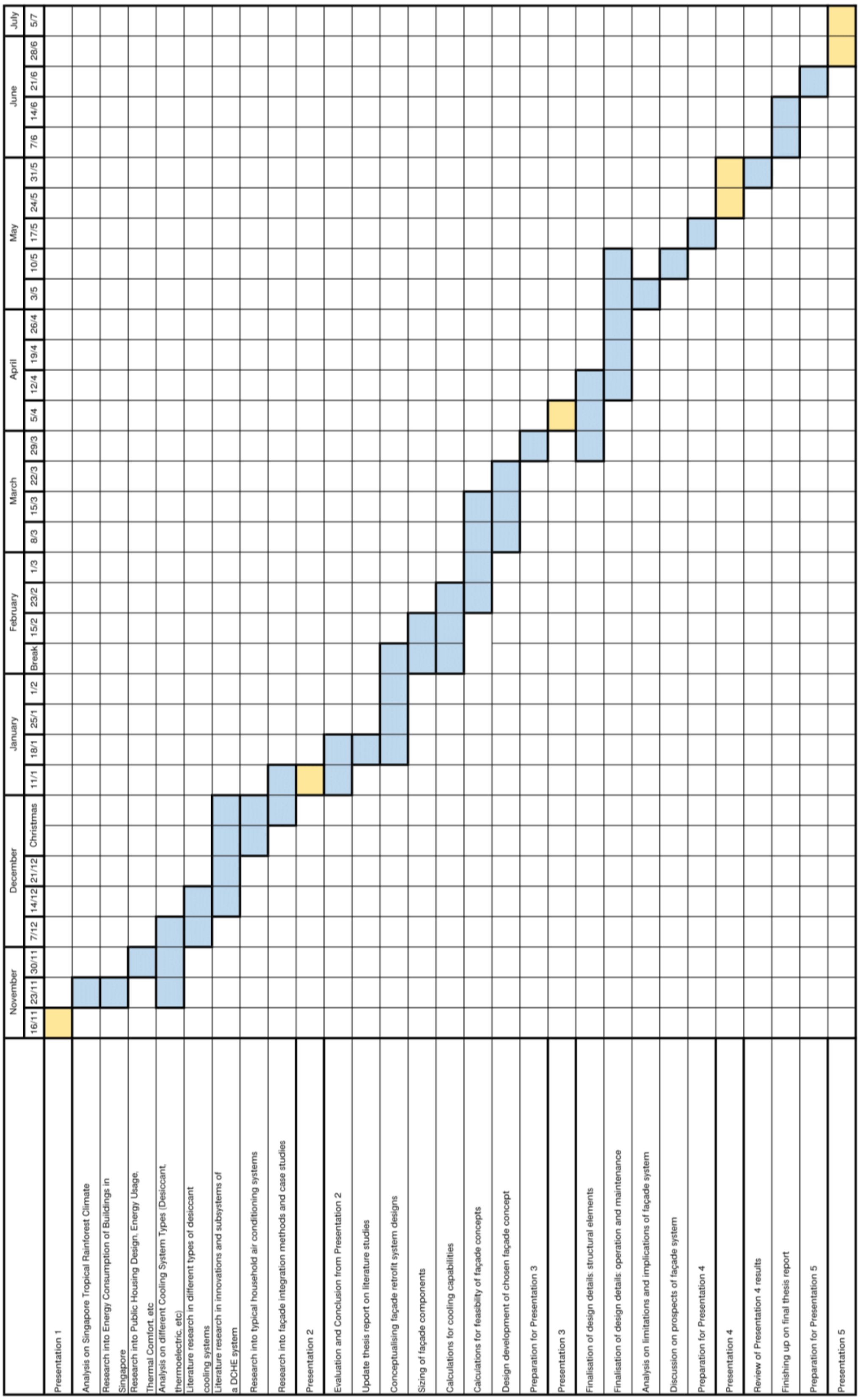


Table 1.1: Time plan for thesis.

2 Context

In this chapter, the focus is on the understanding of the underlying principles behind the context of the research. This includes the climate of the location and the current situation of public housing buildings. This provides background knowledge for an informed system design.

2.1 Climate

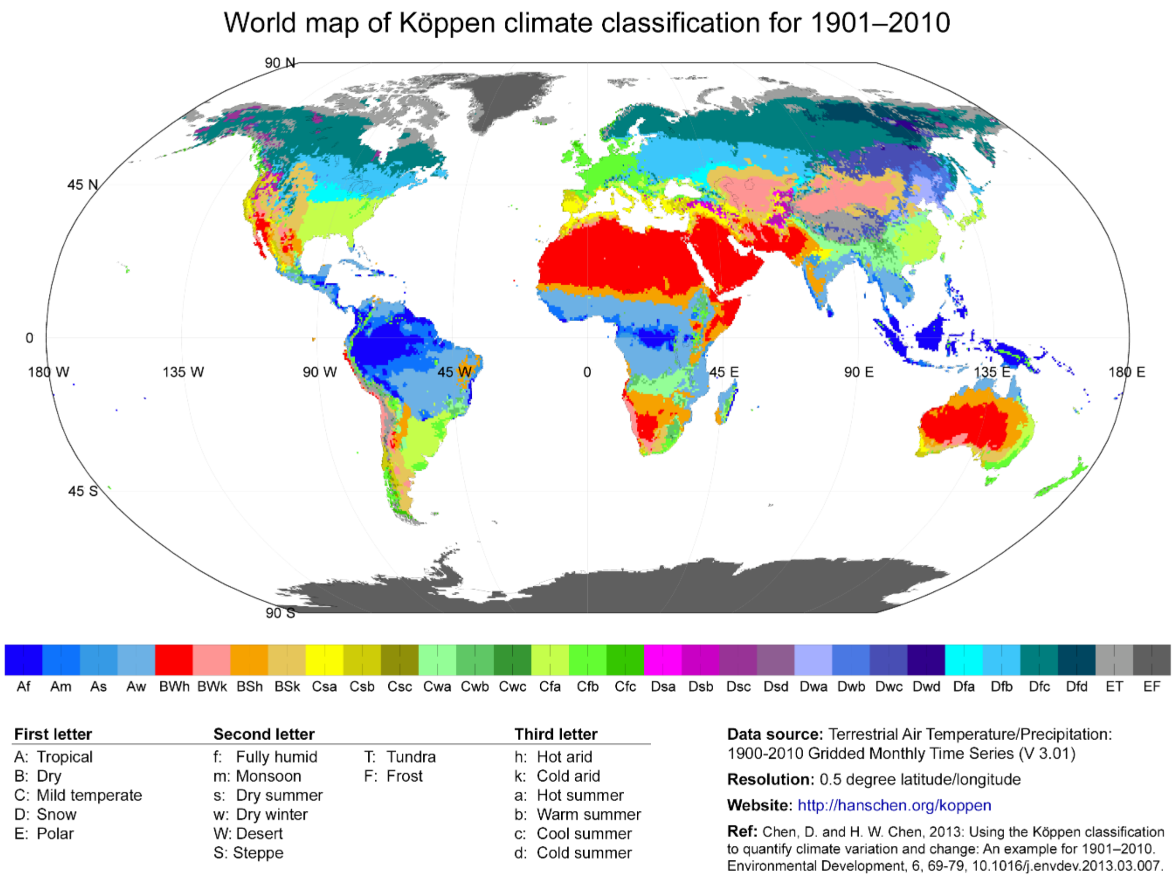


Figure 2.1: World map with climate classifications.

In general, a tropical climate comprises of an average temperature above 18ºC, with considerable rainfall for at least a portion of the year. This happens because there is a strong vertical uplift and convection which, when coupled with an abundance of sunlight, facilitates evaporation. The evaporated water falls back down as heavy rain, which is why storms are most common in midday when the sun is at its strongest (Reis, 2017). As a result, relative humidity hovers between 77 to 88% daily. Another strong characteristic of tropical climates is the warm temperatures, hovering around 80 degrees Fahrenheit (26 to 27ºC) year-round and fluctuating little in any month or year. More fluctuation occurs in daily temperature than in monthly or yearly temperature (London, 2018). Tropical climates typically reside in areas near the equator, such as Indonesia, Brazil and the Congo Basin (Reis, 2017). Tropical climates comprise of only two seasons which are the dry season and the wet season. Changes in solar angle are small. Within the realms of tropical biomes lie different subtypes of tropical climates that differ slightly in humidity; the Savannah climate, Tropical Monsoon climate and Tropical Rainforest climate (Kiprop, 2017).

2.1.1 Tropical Rainforest Characteristics

Being only 1.35° North of the equator, Singapore lies within the area of a tropical rainforest climate, where annual average precipitation is at least 2.4 inches (roughly 6 cm). (London, 2018) With a population of 5,791,901 as of 2018 within its land area of 721.5 km^2, Singapore has one of the highest population densities in the world of more than 8200 people/km^2.

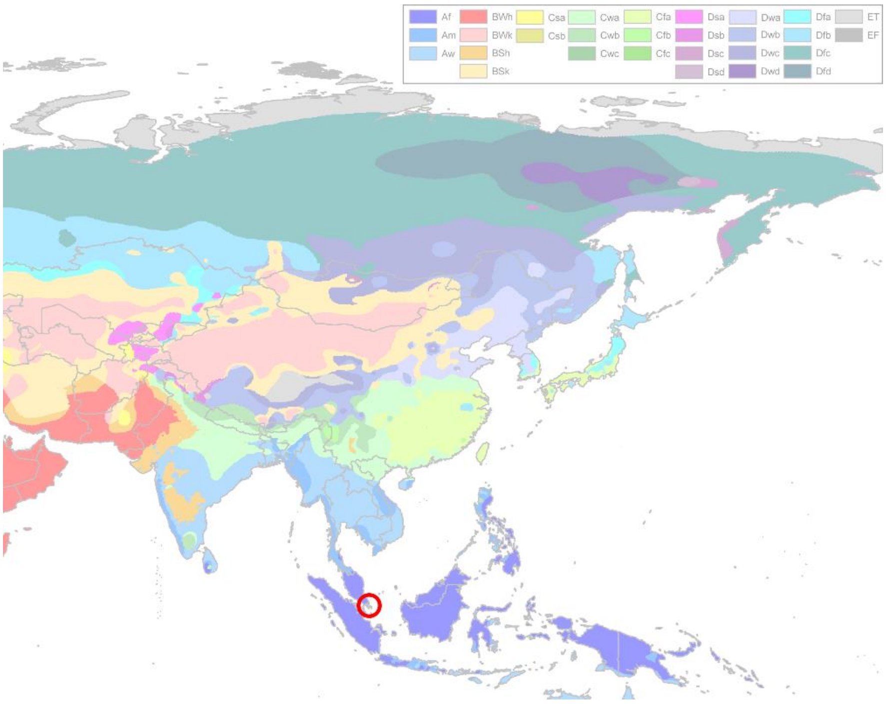


Figure 2.2: Singapore is located in a fully humid tropical zone.

Specifically, Singapore has 2 monsoon seasons, with inter-monsoonal periods in between. The Northeast monsoon occurs from December to March, while the Southwest monsoon happens from June to September. Afternoon and evening thunderstorms happen due to strong surface heating and sea breeze circulation in the afternoon. (MSS, 2011)

Temperature

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	Mean Monthly/ Annual Total (mm)	234.6	112.8	170.3	154.8	171.2	130.7	154.4	148.9	156.5	154.6	258.5	318.6
	Mean Raindays	13	8	13	14	14	12	14	14	13	15	18	18
Temperature (°C)	Mean Daily Max.	30.4	31.7	32	32.3	32.2	32	31.3	31.4	31.4	31.7	31.1	30.2
	Mean Daily Min.	23.9	24.3	24.6	25	25.4	25.4	25	25	24.8	24.7	24.3	24
	24-hr Mean	26.5	27.1	27.5	28	28.3	28.3	27.9	27.9	27.6	27.6	27	26.4
Relative Humidity (%)	Mean Daily Max.	95.3	94.6	95.9	96.6	96	94.8	94.6	94.3	95.5	96.1	96.9	96.3
	Mean Daily Min.	66.7	61.7	62.5	3.3	64.5	63.6	65	64.5	63.7	62.6	66.2	69.5
	24-hr Mean	84.4	82	83.4	84.1	83.5	81.9	82.3	82.2	82.7	83.1	85.7	86.5
Wind Speed (m/s)	Mean Monthly/Annual	2.9	3	2.3	1.6	1.6	2	2.4	2.5	2.1	1.6	1.5	2.2
Thunderstorm and Lightning	Mean Thunderstorm Days	5	6	12	19	19	15	13	13	15	18	18	12
	Mean Lightning Days	6	5	14	23	22	17	14	13	13	19	23	15

Figure 2.3: Monthly mean climate of Singapore, as recorded from 1981 to 2010. (MSS, 2011)

Figure 2.3 above shows the monthly mean temperatures, rainfall and humidity recorded over a period of 20 years. Figure 2.4 and Figure 2.5 below shows the temperature patterns in Singapore being relatively stable, with a daily mean of 27.5°C. The daily temperature range has a minimum usually not falling below 23-25°C during the night and maximum not rising above 31-33°C during the day. (MSS, 2011)

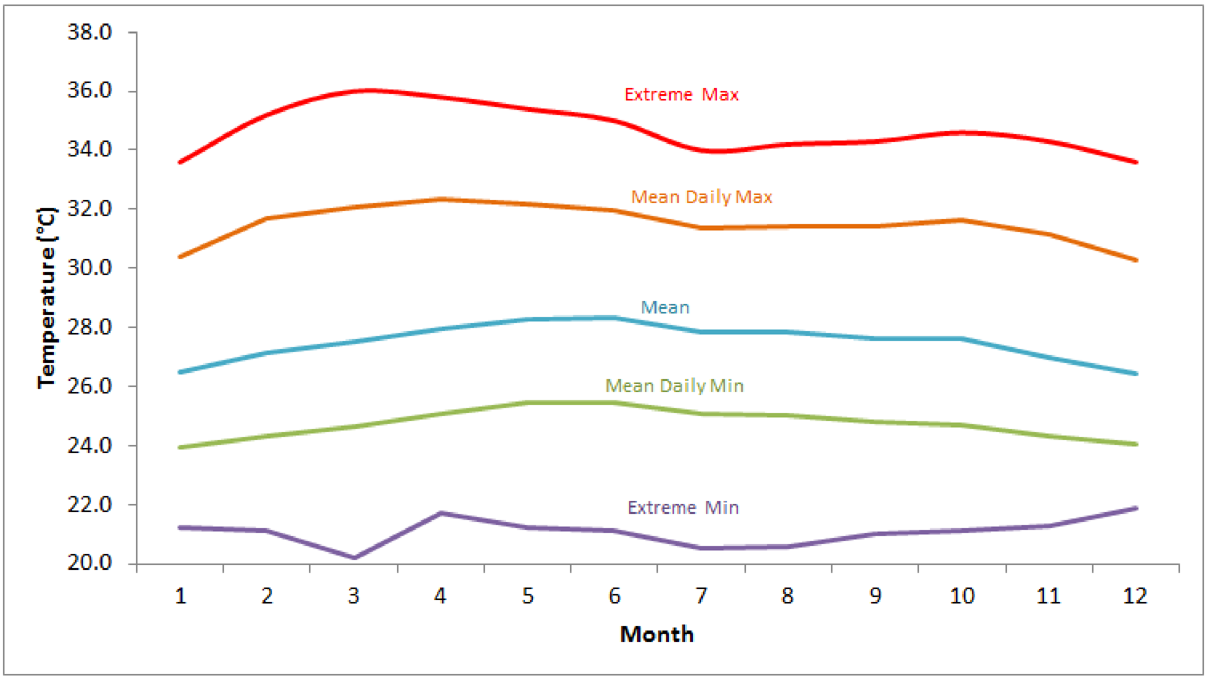


Figure 2.4: Monthly mean temperature of Singapore. (MSS, 2011)

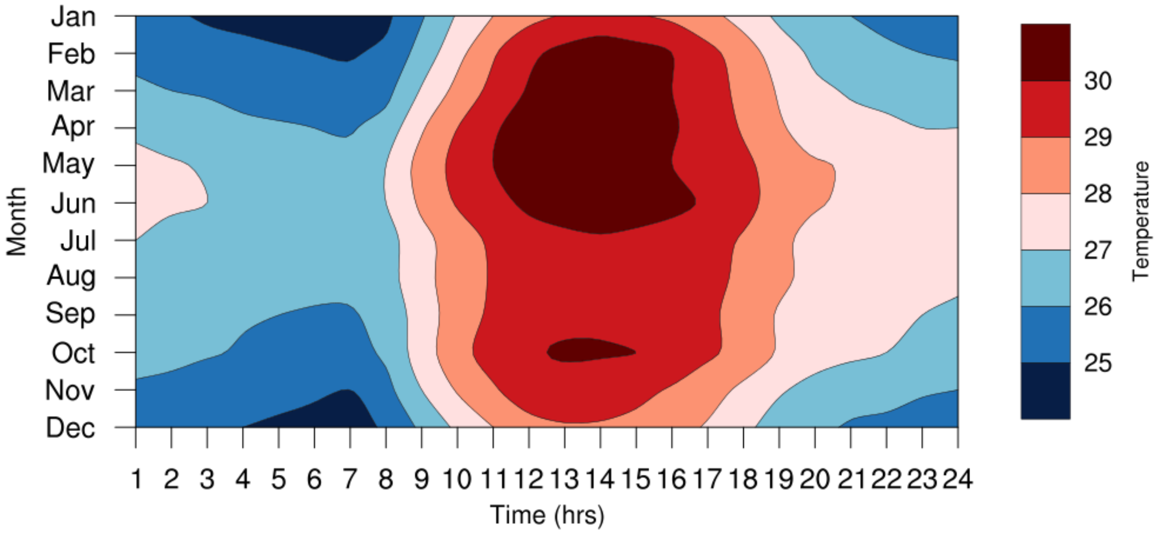


Figure 2.5: Average hourly temperatures per month. (MSS, 2011)

Relative Humidity

Relative humidity is also fairly uniform throughout the year without much monthly variation. Its daily variation is more interesting, as shown in Figure 2.6 and Figure 2.7 below, varying from more than 90% in the morning just before sunrise and falling to around 60% in the mid-afternoon on days when there is no rain. It easily reaches 100% during prolonged periods of rain. Overall, the mean annual relative humidity is 83.9% (MSS, 2011)

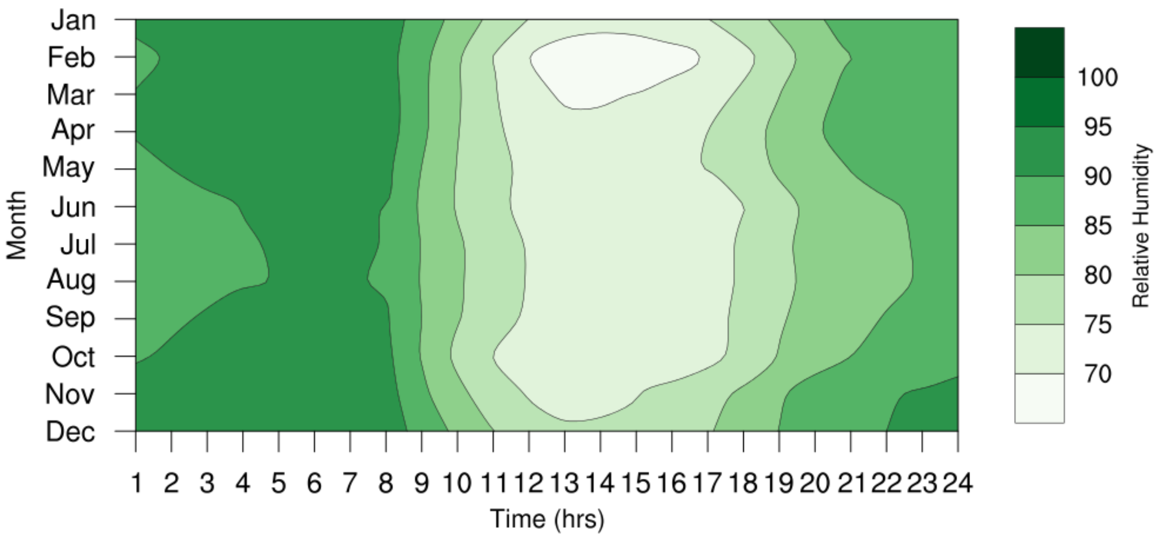


Figure 2.6: Daily Relatively Humidity changes in different months. (MSS, 2011)

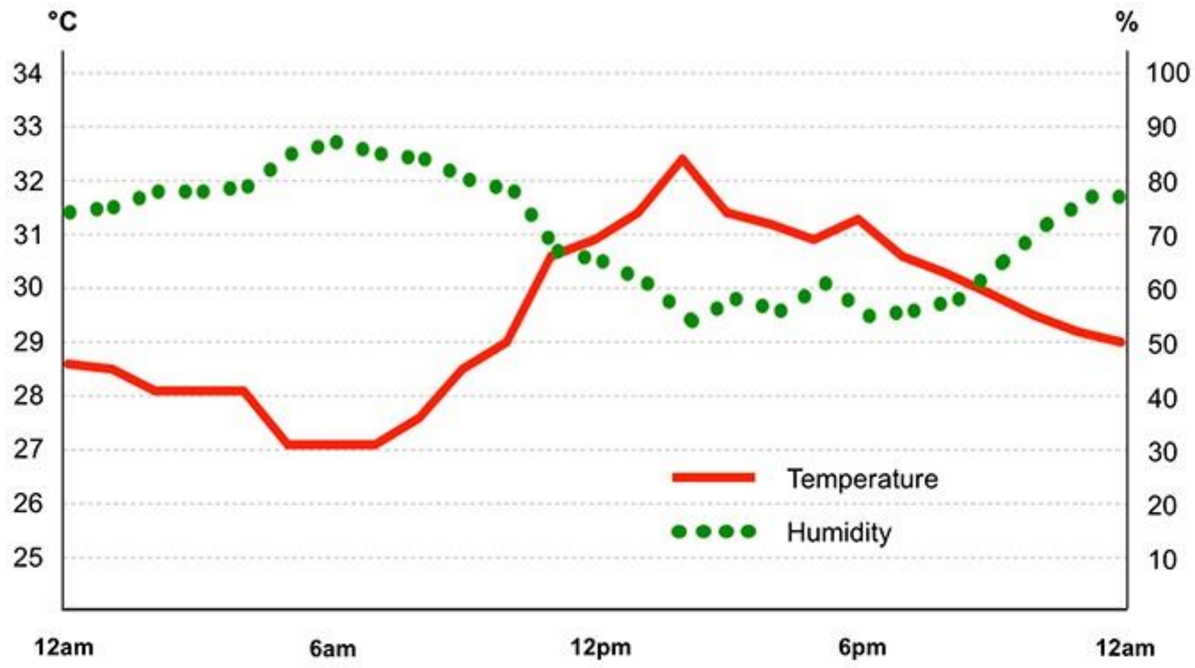


Figure 2.7: Hourly patterns of temperature and relative humidity in Singapore over a 24-hour period. Recorded by the National Environment Agency of Singapore.

From Figure 2.6, it can be seen that the daily trends of temperature and relative humidity are frequently opposite of each other. The lower temperatures are accompanied by higher humidity levels.

Solar Irradiation

Because Singapore is close to the equator, monthly annual solar irradiance does not differ a lot because the sun incidence angle stays close to 90°, as seen in the sun path in Figure 2.8.

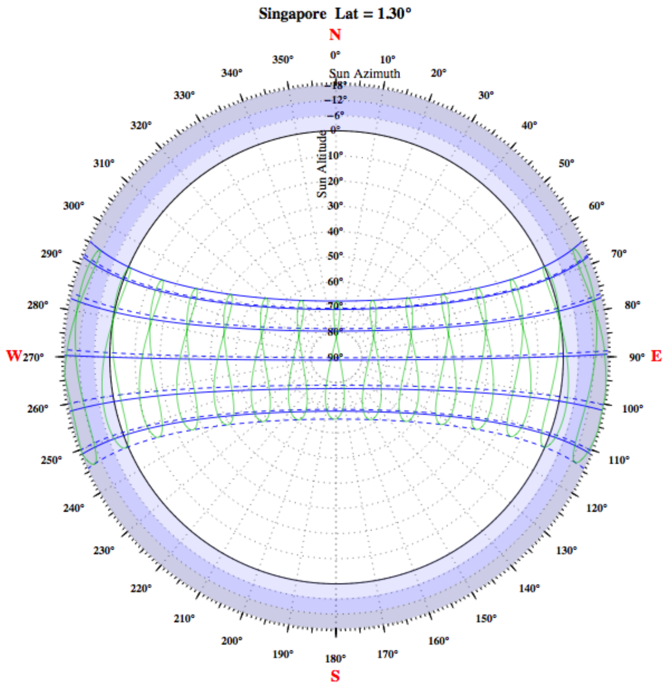


Figure 2.8: Sun path of Singapore.

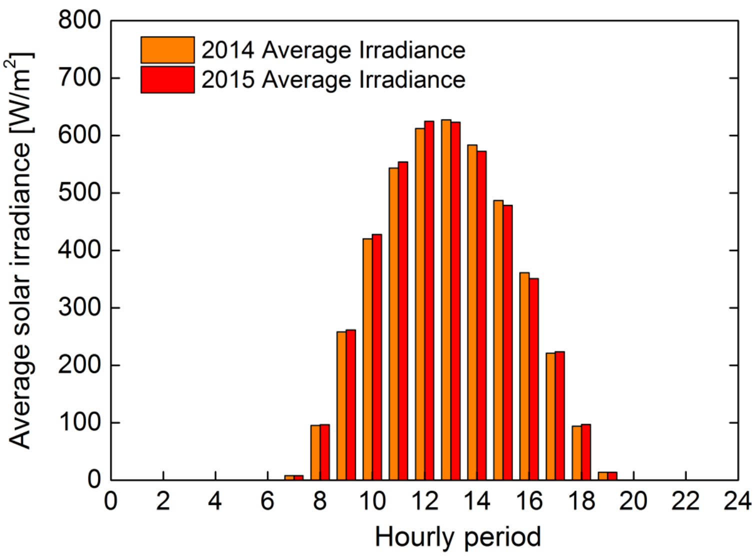


Figure 2.9: Hourly solar irradiance in Singapore recorded in 2014 and 2015. (EMA, 2016)

As seen in Figure 2.9, the daily average solar irradiance is about 4.3 kWh/m^2 which translates into an annual irradiance level of around 1,580 kWh/m^2 averaged across Singapore. (EMA, 2016)

Cloud Cover

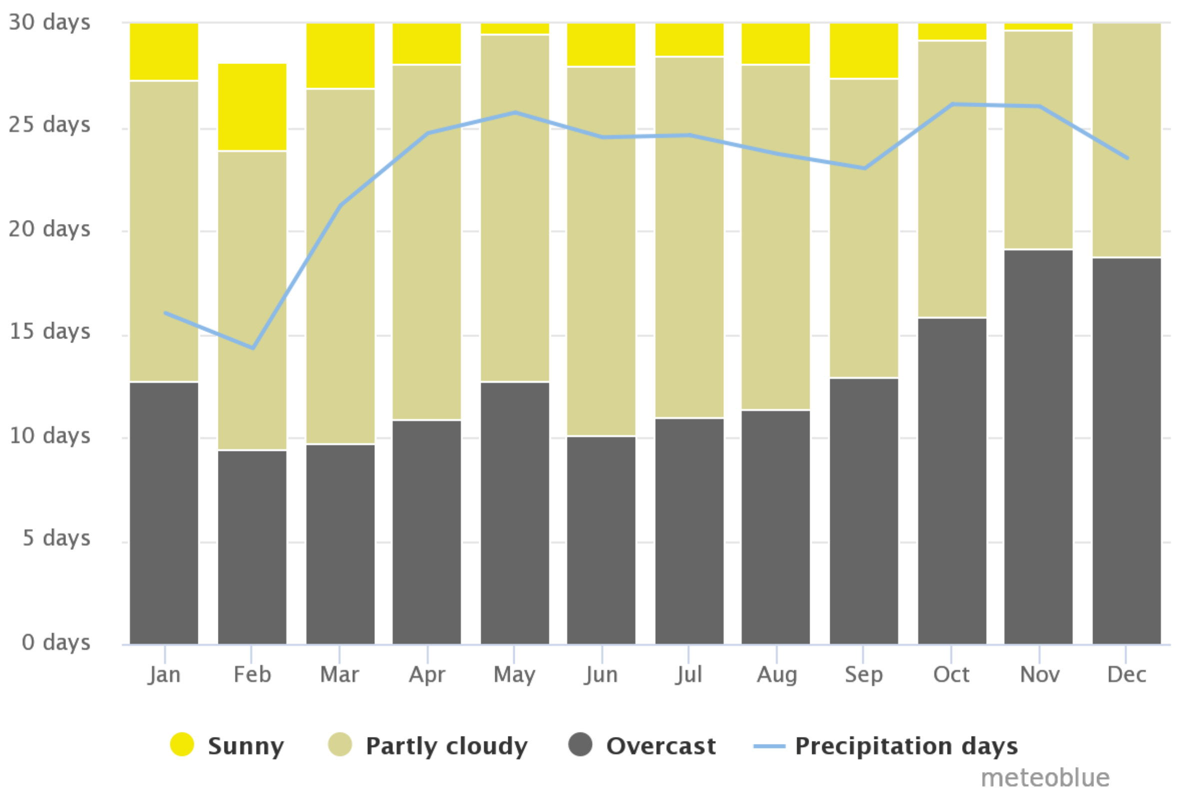


Figure 2.10: Cloudy and sunny days in Singapore. Based on Meteoblue's 30 years of hourly weather model simulations. (Meteoblue, 2014)

In Figure 2.10, sunny days are defined as days with less than 20% cloud cover. Partly cloudy days have 20 to 80% cloud cover and overcast days have more than 80% cloud cover. Singapore therefore has a relatively large amount of cloud cover throughout the year, having overcast weather for roughly half of all days.

2.1.2 Thermal Comfort in Singapore

Thermal comfort is defined as a state of mind expressing satisfaction towards the indoor thermal environment. Because everyone has different levels of tolerance and preferences for various thermal conditions, it is difficult to satisfy everyone in a space. (ASHRAE 55, 2010) There are many thermal comfort models and standards, but this research will focus on the ASHRAE-55 standard, which considers 6 main factors of the user and the environment:

- Metabolic rate of activity
- Clothing insulation
- Air temperature
- Radiant temperature
- Air speed
- Humidity

Because these factors vary over time, this thermal comfort standard only considers steady state scenarios. (ASHRAE 55, 2010) It is also best applied when the activity involved in the space is sedentary such as in office environments. It however does not apply to metabolic rates of sleeping or bed resting, nor is it reliable in determining thermal comfort for children and infants. To quantify thermal sensation, it uses the Predicted Mean Vote (PMV) scale, which scales as such:

+3: hot

+2: warm

+1: slightly warm

0: neutral

-1: slightly cool

-2: cool

-3: cold

An occupant is assumed to be in dissatisfaction if he/she votes +3, +2, -2 or -3 in the scale. This is known as the Predicted Percentage of Dissatisfied (PPD) index. A space is considered to be thermally comfortable if 80% of occupants deem it to be acceptable within this PMV/PPD system. That is, if 80% of the occupants vote within +1, 0 and -1 categories. (ASHRAE 55, 2010)

In 1953, Ellis conducted an investigation on thermal comfort in Singapore and concluded that within humidity levels of 60 to 97%, thermal acceptability was achieved at temperatures between 73 and 78 degrees Fahrenheit (22.8 to 25.5°C). (Ellis, 1953) Later in 1959, Webb used multiple regression analysis and derived a comfortable temperature of 25.9°C. He then later proposed the Equatorial Comfort Index, which was based only on dry and wet bulb temperatures and air velocity. It therefore did not take into account human activity level and clothes. (Webb, 1959) Another study on indoor thermal comfort in naturally ventilated public housing buildings in Singapore suggested that the neutral temperature was 28.5°C, under the conditions of 73.5% relative humidity, 29.4°C outdoor temperature and an air velocity of 0.22ms^{-1}. (de Dear & Leow, 1990) This was 2°C higher than the ISO 7730 international comfort and PMV standards developed in cooler climates using samples of Danish and American students, suggesting that a controlled experiment in a climate chamber was necessary to further study thermal comfort in the tropics. In 1991, R, de Dear then conducted this climate chamber experiment, concluding that at a lower relative humidity of 35%, the neutral temperature was 27.9°C, while at high humidity of 70%, the neutral temperature was 27.6°C, showing how relative humidity has an affect on thermal comfort and the necessary corresponding dry bulb temperature to achieve it. (de Dear, Leow, & Ameen, 1991)

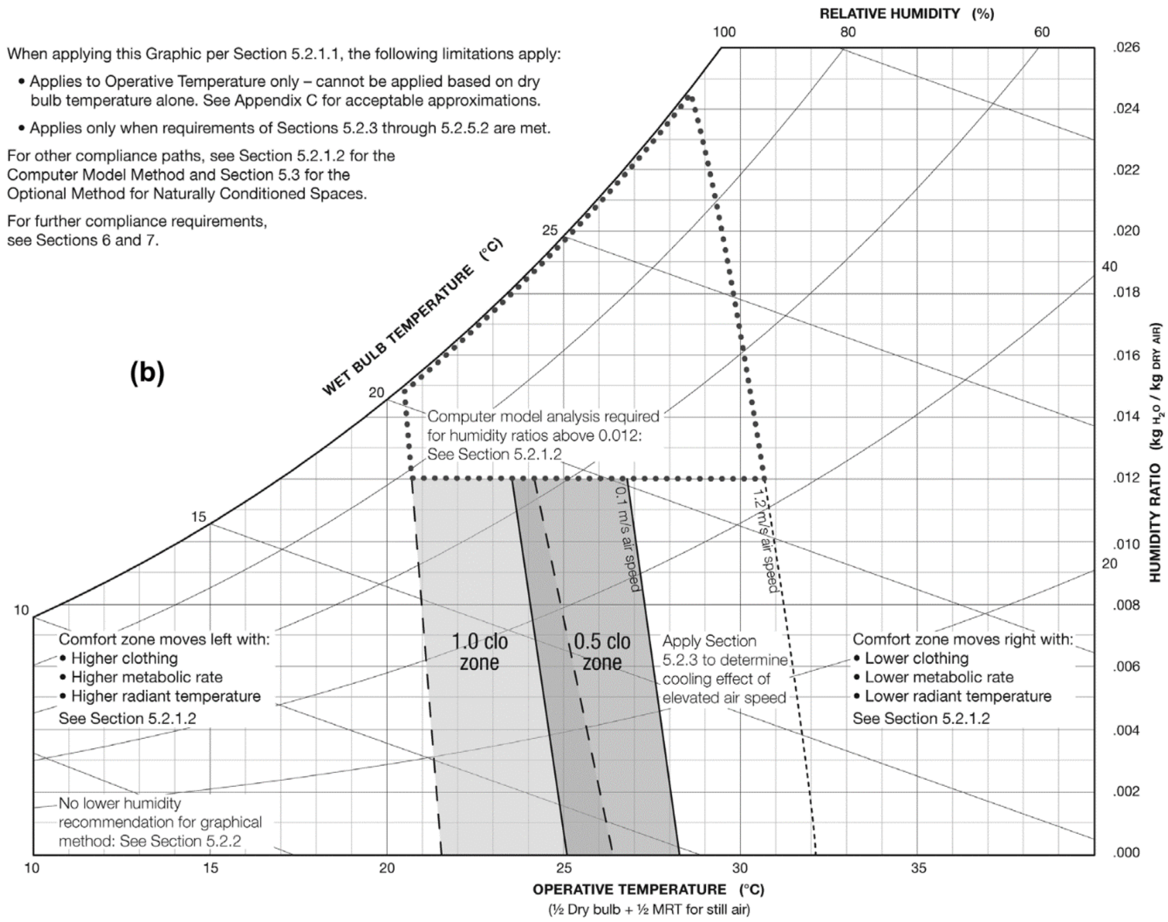


Figure 2.11: Psychrometric chart indicating thermal comfort zones based on several factors. (ASHRAE 55, 2010)

Since a thermally comfortable temperature depends on the relative humidity, a range of values of temperatures and humidity levels is thus necessary. Figure 2.11 above is a psychrometric chart showing the thermal comfort zones based on clothing index, radiant temperature and metabolic rate. The zones indicated only cater to clothing indexes of 1.0 and 0.5. In a tropical climate, it is usually common for residents to be dressed with an index of roughly 0.26 clo units. (de Dear & Leow, 1990)

Another option is using the adaptive model of ASHRAE 55, in which a comfortable operative temperature range can be deduced from the air temperature, mean radiant temperature, mean outdoor temperature and air velocity. Using the mean temperature of Singapore of 27.5°C and a low indoor air velocity of 0.3ms^{-1}, a graph relating suitable operative temperatures as a result of different mean outdoor temperatures can be formed, as seen in Figure 2.12 below.

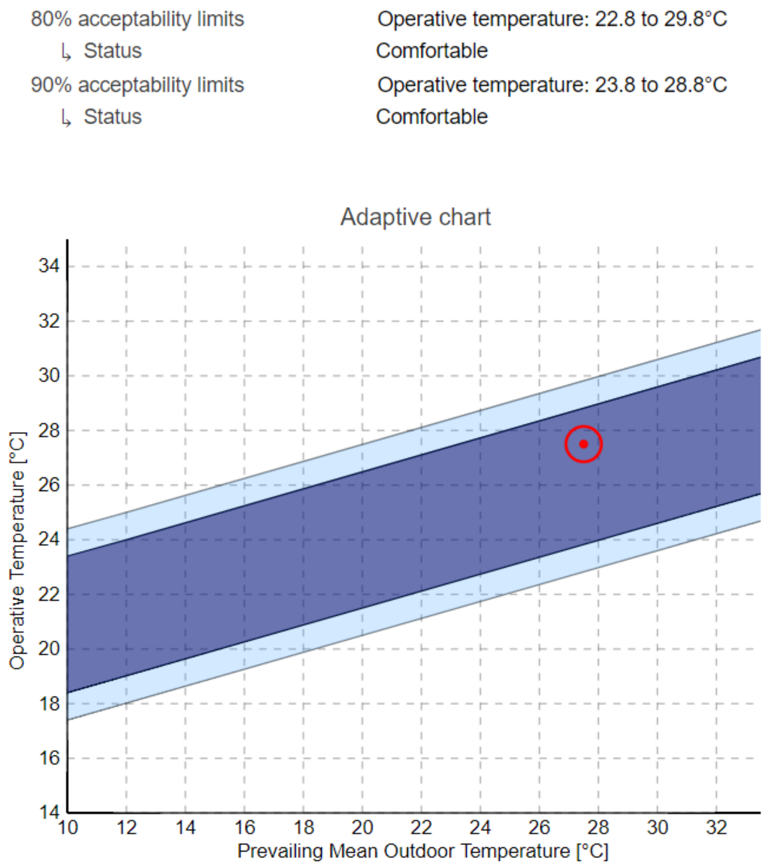


Figure 2.12: Range of comfortable operative temperatures from the adaptive thermal comfort model.Diagram acquired from CBE Thermal Comfort Tool. (Hoyt Tyler, Schiavon Stefano, Piccioli Alberto, Cheung Toby, Moon Dustin, and Steinfeld Kyle, 2017, CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley, http://comfort.cbe.berkeley.edu/)

For an 80% thermal acceptability temperature range, the suitable operative temperature is thus 22.8 to 29.8°C. However, the adaptive thermal comfort model is only valid in cases where the occupants have control over the environment, such as operable windows and change of clothing. Metabolic rates of the occupants' activity must be between 1.0 to 1.3 metabolic units. (ASHRAE 55, 2010) To put things in perspective, sleeping has a metabolic rate of 0.7 units, while other sedentary activities such as reading and typing while seated are valued at 1.0 and 1.1 units respectively.

2.1.3 Climate Design Guidelines

In hot and humid climates such as Singapore, humidity, air temperature, air velocity and other personal factors affect a person's perception of thermal comfort. Perspiration is a human body's way of releasing latent heat. In high humidity and temperatures, the perspiration mechanism is suppressed because sweat is not so easily evaporated in conditions where the vapour pressure is higher than the body's. (McGowan, 2018)

Passive building design strategies to reduce sensible cooling loads, such as external sun shading and controlled window-to-wall ratio (WWR), are effective to a large extent. This is then coupled with active dehumidification devices to reduce the humidity ratio in the space brought about by ventilation and the occupants themselves. (McGowan, 2018)

However, because of how air temperature and relative humidity both determine a space's thermal acceptability, there is no set limit on maximum relative humidity levels for thermal comfort. Higher air temperatures merely require lower relative humidity. The Building and Construction Authority of Singapore (BCA) has general guidelines on indoor conditions of an air-conditioned space (BCA, 1986):

- Dry bulb temperature: 23 – 27°C
- Maximum relative humidity: 75%
- Maximum air velocity: 1.5 ms^{-1}

These values are lower than Singapore's mean temperature and humidity, suggesting that a cooling system in Singapore would require both cooling and dehumidification capabilities. Both sensible and latent cooling is necessary. This concept is illustrated in Figure 2.13 below on the psychrometric chart.

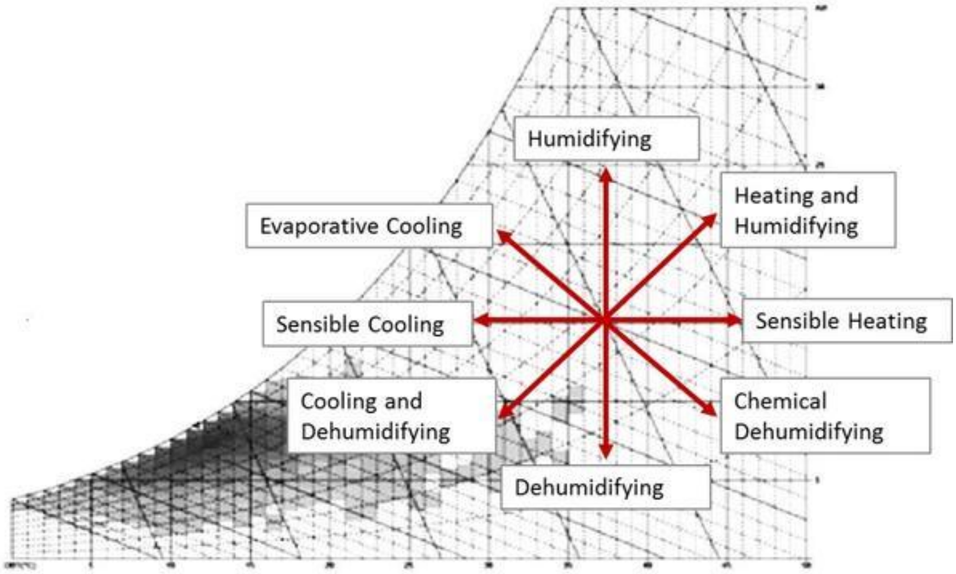


Figure 2.13: Different processes cause shifts in the psychrometric chart. Climate design strategies can be derived from this graphical representation. (Autodesk, 2018)

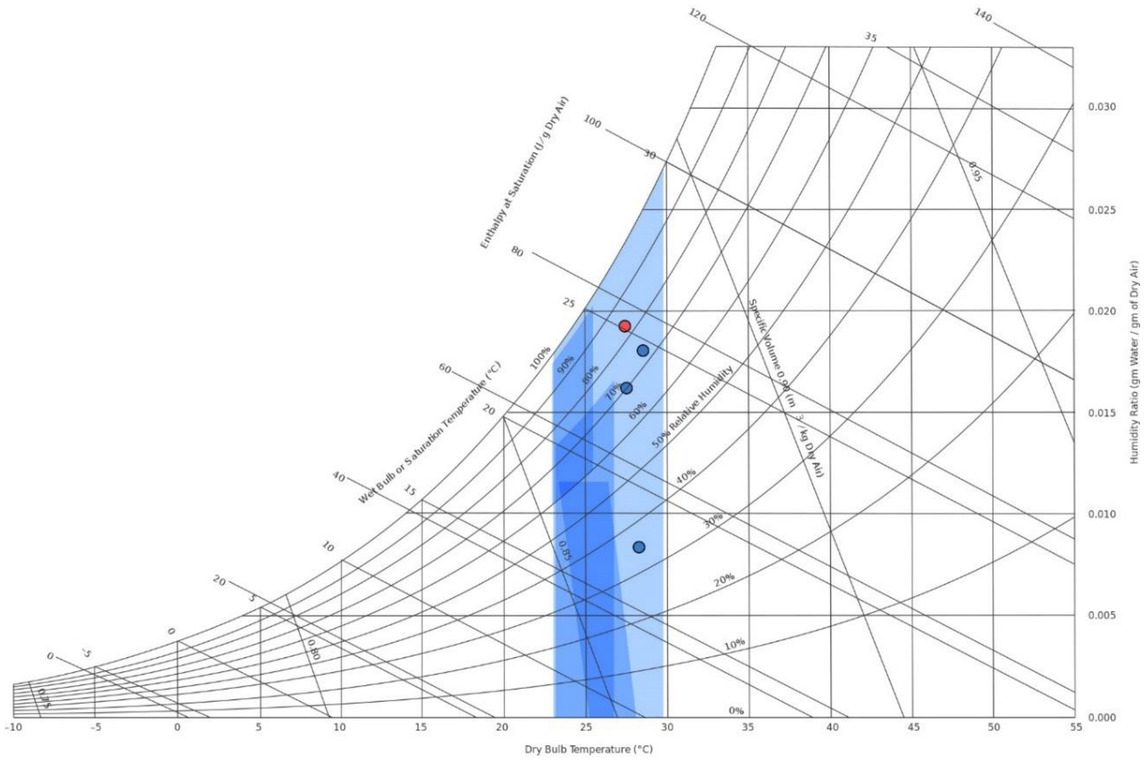


Figure 2.14: Psychrometric chart suggesting that cooling and dehumidification processes are necessary for Singapore.

Figure 2.14 shows the situation of Singapore. The red point denotes the mean climate of Singapore, while the blue points and zones indicate the thermally acceptable conditions according to research papers, standards and guidelines mentioned in this research so far. Based on both Figures 2.13 and 2.14, the conclusion for an appropriate strategy for this climate is cooling and dehumidification. The cooling system will thus have to handle this feat.

2.2 Public Housing

This chapter investigates the current conditions of public housing in Singapore. Understanding the users and the building design helps to further inform the needs and requirements of the retrofit cooling facade system. As of 2017, public housing makes up for 72.6% of all housing building stock in Singapore, with over 1.2 million units accommodating 81% of all residents. (Singapore Department of statistics, 2018)

Figure 2.15: Public housing is regulated by the Housing Development Board of Singapore (HDB). (Source: https://www.todayonline.com/singapore/use-cladding-buildings-here-have-grown-recent-times-experts)

2.2.1 Building Design

The Housing Development Board (HDB) is the government sector in charge of public housing. It has strict regulations on the design of public housing buildings, employing passive cooling strategies in order to minimise the need for additional cooling, and prioritising safety, buildability, durability and maintainability. Natural lighting and ventilation is enforced for all room areas. (HDB, 2012) Guidelines on the calculation of thermal transmittance values of HDB facades are based on thermal transmittance of façade walls and windows, WWR, solar heat gain through the windows, and shading coefficients of sun shading designs. (BCA, 2008) However, a study in 2007 deduced that the most optimal WWR value for the North and South facades of a naturally ventilated residential building in Singapore is 0.24, inclusive of a 300 mm horizontal shading device. (L. Wang, Wong Nyuk, & Li, 2007) Concrete is also the main building material because of good thermal massing properties. Although the design of HDB buildings has changed over the decades, regulations are still in place to ensure safe and comfortable living. Prefabrication of HDB blocks first began in 1980s, facilitating faster construction processes and higher building quality. (The Straits Times, 1982)

In this research, HDB buildings built in the era between 1980s to 1990s will be focused on. There are 2 main typologies of these buildings; slab block and point block. Slab blocks have a linear massing, with common public corridors linking units to the lift lobby. Each block is usually 10 to 13 stories high, with 10 to 12 units per floor. (Teo, 2018) Slab blocks were often positioned along the East-West axis as much as possible to minimise solar heat gain, as seen in Figure 2.17.

Figure 2.16: Rows of slab blocks built adjacent to each other. (Source: https://www.straitstimes.com/askst/askst-how-can-home-owners-use-the-asset-to-generate-wealth-after-retirement)

Figure 2.17: Bird's eye view of slab blocks aligning with the sun path. (Source: Google Maps)

Point blocks were first introduced in the 1970s and were designed to promote privacy by linking the unit entrances directly to the lift lobby. There was therefore no common corridor, unlike slab blocks. As a result, there were usually only 4 units per floor, albeit usually larger units such as 5-room units. For this reason, point blocks are often built taller than slab blocks, some 25 stories. (Teo, 2018)

Figure 2.18: Point blocks were often taller and had larger units. (Source: https://www.straitstimes.com/singapore/quota-for-hdb-subletting-to-foreigners-8-cent-for-neighbourhoods-11-for-blocks)

In both point blocks and slab blocks, passive cooling strategies were employed, such as natural cross ventilation, natural lighting, and building orientation. The façade has sun shading, thermal mass and controlled WWR to further minimise the need for fans and air conditioning. (HDB, 2015)

2.2.2 Thermal Comfort in Households

In 1990, De Dear and Leow conducted field studies on 4 high rise HDB blocks to investigate thermal comfort in naturally ventilated buildings. Surveys were conducted between 0800 and 2200 hours on 583 respondents using the ASHRAE PMV scale. They concluded that the average thermal sensation in the apartment was +0.66 on the ASHRAE 7-point scale, which translates to roughly the midpoint between 'neutral' and 'slightly warm'. This indicates good adaptation of the apartments' occupants to the indoor climate. However, when this thermal sensation value was input into the PMV scale, along with values of air temperature, mean radiant temperature, clothing index, air velocity, relative humidity and metabolic rate, the resultant PMV value was +1.13, which is a 'slightly warm' on the 7-point scale. They deduced that the preferred neutral operative temperature is 28.5°C, which was 1.1°C lower than the actual air temperature in the apartment. (de Dear & Leow, 1990)

Wong conducted questionnaire surveys on 257 participants across 4 different housing estates to investigate thermal comfort in different types of HDB units. He used both the ASHRAE scale and the Bedford scale. They concluded that thermal acceptability was only achieved in the morning with 81.7% of the participants voting the space as thermally comfortable. This was only 57.6% in the afternoon and 77% at night. (Wong et al., 2002) Surprisingly, among those who voted for +2 (warm) and +3 (hot) on the ASHRAE scale for thermal comfort in the afternoon and night, only 41% felt satisfied at night on the Bedford scale, as compared to 49%. This means that people felt more comfortable in the afternoon than at night even though temperatures are higher in the afternoon. Wong attributed this to a few reasons. People adjust their clothing according to the environment, which might affect comfort responses in the afternoon. Acclimatisation to hot afternoon weather could have affected the person's comfort expectations of high thermal sensation. More importantly, the occupants' expectations of indoor environments were affected by their daily working conditions in the office. This means that working adults might be more accustomed to a smaller range of indoor conditions, and carry over this expectations to their home, thereby becoming less tolerant of warmer temperatures which may not be conducive for sleep. (Wong et al., 2002)

Wong then compared thermal comfort between unit types, namely 3-room flats, 4-room flats and maisonettes. 27.5% of the occupants voted warm and hot for the 4-room flats, while 19% and 21% voted that for the 3-room and maisonette units respectively. Consequently, none of the unit types achieved thermal acceptability on the ASHRAE scale as none of them hit the 80% acceptability requirement. They all attained between 70% to 75%. (Wong et al., 2002)

In conclusion, thermal comfort in these residential buildings is not sufficiently met with merely passive cooling design strategies. This is one of the reasons why occupants resort to using air conditioning at home. Moreover, indoor thermal comfort does not guarantee a lower energy usage for cooling, because of societal expectations of indoor comfort brought over from offices. Under this circumstance, in order to reduce cooling loads, thermal comfort is a necessary criterion for the retrofit façade cooling system to fulfil, but not a sufficient criterion.

2.2.3 User Behaviour

Wong also investigated the user behaviour of these housing estates through the same questionnaires.

AC Installation				
Bed	Living	Dining	Study	(%)
■				57.3
	■			1.1
■	■			9
■			■	23
■		■	■	6.2
■	■	■	■	3.4
98.9	13.5	9.6	32.9	(%)

Figure 2.19: Areas of the apartment unit in which the air conditioner is installed in.

Air Conditioner Usage				
Morning	Noon	Evening	Night	(%)
■				0.6
	■			4.2
		■		3
			■	44.6
	■	■		1.2
		■	■	25.9
	■		■	1.8
■	■	■		0.6
■		■	■	3
	■	■	■	0.6
■	■	■	■	1.2
5.4	9.6	25.5	74.4	(%)

Figure 2.20: Time of the day in which the air conditioner is used.

Figures 2.19 and 2.20 are the results from Wong's surveys. Definitions of the time of day are as follows:

Morning: 0700 to 1200 hours

Afternoon: 1300 to 1800 hours

Evening: 1900 to 0000 hours

Night: 0100 to 0600 hours

These figures indicate that most (98.9%) air conditioners are installed in the bedroom, and roughly ¾ (74.4%) of all air conditioner usage happens at night, with 44.6% of the owners using only at night, and 25.9% using in both evening and night. This is because the occupants want to get comfortable sleep after coming home from their office. (Wong et al., 2002) The survey also showed that the fan is less preferred at night, but a higher preference for it in the afternoon.

As such, night cooling in bedrooms in these residential buildings will be the focus for the cooling system to be designed in this research.

2.2.4 An Existing Public Housing Building

There are many HDB building designs with differing building orientations and massing shapes, but the underlying principles behind the passive design strategies of the floorplans and façades are similar. A 4-room apartment unit is chosen as the housing unit to design the cooling system for. This is based on 3 reasons:

- Based on surveys stated in Section 2.2.3, 4-room units have the lowest level of thermal acceptability.
- Among different unit sizes, 4-room units hold the largest share of all public housing units.

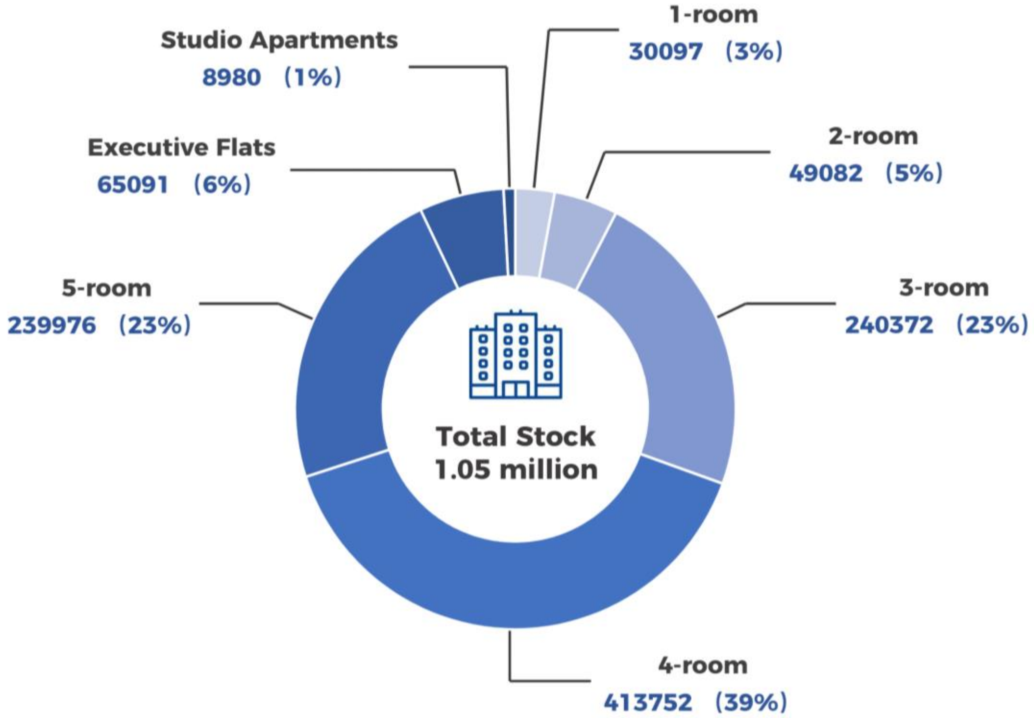


Figure 2.21: Number of units of each type of apartment as of March 2018. (HDB, 2018)

An HDB slab block building constructed with prefabrication in the late 1980s is chosen as the building on which the retrofit cooling facade system will be designed for. It is positioned along the East-West axis and is 12 stories tall, with 10 units per floor. This gives a total of 110 units because the ground floor has no residential units. This block has 70 4-room apartment units and 40 5-room apartment units, whose floorplans are shown below.

Figure 2.22: An aerial view of the chose public housing building for the research.

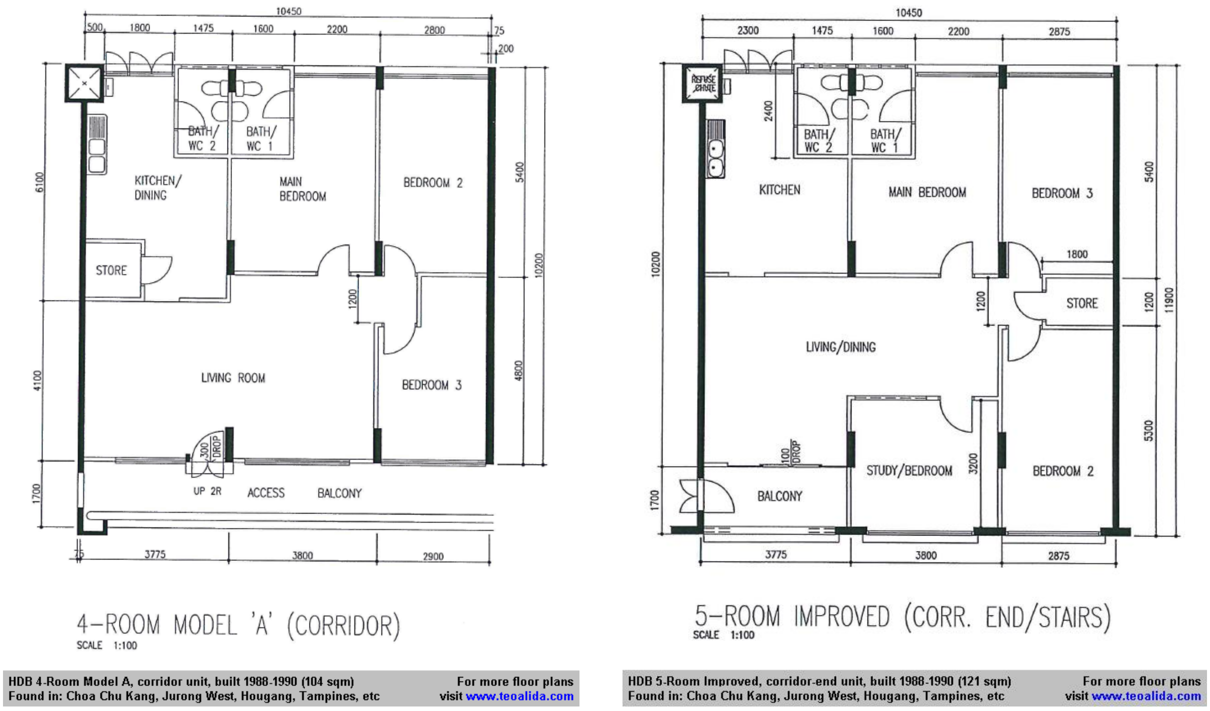


Figure 2.23: Floorplan of the 4-room unit on the left, and 5-room unit on the right. The façades at the top side of the floorplans of both units are similar. They are the north façade of the building.

Figure 2.24: The North facade of the building (Left) and the South facade (Right).

In this building, most of the bedrooms are located on the North façade, which, in Singapore, receives marginally less sunlight compared to the South façade. This makes the North façade more difficult to design solar collection for. Therefore, it makes for a good "worst-case scenario" to work on. The remaining bedrooms are on the South, and only those of the 5-room units do not face a public corridor. Focus of this project will thus be on the North façade.

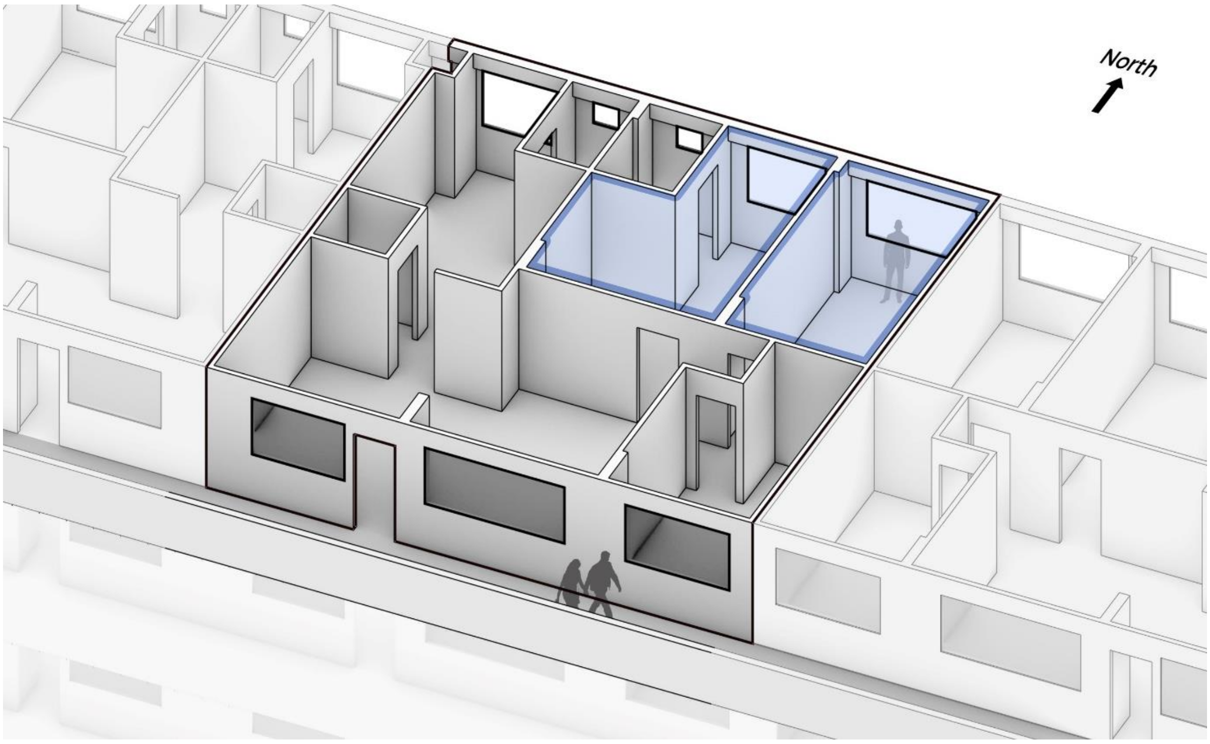


Figure 2.25: Axonometric of 4-room residential unit indicating the targeted bedrooms (Blue).

While there is no sufficient evidence to determine the cooling loads of this specific building, in general 4-room units consume 372.9 kWh of electricity every month in 2017 (Energy Market Authority Singapore, 2018), with an average of 24% of it contributed by air conditioning. (National Environmental Agency, 2017)

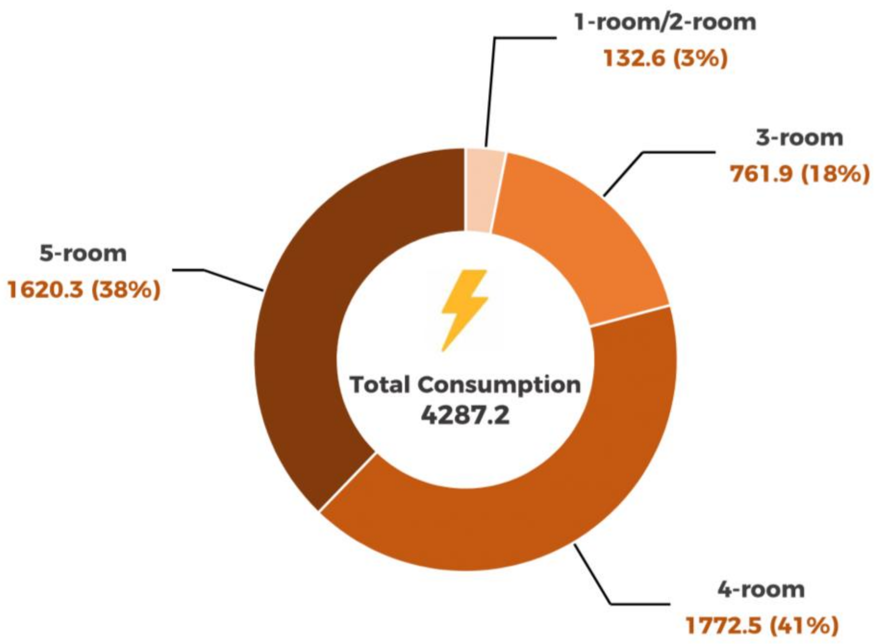


Figure 2.26: Total annual electricity consumption of public housing across different unit types. in GWh. (Energy Market Authority Singapore, 2018)

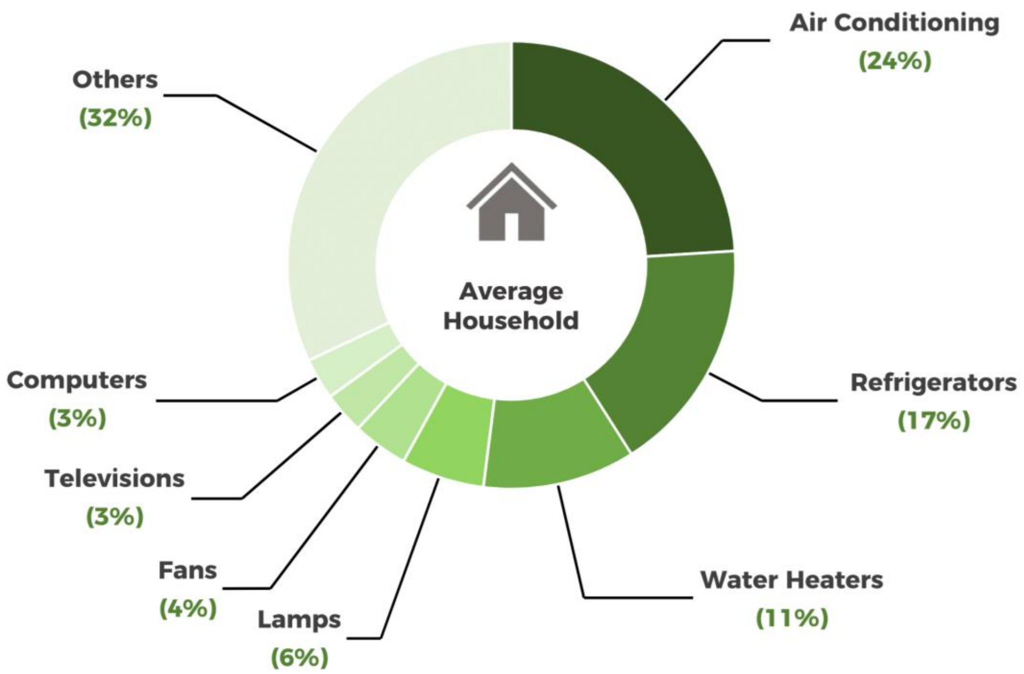


Figure 2.27: The share of electricity consumption by appliance in an average HDB household.

3 Background Study on Desiccant Cooling

There are numerous possible alternatives to a VC air-conditioning system for space cooling, such as electrically activated solid-state technologies, electro-mechanical systems, and thermal driven systems. (Vivekh et al., 2018) However, these strategies often have higher costs and need further research and development for better prospects for practical applications. Carbon emissions resulting from electricity generation serve as an incentive to push for alternatives that use clean energy instead. (Dai, Wang, & Zhang, 2001) Desiccant cooling is chosen as the main cooling strategy in this research based on its ability to carry out both cooling and dehumidification processes, as required by the climate of Singapore. In this chapter, various desiccant cooling methods are explored. Working principles, strategy requirements and design variables that affect its energy performance are discussed. Further details such as desiccant materials and subsystems are also dived into, as they will be incorporated into the main desiccant strategy.

What is Desiccant Cooling?

Desiccant cooling is based on the principle of adsorption, whereby there is direct contact with the air and the dry desiccant material. The desiccant then adsorbs moisture onto its surface, reducing latent load in the air. Desiccant materials have limited adsorption capacity, which is directly proportional to the relative humidity of the air.

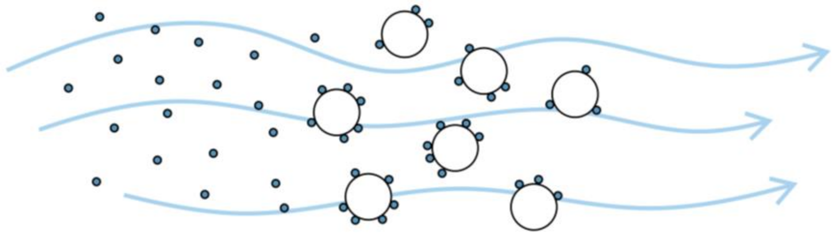


Figure 3.1: Water molecules are adsorbed by the desiccant material, dehumidifying the air.

For a continued dehumidification of the air, the water molecules must be removed from the surface of the desiccant. This process is known as regeneration and is done by applying heat to the desiccant. The heat needed for regeneration can be low temperature because the moisture adsorption depends on relatively humidity. (Vivekh et al., 2018) In desiccant systems the latent load of air conditioning is achieved by the desiccant. On the other hand, the sensible load is accomplished by direct and/or indirect evaporative cooling. (La, Dai, Li, Wang, & Ge, 2010) Because the process of latent cooling and sensible cooling is effectively separated, unlike a VC system, energy consumption is thus lower. (De Antonellis, Joppolo, & Molinaroli, 2010)

3.1 Desiccant Material

There are 2 main categories of desiccant materials; solids and liquids. This research will focus on the use of solid desiccants because they are inexpensive, non-flammable, non-corrosive, environmentally friendly and do not chemically react with the air. They also have higher moisture removal capabilities compared to liquid desiccants and can be cleaned more easily. However, they require a higher regeneration temperature. (Baniyounes, Ghadi, Rasul, & Khan, 2013)

Pure silica (Si) gel and zeolite are widely used desiccant materials because of their excellent hydrophilic nature. (Vivekh et al., 2018) However, they require high regeneration temperatures and do not have high adsorption capacities. (Sahlot & Riffat, 2016) New and advanced desiccants have before been the topic of research for many years to develop composite desiccants and polymeric desiccants with enhanced capabilities.

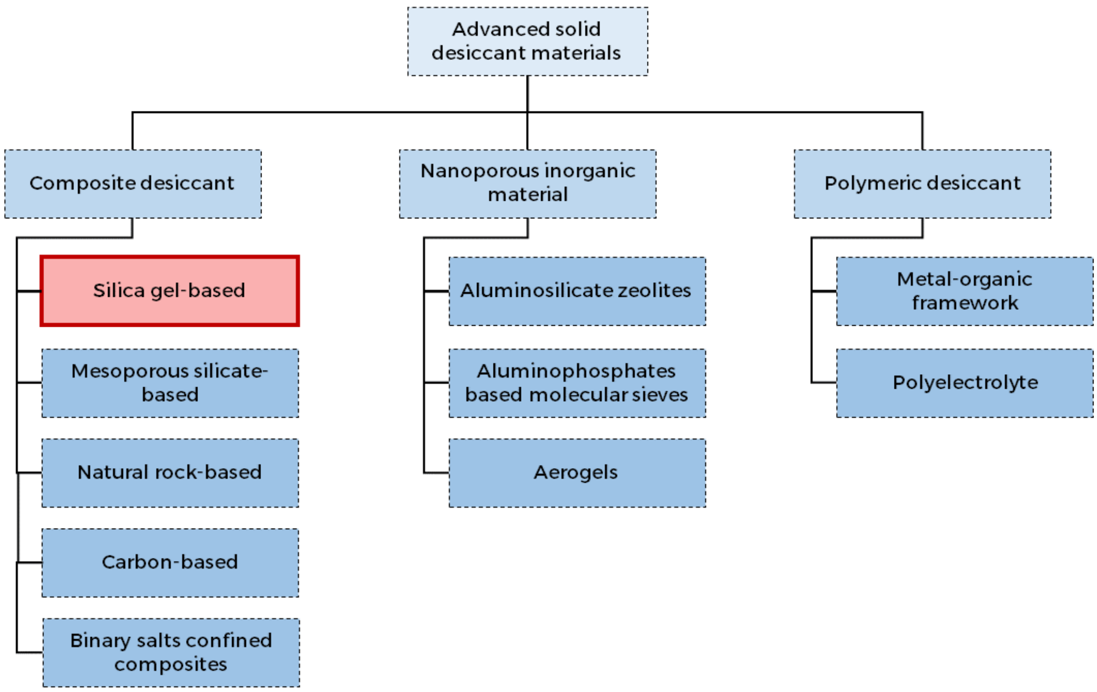


Figure 3.2: A chart showing the classification of various advanced desiccant materials. (Zheng, Ge, & Wang, 2014)

Composite desiccants are the most used advanced desiccant material in solid desiccant systems. They are formed by impregnating a hygroscopic salt to the pores of a porous desiccant material as a host. Pure Si gel is a porous desiccant which is cheap and has stable characteristics. Hygroscopic salts, like Lithium Chloride (LiCl), possess high adsorption capacities compared to porous desiccants, but are unstable in high humidity conditions because of deliquescence. Composite desiccants thus get the best of both worlds by having the stability of porous desiccants and the adsorption capacity of hygroscopic salts. Deliquescence is largely suppressed because the dissolved salt is held in place in the pores of the host matrix. (Zheng et al., 2014)

An example of a composite desiccant is a two-layered material that consists of an Si gel host matrix with its pores impregnated by LiCl. Due to its physical structure, this composite desiccant takes an intermediate position between solid adsorbent and pure hygroscopic salt and can be organized in a way to demonstrate the best features of both systems. The pore surface area of the composite desiccant is 194 m^2/g and the pore diameter is 3.98 nm. (Jia, Dai, Wu, & Wang, 2007) The adsorption of this Si/LiCl composite desiccant at 25°C was 2 to 3 times higher than pure Si gel at high humidity conditions. (Jia, Dai, Wu, & Wang, 2006)

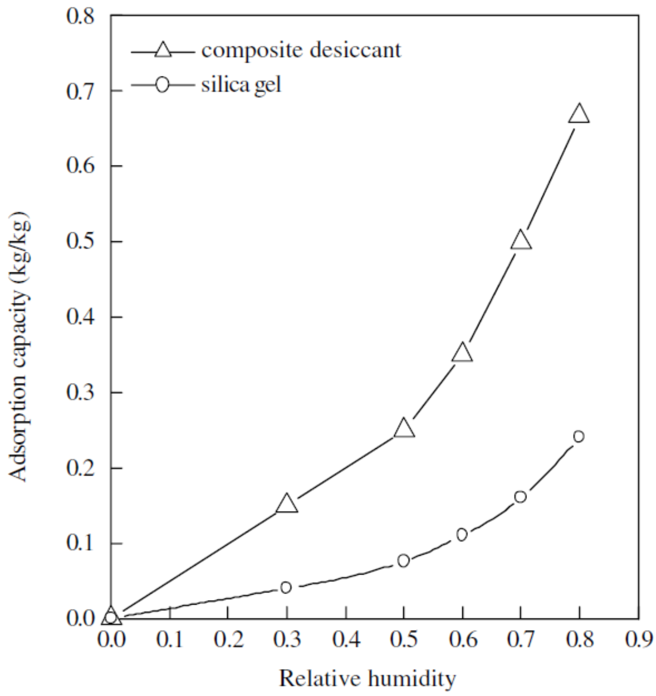


Figure 3.3: Adsorption capacity comparison between the Si/LiCl composite desiccant and Si gel desiccant at 25°C. (Jia et al., 2006)

When applied to a desiccant rotary wheel system, it was shown to have higher dehumidification capacity and faster dehydration rates than a regular rotary wheel system using Si gel. This suggests that the composite desiccant can afford to have lower regeneration temperatures, which leads to lower energy use. (Jia et al., 2007)

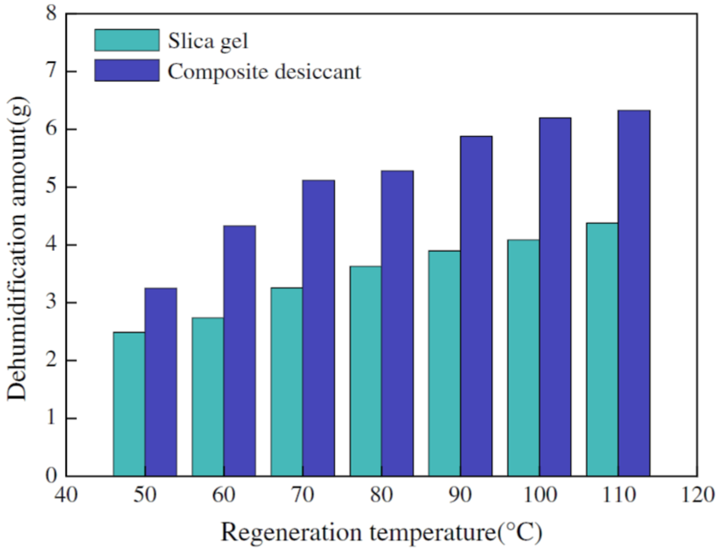


Figure 3.4: A graph of dehumidification amount against regeneration temperatures. (Jia et al., 2007)

From Figure 3.4 it can be seen that the composite desiccant can utilise a lower regeneration temperature to achieve dehumidification amounts equal to that of an Si gel at higher regeneration temperatures. By using this composite desiccant, the rotary wheel system could achieve a system Coefficient of Performance (COP) of 1.8, which is 35% higher than that of a system using Si gel. (Jia et al., 2007) However, the amount of hygroscopic salt to use must be controlled. To much would result in a spill-over phenomenon. (Jia et al., 2007)

The Si/LiCl composite is thus shown to be an effective desiccant material capable of improving the performance of desiccant cooling systems even at high humidity conditions.

3.2 Desiccant Coated Heat Exchanger (DCHE)

There are 3 main types of desiccant cooling methods; fixed bed, rotary wheel and desiccant coated heat exchangers (DCHE). This chapter will briefly explain them, why DCHEs are the most suitable, what its operation requires, and how to calculate its performance.

Fixed Bed

The fixed bed is the simplest method among the 3. It consists of a stationary bed with desiccant matrix packed onto it. Moist air flows over the bed and the moisture is adsorbed to the desiccant material. Dehumidified air thus flows out from the other end of the bed. Regeneration is done in the same manner, but with hot dry air as the input air instead, reactivating the desiccants. (Vivekh et al., 2018) Dehumidification and regeneration thus cannot happen at the same time, so multiple beds are incorporated into a single cooling system to achieve constant dehumidification. These beds are easy to fabricate, but their heat transfer efficient is low because of poor contact between the desiccant matrix and the bed. This leads to lower adsorption capacities and therefore lower cooling performance of fixed bed systems. (Vivekh et al., 2018)

Rotary Wheel

Also known as desiccant wheels, these wheels are impregnated with the desiccant material. The wheel rotates at a constant angular velocity, with moist air flowing through one portion for dehumidification and hot dry air flowing through another for regeneration. (Ge, Li, Wang, & Dai, 2008) The dehumidification and regeneration processes can thus be conducted simultaneously. Due to the process of impregnating the desiccant onto the wheel, air molecules have better contact with the desiccant matrix, improving the utilisation of the desiccant material as compared to the fixed bed system. (Vivekh et al., 2018)

The fixed bed and rotary wheel methods have 2 flaws:

- Regeneration is done by heating the desiccant with regeneration air. This results in 2 heat transfer resistances; from the heat source to the air, and then from the air to the desiccant. This increases irreversibility in the system, leading to a higher regeneration temperature needed to overcome this irreversibility stemming from multiple heat transfer resistances. (Li, Michiyuki, & Takeshi, 2015)
- The dehumidified air has a higher temperature after going through the adsorption process because it is an exothermic process, so heat is released. (Pesaran, 1994) Adsorption capacity is reduced because of this heat. (Zhao, Ge, Dai, & Wang, 2014) Efficiency of the system also further compromised because

more cooling is necessary after the adsorption process to reduce the temperature of the hot air exiting the system. (Li et al., 2015)

A DCHE method solves these 2 problems.

3.2.1 Working Principle

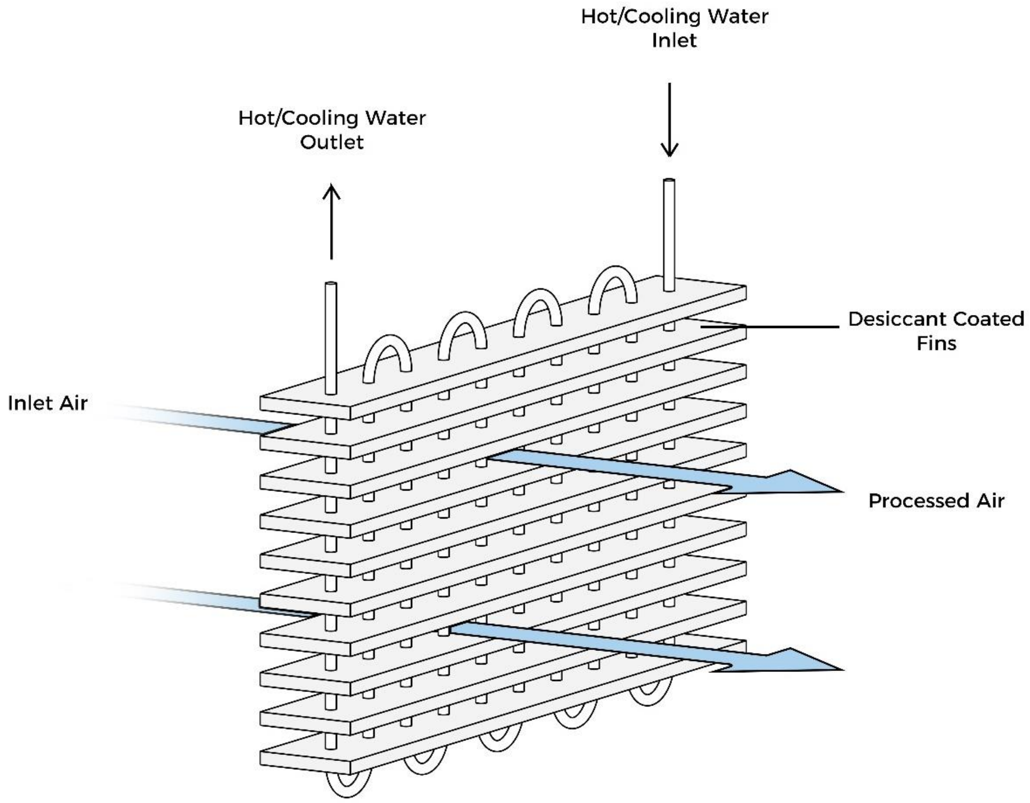


Figure 3.5: A diagram showing how a DCHE works.

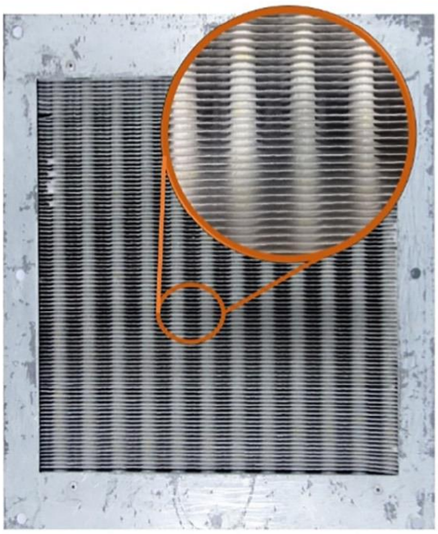


Figure 3.6: An image of a DCHE in real life. (Sun, Dai, Ge, Zhao, & Wang, 2018)

Compared to a rotary wheel system, DCHE systems are low-cost and have higher efficiency (Ge, Dai, & Wang, 2016). Desiccant material is coated on the metal fins of a low-cost conventional fin tube heat exchanger. Process air flows over these fins. Dehumidification and regeneration are done by internally cooling and heating the desiccant with fluids. Adsorption heat is removed by passing cooling fluid through the tubes during dehumidification. A large bulk of latent heat is removed from the air this way, reducing the cooling load. An experiment was done to compare outlet air temperatures with and without cooling water supply. Figure 3.7 shows the results of the outlet air temperature and humidity ratio, with inlet air temperature at a constant 30°C, humidity ratio at 14.3g/kg and regeneration temperature at 60°C. (Ge, Dai, Wang, & Peng, 2010) During regeneration, hot water is passed through these tubes instead of cooling water.

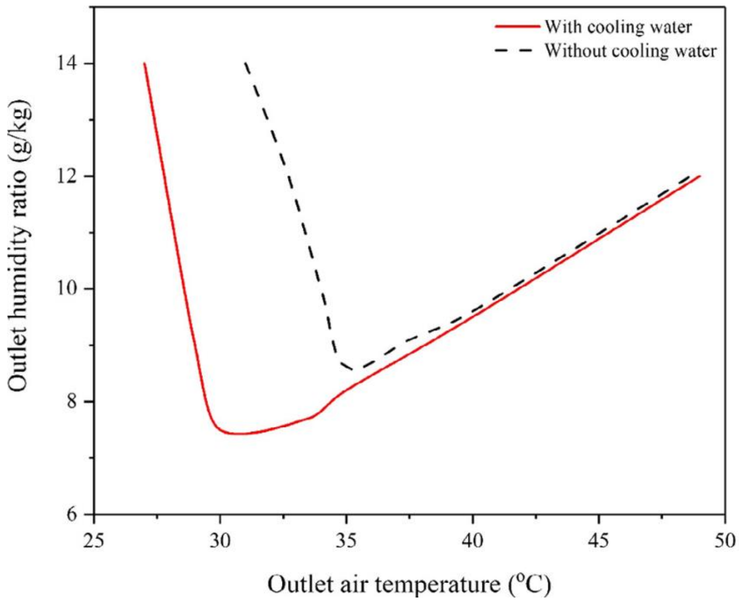


Figure 3.7: Having cooling fluid flow through the desiccant material is shown to help reduce cooling loads by removing adsorption heat. (Ge et al., 2010)

Metal fins with higher thermal conductivity improves the heat transfer process and improves regeneration efficiency. (Li et al., 2015) DCHEs are also solid-state systems, meaning there are no moving parts. They are thus more reliable than rotary wheels systems and require less maintenance. (Jin, Choon, Chun, Jon, & Chua, 2017)

Using composite desiccants in DCHE systems helps with dehumidification capacity as well. By using a composite desiccant of Si with an impregnating LiCl mass concentration of 40%, a DCHE can have an increased dehumidification capacity by 25 to 45% of that of a DCHE using only Si gel. (Zheng, Ge, Jiang, & Wang, 2015) This experiment was done with an inlet air temperature of 30°C, humidity ratio of 16.6 gkg^{-1} and air velocity of 1.7ms^{-1}. The cold and hot water temperatures were 20°C and 50°C respectively.

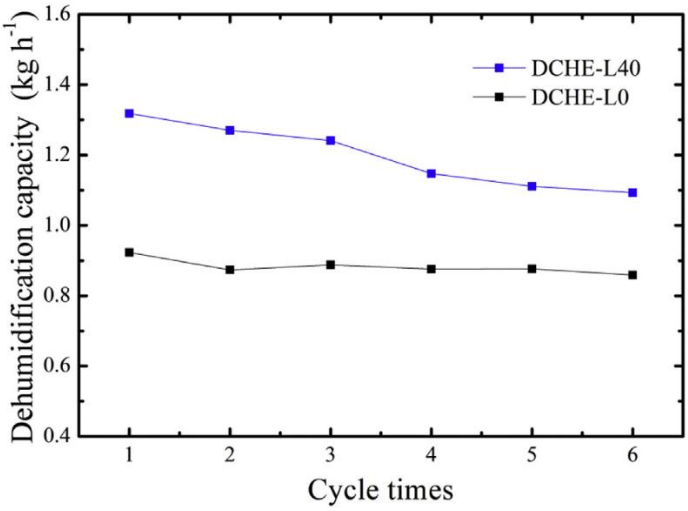


Figure 3.8: Dehumidification capacity comparison between a DCHE using Si/LiCl 40% composite desiccant and pure Si gel. DCHE-L40 is the composite desiccant DCHE. DCHE-L0 is the Si gel DCHE. (Zheng et al., 2015)

3.2.2 Strategy Requirements

Hot and cold water are necessary for a DCHE system, therefore some space is required for these water storage baths which are thermally insulated. Most experiments done have used thermostatic baths of 15 to 30 litres in capacity and capable of providing a maximum of roughly 3kW of heating and cooling energy. Water pumps are needed for the circulation of the fluid through the system, as well as controlling the water flow rate. An energy source is also required to maintain their temperatures. Fans are required for regulation of air velocity.

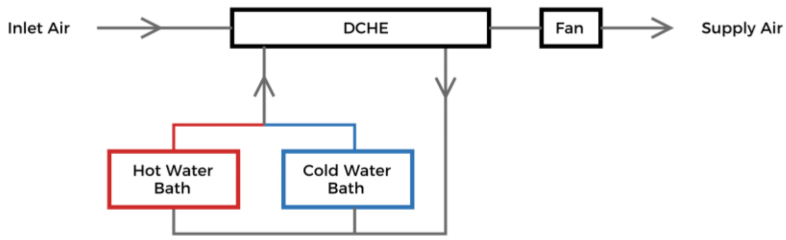


Figure 3.9: Schematic diagram of a system with a single DCHE.

Because dehumidification and regeneration cannot occur simultaneously, like the fixed bed system, a DCHE cooling system would need at least 2 DCHEs alternating between the 2 processes for continuous dehumidification. (Vivekh et al., 2018) Figure 3.10 illustrates this concept. The fans would need to be bi-directional, and water valves must be equipped to the system to control the water loops. (Ge, Dai, Li, & Wang, 2012)

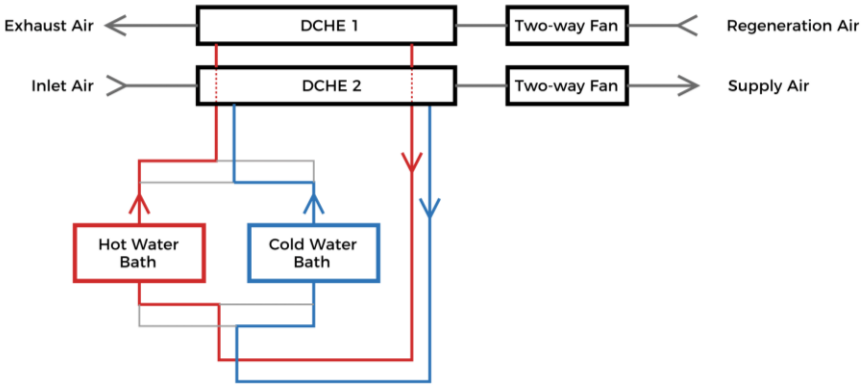


Figure 3.10: Schematic diagram of a system with 2 DCHEs for continuous dehumidification and regeneration. In this case, DCHE 1 is undergoing regeneration and DCHE 2 is undergoing dehumidification.

Regeneration air can be supplied from the indoor space. A DCHE system can also be combined with a multitude of subsystems to improve its performance characteristics and introduce clean energy sources for the hot water bath. These will be mentioned in Section 3.3.

3.2.3 Performance Calculations

In order to understand the energy performance of the façade cooling system, calculations must be done. These calculations are used during the design development of the conceptual facades later in Chapter 4 to ensure that the cooling load of the bedroom is met.

The cooling power of a heat exchanger is denoted as:

$$Q = \dot{m}\,(H_{in} - H_{out})$$

Q is the cooling power, $\dot{m}$ is the mass flow rate of air flowing into the heat exchanger, and H is the enthalpy of the air coming in and out. (Ge, Cao, Pan, Dai, & Wang, 2017)

The mass flow rate of air $\dot{m}$ is calculated as:

$$\dot{m} = \rho_{air} * A * v_{air}$$

ρ_{air} is the density of air, which is assumed as a constant 1.16 kg/m^3 in this research. A is the area of the heat exchanger through which air flows though. This is also known as the minimum free-flow area. v_{air} is the velocity of air. The minimum free-flow area has many parameters, but this research will simplify it down to a calculation dependent only on the frontal area, fin pitch and number of fins. Figure 3.11 illustrates the calculation.

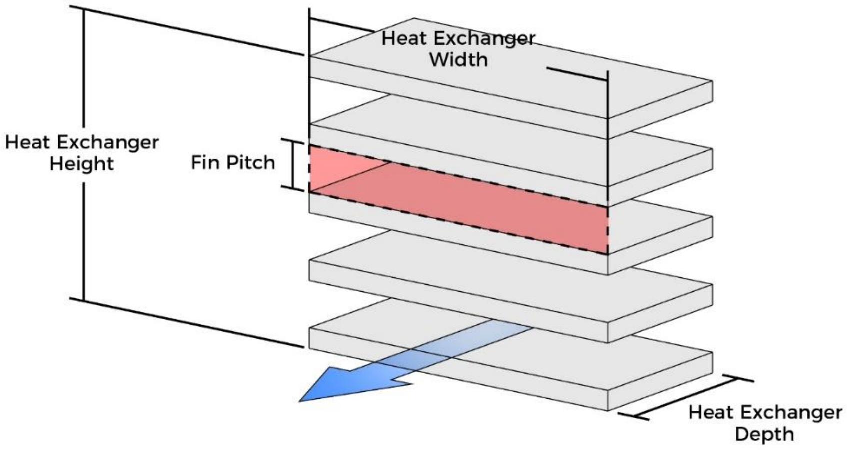


Figure 3.11: Diagram showing the geometric properties of the heat exchanger important for calculations.

$$A = (N - 1) * \text{Heat Exchanger Width} * \text{Fin Pitch}$$

N represents the number of fins in the heat exchanger.

The enthalpy of air H is calculated as:

$$H = 10^3\ (1.006T + Y\ (2501 + 1.86T))$$

T is the respective temperature, and Y is the respective specific humidity. (Jagirdar & Seng, 2018)

These equations are verified by applying the operating conditions of Ge's experiment to them. They are summarised in Table 3.1 below.

Parameter	Value
Heat Exchanger Width (mm)	230
Heat Exchanger Height (mm)	200
Heat Exchanger Depth (mm)	45
Fin Thickness (mm)	0.115
Fin Pitch (mm)	1.5
Inlet Temperature (C°)	30
Outlet Temperature (C°)	28
Inlet Air Specific Humidity (g kg^{-1})	16.1
Air velocity (ms^{-1})	1.4
Hot Water Temperature (C°)	50
Cold Water Temperature (C°)	20
Water Flow Rate (L min^{-1})	1.28

Table 3.1: Parameters from Ge's experiment to verify equations.

$$\dot{m} = (1.16 * ((124 - 1) * 0.23 * 0.0015) * 1.4)$$

$$H_{in} = 10^3 (1.006(30) + (0.0161)(2501 + 1.86(30)))$$

Because there was no information given on the specific humidity of the outlet air, an equation had to be used to calculate it. (Zhao, Dai, Ge, Sun, & Wang, 2015)

$$\text{Moisture Removal} = \frac{(2.91 * D) - 0.01}{(171.45 * D) + (35.14 * V_{air}) + (5.06 * V_{air}^{0.11}) - 0.11}$$

D denotes the heat exchanger depth. This gives a moisture removal of 1.94 g kg^{-1}, resulting in an outlet specific humidity of 14.2 g kg^{-1}.

$$H_{out} = 10^3 (1.006(27.5) + (0.0142)(2501 + 1.86(27.5)))$$

Plugging these values together gives a cooling power of 485.73 W, which is not far from the 450 W attained from the experiment in the research paper. This thus verifies the equations for calculations later on during the design of the conceptual facades.

Cooling power consists of both sensible cooling and latent cooling. Latent cooling is calculated as follows (Zhao, Dai, Ge, Wang, & Wang, 2016):

$$Q_{latent} = \Delta d * \dot{m} * L$$

Δd denotes the moisture removed, and L denotes the latent heat of vaporisation, which is assumed to be a constant 2.256 kJ kg^{-1}. In the example presented above using Ge's experiment, the latent cooling power is calculated to be roughly 303 W, meaning that the remaining 182.7 W is sensible cooling.

3.3 Subsystems

There have been various efforts put into investigating the effects of combining a DCHE system with other subsystems. This section will explore the working principles of these subsystems and how they affect the system performance. They are later incorporated into the cooling facade system during the design development stage to evaluate how the overall system performance improves.

3.3.1 Solar Collector – Evacuated Tube Collector (ETC)

Singapore has an abundance of sunlight all year round, making it a good opportunity to harness clean energy from the sun. There are 3 main kinds of solar collection methods; photovoltaic (PV), thermal, and hybrid PV/thermal collectors. For a desiccant cooling system, thermal energy is important for the regeneration process. This makes thermal collectors a suitable choice of solar energy collection. PV/thermal hybrids are also able to collect thermal energy, but only have an efficiency of 61% for thermal energy, as compared to 80% for thermal collectors. (Good, Andresen, & Hestnes, 2015)

Solar thermal collectors can either water-based or air-based. This research will focus on a water-based system because they have higher efficiencies. (Rawat & Dhiran, 2017) For a DCHE cooling system, water is also better than air as the cooling and heating fluid because it has a higher heat capacity than air.

There are 2 main types of water-based solar thermal collectors; Flat Plate Collectors (FPCs) and Evacuated Tube Collectors (ETCs).

Working Principle of ETCs
An ETC is made of parallel evacuated glass pipes, each consisting of two tubes, one encapsulating the other. The inner tube is coated with selective coating while the outer tube is transparent. Light rays pass through the transparent outer tube and are absorbed by the inner tube. Both the inner and outer tubes have minimal reflection properties. The inner tube gets heated while the sunlight passes through the outer tube. A vacuum is created in between the inner and outer tube, preventing heat transfer whilst allowing sunlight through. This is done by fusing the tubes together at the top and pumping the air out. Heat can then stay inside the inner pipes and collect solar radiation efficiently. (zubriski, 2010)

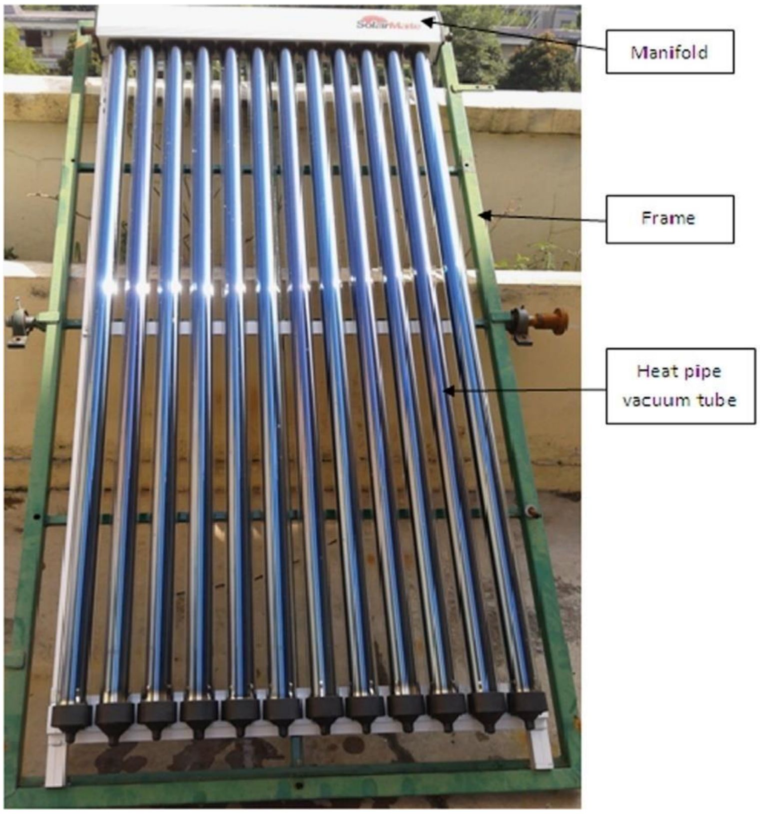


Figure 3.12: Parts of an evacuated tube collector. (Sabiha, Saidur, Mekhilef, & Mahian, 2015)

There are 2 kinds of ETCs; heat pipe, and water-in-glass. Heat pipe systems cost more but have 15 to 20% higher efficiency (Hayek, Assaf, & Lteif, 2011). This research thus assumes the use of heat pipe ETCs.

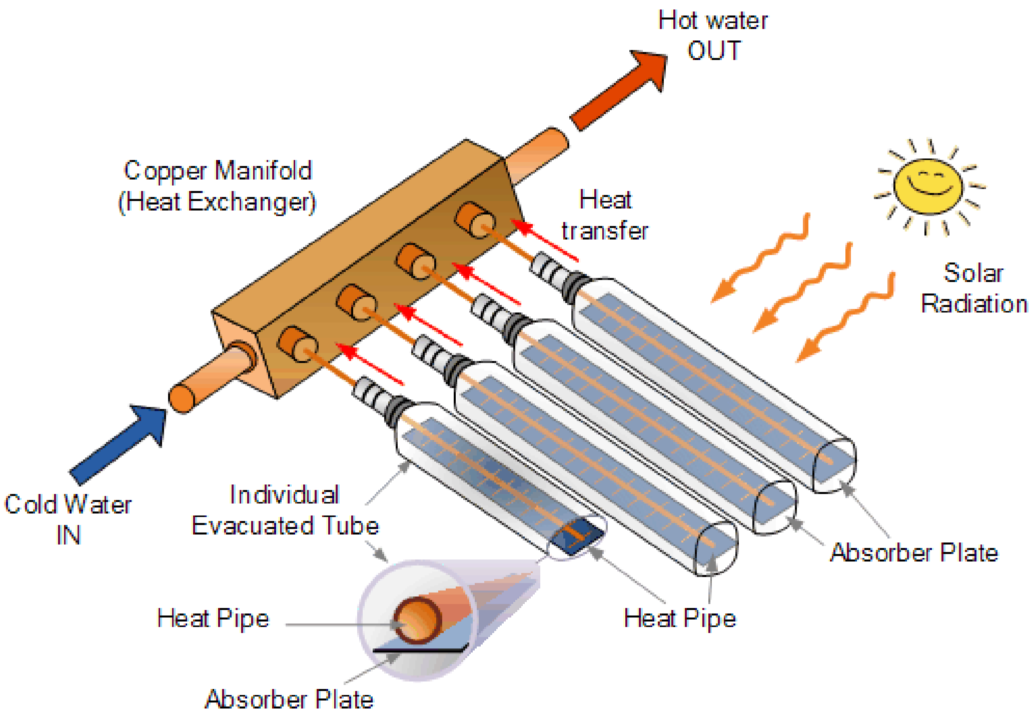


Figure 3.13: Diagram of a heat pipe ETC.

ETCs are more resistant to fluctuations in solar irradiation, which will be the case in Singapore because cloud cover is relatively high. (Wahed & Reindl, 2016) They can also work under various weather conditions because they absorb both direct and diffuse radiation, providing acceptable heat efficiency even in overcast environments. (Kalogirou, 2004) Because of the vacuum in the tubes, heat loss through convection and conduction is much lower compared to FPCs, giving the ETC an advantage in thermal efficiency. The average output of ETCs over an entire year is 25–40% higher than FPCs per net m^2. (Sabiha et al., 2015) Because of the cylindrical shape of the tubes, the sun incidence angle on the tube does not have an influence on the solar absorption. (Z. Wang, Yang, Qiu, Zhang, & Zhao, 2015) Maintenance of an ETC is also easier and cheaper than in an FPC because if a tube is broken or damaged, it can be easily replaced instead of having to replace the entire collector. With a damaged tube, it merely operates at a lower efficiency, whereas an FPC has to be completely shut down if damaged. (Sabiha et al., 2015) Upfront costs of ETCs are also gradually decreasing with the lowering production costs of tubes. (Tang, Yang, & Gao, 2011) For these reasons, ETCs are the chosen type of solar thermal collector to incorporate into the DCHE cooling façade system.

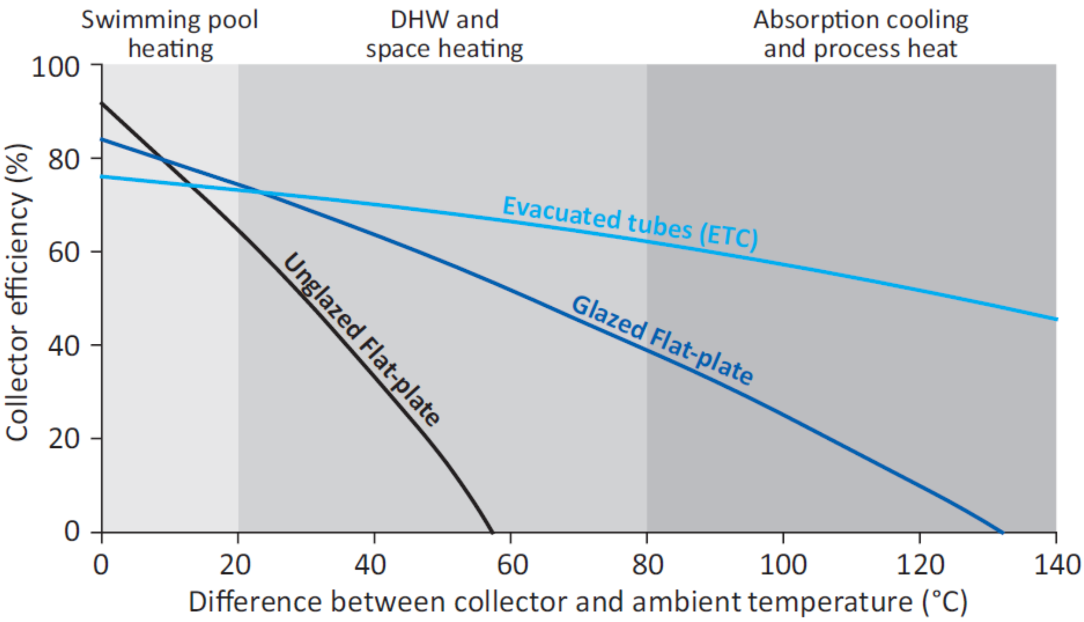


Figure 3.14: Thermal efficiencies against temperature difference ranges of different solar thermal collectors types. (Prieto, 2018)

ETCs are capable of heating water to 95°C. (Z. Wang et al., 2015) It can be incorporated as a subsystem into a DCHE cooling facade system as the heat source for the hot water for regeneration. During regeneration, the hot water loses heat. Because this research is focusing on night cooling, the ETCs must heat the water up to a sufficiently high temperature for it to sustain the heat loss during regeneration through the night. Sunlight will then be used to bring the water temperature up again the next day. This method allows for the omission of an auxiliary heater. Figure 3.15 is a schematic diagram indicating how it can be arranged with the rest of the system.

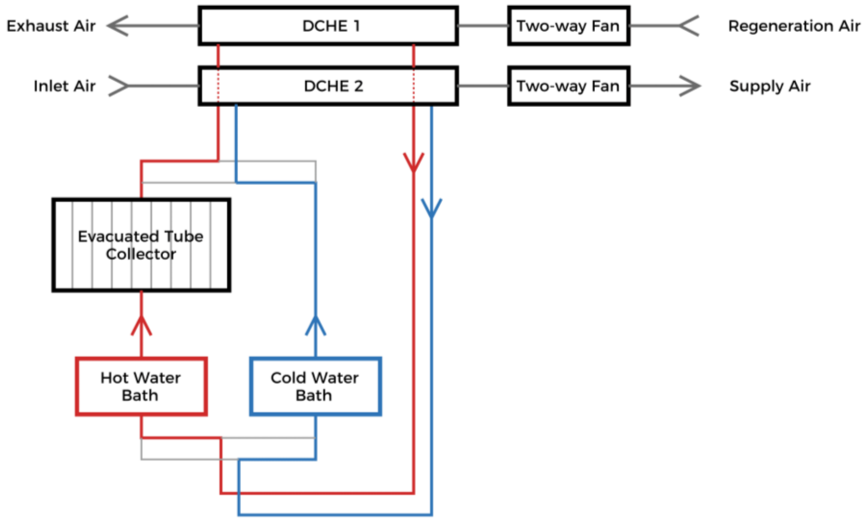


Figure 3.15: Schematic diagram of DCHE system with ETC subsystem added.

From literature research, the collector area used for 1 such DCHE system is 0.89 m^2. (Kumar & Yadav, 2016) This serves as a starting point to develop the conceptual façade designs. In some commercial ETCs, the thermal storage tank is provided with the product and its capacity depends on the size of the ETC. In the experiment done with 0.89 m^2 of collector area, there were 15 tubes. This corresponds to 150 litres (0.15 m^3) of hot water storage capacity of the tank.

Design Variables

The amount of heat collection it is capable of depends on the total collector area, solar irradiation and tube tilt angle. The collector itself can be positioned at any angle against the sun, but the solar absorbers themselves should be angled at a position that best collects the most solar irradiation. While solar irradiation is based on the climate, the collector location, number of tubes, distance between tubes and absorber tilt angle are controllable design variables. They will be considered during the design of the façade system.

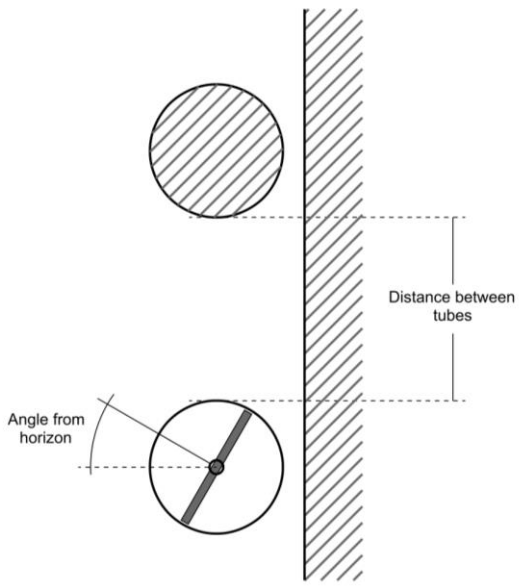


Figure 3.16: Diagrammatic section of an ETC.

Performance Calculation
The ETC is used to collect solar heat to raise the temperature of the hot water storage tank. A simplified calculation is used to determine the temperature of the hot water by the end of the day (Arora, Chitkara, Udayakumar, & Ali, 2011):

$$Q = m * C_p * \Delta T$$

Q represents the solar irradiation collected throughout the day. m represents the mass of hot water to heat up within the given timeframe. C_p is a constant representing the specific heat capacity of water, taken to be 4185.5 J/(kg K). ΔT represents the difference in water temperature before and after all the solar heat has been absorbed.

3.3.2 Heat Recovery Device (HRD)

The HRD subsystem consists of a simple fin tube heat exchanger (HRHE) and a water storage tank (HRST). Waste heat is extracted from the exhaust air to provide additional heat for regeneration. With this system, the regeneration process is split into 2 stages; pre-regeneration and high temperature regeneration. During pre-regeneration, low temperature hot water from the HRST is pumped through the regenerating DCHE. This hot water is not hot enough for proper regeneration, during the high temperature regeneration stage, water from the hot water bath is used instead of from the HRST. This water has a higher temperature so it can conduct the regeneration process better. Meanwhile, the outlet air from the regenerating DCHE passes through the HRHE so its heat is passed to the water in the HRST, to be used for the next regeneration cycle.

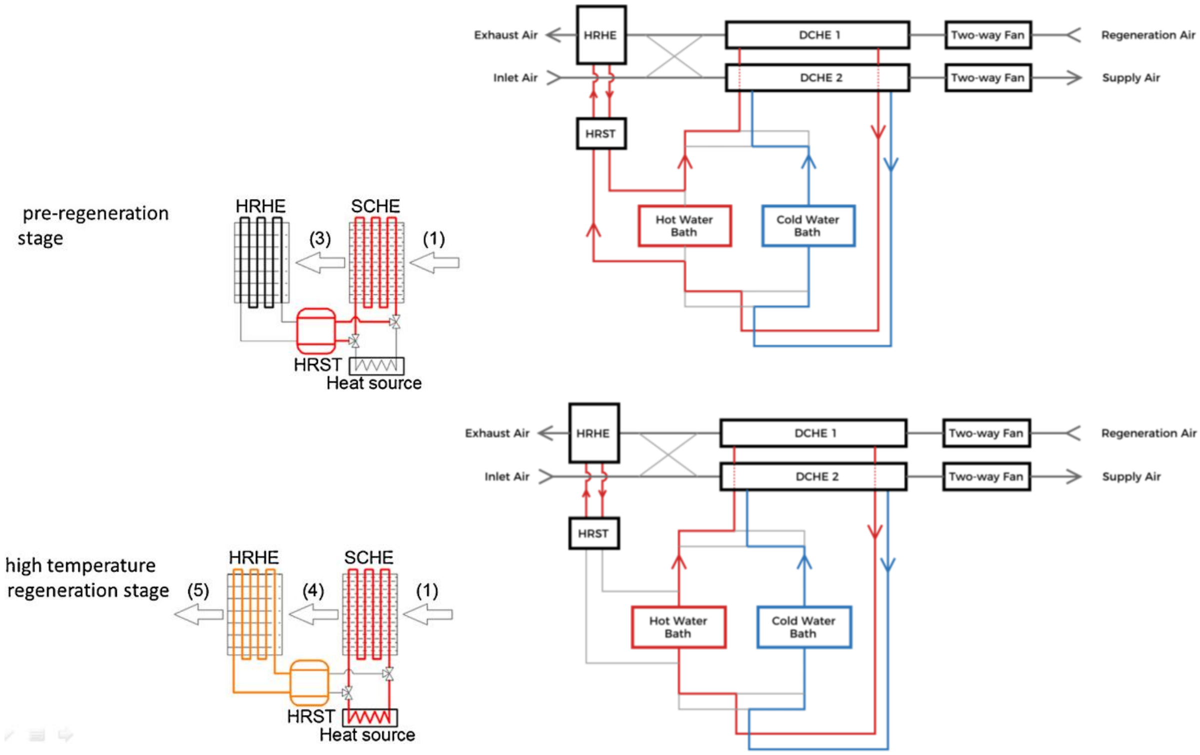


Figure 3.17: Schematic diagrams of how the HRD subsystem assists in the regeneration stage. Pre-regeneration stage (top) and high temperature regeneration stage (bottom).

As seen from Figure 3.17, the only difference between the pre-regeneration stage and the high temperature regeneration stage is the source of the hot water. In both stages, DCHE 1 is being undergoing regeneration, except with a lower water temperature during pre-regeneration.

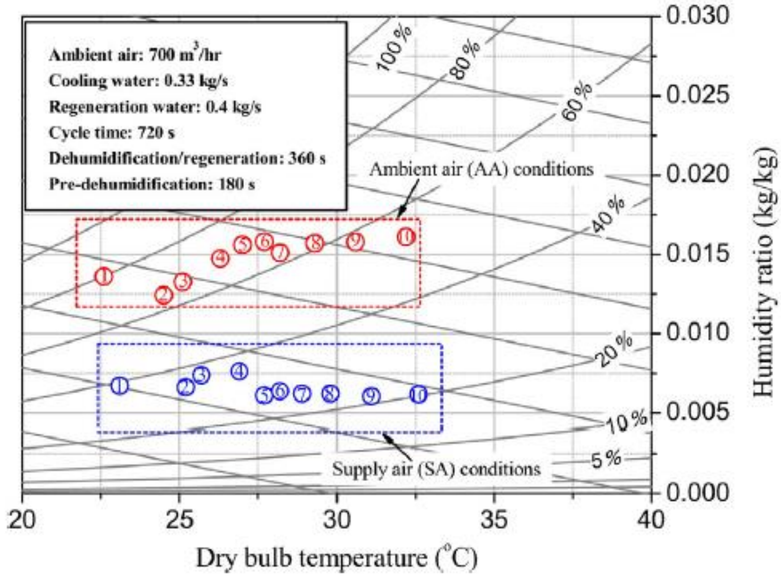


Figure 3.18: Having a HRD subsystem helps to lower the temperature of the outlet air from the DCHE. (Zhao et al., 2016)

With the HRD subsystem, the temperature of the supply air can afford to be even lower, to the point where the air temperature after the adsorption process is only slightly above the ambient inlet air. (Zhao et al., 2016) This is because the impacts of residual heat are reduced. The cooling capacity increased from 2.6kW to 3.35 kW, and the COP of the cycle was 1.19, which was almost twice of a normal DCHE system of 0.6. This is because the energy required for regeneration is significantly reduced. In the experiment involving the HRD in the DCHE system, the HRST was 40 litres and the HRHE was the same dimension as the DCHE, which was 400 x 400 x 150 mm. In this research project, the HRD subsystem is assumed to reduce the required heat energy for regeneration by half. This potentially reduces the required solar collector area or hot water storage tank, or both.

3.3.3 Sensible Heat Exchanger (SHE)

One problem with the basic DCHE system is that during the dehumidification process, the outlet temperature decreases at a gradual rate, while the humidity ratio drops sharply at the start, and then slowly goes back up. As a result, when the outlet humidity is low, the outlet temperature is still high. (Ge et al., 2017) It is thus difficult to obtain an outlet air with both low humidity content and temperature. This problem is illustrated in Figure 3.18.

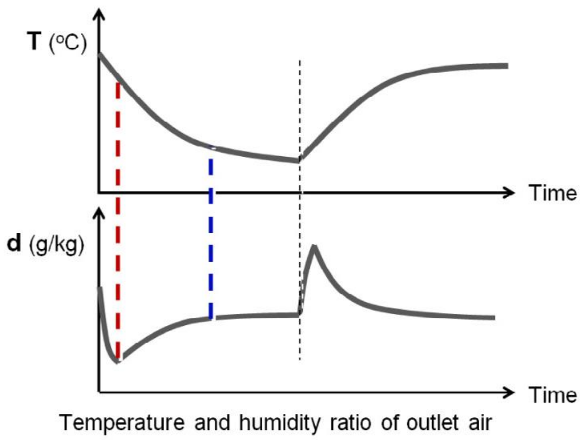


Figure 3.19: Outlet air temperature and humidity ratio graphs during dehumidification and then regeneration.(Ge et al., 2017)

Working Principle

Introducing a sensible heat exchanger (SHE) that operates on the dehumidified air helps to mitigate this issue. It is a low-cost fin tube heat exchanger connected to the same cold water bath as the DCHEs. After the dehumidification from the DCHE, the air is passed through the SHE heat exchanger, where cold water flows perpendicular to the air flow. This results in indirect evaporative cooling which ultimately enables the entire system to produce an outlet air with a lower dry-bulb temperature, without changing the moisture content of the air. This increases the cooling power of the system.

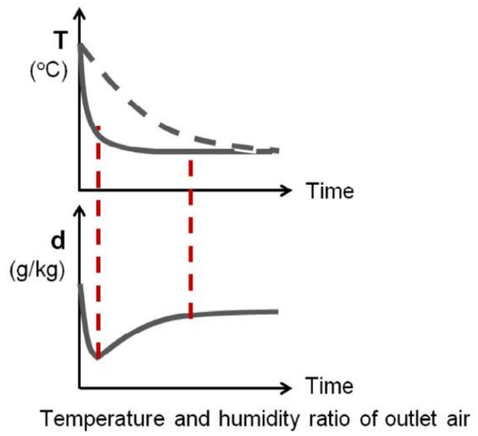


Figure 3.20: The temperature and humidity ratio of the outlet air from the SHE are more synchronised.(Ge et al., 2017)

Additionally, it causes a shift in the temperature-time graph, as shown in Figure 3.20, where the outlet air now has a low temperature that matches the timing of its low humidity level.

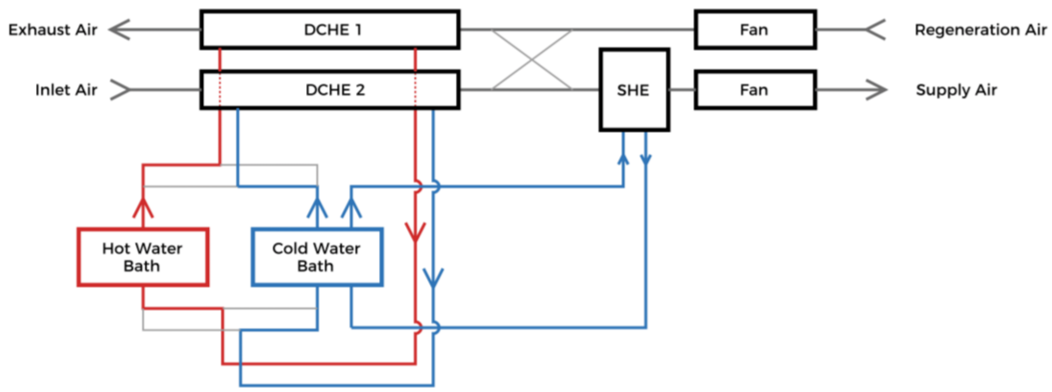


Figure 3.21: Schematic diagram of the DCHE system with the SHE.

The SHE is placed after the DCHEs, as shown in Figure 3.21. Operating conditions that affect its effectiveness include the air velocity and the cooling water temperature. With higher air velocity and lower cooling water temperature, total cooling power and COP are increased even further. Ge's experiment showed that supply air temperature can be reduced by up to 4°C, and the cooling power and COP are increased by 75% and 13% respectively in certain specific conditions. The dimensions of the SHE itself was exactly the same as the DCHE, which was 230 x 200 x 45 mm in the experiment. In this research project, the SHE is assumed to provide additional sensible cooling, with a temperature reduction of 4°C.

3.3.4 Conclusion

DCHE systems have a huge potential in space cooling in tropical climates. The next chapter will discuss case studies of façade integrated systems and different façade integration strategies. Using this knowledge, the DCHE system and the subsystems are integrated as a façade system, making up a few different façade designs. These façade designs are then evaluated and compared based on cost and energy performance calculations. 1 of these designs will be chosen to be further developed for further performance optimisations and design details.

4 Façade Integration

While most HVAC systems are often centralised within the building, decentralised systems have been known to achieve better flexibility and user control, promoting better indoor thermal comfort and high energy efficiency. (Gruner, 2012) This is important especially for buildings where occupants prefer individual control of cooling and heating within the space. (Heating and ventilating review, 2010) Residential buildings fit this description. Such systems also do not require false ceilings or raised floors. In buildings where the floor-to-ceiling height is already at the minimum allowed standards, the building façade is left as the only possible location for such decentralised systems. (Gruner, 2012) This is the case for Singapore's HDB buildings where this height is fixed at 2.6 metres. In Europe, refurbishment projects have also undertaken façade integrated HVAC systems. In this chapter, integration of HVAC systems within facades are discussed. Built examples of new façade systems and retrofitted ones, as well as research prototypes are studied to understand how they are designed, how effective they are and what can be improved. The design parameters and evaluation criteria of the façade cooling system are also established.

4.1 Case Studies

While most of the case studies mentioned in this paper pertain to heating and ventilation systems, they still serve as proofs-of-concept that there is potential in facade integrated cooling systems.

Capricorn Haus, Düsseldorf, Germany

Figure 4.1: Facade module of the Capricorn Haus (Left) and the overall facade pattern (Right).

The façade of this office building is developed by Gatermaan + Schossig and TROX Technik, made of pre-assembled elements to form the whole 2.7 x 3.35 m façade module. It combines windows, a decentralised ventilation unit coupled with heat recovery and a light fitting (Castrillón, 2009) to regulate the indoor climate. (Sacht, 2010) Natural ventilation is facilitated by the small operable window above the ventilation unit, from which supply air can be manually controlled for every façade module.

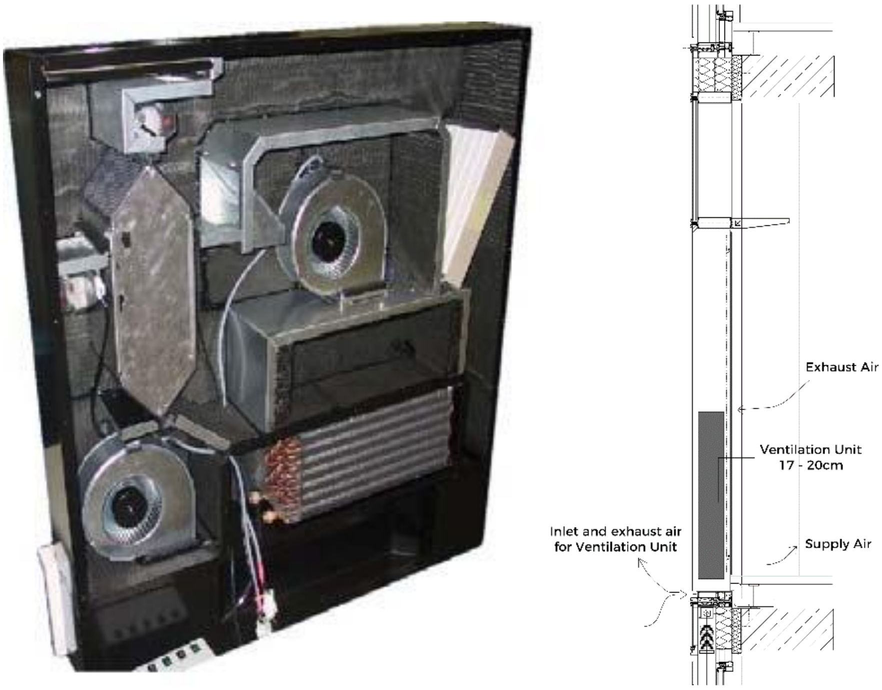


Figure 4.2: Photo of the ventilation unit (Left) and an architectural facade section drawing (Right).

The ventilation unit has a minimum installation depth of 200 mm and has maximum supply air heating and cooling temperatures of 30ºC and 18ºC respectively. It consists of fans, a heat recovery device, heat exchangers and air dampers. On top of that, acoustics were paid close attention to.

Although this project was not a retrofitting renovation one, it still shows how both natural and mechanical ventilation can be incorporated into the façade design with a clean look that defines the aesthetic of the facade. Internal building planning was also made easier because there are less technical services in the ceilings, and enables the building to achieve 26% savings in primary energy consumption under the energy savings regulations. (Gatermann + Schossig, 2008)

Swiss apartment building, Zürich, Switzerland

Figure 4.3: Photos of the apartment before (Left) and after (Right) the renovation project.

This apartment was constructed in 1954, In 2009, this residential building was renovated to substitute and install new building technology systems such as heating systems, ventilation systems, domestic hot water and electric installations. (Miloni et al., 2011)

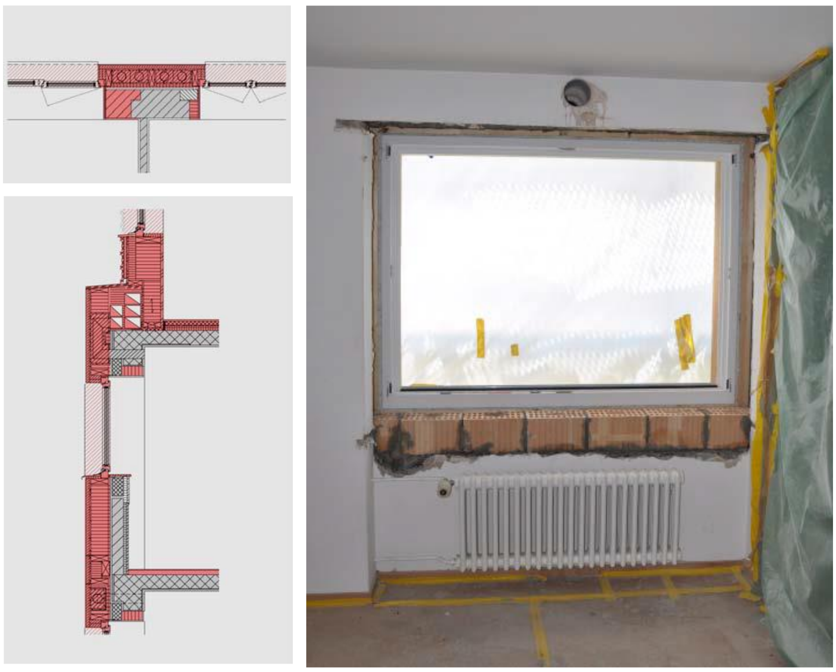


Figure 4.4: Horizontal section of the facade with integrated ventilation ducts (Top left), vertical section of the facade with horizontal ventilation distribution (Bottom left), and an interior photo showing the air inlet above the window (Right). Highlighted in red are the renovation elements.

The ventilation system was integrated within the prefabricated timber façade modules. This included the ventilation ducts and the air inlets and outlets. Ventilation distribution was done throughout the house with the installation of the main device in the annex of the house, along with the heat pump for space heating and hot water. The façade modules are assembled in a factory and transported to the site for mounting. The windows were also meant to be integrated within the module, but they arrived too late to the workshop carpenter and had to be mounted on site. (Miloni et al., 2011) ETCs and PV collectors were installed on the roofs for solar energy collection.

Figure 4.5: Diagram showing the ventilation distribution (Left), and a photo of the prefabricated 3 x 10 m facade module being lifted to be mounted during construction (Right).

All in all, the energy consumption for space heating and hot water was reduced by 88%, and 76% of the energy consumption of this system comprised of solar energy from the ETCs and PV collectors.

This project basically had a centralised heat pump, solar thermal collectors and PV panels, while the façade integrated the ventilation ducts. Construction of the façade modules was a challenge because they were to be fitted onto the existing facades. While this means that the level of intervention of retrofitting for the façade component in this project is low, this also meant that measurements had to be taken of the existing imperfect old walls. Cellulose insulation was used to fill in the gaps between the new and old façade. (Miloni et al., 2011) Air tightness was excellent. The new façade was able to establish a modern look just by paying attention to the patterns and textures of the exterior, transforming the old building to a modern one with better living comfort and new technologies as if it was a new house. (Miloni et al., 2011)

Residential buildings, Dieselweg 3-19, Graz, Austria

Figure 4.6: Photos of the building before (Left) and after (Right) renovation.

Compared to the previous case study, this project features a greater deal of integration within the façade. Its 2008 renovation features façade modules integrated with the window, solar collectors, a ventilation system with heat recovery, and heat distribution pipes. (Miloni et al., 2011) They are developed by Austrian firm GAP solution GmbH featuring a solar comb which traps heat from the sun, thereby reducing the temperature differences between the interior and exterior during winter seasons. This helps to reduce heating demands and losses and improve the U-value of the envelope. In addition to the façade renovation, more solar collectors were installed on the roofs of the building, and heat storage tanks of $5m^3$ each were installed in the basements and connected to the heating pipes in the façade modules.

Figure 4.7: The ventilation ducts are integrated within the facade module (Left) beside the window, where an opaque covering is placed over the supply and exhaust ducts (Right).

During the construction process, the occupants did not have to resettle. The heat distribution pipes are first installed onto the existing façade, and then covered by rockwool. The prefabricated façade modules were delivered by truck to the site and mounted onto the building with a crane. The old windows were then removed from the inside and the solar collectors were connected to the heat pipes. (Miloni et al., 2011)

Figure 4.8: Heat pipes are attached to the existing facade first (Top left) before being covered with rockwool and afterwards the new facade (Top right). The facades facing South were integrated with solar thermal collectors. The rest only featured solar combs. (Bottom)

This renovation project resulted in a 90% reduction in heating demand and an improvement in thermal and user comfort and the indoor environment. (Miloni et al., 2011) While there were indeed interferences and disturbances to the occupants during the construction process, there was no need for them to move out because the process was not too intrusive. Nevertheless, it showed that minimal intervention is preferred by residents. The façade featured only the integration of the ventilation ducts and solar collectors, while the heat storage and majority of the solar collectors were centralised in the basement and on the roofs respectively. The outcome was a success and the building now has a better energy performance.

Solar-powered dehumidification window (SPDW) for residential buildings, research prototype, Guangzhou, China

Figure 4.9: Testing rig of the SPDW (Left). The desiccant beds are integrated within the window (Right).

Among these case studies, this project is the most relatable to the objective of this research. It features desiccant dehumidification beds integrated into a double-glazed window and PV panels as part of the sun shading device. The objective of this prototype was to develop an energy-saving way to supply a residential building with dehumidified air. (Yang, Deng, Wang, Zhao, & He, 2017)

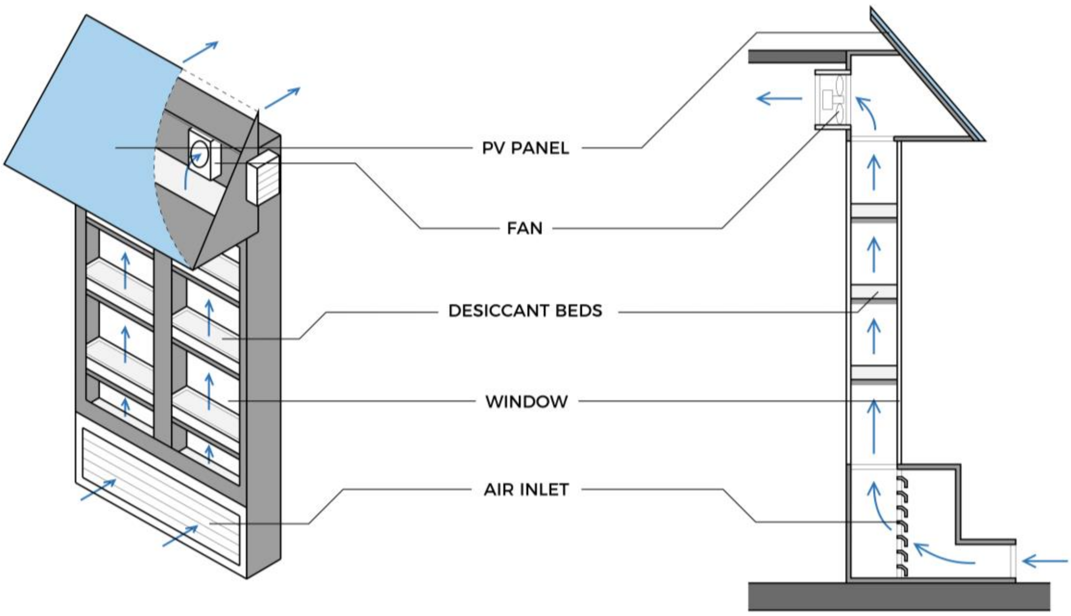


Figure 4.10: Diagram of the main components of the facade.

This arrangement of components can potentially replace the window of a residential building to minimise space required. Solar radiation can be used for the regeneration of the desiccants and harness to provide clean energy for the fans, reducing energy consumption for air conditioning. (Yang et al., 2017) Moisture removal and air temperature of the supply air was measured to evaluate the effectiveness of the system.

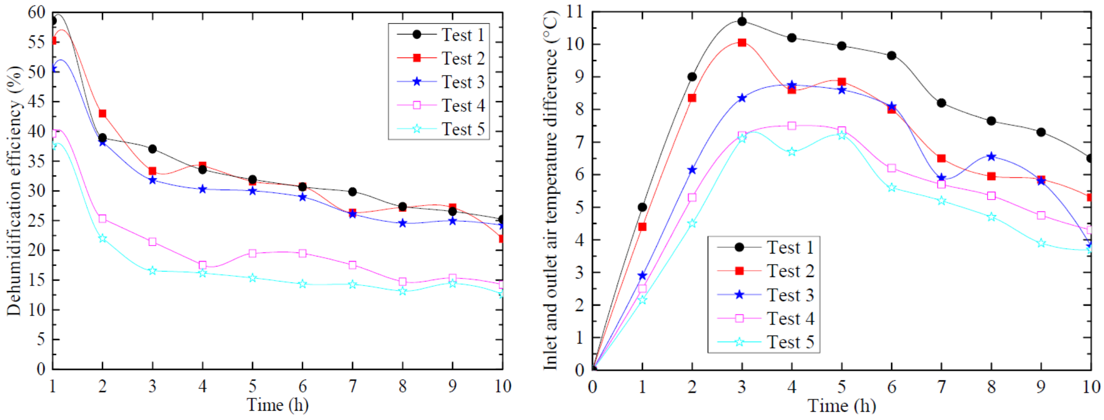


Figure 4.11: Graphs of dehumidification efficiency (Left) and temperature difference (Right) over time.

Within the first 3 hours of operation, moisture removal capability stabilised, but was low. This was the same for dehumidification efficiency. Because adsorption is an exothermic process, the outlet temperature was higher than the inlet, and peaked at the 3rd hour as well. Most of the heat was absorbed by the dehumidified air, while the rest was absorbed by the desiccants. This suggested that measures had to be taken to reduce sensible cooling load. Introducing cooling water was one of the suggestions. (Yang et al., 2017)

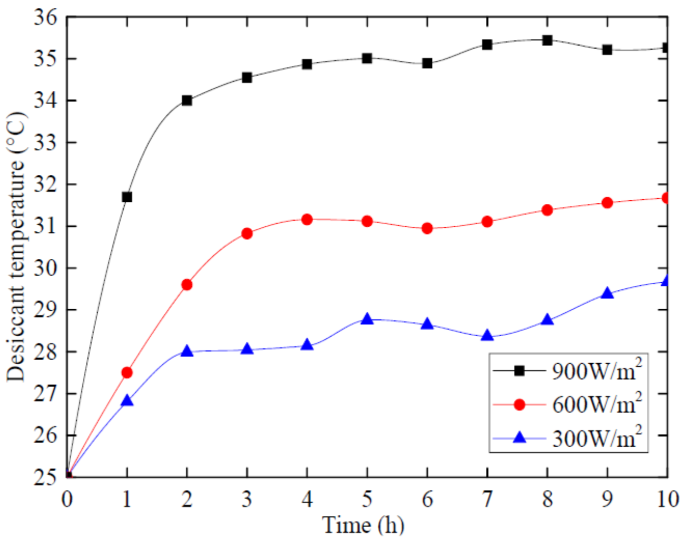


Figure 4.12: Graph of the temperature of the desiccant material over time at different levels of solar radiation.

The temperature of the desiccant was also measured and was seen to rise within the first 3 hours too. This varied with the solar radiation incident on the desiccant beds. With more radiation, the temperature of the desiccants was higher, (Yang et al., 2017) The PV panels were also insufficient to cover the energy consumption of the fans.

This case study further strengthens the need for cooling water and a sensible heat exchanger in the DCHE façade system, and shows the possibility of a window integrated system. Since there is no solar radiation in the night, desiccant and air temperature increments within the window will less of a problem. However, this prototype was also utilising solar radiation as part of the regeneration process, which would be impossible at night. Auxiliary power sources were also necessary for the fans. (Yang et al., 2017) The prototype also did not mention the operability of this desiccant bed window system, meaning that natural ventilation might be difficult with such a strategy because the window is fixed.

Project iNSPiRe, research prototype, Ludwigsburg, Germany

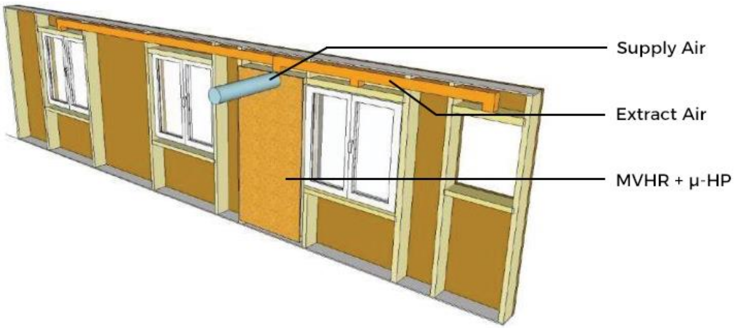


Figure 4.13: The facade module includes heat recovery and a micro heat pump. (Left) Exterior photo of the demonstration. (Right)

This was a project to tackle the problem of high energy consumption of HVAC in residential buildings by researching into the renovation of façade integrated active systems. The main objective of the development of a façade integrated micro-heat pump (μ-HP) was a cost-effective mechanical ventilation system with heat recovery (MVHR) in combination with a vapour compression cycle for heating and optionally cooling (μ-HP) for the application in very energy efficient buildings with a specific heating load in the range of 10 W/m. (Ochs, Siegele, Dermentzis, & Feist, 2015) The facades were prefabricated to save on installation time and effort. Façade integration of the compact active systems also means less space is required for them. Air ducts are also shorter compared to centralised systems. There was minimal intervention necessary for this renovation project because the interior of the building was not involved. (Ochs et al., 2015)

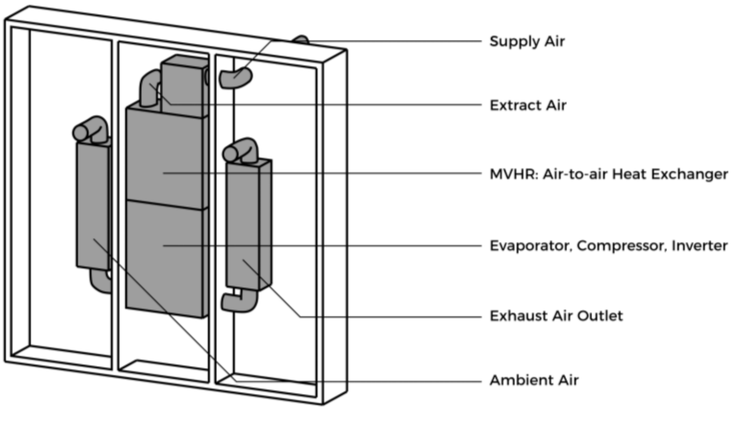


Figure 4.14: The HVAC system is integrated inside the timber facade module.

This façade was tested on a public housing multi-family building built in 1971. The original centralised heating system was deactivated during the demonstration, and the facades were installed for all the rooms; childrens' room, living room, kitchen and dining room, bathrooms and corridors. Thermal comfort was achieved in all spaces except for the bathroom, which would require an additional heating source such as a radiator. (Dermentzis, Ochs, Siegele, & Feist, 2018) The average indoor temperature was higher than before the renovation by 1°C. This was good considering that heating was the objective of this system. The heat recovery ventilator in the façade module reduced the heat demand by 56%, but the electricity consumed by the fans was high, accounting for 1/3 of the total energy consumption of the system. This was due to the pressure losses, of which the narrow diameters of the air ducts, inlets and outlets were to be blamed for, but could be solved by lowering the volume of air flow. (Dermentzis et al., 2018)

This project shows that heat recovery devices make a significant impact on the COP of a HVAC system, and further encourages the use of prefabrication of façade modules and planning for minimal disturbance of the occupants.

E2VENT module, research project

The E2VENT system is an external thermal refurbishment façade system integrating heat recovery and latent heat storage. It is aimed at reducing the peak energy consumption and cooling for summer by developing a modular and durable ventilated façade system. (Basso, Mililli, Herrero, Sanz, & Casaldiga, 2017)

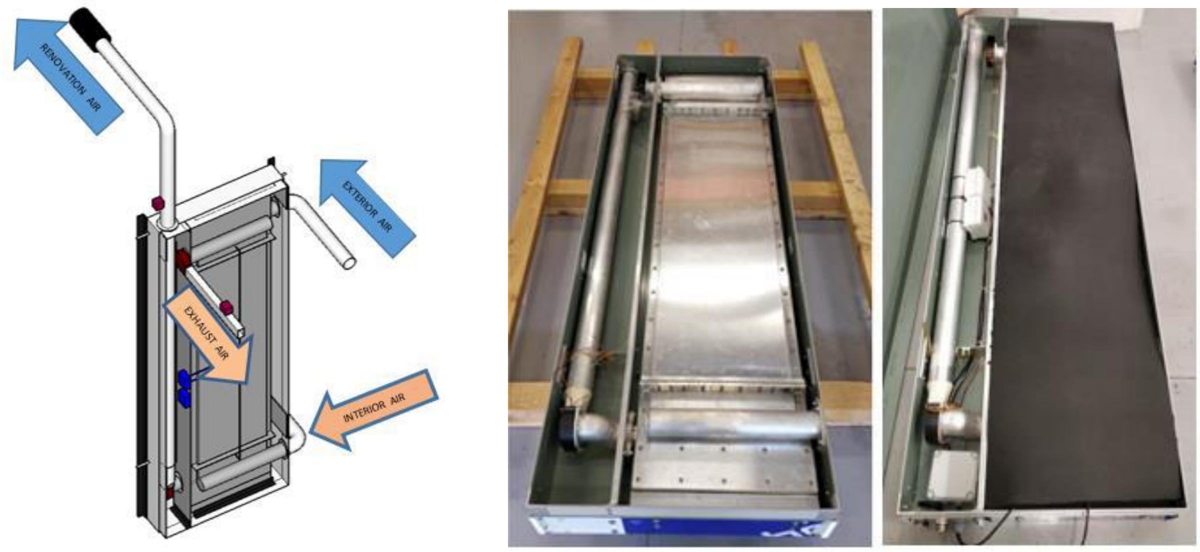


Figure 4.15: The heat recovery unit can be integrated as a slim and long facade module.

The heat recovery unit is an air-to-air heat exchanger installed in the ventilated façade. It provides some pre-cooling during summer seasons and pre-heating during winter. It is compact and removes the need for ventilation ducts throughout the building. The entire module can fit within a 1900 x 650 mm box, 160 mm thick. It weighs about 62 kg. (E2VENT, 2018c)

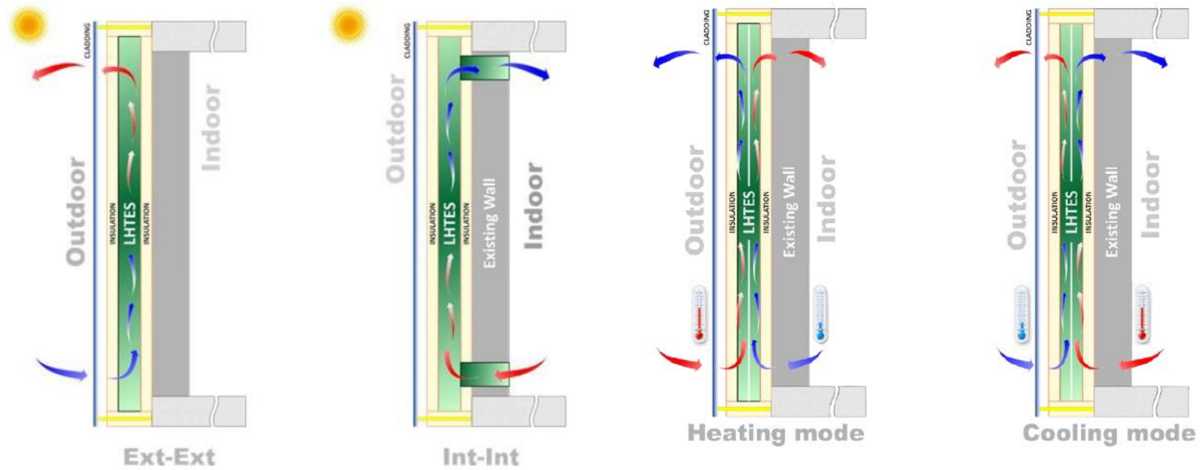


Figure 4.16: The latent storage PCM ventilation unit can faciliate different ventilation configurations for different seasons and user needs.

The latent heat storage is done by using a heat exchanger with phase change materials (PCM). It functions as both a heater and a cooler, depending on the season. During summer, the PCM is solidified at night so it can be used as a cooler the next day. (Dugué, Raji, Bonnamy, & Bruneau, 2017) The prototype fits in a box of 2500 x 600 mm, 160 mm thick, weighing about 180 kg. (E2VENT, 2018a)

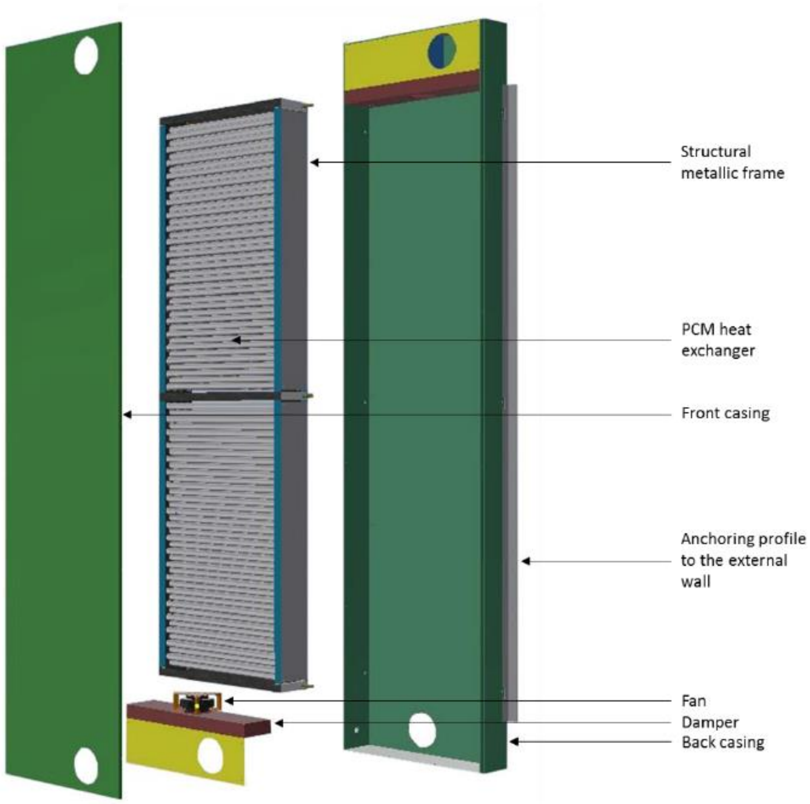


Figure 4.17: Heat exchangers are used for the PCM unit.

These 2 active modules are controlled by a building energy management system (BEMS), which gathers data of the environment to ensure the best performance of the heat recovery and thermal storage devices. The renovation does not require the tearing down of the existing façade, but openings must still be made for the air inlets and outlets. (E2VENT, 2018b)

This project gives some ideas of how a façade cooling system might be designed. Heat exchangers, which are the core of a DCHE system, are demonstrated to be compact enough to fit within façade modules. Although PCM is not so easily applicable in the tropical climate where day and night temperatures do not differ much, it still exemplifies how cooling is possible from a façade system. The only centralised portion of this project is the BEMS module, which can also be installed within the façade. No water storage tanks are involved.

Conclusion

While most of these case studies do not involve desiccant cooling technology, they provide an insight into how a façade-integrated ventilation system can be designed. Some systems are completely decentralised on the façade, while some have connections to other centralised components like solar collectors and water tanks. Most systems were merely integrated as the wall of the façade, while some integrated windows as part of the system. Heat exchangers are relatively compact, making them easy to be integrated. However, their size must correspond to the required cooling capacity. Prefabrication was also a common theme among these retrofit facades, making installation less of a hassle for the residents. Interestingly, there were no cases were the existing façade was completely torn down.

4.2 Façade Integration Locations

One of the lessons learned from the mentioned case studies is how the HVAC systems can be integrated as different parts of the façade. The 3 main facade locations that this research will focus on are the windows, the facade walls, and the sun shading.

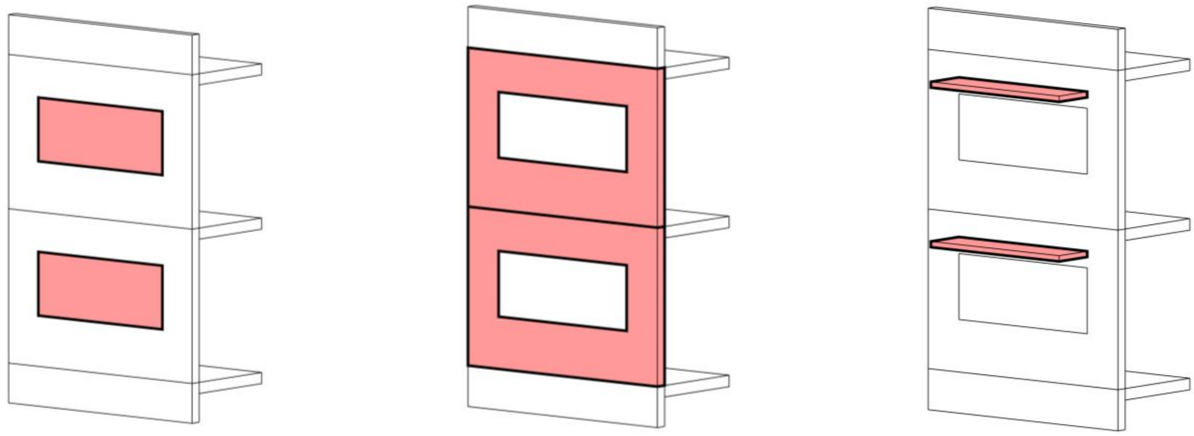


Figure 4.18: The 3 main facade locations for the decentralised components of the DCHE facade system.

These 3 locations apply to the decentralised components, while some other components may be better centralised either on the roof or on the ground. Below is a flowchart depicting the location possibilities of each component.

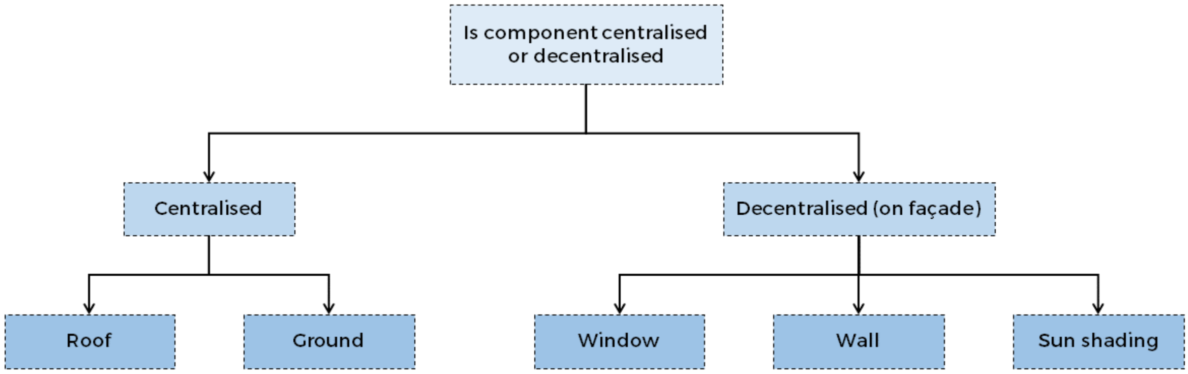


Figure 4.19: Classification of the location of components.

Whether or not a component can or should be centralised depends on both its sizing and function. Some components are better decentralised because a shorter distance between other neighbouring components reduces energy loss. On the other hand, some components require more space, area or are exceptionally heavy. The façade may not be able to accommodate them so easily, so it makes more sense to centralise them and connect them to the decentralised components with ducts. Below is a table listing out the main components for a single façade system, indicating their average sizes based on the case studies and literature research, and the possible locations they can be placed/integrated at. Small scale items such as water valves, fans and pumps are omitted as they are considered to be part of the water tubes and air ducts.

System	Components	Average Sizing	Centralised		Decentralised		
			Roof	Ground	Window	Wall	Sun shading
Main DCHE System	Desiccant Coated Heat Exchanger	318 x 296 x 102 mm			✓	✓	✓
	Hot Water Storage Tank	150 Litres (0.15 m^3)		✓		✓	
	Cold Water Storage Tank	30 Litres (0.03 m^3)		✓		✓	
Solar Thermal Collector	Evacuated Tube Collector	0.83 m^2	✓		✓	✓	✓
Heat Recovery	Heat Exchanger	400 x 400 x 150 mm			✓	✓	✓
	Water Storage Tank	40 Litres (0.04 m^3)				✓	
Sensible Cooling	Heat Exchanger	230 x 200 x 45 mm			✓	✓	✓

Table 4.1: The average sizing and possible locations of each main system component.

The dimension values of the components listed in the table merely serve as a starting point to gauge how much space is required for them. During the development of the conceptual façade designs, and further design development in the later stages, their dimensions are thus not fixed at these values.

Based on Table 4.1, the conceptual façade designs will be an amalgamation of the components at different possible locations. Dimensions will vary based on the corresponding locations.

4.3 Façade Configurations

From the case studies, it was learned that a low level of intervention is preferable for a residential building because there is less disturbance for the occupants. This research will thus stick to low intervention concepts, where the new façade is merely placed over the existing one.

The arrangement of the façade system is a design factor that will affect its aesthetics and functionality. However, this also largely depends on the level of centralising involved.

4.3.1 Existing Facade

The existing North façade consists of 2 main modules; the bedroom module and the kitchen module. Both the 4-room and 5-room apartment take up a whole bedroom module and half of the kitchen module. This is illustrated in Figure 4.22 below.

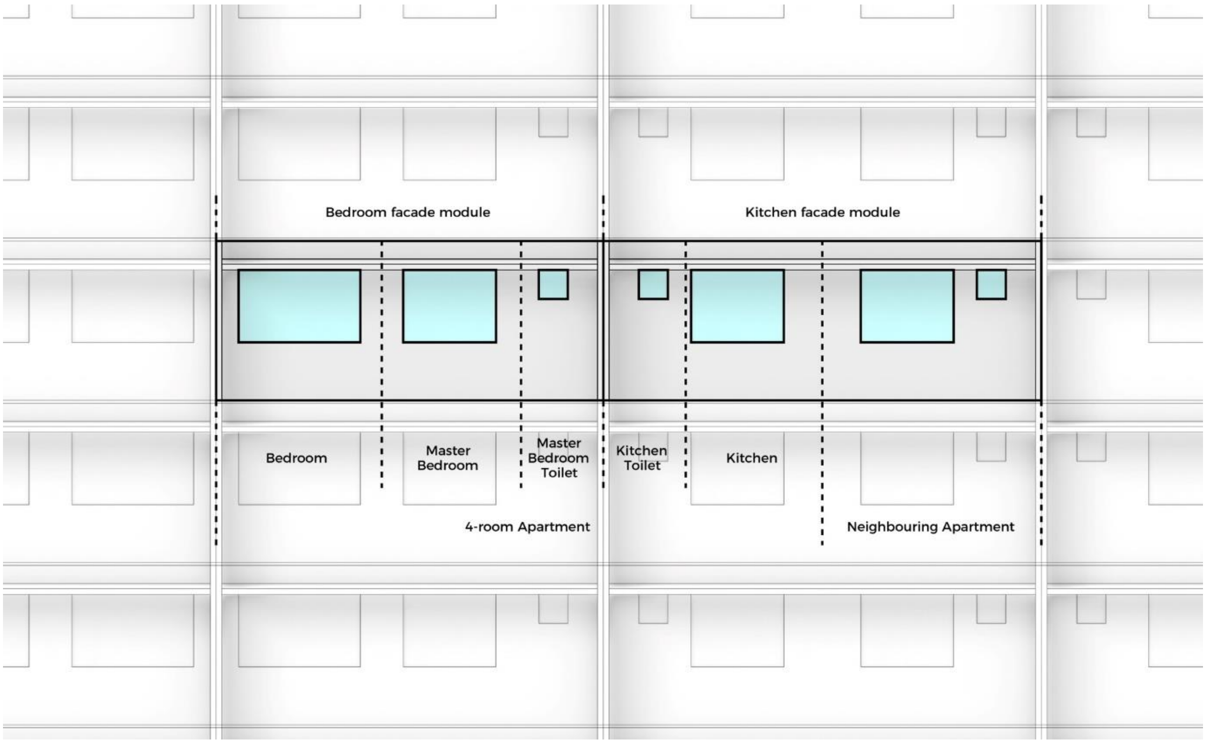


Figure 4.20: Composition of the existing facade.

The existing structural elements are located as shown in Figure 4.23 below. Not much information could be gathered about the façade's section detail as it is deemed confidential. However, it is known that there are structural beams located directly above the windows.

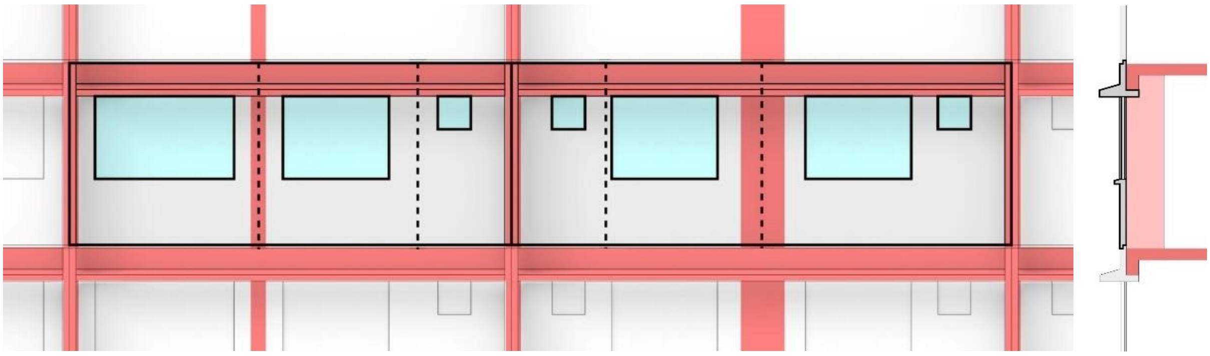


Figure 4.21: Elevation and section of facade highlighting structural beams and columns.

4.3.2 Façade Concepts

There are 2 main façade concepts; fully decentralised and semi-centralised. Having a fully decentralised new façade system would mean that every single component is located on the façade level, including the water tanks and solar collectors. Meanwhile, a semi-centralised system would involve the solar collectors and water tanks placed on the roof and ground level respectively. This means the façade design would be more compact, but it would also require more ducts laid vertically across the façade. Both configurations would differ in terms of maintenance, material use, aesthetics. Table 4.2 summarises this. Figure 4.24 and 4.25 illustrate the potential visual impact of centralising and decentralising.

Fully Decentralised	Semi-centralised
DCHE cooling integrated façade system	
ETCs integrated with façade	ETCs located on rooftop
Water tanks integrated with façade	Water tanks located on ground level

Table 4.2: The difference between the 2 facade concepts.

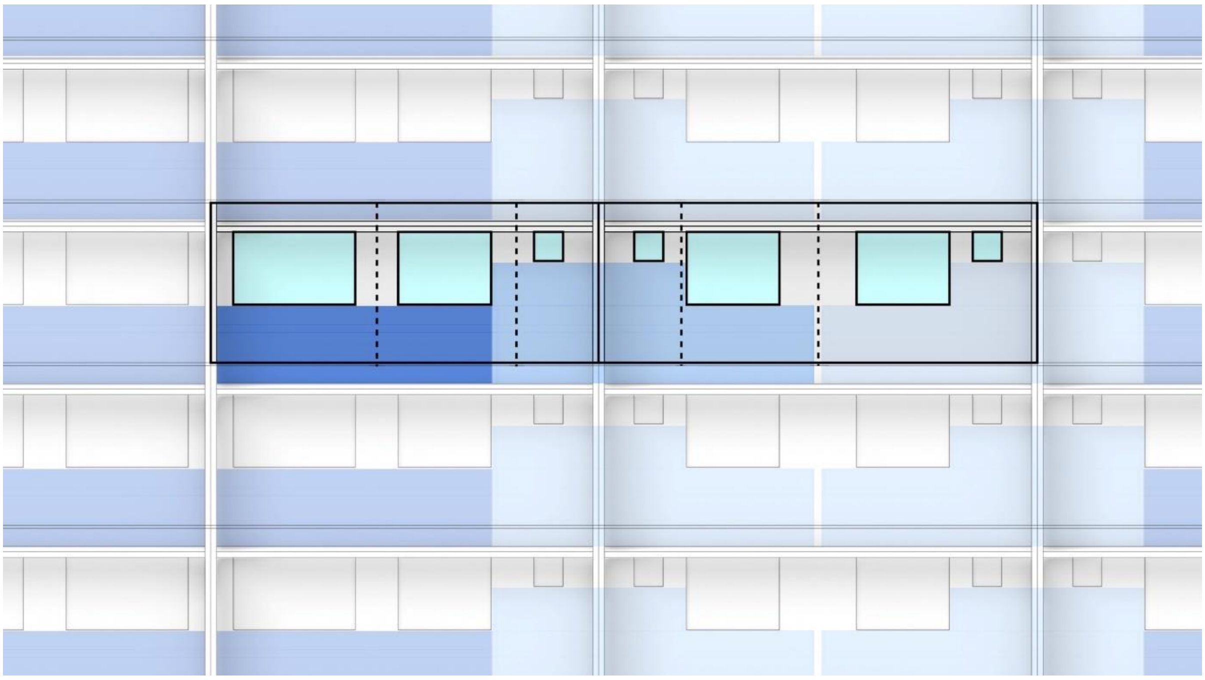


Figure 4.22: Light blue denotes the "centralise-able" components (solar collectors and water tanks). Dark blue denotes the usual components.

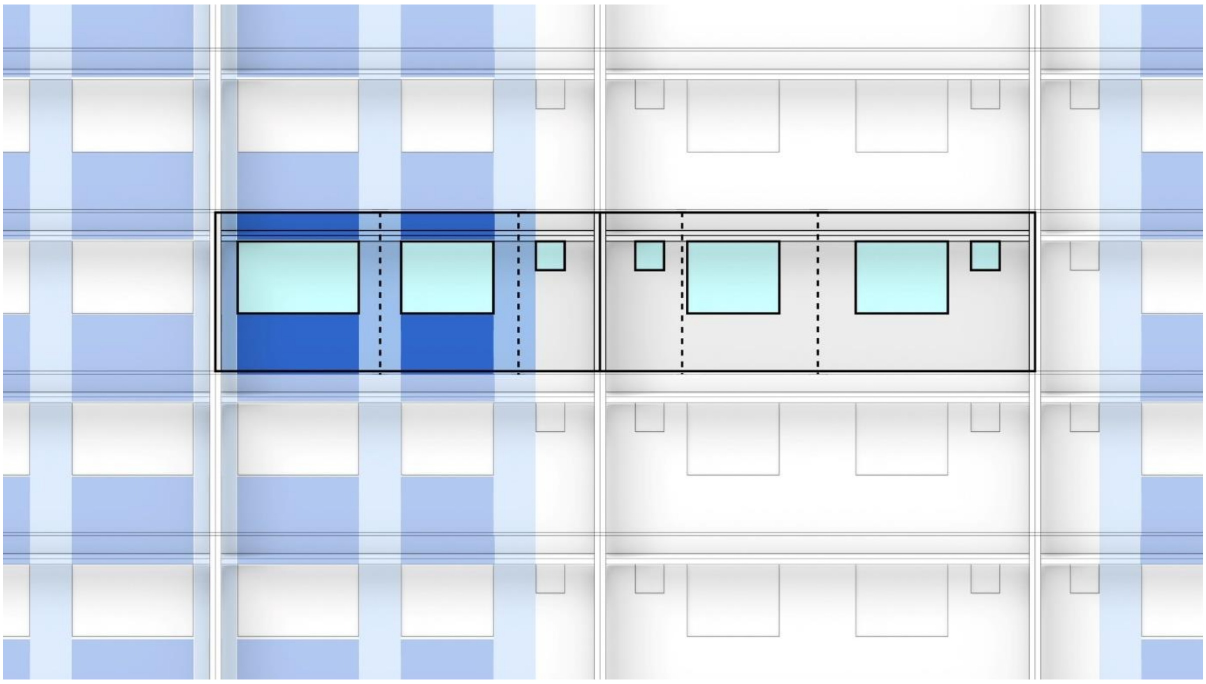


Figure 4.23: Light blue denotes ducts linking to centralised components. Dark blue denotes the decentralised components.

4.4 Façade Design Parameters and Evaluation Criteria

During the conceptual design stage, there are several design parameters that can be controlled, giving rise to different component arrangements that will affect the façade aesthetics, level of intervention, energy performance and maintenance difficulty. These conceptual façade designs are evaluated according to 2 main indicators in Table 4.3. Based on them, a final façade concept is chosen and further optimised and developed in detail. More in-depth performance calculations are also conducted on this final façade design to better evaluate it.

Design Parameters

	Description
Façade Configuration	This pertains to the type of configuration as mentioned in Section 4.3, and directly affects the architectural form of the façade and how much centralising is involved.
Component Location	Most components may be integrated as more than 1 part of the façade. Different placements of the components will result in different façade aesthetics and functionality.
Component Geometry and Dimensions	The geometry of the system components may have to be altered to suit its facade location. The size of the component is also another design parameter. The dimensions may be tweaked, affecting energy performance.

Table 4.3: Design parameters that control the design of the conceptual facades.

Evaluation Criterion

	Description
Material Use	How much material is used for the infrastructure of the system.
Maintenance	The ease of maintenance of different façade designs.
Overall Cost	This is the main evaluation parameter that is determined by the above 4 criteria and is calculated within the lifespan of the system.

Table 4.4: The conceptual facades are evaluated based on these 4 factors.

Requirements

Based on the climate and building programme of the chosen building, certain requirements of the façade system are summarised in Table 4.4 below.

	Description
Night Cooling	The façade system must be able to cool the interior during the night, therefore thermal water storage tanks will be necessary.
Natural Ventilation	The façade must have operable windows to facilitate natural ventilation.
Cooling Power	The façade system should satisfy the required cooling capacity of the bedroom. This is calculated in Section 4.5.
Façade Orientation	The façade design will be for the North façade of the chosen building because that is where most bedrooms are located. However, additional intervention on the South, East and West facades are also a possibility if deemed necessary later.

Table 4.5: Requirements of the facade system.

4.5 Façade Concept Design Process

The process of developing a facade design follows a few steps and starts with the establishment of the required cooling capacity of the bedroom. Figure 4.26 below is a flowchart showing the steps taken to reach a workable façade concept, which will be evaluated in the later stages.

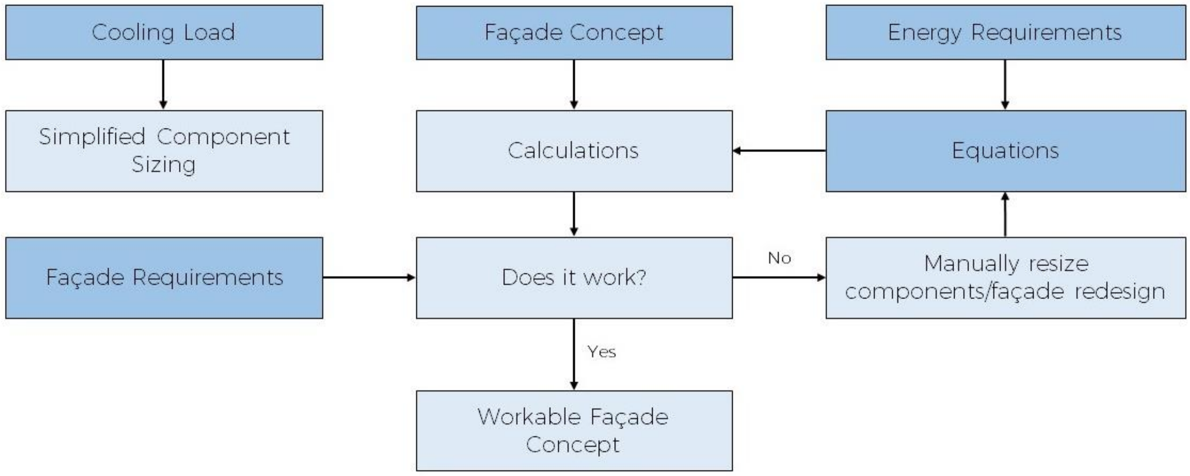


Figure 4.24: Flowchart showing the steps taken in the facade design process. In dark blue are the inputs, while light blue denotes the processes.

4.5.1 Cooling Load

In order to figure out the required cooling capacity of the façade, the cooling loads of the bedrooms must first be understood. The 2 bedrooms on the North façade have a slightly different floor area. The master bedroom is slightly larger, with a floor area of 16.5 m^2 and a volume of 43 m^3. Its cooling load will typically be larger. A model of the master bedroom is created in Designbuilder and has its cooling load calculated to be approximately 2.30 kW. With a safety factor of 1.15, a cooling capacity of 2.64 kW is required of the façade cooling system. 301.68 m^3/h is the required air flow rate to achieve this cooling power. The air flow rate will be used to size the components because it directly affects the cooling capacity and is directly affected by the component sizes.

Required Air flow rate (m^3/h)	Resultant Cooling power (W)
301.68	2640

Table 4.6: Cooling power and air flow rate recommended by Designbuilder.

4.5.2 Simplified Component Sizing

For the DCHE, SHE, and cold water tank, the sizes and air flow rates will be taken from Ge et al. using the composite Si + LiCl desiccant material because it is the only experiment with an SHE. The HRD subsystem and hot water tank are taken from the same experiment from Zhao et al. for the same reason. Moreover, most other experiments use a thermal water bath rather than an actual water tank. The ETC is taken from Kumar & Yadav's experiment. Table 4.7 summarises the component sizes and their corresponding air flow rates.

System	Components	Sizing	Air flow rate (m^3/h)
Main DCHE System	DCHE (composite desiccant)	Frontal Area: 0.046 m^2 Depth: 45 mm	232
	Hot Water Storage Tank	500 Litres (0.5 m^3)	700
	Cold Water Storage Tank	30 Litres (0.03 m^3)	232
Solar Thermal Collection	Evacuated Tube Collector	0.8325 m^2	142.758
HRD	Heat Exchanger	Frontal Area: 0.16 m^2 Depth: 150 mm	700
	Warm Water Storage Tank	40 Litres (0.04 m^3)	700
SHE	Heat Exchanger	Frontal Area: 0.046 m^2 Depth: 45 mm	232

Table 4.7: Component sizes of benchmark performances and their effects on the baseline cooling power and COP.

These values are used to calculate the required component sizes for the concept façade by scaling the component to match the required air flow rate of 301 m^3/h. For the heat exchangers, only the frontal area is resized because the depth does not affect the air flow rate. Table 4.7 below summarises the required component sizes.

System	Components	Scaling Factor	Required Sizing
Main DCHE System	DCHE (composite desiccant)	1.3	Frontal Area: 0.06 m^2 Depth: 45 mm
	Hot Water Storage Tank	0.431	216 Litres (0.216 m^3)
	Cold Water Storage Tank	1.3	40 Litres (0.04 m^3)
Solar Thermal Collection	Evacuated Tube Collector	2.113	1.76 m^2
HRD	Heat Exchanger	0.431	Frontal Area: 0.069 m^2 Depth: 150 mm
	Warm Water Storage Tank	0.431	18 Litres (0.018 m^3)
SHE	Heat Exchanger	1.3	Frontal Area: 0.06 m^2 Depth: 45 mm

Table 4.8: The required component sizes for the concept facade designs, based on the airflow rates from experiments and the required value from Designbuilder.

4.5.3 Calculations

Upon applying further calculations using the equations in Chapter 3.2.3 and 3.3.1, it was discovered that the sizes established in Table 4.7 were insufficient to meet the requirements of cooling power. This is because the values in Table 4.7 assumes certain operating conditions which does not hold true for the Singapore climate. Moreover, the temperature drop during regeneration is not accounted for. According to calculations, the cooling power was 1057.72 W. On top of that, a hot water temperature of 50°C is insufficient to sustain regeneration for 7 hours, considering 50°C is already the minimal regeneration temperature. A larger hot water tank was also required to maintain a hot enough temperature through these 7 hours of operation.

4.5.4 Manual Component Resizing and Tweaking of Operational Conditions

In order to ensure that the design meets the requirements for cooling power of the bedroom at night, whilst meeting its own operating requirements, certain component dimensions and operating conditions were adjusted. Table 4.8 and 4.9 below summarises the changes.

Operation Condition	Original Value	Manual Setting
Air Flow Rate (m^3/h)	302	310
Ambient Air Temperature (°C)	30	27.5
Ambient Air Specific Humidity (g/kg)	16.1	18.9
Hot Water Temperature (°C)	50	80

Table 4.9: Operational conditions altered to suit Singapore's climate and the operational capability of the facade system.

System	Components	Simplified Sizing	Manual Resizing
Main DCHE System	DCHE (composite desiccant)	Frontal Area: 0.06 m^2 Depth: 45 mm	Frontal Area: 0.1 m^2 Depth: 200 mm
	Hot Water Storage Tank	216 Litres (0.216 m^3)	300 Litres (0.3 m^3)
SHE	Heat Exchanger	Frontal Area: 0.06 m^2 Depth: 45 mm	Frontal Area: 0.1 m^2 Depth: 45 mm

Table 4.10: Changes made to component sizes to suit the new operative conditions and achieve the required cooling capacity.

With these new sizings and operational conditions, the façade system can now achieve a cooling capacity of 2640.358 W. The cooling capacity requirement is thus met. The hot water temperature at the end of 7 hours of operation is 50.79°C, which means that regeneration can be done throughout the 7 hours. This does not consider heat loss from the surface of the water tank, which will be done in the later detailed stages. Supply air is 21.5°C with a relative humidity of 69.87%. With an air flow rate of 310 m^3/h, there are slightly more than 7 air changes per hour in the bedroom, which is more than sufficient. However, before proceeding to the actual designing of the façade concepts, the actual required amount of ETC absorber area needs to be calculated in order to know how much physical space should be allocated for them for each concept.

4.5.5 Calculation of Required ETC Sizing

A solar irradiation simulation was done in Rhino Grasshopper to investigate the amount of solar irradiation that the collector would receive when placed at different locations of the building and with different tube distances and absorber tilt angles. Shading from the building and the collector tube above was considered.

North Façade

Singapore is located slightly above the equator. This gives the country a relatively vertical sunpath throughout the year. However, it still shifts between the North and South side. The sun is most North during the summer solstice in 21 June. Likewise, it is most South during the winter solstice in 21 December. This is illustrated in Figures 4.27 and 4.28. Consequently, the summer solstice is when ETCs on the North façade experience the most solar irradiation, while the winter solstice is when the North façade would encounter zero direct sunlight, so ETCs placed there will have to rely solely on diffused and indirect sunlight. As mentioned earlier in Section 2.2.4, The South façade tends to experience slightly more solar irradiation throughout the year. This makes the North façade a bigger challenge for solar heat collection.

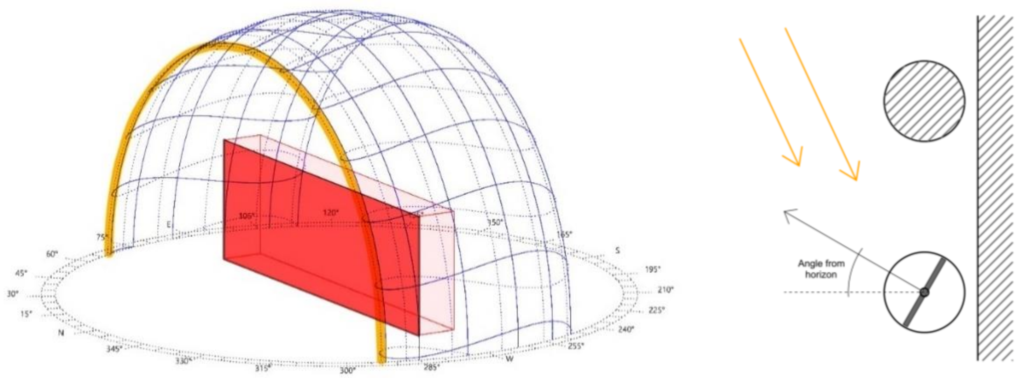


Figure 4.25: Sunpath on the June Solstice. Highlighted in red is the North facade of the building.

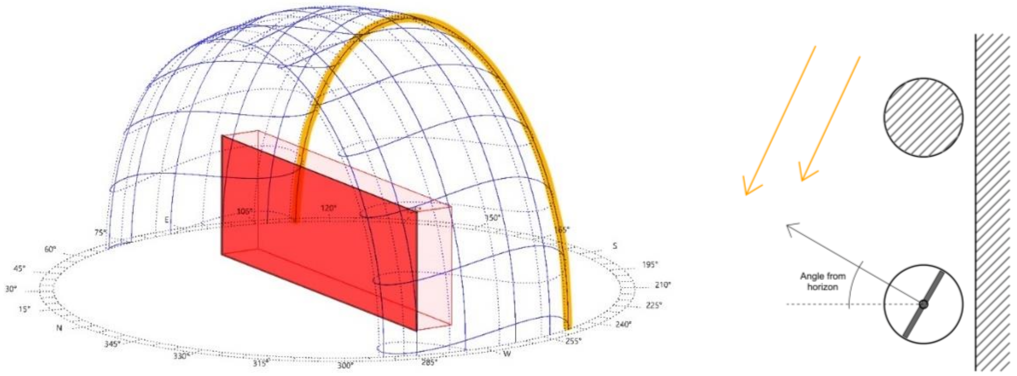


Figure 4.26: Sunpath on the December Solstice. Highlighted in red is the North facade of the building.

When the tube distance was set as a variable between 3 cm to 8 cm, Grasshopper's Galapagos optimisation immediately chose the minimal tube distance possible. This results in a larger number of tubes within a fixed area allocated for ETCs. This means that even though each tube is slightly more shaded by the tube above, a larger number of tubes result in a larger total absorber area, which means more solar heat energy can be absorbed. Using a tube distance of 3 cm, the solar irradiation for different absorber angles were simulated. Table 4.10 and Figure 4.29 show and compare the results between different angles at the solstices.

Absorber Angle from horizon	Annual average solar irradiation per day (kWh/m²/day)	Solar irradiation on December solstice day (kWh/m²)	Solar irradiation on June solstice day (kWh/m²)
0	1.405	1.021	2.39
5	1.526	1.091	2.62
10	1.635	1.151	2.812
15	1.717	1.198	2.968
20	1.786	1.238	3.086
25	1.806	1.249	3.102
30	1.873	1.279	3.213
35	1.923	1.3	3.273
40	1.92	1.287	3.276
45	1.932	1.282	3.303
50	1.928	1.267	3.304
55	1.898	1.233	3.265
60	1.865	1.199	3.217
65	1.819	1.156	3.144
70	1.758	1.104	3.048
75	1.685	1.044	2.928
80	1.598	0.975	2.786
85	1.469	0.888	2.569

Table 4.11: Solar irradiation values from simulation. Highlighted in red is the highest solar irradiation on the worst day of the year.

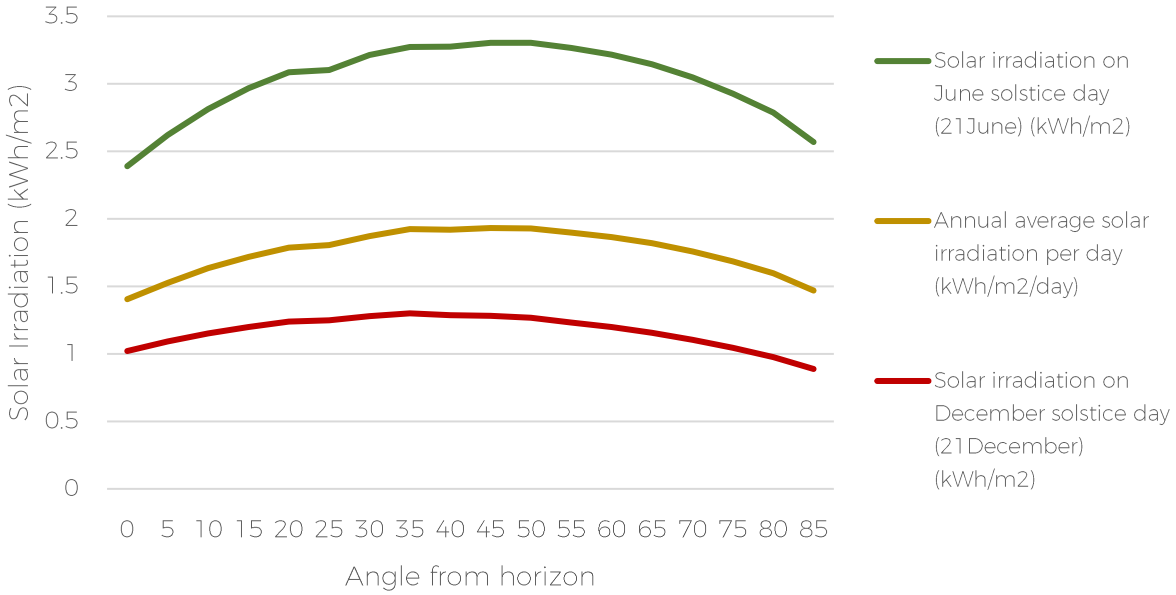


Figure 4.27: Graph visually illustrating the solar irradiation on ETCs on the North facade with different absorber angles.

Since the December solstice is the day with the worst performance, it will be used as the minimum benchmark for ETC sizing. ETCs can collect 1.3 kWh/m^2 of solar energy on that day. From the simulation, it can be seen that the best absorber tilt angle is 35°. Beyond that, the absorber faces too much shading.

In order to find out the required absorber area needed, the amount of heat required to heat up the hot water tank must first be known. This is done by using the equation from Section 3.3.1:

$$\mathbf{Q = m * C_p * \Delta T}$$

From Excel calculations,

$$\Delta T = 29.2\ °C$$

$$m = 300\ kg$$

$$C_p = 4185.5\ J/kg\ K$$

$$\text{Therefore, } Q = 10.197\ kWh$$

The required solar absorber area is thus calculated as:

$$\mathbf{A = \frac{10.197 \div 1.3}{\eta}}$$

where η is the efficiency of the ETC. With an efficiency of 80% based on scientific papers, the total required North facade solar absorber area per bedroom is 9.8 m^2. Since there are 2 bedrooms per apartment unit on the North façade, 19.6 m^2 worth of solar absorber area is required per apartment. In order to check if there is sufficient space on the facade, some estimations were done. For a tube distance of 3 cm, the ratio of absorber area to gross area is approximately 0.5728. This means for every apartment unit, 34.23 m^2 of façade area is required.

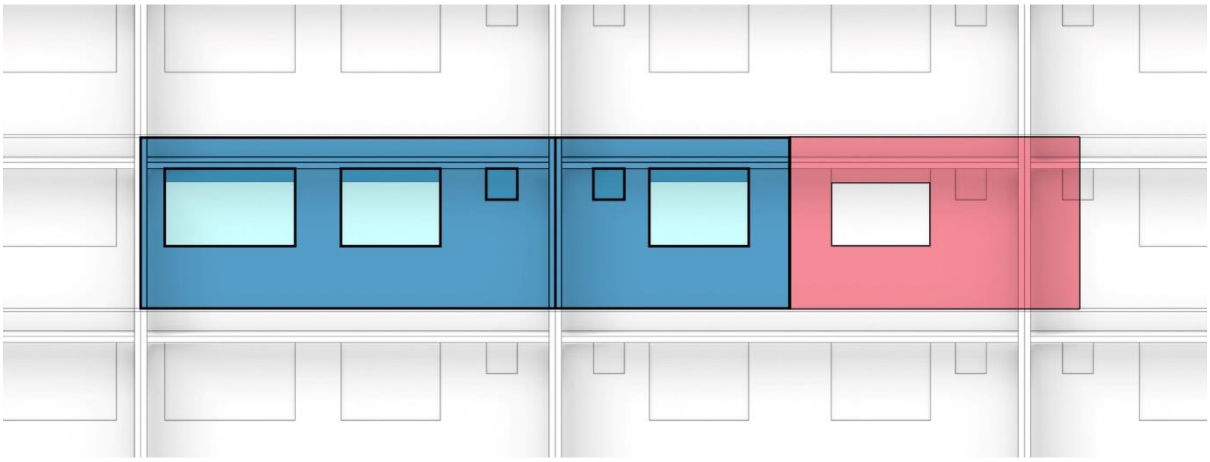


Figure 4.28: Highlighted in dark blue is the maximum available area for a facade-located ETC subsystem per apartment unit. Highlighted in red is the façade area that each apartment lacks.

Figure 5.30 visualises how much space is required versus how much space is available. The coloured areas combined is the required area per apartment unit. In dark blue the maximum available area of 23.44 m^2 per apartment unit, while in red is the amount of façade area that each apartment unit lacks, of 10.8 m^2. The bedroom and kitchen windows area partially covered to use the ETCs as window shading. The toilet windows are covered because they are meant for ventilation. An ETC will not fully block the toilet window. It would only be positioned in front of it. From Figure 5.30, it can be seen that there is insufficient façade space because each apartment unit would have to occupy more than its available area and end up overextending onto the façade area of the neighbouring unit. Only 68.5% of the required façade area was secured.

Rooftop

In Singapore, ETCs are usually tilted roughly 20° Southward to allow for passive cleaning of the collector by rain, (Muttakin, 2018) although fixing them facing directly vertically upwards does result in a higher solar irradiation collection. From the simulation, facing vertically upwards gives an average annual solar irradiation of 4.57 kWh/m^2/day. Table 4.11 shows the performance when the ETC is tilted 20° Southward. The tubes are again set at 3 cm apart.

Annual average solar irradiation per day (kWh/m^2/day)	Solar irradiation on June Solstice (21 June) (kWh/m^2)	Solar irradiation on December Solstice (21 December) (kWh/m^2)
4.259	3.708	4.627

Table 4.12: Solar irradiation on rooftop, with ETCs tilted 20º Southward.

However, solar irradiation can fluctuate a lot per day. A month's average was instead used. Shading from adjacent tubes were also introduced for a more accurate simulation.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Monthly average solar irradiation (kWh/m^2)	4.725	4.524	4.52	4.256	3.912	3.535	3.809	3.911	4.066	4.393	4.183	4.309

Table 4.13: Monthly average solar irradiation on the rooftop ETC.

Figure 4.29: Graph showing how the solar irradiation differs per month.

From Tables 2.12 and Figure 4.31, it can be seen that positioning ETCs on the rooftop grants a much better solar energy collection compared to the North facade. This is because it encounters virtually zero shading and is exposed to direct sunlight for the entire year. In contrast to the North façade, June is the weakest time of the year for roof-located ETCs because the Sun is on the North while the ETCs are pointed slightly towards the South. Using the worst-case average of 3.535 kWh/m2, the calculated required rooftop solar absorber area per bedroom is thus 3.61 m^2, which is a lot less than that of an ETC system placed on the North façade.

However, it is also important to consider the gross area on top of the absorber area. With a tube distance of 3 cm, the ratio of absorber area to gross area is calculated to be 0.625. This means that the gross area of all the required ETCs on the rooftop is 1268 m^2.

Figure 4.30: A Google Maps image of the roof of the building from Northwest direction.

The estimated available rooftop floor area is roughly 1160 m^2. This means there is insufficient rooftop space to fully centralise all the ETCs. Moreover, some space is also required for human access during maintenance and deployment. Assuming a 70 cm walkable area in front of each ETC, this brings the gross area up to 1797 m^2. Thus, the roof only has space for 64.5% of the required ETCs.

4.5.6 Centralised Water Tank Sizing

The water tank volume per bedroom is assumed to not be different between the two façade concepts. The main difference is where the tanks are located.

Façade Concept	Hot Water Tank (Litres)	Cold Water Tank (Litres)
Fully decentralised	300	40
Semi-centralised	66000	8800

Table 4.14: Water tank volumes for each facade concept.

While the water tanks in the fully decentralised concept will have to be designed along with the rest of the façade system, the water tanks for the semi-centralised concept are located on the ground floor. They can thus be merged as 2 large water tanks (1 for hot water, 1 for cold water). Because of this, they will be typical cylindrical water tanks for structural reasons. The size of the hot water tank will be estimated since it is the bigger tank.

Most public housing buildings built in Singapore after the 1970s feature a void deck on the ground level. This design is meant to reduce ground level air flow restrictions, allow pedestrians to walk through buildings for faster travelling times, doubling as shelter, and is considered a public space for communal activities and events. It has a typical floor to ceiling height of 3.6 m and only structural columns occupy the space.

Figure 4.31: The ground floor of the building. Only structural columns occupy the space.

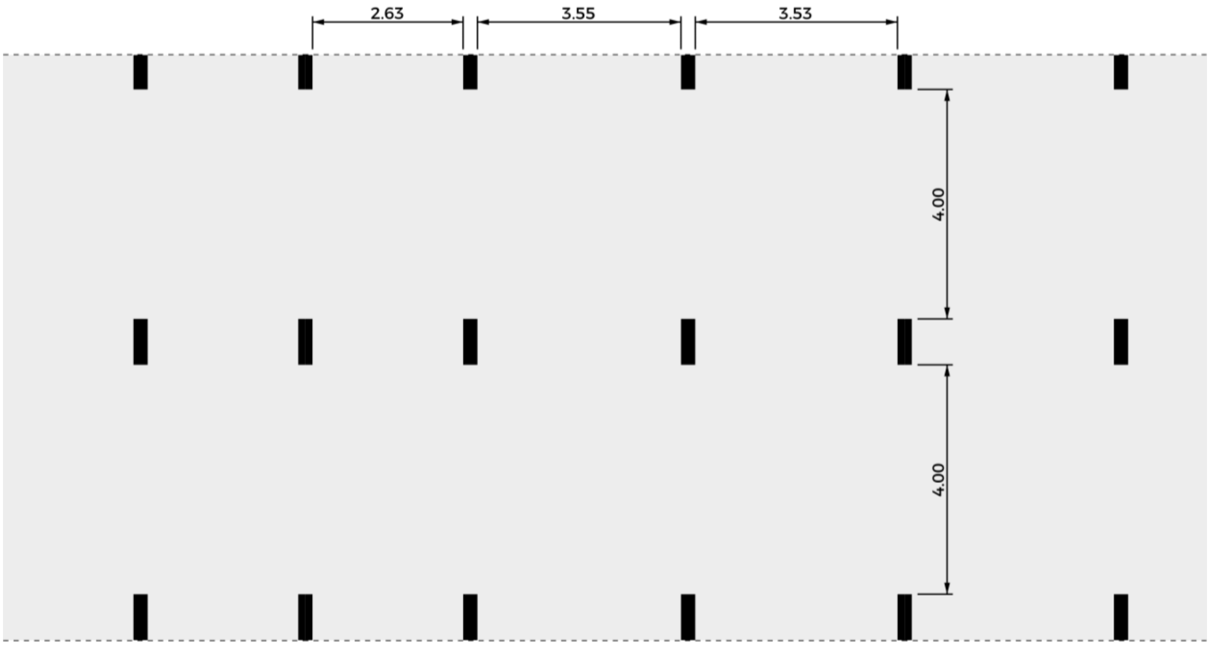


Figure 4.32: Floorplan of void deck. Dimension on metres.

Hot water tank volume = 66000 Litres = 66 m^3

With a water tank height of 3.3 m (in order to not collide with the concrete beams), the diameter of the hot water tank will be 5.046 m. While this would not fit within the constraints of the structural columns seen in Figures 4.32 and 4.33, the hot water can simply be split into 2 tanks, each 33000 litres with the same height of 3m and a diameter of 3.568 m each. The cold water tank has a much smaller volume of 8.8 m^3 so it can fit even more easily in the void deck with a calculated diameter of 1.842 m. Along with 4 cm of insulation, these water tanks can fit as shown in Figure 4.34 below.

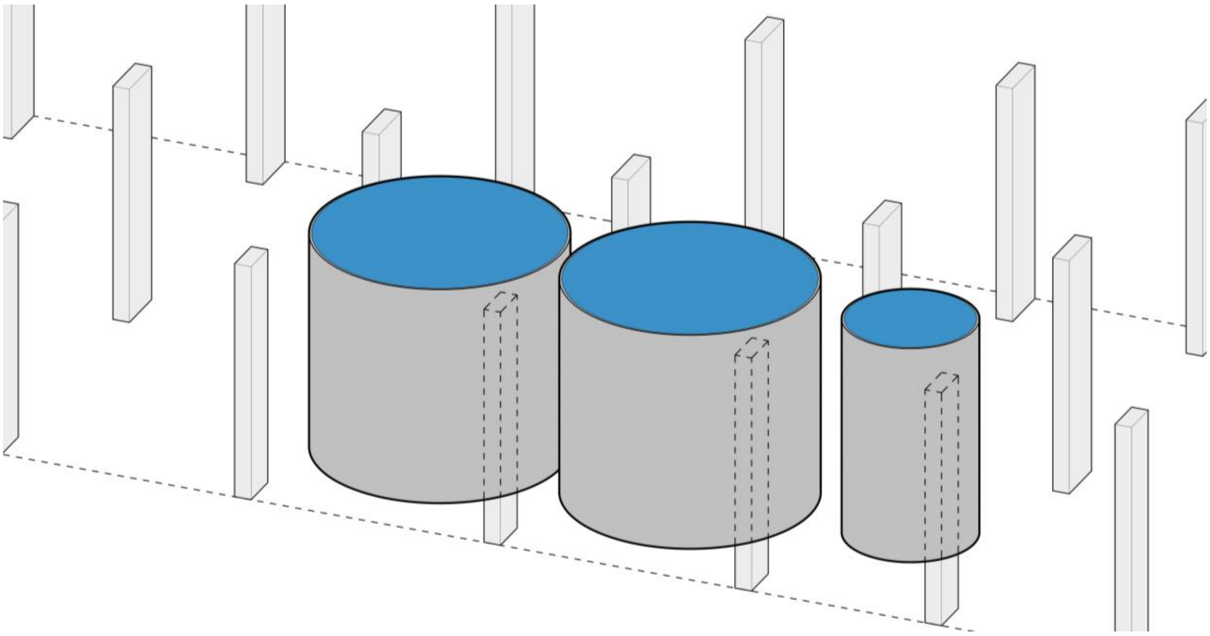


Figure 4.33: Positioning and sizing of the centralised water tanks in the void deck. 2 hot water tanks and 1 cold water tank.

4.5.7 Conclusion

Because the ETC subsystem cannot fully fit within the stated boundaries for both façade concepts, there is not much choice but to combine rooftop and façade placements for the ETCs. As such, the 2 façade concepts must be tweaked. This is done in detail in Section 4.6, where the concepts are adjusted to maintain their intention and mode of operation.

4.6 Conceptual Façade System Designs

The ETCs have been shown to take up more space than initially available. The initial concepts where the ETCs were located either on the rooftop or on the façade is no longer possible. Therefore 2 façade concepts must be tweaked and compromised to cater to this condition.

Fully Decentralised

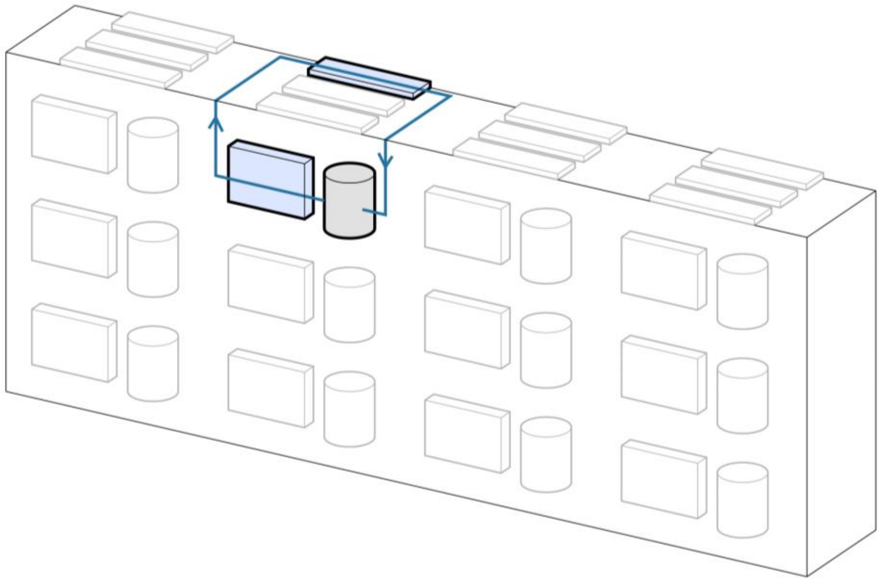


Figure 4.34: Diagram illustrating the water flow system of the fully decentralised concept.

For the fully decentralised concept, priority will be placed on putting as many ETCs as possible on the façade, and the remaining ETCs on the roof. Each bedroom will still have its own dedicated set of water tanks and ETCs. Water flows from the tank and through the façade-located ETCs, before flowing up to the roof and through a few more ETCs to collect the remaining necessary heat, and then flowing back down into the water tank. In this way, the façade system is still decentralised in principle because there is no sharing of water nor ETCs.

Semi-centralised

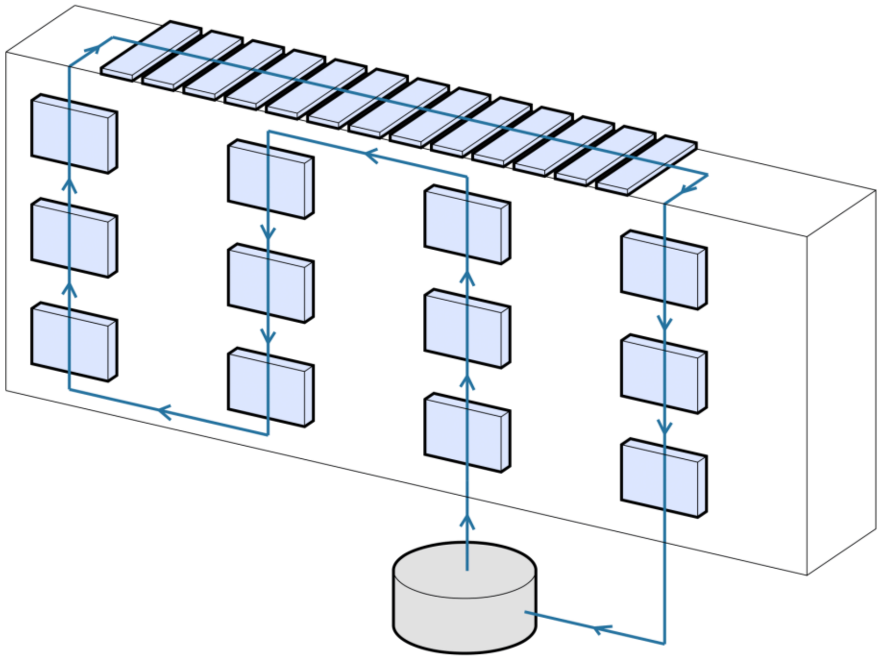


Figure 4.35: Diagram illustrating the water flow system of the semi-centralised concept.

As for the Semi-centralised concept, the priority is placed on filling the roof with ETCs and placing the remaining ones on the façade. The water tanks are centralised on the ground level and water flows upwards through the façade-located ETCs on all levels, before reaching the rooftop ETCs and coming back down again into the water tank. All bedrooms share this water heating system, so it's a centralised one. It is still called "Semi-centralised" because the cooling system itself is still decentralised for each bedroom on the North façade.

Fully decentralised	Semi-centralised
DCHE cooling integrated façade system	
ETCs integrated with façade **and** located on rooftop	
Water tanks integrated with façade	Water tanks located on ground level
Decentralised ETC + water tank system	Shared centralised ETC + water tank system

Table 4.15: Updated facade concepts to cater to availability of space for ETCs.

Table 4.15 above summarises the characteristics of the 2 façade concepts. Both concepts still retain the initial idea of decentralising versus centralising, but the 2 façade designs now must consider additional conditions. Both now have ETCs on the façade, but they have different collector areas required. Water piping must also be planned carefully.

4.6.1 System Overview

This section describes very briefly how the façade cooling system will work.

Daytime

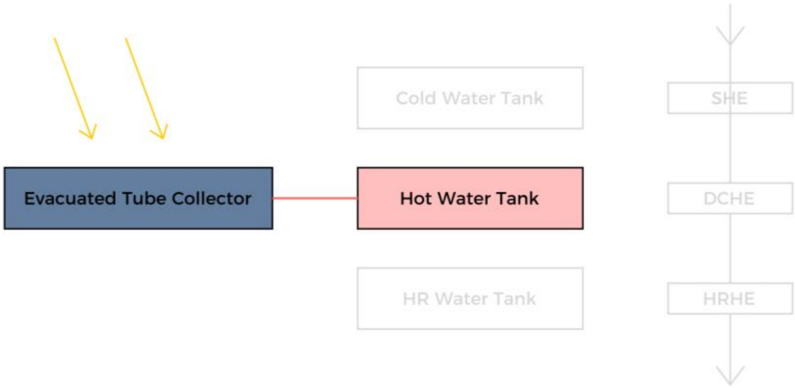


Figure 4.36: Daytime operation.

Throughout the day, solar heat is collected to bring up the water temperature of the hot water tank. The heat is used for regeneration during the night later.

Night-time

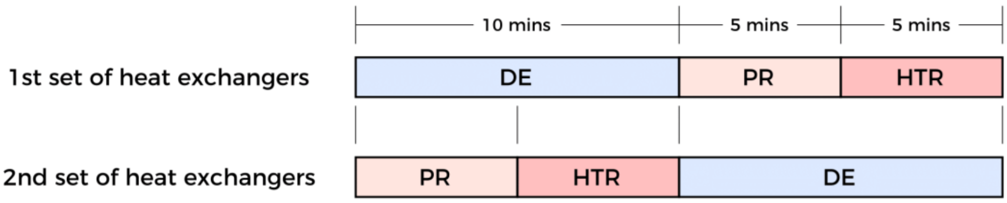


Figure 4.37: Duration of each process.

At night, the façade operates in 3 stages per cycle; dehumidification (DE), pre-regeneration (PR) and high temperature regeneration (HTR). Each procedure lasts a specific time, shown in the diagram above.

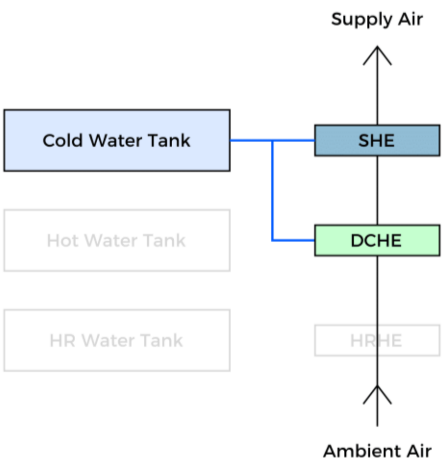


Figure 4.38: Dehumidification process.

During dehumidification, cold water is extracted from the cold water tank and passed through the DCHE and SHE to cool and dehumidify the incoming air. The cold water tank is equipped with a water cooler to keep the cold water temperature at 20°C.

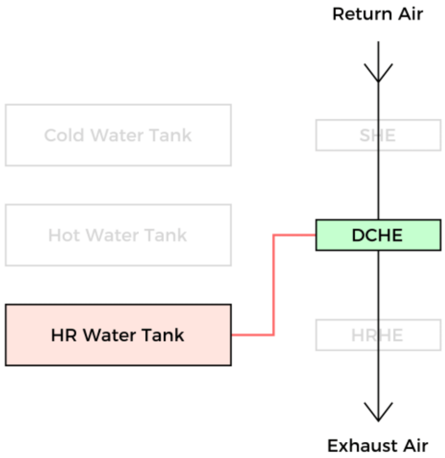


Figure 4.39: Pre-regeneration process.

Pre-regeneration occurs before the main regeneration procedure, and warm water is passed through the DCHE to facilitate regeneration of the desiccant material.

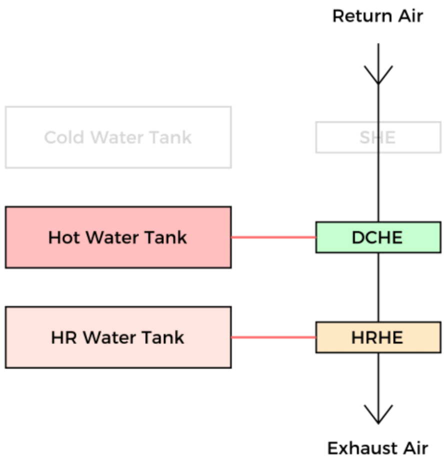


Figure 4.40: High temperature regeneration process.

High temperature regeneration happens for the next 5 minutes, and facilitates a higher quality regeneration because the water temperature being used is higher. Meanwhile, the heat from the air exiting the DCHE is extracted when passed through the HRHE and recycled into the warm water tank, to be used again in the next cycle.

4.6.2 Fully decentralised Façade Design

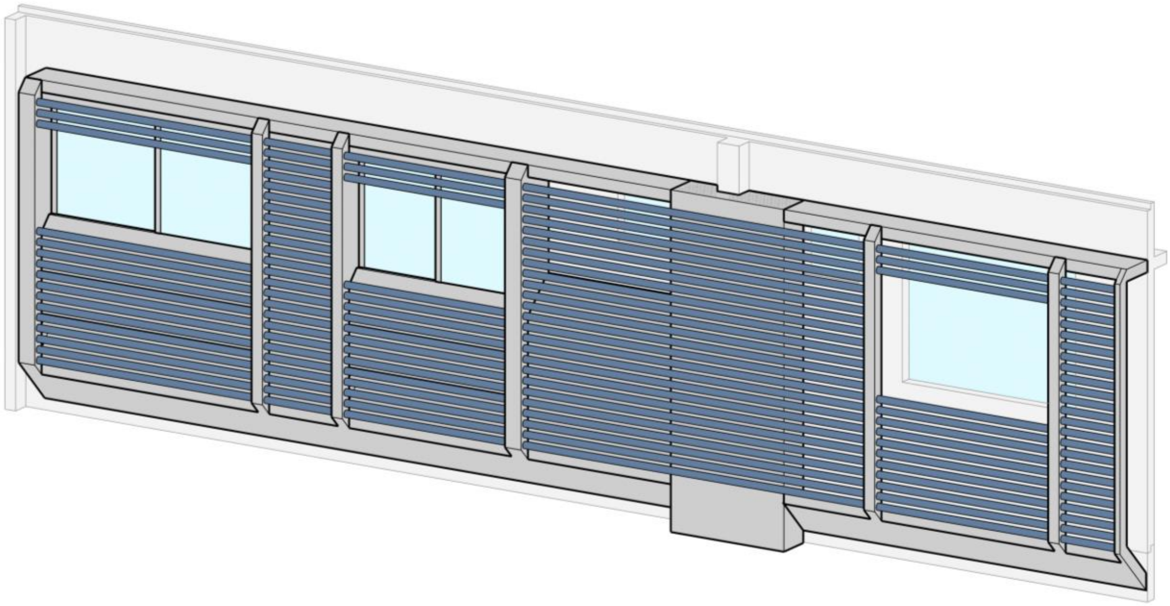


Figure 4.41: The facade module based on the fully decentralised concept.

The fully decentralised façade concept maximises the number of façade-located ETC tubes. The result is a façade that is overwhelmed by the ETC subsystem. The existing façade is almost completely covered. The cold water tank and HRD water tank are located below the cooling system components, while the hot water tanks occupy the sapce beside the cooling system itself. A vertical duct is required to transport water during solar heat collection in the day time. This is located in between the master bedroom and the kitchen. In Section 4.5.5 it was mentioned that an estimated 68.5% of the solar energy collection could be done on the façade, but after the actual designing, only 46.5% of the solar energy collection could actually be done.

Daytime Water Flow

During the day, solar heat is being collected. The share of façade-located ETC tubes are split between the corresponding apartment's bedroom and master bedroom.

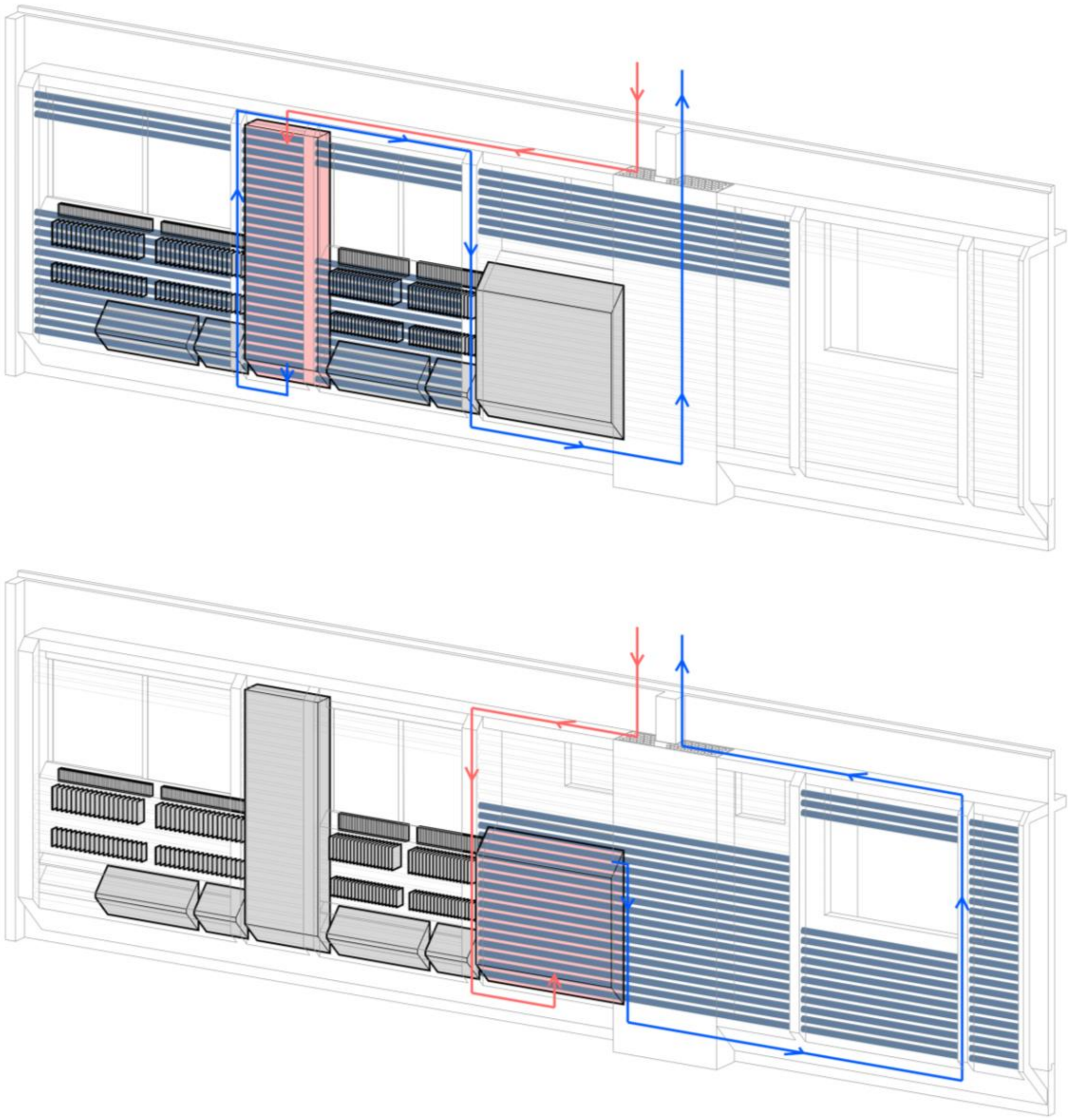


Figure 4.42: Diagram of water flow during solar heat collection within the façade module for each bedroom.

Night-time Cooling Operation

As mentioned earlier, night-time operation involves 3 different stages. The conceptual 2D drawing below illustrates the components of the façade system.

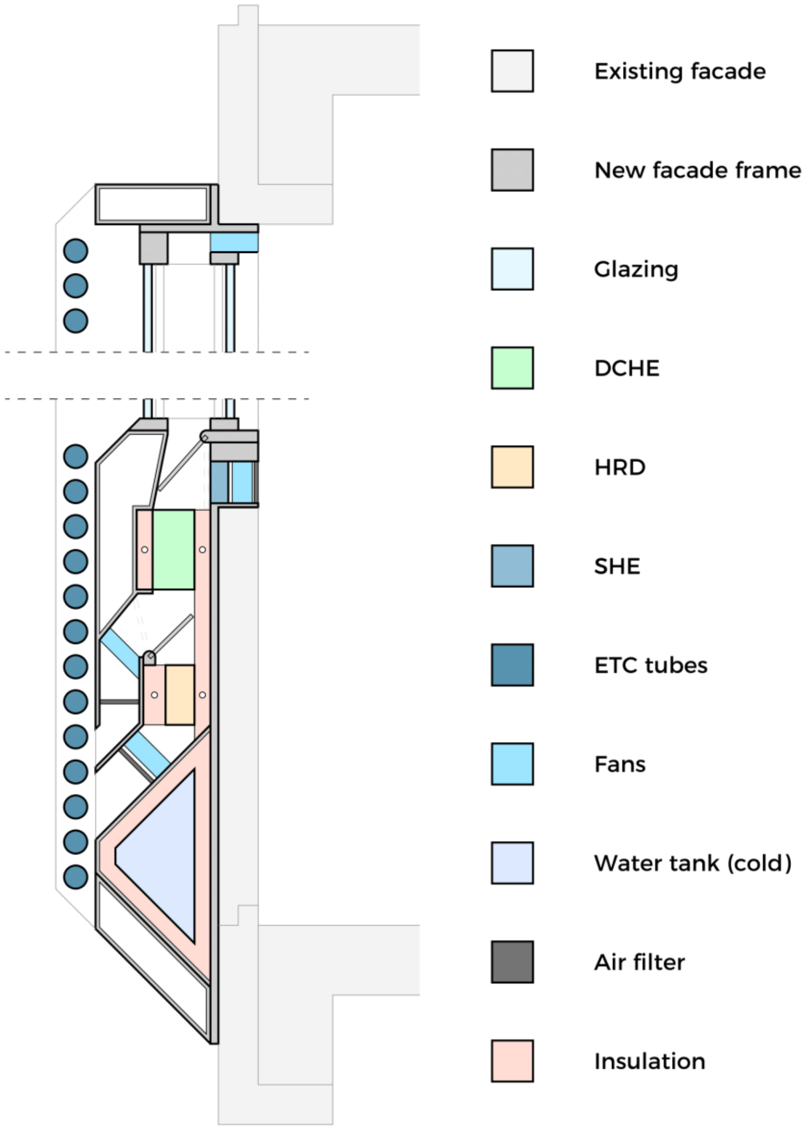
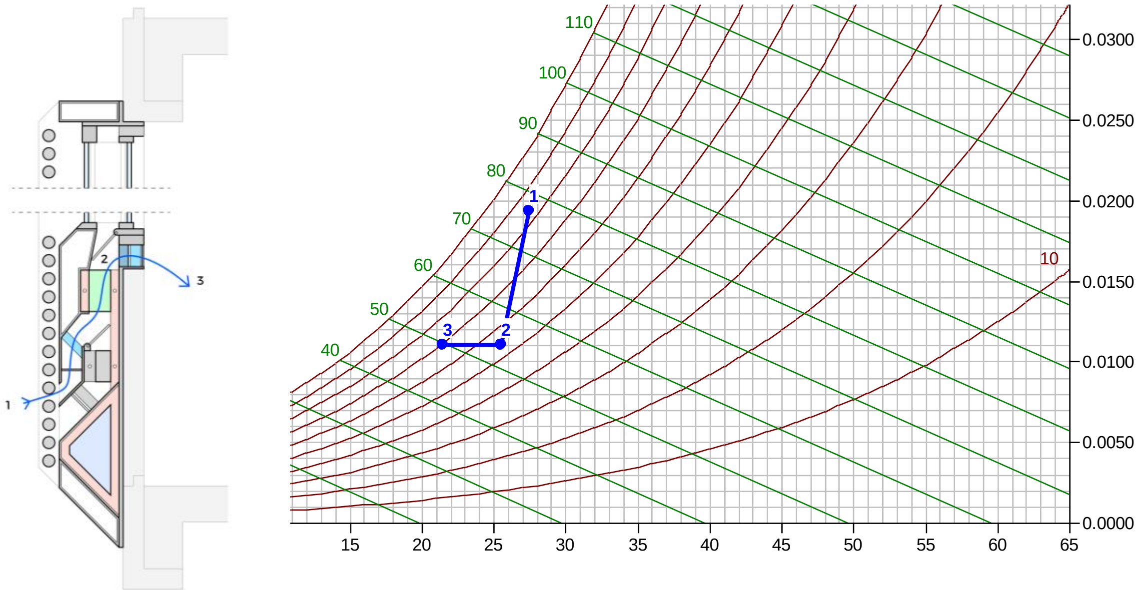


Figure 4.43: Sectional diagram of components within the facade.

This component layout is similar for the semi-centralised façade concept, with the exception of the position of the water tanks and the number of ETC tubes on the façade. This section briefly shows how the air and water flows through the façade system, along with the air temperatures involved. For the pre-regeneration and high temperature regeneration stages, the values of air temperatures are taken from the research experiment from Zhao et al.

Dehumidification

Water from the cold water tank is circulated through the DCHE and SHE heat exchangers to facilitate cooling and dehumidification.



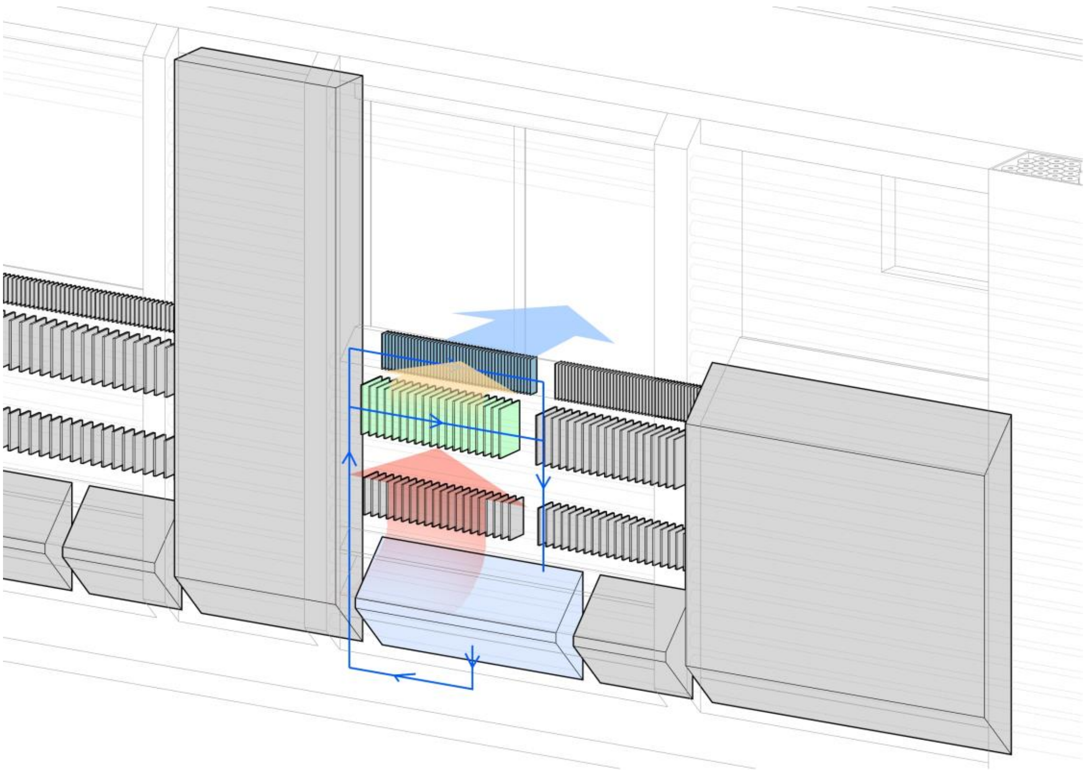


Figure 4.44: Psychrometric chart of dehumidification (Top Right) and air and water flow diagram (Bottom).

Pre-regeneration

Water is used from the warm water tank to regenerate the DCHE. From the experiment, the water temperature ranges between 47 to 53°C. (Zhao et al., 2016)

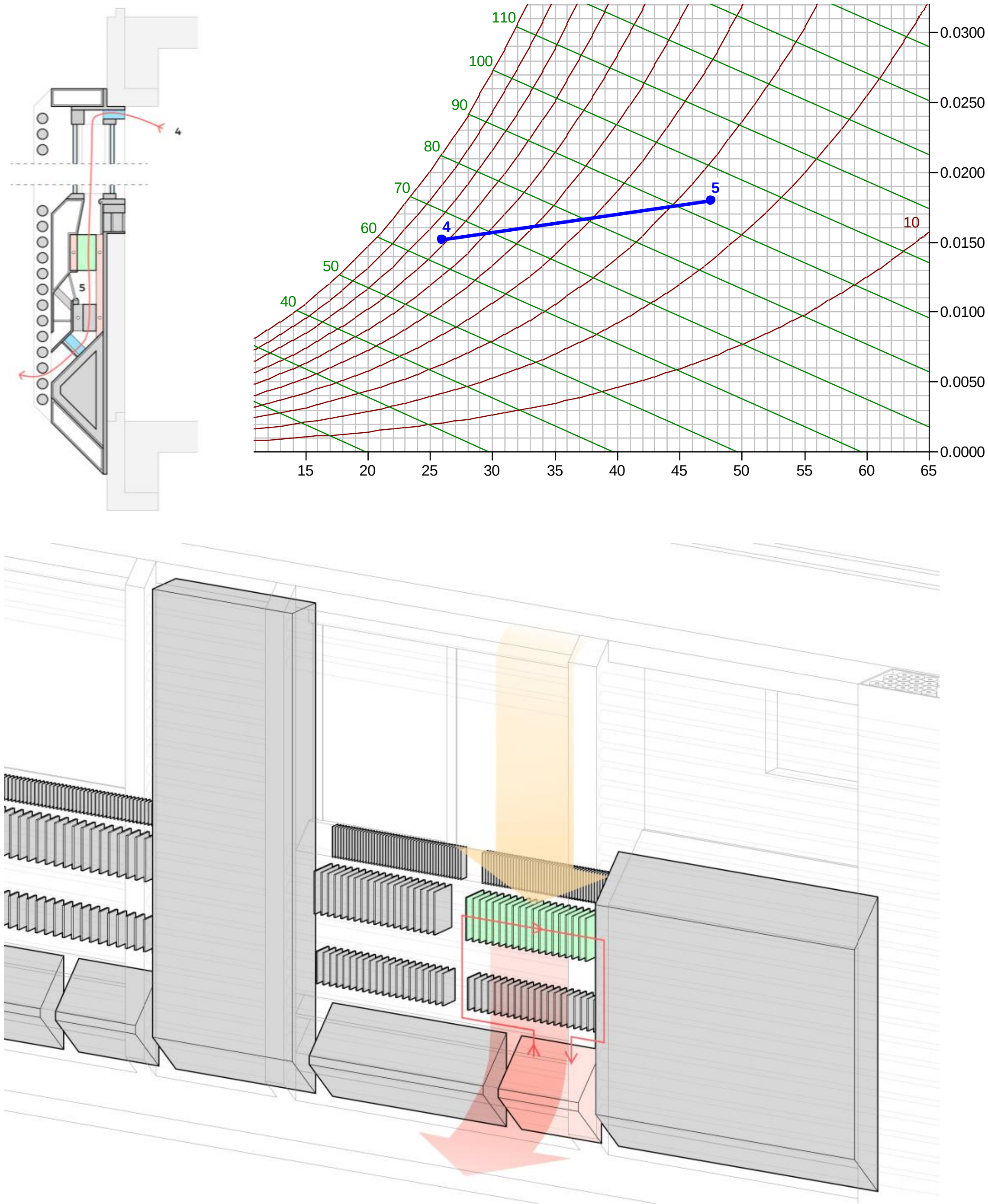


Figure 4.45: Psychrometric chart of pre-regeneration (Top Right) and air and water flow diagram (Bottom).

High-temperature Regeneration

The hot water tank is used for regeneration instead of the warm water tank. This facilitates better quality regeneration. The water temperature used in the experiment was roughly 73.1°C, which is lower than the target temperature for the project. The hot air after regeneration is sensibly cooled by passing it through the HRD heat exchanger with water from the warm water tank flowing through it to collect the heat and regain its temperature for the next pre-regeneration cycle.

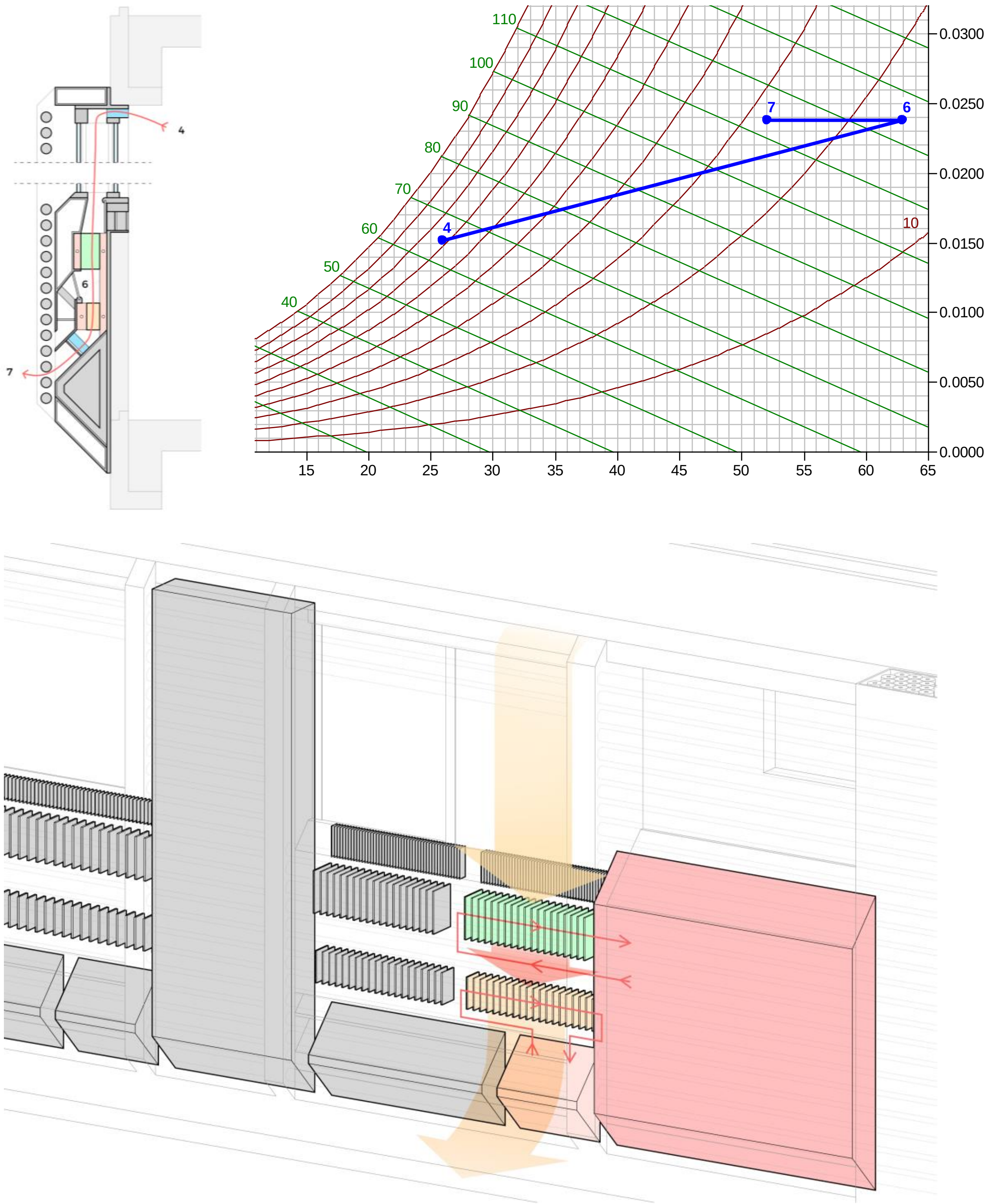


Figure 4.46: Psychrometric chart of high temperature (Top Right) and air and water flow diagram (Bottom).

4.6.3 Semi-centralised Façade Design

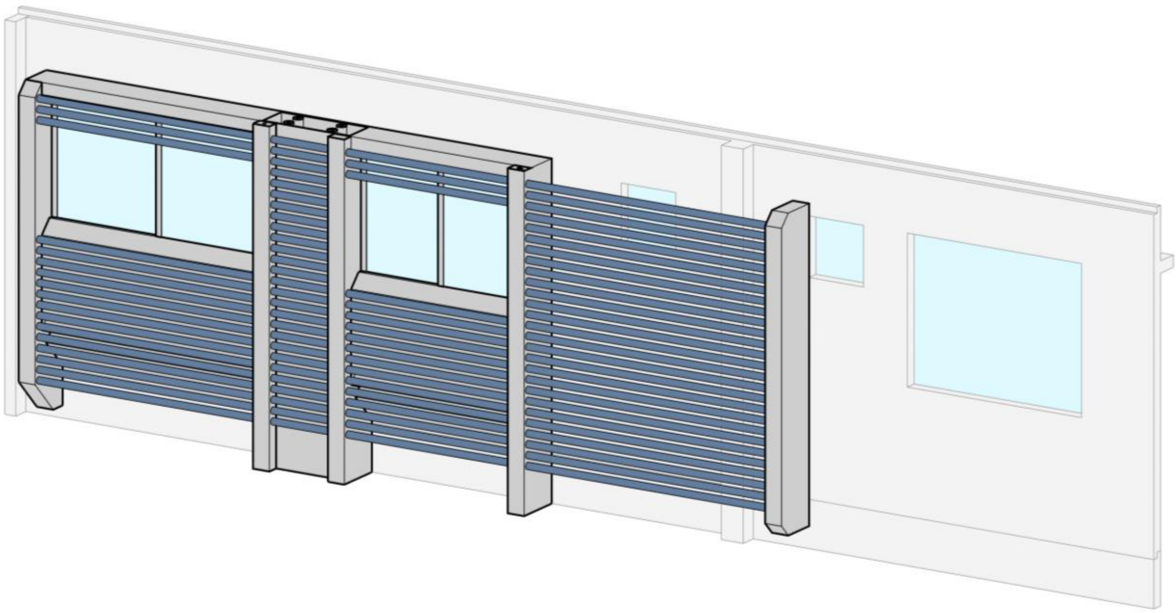


Figure 4.47: The facade module of the semi-centralised concept.

The Semi-centralised façade concept features a smaller façade because it does not contain the cold and hot water tanks on the façade itself. The main vertical duct area is located in between the 2 bedrooms. There is another vertical duct located between the master bedroom and the toilet, used only for solar heat collection in the daytime. The façade cooling system's night-time cooling operation is identical to that of the fully decentralised concept, mentioned in Section 4.6.1. However, water flow differs.

Daytime Water Flow

In the day, the solar water flows either up or down through the ETC tubes, past the rest of the façade. This water flow is separate from the cooling system itself.

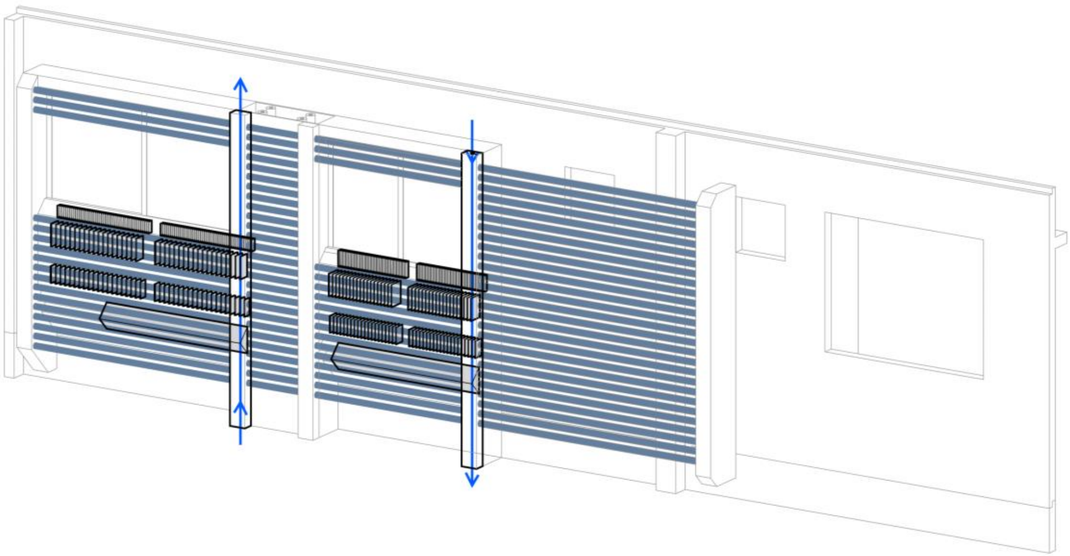
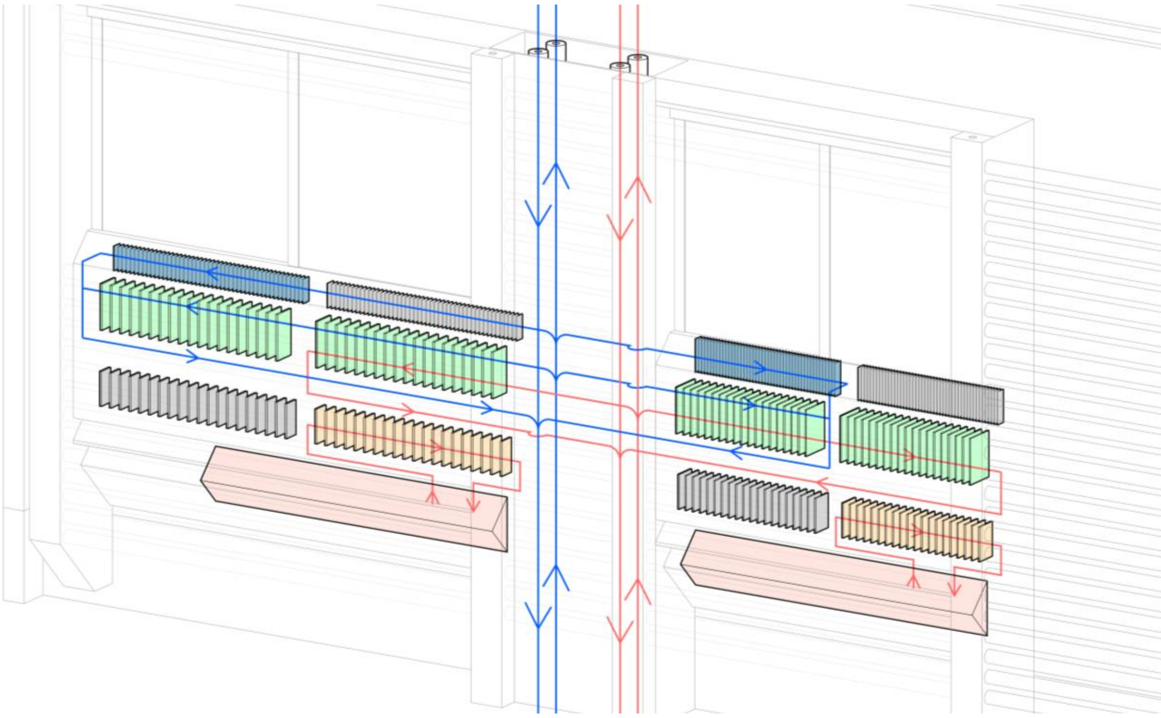


Figure 4.48: Diagram of water flow through the facade module during daytime solar heat collection.

Night-time Operation Water Flow

At night, the hot and cold water flows on the inside of the vertical duct and are distributed to each of the bedrooms' cooling components. Below are diagrams showing both bedrooms in dehumidification and high temperature regeneration, each switching between cycles. Note that the war water tank remains decentralised because of its small size and lightweight property. Energy is thus still needed to maintain a warm water temperature every cycle.



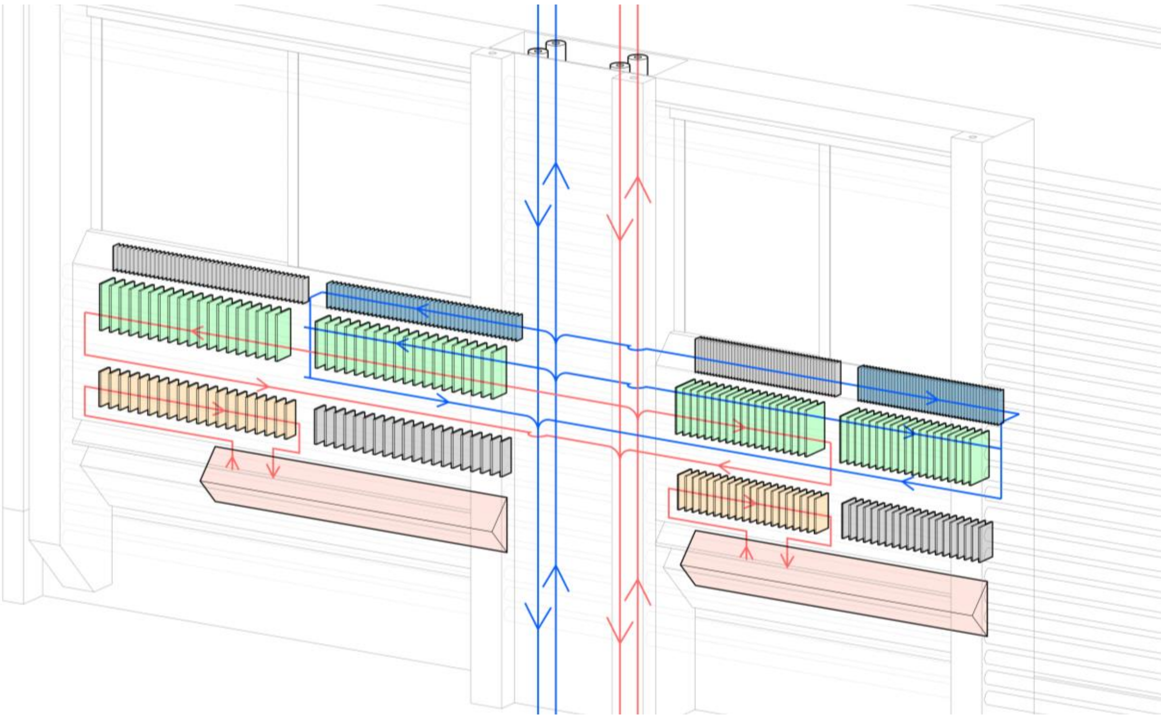


Figure 4.49: Diagrams of air and water flow in the facade module for both bedrooms, alternating between dehumidification and regeneration.

4.6.4 Evaluation and Comparison

While both concepts have the same main purpose of bedroom night cooling and can both achieve it, there are certain design aspects that result in a difference in cost-effectiveness between these 2 concepts. This section will discuss these differences to compare which concept is a more logical choice.

ETC subsystem

Because the fully decentralised system has more tubes on the façade, which is already simulated to receive less solar irradiance on average compared to the roof, it is no surprise that the fully centralised concept requires more ETC tubes. In this project, the roof-located tubes are assumed to be 1.8 m long as described in various commercial products.

	Fully decentralised	**Semi-centralised**
Number of tubes on facade	13310	9900
Number of tubes on roof	4812	5804
Total number of vacuum tubes	**18122**	**15704**
Percentage of solar energy collection secured by façade/roof-located ETC respectively	46.5 %	64.5 %
Percentage of roof area occupied by ETC	82.9%	100%

Table 4.16: ETC numbers between facade concepts.

Although the fully decentralised concept leaves some space on the roof untouched, the semi-centralised concept operates with 13.3% less number of tubes in total. This cost saving is further amplified when calculating the maintenance costs of the subsystem. The expected lifetime of ETC tubes are up to 20 years. When broken down, these tubes can easily be replaced with a new tube. If a tube is not working, the ETC system can still function, albeit at a lower efficiency. In maintenance estimations, assumptions about labour costs and various other aspects are made based on existing commercial products. The tables below state these estimations, along with the calculations for the overall maintenance costs of the ETC subsystem for each façade concept.

Maintenance estimations	
Expected tube lifetime (years) (Aguilar-Jimenez, 2016)	20
Labour cost (Euro/hour) (HomeAdvisor, 2019b)	62
Cost per replacement tube (Euro) (Silicon Solar, 2014)	39
Estimated time spent replacing tube on façade (min)	10
Estimated time spent replacing tube on roof (min)	6
Estimated maintenance cycles per year	2
Total maintenance cycles within tube lifetime	40
Estimated share of tubes to repair during every maintenance cycle (%)	2.5

Table 4.17: Maintenance estimation values used during calculations.

Façade concept ETC subsystem maintenance calculations		
	Fully decentralised	**Semi-centralised**
Number of tubes on façade to repair during maintenance	333	248
Time taken for façade maintenance (hours)	55.5	41.3
Labour cost for façade maintenance (Euro)	3438.42	2557.50
Number of tubes on roof to repair during maintenance	120	145
Time taken for roof maintenance (hours)	12	14.5
Labour cost for roof maintenance (Euro)	745.86	889.62
Total cost per maintenance cycle (Euro)	21853.23	18768.52
Total maintenance cost over lifetime (Euro)	**874129.07**	**750740.80**

Table 4.18: Maintenance costs of ETC system between facade concepts.

All in all, the semi-centralised concept has a 14.1% lower maintenance cost compared to the fully decentralised one.

Water Tanks

There are a few reasons why a centralised water tank system works better.

For the same volume of water, less material is used when there is a lower number of water tanks used to contain it. In addition, placing the water tank on the ground floor with ample space allowed for the optimisation of the tank geometry to be cylindrical, while the façade-located water tanks had to be rectilinear to fit within the geometric boundaries of the façade. This not only affects the material use, but also the heat loss from conduction. It is best to minimise the surface area to volume ratio in this respect, and cylindrical tanks work better for this function. Weight was also another issue that the façade-located tanks brought into the picture. Although no structural calculations were made at this point, more material would be needed to support this many water tanks 12 floors up. A ground-located water tank also easily facilitated maintenance, which brings its cost down even further.

	Fully decentralised	**Semi-centralised**
Hot water tank surface area (m^2)	4.465	58.72
Hot water tank surface to volume ratio	13.95	1.779
Cold water tank surface area (m^2)	1.05	25.73
Cold water tank surface to volume ratio	24.08	2.924
Total surface area of all water tanks (m^2)	**1213.23**	**143.17**

Table 4.19: Water tank surface area comparison between facade concepts.

The semi-centralised concept can be seen to cut back on water tank material costs by 88.2%. While it is clear that the semi-centralised concept triumphs in this respect, it is interesting to know the heat loss from the centralised water tanks as well. This is calculated on one of the 2 hot water tanks.

Hot water tank characteristics	
Water volume (Litres)	33000
4 cm mineral wool insulation heat transfer coefficient (W/m^2K)	0.8
Heat loss from water tank conduction (W)	2466.24
Daytime heat loss	
Energy lost during daytime (kWh)	29.59
Additional façade-located absorber area required (m^2)	28.46
Additional façade-located absorber area required per apartment unit (m^2)	0.259
Night-time operation heat loss	
Heat loss through water tank conduction (kWh)	17.26
Total heat loss from cooling system operation and water tank conduction (kWh)	1139
Hot water temperature after night-time operation (°C)	50.34

Table 4.20: Heat loss due to water tanks.

In Section 4.5.4, the hot water temperature after night-time operation was calculated to be 50.79°C, this shows that after factoring in heat loss through conduction, this temperature only dropped by about 0.35°C, rendering it still usable for regeneration. No additional water tank volume was thus necessary to offset the conduction heat loss. However, the contrary is true when it came to calculating the heat loss in the day. More solar heat was necessary to combat the heat loss, resulting in an additional 0.259 solar absorber area on the façade. This will be considered in Chapter 4.7.

Water Piping

Both concepts featured vertical ducts for water piping. However, because the fully decentralised concept keeps the water flow individualistic, there is no sharing of water pipes. This increases the material use.

In the fully decentralised concept, each apartment introduced 4 additional water pipes (2 per bedroom) into the vertical duct. This means that the façade module serving 12th floor would have a total of 44 water pipes within its vertical duct.

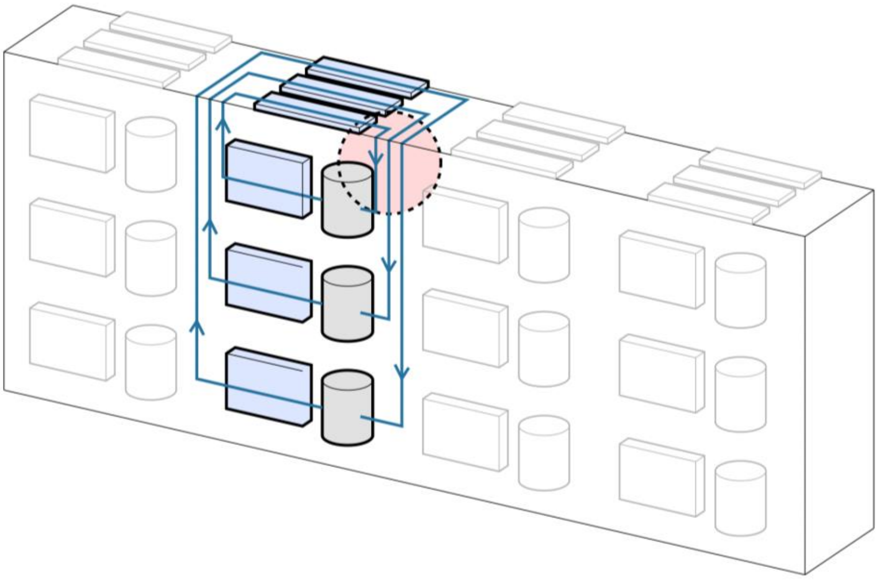


Figure 4.50: Diagram highlighting the point of focus where the facade module will have the most number of water piping.

On the other hand, the semi-centralised concept features only 6 water pipes; 2 for solar heat collection and 4 for hot and cold water distribution (2 per water type in each direction). This severely reduces the material use for water piping for the semi-centralised concept.

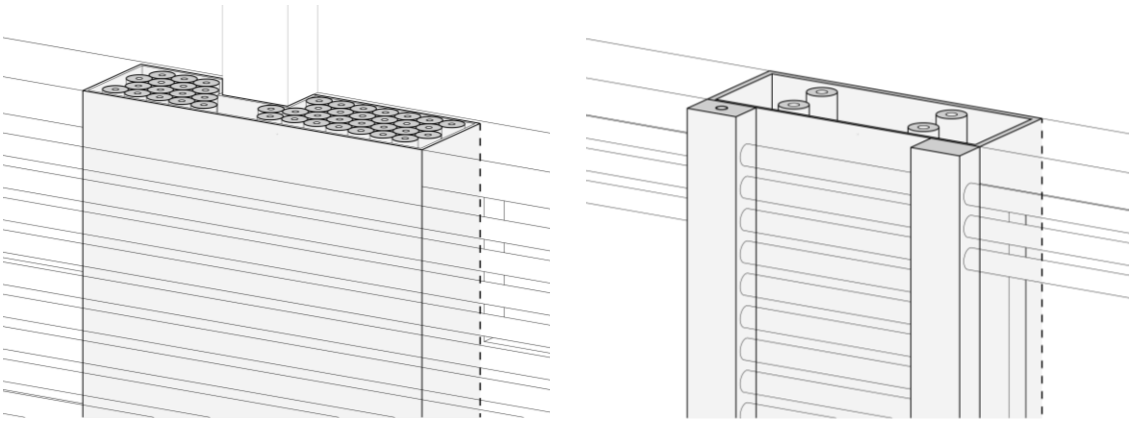


Figure 4.51: Close up of the vertical ducting of the fully decentralised (Left) and semi-centralised (Right) facade module.

This is on top of the fact that the semi-centralised concept requires water pipes of a larger diameter.

Water piping characteristics	
Copper pipe thickness (mm)	1.5875
Required copper pipe nominal bore for fully decentralised concept (mm)	15
Heat loss for 15mm pipe without insulation at ΔT 55°C (W/m)	45
Heat loss for 15mm pipe with 25mm insulation at ΔT 55°C (W/m)	~ 6
Required copper pipe nominal bore for semi-centralised concept (mm)	28
Heat loss for 28mm pipe without insulation at ΔT 55°C (W/m)	76
Heat loss for 28mm pipe with 25mm insulation at ΔT 55°C (W/m)	10
Density of copper (kg/m^3)	8690

Table 4.21: Water piping constants used for calculations.

The above values are taken from general material properties and guidelines of copper piping from (Rodriguez, 2019) and (Engineering Toolbox, 2003).

	Fully decentralised	Semi-centralised
Cross-sectional area of pipe (mm^2)	82.73	147.56
Total length of vertical piping (m)	7392	1311.2
Total volume of piping (m^3)	0.611	0.193
Total weight of piping (kg)	**5314.06**	**1681.36**

Table 4.22: Water piping material usage comparison between facade concepts.

Based on these calculations, the semi-centralised concept saves water piping material by 68.4%. However, as mentioned earlier, during the night-time operation the semi-centralised concept requires the water to travel upwards to the apartment, from the centralised water tank. This results in some heat loss that must be factored in to calculate any additional required ETCs. This is a problem which the fully decentralised concept does not face.

Daytime heat loss	
Total hot water vertical travel length (m)	623.2
Total heat loss with 25 mm insulation (W)	6232
Energy lost during daytime (kWh)	74.78
Additional façade-located absorber area required (m^2)	71.9
Additional façade-located absorber area required per apartment unit (m^2)	0.654
Night-time operation heat loss	
Heat loss experienced at highest residential level (W)	316
Temperature drop while travelling from hot water tank to top residential floor, at 0.4kg/s water mass flow rate (°C)	0.189

Table 4.23: Heat loss due to water piping.

In the day, the total heat loss results in a necessary addition of another small amount of solar absorber area on the façade. At night, the heat loss results in a temperature drop of 0.189°C while the hot water travels from the centralised water tank to the highest (and therefore furthest) apartment unit. However, this temperature drop is not significant enough to reduce the water temperature to render it useless for regeneration. Therefore, no action or remedy needs to be taken for it.

4.6.5 Conclusion

The Semi-centralised concept is no doubt the more logical concept for this façade-integrated cooling system. The table below summarises the cost savings incurred by opting for the semi-centralised concept over the fully decentralised concept, for equipment, materials as well as the necessary tweaks to the semi-centralised concept for heat loss compensation.

Cost Savings	
Reduction in number of ETC tubes	13.34 %
Reduction in ETC maintenance cost	14.12 %
Reduction in material usage for water tanks	88.2 %
Reduction in material usage for water piping	68.3 %
Necessary tweaks	
Required additional solar absorber area per façade module due to water tank heat loss	0.259 m^2
Required additional solar absorber area per façade module due to water piping heat loss	0.654 m^2
Total required additional solar absorber area per façade module	0.9124 m^2
Final hot water temperature by end of night (°C)	50.15

Table 4.24: Summary table of cost savings of semi-centralised facade concept and heat loss compensation tweaks needed.

The necessary tweaks will be incorporated in the next chapter, where the façade details are also discussed.

4.7 Design Development

In this chapter, the semi-centralised façade concept will be developed even further in terms of heat loss accountability, façade detailing, and energy calculations.

4.7.1 Heat Loss Compensation

The initial required façade-located solar absorber area was 6.96 m^2 per apartment unit. When accounting for heat loss through conduction in water pipes and the water tanks, the required area goes up to 7.85 m^2.

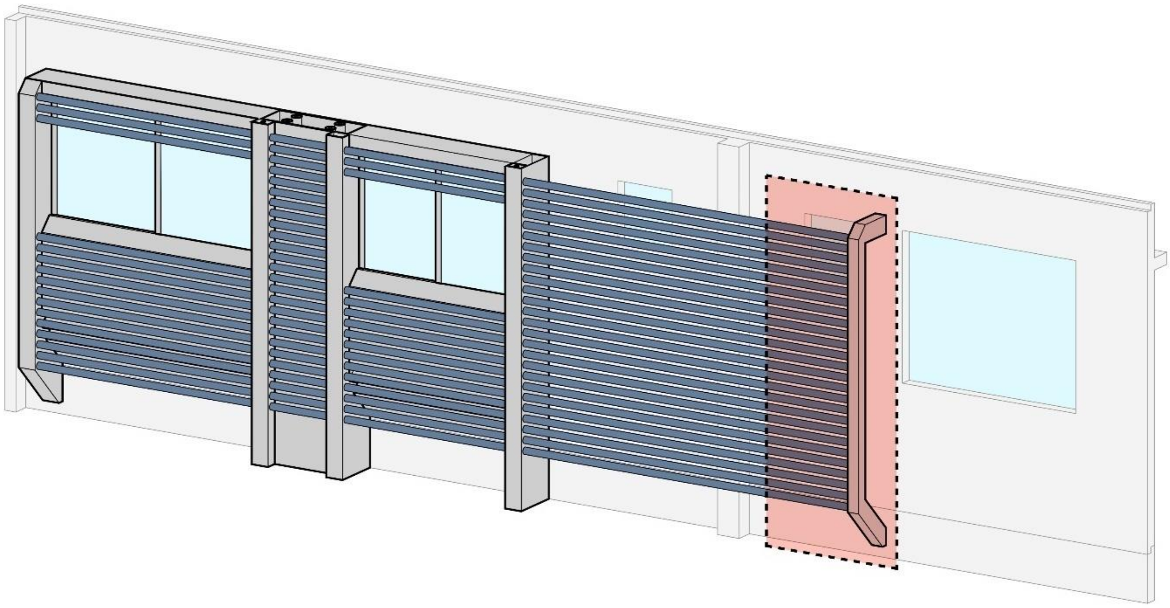


Figure 4.52: Highlight of the extension of the ETC tubes to compensate for heat loss.

This results in the ETC tubes spanning over both toilet windows, almost reaching the kitchen window. The solar absorber area on this façade module is now 7.91 m^2; which is sufficient for heat loss compensation.

4.7.2 Excess Solar Energy Collection

Currently, there are 5804 roof-located tubes and 9900 façade-located ones, making up a total of 15704 tubes and 1382 m^2 worth of solar absorber area. However, the calculation used to acquire the required minimum solar absorber area on the façade and roof are done using the worst solar irradiation for each location. The issue is, the worst-case scenario for the roof does not happen together with the worst-case scenario for the façade. One happens in June, while the other happens in December.

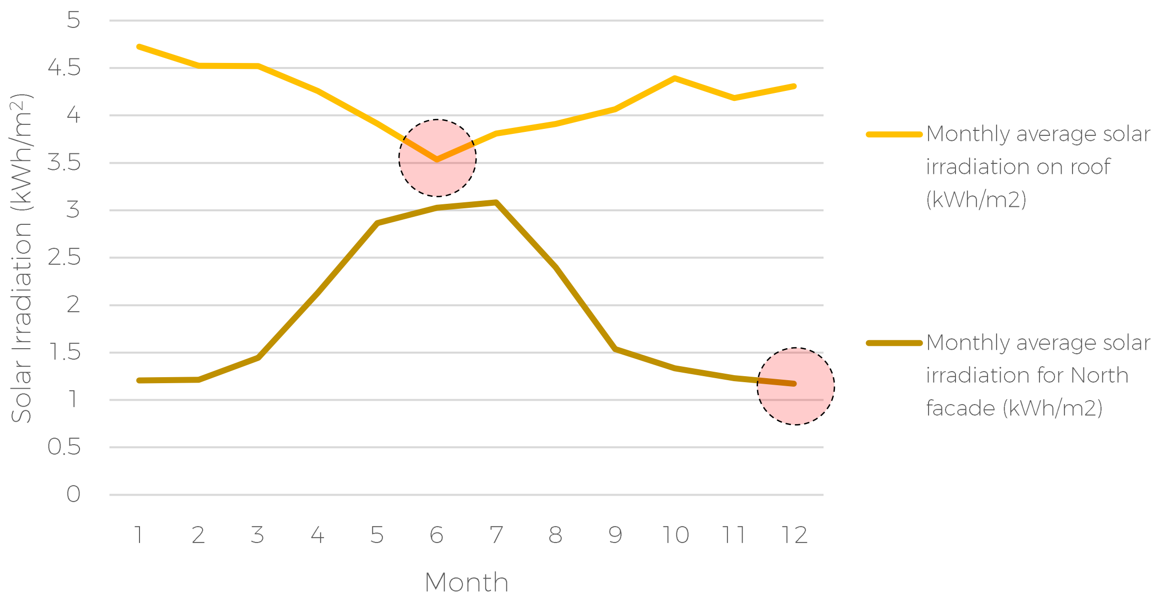


Figure 4.53: Graph showing mismatch between worse-case scenarios of solar irradiation on the roof and façade.

Instead of this approach, the total monthly average daily solar collection was calculated for the entire ETC subsystem. The required daily solar energy is 2292.8 kWh to serve the 220 bedrooms. After accounting for an 80% system efficiency of the ETCs, all months experienced a surplus of at least 200kWh, with the worst-case scenario being November, with a surplus of 276.4 kWh.

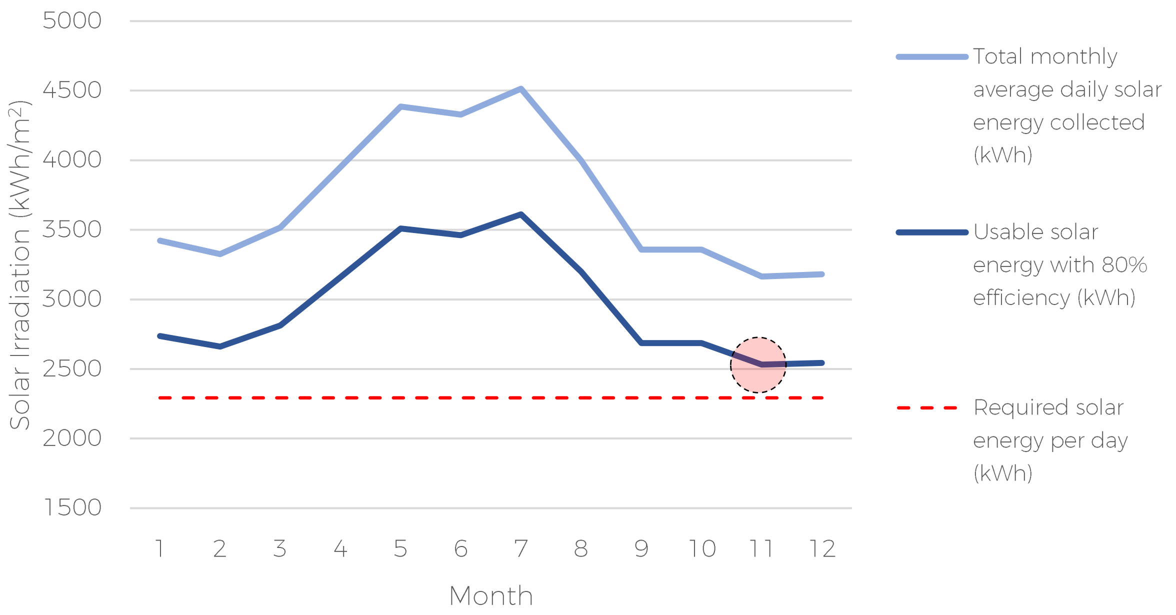


Figure 4.54: Graph showing overall worst-case scenario accounting for total solar energy collected by entire ETC system (roof and façade).

With this surplus, roughly 9.429% of the ETC tubes can afford to be out of service and the hot water tank will still perform adequately in the worst month (November). This translates to 1439 tubes out of order.

Solar Energy Supply and Demand	
Required solar energy per day (kWh)	2292.8
Usable solar energy acquired from ETC subsystem per day, with 80% efficiency, in worst-case month of November (kWh)	2569.2
Daily minimum surplus of solar heat energy (kWh)	276.4
Percentage of ETC tubes in excess (%)	10.76
Estimated number of ETC tubes in excess	**1689**
Maintenance	
Number of maintenance cycles per year	2
Number of façade-located ETC tubes to replace during each cycle	248
Number of roof-located ETC tubes to replace during each cycle	145
Total number of ETC tubes to replace during each cycle	**393**

Table 4.25: Excess ETC tubes to account for breaking down.

With an average total of 393 tubes replaced per maintenance cycle (2 cycles per year), having more than 1689 tubes broken down at any point in time is highly unlikely. This makes the ETC subsystem sufficiently operable for the entire year, and more.

5 Design Finalisation

The conceptual design has been set and the main calculations for its workability and its proof of concept have been discussed in the previous chapter. Details of the façade module, in terms of its structural elements, assembly, operation and maintenance, will be described and elaborated on in this chapter, followed by an evaluation of its usage, its implications on society, and its limitations.

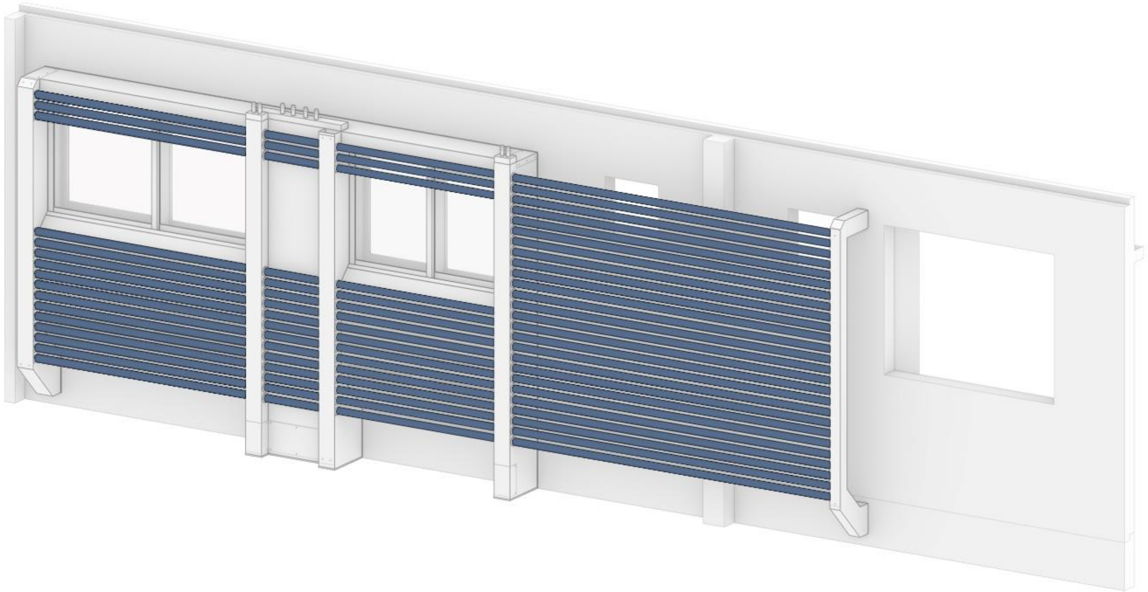


Figure 5.1: Finalised facade module.

Figure 5.2: A visualisation of the finalised facade module on the existing building.

The final design of the façade module has a subjectively sleek look, with its ETC tubes spanning horizontally across the existing façade. Vertical aluminium elements express the connectivity between the neighbouring modules above and below. The kitchen window is left untouched because it is often used for the hanging of laundry.

5.1 Structural Elements

The façade module is meant to be prefabricated before it is brought to the site. The prefabricated module consists of majority of the parts, with exceptions to certain aluminium coverings meant to be assembled on site, or for maintenance.

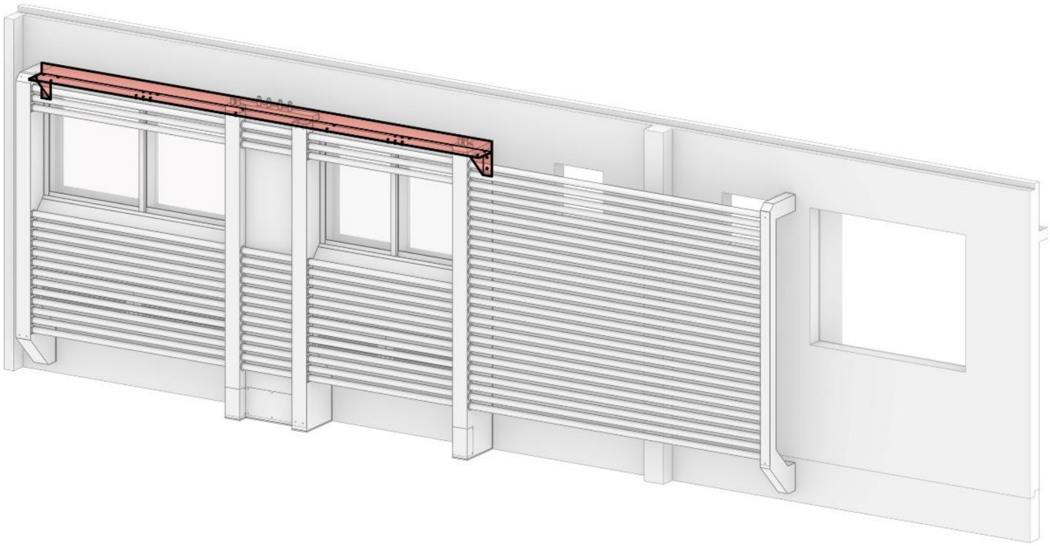


Figure 5.3: Highlight of the location of the main structural element in the facade module.

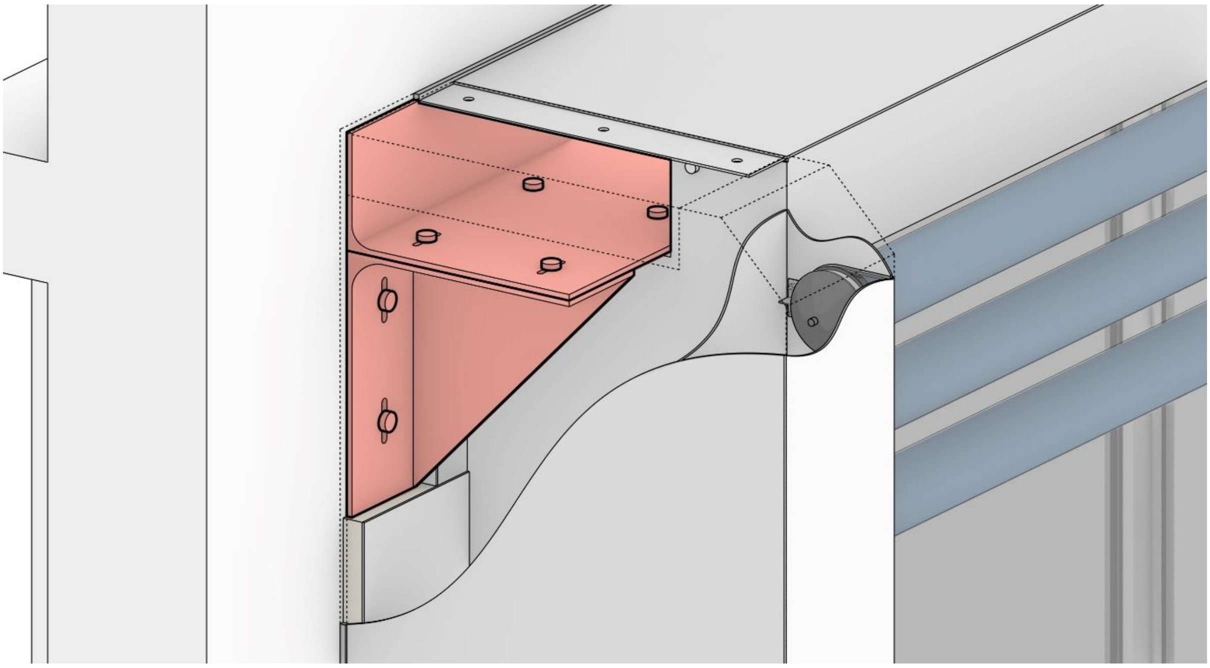
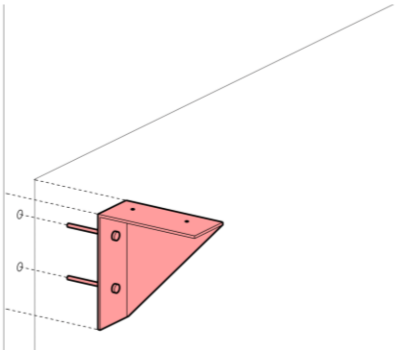
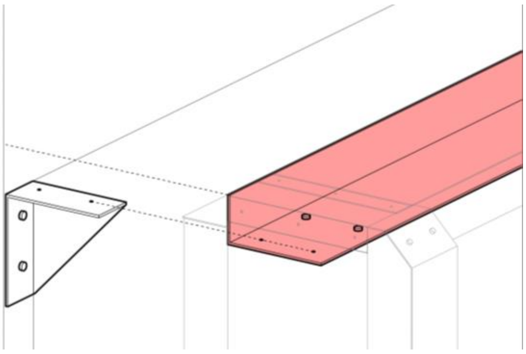


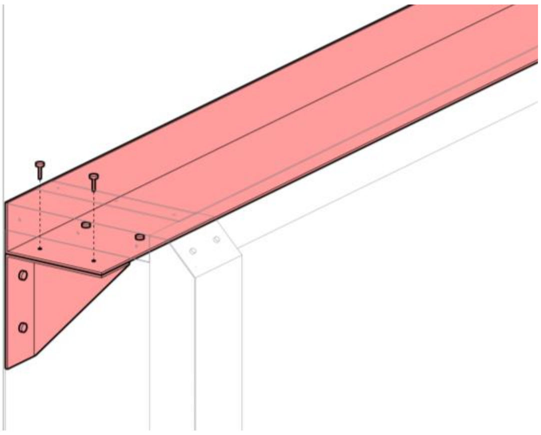
Figure 5.4: Image revealing structural elements at the corners of the facade module, consisting of an L-beam within the prefabricated module, resting on a steel mounting bracket.



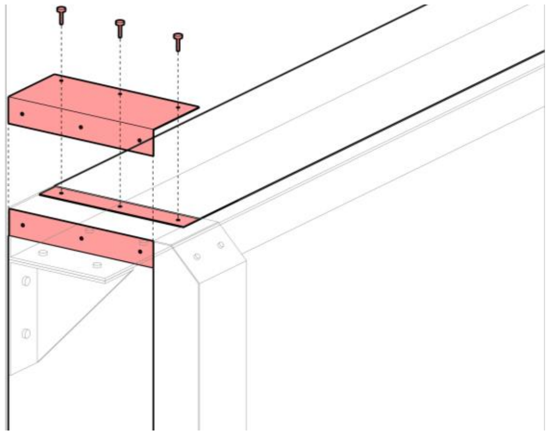
Step 1: Steel bracket in existing façade.



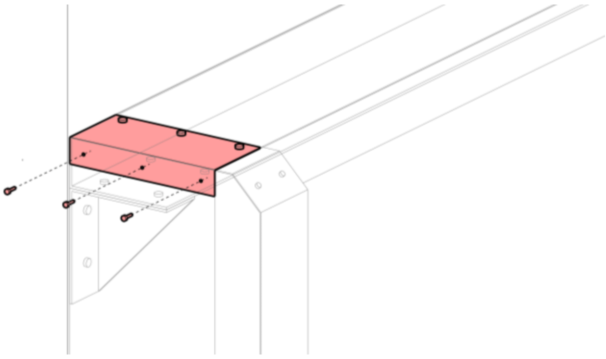
Step 2: Placing facade module on steel facade bracket.



Step 3: Bolting steel elements together.



Step 4: Aluminium element for protection.



Step 5: Securing aluminium element and sealing it.

Figure 5.5: Assembly steps to join the facade module to the existing facade.

Before the façade module is assembled onto the existing façade, a steel bracket is screwed into it (Step 1). The façade module consists of a steel L-beam located inside its top portion, upon which the rest of the module is hung from. This L-beam rests on a steel façade bracket (Step 2). These steel elements are bolted together (Step 3), with leeway for movements and thermal expansion. An aluminium corner element is attached and sealed to cover the connection for rain protection (Steps 4 and 5). The connection between the steel and aluminium elements are supplemented with sealant to avoid galvanic corrosion.

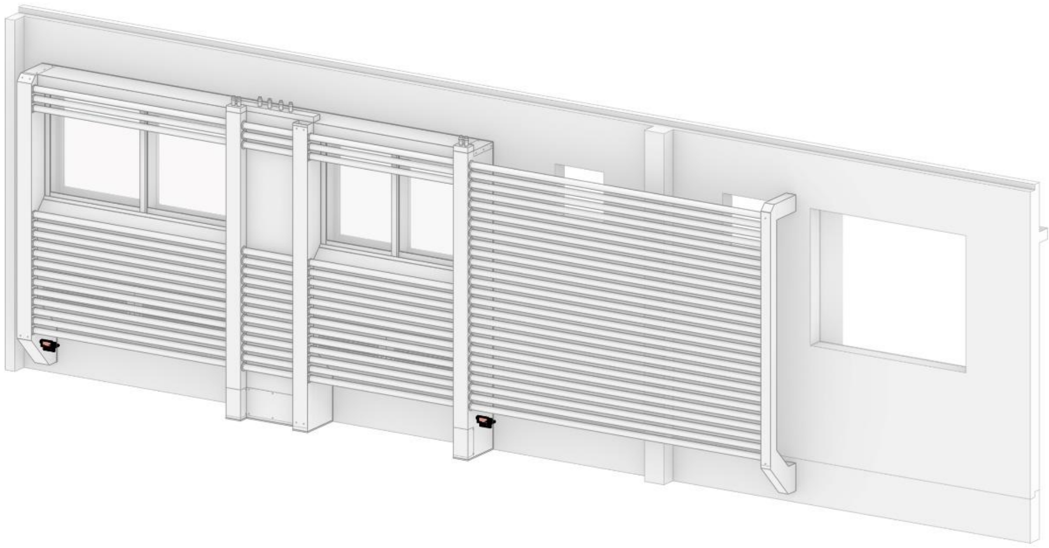


Figure 5.6: Highlight of the location of the bottom steel hook element.

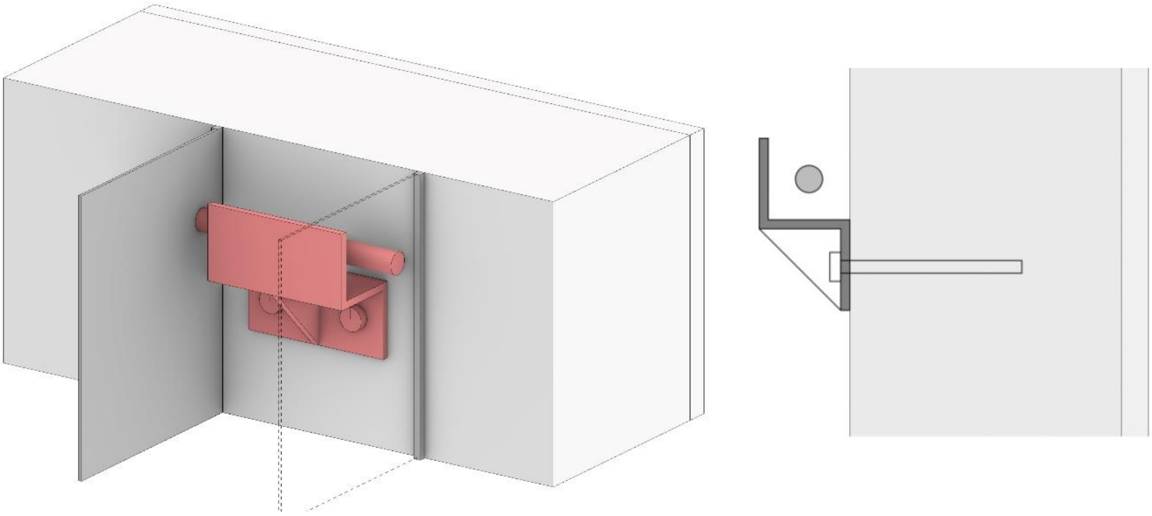


Figure 5.7: Zoom in image of the steel element (Left), with sectional diagram (Right).

At the lower part of the façade module, small steel L-brackets have also been attached to the existing façade prior to assembly. The façade module has a steel tube meant to be 'inserted' within the L-bracket. This is not a load-bearing component, but merely serves to ensure that the façade module is not able to be lifted too much off the surface of the existing façade.

5.2 Operation and Detailing of Movable Parts

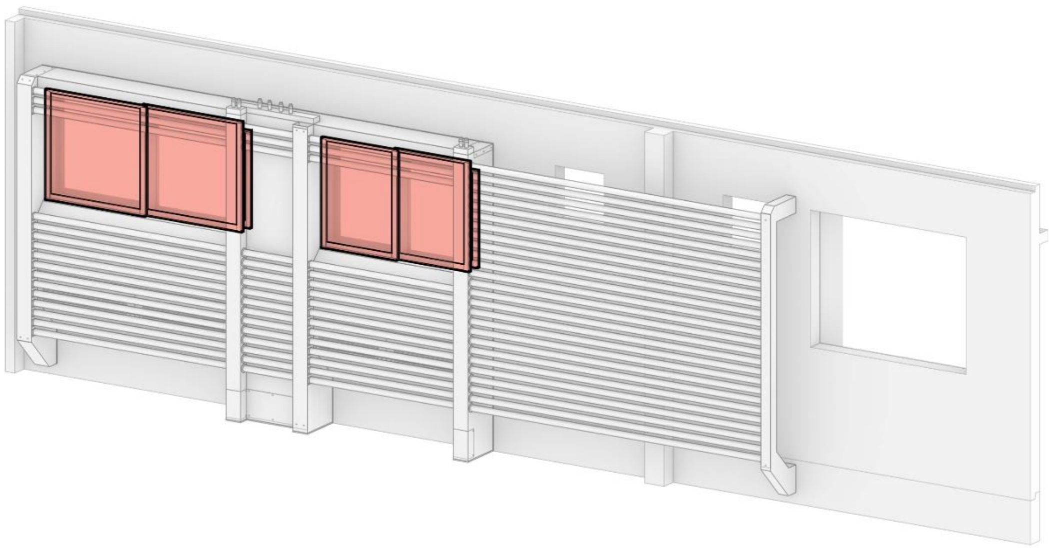


Figure 5.8: Highlight of the sliding window component in the facade module.

One of the requirements for the façade design is to have operable windows. This is for natural ventilation should the occupant prefer it. In this façade design, it is not possible for the cooling system to be in effective operation if the windows are open. This is not a problem because the users are not supposed to leave the windows open while the cooling system is switched on anyway. This rule applies even for current traditional air-conditioners. Either the windows are opened, or the cooling system is switched on, but not both at the same time. Doing so will greatly reduce the regenerative ability and the system will not be effective for the next dehumidification/regeneration cycle.

Each façade module consists of 4 glazing panels, each individually operable. A stationary aluminium extrusion acts as a centre divider between the 2 halves to separate the air flow. EPDM is used as a seal to ensure airtightness of the window frames.

In a tropical climate like Singapore, windows are usually either single or double glazed. A single glazed window allows for heat to escape from the interior, while a double glazed one offers extra insulation but are naturally more expensive. Single glazed windows are used in this project because at such a large scale, cost plays a huge role in feasibility. The necessity of an extra layer of glazing is also debatable since the building's thermal massing causes interior heat radiation in the night, which is preferably removed from the bedroom as quickly as possible.

Thermal breaking of the window frame is also another point of discussion when it comes to tropical glazing. It provides insulation along the aluminium window frames, so heat conduction is greatly reduced. This is extremely effective in temperate and arid climates where the difference between interior and exterior temperatures can vary greatly. However, Singapore's air temperature varies from 25 to 32°C all year round, which is relatively close to the recommended indoor temperatures of 23 to 27°C, as stated in Section 2.1.3. As such, while a thermal break would indeed provide better insulation nonetheless, its financial worth is questionable when its upfront cost is weighed with the energy cost savings it incurs. Thermal breaking is therefore forgone for this project.

With regards to window cleaning, a window cleaner on the outside is required to clean the outer sides of the outer 2 window panels as they are inaccessible from the bedroom side. This is not a big problem because the air quality in Singapore is considerably clean. A window cleaning schedule aligning with the ETC maintenance schedule of twice a year is sufficient.

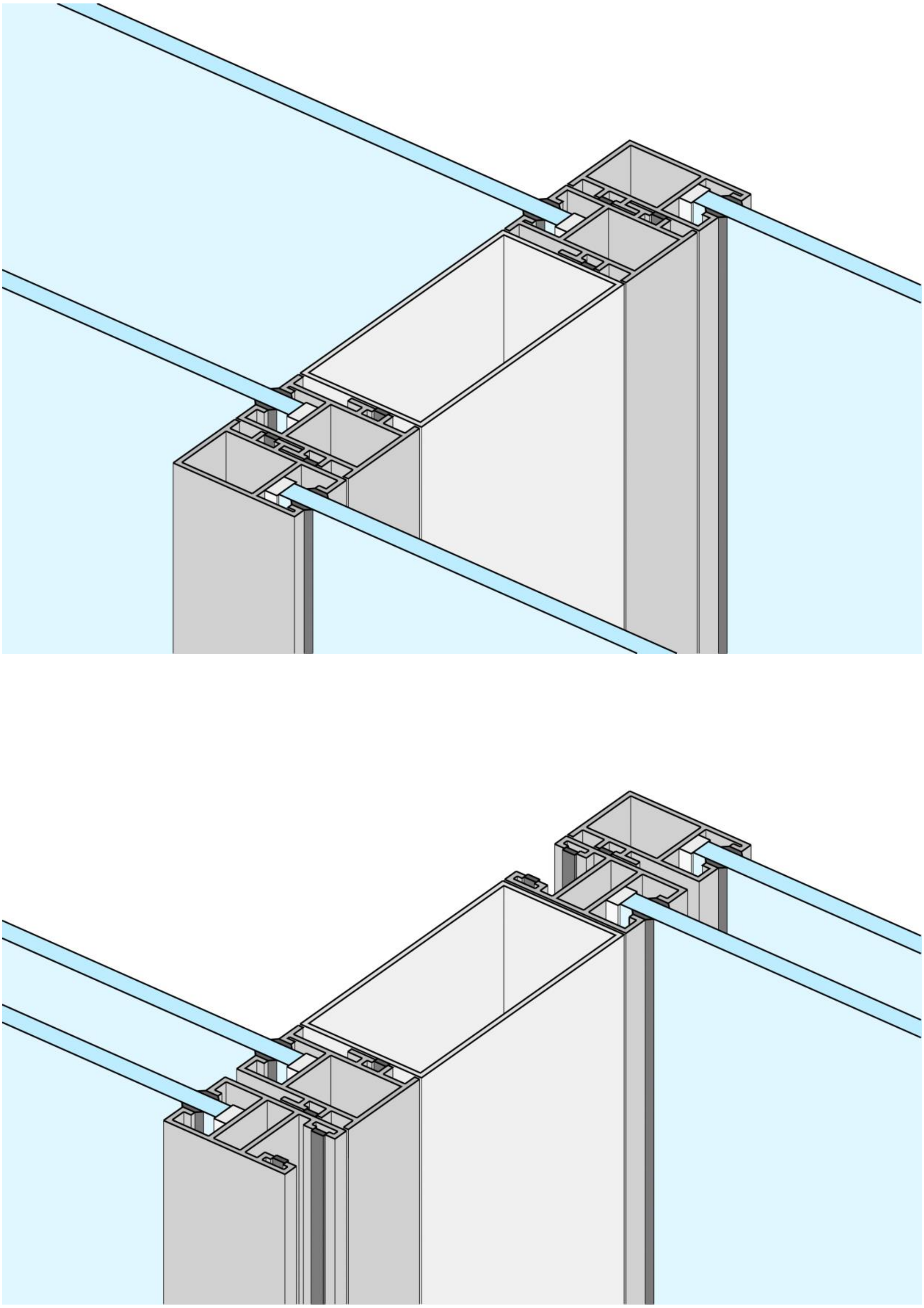


Figure 5.9: Axonometric sectional diagrams of the middle divider during the operation of the sliding windows when closed (Top) and open in both directions (Bottom).

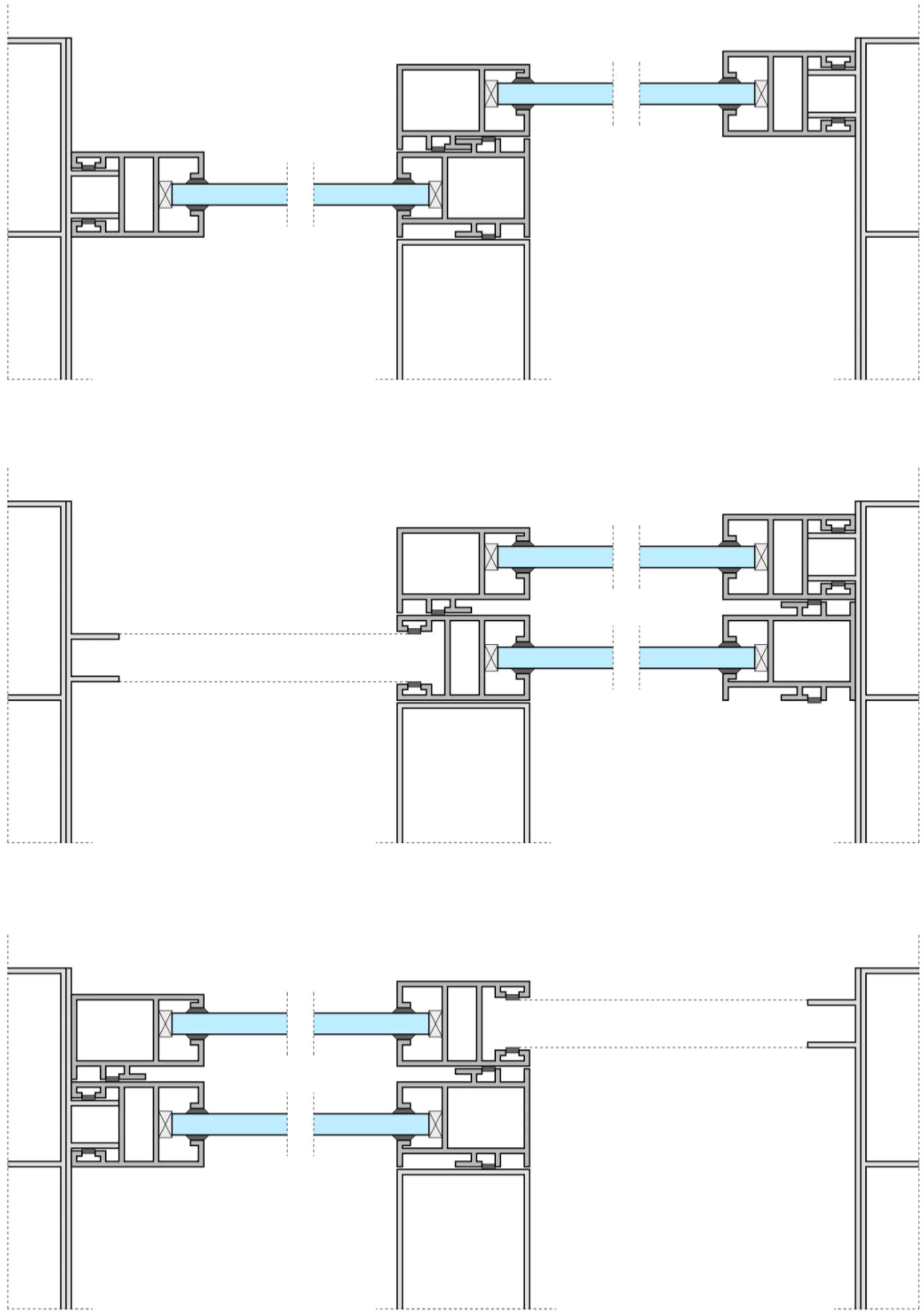


Figure 5.10: Horizontal section of windows during operation. Closed (Top), open on left (Middle) and open in right (Bottom).

Below the sliding windows lie most of the façade module. Flaps are used to direct air flow between dehumidification and regeneration. A good amount of EPDM is used at the tips of the flaps to create airtight air channels. It operates on battery power.

1:	Aluminium Facade Frame	11:	Rainwater Drainage Gap
2:	Sealant	12:	DCHE
3:	Structural L-Beam	13:	Rockwool Insulation
4:	Galvanic Corrosion Sealant	14:	Copper Piping
5:	Evacuated Tube	15:	SHE
6:	Sliding Window	16:	Existing Plaster
7:	Fan	17:	Existing Concrete Facade
8:	Air Grill	18:	Air Filter
9:	Flap	19:	HRD Heat Exchanger
10:	EPDM	20:	Warm Water Tank

Table 5.1: Facade module component list.

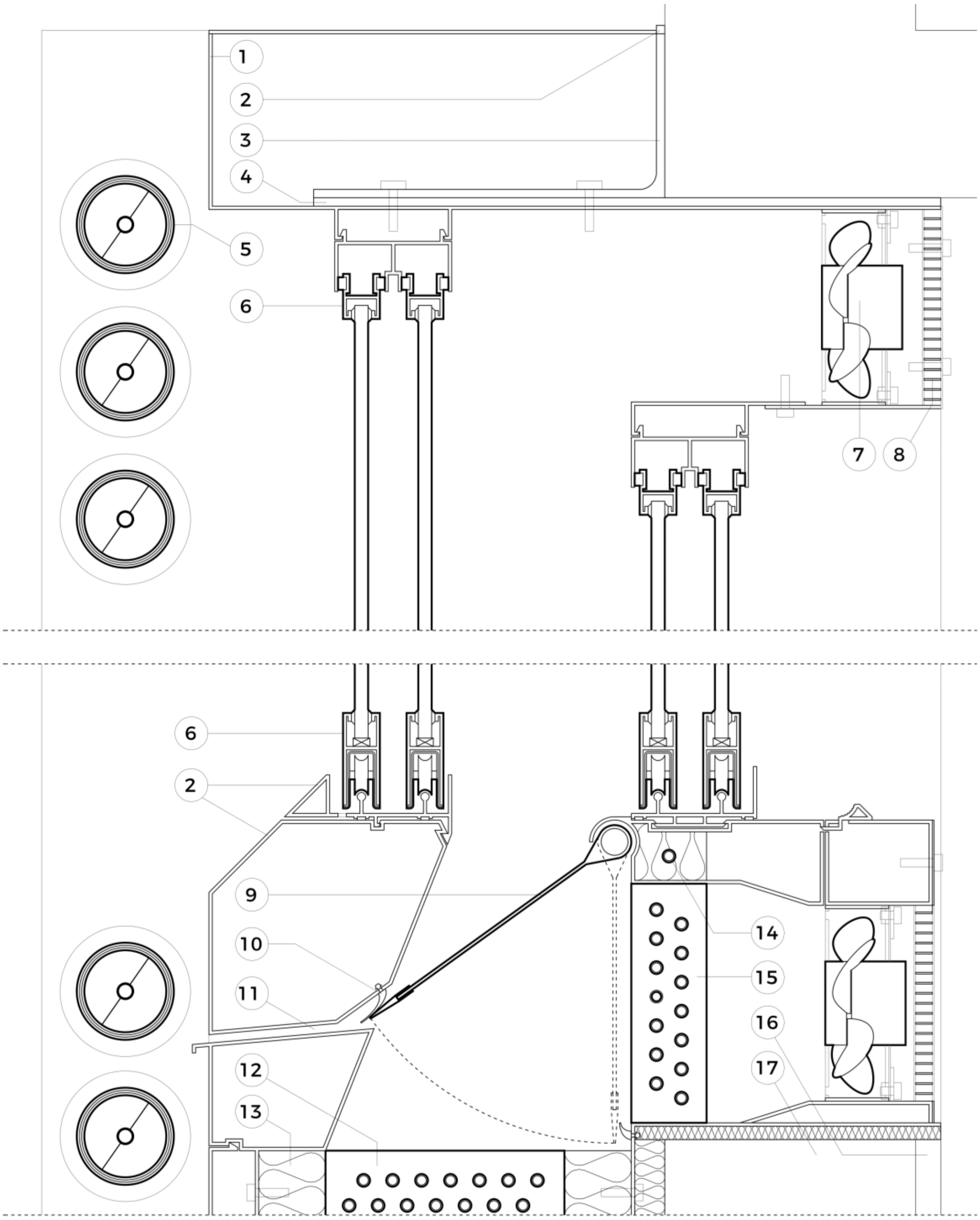


Figure 5.11.1: Detailed section with components.

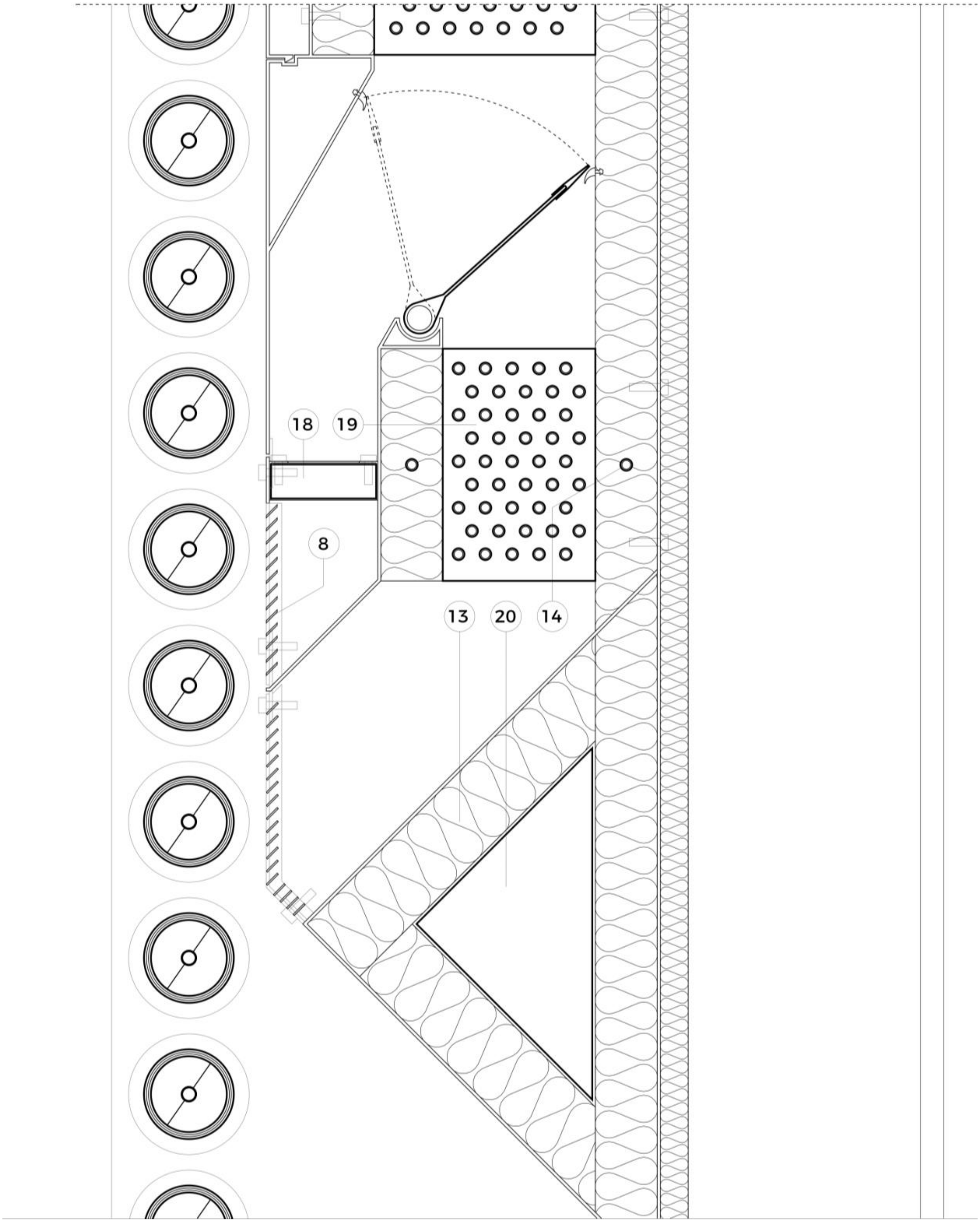


Figure 5.11.2: Detailed section with components.

Table 5.1 is a list of important components in the façade module, shown in Figures 5.11.1 and 5.11.2. It is worth noting that in the event that the system is not in use and the windows are open, rain can infiltrate into the window cavity. The flaps are in the angled position. The EPDM at the drainage gap is not continuous, so the rainwater can flow past it and into the drainage gap and out of the façade module, keeping the heat exchangers dry.

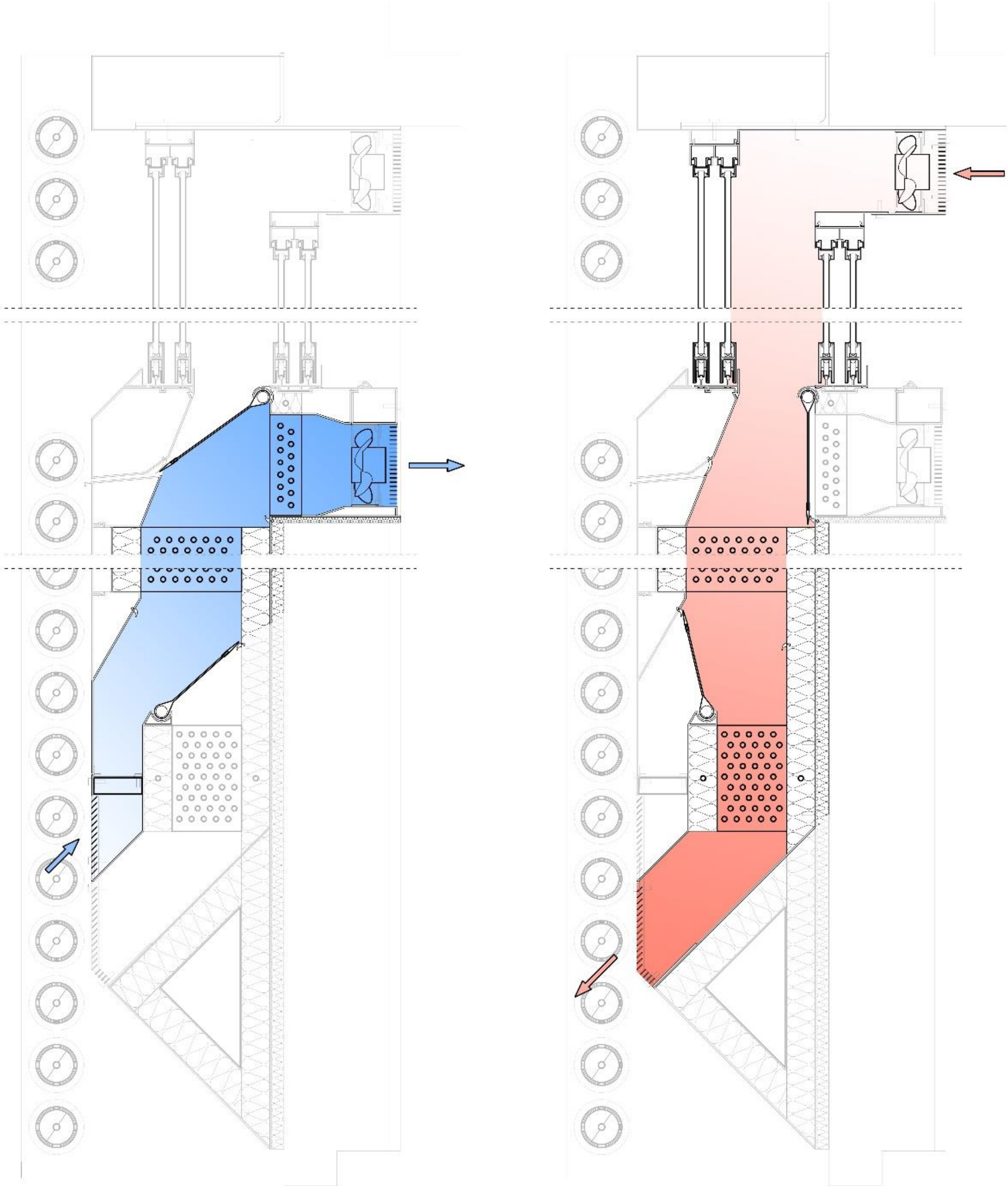


Figure 5.12: Detailed operational section of dehumidification (Left) and regeneration (Right).

The picture above shows in detail the operation of the façade cooling system, between dehumidification (Left) and regeneration (Right). During both processes, hot and cold water is pumped through the relevant heat exchangers.

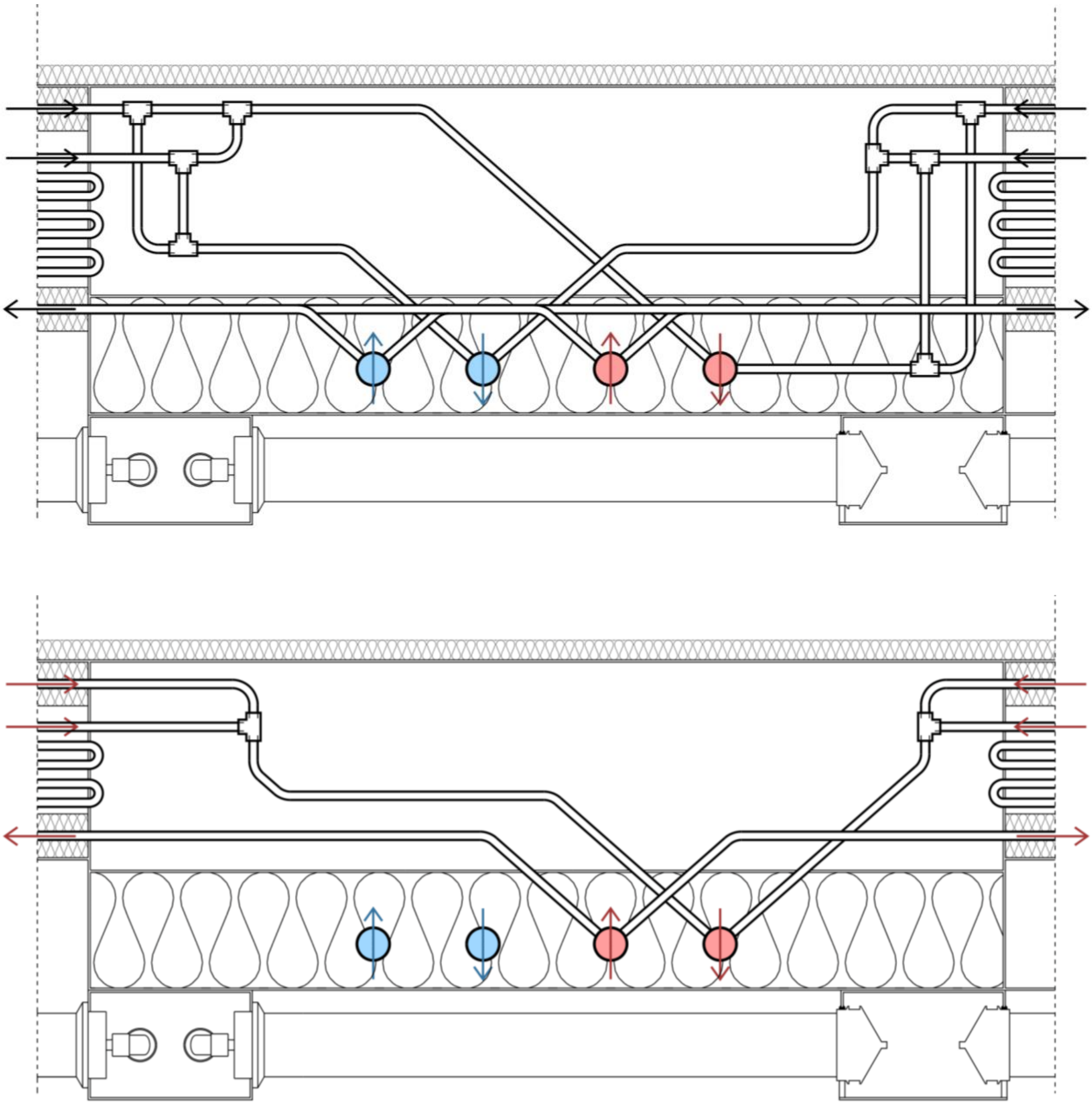


Figure 5.13: Horizontal section through vertical duct showing water piping network DCHEs (Top) and HRD heat exchangers (Bottom).

These two pictures show the horizontal section through the vertical duct, with the copper piping connecting the heat exchangers with the vertical piping. The network of the piping enables both hot and cold water to reach the heat exchangers.

5.3 Façade Maintenance

There are some parts of the façade module where maintenance must be factored in. These parts must be removable and thus accessible either from the interior of the bedroom or the exterior.

5.3.1 Vertical Ducting

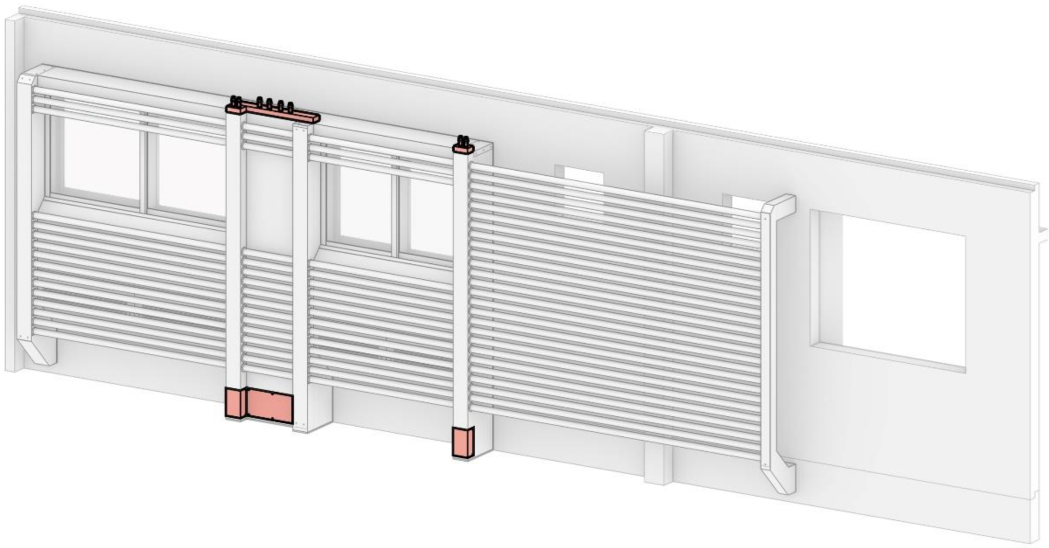


Figure 5.14: Highlight of location of vertical ducting connection.

During the assembly process, the vertical ducting elements must be carefully positioned. Because of imperfections in manufacturing, a fully perfect vertical alignment of the copper pipes through all levels is near impossible. Moreover, movement must still be considered. For this reason, a flexible steel tubing is used to connect the copper pipes across the façade modules.

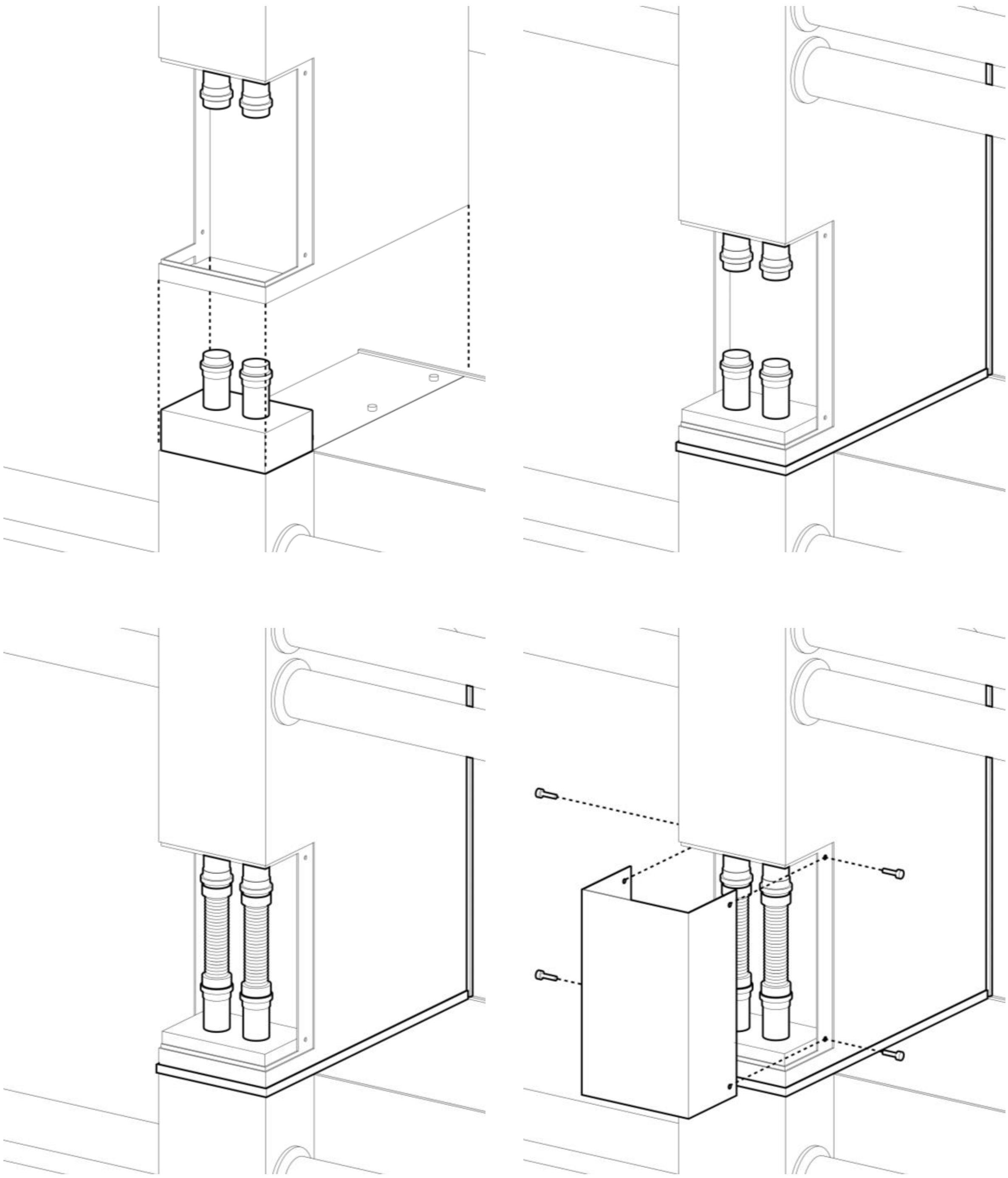


Figure 5.15: Steps for facade assembly relating to vertical duct connection.

Step 1 (Top left): Resting the facade module above onto the one below.

Step 2 (Top right): Applying sealants to waterproof contact points of facade modules.

Step 3 (Bottom left): Attaching of flexible steel piping across copper pipes of both façade modules.

Step 4 (Bottom right): Mounting of aluminium panel covering.

The prefabricated façade modules have exposed vertical pipes. When the module above is structurally attached to the existing façade, the copper pipes are linked with a detachable and flexible steel tubing. This tubing has a lower thermal conduction than the copper pipes, so insulation is not necessary. An aluminium element is then screwed on to cover this portion. During maintenance, it can be unscrewed, and the piping connection can be inspected and repaired if necessary.

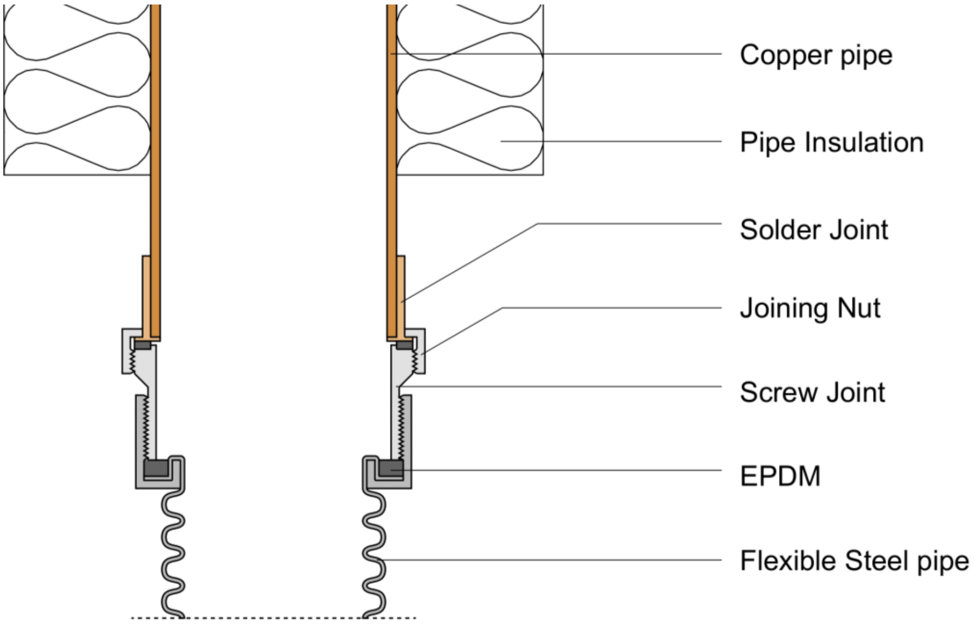


Figure 5.16: Detailed section of joint between copper piping and flexible steel piping.

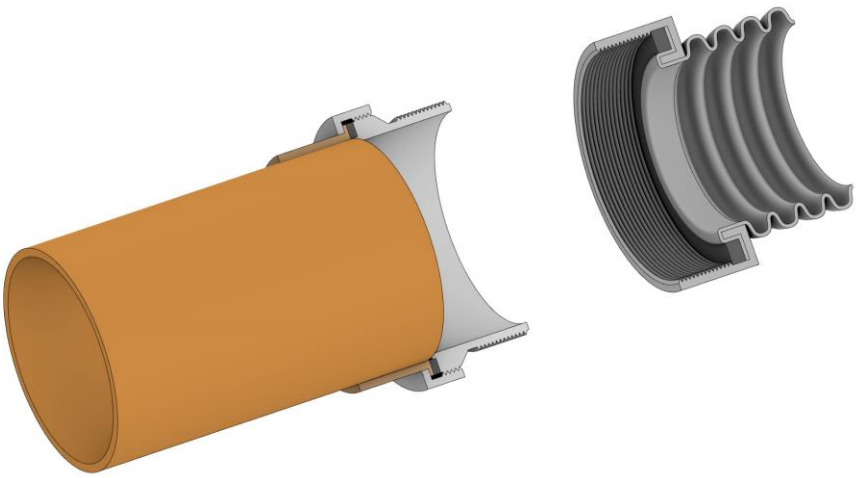


Figure 5.17: Axonometric diagram of copper piping and flexible steel piping.

The connection between the copper pipe and the steel tubing is based on existing products where EPDM is used to ensure water tightness. Tapered threading is also used as a secondary line of defence for water tightness.

5.3.2 Evacuated Tubes

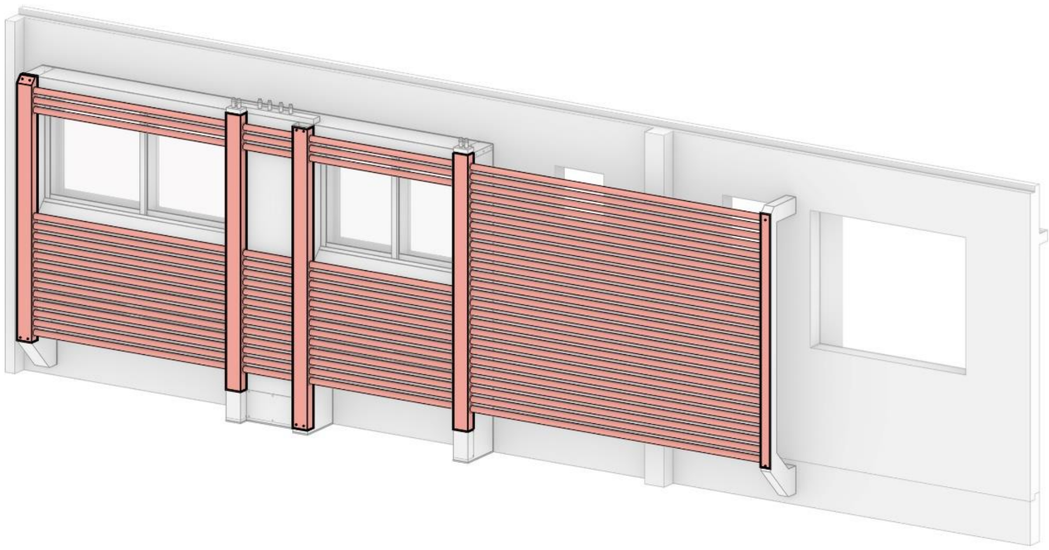


Figure 5.18: Highlight of ETC system on facade module.

The ETC system comprises of the façade-located tubes and is directly connected to the vertical piping. The attachment points of the tubes are in the form of 5 vertical aluminium frame elements, 2 of which house the vertical copper pipes that water runs through during the daytime solar heat collection. The other 3 aluminium elements serve merely as the ETC tube holders.

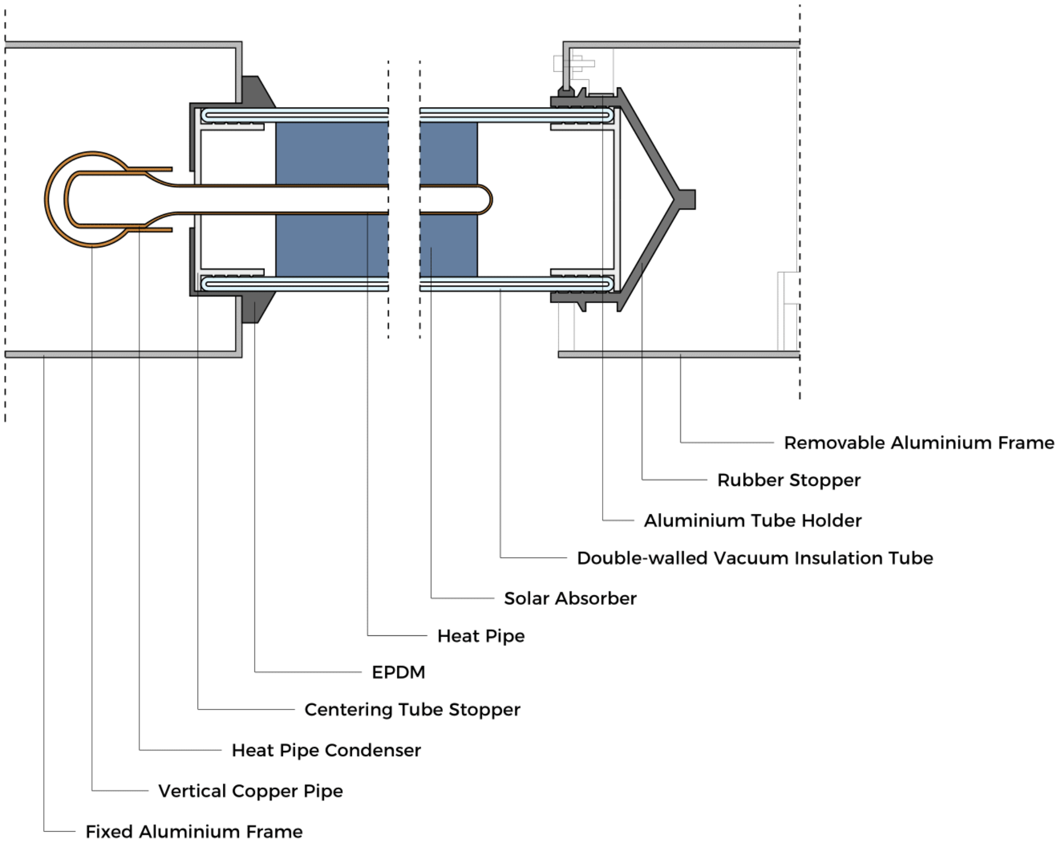


Figure 5.19: Detailed section of ETC tube, with components.

It features a vacuum-insulated tube surrounding the solar absorber material, which collects the solar heat and transfers it to the liquid in the heat pipe. The heat is then transferred from this liquid to the water flowing through the vertical copper pipes through conduction through the heat pipe condenser. EPDM and rubber stoppers ensure that the ETC tube is nicely fit into the aluminium frame.

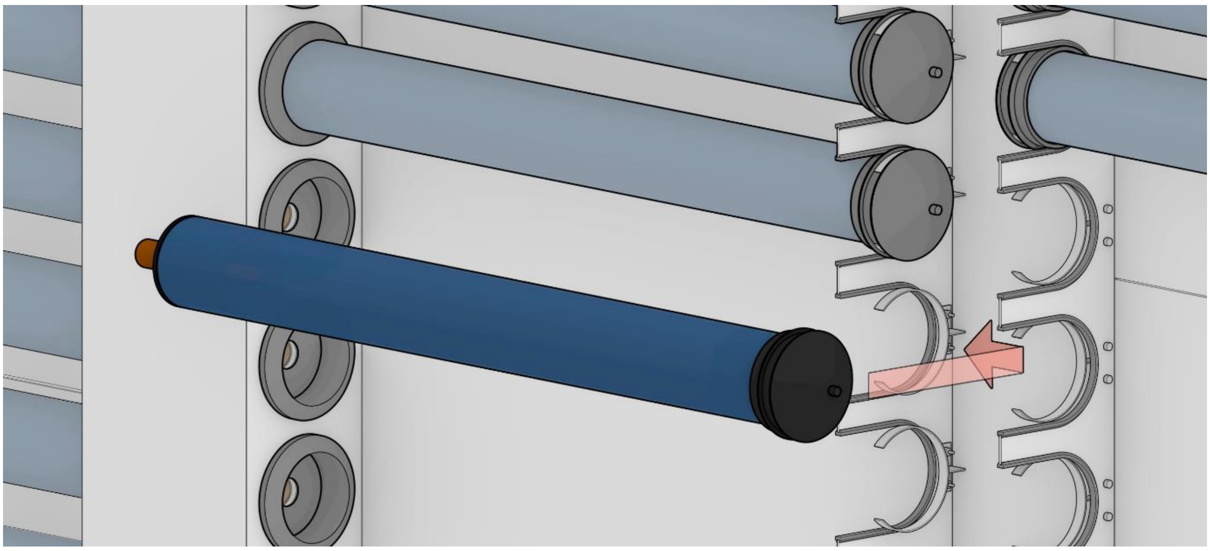


Figure 5.20: Instructional diagram of mounting of ETC tubes on facade module.

During assembly and maintenance, the ETC tube is inserted by first pushing it into the aluminium tube holder to secure its position in 1 axis. The tube is then shifted it towards the vertical copper pipe to insert the heat pipe condenser into it, thus establishing the connection with the vertical ducting system and fully securing its position on the façade module.

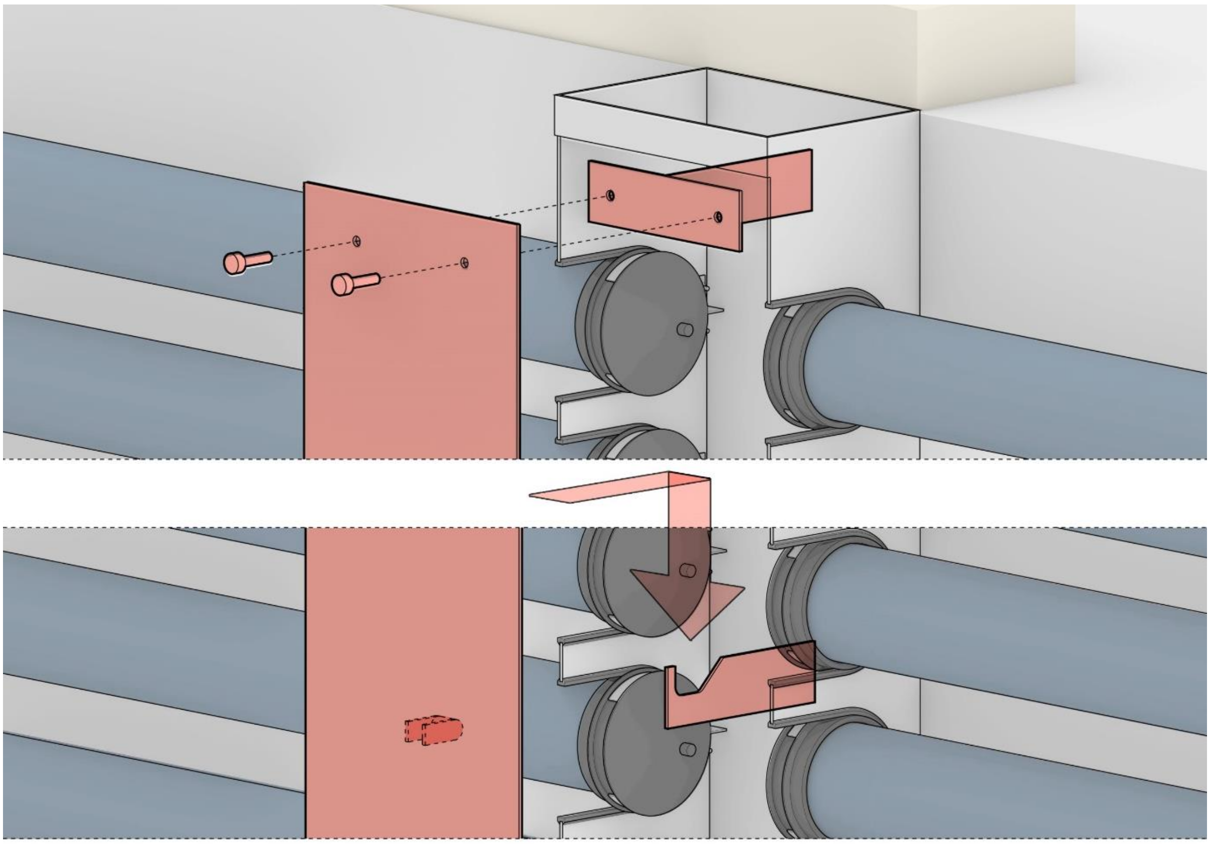


Figure 5.21: Instructional diagram of mounting of aluminium covering.

An aluminium panel is needed to cover up the ETC insertion points. It serves as a safety locking feature to ensure no ETC tubes fall off the façade module if they get dislodged, and as an architectural cladding to create a cleaner finish to the façade aesthetic. It is assembled only after all the ETC tubes have been properly inserted, and is done so by first hooking it onto 3 hooks located within the vertical aluminium frame, and then bolting it to the brackets at the top and bottom. In the image above, only the top bracket and 1 hook is shown. This panel is easily dismountable for maintenance purposes.

5.3.3 Fans and Air Filters

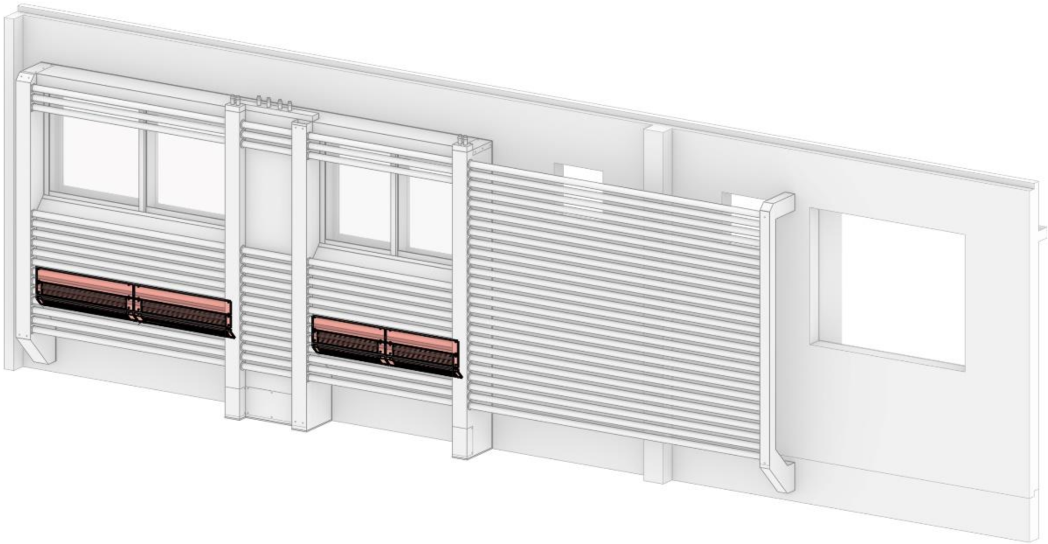


Figure 5.22: Highlight of maintenance areas on the front of facade module.

The fans and air filters are based on existing commercial products. The fan is based off cooler systems for computers and server systems, while the air filters are based off washable filters for a HVAC system in a residential house. It is recommended that the air filter is washed roughly 3 months. However, this number is dependent on the size of the house and the number of occupants for which it serves. Since cleaning is scheduled once every 3 months for an entire house, inclusive of 4 occupants (for a family), an air filter serving just a bedroom and 1 or 2 occupants would require less cleaning. Maintenance for the fans and air filters in this façade modules is thus scheduled to align with the ETC maintenance, which is twice a year.

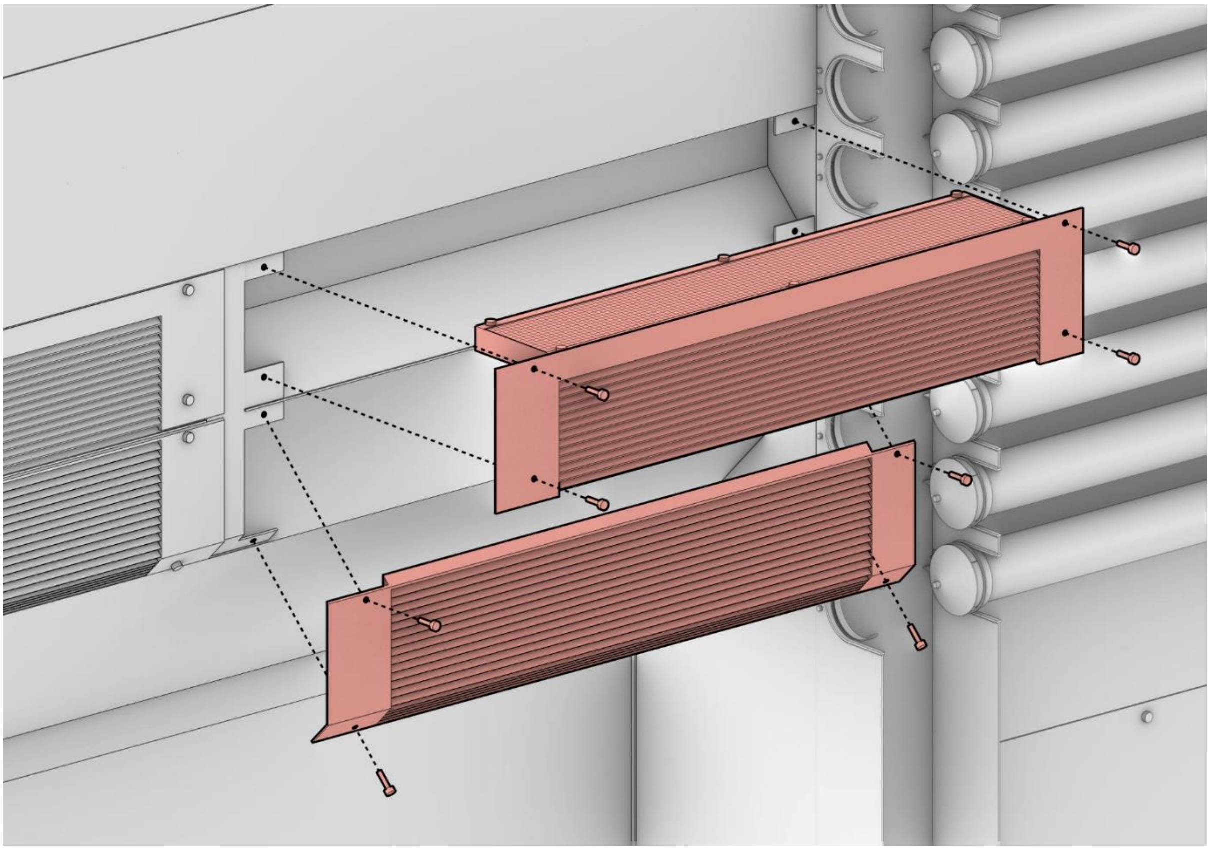


Figure 5.23: Instructional diagram on assembly of fan units, air filter and air grills on the front of the facade module.

The maintenance for the ambient air and exhaust air grills are done outside the façade module, along with the air filter component. This procedure requires the removal of the ETC tubes beforehand. The components are detachable as shown in the diagram above. The air filters can be sprayed with water and dried before being put back in. The air grill component is slid up at an angle.

The fan and air grills that can be cleaned by the occupant are located obviously on the interior side of the façade module where it can be easily accessed form indoors. There are 2 main components on this side: the top and the bottom component. Each of them comprises of a set of 3 fan units and 1 air grill.

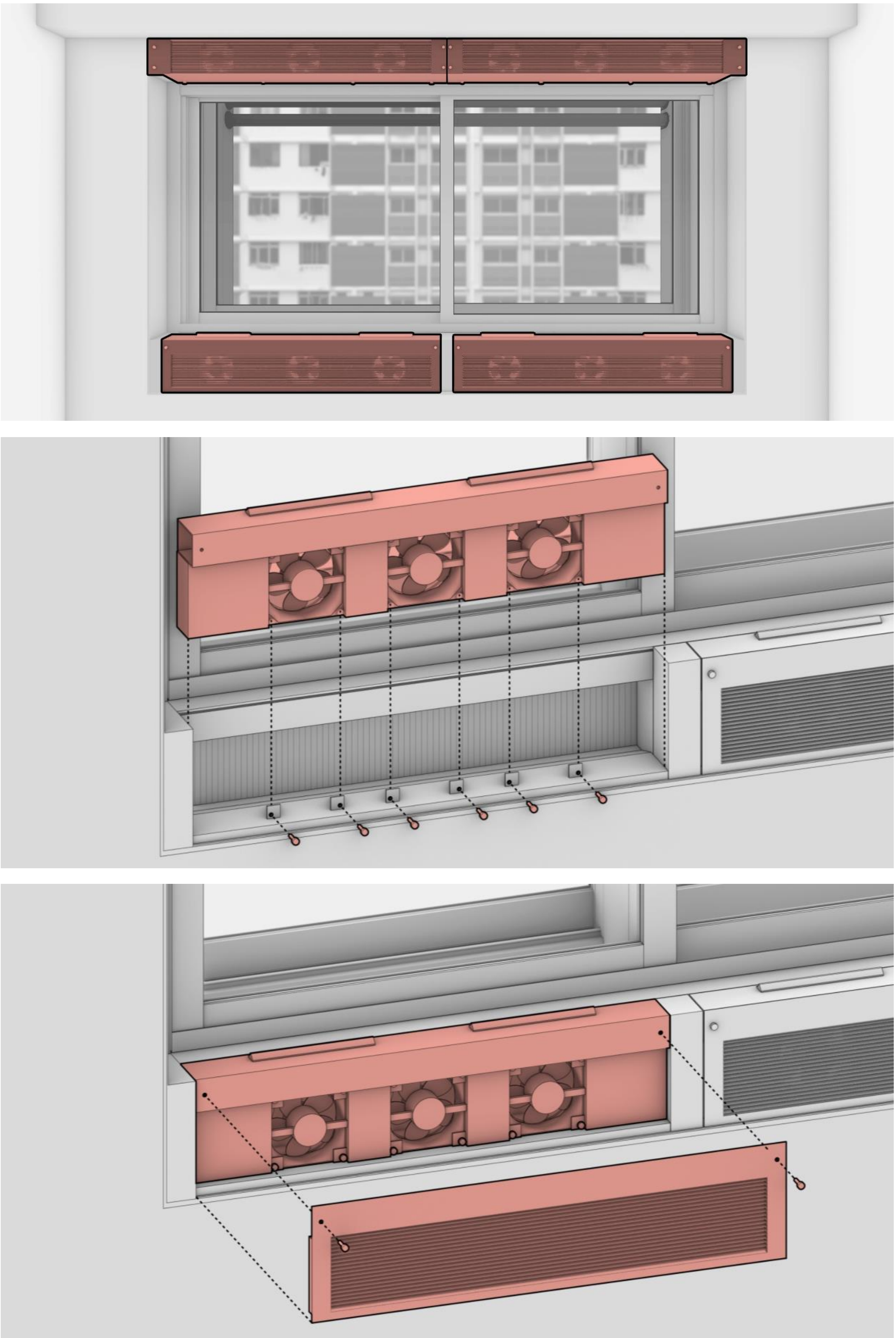


Figure 5.24: Diagrams of interior fan and air grills (Top) and their assembly sequence (Middle and Bottom).

For the bottom components, the air grill must be detached first before exposing the attachment points for the fan component. Removing the fan component requires the occupant to unscrew the 6 screws at the bottom before pulling the catch at the top and lifting the entire component.

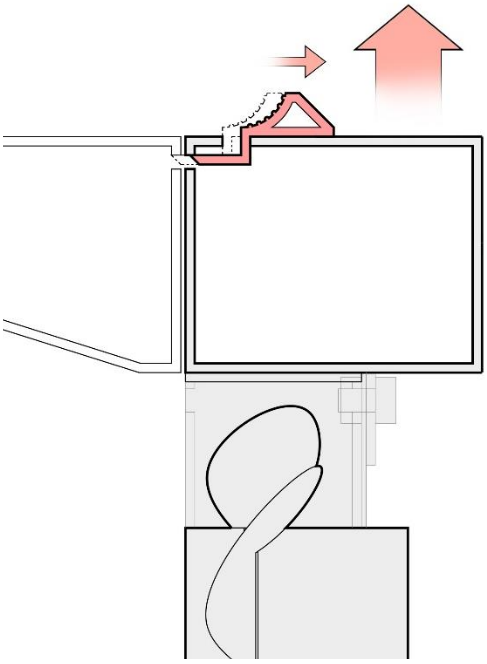
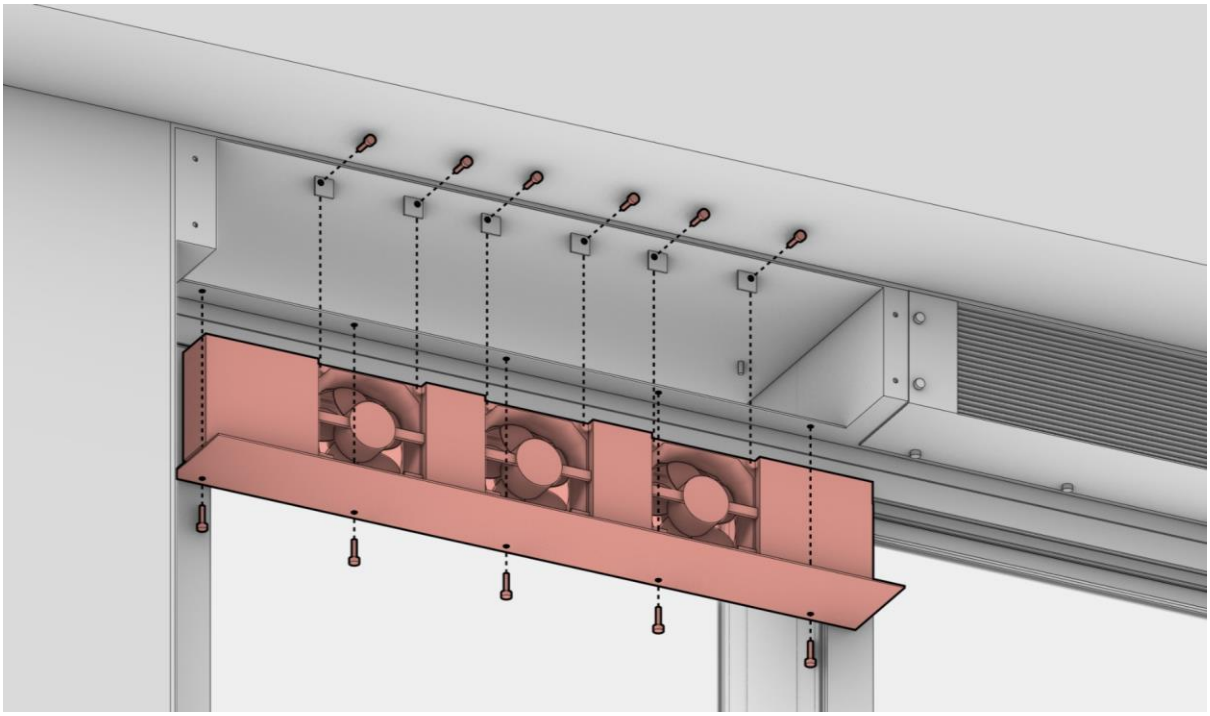


Figure 5.25: Instructional sectional diagram on the removal of the fan units by pulling the catch on the top.



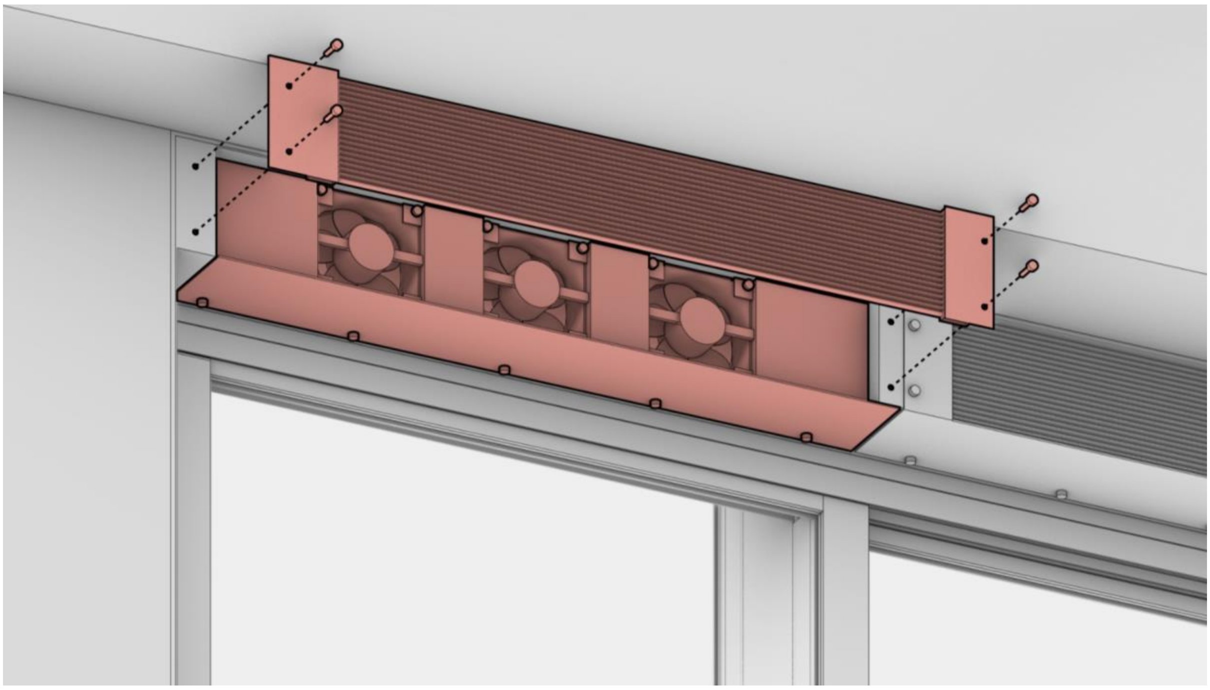


Figure 5.26: Instructional diagrams on the mounting of the top fan units (Top) and air grills (Bottom).

The fan and air grill component at the top for return air is designed in a similar way. The air grill is first detached before the fan component can be. For the fan component, no catch is involved, but it is screwed to the façade module itself.

5.4 Energy Calculations

In order to get a sense of how far this façade module is from becoming a reality, calculations are done to investigate how much energy is consumes for its operation and how much noise it makes.

5.4.1 Energy Consumption and Efficiency

The table below is a summary of the daily power consumption for the components that require energy. The full calculations can be found in the appendices.

Component	Daily Power Consumption per bedroom (kW)
Warm Water Tank	0.53
Cold Water Tank	1.223
Fans	0.00912
Water pumps in the day	0.06714
Water pumps in the night	0.0666
Total	**1.896**

Table 5.2: Power consumption of a facade module when cooling 1 bedroom.

Cooling Capacity (kW)	Power Consumption (kW)	Energy Efficiency
2.64	1.896	1.39

Table 5.3: Summary of energy efficiency of cooling system.

Considering a traditional air-conditioner has an energy efficiency between 3 to 5, an energy efficiency of 1.39 means that applying this façade module at present will incur higher energy consumption in order to provide the same amount of cooling. Its running cost is also thus higher, so it would not be financially viable.

5.4.2 Noise Calculation

The façade module is meant to be used in the night. The nature of its purpose demands that its noise generation be kept within an acceptable level. For comparison sake, commercially available air-conditioners which boast quiet operations generate a noise between 21 to 36 dB (Airconditioning-systems.com, 2018).

The fan units in the façade module are based on a commercially available fan system meant for the cooling of computers. (Noctua, 2018) It provides an airflow rate of 70.74 CFM and generates 25.1 dB of noise. Its airflow capabilities are the reason for its quantity per façade module. During operation, a total of 6 fans can be heard from the bedroom side (3 for supply air and 3 for return air). This amounts to 32.9 dB of noise generated, which is within the range of quiet air-conditioners. It is therefore deemed acceptable for night-time operation. Calculations can be found in the appendices.

5.5 Evaluation of Retrofit Façade System

The façade module is an integrated façade system with its components working together in tandem for the same purpose of bedroom night cooling. For this reason, it is difficult to develop it as a modular system because each component relies on another to function well. The structural system had to involve façade brackets that are screwed into the existing façade, and a lot of sealant is used between the façade module and the existing façade itself. While some maintenance can be done by the apartment occupants very easily, other parts require a maintenance worker standing on a gondola outside the bedroom façade to check and replace the ETC tubes, clean the windows, inspect the vertical pipe connections and wash the air filter. In the end, its overall energy efficiency is unsurprisingly not on par with traditional air-conditioners.

With the theoretical design of the façade system complete, it is important to recognise its effects on society, the environment and its users, along with its limitations. This paints a better picture about the feasibility of the system as a whole by bringing other unseen costs and considerations to the table and questioning its workability in different circumstances.

5.5.1 Implications

While the façade module has a clear purpose of indoor night cooling, there are implications to its existence and operation.

Architecture

Contrary to the traditional air-conditioner, which is designed without the consideration of its immediate context and instead encourages building design to accommodate it, the façade module designed in this thesis is done in reverse, where the façade exists along with the cooling system itself. This results in the necessary evaluation of its architectural value in the built environment.

The façade module is covered mostly by the ETC tubes, which brings about an aesthetic that stems directly from an engineering necessity, like how the outdoor unit of a traditional air-conditioner features a large fan as part of its compressor component. While the ETC tubes are subjectively better looking, it is important to remember that this façade module will be placed across the entire North façade. The resulting composition overwhelms the existing façade, where only the kitchen is left untouched.

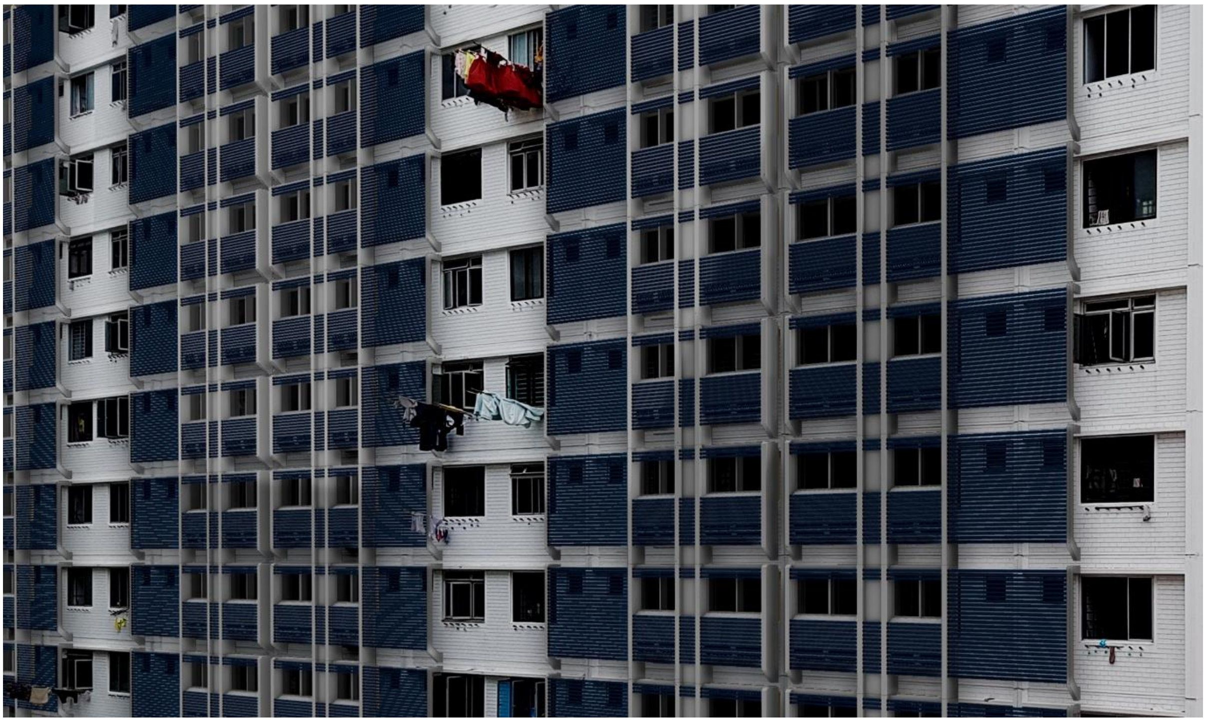


Figure 5.27: A visualisation of the array of facade modules on the existing building.

On the level of individual buildings, the aesthetic of the façade module is deemed to be good-looking and stands for a functional aesthetic. However, on a larger scale, this opinion changes.

Since this project looks at existing public housing buildings, its concept is imagined to be replicated across the country. This spawns a debate as to whether such a façade-integrated cooling system is desirable, as it completely alters the look of entire neighbourhoods, and can even be seen as a direct statement on how much energy the country uses for building cooling.

Figure 5.28: A speculative visualisation of what it would look like if the facade module was replicated onto other public housing buildings.

On such a scale of implementation, multiple variants of the façade module should be designed to introduce different aesthetics within the same cooling principle. While that is admittedly out of the scope of this thesis, it would be taken as a potential next step forward.

Instead, some calculations were done to investigate if it is financially viable to replace the façade-located ETC tubes with a water heater system for the centralised water tanks instead. Architecturally, this results in a different expression, where the façade module is more clearly seen as an entity attached onto the building. From a practical perspective, maintenance could be carried out faster per façade module because there are no ETC tubes to be removed or attached. Having such an exposed aluminium frame also creates an opportunity for aesthetical alterations, such as colours as patterns, which is a strategy used by the public housing buildings to create a sense of individualism among the sea of buildings with the same typology.

Figure 5.29: A visualisation of what the facade modules would look like without the facade-located ETC tubes.

On top of that, this façade-integrated cooling system was designed with the façade-located ETC tubes in mind. Removing this from the equation right from the start of the design phase could have led to a different architectural form of the façade module because there is more flexibility with the layout of the components.

Electric Cost in Singapore 2018 (Euro/kWh)	0.1346
Electric Water Heater COP	0.9
Maintenance Frequency (per year)	2
Façade-located ETCs	
Initial Cost (Euro)	386100
Maintenance Cost per cycle (Euro)	12210
Daily Operating Cost (Euro)	0.11
Estimated Lifetime (years)	20
Water Heaters	
Initial Cost (Euro) (HomeAdvisor, 2019a)	2400
Maintenance Cost per cycle (Euro) (Reliable Water Services, 2018)	272
Daily Operating Cost (Euro)	112.53
Estimated Lifetime (years)	10

Table 6.1: Financial costs of facade-located ETC tubes versus water heaters.

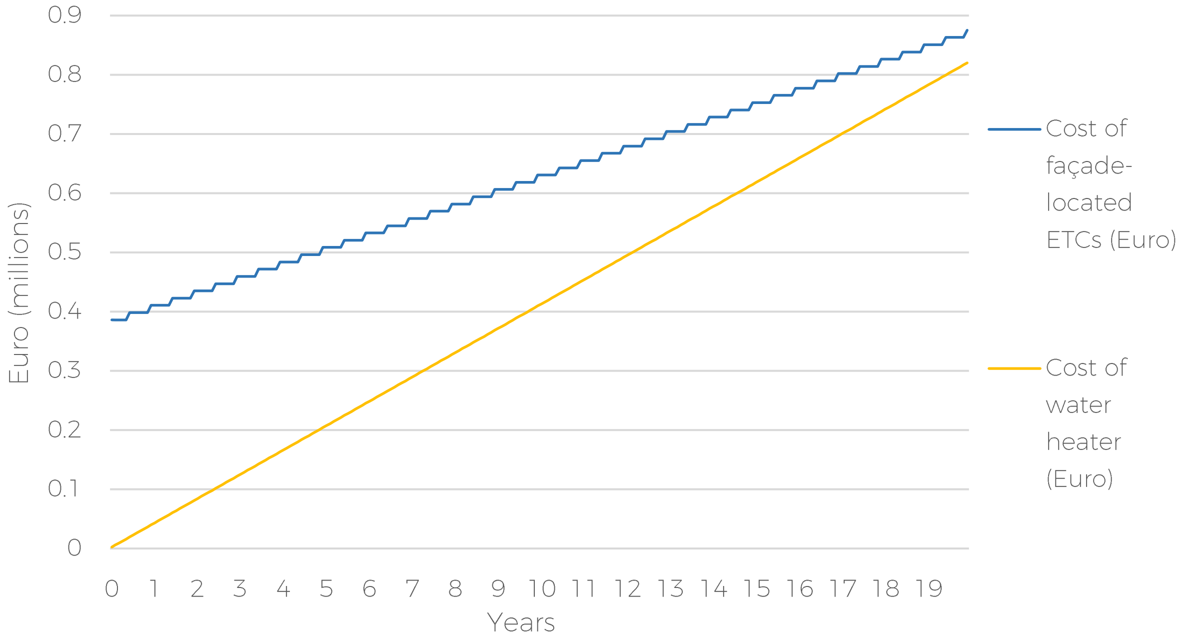


Figure 5.30: Graph showing financial costs of the facade-located ETC tubes versus water heaters, over the lifetime of ETC tubes, which is 20 years.

The graph above shows the financial cost of the façade-located ETCs versus 2 water heaters (1 per hot water tank) over a period of 20 years, which is the estimate lifetime of an ETC system. This simple graph only considers the initial costs, maintenance costs every 6 months, and daily operating costs. It can be seen that the cost of an ETC system mainly consists of its initial and maintenance costs, while the water heater has a tremendous daily operating cost. Within 20 years, the water heater technique makes more sense, even though the water heaters have a lifetime of 10 years, which means a replacement is necessary at the 10-year mark. Moreover, if the façade module is meant to last more than the calculated 20 years, the ETC system would need a replacement, incurring another set of initial costs. However, this simple calculation is based off the following assumptions:

- Inflation and energy costs over the 20-year period is neglected. This directly affects the financial viability of the two possibilities shown, especially for the water heater idea. If energy costs increase just a small amount, the façade-located ETCs may become the more logical choice.
- Maintenance costs are assumed to be constant over the time period. This affects the façade-located ETCs more. In reality, the breakdown of majority of ETC tubes happens towards the end of their lifetime. The graph will look different if a more realistic maintenance cost is modelled. However, this should not affect the total costs by a large amount.
- The façade-integrated cooling system is never upgraded with better technology. Since this is considered a product provided by the government for the public, it is expected that the required standards and quality of the system

are raised over time. It is possible that within the 20-years, the ETCs are replaced with ones with better heat collection capabilities and better robustness which would lower the maintenance costs. Likewise, the water heaters could be replaced with more energy efficient ones which would lower the operating costs.

The energy performance is also calculated, simply by comparing how much energy is required everyday to heat up the hot water tank.

Energy Efficiency	
Façade-located ETCs	1.39
Water Heater	1.23

Table 6.2: Comparison of energy efficiencies between a system using facade-located ETCs versus water heaters.

This paints a picture of how much energy is saved with the use of façade-located ETCs. While water heaters may be financially more sensible, its energy consumption introduces a dilemma between monetary and environmental priorities. Ultimately, the total carbon emissions resulting from the manufacturing of the facade-located ETCs and the operation of the water heaters is not examined in this paper, but it is an issue worth mentioning.

The accurate prediction of the overall costs of the façade-located ETCs versus the water heaters is beyond the scope of this thesis and this section merely serves as a discussion point about an alternative to a façade module that brutally plasters the building façade with ETC tubes.

Urban Heat Island Effect

Traditional air-conditioners function based on throwing heat out of the cooled space. This results in hot air exhausted from the system which contributes to heat in urban areas. The urban heat island effect (UHI) is an issue that currently affects Singapore almost country-wide.

Figure 5.31: A visual representation of the UHI effect in Singapore. (Source: http://www.rocagallery.com/mitigating-urban-heat-islands)

In the case of the façade-integrated cooling system, air of up to 55°C is exhausted from the regeneration phase. The temperature difference between the exhaust air and the ambient air is thus 27.5°C. This is notably larger than the compressor discharge temperature of traditional air-conditioners, which usually range between 20 to 30°F (Tomczyk, 2004), which translates to 11.1 to 16.6°C. This means that traditional air-conditioning systems heat the ambient air up to roughly 44°C, so the façade-integrated cooling system would have a larger negative contribution towards the UHI effect in Singapore than the existing vapour compression technology, undermining its environmental sensitivity.

Daylighting

It is interesting to know how the façade module has affected the bedroom daylighting situation, given that the module itself has a full thickness of 40cm and includes shading by the ETC tubes. A daylighting simulation is conducted on one of the bedrooms, shown below.

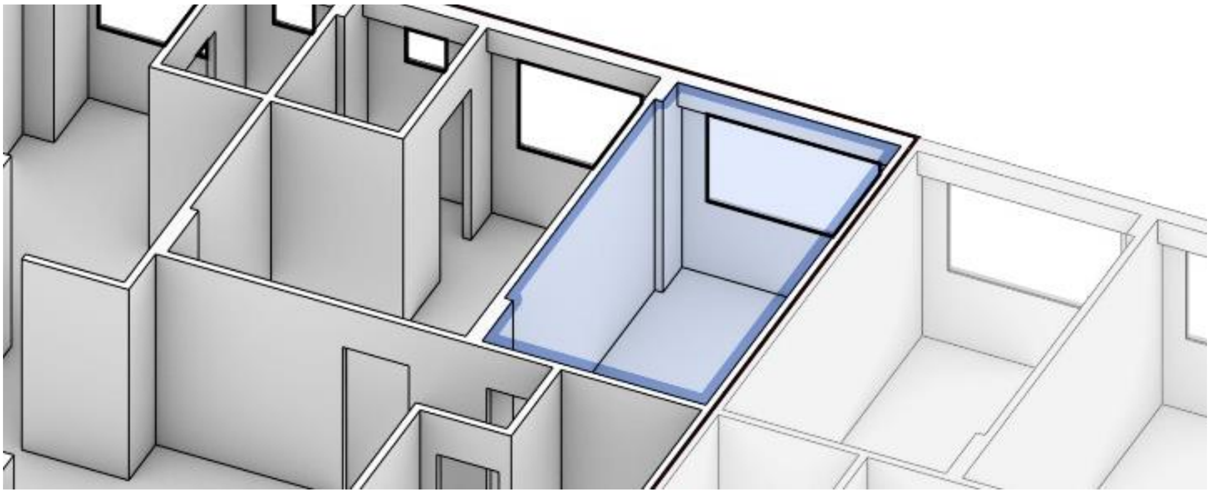


Figure 5.32: Bedroom on which the daylighting simulation was done.

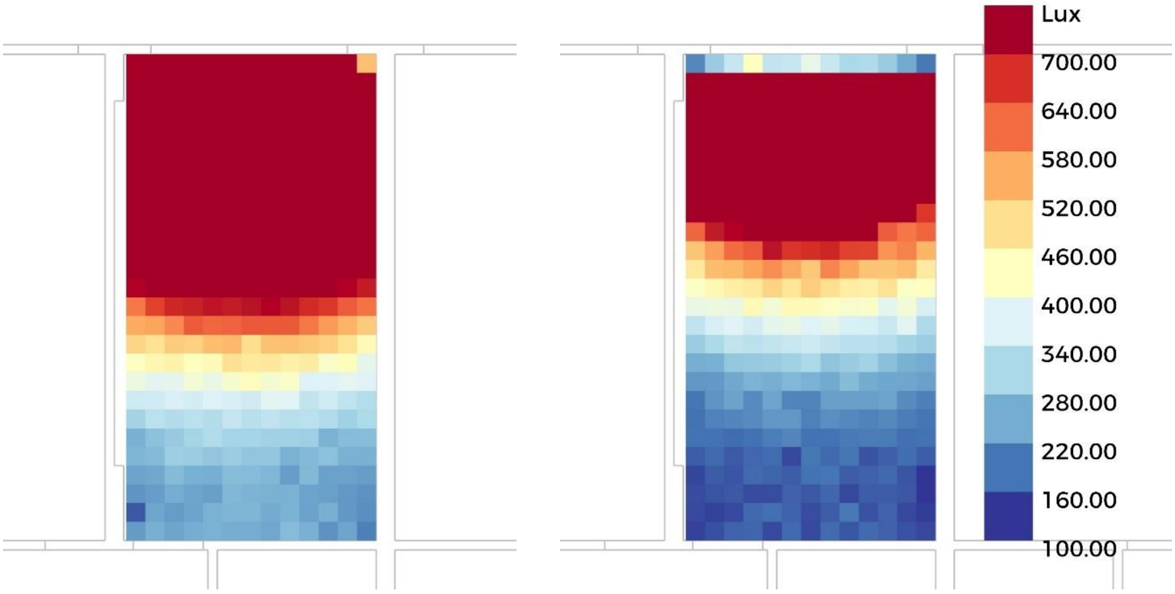


Figure 5.33: Results of daylighting simulations on the existing facade (Left) and the same condition but with the facade module attached (Right).

The picture above shows the daylighting scenario on 21December at 12pm, when the Sun is on the South side. Illumininance is thus a result of mostly diffuse skylighting. A value of 150 lux is preferable for bedrooms, while 300 is suitable for activities like reading. 700 lux entails lighting quality similar to that of supermarkets and mechanical workshops. (NOAO, 2019) On the left is the situation without the façade module, while on the right is one with the façade module. It can be seen that the façade module indeed does reduce the daylighting in the bedroom. While there is still sufficient natural light for comfort in most of the bedroom, the deeper sections seem to have a bit of struggle in this aspect. It is thus possible to conclude that for the best daylighting scenarios, an area of improvement for the façade module could be to reduce its shading amount by a tiny bit, either by reducing its overall thickness or removing a couple of ETC tubes located at the top of the window.

5.5.2 Limitations

A façade design is never fully perfect, and this façade module is no exception. There are problems posed by its own design that may need solving.

Daytime Cooling

The façade module is intended for night cooling. The hot water tank only has sufficient heat to last 7 hours through the night. If it is switched on in the day, there will be less heat for the night. This might be a problem during weekends when there is a higher likelihood that there are occupants present and demand cooling. However, the façade module also supports natural ventilation for this purpose and may be able to provide enough daytime cooling if cross-ventilation is utilised.

Limited Bedroom Cooling

This applies to this specific public housing typology where a public corridor links the elevators to the unit entrances. The picture below shows the 4-room unit of the chosen building, with the public corridor highlighted in yellow. This typology is no longer in production because the bedrooms facing the corridor lack privacy. However, the existing buildings of this typology experience a greater difficulty in incorporating façade-integrated cooling systems on the side of the public corridor. Attaching façade-located ETCs on the corridor balustrades would have easily been done in this thesis if calculations deemed it to be necessary, as the ETC system is centralised anyway. However, the question would be on the cooling of the bedroom highlighted in red in the picture below.

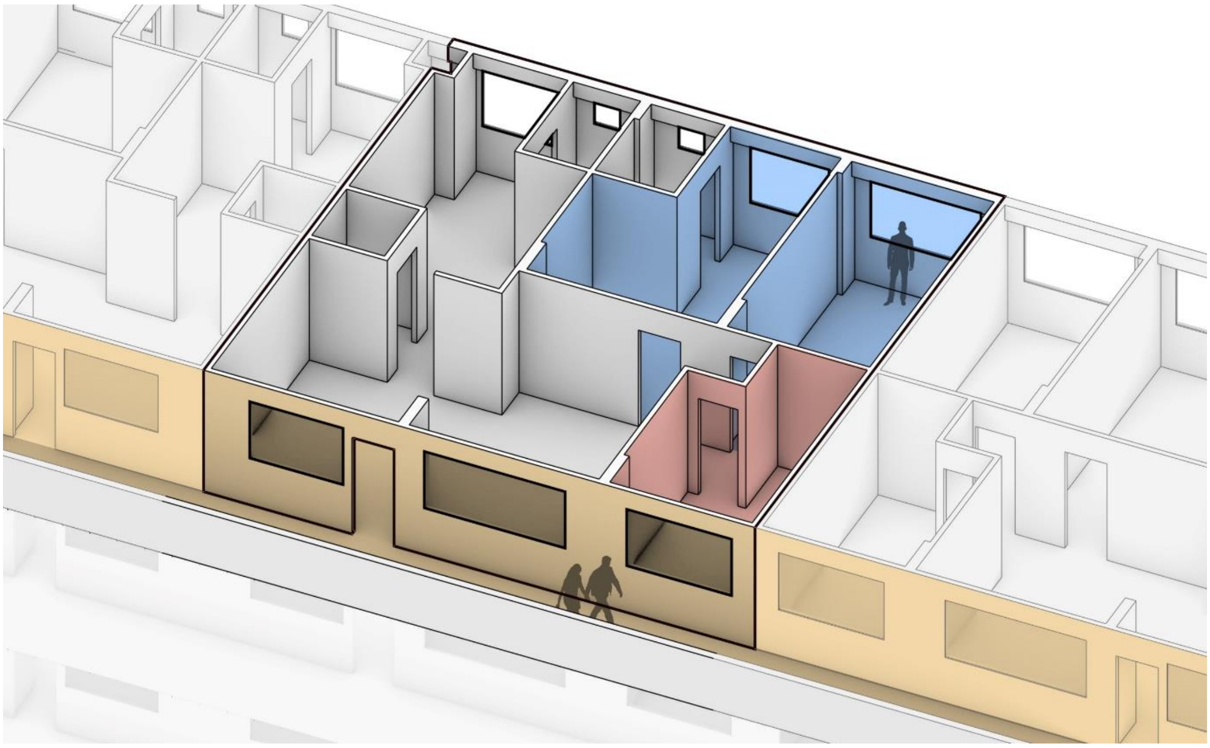


Figure 5.34: Axonometric of the 4-room residential unit with the public corridor (Yellow), bedrooms cooled by the façade system (Blue) and uncooled bedroom (Red).

It is debatable as to whether the wall separating this bedroom and the public corridor is considered a façade or merely a wall. If cooling was attempted on this bedroom, the cooling system may be arguably less of a façade-integration and more of a cooling product. In addition, the cooling system may occupy space in the public corridor, which is often also used and occupied by the residents' belongings (potted plants, bicycles, etc), Due to these social concerns and architectural grey areas, this thesis focused on 2 out of 3 bedrooms per apartment, shown in blue in the picture above. Modern public housing buildings would not have this issue because all bedrooms directly face the exterior instead of a public space.

Height Limit

The façade module uses ETCs both on the roof and the façade. The roof is already fully utilised while the façade has a small amount of space left. The chosen building in this thesis has 11 levels of 10 residential units each, and barely has any space left for more ETCs. In other words, this façade module may not be entirely plausible to provide space cooling for a taller residential building, because more ETCs would be needed.

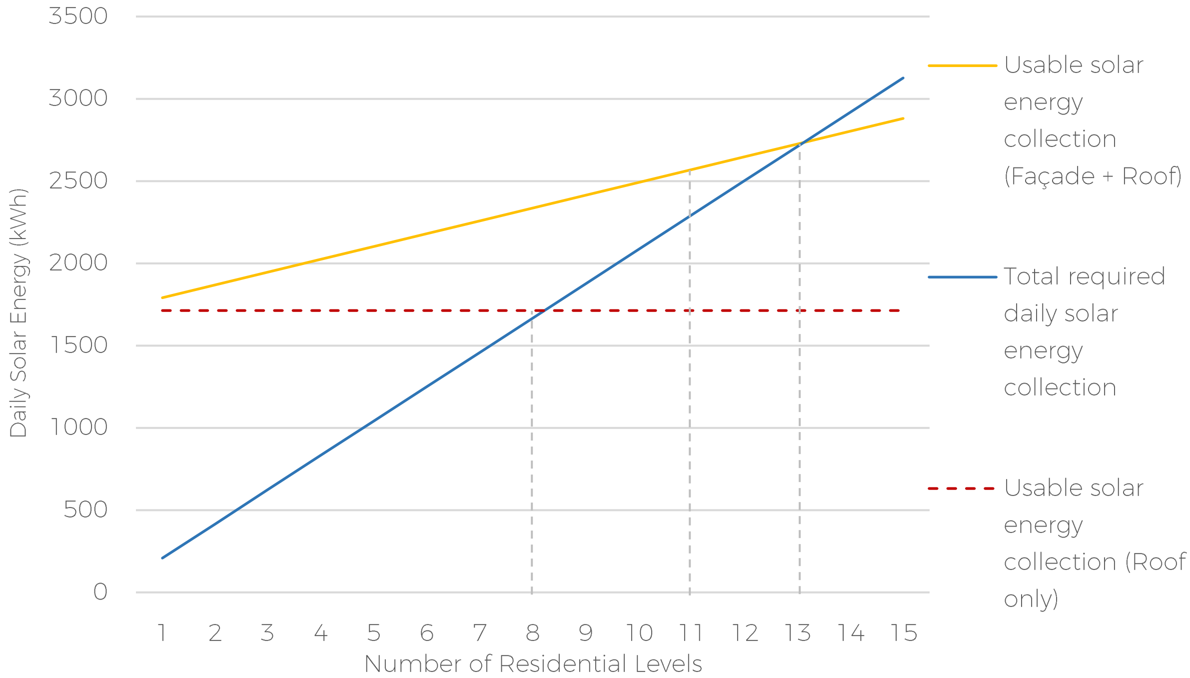


Figure 5.35: Graph indicating the required and available solar energy based on building height.

The graph above shows that for a building with an identical typology and floor area as the chosen building, the maximum building height would be 13 residential floors. Above which, the entire façade cooling system will no longer be able to provide enough solar heat collection even when including the roof-located ETCs. The red dotted line signifies the roof area, which is taken to be a constant because it does not change with respect to building height. The graph shows that if the chosen building had only 8 residential floors instead of 11, it would have been possible to design the façade system completely without façade-located ETCs. Calculations are located in the appendix chapter.

Transferability

Building upon the height limitation of the façade module, there are many other factors that limit the transferability of this cooling system across the tropical climate.

Architectural parameters like the building massing, orientation, typology and urban context largely determine the effectiveness of the system.

Figure 5.36: An aerial view of Hong Kong. (Source: https://iso.500px.com/drone-photos-show-the-crazy-urban-density-of-hong-kong/)

In a place like Hong Kong, residential buildings are constructed taller than those in Singapore and more closely-packed. This typology means that the roof area is very limited and the façade area is larger. The façade system will not work well because even with plenty of façade space, they will be shaded by the adjacent tall buildings.

Figure 5.37: Many Vietnamese houses are built deep and narrow. (Source: https://www.bestpricevn.com/travel-guide/article-the-tube-houses-of-hanois-old-quarter-338.html)

In Ho Chi Minh City, Vietnam, many street houses tend to be deep and feature narrow facades. The facade often features a balcony overlooking the street, and the ground level lacks space for water tanks. While their low height poses as an advantage, the building typology demands a completely different façade module design.

Figure 5.38: Sao Paolo, Brazil, with different building typologies. (Sources: https://thelchat.jcink.net/index.php?showtopic=6119&st=35, https://psmag.com/social-justice/health0brazils-billion-dollar-free-public-gym-experiment-85284

The central areas tend to contain taller buildings, while the suburban areas have distinctively shorter blocks. The picture on the right in Figure 6.12 shows these short and linear blocks of flats in Sao Paolo, which might bear similar characteristics to the building designed for in this thesis, and may therefore stand a higher chance at being viable for the façade system.

Figure 5.39: A typical void deck on the ground floor of most public housing buildings. (Source: https://oss.adm.ntu.edu.sg/tanj0217/)

Singapore is known for having high-rise public housing buildings with an empty ground level. This is a characteristic that may not be present in the high-rise residential buildings of other tropical countries. As such, the strategy of locating water tanks on the ground level may be more difficult elsewhere beyond Singapore. A specific patch of land area nearby the building is required for them. Alternatively, the water tanks may be placed underground, but that would incur more initial costs.

Figure 5.40: The Pinnacle@Duxton, the tallest public housing project in Singapore to date (Left). Community roof gardens are an up and coming trend among modern public housing in Singapore (Right).

Even within Singapore, the façade system struggles to adapt to the different building typologies. Not all residential buildings are strictly aligned along the East-West axis. While this fosters more character on the urban scale, it inevitably affects their suitability for façade solar heat collection. The modern public housing buildings in Singapore also increasingly feature roof gardens as a method of urban cooling and as a communal space for the residents and the public. While this is justified and improves the living quality, it clashes with the façade system's required roof space. The façade system would then have to rely solely on façade solar heat collection, which has already been established to be insufficient in Section 4.5.5.

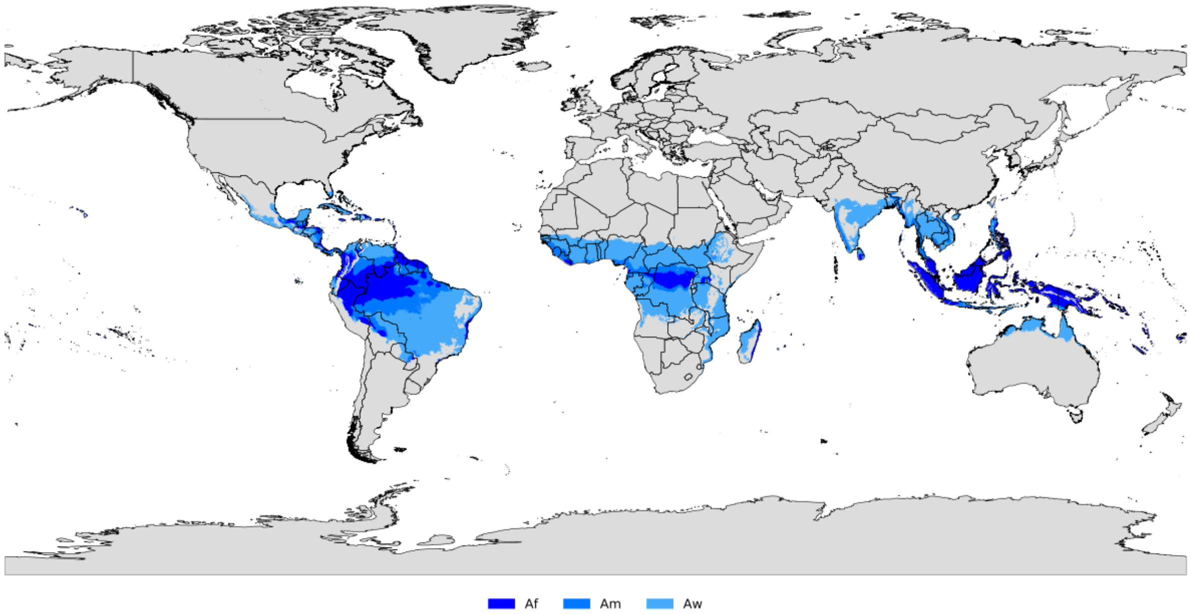


Figure 5.41: Conditions also differ within tropical zones. (Source: https://en.wikipedia.org/wiki/Tropical_climate)

Within the tropics, environment conditions also differ along a spectrum. Air temperatures and humidity levels are affected by the latitude and altitude. Solar irradiation and cloud cover also differs with location. Further away from the Equator, seasonal differences start to take effect and climate conditions become less constant throughout the year. For example, Hong Kong is deemed as subtropical, with its conditions in June similar to Singapore. However, in December, temperatures vary between 15 to 21°C. Over in Honduras lies the city of Tegucigalpa. With a tropical savanna climate at almost 1km in altitude, air temperatures at night there stay below 20°C. In such a climate, though tropical, night cooling maybe not even be necessary. The façade system therefore cannot be placed anywhere simply on the argument that it is within the tropics, because climate conditions are defined by a multitude of factors, even within a tropical realm.

Figure 5.42: Jakarta, Indonesia is ranked the 3rd most polluted city in the world. (Source: https://www.straitstimes.com/asia/se-asia/jakartans-finding-it-harder-to-breathe-capital-ranks-as-worlds-third-most-polluted-city)

The cooling principle of the façade module extracts fresh air from the immediate exterior of the bedroom. This becomes a health concern if the air quality of the location is bad. In areas like Indonesia, where mass deforestation occurs frequently, or in parts of India where air pollution levels are significantly higher than in Singapore, this façade module fails to provide adequate fresh air. The air filter may block some dust particles, but it also requires washing to remove the trapped particles. In such circumstances, more frequent washing is needed, which may prove to be a financial burden. To solve this problem, the façade module would have to be redesigned specifically to allow for an easy access to the air filter from the bedroom side.

Energy Consumption

At present, the cooling technology has not yet reached a point where it is more financially viable than vapour compression systems. This brings up the point that this façade system is not worth becoming a reality yet. Even though no refrigerants were used, the overall lower energy efficiency means that more energy will be consumed, which in turn introduces more greenhouse gas emissions from power plants.

5.5.3 Assumptions

As this is very much an engineering product as it is an architectural one, some assumptions were indeed made to simplify the engineering problems to suit the scope and time constraints of the thesis.

Engineering Details
The calculations done for cooling capacity and required solar absorber area are based on several assumptions and omissions of details.

- A heat exchanger is composed of fins and tubes. The tubes affect the airflow and air velocity. This influences the actual airflow rate and heat transfer rate.
- Air pressure drops happen as air is being pushed from one side of a finned-tube heat exchanger to another. Air velocity can be reduced across the heat exchanger as a result.
- Heat exchanger materials also play an important part because their heat conduction is crucial in determining the lag time of air temperature change within the DCHEs when transiting from dehumidification to regeneration process.
- The efficiency of evacuated tube collectors has been blanketed as 80% for this project, yet there are many factors that determine its actual value, such as the cross-sectional shape of the absorber and the quality of the copper piping and vacuum tube. In reality, efficiency is not a constant.

These details have all been ignored for the purpose of simplicity and on grounds that they do not drastically affect the architectural form of the façade module. However, they must be considered should a prototype be built.

Worst-case Scenario Calculations
It is understood that not everyone demands cooling at night. Only 76% of public housing occupants own an air-conditioner. Yet, this thesis assumes 100% of occupants demanding night cooling. This leads to an oversizing of the centralised components which might have made a difference in the development of the façade concepts. Nevertheless, assuming a worst-case scenario ensures that the system works well in a normal scenario.

Climate
Singapore is located only 1° above the equator, with a North-South span of a tiny 27km. It is thus reasonable to assume that the entire country experiences the same climate throughout the year, and the temperature range over a period of 24 hours is identical between the 'summer' and 'winter' periods. The energy calculations employ this assumption to simplify the calculation process because any seasonal difference is minimal.

5.5.4 Prospects

This façade-integrated cooling system is meant to be an extrapolation of current technology to explore a possible outcome of the gradual phasing out of refrigerants due to the Montreal Protocol. It imagines a world where air-conditioning is no longer reliant on refrigerants with high global warming potential, but rather, in this case, water.

Energy Consumption

As mentioned in Section 4.8.4, with current technology, such a façade-integrated cooling system will not be financially nor energy viable. Some time is needed for it to mature enough to become even something that air-conditioning firms would venture into as a potential commercial product. At present, desiccant cooling remains in the technological reserve for research and experimentation rather than being used widespread as a main cooling concept. Currently, research is already being done to explore better desiccant materials. Electric water tanks and evacuated tube collector systems are already in the market and continue to improve on their efficiency. With enough time, solar-driven desiccant cooling could hopefully play a bigger role in space cooling in tropical climates.

Government Initiatives

Research has been done by research groups in Singapore to figure out ways to improve outdoor comfort in an urban tropical climate. Desiccant systems are one of the many ways listed, where it is stated that comfortable and healthy indoor environments can be achieved with the use of desiccant systems and improve building energy efficiency by transferring workload from latent cooling to sensible cooling. The use of desiccant systems is feasible in Singapore and offer thermal comfort in hot and humid climates along with lower primary energy resource consumption. (Ruefenacht & Acero, 2017) With enough understanding and recognition of desiccants as a potential cooling system, the Singapore government may opt to conduct more in-depth research and development into its technologies for future cooling.

6 Conclusion

The façade system has been shown to be capable of providing the necessary cooling capacity for night cooling in a public housing building in Singapore, but also has drawbacks and consequences. This chapter takes a step back and looks at how it answers the main research question and its sub questions, before bringing the project to a close.

6.1 General Conclusion to Research Question

To recap, the main research question was,

"How feasible is a retrofit façade-integrated desiccant cooling system for high-rise public housing in a hot and humid tropical climate?"

Research into the technology of DCHE-based cooling systems and possible subsystems, as well as case studies on built façade-integrated HVAC systems, has led this thesis towards the investigation between fully decentralised versus semi-centralised façade concept systems. Calculations have shown that while both concepts can achieve the required cooling capacities, the system with more centralised components was inevitably more cost-effective.

The architectural integration of the cooling system was explored by positioning the components at various locations of the façade instead of consolidating them within a small space. ETC tubes doubled as the shading device. However, since this is a retrofit façade module, its dimensions and positioning of the components also depends on the dimensions of the existing façade. Connection to the existing façade was done with structural façade brackets, and sealants and insulation were layered in between the existing façade and the façade module.

The centralising of components was done on the ground level and the roof space of the high-rise public housing building. Connection between them and the decentralised cooling systems was done with insulated vertical water pipes running within each façade module. Natural ventilation through the façade module is also made possible because it serves as a passive cooling strategy in the tropical climate.

Energy calculations have shown that while it is capable of delivering sufficient cooling power, it is not yet ready to be commercialised and requires more years of further and deeper research into its technology before becoming economically feasible. Beyond energy consumption, its contribution the urban heat island effect poses as a big barrier to its realisation. Unless future desiccant cooling technology manages to resolve the UHI issue, the façade module will not be feasible to implement on a large scale because the urban air will be heated up considerably.

In the event that the façade system is implemented widespread across Singapore, multiple architectural forms of the facade module should be explored to adjust to different building typologies and avoid urban monotony. If finance is prioritised over the environment, then there is an option to replace the façade-located ETCs with water heaters. However, implementing this façade system outside Singapore may be a more complicated job because its feasibility largely relies on architectural and climate factors. The building massing, orientation, typology, urban context, and environmental conditions will determine the necessity and feasibility of the façade system. In some areas, it may not be needed while in other areas it may require redesigning, or it may not even be physically possible or feasible to implement with the current technology. However, its workability in the chosen building in this thesis serves as a proof of concept of a retrofit façade-integrated cooling system for built high-rise residential buildings in the tropical climate and it is not impossible to find locations outside Singapore where its principle may be borrowed successfully.

6.2 Conclusion to Research Sub Questions

Context

- What are the requirements of a cooling method for a tropical rainforest climate?

A tropical rainforest climate consists of warm temperatures and high humidity all year round, with high rainfall and high cloud cover. In such a condition, the cooling method must thus be able to reduce both dry-bulb temperature and humidity ratio of the air to create a thermally comfortable environment. In the case of Singapore, with temperatures hovering around 25 to 32°C daily and relative humidity constantly above the high 70s, a cooling method like desiccant cooling is promising because it removes moisture from the air and brings down the temperature. With high cloud cover, any reliance on direct solar irradiation is limited.

- What are the current design aspects, user behaviour and cooling loads in a typical public housing building?

With passive cooling strategies already in place in these buildings, active cooling is the next step towards a better indoor thermal comfort. A large portion of public housing buildings consider the equatorial sunpath, so the facades mostly face the North and South. Public corridors host access to the apartment units, whose floorplans encourage cross-ventilation. Thermal massing is used to dampen the heat absorption in the daytime, but results in indoor heat emission after sunset, which is one of the reasons why residents tend to use air-conditioning in the night. Night cooling is thus the main problem to solve. The chosen building has bedrooms with cooling loads of 2.6kW.

Strategy

- What is an appropriate active cooling strategy and how can additional subsystems be integrated to it to improve its energy performance?

While there are multiple ways to conduct desiccant cooling, the desiccant-coated heat exchanger method was chosen because it is a solid-state method that requires less maintenance than a rotary wheel system. A silica-based composite desiccant material was used in favour over the typical silica gel material because it has a better dehumidification performance. A heat recovery subsystem, solar heat collection and additional sensible cooling subsystems were integrated to the cooling strategy to further improve its overall cooling performance and reduce its required physical space and operational energy consumption. This helps to maximise the energy efficiency of the cooling system to achieve the required cooling capacity for the bedrooms.

- What are the design parameters of this system and its components that influence their performance?

The performance of DCHEs depend on its design and the operating conditions. In this thesis, the air and water flow rates and temperatures are the main performance variables, along with some important geometric parameters of the heat exchanger itself. The ETC performance is affected by the solar irradiation, solar absorber area and the tube tilt angles. The SHE and HRD subsystems are largely affected by the air and water flow rates and temperatures as well.

Design

- What are the different ways in which this cooling strategy can be integrated as a façade system, and which one is more cost-effective?

A façade-integrated HVAC system can be either fully decentralised on the façade itself or semi-centralised, whereby the façade module would be connected to various other components centralised at other parts of the building. This thesis thus focuses on comparing a fully decentralised façade cooling system against a semi-centralised one. Based on calculations, the semi-centralised concept was more cost-effective because it uses less material for the water tanks and water piping, and features a more efficient physical distribution of the ETC tubes. It uses the void deck to place the water tanks, and both the roof and façade for solar heat collection. Maintenance must be done by both the residents and an appointed maintenance crew at least bi-annually to clean the windows, fans, air filters, and monitor the state of the ETC tubes.

- What implications and limitations does the façade system have?

The façade system alters the look of the building façade and potentially the urban environment. Based on calculations, it would be financially more viable to replace the façade-located ETC tubes with a water heater for the water tanks, but the operation of the water heaters may induce more carbon emissions. Singapore's Urban Heat Island effect is unfortunately further worsened by the façade system because its exhaust air is warmer than the heated air from an air-conditioner's condenser. The bedroom daylighting is marginally worsened due to the shading from the façade module, but there is still sufficient lighting in the bedroom for relevant bedroom activities. The minor issues of the façade system pertain to how it is unable to conduct cooling on the 3rd bedroom of the apartment due to its location and the building typology, and how daytime cooling is discouraged because it reduces the total possible cooling duration at night later on. The main limitation of the façade module is its ability to adapt to other scenarios of high-rise residential buildings. The building's height, massing, façade orientation, and typology all pose as limits to the façade system. In some situations, the façade system just has to be redesigned to cater to the different building type, but in other situations, the façade system is just not feasible. Above all, its energy consumption means that it will never become a reality in the near future because it is unable to compete with the energy efficiency of existing domestic air-conditioning systems.

6.3 Reflection on Graduation Project

This project focuses on how a retrofit facade-integrated cooling system may be implemented on an existing high-rise residential building in the tropics and how feasible it actually is. It narrows down towards an environmentally-friendly cooling method, under the premise that typical air conditioner refrigerants are gradually getting phased out under the Montreal Protocol. It is therefore an exploration into future cooling systems for existing buildings.

From Research to Design

For P2, work mostly consisted of literature reviews of cooling technologies and the context. Case studies were also investigated to gain a sense of how HVAC systems can be integrated into the façade. This helped to narrow the project down to a scope that focuses on retrofit facades meant to be attached onto existing facades, as opposed to tearing down the existing walls and completely replacing them with new ones. The case studies also shed some light on how the cooling system may be incorporated not just as something attached to the outer wall, but also forming the basis of the façade, resulting in an architectural integration of a cooling system.

For P3, the project was ultimately narrowed down to investigate 2 main ways that the system can be structured: decentralised versus centralised. While it is not so much of a surprise that the centralised concept is more cost-effective in the end, it is worth noting that this outcome could not have been based on simple assumptions of typical costs of centralised and decentralised systems, because the range of case studies included built projects of both centralised and decentralised systems, suggesting that the choice between centralised and decentralised is not clear cut and therefore calculations had to be made. Their workability highly depends on the design of the existing building and its context. It is also based on further calculations that the project was forced to alter these initial concepts to suit the context. This led to the necessary alteration of the concepts to allow for the placing of the ETCs on both the facade and roof for both concepts. The calculations were all done in Excel using equations retrieved from scientific papers. These equations were tested using values from research papers to verify its accuracy. Simple simulations were also done in Grasshopper for solar irradiation on the roof and facade, with a bit of optimisation for the facade.

Initially, the cooling load was determined merely by calculation from the statistical average energy consumption of air-conditioners in Singapore. Using this cooling load value gave some comfortable results where the solar collectors could be completely roof-based or façade-based. However, DesignBuilder gave a completely different picture, showing a much higher cooling load. This could be because the statistical average does not show the highs and lows of the data, while DesignBuilder gives the peak cooling load. Using the DesignBuilder cooling load thus ensured that the facade system could properly cater to the bedroom's cooling load in all scenarios, rather than just the statistical average, which might not even be the case in reality because it is possible that the average is attained from many extreme highs and lows. The DesignBuilder cooling capacity was thus the more accurate value to work with.

2 rounds of component sizing were done; the first was mainly to give a starting point for the sizes, while the second was to fine tune the sizes according to the equations to achieve the required cooling capacity. A few important design-related values (such as the ETC's ratio of absorber area to gross area) were determined directly by the geometry designed in Rhino used for the solar irradiation simulations. The calculations in Excel were also checked by recalculating them using a different order of steps. Overall, this approach feedbacks if the facade cooling system works or not. With the manual component sizing, it was 'forced' to work, and it gave a feedback on how much space was needed, resulting in the conclusion in which more space was required for both facade concepts. On top of that, the focus on the worst-case scenarios throughout the project ensured a 'safety factor' so that the system was slightly oversized and working all the time.

Design development was also done to find out how much heat loss there was and to compensate for it. Excess solar heat energy collection was also investigated to know the required maintenance schedules to ensure the system worked well. Christien mentioned about how it is important to take note of the heat loss through the system. Factoring this into the calculations led to a conclusion that a small amount of ETCs had to be added to the facade in addition to those already there. The geometry of the water tank also affected both the material use and the heat loss through conduction. Maintenance costs were done by rough estimations rather than hard numbers so that a rough but fair comparison could still be done between the facade concepts. Because the entire system was eventually oversized, some calculations were also done to investigate how oversized it really is, and how much system failure can be tolerated before its performance dips below the required levels. Adding the maintenance calculations to this, it was discovered how frequent maintenance cycles had to be to ensure the system failures stay below the accepted values.

For P4, the façade module details pertaining to structural elements to attach it to the existing façade, maintenance procedures, and joint and window details were developed. Design details drew inspiration from existing window frame products designed for tropical climates, existing vacuum tube collector products, and consultations from the architecture faculty. Existing commercial products for fans and air filters were also explored to understand their dimensions and noise levels. Both Alejandro and Christien brought up valid points about the design and detailing of the façade module all the way until the P5 presentation.

Overall, the design of the facade system is informed by scientific research done beforehand. Although some assumptions were made regarding detailed engineering aspects, this project serves to give designers and engineers a rough idea as to how a tropical retrofit facade-integrated cooling system may be conceived, how it functions, under what context is it applicable, and under what conditions does it perform well and poorly. It also gives some insight into other factors that determine if such a cooling concept is feasible on a large scale. As a method of space cooling, it is relevant to areas of the world where cooling is much needed. However, the operating conditions and environments of the façade module is highly specific, so it cannot merely be replicated in any other part of the world, even within the same country. Its feasibility is therefore very limited, but as time progresses, advancements and improvements in its technology may pave way for more adaptable designs.

Relevance to Society

While it is no secret that such a retrofit façade system is far from becoming a reality, its existence directly influences the world of architecture and the built environment, as described in Section 6.2.1. The façade module in this thesis focuses on its workability. This puts the architectural form of the façade on a lower priority, which, while not necessarily taken as a negative aspect, transforms the urban environment towards a more monotonous layout. However, it could also be argued that with this specific retrofit façade-integrated cooling concept, various other façade forms could also be derived. This thesis merely focuses on the workability of 1 style. Nevertheless, it is important to know that this façade can and will alter the look of a city, which has significant effects on the future of public housing designs and their desirability. Urban heat island effect is also mentioned in Section 6.2.1, where the retrofit façade is proven to have a more detrimental effect than the traditional air-conditioner. However, this might change as desiccant technology progresses with improvements in efficiency. Any in case, the UHI problem would still pose as a barrier to the realisation of this retrofit façade system.

The application of this system was focused on tropical high-rise residential buildings, but its transferability is largely limited to the building typology. Void decks are common in Singapore's public housing buildings, but the same cannot be said for residential buildings in other countries. The massing, urban context and building orientation also largely determine the maximum effective height of the retrofit system and the effectiveness of façade solar heat collection. Large parts of Indonesia experience bad air quality due to deforestation. This limits the use of the retrofit façade system since it takes air directly from the outside. The retrofit façade system would need to be redesigned to specifically cater to such polluted regions where the air filter needs to be much more easily accessible for frequent washing.

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8 Appendices

8.1 Figures

8.2 Tables

8.3 Calculations

8.3.1 Component Sizing

Required air flow rate (m3/h)	**301.68**

DCHE (from experiment by Ge et al, 2017)	
Experimental size (m)	0.23 x 0.2 x 0.045
Frontal Area (m2)	0.046
Thickness (m)	0.045
Experimental air flow rate (m3/h)	232
Sizing factor	1.300344828
Required frontal area (m2)	0.059815862
Required frontal area, rounded (m2)	0.06

SHE (from experiment by Ge et al. 2017)	
Experimental size (m)	0.23 x 0.2 x 0.045
Frontal Area (m2)	0.046
Thickness (m)	0.045
Experimental air flow rate (m3/h)	232
Sizing factor	1.300344828
Required frontal area (m2)	0.059815862
Required frontal area, rounded (m2)	0.06

HRD (from experiment by Zhao et al. 2016)	
Experimental size (m)	0.4 x 0.4 x 0.15
Frontal Area (m2)	0.16
Thickness (m)	0.15
Experimental air flow rate (m3/h)	700
Sizing factor	0.430971429
Required frontal area (m2)	0.068955429
Required frontal area, rounded (m2)	0.069

ETC (from experiment by Kumar, A., & Yadav, A. 2016)	
Experimental size (m2)	0.8325
Experimental air flow rate (m3/h)	142.76
Sizing factor	2.1132
Required frontal area (m2)	1.7593
Required frontal area, rounded (m2)	1.76

Cold water tank (from experiment by Ge et al, 2017)	
Experimental size (Litres)	30
Experimental air flow rate (m3/h)	232
Sizing factor	1.300344828
Required volume (Litres)	39.01034483
Required volume, rounded (Litres)	40

Cold water tank (from experiment by Ge et al, 2017)	
Experimental size (Litres)	30
Experimental air flow rate (m3/h)	232
Sizing factor	1.300344828
Required volume (Litres)	39.01034483
Required volume, rounded (Litres)	40

Hot water tank (from experiment by Zhao et al. 2016)	
Experimental size (Litres)	500
Experimental air flow rate (m3/h)	700
Sizing factor	0.430971429
Required volume (Litres)	215.4857143
Required volume, rounded (Litres)	216

8.3.2 Cooling Capacity

Bedroom Properties	
Floor area of bedroom (m^2)	15.12
Floor area of Master bedroom without toilet (m^2)	16.54
floor to ceiling height (m)	2.625
volume of Master bedroom (m^3)	43.4175
Required Air Change Rate (/h)	3
Required volumetric flow rate of air (m^3/s)	**0.036181**
COP of VCS	5.4
Number of hours of air conditioning usage per night	7
Required cooling capacity from Designbuilder (kW)	2.64
Required cooling capacity from Designbuilder (W)	**2640**
Required volumetric flow rate of air from Designbuilder (m^3/s)	0.0838
volumetric flow rate of air (m^3/h)	**301.68**

Air Properties	
Density of air (kg/m^3) (at 1stp, 27.5deg, 83% RH)	1.16
temperature inlet (Celsius)	27.5
specific humidity inlet (kg/kg) (at 1 stp, 83% RH)	0.01892
enthalpy inlet (J/kg)	75951.68
Pressure Drop (Pa) (at 0.7 air velocity)	17
volumetric flow rate of air (m^3/h)	310
volumetric flow rate of air (m^3/s)	0.086111
Air velocity (m/s)	0.933454
mass flow rate of air (kg/s)	0.099889
Air Change Rate (/h)	7.139978
Specific heat capacity of air (J/kg K)	1005
fan COP	0.35
Fan power consumption (W)	8.365079

Water Properties	
Density of water (kg/m^3)	1000
Cooling water temperature (Celsius)	20
Regen water temperature (Celsius) (80)	80
Specific heat capacity (J/kg K)	4185.5
Mass flow rate of water (for night) (kg/s)	0.08
Volumetric flow rate of water (m^3/s)	0.00008
Mass flow rate of water (for day) (kg/s)	0.02
Latent heat of vaporisation (J/kg)	2256000

DCHE			
dehumidification		regeneration	
average cyclic moisture removal (kg.kg)	0.007944	average cyclic moisture removal (kg.kg)	0.007944
temperature outlet (Celsius)	25.5	temperature outlet (Celsius) (34.5)	55
specific humidity outlet (kg/kg)	0.010976	specific humidity outlet (kg/kg)	0.023044
enthalpy outlet (J/kg)	53624.39	enthalpy outlet (J/kg)	115320.6
heat exchange betweeon air and water (W) (sensible + latent)	2230.248	heat exchange betweeon air and water (W) (sensible + latent)	-5061.3
Sensible cooling power (W)	200.7767	Sensible heating power (W)	2911.262
Latent cooling power (W)	2029.472	Latent heating power (W)	2150.038
cooling water temperature out (Celsius)	20.59962	Heat from heating water with HRD (W)	-2530.65

DCHE geometry constants	
fin pitch (m)	0.0015
fin thickness (m)	0.000115
Depth (m) (0.1)	0.2
Width (m)	0.5
Height (m)	0.2
Volume (m^3)	0.02
fin area (m^2)	0.1
number of fins	124
total transfer surface area (m^2)	24.8
surface area density (m^2/m^3)	1240
minimum free-flow area (m^2)	0.09225
frontal area (m^2)	0.1
ratio of minimum free-flow to frontal	0.9225

SHE	
temperature outlet (Celsius)	21.5
specific humidity outlet (kg/kg)	0.010976
enthalpy outlet (J/kg)	49518.72
heat exchange betweeon air and water (W) (sensible only)	410.1099
cooling water temperature out (Celsius)	21.22479

Indoor Air	
temperature outlet (Celsius)	26
specific humidity outlet (kg/kg)	0.0151
enthalpy outlet (J/kg)	64651.34

SHE geometry constants	
fin pitch (m)	0.0015
fin thickness (m)	0.000115
Depth (m)	0.045
Width (m)	0.5
Height (m)	0.2
Volume (m^3)	0.0045
fin area (m^2)	0.0225
number of fins	124
total transfer surface area (m^2)	5.58
surface area density (m^2/m^3)	1240
minimum free-flow area (m^2)	0.09225
frontal area (m^2)	0.1
ratio of minimum free-flow to frontal	0.9225

Total Cooling Power of whole cooling system (W)	2640.358
Latent cooling power (W)	2029.472
Sensible cooling power (W)	610.8866

Supply Air	
Temperature (Celsius)	21.5
Humidity ratio (kg/kg)	0.010976
air pressure (kPa)	101.325
water vapour saturation pressure (kPa)	2.55917
Relative Humidity (%) (from psychrometric chart)	69.86641

Regen Water		with HRD
heat loss to regen over night (Wh)	20378.83	10189.42
water tank volume (Litres)	300	
regen water temperature after night (Celsius)	21.57305	50.78653

Cold Water	
sensible heat gain from air (W)	610.8866
water tank volume (Litres)	40

8.3.3 Required ETC Absorber Area

Roof solar irradiation

Month	Day	Solar irradiation per day (kWh/m²/day)	Month's average per day (kWh/m²/day)
1	7	4.667	4.725
	14	3.239	
	21	4.732	
	28	4.049	
2	7	5.444	4.524
	14	5.112	
	21	4.787	
	28	4.339	
3	7	4.962	4.52
	14	4.677	
	21	4.654	
	28	6.199	
4	7	4.295	4.256
	14	4.273	
	21	4.419	
	28	4.038	
5	7	5.046	3.912
	14	4.14	
	21	4.925	
	28	3.585	
6	7	4.495	3.535
	14	4.336	
	21	3.708	
	28	3.572	
7	7	3.155	3.809
	14	2.751	
	21	4.426	
	28	4.784	
8	7	4.841	3.911
	14	3.887	
	21	3.49	
	28	4.11	
9	7	5.307	4.066
	14	4.413	
	21	2.807	
	28	3.449	
10	7	4.588	4.393
	14	2.652	
	21	6.854	
	28	4.796	
11	7	2.923	4.183
	14	4.691	
	21	4.846	
	28	4.643	
12	7	1.812	4.309
	14	4.645	
	21	4.627	
	28	6.505	

Centralised ETC system

Building Dimensions	
Length (m)	112.5
Width (m)	11.9
Roof obstruction length (m)	28
Roof obstruction width (m)	6.4
Roof total floor area (m^2)	1338.75
Roof usable floor area (m^2)	**1159.55**
Constants	
ETC efficiency (%) (based on literature reviews)	0.8
ETC collector cost (SGD/m^2)	450
ETC collector cost (Euro/m^2)	292.5
Cost of water pump as ratio of ETC	0.1
SGD to Euro exchange rate (based on google in March 2019)	0.65
regen water temperature after night (Celsius)	50.78652
regen water temperature by evening (Celsius)	80
Specific heat capacity (J/kg K)	4185.5

Calculations for roof space

Total mass of hot water (Litre)	66000
Required solar energy per day (kWh)	2241.6715
Required total roof solar absorber area (m^2)	792.67026
Absorber area to Gross area ratio (depending on product)	0.6257
Estimated floor area required for solar collectors (m^2)	1266.853
Absorber area to Gross area ratio (with walking space)	0.441468
Estimated roof floor area required (m^2) (with walking space)	**1795.533**

Calculations for façade-located ETC tubes

% of ETCs secured by roof	**0.645797**
Solar absorber area on roof (m2)	511.9042
Remaining lacking gross area for façade (m2)	635.9828
Total solar absorber area for façade based on roof ratio (m2)	280.766
Solar absorber area for façade per bedroom with roof power (m2)	1.276209
Solar absorber area for façade per bedroom with façade power (m2)	**3.470307**
Required gross area for façade per bedroom with façade power (m2)	**6.058283**
Total solar absorber area for semi-centralised (m2)	1275.372
% less solar absorber area for semi-centralised concept	**10.62205**

8.3.4 Water Tank Material Calculations

Fully decentralised	
Hot water tank surface area (m2)	4.465
Hot water tank volume (Litres)	320
Hot water tank surface-volume ratio	13.95313
Cold water tank surface area (m2)	1.0497
Cold water tank volume (Litres)	43.6
Cold water tank surface-volume ratio	24.07569
Total surface area of all water tanks (m2)	1213.234

Semi-centralised	
Hot water tank surface area (m2)	58.72
Hot water tank volume (Litres)	33000
Hot water tank surface-volume ratio	1.779393939
Cold water tank surface area (m2)	25.73
Cold water tank volume (Litres)	8800
Cold water tank surface-volume ratio	2.923863636
Total surface area of all water tanks (m2)	143.17
% material savings for semi-centralised concept	**88.19930862**

8.3.5 Water Piping Material Calculations

Constants	
Copper pipe thickness (mm)	1.58 7
Heat loss at delta T 55°C without insulation, nominal bore 15mm (W/m)	45
Heat loss at delta T 55°C without insulation, nominal bore 28mm (W/m)	76
Heat loss at delta T 55°C with 25mm insulation, nominal bore 15mm (W/m)	6
Heat loss at delta T 55°C with 25mm insulation, nominal bore 28mm (W/m)	10
Density of copper (kg/m^3)	8690
Building	
Void deck height (m)	3.6
Number of residential floors	11
residential unit floor to floor height (m)	2.8
Number of units per level	10
Total building height (m)	34.4
Number of bedrooms per unit	2
Water	
Mass flow rate of water (kg/s) for day time	0.02
Mass flow rate of water (kg/s) for night time(0.4 or 0.08)	0.08
Specific heat capacity (J/kg K)	4185

Fully decentralised	
Required copper pipe nominal bore (mm)	15
Total copper pipe diameter (mm)	18.175
Vertical piping length for 2nd floor apartment (m)	30.8
Total piping distance (up + down) (m)	61.6
Max heat loss without insulation (W)	2772
Max heat loss with 25mm insulation (W)	369.6
Cross sectional area of pipe (mm^2)	82.7264794
Cross sectional area of pipe (m^2)	8.2726E-05
Vertical piping length for different floors apartment (m)	
1	5.6
2	11.2
3	16.8
4	22.4
5	28
6	33.6
7	39.2
8	44.8
9	50.4
10	56
11	61.6
Total length of vertical piping (m)	7392
Total volume of piping (m^3)	**0.61151414**
Total weight of piping (kg)	**5314.05784**

Semi-centralised	
Required copper pipe nominal bore (mm)	28
Total copper pipe diameter (mm)	31.175
Vertical piping length from water tank to roof (m)	34.4
Total piping distance (up + down) (m)	68.8
Heat loss without insulation (W)	5228.8
Heat loss with 25mm insulation (W)	688
Cross sectional area of pipe (mm^2)	147.5611
Cross sectional area of pipe (m^2)	0.0001476
Total vertical water travel length (m)	1311.2
Total volume of piping (m^3)	**0.193482111**
Total weight of piping (kg)	**1681.359549**
% material savings for semi-centralised concept	**68.36015718**

8.3.6 Heat Loss Calculations

Water Tanks

Per hot water tank	
mineral wool insulation 4cm heat transfer coefficient (W/m^2K)	0.8
heat loss from water tank conduction (W)	2466.24
Water tank volume (Litres)	33000
Specific heat capacity (J/kgK)	4185.5
Solar collector adjustment	
Energy lost during daytime (kWh)	29.59488
Total additional façade absorber area required (m2)	**28.45661538**
Additional façade absorber area required per apartment unit (m2)	**0.258696503**

Water Piping

Total length of vertical piping (m)	688
Total heat loss without insulation (W)	26144
Total heat loss with 25mm insulation (W)	3440
Total volume of piping (m^3)	0.101522
Total weight of piping (kg)	882.22649
Heat loss experienced per level during Night-time operation (W)	
1	72
2	128
3	184
4	240
5	296
6	352
7	408
8	464
9	520
10	576
11	632
Worst temperature change while travelling up to top floor (Celsius)	**0.9437343**
Minimum hot water temperature to leave water tank for regen	50.943734

Heat loss experienced during Daytime solar heat collection	
Total vertical water travel length (m)	623.2
Total heat loss without insulation (W)	47363.2
Total heat loss with 25mm insulation (W)	6232
Total volume of piping (m^3)	0.091960076
Total weight of piping (kg)	799.1330618
Total solar energy lost (kWh)	74.784
Total additional façade absorber area required (m2)	**71.90769231**
Additional façade absorber area required per apartment unit (m2)	**0.653706294**

Factoring in heat losses from water pipes and tank conduction	
Additional facade solar absorber area required per apartment (m2)	**0.912403**
Required final solar absorber area per apartment on façade (m2)	**7.85301**
Actual solar absorber area per apartment on façade (m2) (from rhino)	**7.91**
Actual total solar absorber area on façade (m2)	**870.1**
Total solar absorber area for whole building (m2)	**1382.00**
% less solar absorber area for semi-centralised concept	**3.14926**

8.3.7 Excess Solar Energy Calculations

Month	Monthly average solar irradiation on roof (kWh/m²)	Monthly average solar irradiation for North facade (kWh/m²)	Total solar collection on roof (kWh)	Total solar collection on façade (kWh)	Total monthly average daily solar energy collected (kWh)	Usable solar energy with 80% efficiency (kWh)	Required solar energy per day (kWh)
1	4.725	1.206	2418.747437	1049.3406	3468.088037	**2774.470429**	2292.8169
2	4.524	1.214	2315.854689	1056.3014	3372.156089	**2697.724871**	2292.8169
3	4.52	1.446	2313.807072	1258.1646	3571.971672	**2857.577337**	2292.8169
4	4.256	2.131	2178.664358	1854.1831	4032.847458	**3226.277966**	2292.8169
5	3.912	2.866	2002.569306	2493.7066	4496.275906	**3597.020725**	2292.8169
6	3.535	3.027	1809.581416	2633.7927	4443.374116	**3554.699292**	2292.8169
7	3.809	3.083	1949.843172	2682.5183	4632.361472	**3705.889177**	2292.8169
8	3.911	2.399	2002.057402	2087.3699	4089.427302	**3271.541842**	2292.8169
9	4.066	1.535	2081.402556	1335.6035	3417.006056	**2733.604845**	2292.8169
10	4.393	1.333	2248.795236	1159.8433	3408.638536	**2726.910829**	2292.8169
11	4.183	1.23	2141.29535	1070.223	3211.51835	**2569.21468**	2292.8169
12	4.309	1.172	2205.795281	1019.7572	3225.552481	**2580.441985**	2292.8169

Hot water temperature by end of night (Celsius)	50.12
Required solar energy per day (kWh)	2292.81
Usable solar energy in worst -case scenario (Nov) (kWh)	2569.21
Surplus in worst-case scenario (Nov) (kWh)	**276.397**
Maximum percentage of ETC you can afford to breakdown all year (%)	**10.758**
Resulting ETC efficiency with max % of ETC tube broken down (%)	**71.393**
Number of ETC tubes that can afford to be broken down	**1689.446**

8.3.8 Energy Consumption and Efficiency

Decentralised Warm Water Tank (only night-time use)	
Water Temperature Start (Celsius)	53
Water Temperature End (Celsius)	49.2
Delta T (Celsius)	3.8
Water Volume (Litres)	18
Energy needed to heat water every cycle (J)	286288.2
Time taken per cycle (mins)	10
Number of cycles per night (7 hours)	42
Total energy needed to heat water every night (J)	12024104
Heater COP	0.9
Energy consumption per bedroom (kWh)	**3.711143**
Power consumption per bedroom (kW)	**0.530163**
Total energy consumption every night (kWh)	816.4515
Power consumption every night (kW)	116.6359

Centralised Cold Water Tank (only night-time use)	
sensible heat gain from air (W)	134395.05
water tank volume (Litres)	8800
water tank surface area (m^2) (from rhino)	25.73
mineral wool insulation 4cm heat transfer coefficient (W/m^2K)	0.8
heat loss from water tank conduction (W)	154.38
TEC cooler COP	0.5
power consumption for water cooler (W)	269098.85
Power consumption every night (kW)	269.09885
Energy consumption every night (kWh)	1883.692
Power consumption every night per bedroom (kW)	**1.2231766**

Fans (only night-time use)	
Required air flow rate (m3/h)	310
Required air flow rate (CFM)	182.435
Fan air flow rate (CFM) (based on commercial product)	70.74
Number of fans per fan module	3
Air flow rate of 1 fan module (m3/h)	360.56178
Number of fan modules per bedroom	4
Fan voltage (V)	12
Fan Current (A)	0.19
Fan power consumption (W)	2.28
Fan power consumption per bedroom (kW)	**0.00912**
Fan energy consumption per bedroom (kWh)	**0.06384**

Façade-located ETCs	
Total solar absorber area for whole building (m2)	1382
Actual total solar absorber area on façade (m2)	870.1
Annual average share of solar energy collected by façade ETCs	0.42044
Maximum share of solar energy collected by façade ETCs	0.59275
Maximum solar energy collected by façade ETCs (kWh)	**2682.52**
Day time facade water pump power consumption (kW)	**0.06714**
Day time facade water pump energy consumption (kWh)	**0.80573**
Daily operating cost of just façade-located ETCs (Euro)	0.10841
Total operating cost of façade-located ETCs over 20 year lifetime (Euro)	791.398
Night-time power consumption per water pump (kW)	0.03333
Night-time power consumption for 2 water pumps (kW)	0.06666
Night-time energy consumption for 2 water pumps (kWh)	0.46662
Daily operating cost of water pumps for night-time (Euro)	**0.06278**
"initial cost" of façade-located ETC tubes (Euro)	386100
Total maintenance cost of facade-located ETCs (Euro)	488400
Total investment cost of façade-located ETCs (Euro)	**875291**

Cooling Capacity per bedroom (kW)	2.640358
Total power consumption per bedroom (kW)	1.896263
Power Efficiency	1.392401
Daily cooling energy per bedroom (kWh)	18.48251
Daily energy consumption per bedroom (kWh)	13.60956
Energy Efficiency	1.358053

8.3.9 Fan Noise

The equation to calculate the noise level of a source with multiple of the same sources is as follows:

$$L_t = L_s + 10 \log (n)$$

Where L_t is the total signal level in dB, L_s is the noise level of 1 source in dB, and n is the number of sources.

Based on commercial product "Noctua NFP-12 redux-1700 PWM", Ls = 25.1 dB.

During operation, the total number of fan units running is 6, so n = 6.

$$L_t = 25.1 = 10 \log (6) = 32.1 \text{ dB}$$

8.3.10 Water Heater Substitute Calculations

Constants	
ETC system efficiency	0.8
Hot water temperature by end of night (Celsius)	50.12
Required solar energy per day (kWh)	2292.
Usable solar energy in worst -case scenario (Nov) (kWh)	2569.
Surplus in worst-case scenario (Nov) (kWh)	276.4
Maximum percentage of ETC you can afford to breakdown all year (%)	10.75
Resulting ETC efficiency with max % of ETC tube broken down (%)	71.39
Number of ETC tubes that can afford to be broken down	1689.
Mass flow rate of water (kg/s) for daytime	0.02
Volumetric flow rate of water for daytime (m3/h)	0.072
Mass flow rate of water (kg/s) for night-time	0.08
Volumetric flow rate of water for night-time (m3/h)	0.288
Specific heat capacity (J/kg K)	4185
Density of water (kg/m3)	1000
Differential height for daytime water pumping with façade-located ETCs (m)	311.6
Differential height for daytime water pumping without façade-located ETCs (m)	34.4
Maximum differential height for night-time water pumping (m)	34.4
Water pump efficiency	0.9
Water motor efficiency	0.9
Gravity (m/s2)	9.81
SGD to Euro exchange rate	0.65
Electric energy cost in SG (SGD/kWh in 2018)	0.207
Electric energy cost in SG (Euro/kWh in 2018)	0.1346

Energy Requirement of Water Heaters

Month	Total solar collection on roof (kWh)	Usable solar energy with 80% efficiency (kWh)	Required solar energy per day (kWh)	Usable solar energy from roof (kWh)	Remaining energy required from heaters with excess for roof ETC 10% margin for breakdown (kWh)
1	2418.747437	2774.470429	2292.8169	1934.997949	551.3187456
2	2315.854689	2697.724871	2292.8169	1852.683751	625.4015242
3	2313.807072	2857.577337	2292.8169	1851.045657	626.8758084
4	2178.664358	3226.277966	2292.8169	1742.931486	724.1785624
5	2002.569306	3597.020725	2292.8169	1602.055445	850.9669995
6	1809.581416	3554.699292	2292.8169	1447.665132	989.9182808
7	1949.843172	3705.889177	2292.8169	1559.874537	888.9298164
8	2002.057402	3271.541842	2292.8169	1601.645922	851.3355705
9	2081.402556	2733.604845	2292.8169	1665.122045	794.2070596
10	2248.795236	2726.910829	2292.8169	1799.036189	673.6843302
11	2141.29535	2569.21468	2292.8169	1713.03628	751.0842482
12	2205.795281	2580.441985	2292.8169	1764.636225	704.6442974

Replacing façade ETCs with 2x hot water heaters	
Heater COP (Electric)	0.9
Average daily energy demand from both water heaters (kWh)	**752.712**
Average daily power consumption per bedroom (kW)	**0.3168**
Maximum daily energy demand from both water heaters (kWh)	989.918
highest daily energy consumption of substitute water heaters (kWh)	1099.91
Highest daily energy consumption per bedroom (kWh)	4.99959
Highest daily power consumption per bedroom (kW)	0.41663
Highest daily operating cost of both water heaters (Euro)	147.993
Maximum operating cost of both water heaters over lifetime (Euro)	540174
Average operating cost of both water heaters over lifetime (Euro)	**410736**
initial cost of a water heater (SGD)	1200
Maintenance cycle duration of water heater (years) (?)	0.5
Life expectancy of water heater (years)	10
Number of maintenance cycles over lifetime	20
Cost per maintenance per water heater (Euro)	136
Total maintenance cost of 2x hot water heaters for lifetime (Euro)	5440
Total investment cost of 2x hot water heaters for lifetime (Euro)	418576
Investment cost of 2x hot water heaters for 20 years (Euro)	**837152**

8.3.11 Height Limit Calculations

Number of bedrooms per floor	20
Building roof area (m2)	1160
Average available roof area per bedroom (m2)	58
Available façade area per bedroom (m2) from rhino	23.44
Number of residential floors	11
Available building façade area (m2)	5156.8
Required daily solar energy per floor (kWh)	208.4379
Roof solar energy collection (kWh)	2141.295
Facade solar energy collection for 11 floors (kWh)	1070.223
Facade solar energy collection per floor (kWh)	97.293
ETC efficiency	0.8

Number of floors	Usable solar energy collection (Façade + Roof)	Total required daily solar energy collection	Usable solar energy collection (Roof only)
1	1790.87068	208.4379	1713.03628
2	1868.70508	416.8758	1713.03628
3	1946.53948	625.3137	1713.03628
4	2024.37388	833.7516	1713.03628
5	2102.20828	1042.1895	1713.03628
6	2180.04268	1250.6274	1713.03628
7	2257.87708	1459.0653	1713.03628
8	2335.71148	1667.5032	1713.03628
9	2413.54588	1875.9411	1713.03628
10	2491.38028	2084.379	1713.03628
11	2569.21468	2292.8169	1713.03628
12	2647.04908	2501.2548	1713.03628
13	2724.88348	2709.6927	1713.03628
14	2802.71788	2918.1306	1713.03628
15	2880.55228	3126.5685	1713.03628