AR3B025 Building Technology Graduation Studio
Master Thesis

Solar Desiccant Cooling Integrated Facade Design

Exploration potential for minimizing cooling energy consumption in office buildings in hot-humid climate

Weili Huang
Student no. 5794552

First mentor: Thaleia Konstantinou
Second mentor: Eric van den Ham
Third mentor: Hamza Hamida

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Abstract

Buildings consume tremendous energy, and many are used for air conditioning, especially in office buildings. New alternatives to conventional air conditioning have become a global priority. Several studies have shown that applying solar cooling systems to façade systems is very promising in hot regions because it is recognized as a sustainable and environmentally friendly alternative to traditional compression refrigeration systems.

The intention of this research is to explore the design and development potential of solar desiccant cooling technology integration in façade systems. This study takes Shenzhen, a city in southern China, as the case with hot and humid subtropical climate contexts, and the target building typology is the new-built high rise office building. The biggest challenge is to study how to integrate multiple systems into one façade module and how they work. Additionally, it is also significant to evaluate to what extent the design solution contributes to minimizing cooling energy consumption. This thesis aims to identify the technical constraints to overcome for façade application and establish some instrumental design guides that can potentially feed future work.

Keywords

Hot-humid climate, High-rise office buildings, Solar cooling technology, Façade integration, Desiccant cooling, Desiccant enhanced evaporative cooling, Decentralized cooling

List of abbreviations

FI	Facade Integrated
SCT	Solar Cooling Technology
PV	Photovoltaic
ST	Solar Thermal Collectors
SF	Solar Fraction
BIPV	Building Integrated Photovoltaics Systems
BIST	Building Integrated Solar Thermal Collectors Systems
FIPV	Facade Integrated Photovoltaics
FIST	Facade Integrated Solar Thermal Collectors
SDEC	Solid Desiccant Cooling
LDEC	Liquid Desiccant Cooling
LDEVap	Liquid Desiccant Enhanced Evaporative (Cooling)
WWR	Window-to-Wall Ratio
WFR	Window-to-Floor Ratio

1

INTRODUCTION

1.1 Background

Our built environment is struggling with a paradoxical situation. Due to global climate change and associated rises in temperature, higher energy demand is required for more cooling space in buildings. (Santamouris, 2016) In contrast, more greenhouse gas emissions caused by higher cooling demand exacerbate global warming again.

1.1.1 Climate change and global warming

Climate change is an indisputable fact. In the IPCC (Intergovernmental Panel on Climate Change) climate change report 2021, it presents that climate change has reached a point where it is widespread across the world, rapidly changing, and intensifying (IPCC Climate Change Report, 2021). According to an analysis by NASA, global temperatures in 2023 ranked highest in the 144-year record, at 1.4°C above the early industrial (1881-1910) baseline average. (NASA, 2023) In fact, among all human activities, building-related construction and usage account for a large proportion. (Figure 1.1)

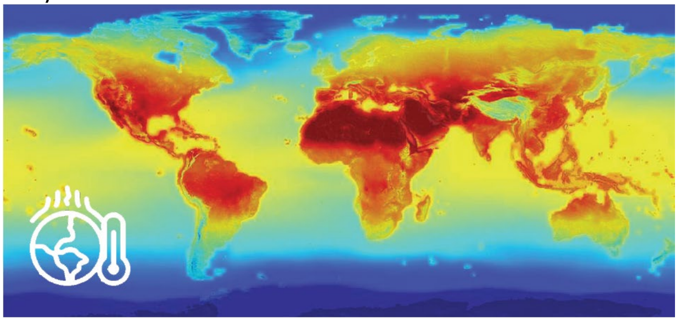


Figure 1.1 Climate change and global warming

(source: House of Lords Library, uk parliament, 2024)

1.1.2 Growth in cooling demands and energy consumption

As global temperatures continue to rise, the cooling demand in buildings gets to 37%, which has also led to increasing energy consumption. It was estimated that the global energy demand for building space cooling may continuously increase to 2050. (IEA Global Air Conditioner Stock, 2019,Figure 1.2)

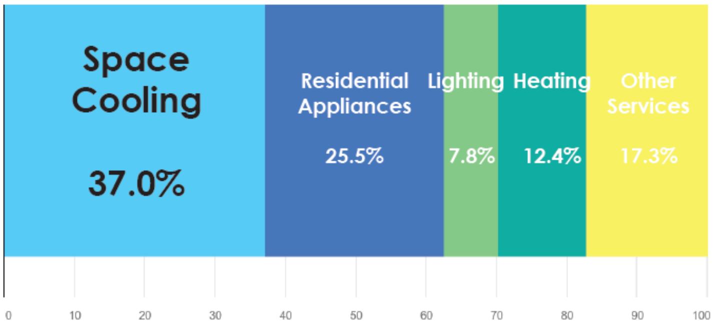


Figure 1.2 Rapid growth in global cooling demands

(source: IEA Global Air Conditioner Stock, 2019)

To be precise, a large portion of cooling energy is consumed in office buildings which may reach over 50% in hot climate regions. (Qi, 2006; Prieto, 2018). Meanwhile, building facades, as the first layer of building envelope, play an important role in helping buildings resist atmospheric changes. According to some statistics, building facades contribute to large thermal transmittance in buildings and account for 20-30% of total energy consumption (Dall'O', Galante, & Pasetti, 2012). (Figure 1.3)

Figure 1.4 Building facades contribute to large thermal transmittance and energy consumption

(source: google images)

At the same time, with higher requirements for living standards and space comfort, people's investment in air-conditioning products has also increased significantly. Therefore, the trend of strong reliance on the conventional cooling solution – air conditioning devices emerges. As an example, yearly sales of room air conditioning units are expected to grow by 10-15%, going from 100 million worldwide in 2014 to over 1.6 billion by 2050 (Montagnino, 2017). These call for effective actions to be taken to minimize cooling needs' impact on global energy consumption.

Our built environment is struggling with a paradoxical situation. As a result, the above situation leads to a vicious circle: Global warming – Higher building (space) cooling demands – More reliance on air conditioning systems – Rapid growth of energy consumption – Increasing emission of greenhouse gas – Exacerbation of global warming again. Hence, sustainable cooling technologies applied to buildings are urgently needed. (Figure 1.5)

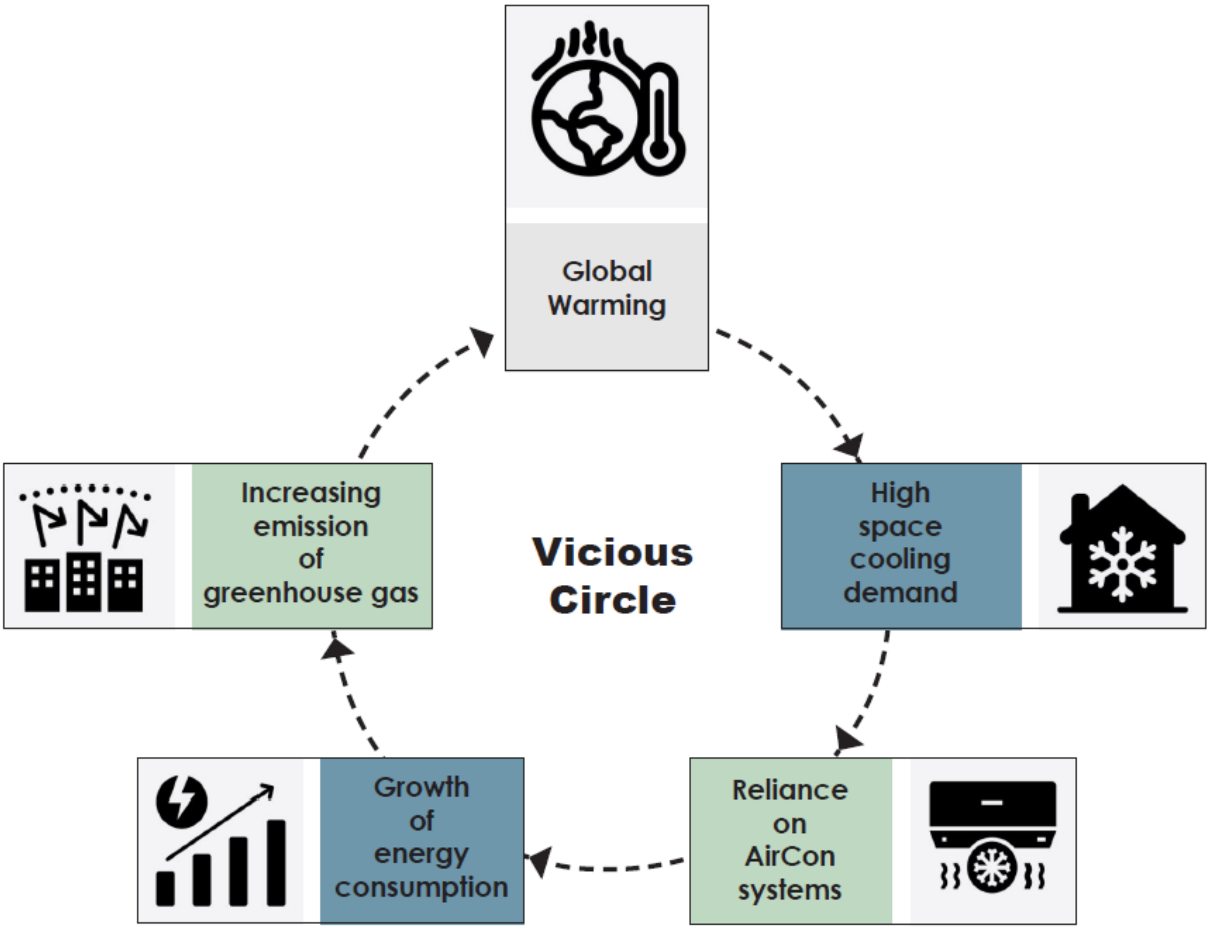


Figure 1.6 Vicious circle

(graphic: own work, 2024)

1.2 Problem statement

1.2.1 Research gap

This research initially began with two research gaps, leading to the generation of the problem statement. Based on some existing studies about the main barriers to this topic (IEA SHC Task41; Prieto, 2018), two research gaps have been found:

[a] Research gap One: lack of commercial maturity in building facade application

Solar cooling technologies have already received widespread application in building products on a small scale, like solar cooling containers and cold rooms, solar chimneys, solar energy shading devices and so on. However, the development of SCIF is still in concept but isolated from commercial use. In this situation, solar cooling devices usually work as stand-alone cooling generators, for example, being placed on the roof to harvest energy to provide electricity for the building's cooling systems, rather than behaving as part of the facade components. (SolarInvent.Freescoo) (Figure 1.7)

Figure 1.8 Research gap One

(source: google images)

[b] Research gap Two: lack of identified design guides for all stakeholders.

Due to the absence of the commercial application, there is a knowledge gap regarding identified guides of design consideration for all design stakeholders, including architects, facade designers, HVAC engineers, facade builders and system suppliers (Hamida et al., 2023). In this situation, professional knowledge from cross-aspects is highly required, including facade technology, solar energy transition and climate-responsive design. (Figure 1.9)

According to the current study by Prieto, barriers during the entire application process caused by lacking related knowledge among designers, producers and stakeholders are perceived as the most crucial issues to overcome. (Prieto, 2018).

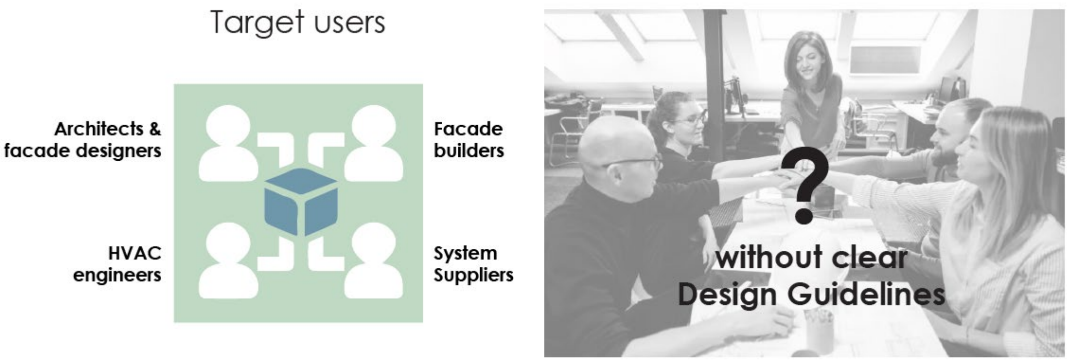


Figure 1.10 Research gap Two

(graphic: own work, 2024)

1.2.2 Problem statement

Regarding the specific climate contexts in hot-humid regions, there are no clear technical solutions associated with instrumental design guides that can provide designers with referential considerations while identifying the design process of solar cooling integrated façade.

1.3 Research objective

The main research objective:

To explore the design possibility of solar cooling integrated facade system for office buildings in specific climate conditions, aiming to evaluate the performance of the design proposal that contributes to reducing cooling energy consumption and optimizing indoor thermal comfort.

The sub-objectives are the following:

To identify all key design factors with adjustable parameters that can affect SCIF design process.

To provide technical design solutions (as exemplary facade prototypes) with performance evaluation.

To generate instructional design guides for SCIF along with referential considerations.

1.4 Research question

The main research question:

"**In hot-humid climate, how can the design application of solar cooling integrated facades minimize the cooling energy consumption for office buildings and optimize the indoor thermal comfort?**"

The following sub-questions derive from the main research question and connect to the sub-objectives in three aspects:

[a] About design factors and adjustable parameters:

"What are the specific design factors and adjustable parameters that enable to affect the design process of solar cooling integrated facades?"

[b] About design solutions:

"In terms of the performance, to what extend the solar cooling facade design solutions can reduce the cooling energy consumption and how to evaluate it?"

[c] About design guides:

"Based on the design factors, parameters and evaluation results, how to generate a design guide for solar cooling integrated façade system?"

1.5 Research context and scope

1.5.1 Location context

This research focuses on China. Located in the heart of East Asia, China is one of the fastest-growing economies in the world, but it also faces the challenge of excessive energy consumption. In 2022, China has ranked first in the mapping of energy consumption breakdown among all the countries. (Figure 1.11)Regarding the cooling demand, China accounted for about one-third of the global growth in energy used for space cooling in the past two decades, driven mainly by growth in A/C ownership in urban areas, particularly in the hot and humid regions in Southern China. (IEA The Future of Cooling in China, 2019)

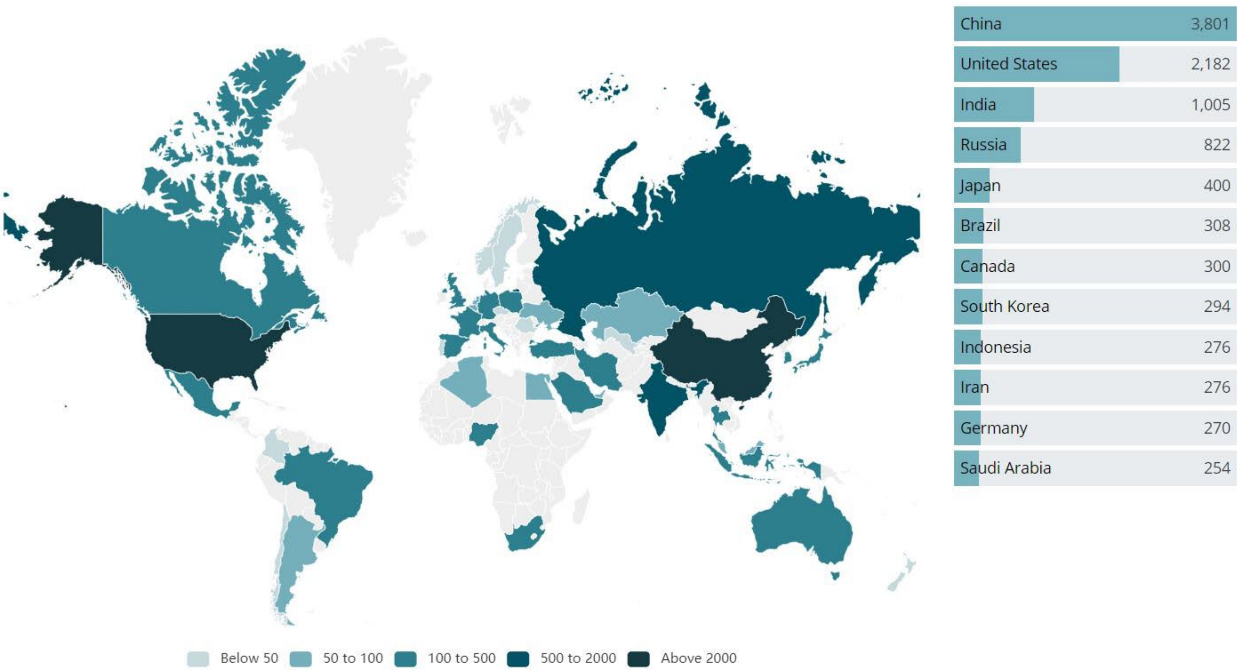


Figure 1.12 The mapping of energy consumption breakdown among all the countries

[a] Target city: Shenzhen

Shenzhen (22° 32′ 29.4″ N, 114° 3′ 34.56″ E), one of the most iconic cities in China, located in the heart of the Pearl River Delta in south of China, bordering Hong Kong to its south. (Figure 1.13) With a population of 17.56 million reported in 2020, Shenzhen is the third most populous city in China after Shanghai and Beijing. Additionally, as a special economic zone, Shenzhen is highly developed in economy and technology (Wikipedia, 2023). (Figure 1.14)

Figure 1.15 The target city: Shenzhen

(source: google images)

Figure 1.16 Shenzhen city view

(source: google images)

[b] Why Shenzhen?

There are two main reasons for choosing Shenzhen as a target city for research. First, Shenzhen is an air-conditioned city. With the hot-humid subtropical climate conditions, Shenzhen is a city that heavily relies on air-conditioning systems. Due to presented data on 'Report of Monitoring Energy Consumption of Large Public Buildings in Shenzhen 2022', 24.1% of electricity consumption has been calculated in air-conditioning cooling, especially in office buildings. Hence, solutions for reducing cooling energy consumption in urgently needed. (Figure 1.17)

Second, Shenzhen is a façade-building city. According to statistics, the total surface area of the existing building facades in Shenzhen has reached 56.73 million square meters, including 40 million square meters of glass facades. Besides, data recorded by CTBUH (the Council on Tall Buildings and Urban Habitat), Shenzhen is also a skyscraper city where it has the second largest number of over 150-meters high-rise buildings in the world. Therefore, the demand for the construction of massive energy-efficient curtain wall buildings has given rise to the potential development of this research topic. (Figure 1.18)

Figure 1.19 An air-conditioning city

Figure 1.20 A facade city

(source: google images)

1.5.2 Climate context

[a] Climate zone

Under the Köppen–Geiger climate classification, Shenzhen features a humid subtropical climate (Cwa) which stands for a warm sea climate with hot and humid summer and warm dry winter. (Shown in Figure 1.21)

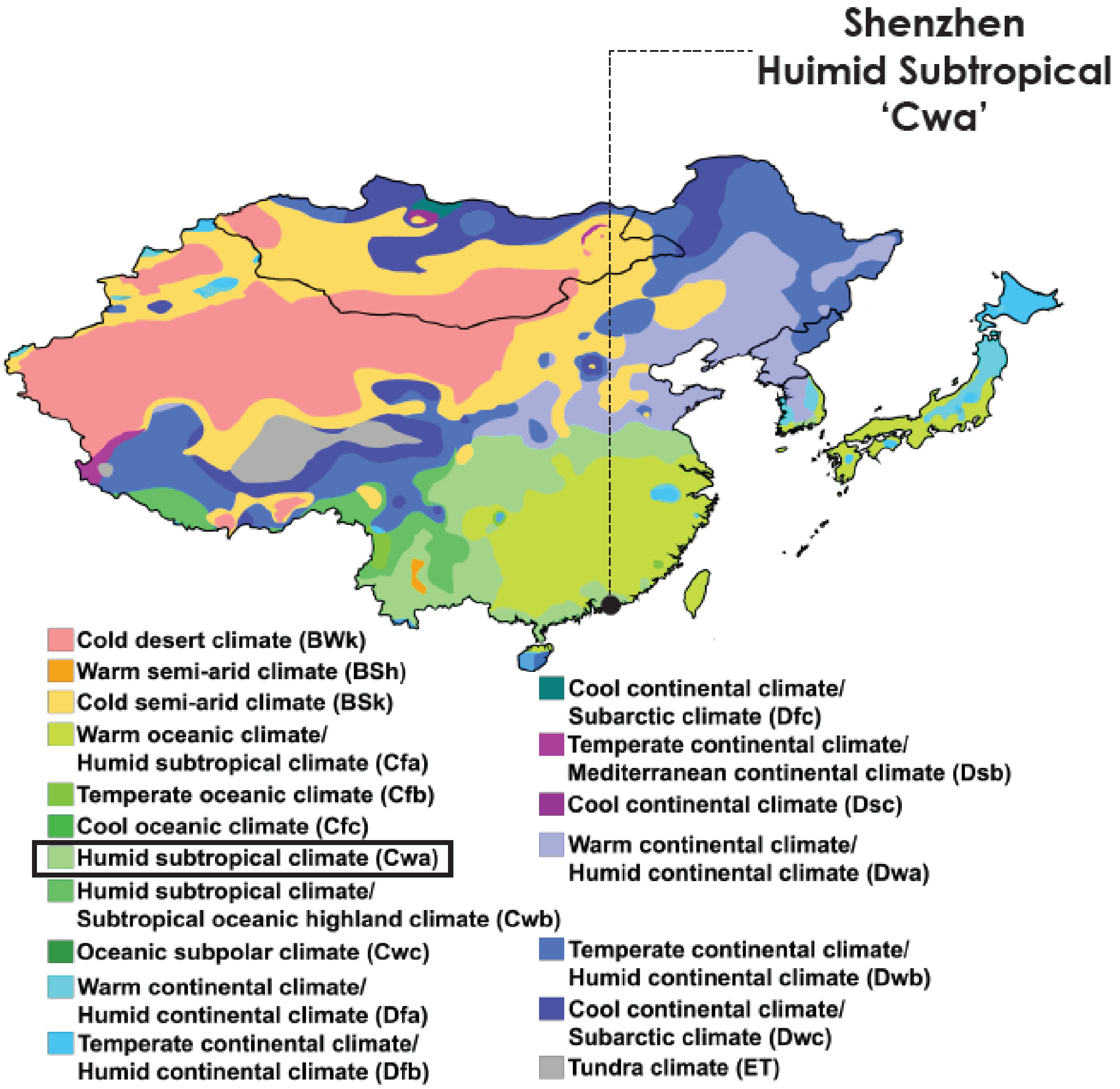


Figure 1.22 Koppen climate classification

(source: https://commons.wikimedia.org/wiki/File:Koppen-Geiger_Map_Eastern_Asia_future.svg)

As a region with a hot-humid climate, Shenzhen experiences higher humidity levels but lower temperature differences most of the year. Particularly, the mean temperature ranges between 26°C and 32°C with about 80% of relative humidity during summertime.

The intensity of solar radiation is also high in summer, as well as the long sunshine hours. Furthermore, Shenzhen is also a city with a high level of precipitation.

[b] Psychrometric chart

Through the weather data analysis of Shenzhen by Climate Consultant v6.0 program, the psychrometric map clearly shows the annual characteristics of the climatic comfort in this city. Each 'dot' on the chart represents the temperature and humidity of each 8760 hours per year. (Figure 1.23)

According to ASHRAE standard 55 using the PMV index, the result shows that only 675 hours of a year are in indoor comfort zones and about 38% of the time (pattern in cyan) the indoor temperature meets the comfort standard. (Figure 1.24)

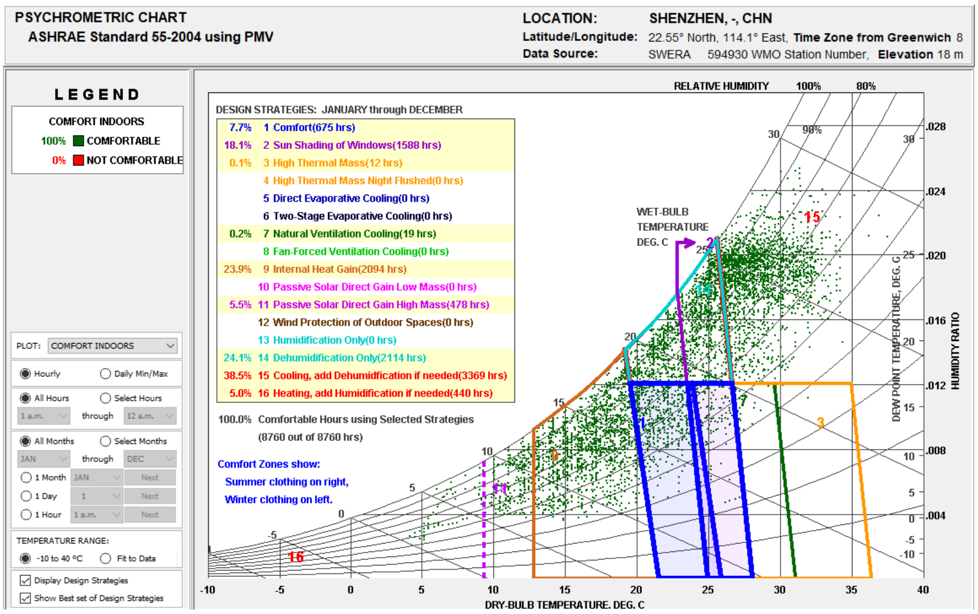


Figure 1.25 Psychrometric chart of Shenzhen

(graphic: own work, 2024)

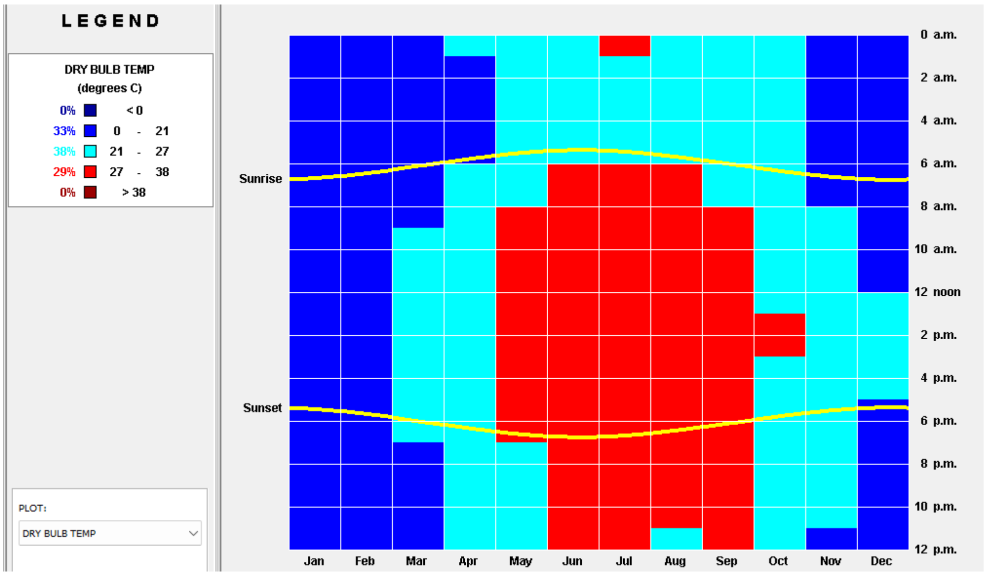


Figure 1.26 Dry bulb temperature zones in Shenzhen

(graphic: own work, 2024)

Different design strategies are given on this chart and six of them are the main yearly concerns:

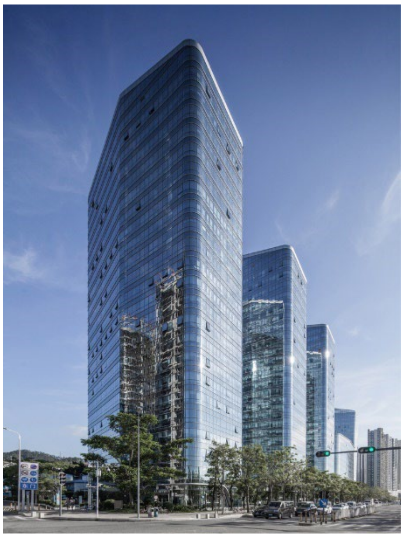
[a] 38.5% of the time, cooling is needed.
[b] 62.6% of the time, dehumidification is necessary.
[c] 23.9% of the time, internal heat gain matters.
[d] 18.1% of the time, sun shading of the windows is required.
[e] Natural ventilation for cooling could be neglected as it shows no effectiveness.
[f] Heating could also be neglected due to its less significant percentage.

In conclusion, thermal comfort in buildings needs to be achieved by both applying passive and active strategies under the hot humid climate conditions in Shenzhen. For example, providing available shading solutions is a passive way to prevent building from excessive solar heat gain, while applying suitable cooling and dehumidification systems to buildings are the active ways to remove the internal heat.

1.5.3 Features of office buildings in Shenzhen

Shenzhen has developed from a small fishing village into a metropolis just in 40 years. It is a city where high-tech and financial industries are its mainstays industries. Hence, there are many top-grade high-rise office buildings with large enterprises and multinational companies' headquarters in Shenzhen. According to Colliers' quarterly reports in 2023, Shenzhen has over 9 million square meters of office space. Most architects love to use a universal and modern design language – fully glazed curtain wall, to design the building facades systems, aiming to showcase the companies' successful image and their brands' values. As a result, most office buildings feature international glass curtain wall façade systems. Some Representative office buildings in Shenzhen are typically characterized as mentioned. (Figure 1.27)

1



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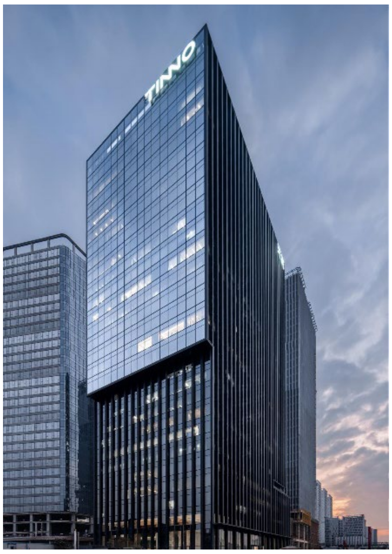

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Figure 1.28 Representative office buildings in Shenzhen

(1- Shenzhen Software Industry Base, Plot 1; 2- Shenzhen Science and Technology City Tower B; 3- Shenzhen Haiwang Tower; 4- Shenzhen Baidu Headquarter; 5- Shenzhen TINO headquarters; 6- Guosen Investment Tower; 7-Guoyin Minsheng Financial Building; 8- Shenzhen Qianhai Hualian City Business Center) (source: google images)

In fact, using the high-glazing ratio curtain wall systems in hot-humid subtropical climates is not wise. Although it has been an energy-saving conscious that most high-rise office buildings in Shenzhen have adopted this façade system with low-E coated insulating double-glazing units, the proportion of energy consumed due to large amounts of heat gain through the glazing is still high.

Moreover, regarding the building cooling modes, most high-rise office buildings use centralized cooling systems except those with stand-alone air-conditioners, such as VAV, VRV, and FCU, are some of the most-used centralized cooling systems. Because the layout of the energy center (cooling center) is usually decided in the early stage of architectural design. (Remarked: VAV- Variable Air Volume; VRV- Variable Refrigerant Volume; FCU- Fan Coil Unit)

1.5.4 Research scope and boundary conditions

[a] Building typology and status

This research focuses on the new-built high-rise office buildings. Because new-built office buildings have more design freedom than existing ones, and less constraints on design regulations and original structural safety issues. Meanwhile, they have fixed business hours during daytime for solar radiation and HVAC systems. The target building typology for this research is determined to be the one with unitized glass curtain wall façades.

[b] Specific climate conditions

This study mainly focuses on the humid subtropical climate zone, where the high temperature and humidity both prevail. Because many cities in Southern China, especially the main cites in Pearl River Delta area like Guangzhou, Hong Kong, and Macao, have the same climate conditions. Therefore, the study on such climatic characteristics is of wide applicability.

[c] Standards for indoor thermal comfort

Defined by ASHRAE Standard 55, thermal comfort is a psychological state that indicates subjective satisfaction with the thermal environment. In this study, this international standard with PMV (Predicted Mean Vote) index will be applied to both research and further design stages.

1.6 Research methodology

The overall structure of the thesis will consist of three main sections: research, design, and conclusion. Therefore, the methods used in this thesis are different.

First in the research section, literature view and case study are two primary methods applied to outline the research framework. Through relevant literature and a series of reference cases, available experience, and information (including the technical basics in solar energy system, state-of-the-art solar cooling technologies and facade system with solar cooling integration) will help define the key design factors with adjustable parameters, which give rise to defining the problem statement for this research accordingly. As followed, the research objectives and research questions are also formulated sequentially.

Secondly in the design section, the design process follows such a plan: pre-design – design implement – design assessment.

In the pre-design stage, the main task is to address the environmental contexts, aiming to analyze the weather conditions and determine the climatic strategies. In the design implement stage, different design scenarios are planned to be established: base case, improved base case, design scenario A, and design scenario B. Various intentions and design strategies are included in each scenario. In assessment stage, the design outcomes are then to be tested by using several simulation programs. Synchronously, energy calculation work will constantly take place. Finally, the simulated results are evaluated quantitatively and qualitatively in terms of corresponding criterion.

After design assessment, the design finalization work is implemented based on all results obtained from simulation and evaluation stages. This section includes façade components and details design, as well as the assembly process plan.

Finally, it is the conclusion section. The primary purpose of the conclusion is to respond to the research questions and to provide an outlook on the future development for this research. Based on all the design results and conclusions, this study ends up an experimental design guide, aiming to provide some instructional and referential considerations for solar cooling integrated façade design.

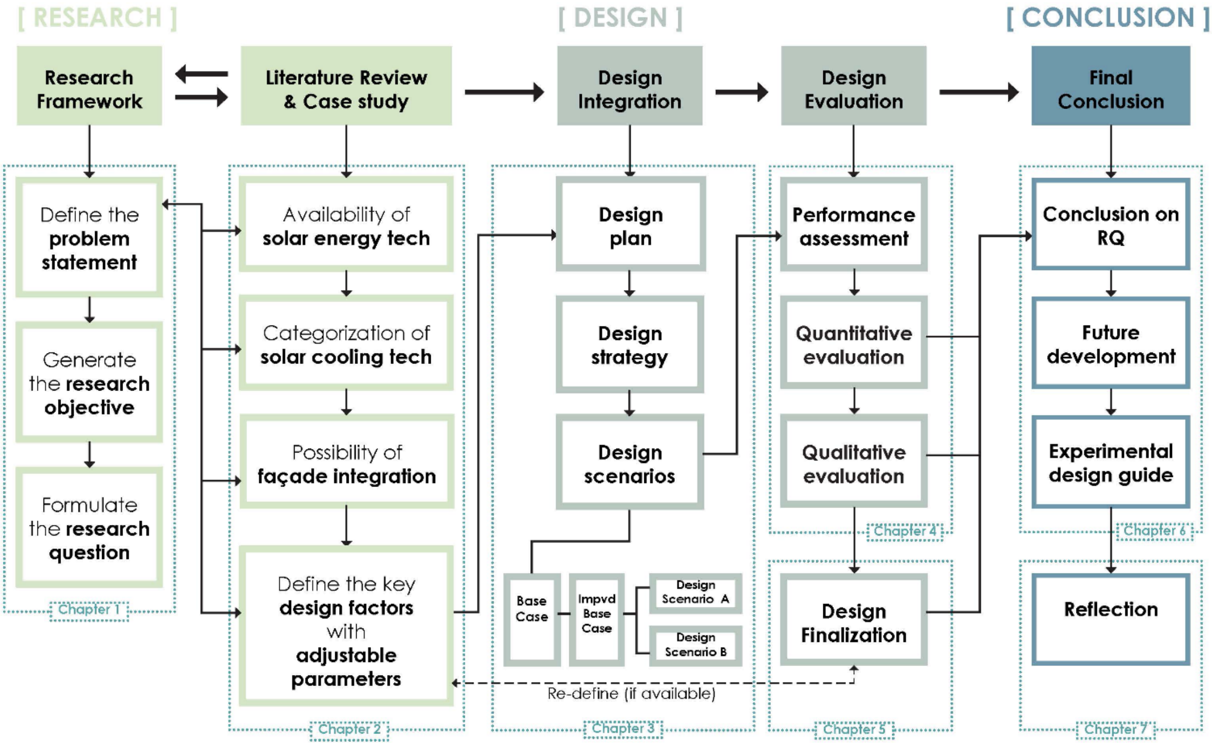


Figure 1.29 Research methodology

(graphic: own work, 2024)

2

DESICCANT ENHANCED COOLING TECHNOLOGY

2.1 Overview of solar cooling technology

2.1.1 Availability of solar energy technology

As the world seeks more sustainable and renewable energy sources, the application of solar energy technologies in the building industry has dramatically increased over the years.

BIPV (Building integrated Photovoltaic systems) and BIST (Building-integrated solar thermal systems) are the most common forms of solar energy application in architectural field (Prieto, 2018), such as solar façades, solar roofs, solar chimneys, etc. In façade applications, they could also be classified as 'FIPV' (Facade integrated Photovoltaic) or 'FIST' (Facade integrated Solar Thermal Collectors). The basic differences are that FIPV systems can generate solar electricity by PV cells components, while FIST converts the sun radiation into heat in which the solar energy is conveyed into the air, liquid (hot water), or both. (Figure 2.1)

Ventilated façades with BIPV

Glazing façades with BIST

Skylights with BIPV

Roof with BIPV

Figure 2.2 Solar energy facade is widely used in the commercial mar

(source: google images)

The main features of solar energy integrated façade are listed below (Debbarma, M. 2017; Prieto, 2018):

[a] Enable to generate long-term renewable and clean energy for building applications.
[b] Contribute to CO_2 reduction.
[c] Good thermal performance

[d] Suitable for new construction and for renovation
[e] Good for design innovation and sustainability
[f] Higher cost and technical complicatedness

There are various of fields that solar energy technology applied to the buildings' envelopes:

[a] Ventilated façade with PV integration
[b] Skylights with PV integration
[c] Roof cladding with PV/ST integration
[d] Glazing façade with solar thermal collectors' integration

2.1.2 Categorization of solar cooling technology

Conventional vapor compression air-conditioning systems traditionally used chlorofluorocarbons and hydrochlorofluorocarbons as refrigerants. However, due to their ozone-depleting and global warming potential, many of these substances have been phased out or are being phased out under international agreements such as the Montreal Protocol.

As a mature technology since the 70s, solar cooling technology (STC) is recognized as a promising alternative to conventional vapor compression refrigeration (Goetzler et al., 2014). Driven by solar energy and combined with evaporative coolers, SCT is based on generating conditioned air or chilled water from sun radiation without refrigerants. The potential benefits of SCTs include saving primary energy, achieving refrigerant free and reducing peak demand for energy cost-saving (Hamida et al., 2023).

According to current research, STCs are usually categorized in terms of their energy input, under either solar electric or solar thermal processes. (Henning, 2007; Prieto et al., 2017a), which means that either being driven by electricity from PV panels or heat harvested by solar thermal collectors (ST). Table 2. 1 shows the available solar cooling technologies.

Solar energy input	**Cooling principle**	**Cooling technologies**
Solar-electric process	vapour compression cooling	Compression heat pump
	Thermo-electric cooling	Peltier modules
Solar-thermal process	Sorption cooling	Absorption heat pump/chiller
		Adsorption heat pump/chiller
	Desiccant cooling	Solid desiccant + (Evaporative cooling)
		Liquid desiccant + (Evaporative cooling)
	Thermo-mechanical cooling	Steam ejector system
		Stirling engine
		Rankine cycle heat pump

Table 2.1 Available solar cooling technologies

(The table data based on Refs. Prieto et al., 2017)

Due to the environmental hazards by using refrigerants, vapor compression cooling is not included in this further research; similarly, thermos-mechanical are also excluded due to lack of available information for integration development. (Prieto, 2018) Hence, the following options are the most promising solar cooling technologies in recommended which have high potential to be integrated with building envelope systems (Table 2. 2)

[a] Thermo-electric cooling
[b] Sorption cooling, including absorption and adsorption cooling technologies)
[c] Desiccant cooling, including solid desiccant cooling and liquid desiccant cooling technologies)

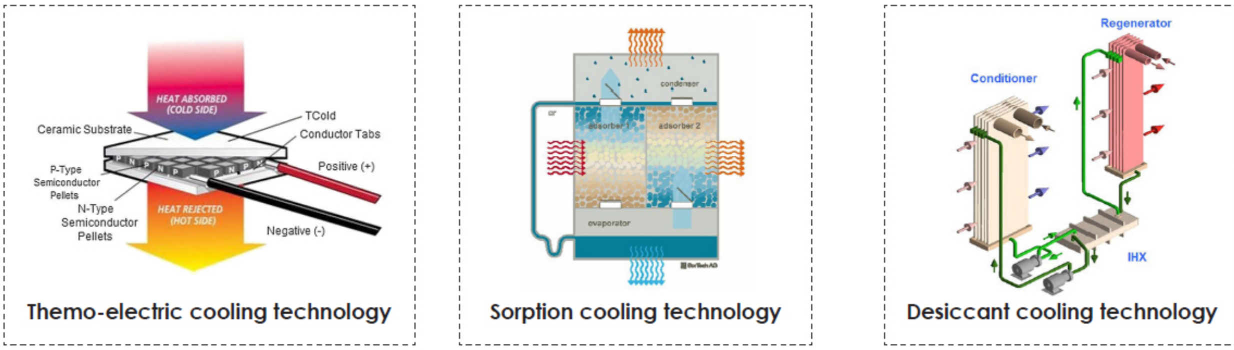


Figure 2.3 Thermo-electric cooling Sorption cooling and Desiccant cooling

(source: google images)

Solar cooling technologies	Pros.	Cons.	Notes
Themo-electric cooling technology	Recommended for temperate dry climate Small and compact size Refrigerant free Quick operation	High cost Low efficiency on current materials	
Sorption cooling technology	Recommended for hot arid tropical, temperate dry and temperate humid climate High maturity in cooling and large COP	Large size High up-front/maintenance fee	Including absorption and adsorption cooling technologies
Desiccant cooling technology	Recommended for hot humid subtropical, hot dry subtropical climate Temperature and humidity control separately Small and compact size	Complicated systems	Including solid and liquid desiccant cooling technologies

Table 2.2 The most promising solar cooling technologies with features

(The table data through literature view)

In conclusion, each option has its technical characteristics, and the selection focuses on determining the project's geographic location and its climatic characteristics.

2.1.3 Possibility of façade integration

From a long-term perspective, SCT façade has huge potential and possibilities in design application. Nevertheless, before discussing the possibilities, some main barriers to development cannot be ignored.

According to the research by IEA SHC Task 41, the main barriers for façade façade integration with solar cooling technologies is summarized in six aspects: 'Interest', 'Economy', 'Knowledge', 'Information', 'Product', 'process'. Among all these aspects, the barrier of 'product' ranks the top which means that lack of products suitable for quality building integration and complementary building components. (Prieto, 2018) In other words, there are no off-the-shelf integrated products that can be directly applied to a façade system.

In the current commercial market, solar cooling technologies are widely used in small-scale products currently (Prieto, 2018), such as solar cooling chillers, solar cooling containers or cold rooms for storage, etc. However, in building level, the façade integration of solar cooling technology remains explored with only demonstration projects and pilot experiences for all participants, although they are seen as the new type of active facade systems with high thermal performance and energy autonomy (Balaras et al., 2007; Henning & Döll, 2012).

Several small-scale experimental buildings or facilities have tried the possibilities of solar cooling technology with façade integration in hot climate conditions. For instance, some researchers at Graz University of Technology made an outdoor test facility for Facade-integrated decentralized cooling system naming "COOLSKIN" in 2018. (Brothaler, T. et al., 2021). (Figure 2.4, Figure 2.4.)

Figure 2.6 'COOLSKIN' testing facade

(source: Brothaler, T. et al., 2021)

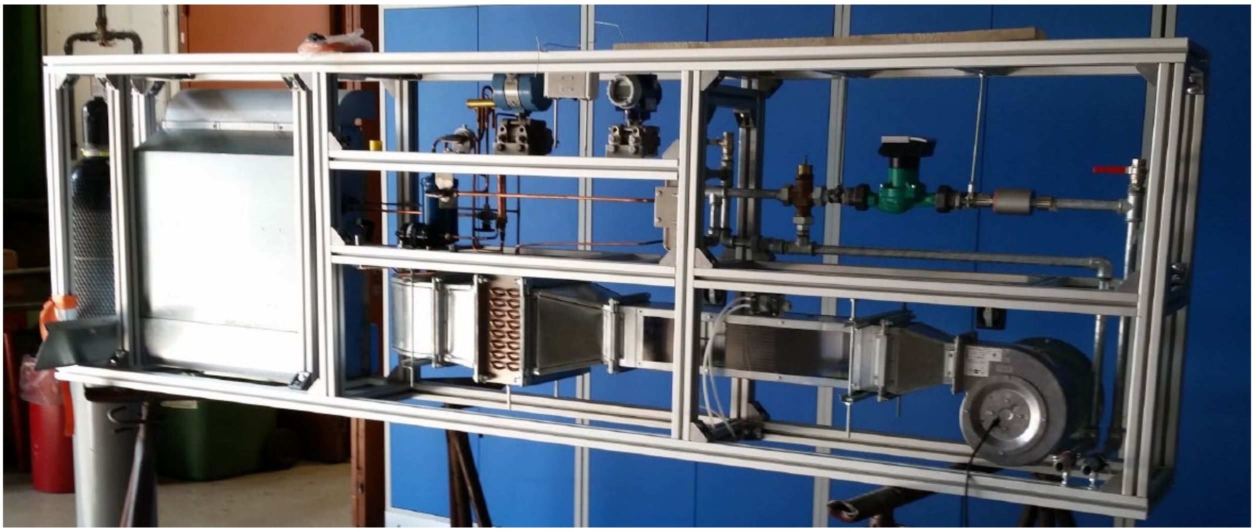


Figure 2.7 'COOLSKIN' integrated experimental devices
(source: Brothaler, T. et al., 2021)

2.1.4 Summarization

Based on the extensive literature review, three significant systems are worth considering when designing the solar cooling integrated facades. These systems are solar energy systems, cooling systems, facade systems. In each system, there are several key design factors to consider. Therefore, it is a design process of multi-systematic integration.

[a] Solar energy system

As the power engine of the whole system, the solar energy system consists of two main design factors – energy harvest and energy storage. The following chart shows the categorization of solar energy systems. (Figure 2.8)

In summary, the most significant decision to be made is choosing which option will be used as the solar energy engine, either systems of PV-powered with solar electricity process, or ST-driven with solar heat process.

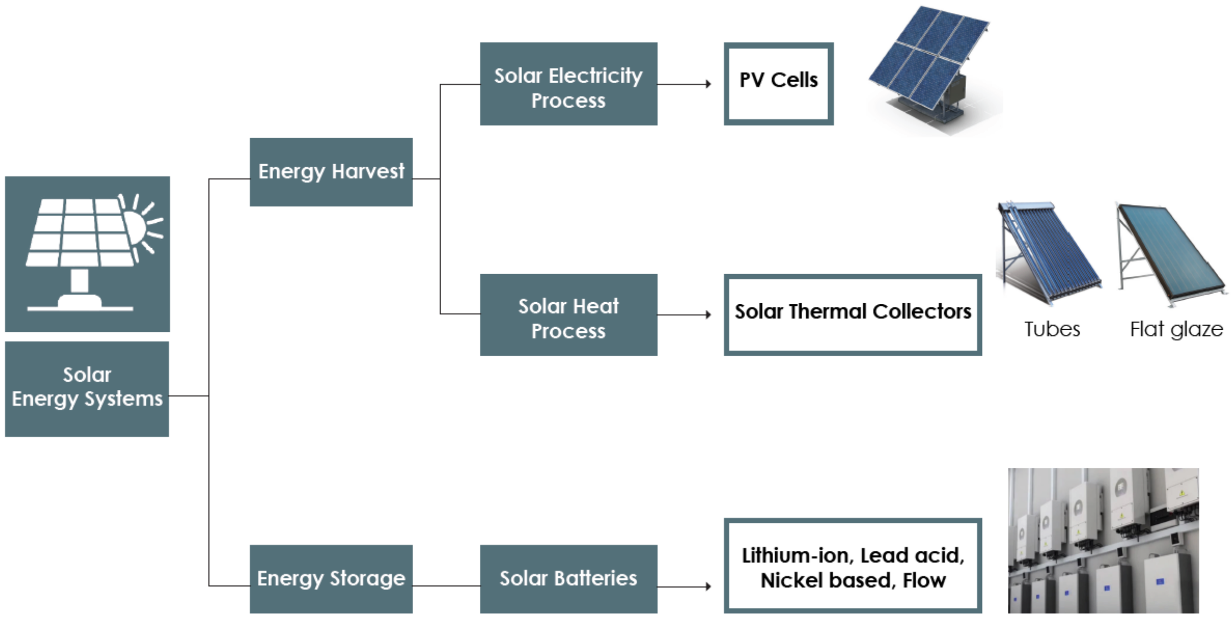


Figure 2.9 design factors on solar energy system

(graphic: own work, 2024)

[b] Cooling system

Powered by the solar energy system mentioned above, the cooling systems comprise three parts: cooling generators, cooling distributors and cooling deliveries. As shown in the illustration below, there are a few sub-factors with different technical options involved in the cooling systems family. (Prieto, 2018) (Figure 2.10)

In summary, the most suitable SCT options need to be determined to meet the demand of the specific design requirements. For example, based on certain experiments (Prieto, 2018), sorption cooling and thermo-electric technology are more recommended for hot-dry regions, while desiccant cooling options are the preferences for the hot-humid climate conditions.

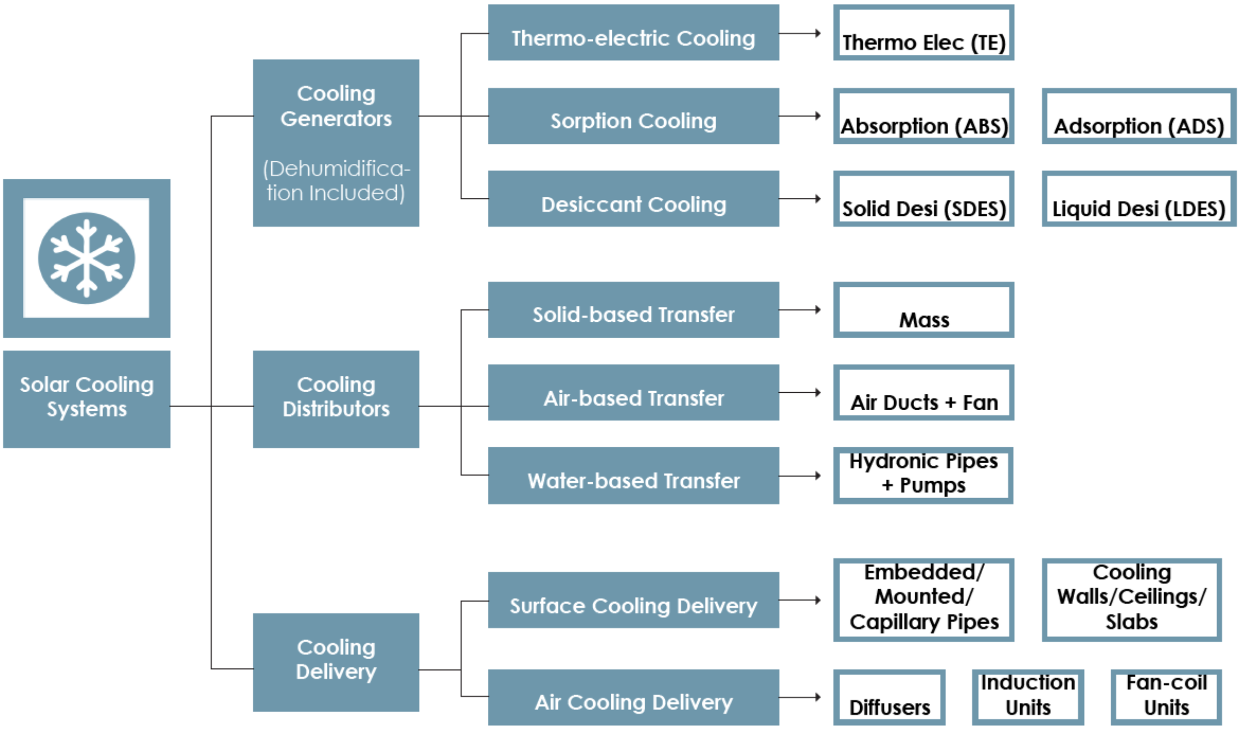


Figure 2.11 Design factors on cooling system

(graphic: own work, 2024)

[c] Facade system

As Herzog et al. (Herzog et al., 2004) noted, solar cooling integrated facade has both roles in functions: Protective (facade components for building envelope safety) and Regulatory (solar cooling systems for adaptive comfort) functions. Hence, to integrate the solar cooling systems into facade units, the following design factors in the facade system shown in the diagram need to be well organized. (Figure 2.12)

In summary, to compact the cooling systems into building facade elements, the most important design factors to be considered for facades are the cladding system, the shading system, and the ventilation system. Within all these factors, there are several adjustable design parameters involved, which are all relevant to the performance of the design outcomes.

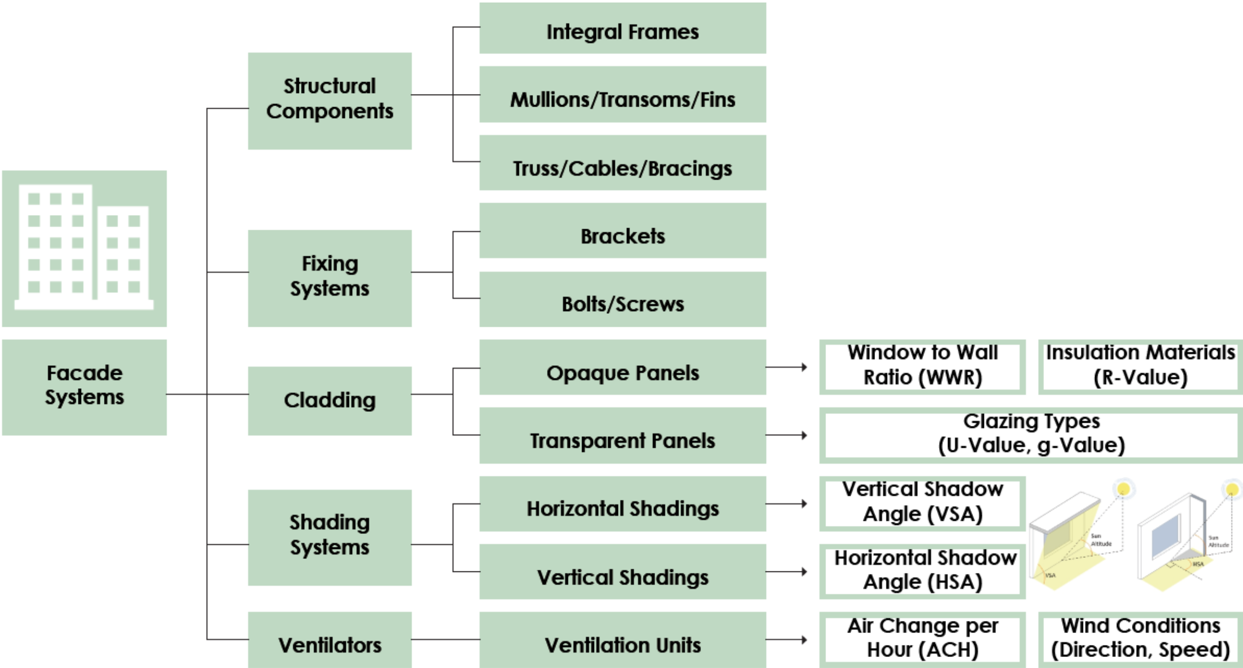


Figure 2.13 Design factors on facade system

(graphic: own work, 2024)

[d] Conclusion

In general, solar energy systems determine the source of power; cooling systems continuously provide the building with conditioned air; façade systems work as a binder that integrates all the systems Incorporated together. All the above-mentioned facts should be considered during the further design stage.

2.2 Desiccant cooling technology

In the previous chapter of the five solar cooling technologies mentioned, desiccant cooling is considered the most suitable technology particularly for hot-humid climates. Several studies have demonstrated the advantages of this technology in hot-humid climates. (e.g. Hernandez et al., 2020; Suwannapruk et al., 2020; Prieto, 2018; Tanuharja, 2015; Raj, 2019) That is because this technology separately controls the temperature and humidity of the supplied air through cooling and dehumidification processes, respectively.

Combined with evaporative cooling devices and driven by thermal energy, desiccant cooling systems are essentially open sorption cycles, utilizing cold water as the refrigerant to supply cooling through the heat absorption when water evaporates. At the same time, by indirect contact with the desiccant materials, moisture in the humid air will be effectively removed.

The desiccant (sorbent) can be either solid or liquid and is used to exchange sensible and latent heat of the conditioned airflow. (Balaras et al., 2007)

2.2.1 Solid desiccant cooling (SDEC)

[a] Brief description

Desiccant materials: silica gel, or zeolites
The representative system: rotary desiccant wheel

Working principle: the operation of SDEC system is based on using a rotary desiccant wheel in which the air is dehumidified. (Figure 2.14) The generated dry air is cooled in a sensible heat exchanger (rotary regenerator) then further cooled by an evaporative cooler. The final cool air will condition the room. (Dincer et al., 2007)

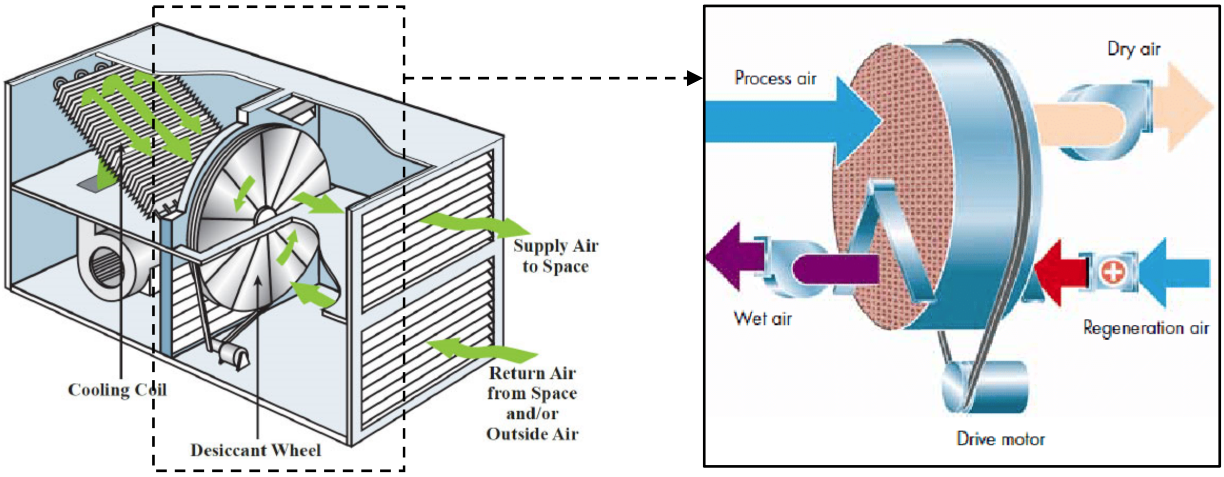


Figure 2.15 Diagram of working principle for SDEC system

[b] Main features

Solid desiccant sorbents are highly durable, inexpensive, less subject to desiccant carryover and corrosion when compared to liquid desiccants. However, the system of SDEC is slightly complicated and generally large in geometry, and the capacity of silica gel is low, while zeolites with also low capacity but high in regeneration cost. (Prieto, 2018; Vivek et al., 2018)

2.2.2 Liquid desiccant cooling (LDEC)

[a] Brief description

Desiccant materials: strong organic acid solution of LiCl, or Libr, or $CaCl_2$; weak organic acid solution of $CHKO_2$, or $HCOON_a$
The representative system: 'wet film' technology

Working principle: Liquid desiccant solution can be applied onto a carrier or sprayed in the system by nozzles, absorbing moisture from the humid air by indirect contact with humid air through 'wet films' (described in the following paragraphs). As it is highly diluted with water, the liquid desiccant must be pumped back to the regenerator system and heated until the moisture is removed again before re-entering the working circulation. Finally, the air cooled by the evaporative conditioner will condition the room (Kozubal et al., 2011; Elmer et al., 2016, Prieto, 2018) (Figure 2.16 ,Diagram of working principle for LDEC system)

A

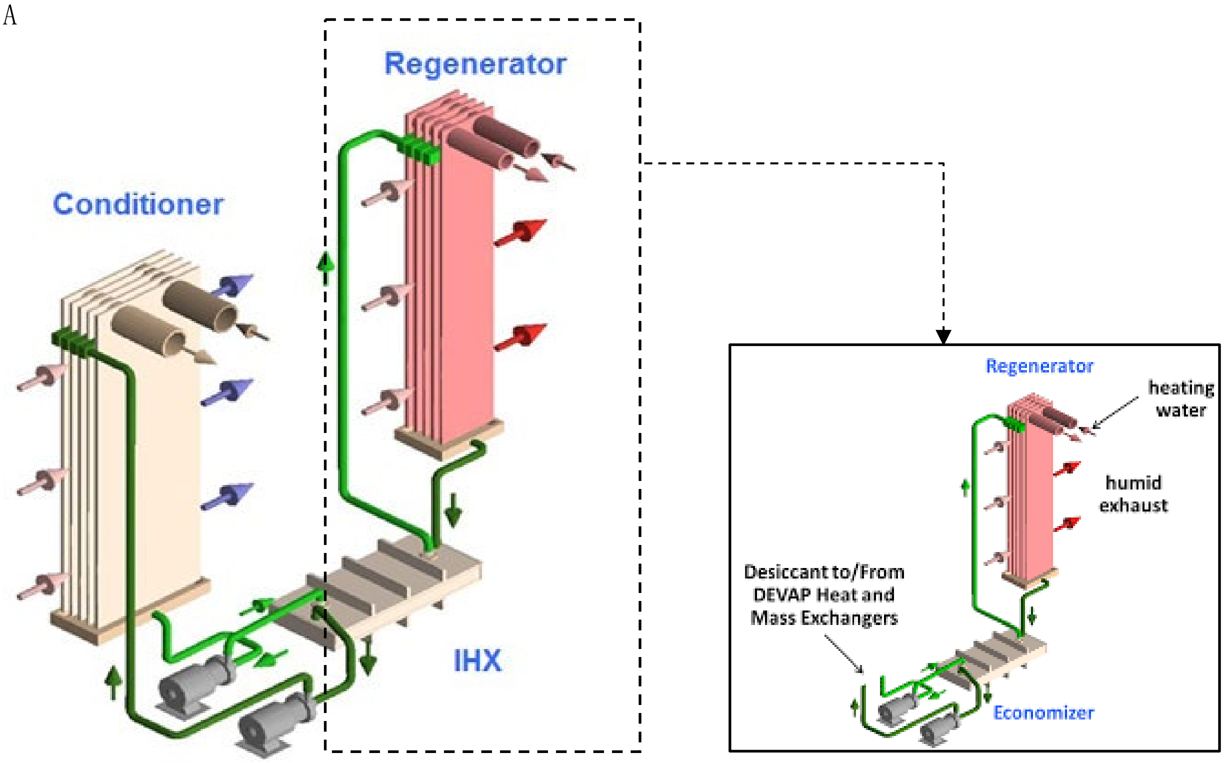


Figure 2.17 Diagram of working principle for LDEC system

[b] Main features

Compared with SDES, LDES have lower regeneration temperatures, greater dehumidification capacity and a lower air side pressure drop. However, corrosive risks and certain issues regarding health are the main drawbacks. (Elmer et al., 2015)

2.2.3 Features comparison

As seen in the comparison of features between SDEC and LDEC (Table 2. 3), the later has more pronounced advantages in dehumidification performance and more small-compact sizes in geometry. Additionally, compared with solid materials, the liquid desiccant solution is more cost-efficient and requires a low temperature for regeneration, potentially allowing less energy to be consumed during the regeneration process.

Desiccant cooling	Pros.	Cons.	Refs.
Solid desiccant cooling (SDEC)	(1) Desiccant materials with non-corrosiveness (2) High durability (3) Temperature and humidity control separately (4) avg COP approx. 1.0 when integrated with evaporative cooling	(1) Low performance in dehumidifcation with desiccant materials (low capacity of si-ica gel, low capacity but high cost in zeolites) (2) Complicated system Generally large size in geometry comparing with conventional cooling systems	Prieto, 2018; Vivekh 2018
Liquid desiccant cooling (LDEC)	(1) High performance in dehumidifcation (2) High potential indoor air quality (capacity of absorbing pollutants and bacteria) (3) Low-pressure drop, for use with low regeneration temperature (4) Small and compact size in geometry (5) avg COP approx. 1.0 when integrated with evaporative cooling	(1) Aqueous solutions are highly corrosive (exceptional for weak acid solutions like CHKO2, or HCOONa, and plastic materials must be used) (2) Health hazards due to carry-over with supply air stream (micro-porous unidirectional permeable membrane must be used) Slightly complicated system	Prieto, 2018; Elmer et al., 2016; Kohlenbach & Jakob, 2014

Table 2.3 Features comparison between SDEC and LDEC

(The table data based on Refs. Prieto, 2018; Vivek et al., 2018; Elmer et al., 2016; Kohlenbach & Jakob, 2014)

Despite health concerns, some studies have demonstrated that utilizing ‘wet film’ can prevent desiccation solutions from entrainment into the supply or process air stream. Researchers have used hydrophobic membranes to cool and dehumidify the air without providing direct contact with the liquid desiccant. The semi-permeable membranes used are microporous polypropylene. (Keniar et al.,2015) A product from Celgard (a UK company name, Figure 2.18, Figure 2.19) has been identified as possible candidates with the thickness of 25 μm and the pore size of about 0.1 μm. (Kozubal et al., 2011)

Another problem for liquid desiccant that cannot be ignored is corrosion. Desiccant solutions are corrosive to metal materials (Baniyounes, Liu, et al., 2013) Therefore, desiccant carriers or piping systems need to be made of plastic or any other non-corrosive materials. Additionally, some research has been conducted to use weak organic acid solutions like CHKO2 (materials with no corrosion risks but same high capacity in dehumidification with 30-47% reduction in moisture removal) instead of strong halide salts. (Elmer et al., 2016)

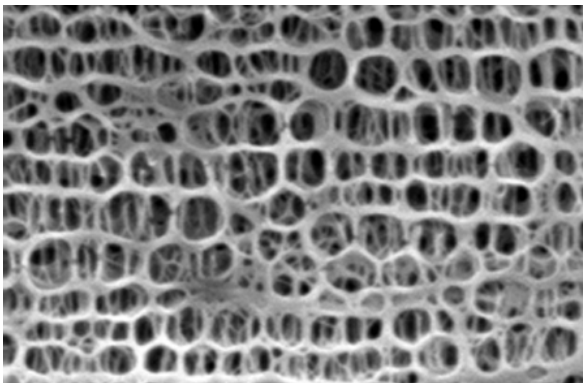


Figure 2.20 Scanning electron microscope photograph of a micro porous membrane

(Patent Pending, Celgard product literature)

Figure 2.21 Products of Celgard

In conclusion, both considering the materials capacity (cooling and dehumidification) and components' sizing feasibility, LDES has highly operational potential in façade integration. Therefore**, LDES will be the candidate of the main technology to apply in further research and design in this thesis.**

2.3 Liquid desiccant enhanced evaporative cooling system

Liquid desiccant enhanced evaporative (LDEVap) cooling system (or air-conditioner) is an emerging solution that combines liquid desiccant technology with evaporative cooling technology. (Figure 2.22) It supplies refrigerants-free cooling and reduces the energy consumption. (NREL Technical report, 2011)

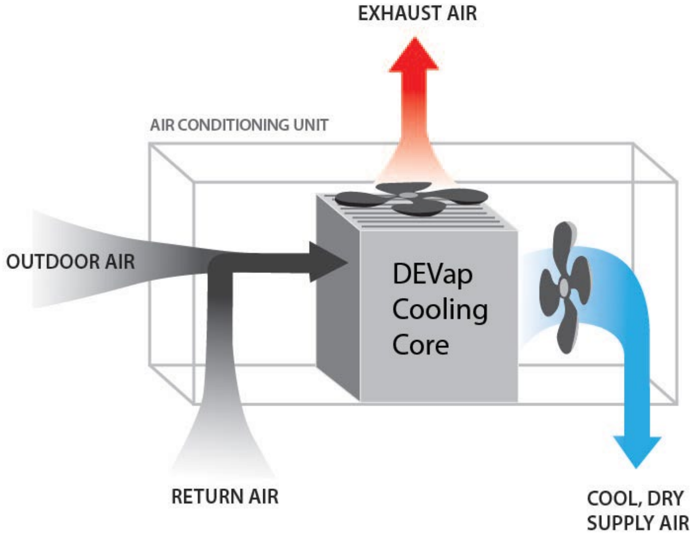


Figure 2.23 Concept of LDEVap air-conditioning

(source: NREL Technical report, 2011)

[a] System composition

A liquid desiccant enhanced evaporative cooling system consists of three main components: (I) dehumidifier (II) regenerator (III) evaporative cooler (sensible cooling device). (Elmer et al., 2016). (Figure 2.24)
Other Auxiliary components include heat source generators (e.g. solar hot water tanks), desiccant solution and cold-water tanks, hydronic system(pipes), air ducts, electric fans, and pumps.

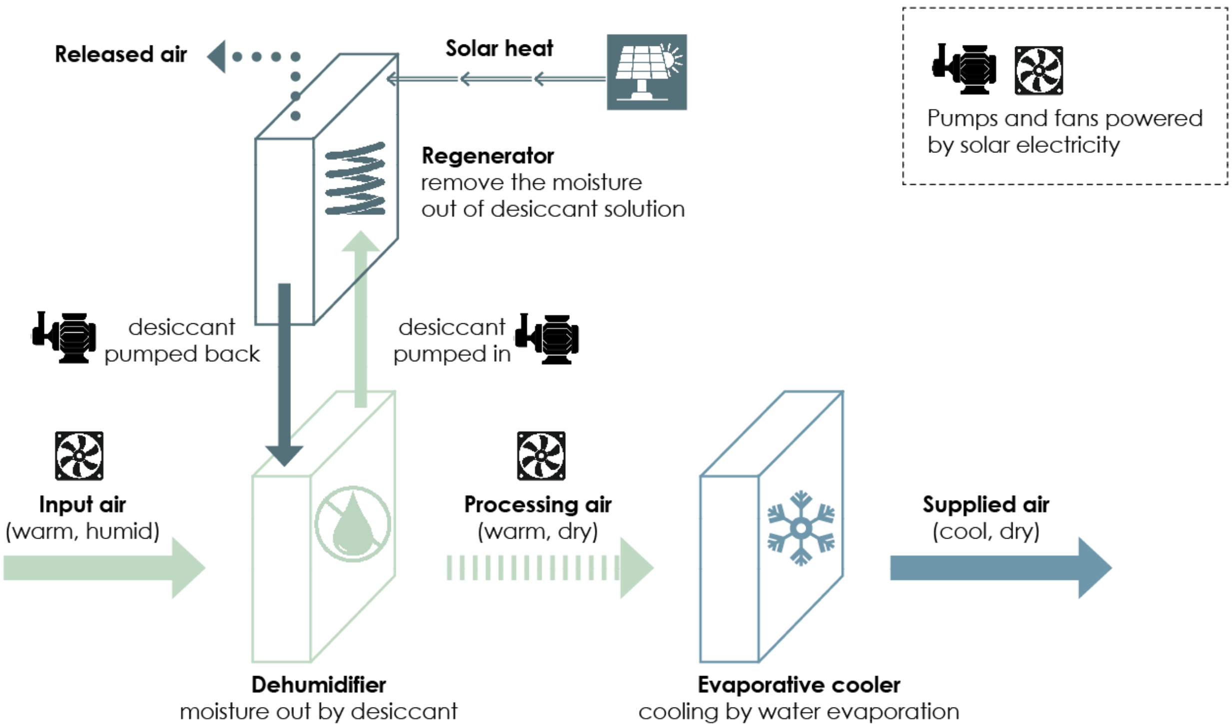


Figure 2.25 System composition in LDEVap cooling system
(graphic: own work, 2024)

[b] Working principles

The dehumidifier removes the moisture from the input air passing through the liquid desiccant across those layers of wet film. As more moisture is continuously absorbed, the liquid desiccant solution becomes diluted, weakening its ability to absorb moisture. (Elmer et al., 2016)

The regenerator evaporates off the moisture from the liquid desiccant solution and increases its concentration again. In this process, the desiccant solution is heated to a temperature at which the equilibrium vapor pressure is above ambient. Due to the pressure difference, the vapor desorbs from the desiccant solution and is carried away by an air stream. This is to enhance the dehumidification capacity of the desiccant solution and provide air-sensible cooling accordingly. (NREL Technical report, 2011)

The evaporative cooler cools the air through the evaporation of water. As cold water takes away a large amount of heat during the evaporative process, the temperature of the dry air will drop significantly. Finally, the conditioned air (cool and dry air) will be supplied to the room after flowing through the evaporative cooler. That's the entire LDEVap's cooling process. (Elmer et al., 2016)

[c] Benefits

Cost savings and reduction in electricity consumption are the most outstanding benefits for LDEVap cooling systems. Because the energy input is largely switched away from electricity to low-grade thermal energy that can be renewably sourced from solar energy. Its estimated savings are between 30 and 90 percent compared to a regular A/C unit which consumes much energy during the refrigeration cycle.

Utilizing cold water as the refrigerant, LDEVap cooling systems also benefit the environment by cutting off the need for the coolants chemicals (e.g. R-22, also known as Freon) used in conventional A/C units. (NREL Technical report, 2011)

[d] Available experience for small-scale projects

Currently, most research on liquid desiccant-based cooling systems has focused on small capacity ranges (below 30 kW), benefiting potentially compact units for small-scale projects. (Prieto, 2018) For example, Kozubal et al. (2011) developed a membrane-based desiccant indirect evaporative system within a sealed packaged unit of 600 x 500 x 480(mm) to cover a cooling demand of around 3.5 kW. (NREL Technical report, 2011). Similarly, Chen et al. (2017) designed a membrane based liquid desiccant A/C, comprised of highly compact modules for regeneration and dehumidification of 410 x 230 x 210(mm) each. (Prieto, 2018)

Remarkably, the research project conducted by Elmer et al. (2016) has a high applicability. First, the experiment was conducted under simulated weather conditions with 0 to 40° C airflow temperature range, as well as 10 to 80% relative humidity, which are extremely similar with Shenzhen's weather characteristics. Besides, the experimental cooling devices used in this research have the most compact dimensions in components size and volume with the core size of 1000 x420 x240 (mm), which is well-suited for façade components integration. (by Elmer et al. (2016)) It highly integrates dehumidifier, regenerator, and evaporative cooler cores in one geometric unit. Based on wet film technology, this laboratory device has an average $COP_{thermal}$ 0.72 and average $COP_{electricity}$ 2.5. Furthermore, according to its experimental components, it uses the immersion water heater (electric process device) to heat up the water for the regenerator section, which can use solar thermal input as an alternative. Therefore, this thesis plans to take this experimental device as a benchmark cooling unit for further design. A list of a single set of laboratory equipment is shown in Table 2. 4:

Equipment	Quantity	Property
LDEVap cooling unit	1	
Cylindrical water heater	1	120 L
Electrically driven axial fan	3	23W 240V AC, 500m^3/h
Single phase centrifugal magnetically driven pump	2	15W, 0-10L/min
Wilo-Smart A-rated circulating pump	1	99W (reference to the product of Wilo Star-Z 25/6-3), 230V AC
Galvanized steel spiral tube duct	by length	125mm diameter
PVC-U plastic pipe with plastic fittings	by length	20mm diameter
Copper hot water pipe with fittings	by length	22mm diameter

Table 2.4 List of a single set of laboratory equipment

(The table data based on Refs. Elmer et al., 2016)

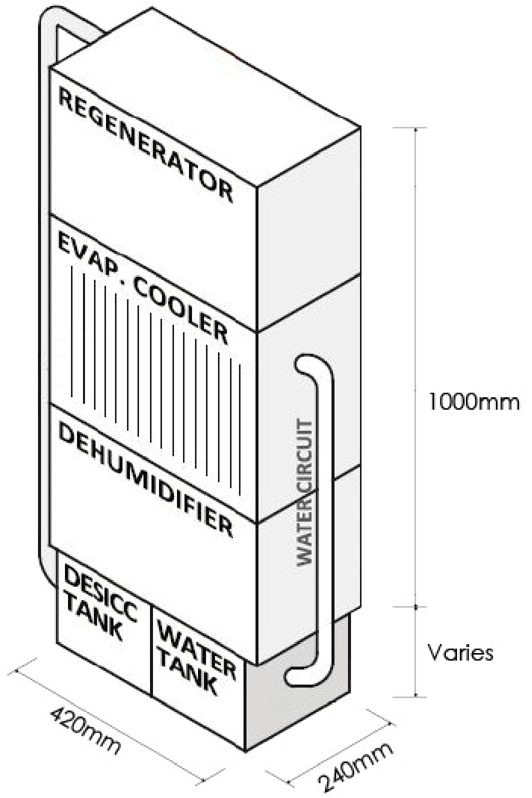


Figure 2.26 Dimensions of LDEVap cooling unit

by Elmer et al. (2016)

Figure 2.27 Highly integrated devices

by Elmer et al. (2016)

The basic parameters for this LDEVap cooling unit according to the experiment:

Profile size:	1000(h)x420(w)x240(d) mm (excluding liquid tanks)
Wet film materials:	Microporous polypropylene semi-permeable membranes
Desiccant materials:	CHKO2 solution (weak organic acid solution)
Cooling capacity:	avg 1.1 kw

Dehumidification capacity: 30%-47% ratio of moisture reduction (avg: 39%)
COP $_{thermal}$ avg: 0.72 (solar heat to desiccant cooling output)
COP $_{electricity}$ avg: 2.5 (solar electricity to the power of fans and pumps)
The concept of its workflow is shown in the following diagram (Figure 2.28):

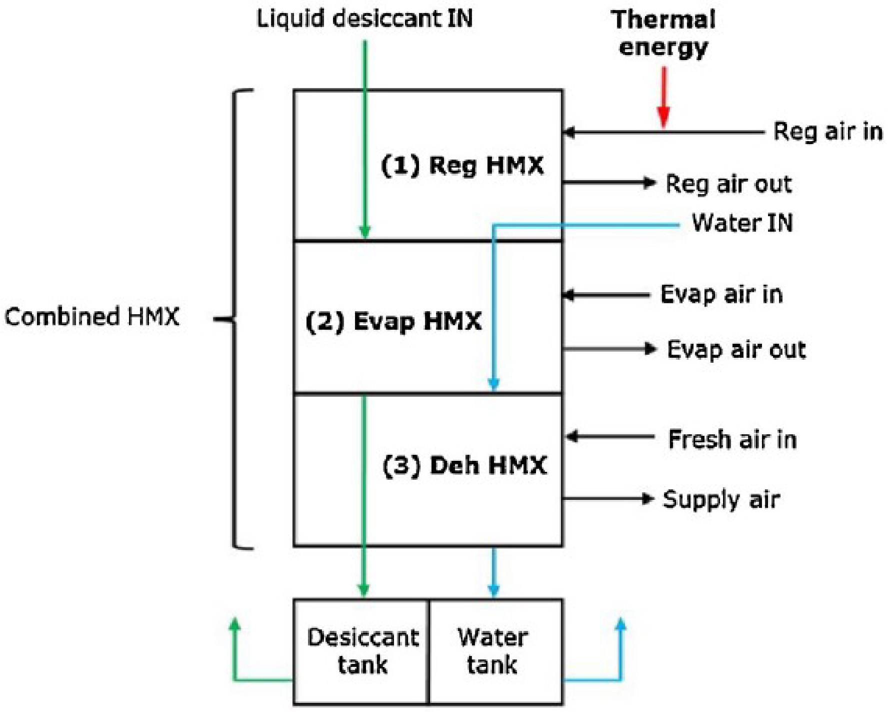


Figure 2.29 The concept of the workflow for liquid desiccant enhanced evaporative cooling unit (The diagram based on Refs. Elmer et al., 2016)

2.4 FI decentralized cooling mode

2.4.1 Main features

In fact, integrating small-scale cooling devices into the building façade units forms another cooling mode – 'Facade Integrated (FI) decentralized cooling', which notably differs from the most conventional cooling mode - centralized cooling. In general, this cooling mode decentralizes the conventional A/C systems initially attached in the heart of main building into individual facade units, through which it obtains higher space efficiency in buildings. There are some main features for FI decentralized cooling mode as followed:

[a] Energy autonomy

Because of the FI energy system, each façade unit has the ability to generate energy and even store power independently. Theoretically, it enables to achieve energy self-sufficiency.

[b] Systematic flexibility

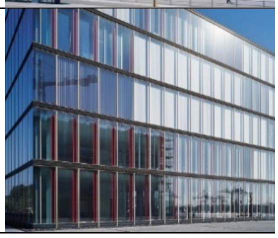
Separating the cooling systems from the building core structure dramatically improves the ease of technical upgrades with minimum building disruption. (Roosmalen et al. 2021) For the cooling system itself, higher design, manufacture, and installation flexibilities are achieved.

[c] Different ways of air intake and exhaust

This is the most obvious difference from the centralized system. A conventional centralized system has a central chiller from which ducts run through the entire building. This chiller takes the unconditioned fresh air, treats it, and supplies it to the building through the ducts while extracting the heat from the spaces. In the decentralized system, fresh air is taken through the façade and is also treated by the facade units before supplying into the room. In terms of exhaust, the air is either ejected by the same component locally or has a central system which helps remove the exhaust air. (Raj, 2019)

2.4.2 Reference projects

Some existing research projects about FI decentralized HVAC systems are listed Table 2. 5(The data collection based on Refs. Roosmalen et al.2021 and TROX manufacture sheet 2016):

No.	Project (complete year)	Location	Building /Façade type	FI Decentralized HVAC systems	FI renewable energy	Building image
D1	Capricorn (2006)	Düsseldorf, Germany	Ofice /Unitized curtain wall	-Decentralized ventilation system -Opaque panels integration with heat pump	no	
D2	Laimer Würfel (2007)	Munich, Germany	Office /Perforated metal-glass facade	-Decentralized ventilation system -Heating/Cooling/ Humidification -Opaque panels integration	no	
D3	Neumühlen 19 (2002)	Hamburg, Germany	Office /Double-skin curtain wall	-Decentralized ventilation system -Heating/Cooling -Floor integration air intake	no	

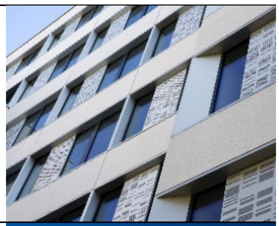
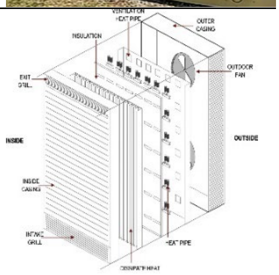
D4	Feldberg-strasse office building (2008)	Frankfurt, Germany	Office /Perforated metal facade	-Decentralized ventilation system -Opaque panels integration	no	
D7	Solar XXI Building (2006)	Lumiar, Lisbon, Portugal	Office /Perforated metal-glass FIPV, FIST	-Passive heating and cooling systems	PV/ST	
D8	TEmotion (2019)	Germany	Experimental building/ Unitized curtain wall FIPV	- Decentralised ventilation systems -Decentralized thermoelectric heating and cooling unit	PV	
D9	CoolSkin (2018)	Vienna, Austria	Experimental building/ Perforated glazing facade	-Decentralized Heat pump system	PV	
D10	Thermo-electric Peltier	Navarra, Spain	Experimental façade units/ rear-ventilated opaque panels	-Decentralized thermoelectric heating and cooling unit -Decentralized ventilation system	PV	

Table 2.5 Selected research projects about FI decentralized HVAC systems

2.5 Conclusion

As recommended by the previous research, desiccant cooling technology is well-suited under this hot-humid climate conditions to address with the sensible and latent cooling load, compared to other cooling options.

For the sake of higher performance and more compact systematic size, liquid desiccant enhanced evaporative cooling system demonstrates more of its advantages compared to the solid-based options. Experimental device by Elmer et al. (2016) is chosen as the benchmark cooling unit for the further research and design stages. Nevertheless, there are still multiple challenges for the following steps, such as how to integrate it with solar thermal collectors, how to utilize the size of the existing equipment to combine it with the façade components, and how much it will reduce the energy consumption and improve the indoor thermal comfort are all essential concerns. Additionally, FI decentralized cooling mode will be applied as an available design strategy to the further design.

3
FAÇADE DESIGN INTEGRATION

3.1 Design plan

In this chapter, the whole design process of solar cooling integrated façade system will be described step by step, and multiple design strategies and design tools will be applied to the corresponding situations.

3.1.1 Overview of design process and strategy

The entire design process is planned to be divided into three main stages: pre-design stage, design implement stage, and assessment stage.

[a] Pre-design stage

In the pre-design stage, the main task is to address the environmental contexts, aiming to analyze the weather conditions and determine the climatic strategies.

[b] Design implement stage

outlines the framework of the design implement stage. In this stage, different design scenarios are established: base case, improved base case, design scenario A, and design scenario B. Each design scenario has its specific design intent, and the design strategy applied differs. Therefore, the input parameters for energy simulation in each design scenario follow the corresponding design conditions.

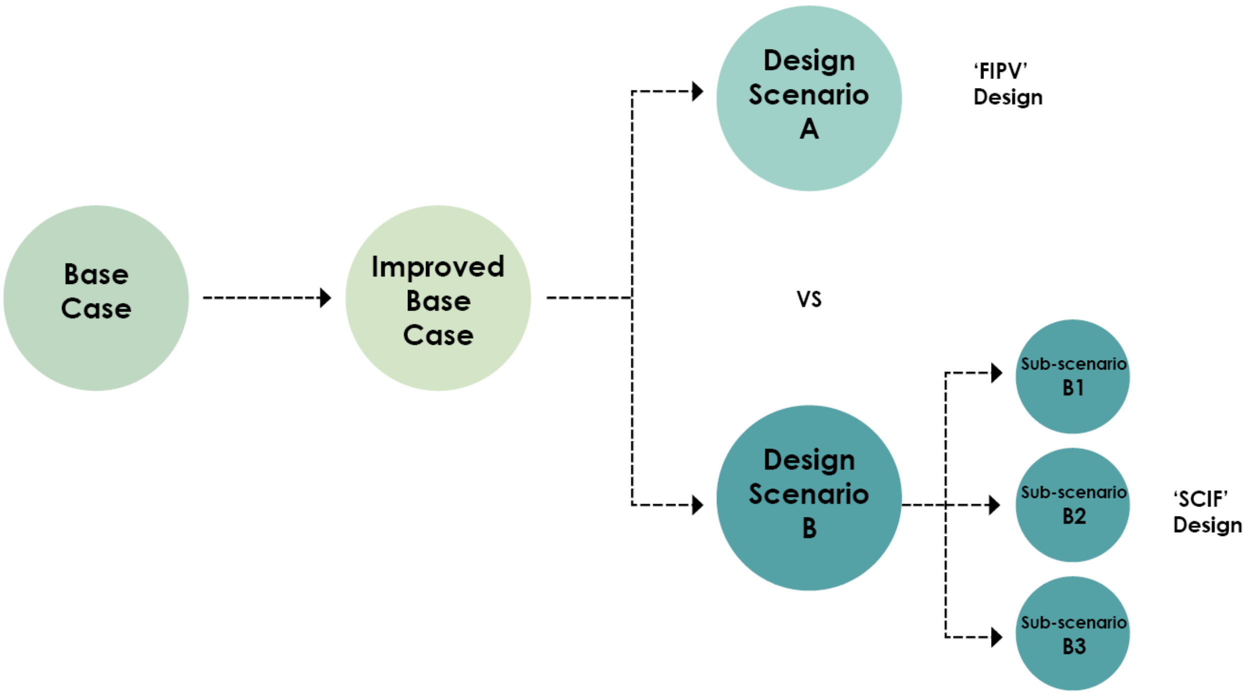


Figure 3.1 The framework of design implement stage

(graphic: own work, 2024)

Base case – the initial setting and design to the façade.

In the base case scenario, a generic office building as a benchmark archetype with various initial design parameters is set up, including constant and variable parameters. In this scenario, the basic façade unit is designed and dimensioned. Besides, the base case building uses the conventional mode of the centralized cooling system.

Improved base case – the Application of passive design strategies to the façade.

The intention of the improvement is to prevent the building from overheating by solar radiation. Therefore, the design intention is to apply various passive design strategies to the building facades. The optional measures include Window-to-Wall Ratio (WWR), glazing types, external wall and insulation materials, sun shading elements, etc. (Figure 3.2)

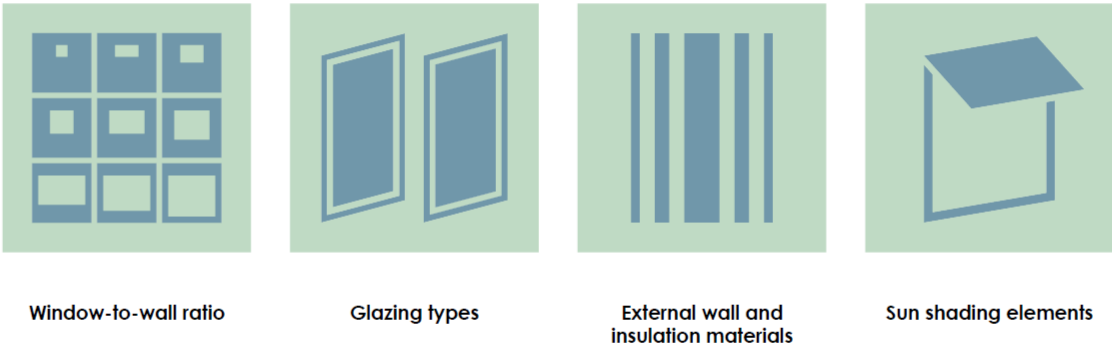


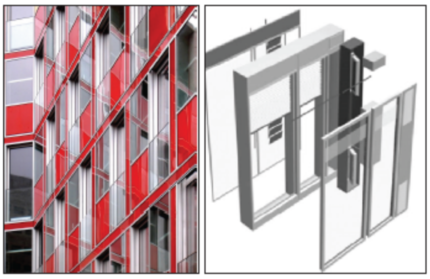
Figure 3.3 Passive design strategy

(graphic: own work, 2024)

Design scenario A – the Application of active design strategies to the façade.
This scenario is mainly about FIPV design. It aims to utilize façade systems to generate renewable energy for buildings' conventional A/C systems and reduce the electricity requirement from the utilities. Hence, dedicated PV panels are mounted to the façade system to investigate their effectiveness.

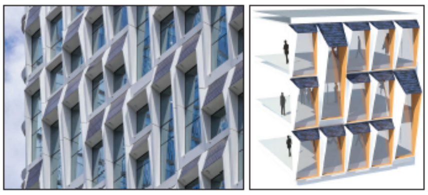
Design scenario B - the Application of solar cooling strategies to the façade.

This scenario is mainly about FIST design and application of liquid desiccant evaporative cooling technology. It changes the original centralized cooling mode to the decentralized way. This design scenario is divided into three sub-scenarios (scenario B1, B2, B3), which differ in solar energy systems – different ratios of ST/PV coverage. Additionally, some reference projects show the potential direction of the design proposal for this scenario. (Figure 3.4)



Capricorn house, Düsseldorf, 2008
Facade type:
Unitized facade, metal frame with glass, built-in ventilator

SolarXXI building, Lisbon, 2006
Facade type:
Unitized facade, metal frame with PV cells and glass panel



Hanwha headquarters building, Seoul, 2019
Facade type:
Unitized facade, metal frame with glass panels, built-in PV cells

Feldbergstrasse office building, Frankfurt, 2009
Facade type:
Unitized facade, metal frame with glass panels, built-in ventilator and heat exchanger

Figure 3.5 Potential design directions in design scenario B

[c] Assessment stage

The assessment will compare the performance data among all scenarios; therefore, the energy simulation and evaluation are carried out in this stage. The assessment compares multiple results, such as the cooling demand, the total electricity used in cooling, and their intensities per square meters, while the amount of renewable energy (solar electricity or solar heat) generated are recorded. It is a process that determines whether all the design strategies applied can contribute to reducing cooling energy consumption in the testing building.

3.1.2 Design tools

In terms of different design stages, various design tools are used (Figure 3.4 Various design tools):

Climate Consultant | Ladybug | Galapagos | DesignBuilder | System Advisor Model

Figure 3.6 Various design tools

[a] Climate Consultant

Climate Consultant (Version 6.0) is a graphic-based computer program that helps designers understand the local climate characteristics of their projects and provides effective design strategies in response to specific weather conditions. Using annual 8760 hours EPW format weather data that is available for free by the Department of Energy for thousands of weather stations around the world, it helps designers to create more energy efficient, more sustainable buildings. Climate Consultant is mainly used in the pre-design stage.

[b] Ladybug and Galapagos

Ladybug is a Grasshopper plug-in which works as an interface for sun radiation analysis. Based on the EnergyPlus engine (an energy simulation program), it contributes to mapping the weather data and visualizing the connection between the orientations of the façade and solar exposure.

Galapagos, another Grasshopper plug-in, serves as an evolutionary solver. Working with Ladybug, Galapagos helps to select the best values or the solutions closest to the limitation for each task. (e.g. the minimal WWR value for façade glazing due to a series of regulation limitations, or best tilt angle for PV panels, etc.)

Ladybug and Galapagos are normally used in both the pre-design and design implement stages.

[c] DesignBuilder

DesignBuilder (Version 7.2) is the software that has the graphical interface of EnergyPlus, which is a validated simulation platform for buildings. In this research, the program is used to simulate the design cooling load and design capacity requirements of the target area, helping to understand the differences in results generated on each façade design scenario. DesignBuilder is primarily used in the assessment stage.

[d] System Advisor Model

Developed and distributed by the U.S. Department of Energy's National Renewable Energy Laboratory, System Advisor Model is a free-use application for techno-economic analysis of energy technologies. SAM can simulate the performance of many types of renewable energy, like photovoltaic, concentrating solar power, solar water heating, wind, geothermal, and biomass power systems and includes a basic generic model for comparisons with conventional or other systems. (source: sam.nrel.gov)

3.1.3 Methods of simulation and evaluation

DesignBuilder is mainly used as a performance simulation tool to understand the differences in various scenarios in this research. The weather data of Shenzhen is used as the base climate conditions for all calculations imported to the DesignBuilder program. Different façade models are validated in different design scenarios, and the conditions for simulation are based on the setting of base case building which is described in the following section.

The simulated results are evaluated quantitatively and qualitatively, leading to the final conclusions. One of the methods for quantitatively evaluating the design performance was based on the approach used by Prieto (2018) and Noaman et al. (2022) in their corresponding research projects, i.e. comparisons of Solar Fraction (SF) of the system. Meanwhile, the simulated results of cooling demand and energy consumption in each scenario are also comparable data for performance assessment.

The qualitative evaluation results are evaluated from five angles: Integration feasibility, energy performance, assembly and maintenance, design aesthetics and space efficiency, and other uncertainties. These angles are derived from the study by Prieto (2018), who assessed and discussed his research results by checking the identified main barriers to façade integration.

3.2 Pre-design

3.2.1 The analysis of weather data

[a] Extreme period in summertime

The weather data of Shenzhen in the past 30 years are given in Table 3. 1. As seen in the table, summertime ranging from June to September is the most extreme period throughout the year, of which July is the hottest month with the daily mean temperature of 29.0 Co and the average relative humidity of 79%, requiring the highest cooling demands. Figure 3.7 also indicates that discomfort (Dash line framed) dominates in extreme periods.

Climate data for Shenzhen (1991–2020)													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	29.1 (84.4)	28.9 (84.0)	32.0 (89.6)	34.0 (93.2)	36.8 (98.2)	36.9 (98.4)	38.7 (101.7)	37.1 (98.8)	36.9 (98.4)	35.2 (95.4)	33.1 (91.6)	29.8 (85.6)	38.7 (101.7)
Mean daily maximum °C (°F)	19.8 (67.6)	20.8 (69.4)	23.2 (73.8)	26.7 (80.1)	29.7 (85.5)	31.3 (88.3)	32.3 (90.1)	32.2 (90.0)	31.5 (88.7)	29.2 (84.6)	25.7 (78.3)	21.5 (70.7)	27.0 (80.6)
Daily mean °C (°F)	15.7 (60.3)	16.8 (62.2)	19.4 (66.9)	23.1 (73.6)	26.4 (79.5)	28.3 (82.9)	29.0 (84.2)	28.8 (83.8)	27.9 (82.2)	25.5 (77.9)	21.7 (71.1)	17.4 (63.3)	23.3 (74.0)
Mean daily minimum °C (°F)	13.0 (55.4)	14.2 (57.6)	17.0 (62.6)	20.7 (69.3)	24.0 (75.2)	26.0 (78.8)	26.6 (79.9)	26.3 (79.3)	25.5 (77.9)	22.9 (73.2)	19.0 (66.2)	14.5 (58.1)	20.8 (69.5)
Record low °C (°F)	0.9 (33.6)	0.2 (32.4)	3.4 (38.1)	8.7 (47.7)	14.8 (58.6)	19.0 (66.2)	20.0 (68.0)	21.1 (70.0)	16.9 (62.4)	9.3 (48.7)	4.9 (40.8)	1.7 (35.1)	0.2 (32.4)
Average rainfall mm (inches)	35.2 (1.39)	36.8 (1.45)	64.0 (2.52)	140.1 (5.52)	237.1 (9.33)	368.7 (14.52)	309.5 (12.19)	364.3 (14.34)	242.5 (9.55)	73.4 (2.89)	31.7 (1.25)	29.6 (1.17)	1,932.9 (76.12)
Average rainy days (≥ 0.1 mm)	5.5	7.8	9.9	11.4	14.3	18.4	17.2	16.7	13.2	5.9	4.6	5.2	130.1
Average relative humidity (%)	68	74	77	79	79	80	79	79	75	67	67	64	74
Mean monthly sunshine hours	137.3	101.6	99.7	115.2	153.0	169.8	214.8	178.6	170.1	188.7	168.8	155.4	1,853
Percent possible sunshine	40	31	27	30	37	42	52	45	47	53	51	47	42

Table 3.1 Recorded climate data of Shenzhen (1991-2020)

(source: Wikipedia)

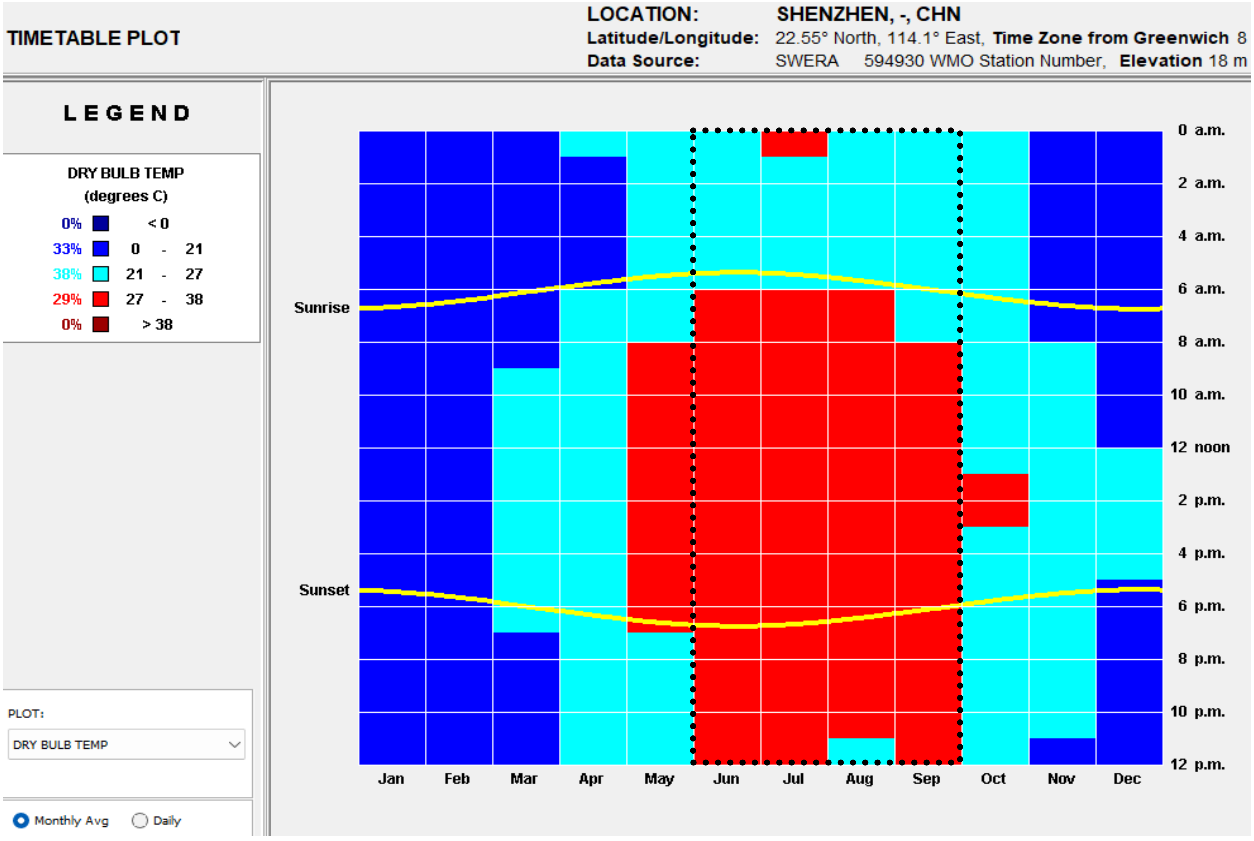


Figure 3.8 Timetable plot for comfort zone

(graphic: own work, 2024)

[b] Direct sun hours analysis

Ladybug also provides the analysis of direct sun hours, which also shows that apart from the roof, the west façade is obviously in challenges during the summertime compared to other elevations. (Figure 3.6)

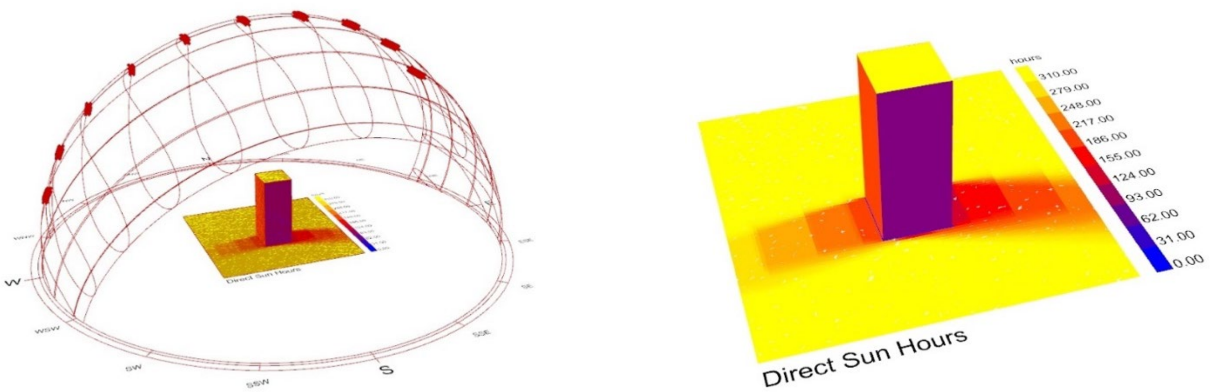
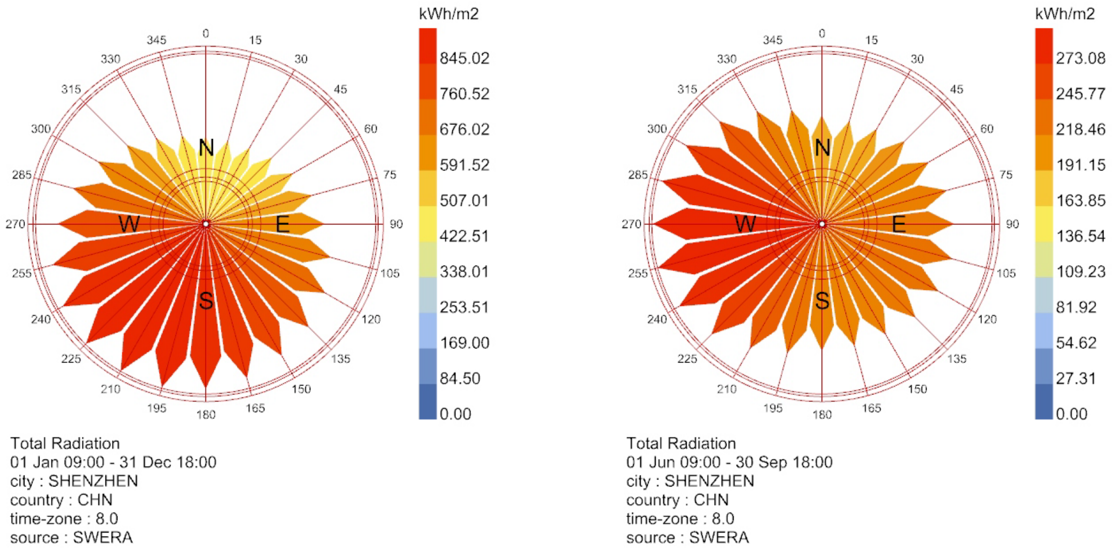


Figure 3.9 Sun hours analysis

(graphic: own work, 2024)

[c] Sun radiation analysis

The following two graphs show the solar radiation pattern of the whole year and the summertime (from June to September) in Shenzhen, respectively. Analyzed through Ladybug in Grasshopper, they indicate that orientation west has the most solar load during the summertime, and the east and south elevations rank similarly, while the north side has the least sunshine intensity. In contrast, the orientation southwest gains the most solar resources in the annual graphic. (Figure 3.7)



The solar radiation rose (Annual pattern)

The solar radiation rose (Summertime from June to September)

Figure 3.10 Sun radiation analysis for Shenzhen

(Graphic: own work, 2024)

[d] Solar load

The program System Advisor Model provides the data of monthly solar irradiation load in Shenzhen for further calculation work. (Table 3. 2)The data are generated in accordance with the following key inputs on SAM:

Location: EnergyPlus weather file same as the one used in DesignBuilder

Array Type:Fixed roof mount

Tile angles: 90° for vertical installation and for overhangs it could be 0° or 30° or others.

Azimuth angel: West - 270° (noted: North - 0 °, East - 90 °, South - 180 °)

	Plane of array irradiance (kWh/m2)	Daily average solar irradiance (kWh/m2/day)	Daily average solar irradiance (kWh/m2/day)
Jan	98.8836	3.18979	1.70145
Feb	91.427	3.26525	1.68969
Mar	115.965	3.7408	1.88818
Apr	128.978	4.29926	2.17201
May	147.655	4.76307	2.34473
Jun	146.294	4.87645	2.3331
Jul	153.88	4.96386	2.40872
Aug	149.468	4.82153	2.46753
Sep	131.79	4.39301	2.19057
Oct	131.859	4.25352	2.30701
Nov	110.533	3.68442	1.81818
Dec	102.076	3.29279	1.78329

Table 3.2 Monthly Available solar radiation in Shenzhen

(table: generated by SAM, 2024)

(Noted: the left and middle columns are based on 0 degrees tilt angle, while the right columns are in vertical conditions with 90 degrees tilt angle)

For example, the daily solar load in July is approximately 4.96 kwh/m^2/day (for tilt angle 0 °) and 2.41 kwh/m^2/day (for tilt angle 90 °). The mean annual solar load in July is approximately 4.13 kwh/m^2/day (for tilt angle 0 °) and 2.09 kwh/m^2/day (for tilt angle 90 °).

3.2.2 Climatic strategies

According to the psychrometric chart generated by Climate Consult v6.0 throughout the summer (ranging from June to Argust) between 09.00–18.00, all the 'red dots' are almost out of comfort zone shown in Figure 3. 3 Psychrometric chart with comfort zone (Summer comfort is in the right blue frame)

As noted in, Figure 3. 4the suggested strategies are 94.8% provided by cooling and dehumidification, 72.3% provided by sun shading to achieve the indoor thermal comfort, while the natural ventilation barely contributes to the cooling purpose (only 0.1%). In other words, the results require both passive cooling strategies (to add sun shading elements) and active cooling strategy (to supply space cooling) to achieve indoor thermal comfort.

In summary (Figure 3.8), the comfortable ranges during the extreme period (from June to September, time ranges 9.00-18.00) are listed:

Indoor comfort (dry bulb) temperature range: 23.6 C° – 28.2 C°, avg at 26 C°
Indoor comfort relative humidity max limit: < approx. 66%.
Indoor comfort relative humidity min limit: 30%. (defined by Chinese national design regulation, Code for thermal design for civil building, code: GB50176-2016)

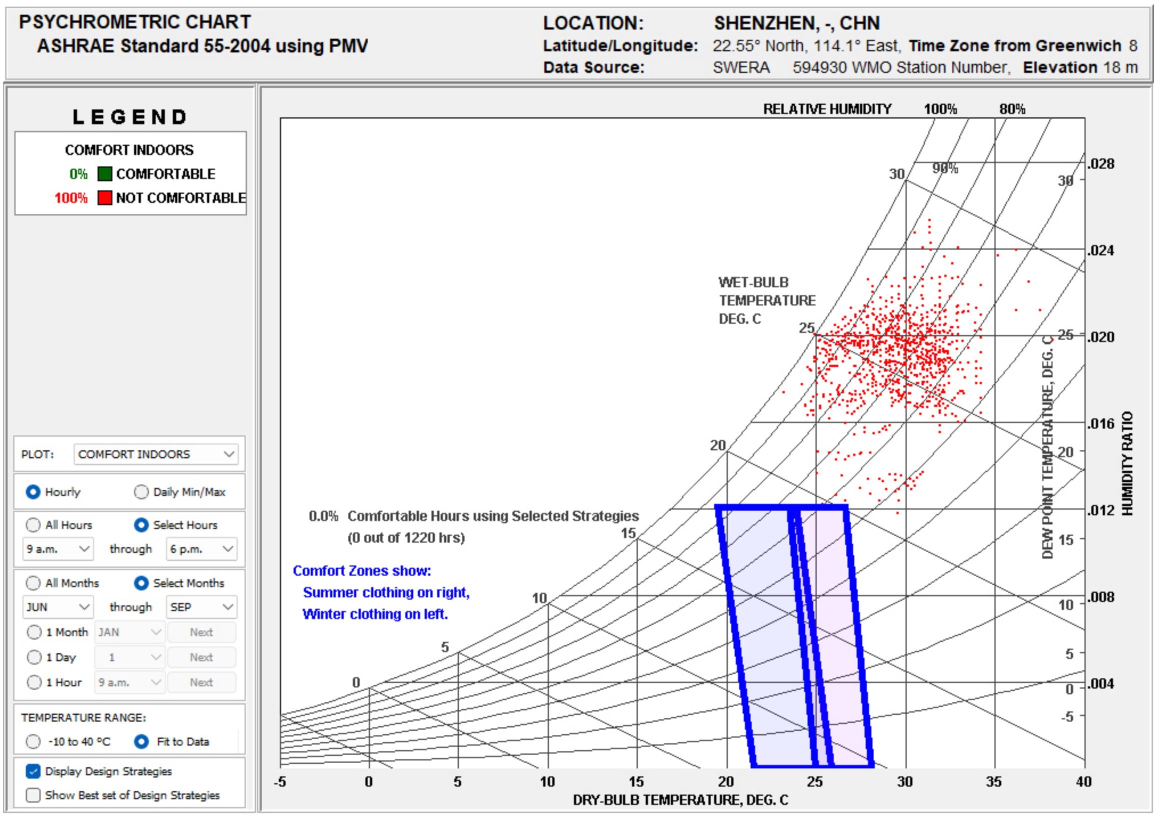


Figure 3.11 Psychrometric chart with comfort zone

(graphic: own work, 2024)

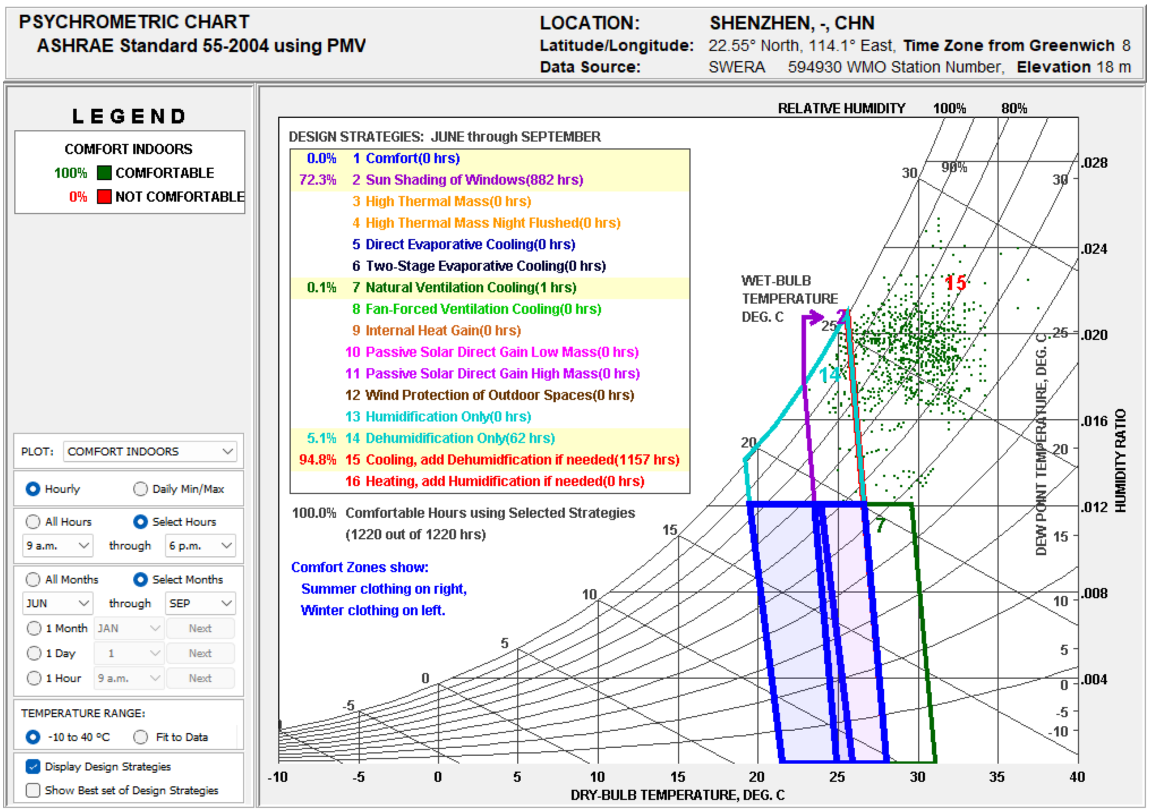


Figure 3.12 Psychrometric chart with comfort zone

(graphic: own work, 2024)

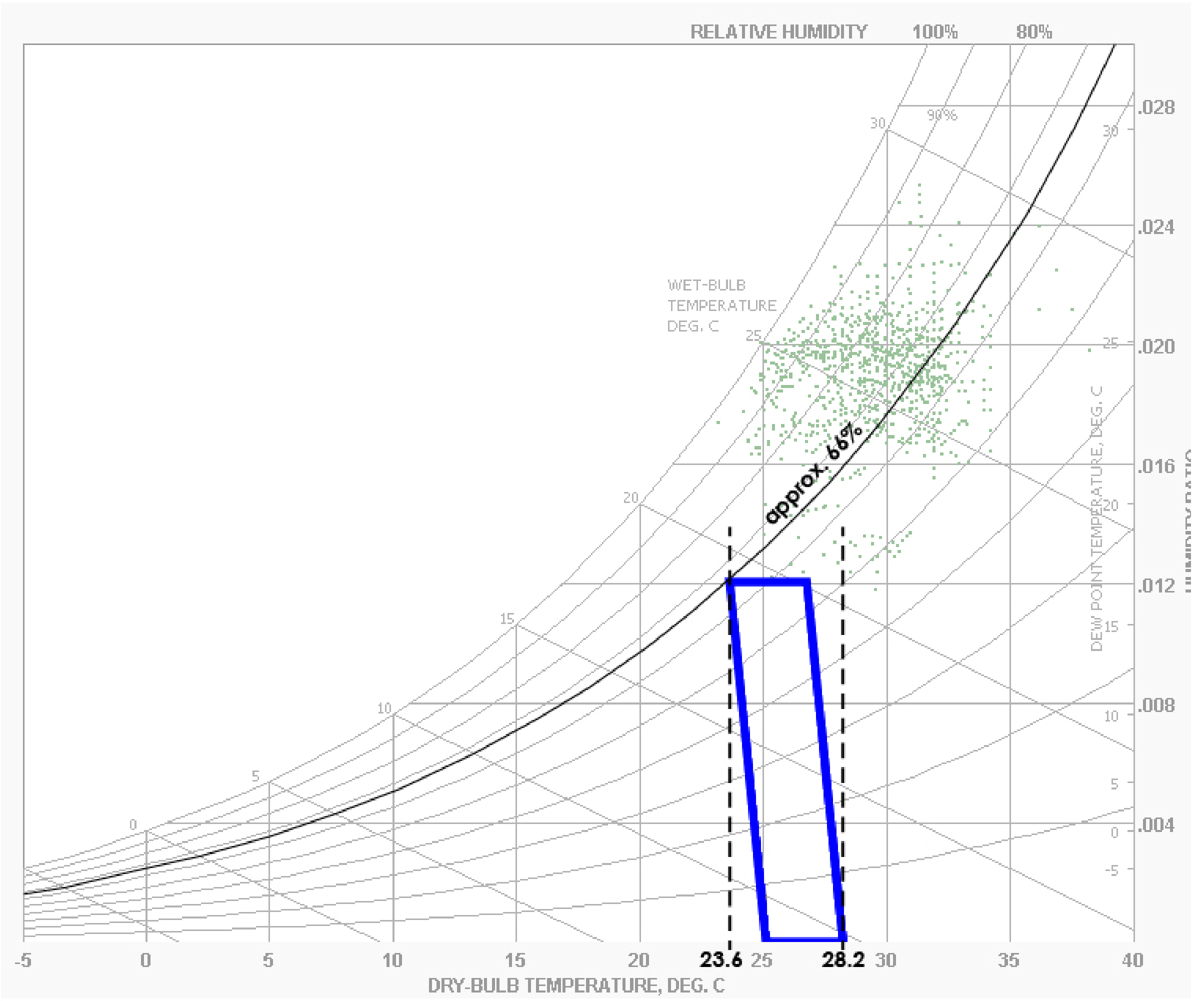


Figure 3.13 Range of indoor thermal comfort

(graphic: own work, 2024)

BASE CASE DESIGN

3.3 Base case

3.3.1 The base case building

To carry out the initial design, the type of base case building that can behave like the most common generic office buildings in Shenzhen must be determined at this stage, as this will become a benchmark archetype for further design development and energy simulation.

[a] Building status

The section of boundary conditions defines the base case building as a newly built high-rise office building. That is because a new building has more design freedom and no safety issues from the existing structure.

[b] Building typology

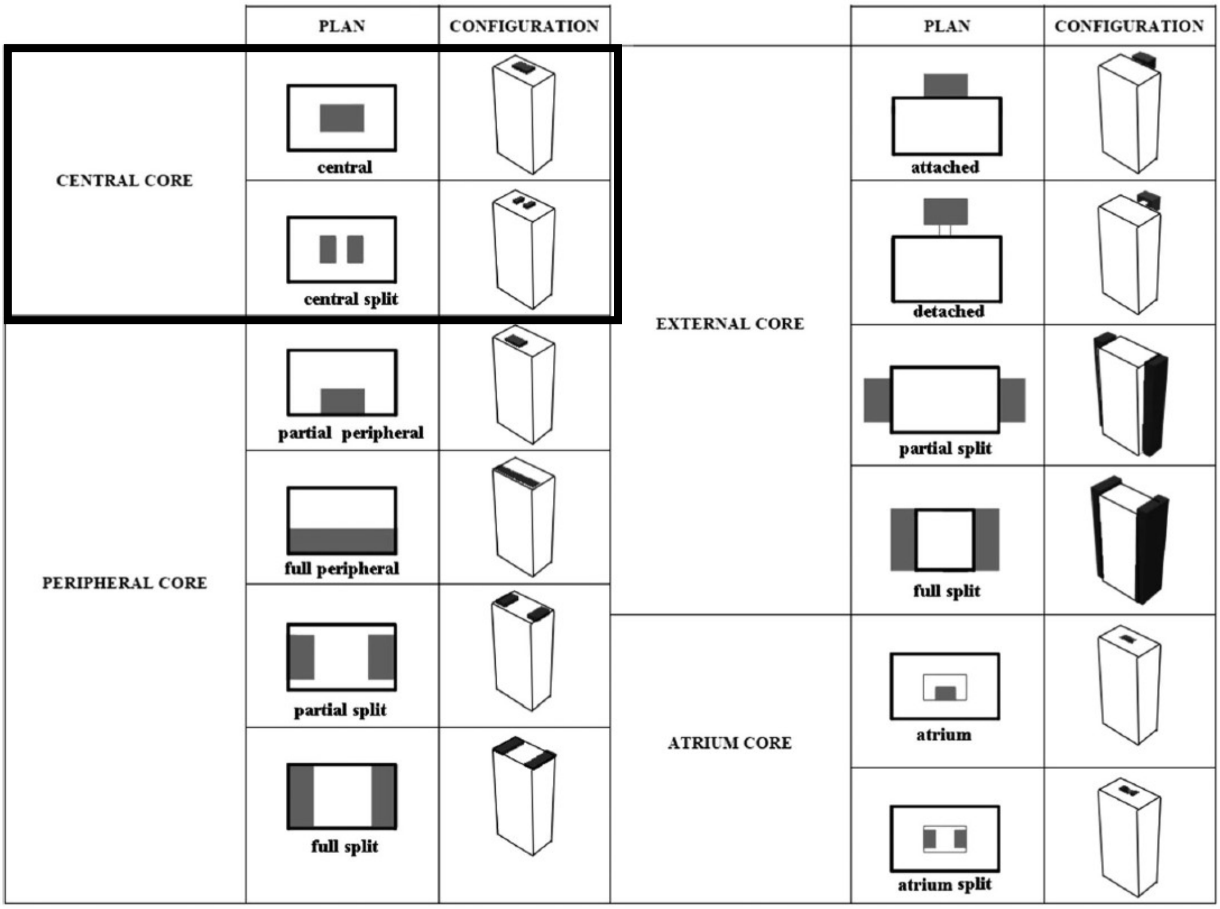
Shenzhen is one of the skyscrapers centers in the world. According to the database of CTBUH (The Council on Tall Buildings and Urban Habitat), Shenzhen has the second highest number of high-rise buildings over 150m in the world (Hong Kong is #1, New York is #3), and tall buildings under 150m and 100m are even countless in this city. This type of building has a large façade area and receives more solar radiation, but the energy consumption of this typology is usually high. Therefore, the basic building typology is determined as a generic office tower with a height ranging from 100m to 150m. Some reference projects demonstrate this typology. (Figure 3.14)

Figure 3.15 Representative office buildings typology as the base case building

(Left- Shenzhen Software Industry Base, Plot 1; Middle - Shenzhen Haiwang Tower; Right - Shenzhen TINO headquarters) (source: google images)

[c] Typical floor plan layout

Some studies (Ilgın et al., 2020) have shown that the arrangement of central core is the most preferred core layout with the highest space efficiency in high rise office buildings among all core plannings, even the number of central-core cases in all research candidates are the majority (95% shown in Figure 3.12). Meanwhile, to provide each elevation same conditions in façade area, as well as the uniformity for all indoor workspaces in dimensions, it is decided to shape the typical floor plan in square, in other words, the aspect ratio is 1:1.



Core planning	#	app.%
Central core	88	95%
Peripheral core	2	2%
External core	1	1%
Atrium core	2	2%
TOTAL	**93**	**100%**

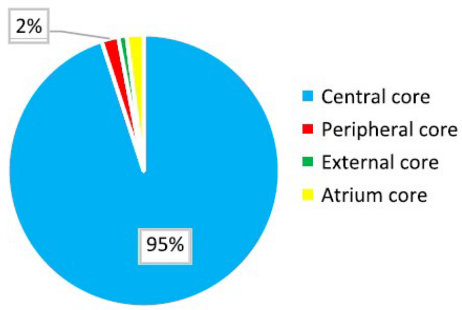


Figure 3.17 Research on core arrangements in high-rise office buildings

(source: Ilgın et al., 2020)

[d] Structural grid

As the building height defined, it is assumed that the structural grid for the workspace is 9000 x 9000 mm which is based on the empirical dimensions of structural design for high rise office tower with this height, while also taking car-parking size into account (three cars parked in row in one grid). (Figure 3.13) Additionally, for the sake of construction and manufactory modules in building application, 300mm is the most common value in China. For example, doors and windows, façade panels, ceiling grid, office furniture and so on, are usually made in 300 mm module. (Architectural Design Dataset Volume 3: Office, 3rd Edition 2017)

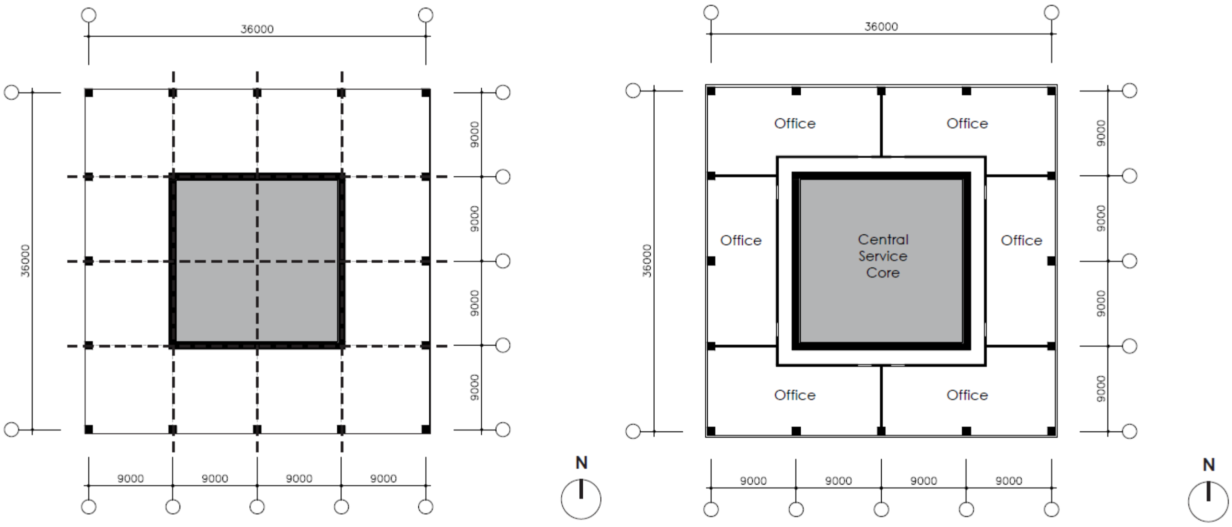


Figure 3.18 Structural grid (left) and typical floor plan layout (right)

(graphic: own work, 2024)

[e] Floor height and indoor ceiling height

According to the local regulations of Shenzhen architectural design rules (Edition 2022), the maximal floor height (floor finish to finish) for an office building is 4.5m, except for the ground floor lobby. (It would be calculated twice the area if the floor height was over 4.5m for any typical office level. (Figure 3.14)

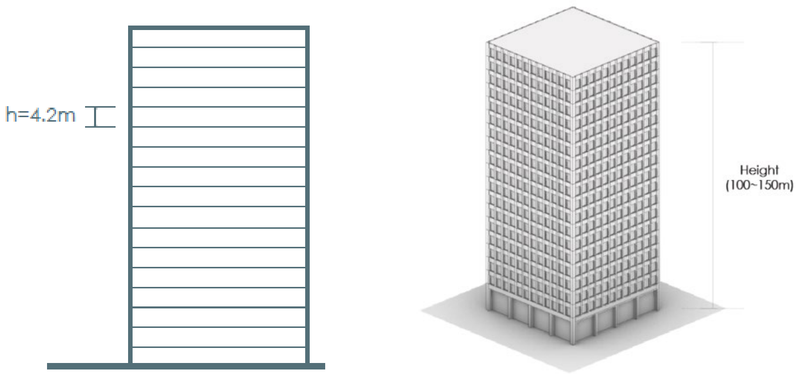


Figure 3.19 Building height, floor height, indoor ceiling height

(graphic: own work, 2024)

In terms of the clear height control for office space, the minimal limit is not less than 2.9m when using decentralized A/C systems or just being as a free running (no A/C applied) building. The criteria are given by the Chinese national regulations- Standard for design of office building (JGJT 67-2019).

Therefore, it has been assumed that the floor height is 4.2m and the indoor clear height is 3m for the base case building.

[f] Façade typology

Considering all the reference projects in the case study regarding FIPV/FIST buildings, FI decentralized HVAC systems and those most common office buildings in Shenzhen, the façade typology of the base case building is a unitized metal-glass curtain wall system. (Figure 3.20) The metal components consist of the window frames and the opaque cladding panels, usually made in aluminum; the glass components are the glazing panels.

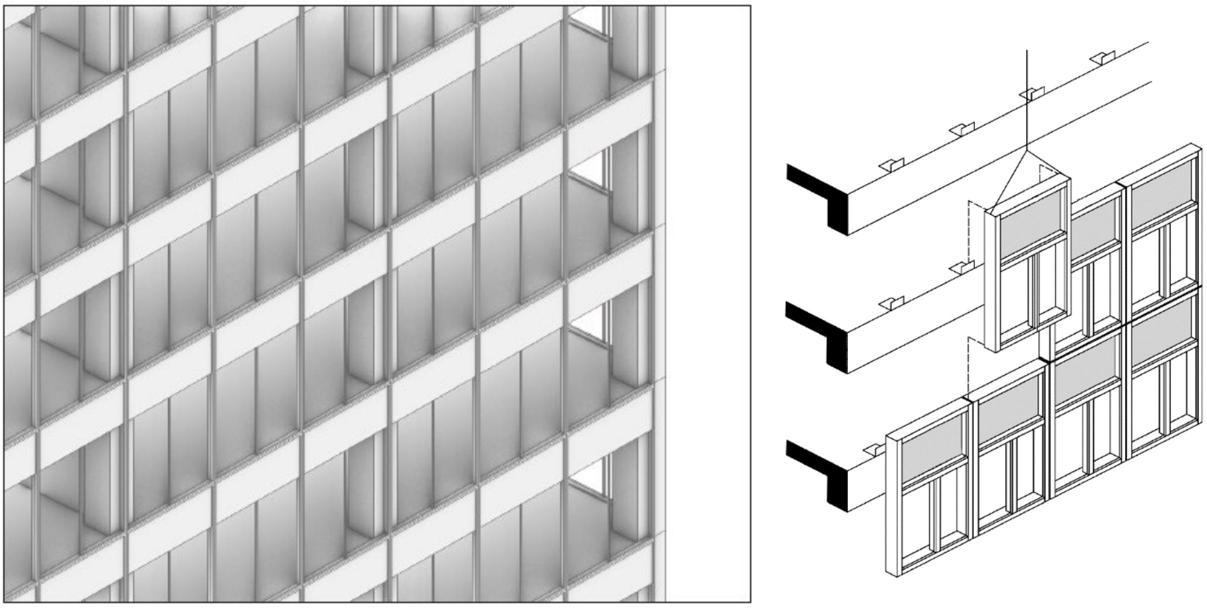


Figure 3.21 The façade typology for base case building

(graphic: own work, 2024)

[g] Building orientation

Regarding the solar radiation analysis in the previous subsection, orientation west has the most solar load during the extreme period. Therefore, the target building orientation will focus on the west elevation.

[h] Target room

In a typical floor, a west-oriented office room of 18m by width (2 structural grid) and 7.3m by depth is chosen as a target room both for the further façade design and energy simulation. (Figure 3.16)

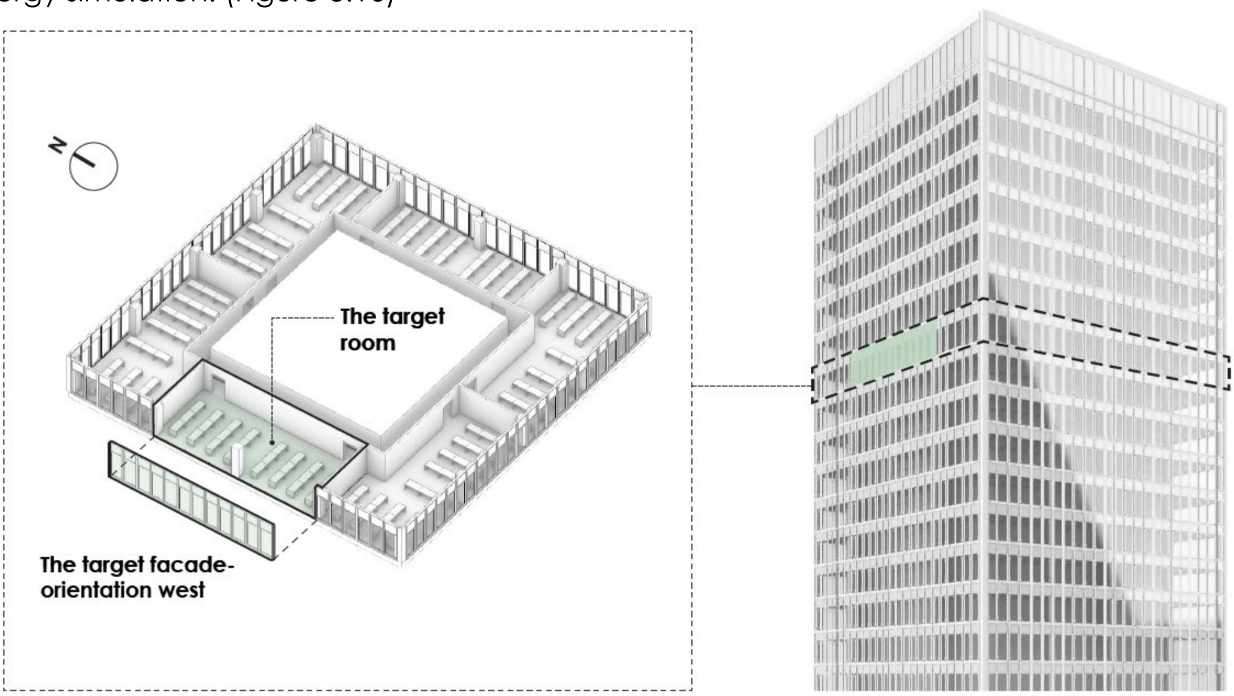


Figure 3.23 The target room

(graphic: own work, 2024)

Table 3. 3 shows all the constant parameters for the base case building:

Items	Configurations	Interpretation	Refs source / design regulation
Building status	generic new-built office building	more design freedom and no safety issues from existing buildings' structure	Hamida H. et al. 2023.
Building height	100m<Height<150m	buildings with this height range make up most high-rise buildings in Shezhen (over 80% of all recorded buildings)	(1) CTBUH report 2020; (2) Database from 'Shenzhen existing building curtain wall information management platform'
Typical floor plan layout	core arrangement-central core	the most preferred core arrangement and highest space efficiency in high rise office buildings among all core plannings	Ilgın et al. 2020.
Aspect ratio of floor plan	1:1 square	uniformity for all indoor workspaces in dimensions	-
Floor-floor height	max 4.5m (taking 4.2m for design)	max limit to office floor height in Shenzhen	Shenzhen architectural design rules (Edition 2022) (Local design regulation)

Interior clear height	min 2.9m (taking 3.0m for design)	min limit to office space with decentralized cooling systems in China	Standard for design of office building (National design regulation, code: JGJT 67-2019)
Building orientation	target rooms with west-facing façade	the west orientation that has the most solar radiation load in July	Solar radiation analysis (Own work, 2024)
Façade typology	unitized metal frame - glass façade	the most numerous types of façades in Shenzhen	Database from 'Shenzhen existing building curtain wall information management platform'
Structural typology	steel-concrete composite with core tube structure	the most common structural type for high-rise buildings	Ilgın et al. 2020.
Structural grid	9m x 9 m	empirical dimensions of structural design, while also taking car-parking size into account	Architectural Design Dataset Volume 3: Office (3rd Edition 2017) (Design reference book in China)

Table 3.3 Constant parameters for the base case building

3.3.2 Adjustable parameters inputs

The adjustable parameters are based on the design decision and simulation requirements, mainly including the construction parameters, activity parameters, and HVAC systems parameters.

[a] Construction parameters

The construction parameters are mainly about different materials used in the target room of the base case building. They comprise the constructive materials of internal partitions, ceiling, internal floor, and the external curtain walls. (Table 3. 4)

Construction parameters	Configuration	Limitation of regulation	Refs source / design regulation
Office dimensions	18x7.3x4.2 m (width x depth x height); room area: apprx. 130 m²	-	Design proposal
Internal partitions	Lightweight 2 x 25mm gypsum plasterboard with 100mm cavity (U-value=1.64 W/m²K)	-	(1) Materials library provided by DesignBuilder 7.0 software; (2) Qiu et al. 2021; (3) Dina S.
Ceiling	Exposed ceiling with 10mm metal deck + fire coating (U-value=1.36 W/m²K)	-	

Internal floor	Timber floor finish + 100mm cast concrete slab + 10mm metal deck (U-value=1.36 W/m²K)	-	Noaman et al. 2022
External wall (glazing components)	Double glazing: **Generic Low-E glass 6mm+12mm air+Generic clear glass 6mm** (WWR=69%, U-value=1.77 W/m²K, SHGC=0.24, Vt=0.75)	Limits of regulation for glass façade: Max WWR≤70% for any orientation U-value≤2.50 W/m²K SHGC≤0.24 Visible transmittance≥0.4	(1) Design standard for energy efficiency of public buildings (National design regulation, code: GB50198-2015)
External wall (opaque components)	Metal cladding: **Aluminium cladding 5mm with heat-reflective coating + EPS expanded polystyrene (standard) 80mm + EPDM water barrier + aluminium cladding 5mm (interior surface)** (U-value=0.46 W/m²K)	Limits of regulation for opaque metal façade: U-value≤0.8 W/m²K	(2) Materials library provided by DesignBuilder 7.0 software;

Table 3.4 Construction parameters

(The table data based on the materials library of DesignBuilder v7.2)

[b] Activity parameters

The activity parameters mainly reflect the operational characteristics of this generic office building. They comprise its operation hours during weekdays, cooling set point temperatures and indoor relative humidity in summertime, density of occupancy, lighting, and equipment for daily use. (Table 3. 5)

Activity parameters	**Configuration**	**Refs source / design regulation**
Operation hours	9:00-18:00	Design standard for energy efficiency of public buildings (National design regulation, code: GB50198-2015)
Thermal comfort range during summer design time	Cooling set point temperature: 26℃ (9:00-18:00) Relative humidity: 40%≤RH≤60% for summer; 30%≤RH≤60% for winter	(1) Shenzhen Technical Guidelines for Ultra-Low Energy Consumption Buildings (Edition 2021) (Local design regulation) (2) Code for thermal design for civil building (National design regulation, code: GB50176-2016)
Occupant density	0.05 person/ m^2 (7:00-9:00) 0.1 person/ m^2 (9:00-18:00)	Standard for design of office building (National design regulation, code: JGJT 67-2019)
Lighting density	9 W/m^2 for a minimum illuminance of 400 lux; 750mm for the working plane height	Design standard for energy efficiency of public buildings (National design regulation, code: GB50198-2015)
Equipment density	15 W/m^2	

Table 3.5 Activity parameters

(The table data based on the materials library of DesignBuilder v7.2)

[c] HVAC systems parameters

As analyzed by the Climate Consultant program, natural ventilation is barely helpful for cooling in this case. Hence, the mechanical ventilation system is used in the base case building. As this study mainly focuses on space cooling service, mechanical ventilation is decided to be set up independently of the A/C system so that energy consumption will also be simulated separately.

The HVAC systems parameters for the target room are shown in the Table 3. 6.

HVAC system parameters	**Configuration**	**Values**	**Refs source / design regulation**
Main A/C system	Centralized system: Horizontal fan coil unit (4-Pipe) and air-cooled chiller	The nominal seasonal COP for cooling: 1.8	(1) Qiu et al. 2021; (2) HVAC data provided by DesignBuilder 7.0 software;
Main Mech Vent system	AHU (Air Handling Unit)	3 ACH (Standard) 0.1m^3/s (Design flow rate)	Design standard for energy efficiency of public buildings (National design regulation, code: GB50198-2015)
	Minimum fresh air for hygienic purpose	30 m^3/ h*person (8.33 l/s*person)	
	Model infiltration	0.2 (for air-tight facade)	ASHRAE CLTD Method for Commercial Building infiltration levels

Table 3.6 HVAC systems parameters

(The table data based on the materials library of DesignBuilder v7.2)

3.3.3 Preliminary façade design for base case

There are two steps in the preliminary façade design: the first is to determine the initial value of WWR, and the second is to design the basic dimensions of the façade module based on the WWR results.

[a] The initial value of Window-to-Wall Ratio (WWR)

From the perspective of cooling and heating loads, the façade energy performance of low WWR is better than that of high values in most cases. (Kull et al.,2015) This is reflected in Chinese national regulations to set the WWR limit as a prescriptive target. According to the regulation of the design standard for energy efficiency of public buildings (GB 50189), WWR value of each single elevation should not exceed 70% (upper limit).

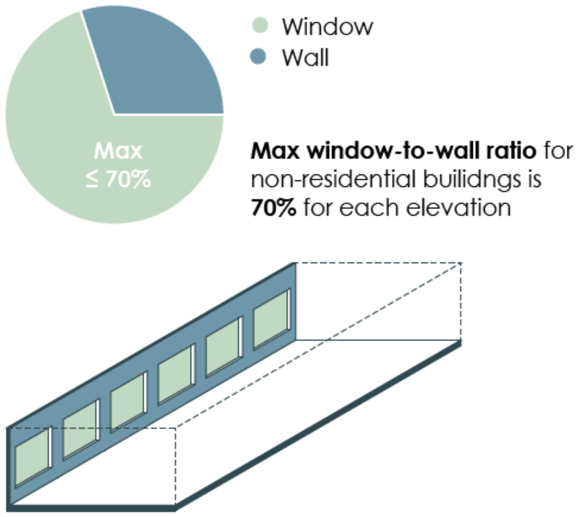


Figure 3.24 Regulation limit of WWR

(graphic: own work, 2024)

Therefore, the first design decision is to set a maximum possible value of WWR for the target room façade by using 'Honeybee', a Grasshopper plug-in, to adjust the opening apertures on façade surface. The generated results give a solution on how to subdivide the facades in modules, both meeting the demands of not-larger-than-70% limit and the maximum glazing area. As shown in Figure 3.25, the corresponding WWR 69% with 6 façade divisions are the computationally calculated outcomes, and the Grasshopper workflow is shown in Figure 3.26

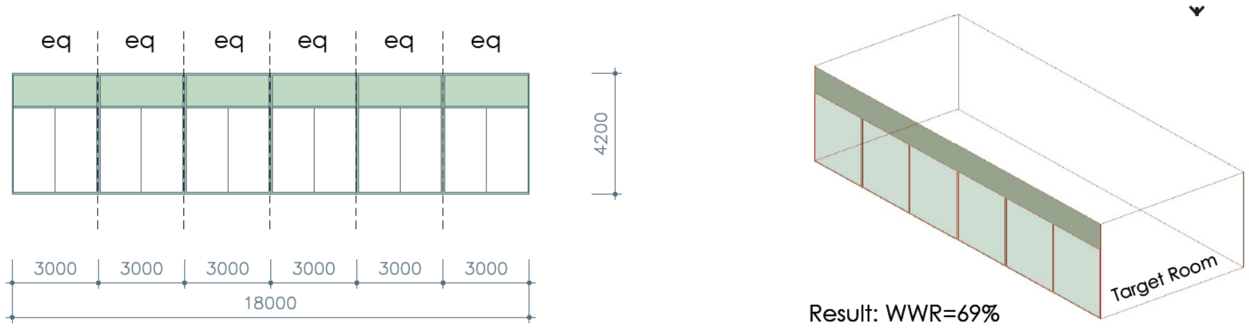


Figure 3.27 Façade division with WWR 69%

(graphic: own work, 2024)

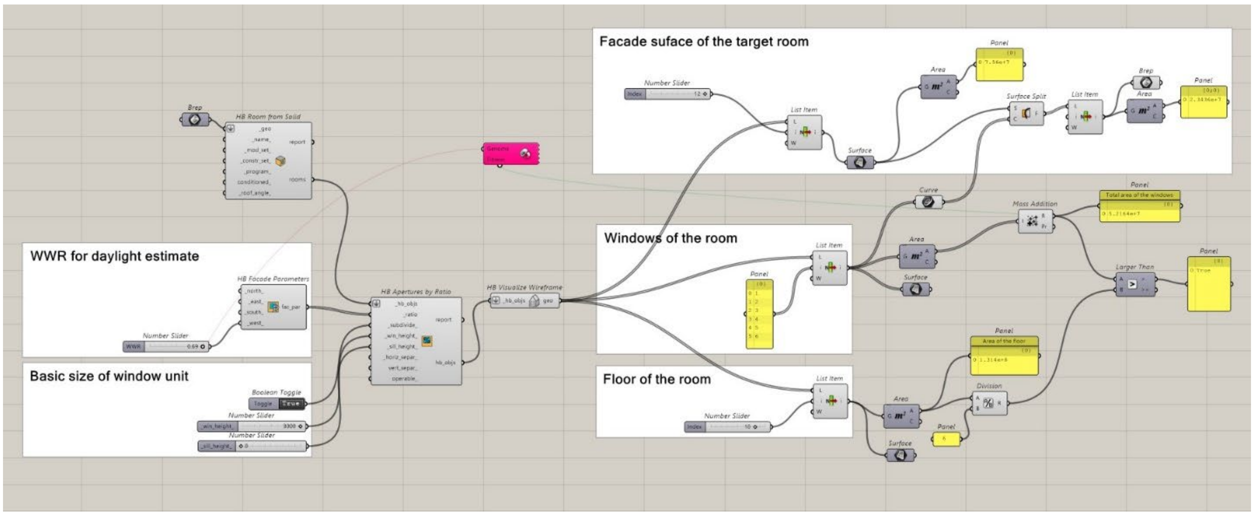


Figure 3.28 Grasshopper workflow to generate the maximal WWR

(graphic: own work, 2024)

[b] Façade module of base case

Based on the 69% of WWR results, the proportions of a single façade unit are as follows: vertically, the height of the glazing in the façade module is 3 meters, controlled by the indoor clear height; horizontally, the glazing is again subdivided into two pieces, since a width of about 3 meters is too large for a single piece of glazing, and would not be an economical and safe result.

Materially, each façade module consists of two sections - the opaque metal cladding and the transparent glazing. (Figure 3.29) They have different layer settings, while both should meet the requirement of the relative energy efficiency regulations. Additionally, there is no external sun shading element included in the base case façade model.

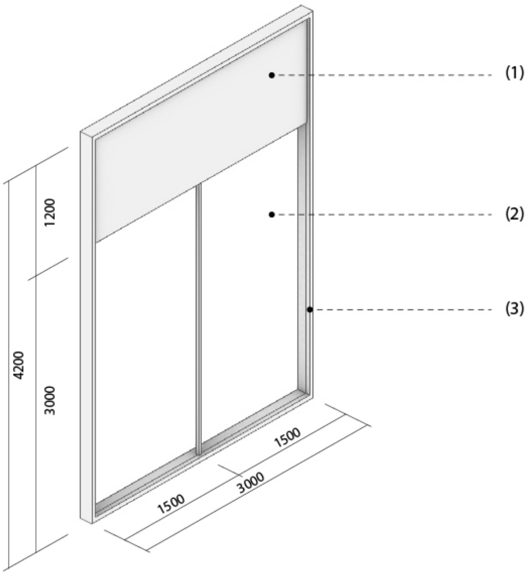


Figure 3.30 The dimensions of the base case façade module
(graphic: own work, 2024)

See the materials of the base case façade module in Table 3. 7:

(1) The opaque section – metal cladding	**Properties**
From outdoor to indoor: Aluminium cladding 5mm with heat-reflective coating EPS expanded polystyrene (standard) 80mm. EPDM water barrier Aluminium cladding 5mm	U-value=0.46 W/m² K (≤0.8 W/m² K max limit)
(2) The transparent section – double glazing	**Properties**
From outdoor to indoor: Generic Low-E glass 6mm 12mm air Generic clear glass 6mm	U-value=1.77 W/m² K (≤2.50 W/m² K max limit) SHGC=0.24 (≤0.24 max limit) Visible transmittance=0.75 (≥0.4 min limit)
(3) The façade frame	**Properties**
Aluminium window frame with thermal break	Thickness: 7mm U-value=5.014 W/m² K

Table 3.7 The materials layer of the base case façade module

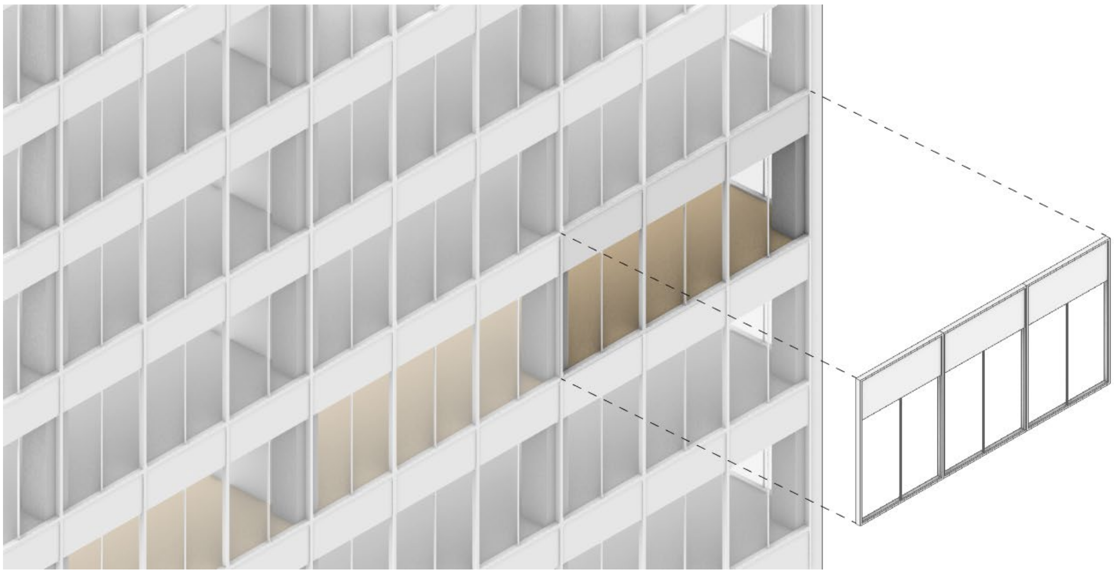


Figure 3.31 Façade visualization with axonometric view for base case (graphic: own work, 2024)

IMPROVED BASE CASE

3.4 Improved base case

For improved base case, it is intended to reduce the overheat gain through the base case façade systems. Therefore, a few passive cooling design strategies are applied to the façade models, main measures are the optimization of the WWR value and the design of sun shading elements. The double glazing and insulation materials of the external walls have already matched the energy efficiency standards, so these two parameters will remain unchanged from the base case scenario.

3.4.1 The optimization of WWR

As mentioned, a lower WWR is better for reducing the heat gain through glazing facades. However, it's not always as good as it indicates, as the smaller opening area also reduces the amount of daylight entering the office space. According to Chinese national design regulation - standard for daylighting design of buildings (GB 50033), the Window-to-Floor Ratio (WFR) is used as an estimation parameter to limit the minimal opening areas on office facades. As required, regarding the daylight climate zones where Shenzhen belongs, the minimal WFT is 1/6 and the calculation height should be above 700mm (office working plane height), which means the floor area of the target room can be at most 6 times larger than the opening (transparent panels) area. (Figure 3.22)

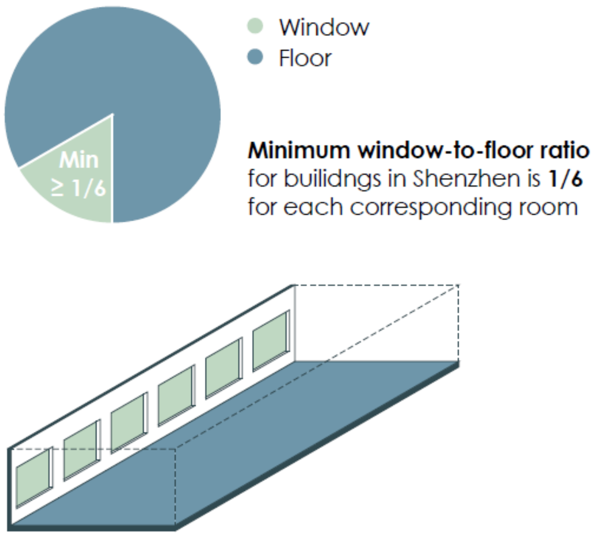


Figure 3.32 Regulation limit of WFR

(graphic: own work, 2024)

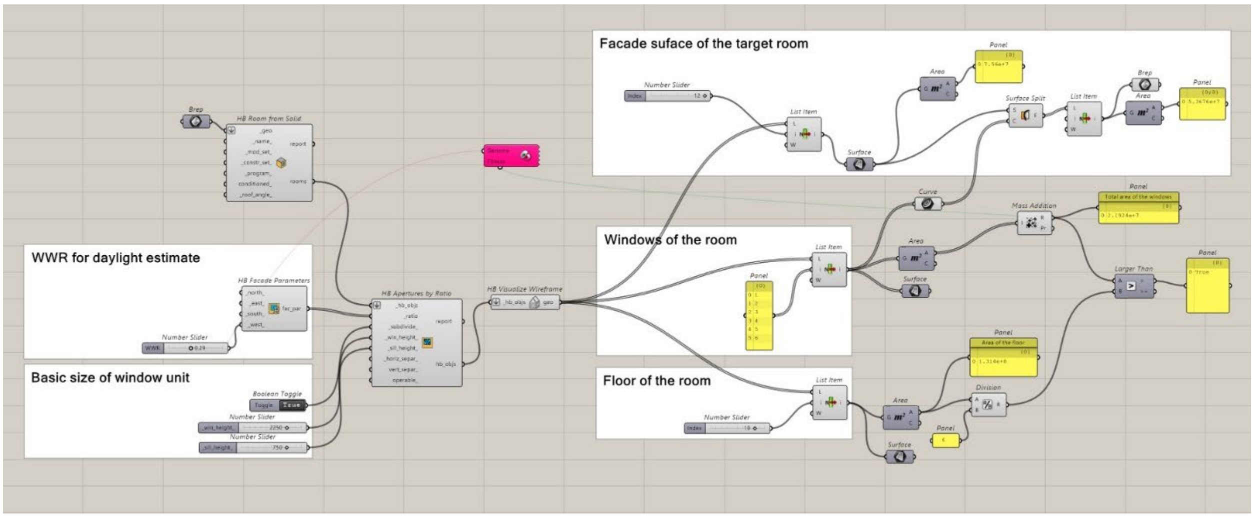


Figure 3.33 Grasshopper workflow to generate the minimal WWR
(graphic: own work, 2024)

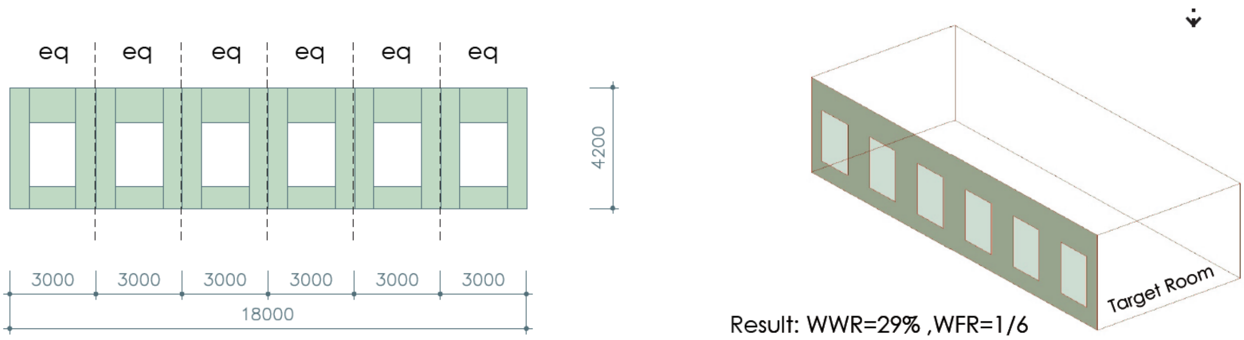


Figure 3.34 Façade division with WWR 29%
(graphic: own work, 2024)

Through running the Grasshopper program again based on the minimal opening area required by WFR limit, the lowest permissible WWR is generated accordingly. (Figure 3.35, Figure 3.36) The principle is: The floor area of the target room – the minimal area of openings on the façade – the permissible WWR minimum.

Finally, the optimized WWR is 29% and the proportion between the transparent and opaque components in the façade module also changes (Figure 3.37). The WWR optimization outcomes are showing in Figure 3.38

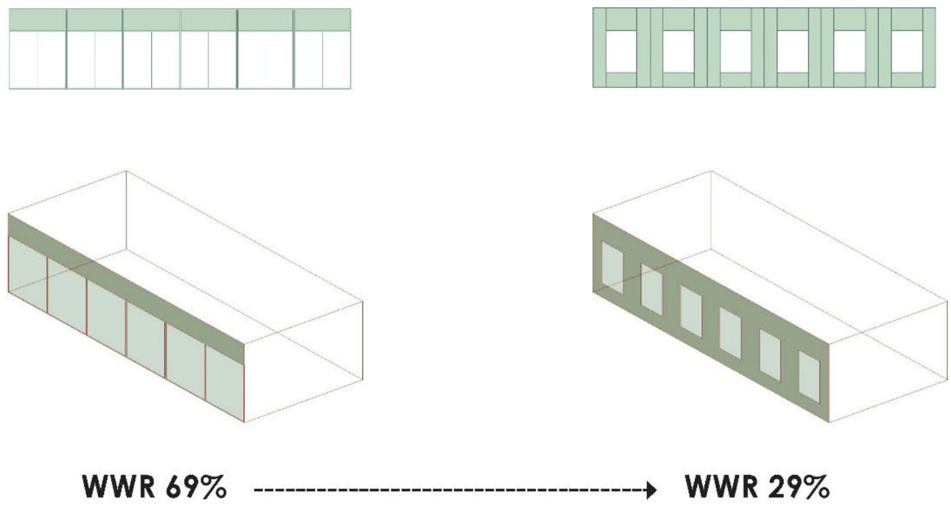


Figure 3.39 WWR optimization
(graphic: own work, 2024)

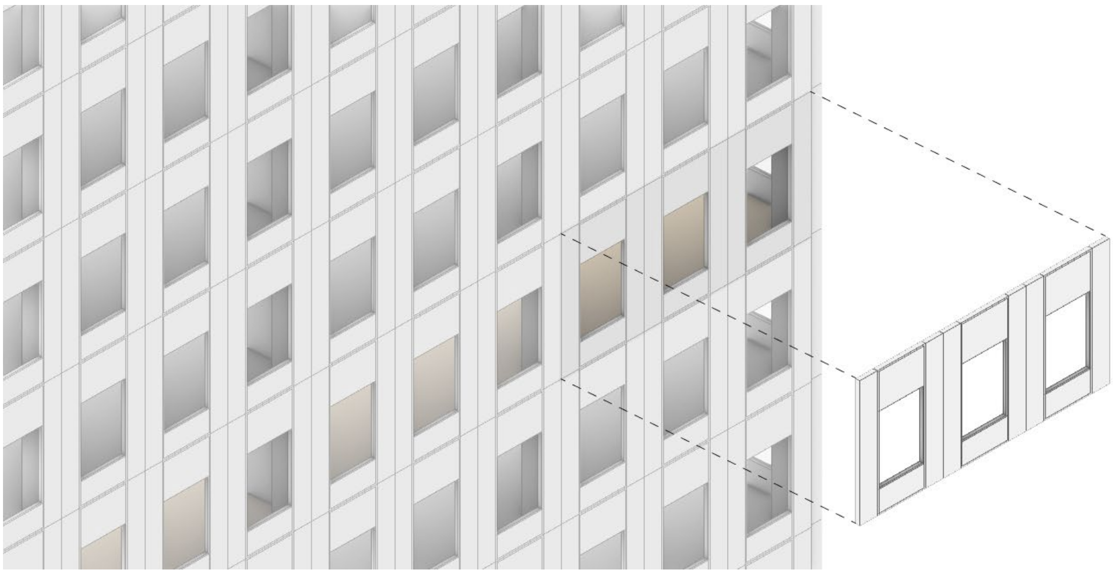


Figure 3.40 Façade visualization with WWR 29% with axonometric view for improved base case
(graphic: own work, 2024)

3.4.2 Sun shading elements design

[a] Rules of the thumb and the shading forms

As one of the passive strategies suggested by Climate Consultant software, sun shading elements have over 70% significance in addressing discomfort issues. The critical factor in determining the form of shading is the sun's angle, which consists of the horizontal and vertical shadow angles, which can be calculated when the sun angles (azimuth and altitude) are known (Figure 3.27).

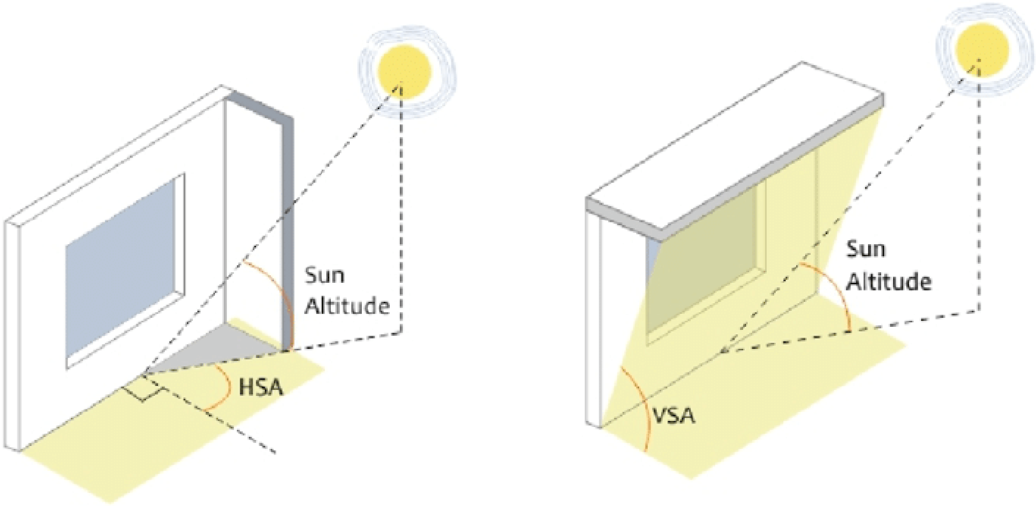


Figure 3.42 The critical factors affecting the forms of sun shading – HSA and VSA

(source: NZEB, n.d.)

Sun Shading elements can be formed according to the orientation of the windows. There are some rules of thumb that Indicate the most suitable shading types to use for each orientation in the northern hemisphere. These are just empirical data and still have many variations to these basic types.

North	Not required
East or West	Vertical elements / (movable) louvres / egg crate
South	Horizontal elements

[b] Sun shading chart

Climate Consultant software also provides sun shading charts that can be used as a tool to help decisions making for sun shading proposals on each elevation. (Figure 3.28, Figure 3.29, Figure 3.30, Figure 3.31)

Sun shading chart (Jun-Dec)

Red: shading needed
Yellow: shading helps
Blue: sun needed
Bold frame: peak time for heat radiation (10.00-14.00, summer-time)

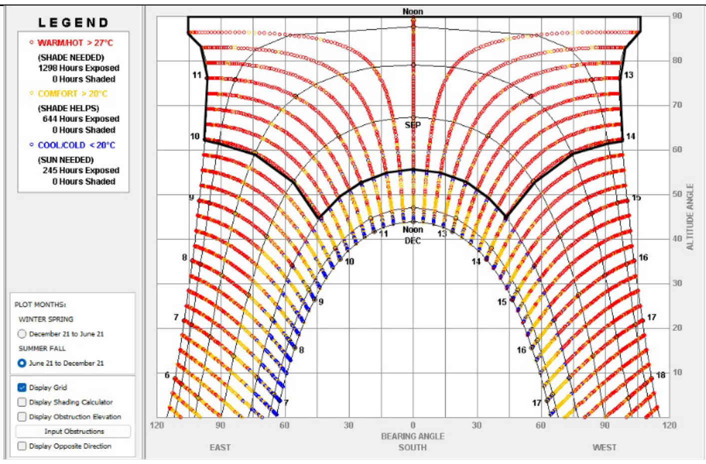


Figure 3.43 Sun shading chart for Shenzhen

Orientation East

Period: June – December
VSA: 60° (for 10.00-12.00)
HSA: n/a

Sun shading proposal:
fixed overhang (for 10.00-12.00)
movable louvres or vertical sun blind (for 8.00-10.00)

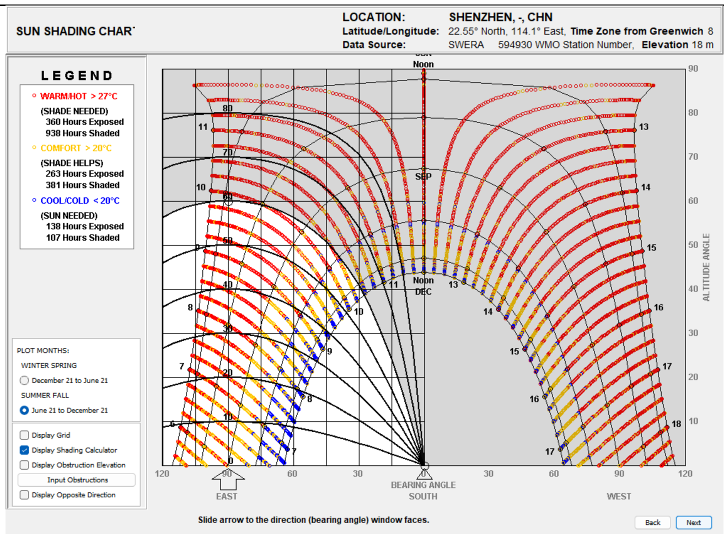


Figure 3.44 Sun shading calculation for orientation East

Orientation South

Period: June – December
VSA: 55° (for 8.00-16.00)
HSA: 15° (for 16.00-18.00)

Sun shading proposal:
fixed overhang (for 8.00-16.00)
west vertical fin (for 16.00-18.00)

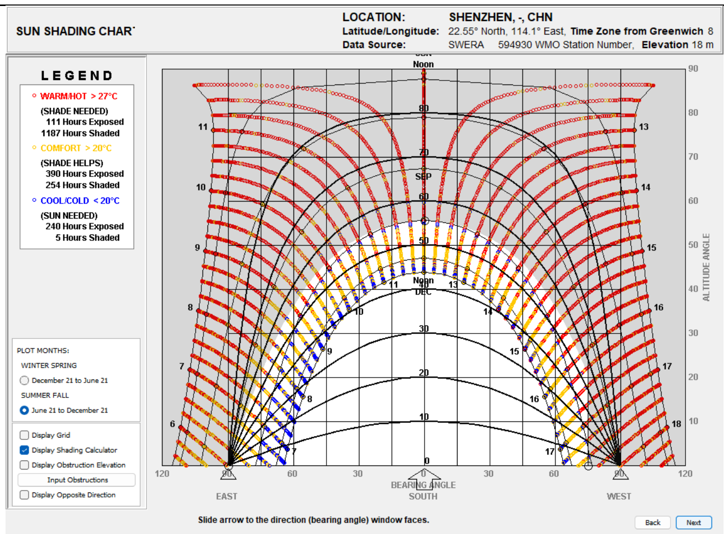


Figure 3.45 Sun shading calculation for orientation South

Orientation West

Period: June – December
VSA: 60° (for 12.00-14.00)
HSA: n/a

Sun shading proposal:
fixed overhang (for 12.00-14.00)
movable louvres or vertical sun blind (for 14.00-16.00)

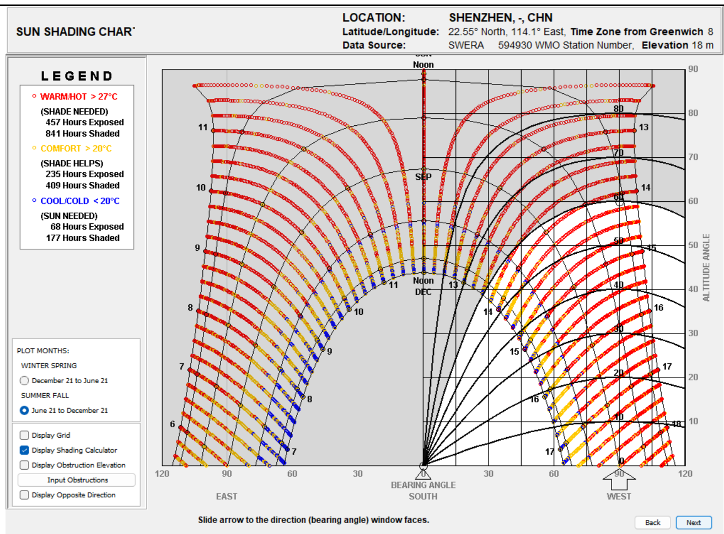
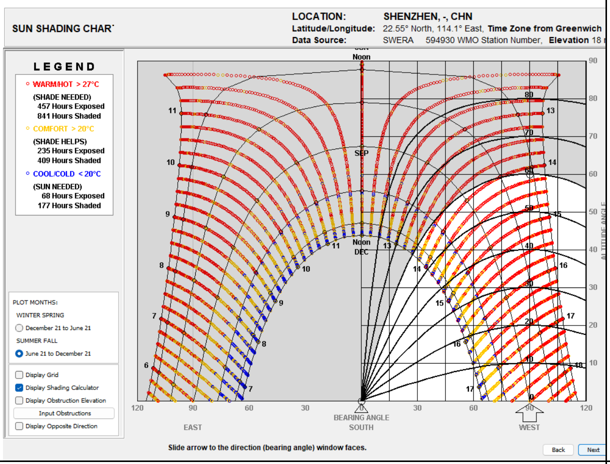


Figure 3.46 Sun shading calculation for orientation West

[c] Sun shading proposal for orientation west façade

Because this study focuses on the west facade during summertime. The sun shading design proposal needs to reflect the whole year's requirements. The comparison of sun shading chart between summertime and wintertime are as follows (Figure 3.47):

Orientation West during summer-fall

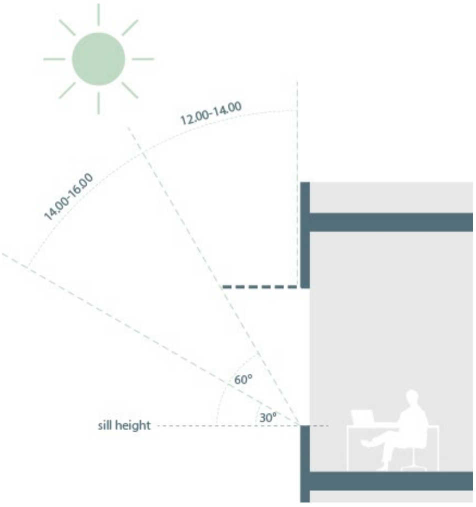


VSA: 60° (for 12.00-14.00)
59° - 30° (for 14.00-16.00)

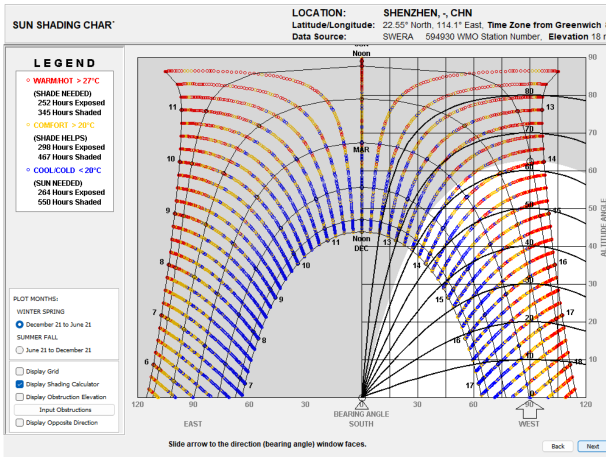
HSA: n/a

Sun shading criteria:

(1) overhand shading needed from 12.00-14.00.
(2) vertical sun blind needed from 14.00-16.00.



Orientation West during winter-spring



VSA: 62° (for 12.00-14.00)
61° - 35° (for 14.00-16.00)

HSA: n/a

Sun shading criteria:

(1) overhang shading needed from 12.00-14.00.
(2) sun needed while sun blind is optional from 14.00-16.00.

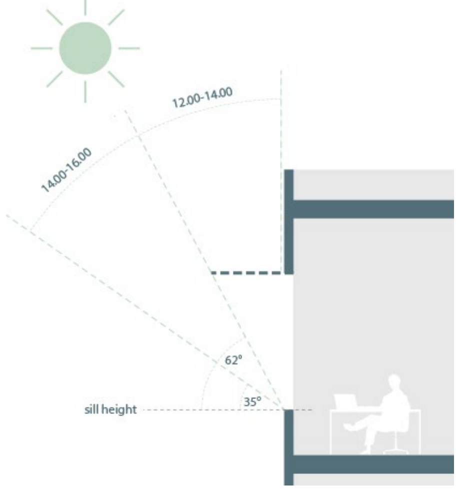


Figure 3.48 Sun shading chart for the west façade for all seasons

(graphic: own work, 2024)

Based on the analysis of the whole year sun path diagram, the most suitable proposal for west facade is to add fixed full-width horizontal shading panel and vertically non-fixed sun blind. The proposal is as follows (Figure 3.49).

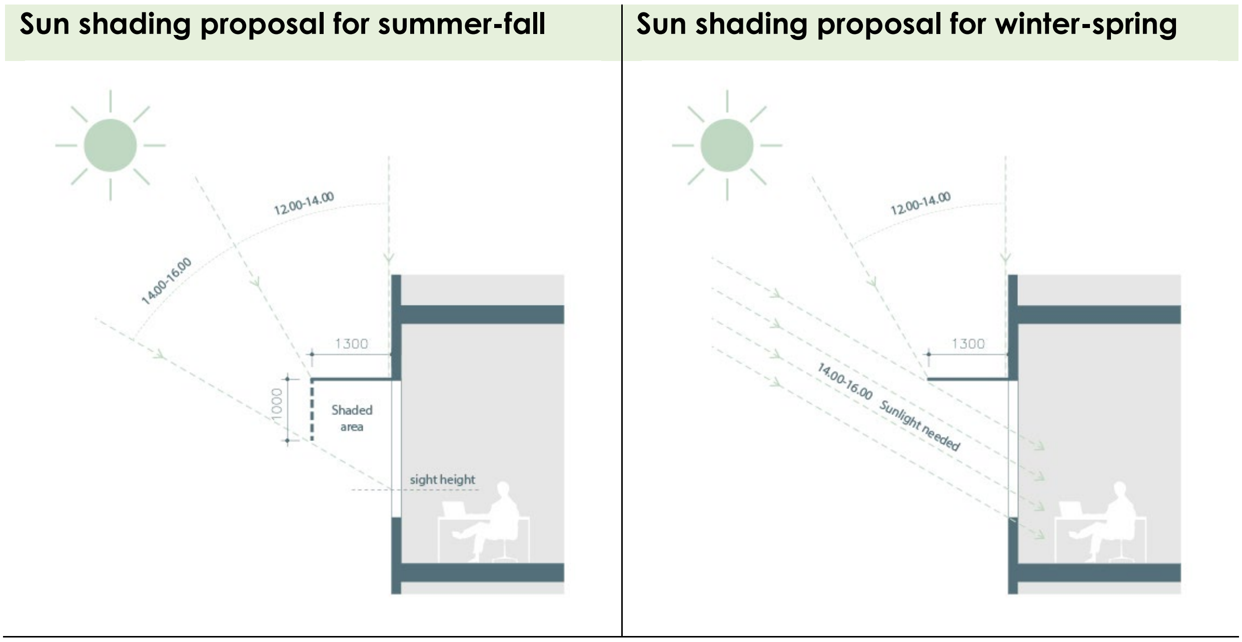


Figure 3.50 Sun shading proposal
(graphic: own work, 2024)

As seen in the figure, sun shading proposal for the west facade:

(1) A fixed overhang panel with at least 1300m depth and the full width of the opening are necessary, which enables to fully shade the openings during peak time throughout a year.
(2) A non-fixed vertical sun blind is optional. It can work at 14.00-16.00 during summer-fall seasons, while it should remain unblocked at the same time slots during winter-spring.
(3) An internal curtain or louvers is always useful.

[d] The fixed overhang shading panel design

Orientation: west
Form: overhand shading
Size: 1740(w) x 1300(d) x 50(thickness) mm
Materials: aluminium panel with high heat-reflective coating
Available hours: 12.00 – 14.00 (Full year)

(Shown in Figure 3.51)

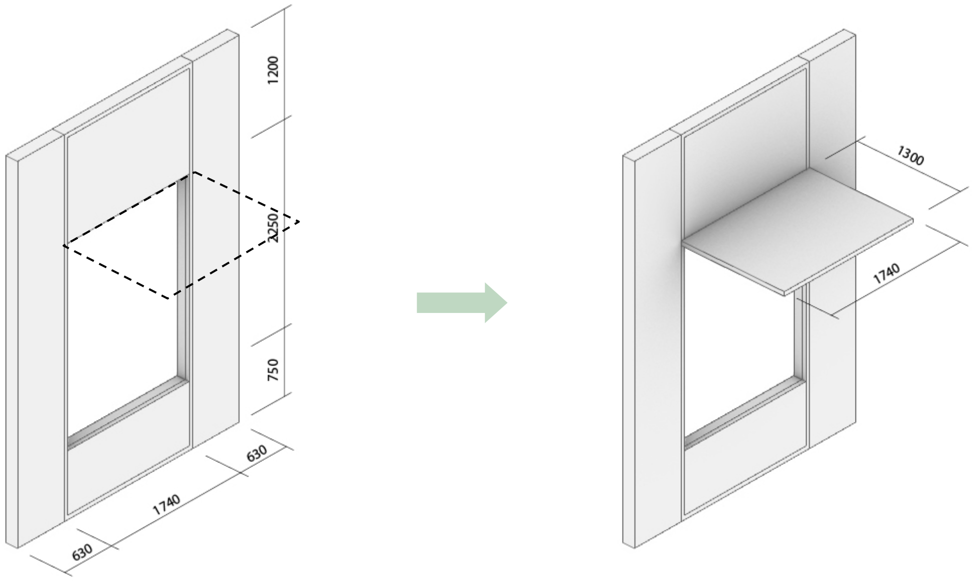


Figure 3.52 Fixed overhang shading panel design
(graphic: own work, 2024)

[e] Optional non-fixed sun blind design

Three options of supplemental shading proposals are shown in Figure 3.53:

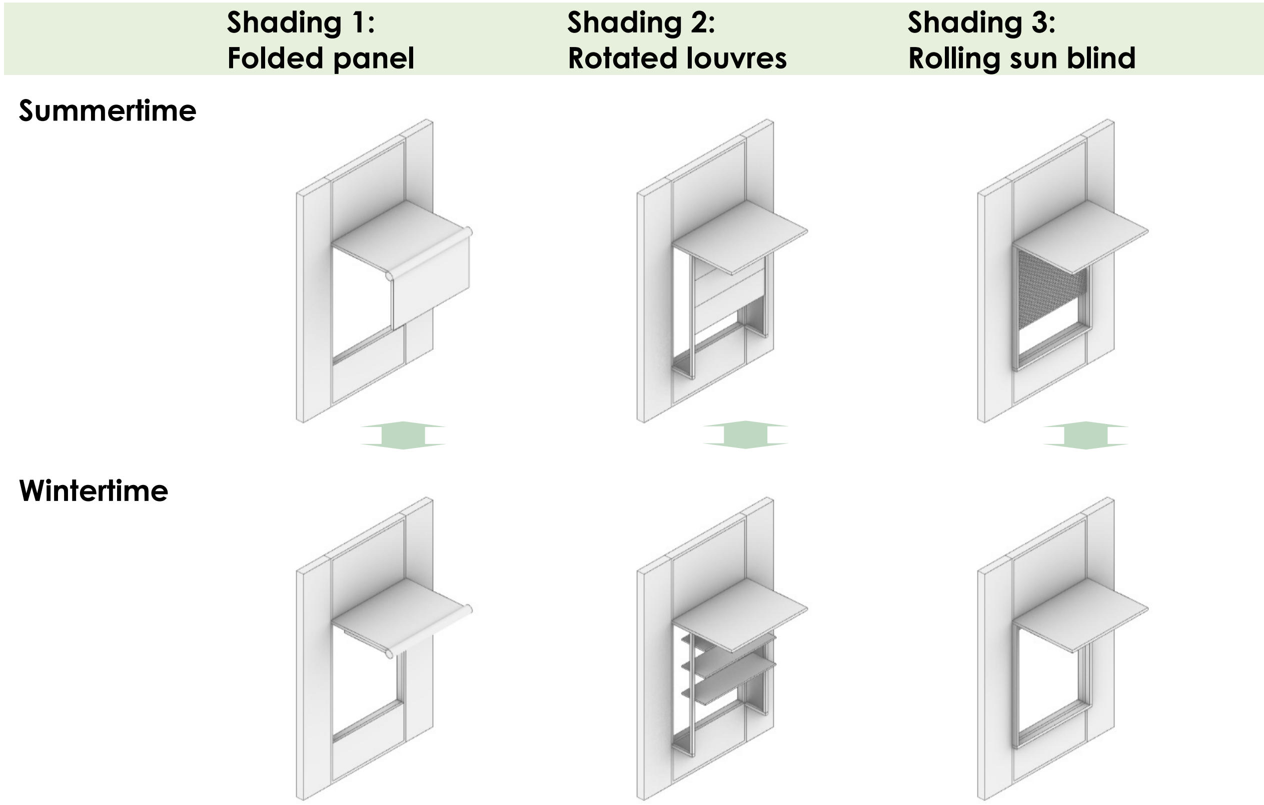


Figure 3.54 Optional non-fixed sun blind

(graphic: own work, 2024)

By Qualitative assessment:

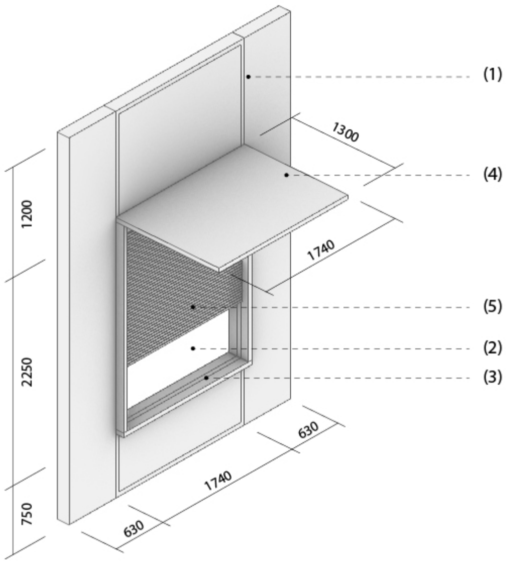
	Shading 1: Folded panel	Shading 2: Rotated louvres	Shading 3: Rolling sun blind
Safety	*	**	***
View	***	*	**
Material durability	**	***	*
Ease of maintenance	*	*	***

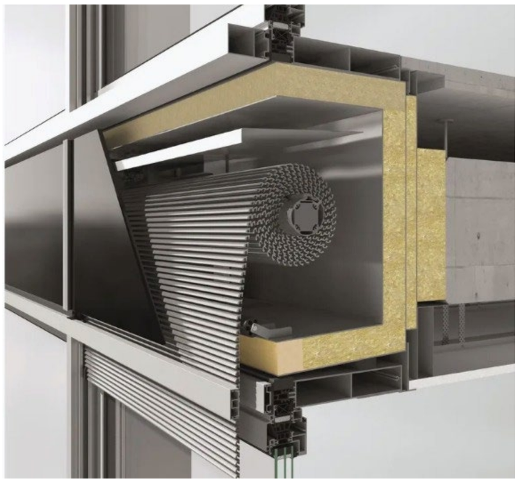
Table 3.8 Qualitative assessment of non-fixed sun blind options

(Note: * Low level; ** Medium level; *** High level)

The qualitative assessment of the design options, considering safety, view, material durability, and ease of maintenance, suggests that **Shading 3 has the priority** to as the feasible solution for supplemental external shading.

3.4.3 Dimensions and materials for façade module of improved base case





Concealed toughened blind.

Figure 3.55 The dimensions of the façade module for Improved base case
(graphic: own work, 2024)

The materials of the façade module for Improved base case (Table 3. 9):

(1) The opaque section – metal cladding	**Properties**
From outdoor to indoor: Aluminium cladding 5mm with heat-reflective coating EPS expanded polystyrene (standard) 80mm. EPDM water barrier Aluminium cladding 5mm	U-value=0.46 W/m² K (≤0.8 W/m² K max limit)
(2) The transparent section – double glazing	**Properties**
From outdoor to indoor: Generic Low-E glass 6mm 12mm air Generic clear glass 6mm	U-value=1.77 W/m² K (≤2.50 W/m² K max limit) SHGC=0.24 (≤0.24 max limit) Visible transmittance=0.75 (≥0.4 min limit)
(3) The façade frame	**Properties**
Aluminium window frame with thermal break	Thickness: 7mm; U-value=5.014 W/m² K
(4) The fixed shading	**Properties**
Aluminium overhand shading panel	Thickness: 50mm

(5) The non-fixed sun blind	Properties
Concealed toughened blind made in aluminium micro louvre blades with anodised surface	Reference product: Schüco Sun Shading System CTB in Schüco Façade System FWS 50/60

Table 3.9 The materials layer of the façade module for Improved base case

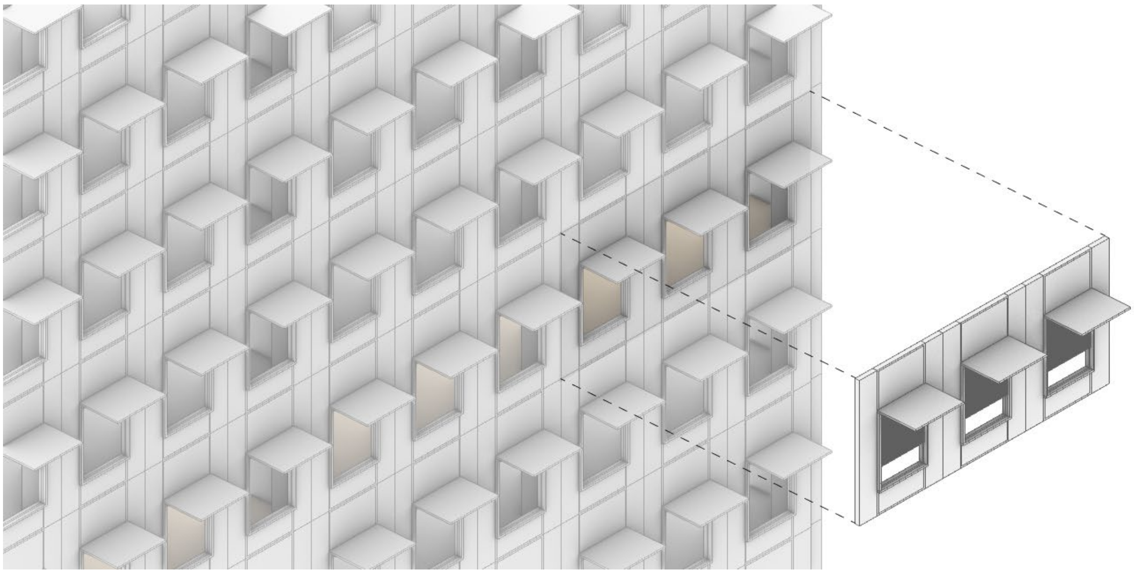


Figure 3.56 Façade visualization with axonometric view for improved base case
(graphic: own work, 2024)

DESIGN SCENARIO A

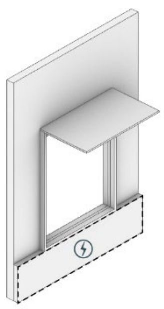
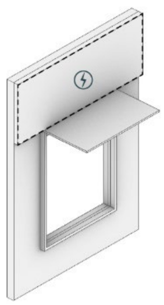
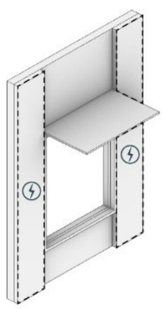
3.5 Design scenario A

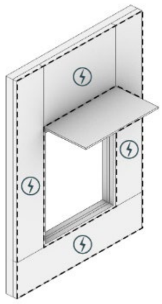
The main measure in this scenario is to integrate dedicated PV panels into the façade modules and to calculate how much renewable electricity the façade units can generate to feed the existing cooling system.

3.5.1 FIPV design

[a] FIPV design options

According to some relevant studies, the generation efficiency of conventional PV is not at a high level. Therefore, the available area exposed to the solar radiation is the key factor of its capacity. As followed, there are a few conceptual options to integrate PV panels.

FIPV design options	Properties
 2.1 m^2	**Option 1: Parapet FIPV** Position: Sill parapet Size: 3000(w) x 700(h) mm Available area for FIPV: 2.1 m^2 PV coverage ratio: 23.8%
 3.45 m^2	**Option 2: Shadowbox FIPV** Position: Shadow box front panel Size: 3000(w) x 1150(h) mm Available area for FIPV: 3.45 m^2 PV coverage ratio: 39.1%
 5.29 m^2	**Option 3: Side panels FIPV** Position: Side cladding panels Size: 630(w) x 4200(h) mm x 2 units Available area for FIPV: 5.29 m^2 PV coverage ratio: 60.0%



8.83 m^2

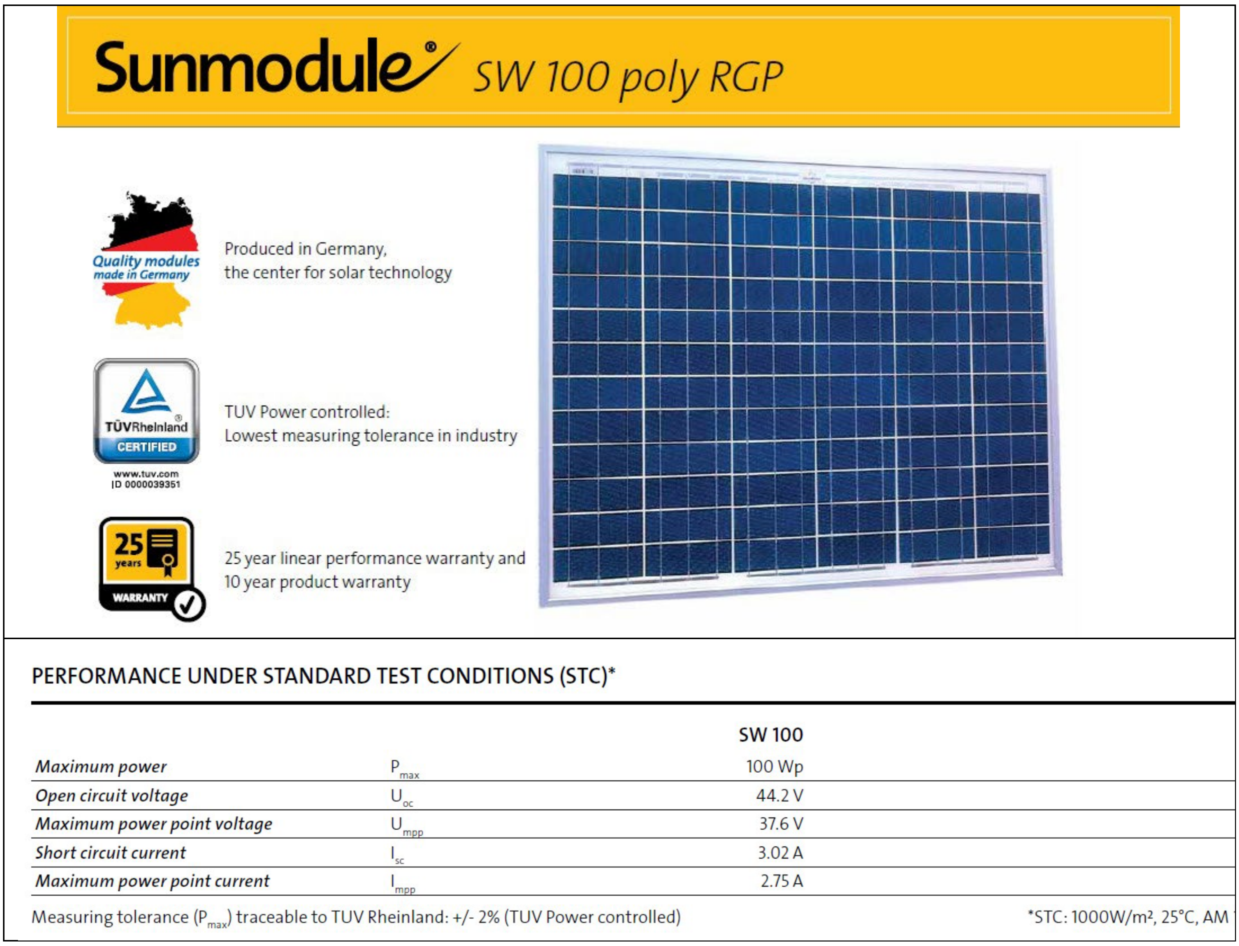
Option 4: Full-Coverage FIPV

Position: All opaque cladding panels
Available area for FIPV: 8.83 m^2
PV coverage ratio: 100.0%

Figure 3.57 FIPV design options with various coverage ratios
(graphic: own work, 2024)

[b] Photovoltaic modules

For calculation purpose, this research assumes to use the specific product data from a German company Solarworld. The PV panel names SW 100 Ploy RGP ('100' means the maximum power is 100 W_p), and its main parameters are shown in the Table 3. 10



Sunmodule® SW 100 poly RGP

Quality modules made in Germany — Produced in Germany, the center for solar technology

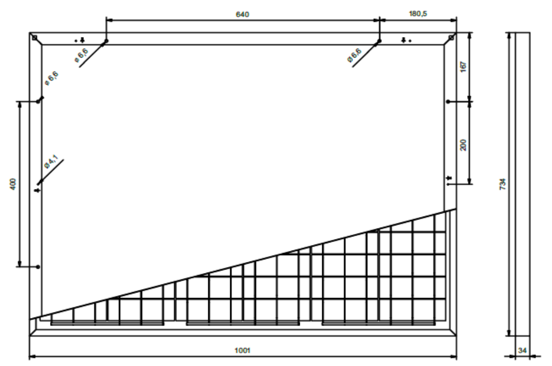
TÜVRheinland CERTIFIED, www.tuv.com ID 0000039351 — TUV Power controlled: Lowest measuring tolerance in industry

25 years WARRANTY — 25 year linear performance warranty and 10 year product warranty

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

		SW 100
Maximum power	P_{max}	100 Wp
Open circuit voltage	U_{oc}	44.2 V
Maximum power point voltage	U_{mpp}	37.6 V
Short circuit current	I_{sc}	3.02 A
Maximum power point current	I_{mpp}	2.75 A

Measuring tolerance (P_{max}) traceable to TUV Rheinland: +/- 2% (TUV Power controlled) *STC: 1000W/m², 25°C, AM



DIMENSIONS

Length	734 mm
Width	1001 mm
Height	34 mm
Frame	Clear anodized aluminum
Weight	8.0 kg

COMPONENT MATERIALS

Cells per module	7
Cell type	Poly crystallin
Cell dimensions	52 mm x 156 mr
Front	tempered glas (EN 1215C

THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.051 %/K
TC U_{oc}	-0.31 %/K
TC P_{mpp}	-0.41 %/K

ADDITIONAL DATA

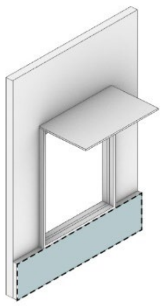
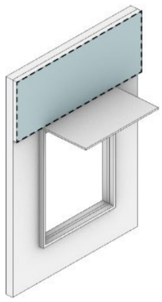
Power sorting	+/- 5

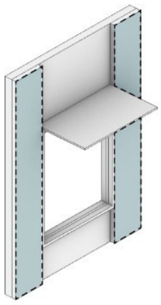
Table 3.10 Manufacture sheet of Photovoltaic Product ‘SW 100 poly RGP’

Based on the given data, the module efficiency is 13.6% by calculation ($100W_p/0.735\ m^2$). Additionally, regarding the data of cell dimensions 52mm x156mm and 72 cells in one module, it can be counted that every individual PV module with $0.735m^2$ area ($0.734x1.001=0.735m^2$) is equivalent to $0.584m^2$ ($52x156x72x10^{-6}\ m^2$) of active PV cells. Therefore, for ease of calculation, the dimensions of an individual PV module can be simplified as:

1 PV module ($0.735\ m^2$) = $0.584\ m^2$ active PV cell module

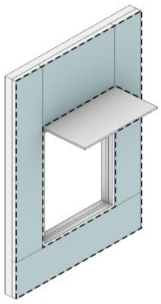
[c] PV modules with active PV cells (Figure 3.58)

FIPV design options	Module data
	**Option 1: Parapet FIPV** Available area: $2.1\ m^2$ Number of integrated PV modules: 2.5 ($2.1\ m^2/0.735\ m^2$= 2.85, so counted as 2 full modules and half modules) Active PV cells = 2.5 x $0.584\ m^2$ = $1.46\ m^2$
	**Option 2: Shadowbox FIPV** Available area: $3.45\ m^2$ Modules of active PV cell: 4.5 ($3.45\ m^2/0.735\ m^2$= 4.69, so counted as 4 full modules and half module) Active PV cells = 4.5 x $0.584\ m^2$ = $2.63\ m^2$



Option 3: Side panels FIPV

Available area: 5.29 m^2
Modules of active PV cell: 7
(5.29 m^2/0.735 m^2 = 7.19, so counted as 7 full modules)
Active PV cells = 7 x 0.584 m^2 = 4.09 m^2



Option 4: Full-Coverage FIPV

Available area: 8.83 m^2
Modules of active PV cell: 12
(8.83 m^2/0.735 m^2 = 12.01, so counted as 12 full modules)
Active PV cells = 12 x 0.584 m^2 = 7.01 m^2

Figure 3.59 FIPV options with active PV cells calculation
(graphic: own work, 2024)

[d] Selected option

With the same efficiency of the energy harvest, there's no doubt that **Option 4** with full coverage of PV panels (8.83 m^2) contains the largest area of active PV cells (7.01 m^2) exposed to the sun, which means that it can nominally generate the most significant amount of electricity. The setting of simulation parameters (in DesignBuilder program) for active PV cells are shown in Table 3. 11.

Cell type	1-Crystalline Silicon
Cells in series	72
Active area (m2)	0,58
Transmittance absorptance product	0,9000
Semiconductor bandgap (eV)	1,12
Shunt resistance (ohms)	1000000,00
Reference temperature (°C)	25,00
Reference insolation (W/m2)	1000,00
Module heat loss coefficient (W/m2-K)	30,00
Total heat capacity (J/m2-K)	50000,00
Rated electric power output per module (W)	100,00
Availability schedule	Copy of PV panel efficiency: Always 0.
Current	
Short circuit current (A)	3,02
Module current at max power (A)	2,75
Temperature coefficient of short circuit current (A/K)	0,00154
Voltage	
Open circuit voltage (V)	44,2
Module voltage at max power (V)	37,6
Temperature coefficient of open circuit voltage (V/K)	-0,137
Nominal Operating Cell Temperature	
NOCT ambient temperature (°C)	20,00
NOCT cell temperature (°C)	46,00
NOCT insolation (W/m2)	800

Table 3.11 Simulation parameters for active PV cells

(The table data based on the materials library of DesignBuilder v7.2 and the manufacture sheet)

3.5.2 Dimensions and materials for façade module of design scenario A

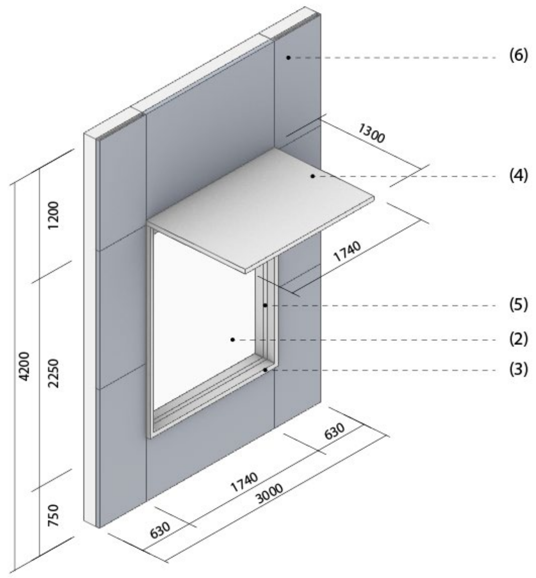


Figure 3. 1 Façade module for design scenario A (graphic: own work, 2024)

The materials of the façade module for design scenario A (Table 3. 12):

(1) The opaque section – metal cladding	Properties
From outdoor to indoor: Aluminium cladding 5mm with heat-reflective coating EPS expanded polystyrene (standard) 80mm. EPDM water barrier Aluminium cladding 5mm	U-value=0.46 W/m² K (≤0.8 W/m² K max limit)
(2) The transparent section – double glazing	**Properties**
From outdoor to indoor: Generic Low-E glass 6mm 12mm air Generic clear glass 6mm	U-value=1.77 W/m² K (≤2.50 W/m² K max limit) SHGC=0.24 (≤0.24 max limit) Visible transmittance=0.75 (≥0.4 min limit)
(3) The façade frame	**Properties**
Aluminium window frame with thermal break	Thickness: 7mm; U-value=5.014 W/m² K
(4) The fixed shading	**Properties**
Aluminium overhand shading panel	Thickness: 50mm
(5) The non-fixed sun blind	**Properties**
Concealed toughened blind made in aluminium micro louvre blades with anodised surface	Reference product: Schüco Sun Shading System CTB in Schüco Façade System FWS 50/60
(6) The Photovoltaic	**Properties**
SW 100 Poly RGP	Efficiency: 13.6%; Thickness: 35mm

Table 3.12 The materials layer of the façade module for design scenario A

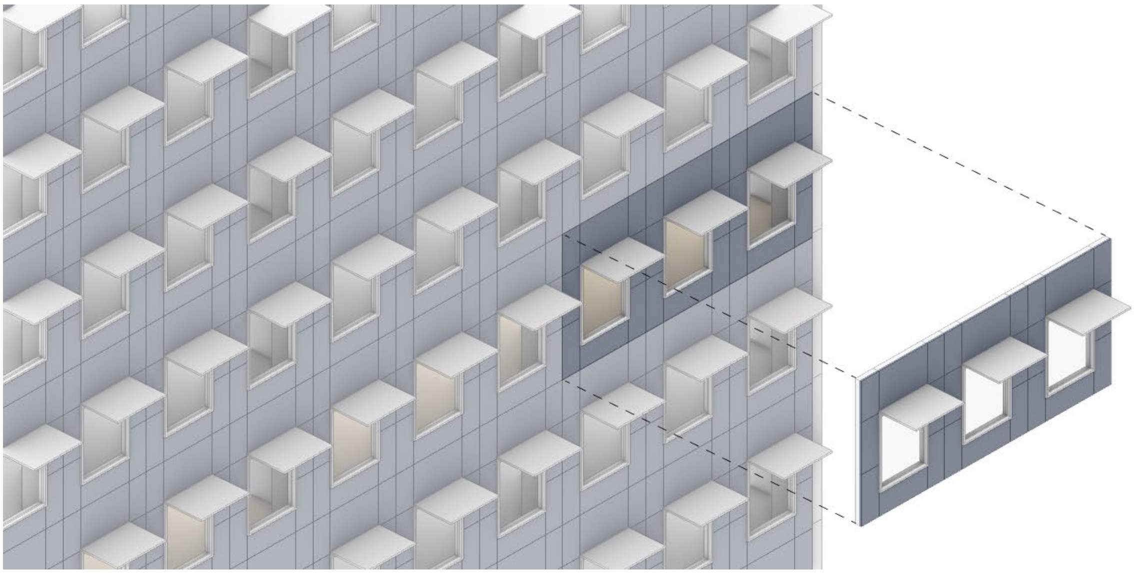


Figure 3.60 Façade visualization with axonometric view for design scenario A
(graphic: own work, 2024)

DESIGN SCENARIO B

3.6 Design scenario B

To compare with design scenario A, the main strategies in design scenario B are utilizing solar desiccant cooling technology for the façade integration design.

3.6.1 'Built-in' cooling system

[a] LDEVap cooling unit

Figure 3.41 shows the outline size of experimental device by Elmer et al. (2016), this LDEVap cooling unit consists of three components – dehumidifier, evaporative cooler and regenerator. The new facade module needs to create more internal space to conceal this cooling system, therefore, the facade components should get 'thicker' for more 'room'.

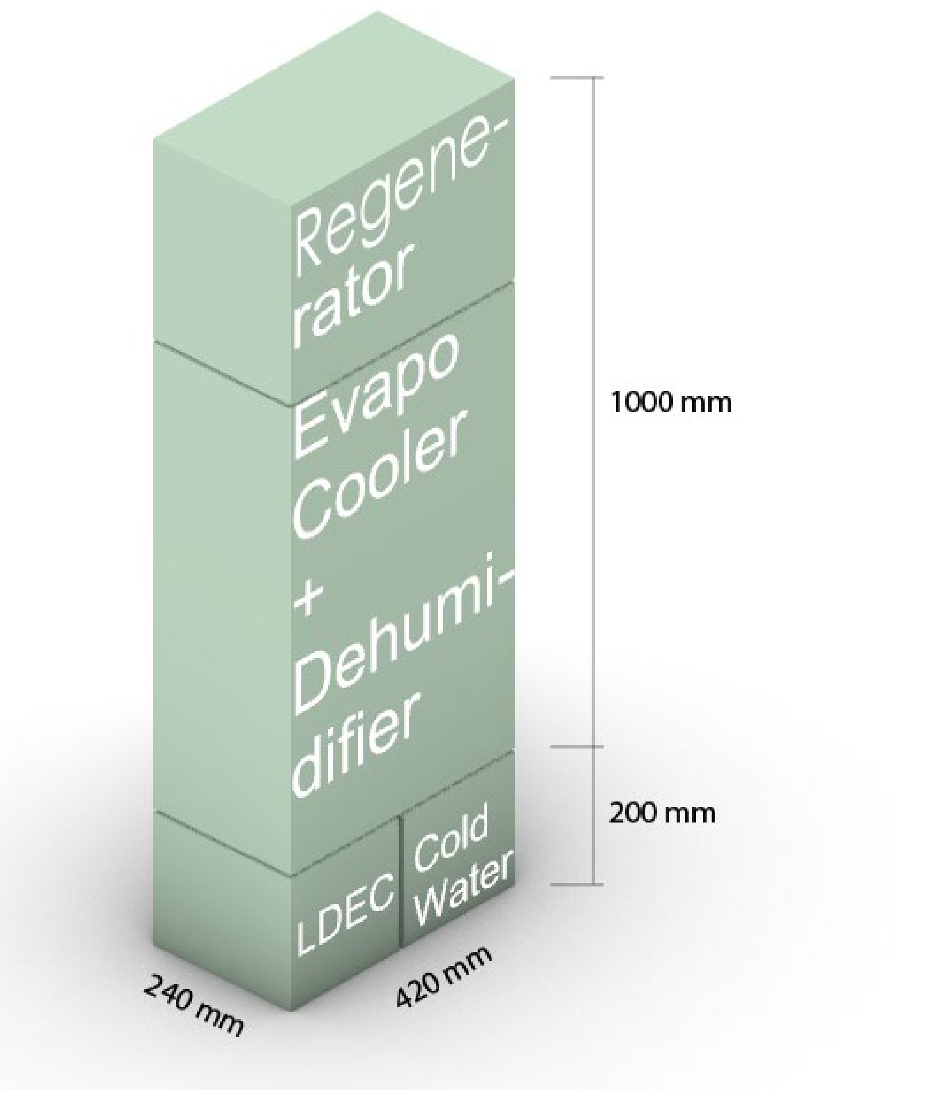


Figure 3.61 LDEVap cooling unit derived from Elemer's experimental device
(graphic: own work, 2024)

[b] Design concept

The design concept is to integrate the desiccant cooling devices into the “body” of the façade module, so that it can be used as a ‘plug-and-play’ façade product. (Figure 3.42)

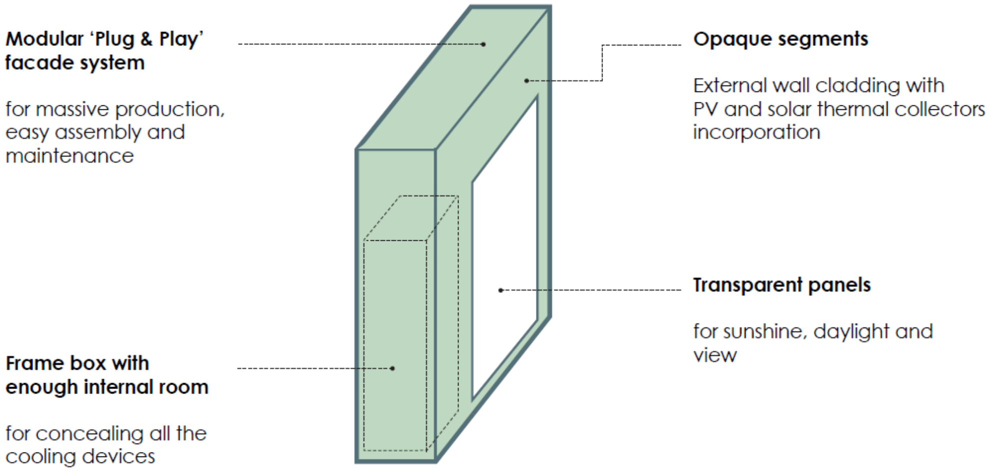


Figure 3.62 Design concept – frame box modular façade

(graphic: own work, 2024)

[c] Re-sizing of the façade components

The primary size of the cooling unit is 1200(h)x420(w)x240(d) mm (including its integrated liquid tank at the bottom).Based on the module size of the improved base case, the thickness of the façade module needs to be increased by 350mm (design estimation) on both sides of the opening, considering creating enough space both to accommodate the LDEVap cooling unit and its auxiliary devices, such as a hot water cylinder with the volume of 120L, a number of fans and pumps, and several sets of pipes and ducts. Therefore, the outline size of the façade ‘frame box’ is shown in Figure 3.43

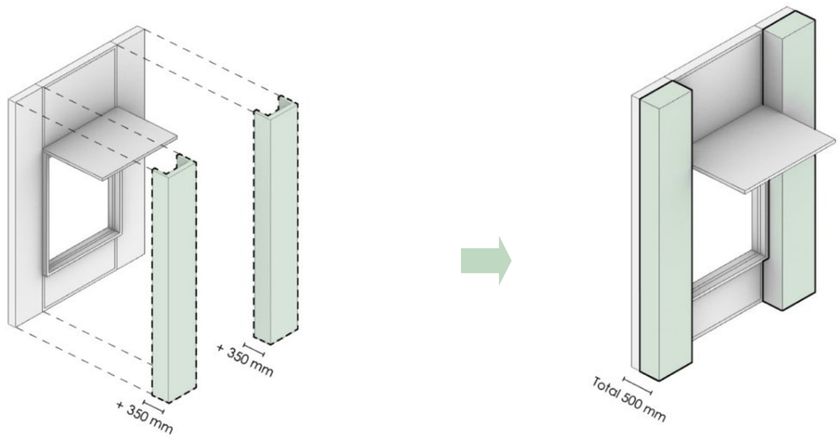


Figure 3.63 To create enough space to accommodate cooling units

3.6.2 FIST design

The liquid desiccant, which has already absorbed moisture from the air, becomes a weak solution and needs to be pumped to the regenerator unit for heating. As the moisture evaporated off into the atmosphere, the desiccant solution is pumped back into the dehumidifier to complete the next dehumidification cycle. In Elmer's laboratory, electricity is the source of heat, while this design can use renewable solar energy as an alternative heat source.

Generally, there are two common types of solar collectors: flat plate collectors and evacuated tube collectors. (Figure 3.64) It has been shown that the latter can convert heat more efficiently than the former for the same area of solar heat received. (Prieto, 2018)

Evacuated tube collectors with heat pipes (ETCHP) usually have parallel rows of glass tubes. The outer tube has a protective function, while the inner tube is coated with a porous coating. Between the tubes is formed a vacuum. The heat pipe is positioned co-axially to the glass tubes. It is filled with a heat-sensitive liquid at a low boiling point. The heat exchange fin transmits the heat between the absorber and the heat pipe. (Figure 3.44) A set of pipes is connected to the manifold tube where the heat exchange between the heat pipes and the solar fluid occurs. The manifold tube is not involved in the absorption of solar radiation. (Olek et al., 2016)

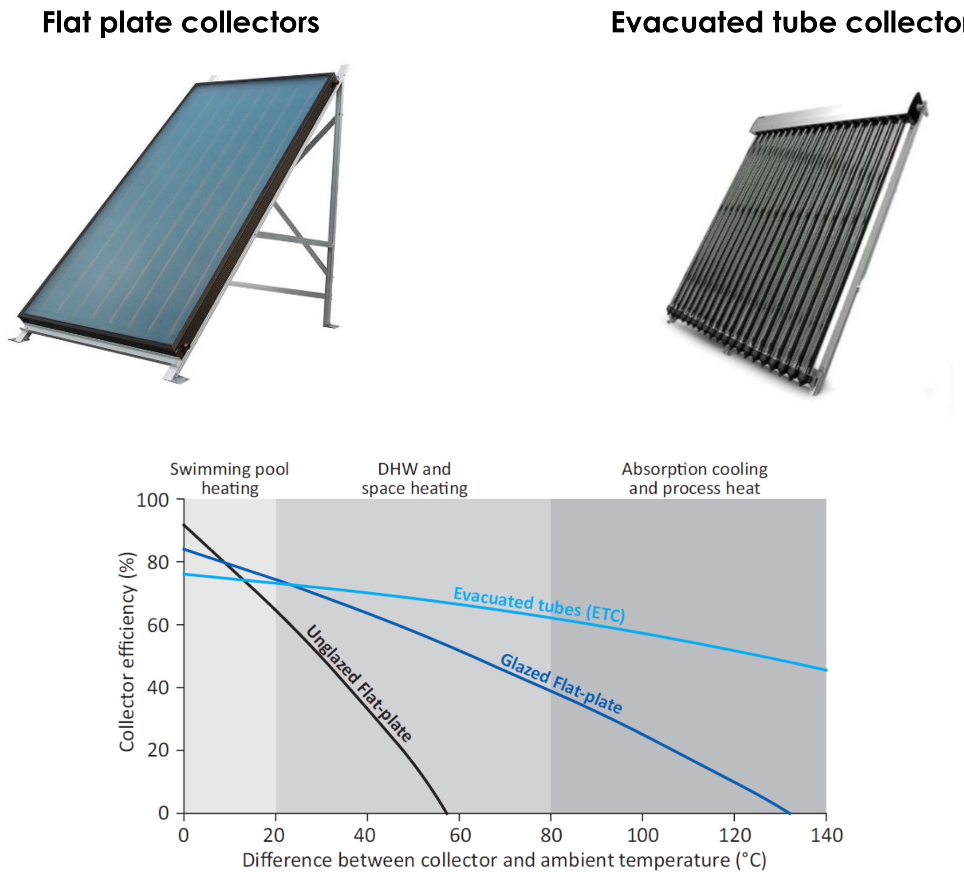


Figure 3.65 Typology of solar thermal collectors and the efficiency comparison (source: Prieto, 2018)

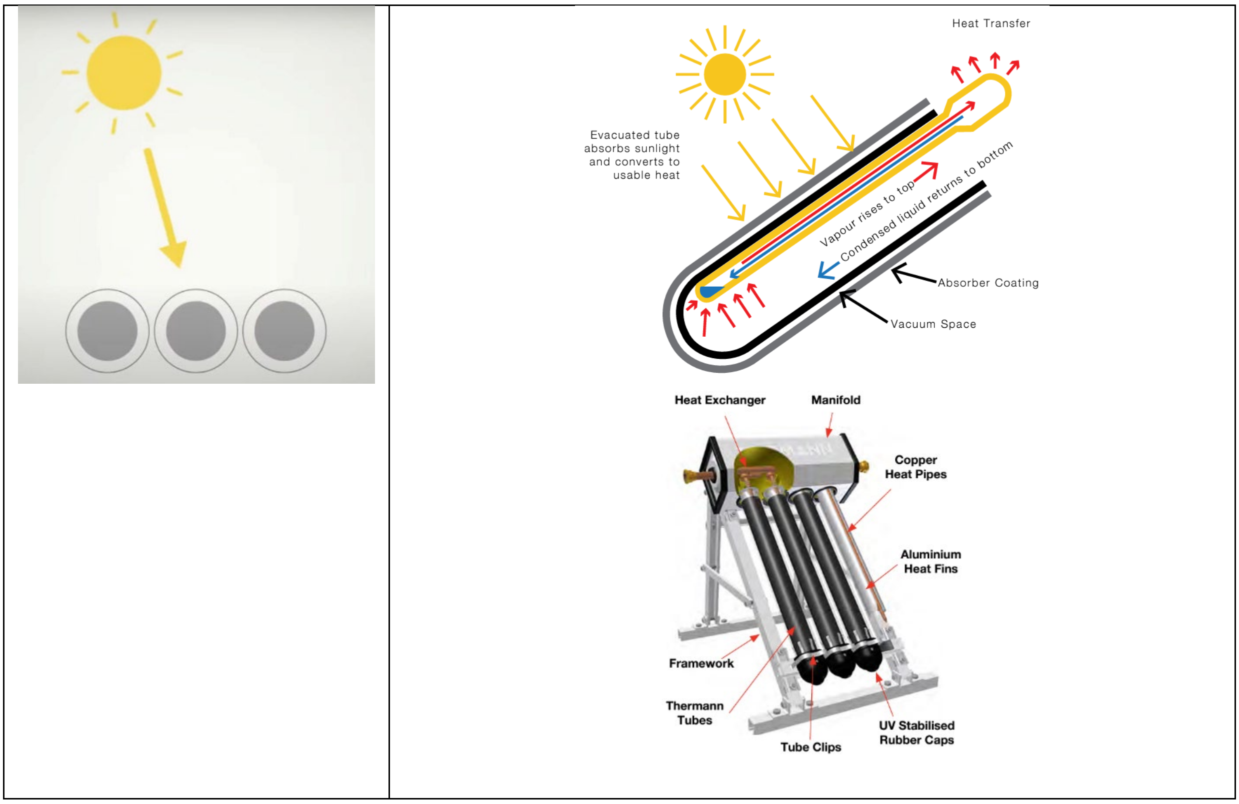


Figure 3.66 Working principle of evacuate tubes collectors

(source: manufacture sheet of Thermann, 2013)

The design idea is to integrate solar evacuated tubes collectors into the façade module, utilizing the space above the sun shading panel. Each façade module integrates 2.21m^2 of evacuated tube solar thermal collector on the top of overhang shading panel. (Figure 3.46, Figure 3.47)

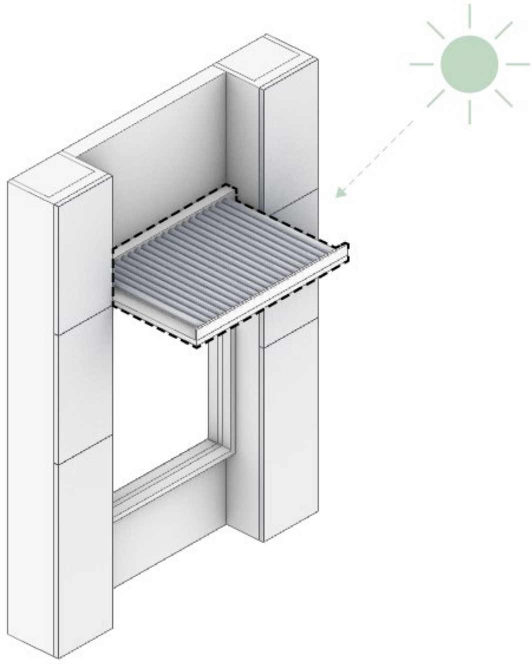


Figure 3.67 FIST design for two types of façade module

(graphic: own work, 2024)

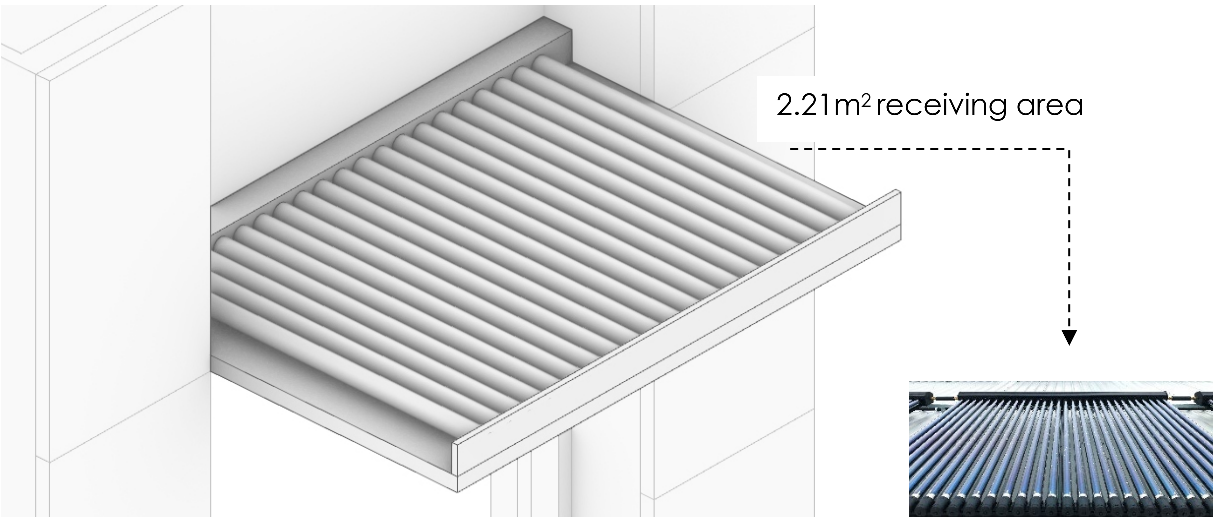


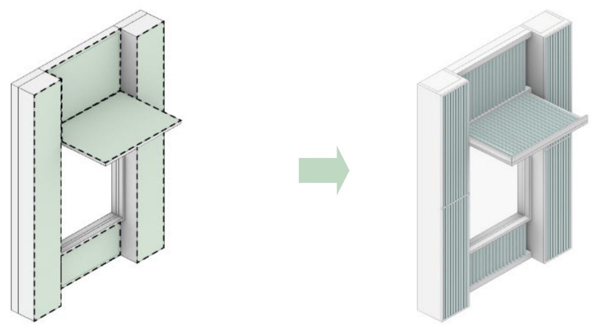
Figure 3.68 Evacuated tube collectors integrated above the overhang shading panel
(graphic: own work, 2024)

3.6.3 Design proposals for sub-scenarios

LDEVap cooling system is driven by heat (heat exchange chain: solar heat - hot water cylinder - regenerator), while its auxiliary fans and pumps need to be powered by electricity. Except the ST collectors on the shading top, the elevation cladding panels also can be converted into PV/ST panels exposed to the sun, therefore, design scenario B is divided into three sub-scenarios (sub scenario B1, B2, B3), which differ in the solar energy systems – different ratios of ST / PV coverage on façade modules.

[a] Sub-scenario B1

Sub-scenario B1 features 100% ST façade coverage with a ST integrated overhang shading panel, which means this sub-scenario can only produce solar heat to sup-port the cooling outputs. At the same time, the grid should meet the electricity demand for the fans and pumps.



ST collectors' area:

8.83 m^2 on vertical surfaces
2.21 m^2 on horizontal surfaces

Solar thermal collectors

Figure 3.69 Façade module proposal for Sub-scenario B1

(graphic: own work, 2024)

[b] Sub-scenario B2

Sub-scenario B2 features 100% PV façade coverage with a ST integrated overhang shading panel, which means this sub-scenario can produce both solar heat and solar electricity.

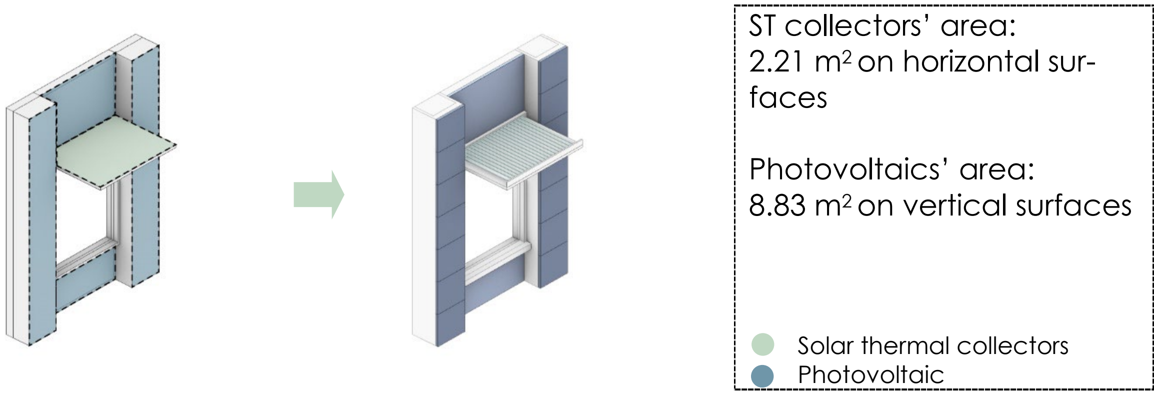


Figure 3.70 Façade module proposal for Sub-scenario B1

(graphic: own work, 2024)

[c] Sub-scenario B3

Sub-scenario B3 combines the features of both B1 and B2, i.e. a mixed-use of PV and ST covering the façade module, yet the overhang shading with solar thermal collector remains unchanged.

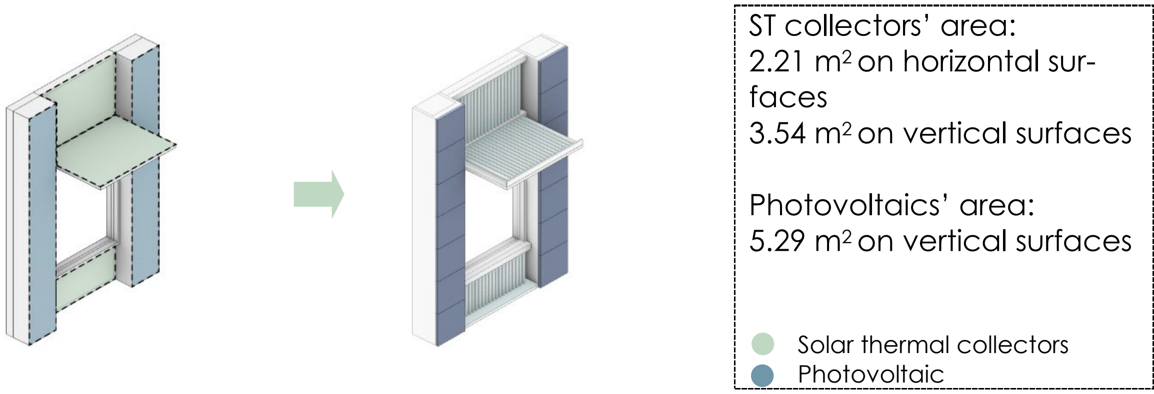


Figure 3.71 Façade module proposal for Sub-scenario B3

(graphic: own work, 2024)

3.6.4 Dimensions and materials for façade module of design scenario B

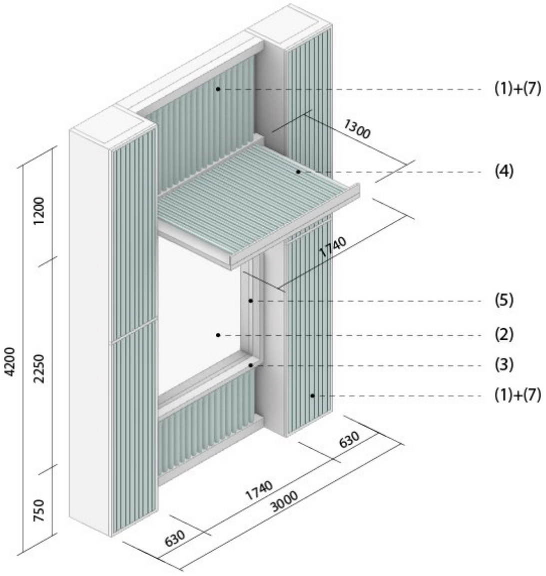


Figure 3.72 Façade module of sub-scenario B1

(graphic: own work, 2024)

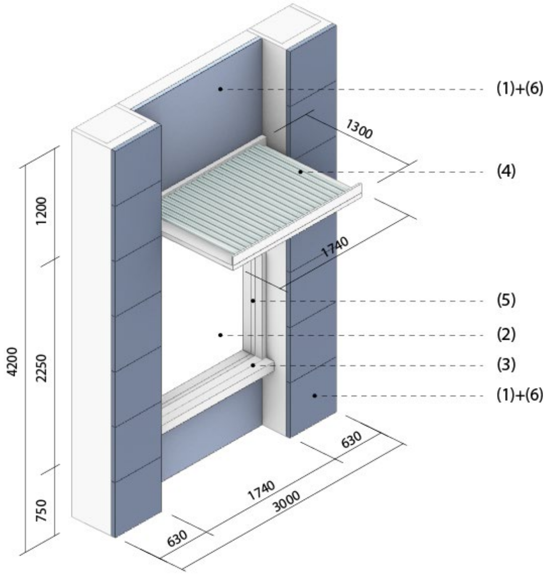


Figure 3.73 Façade module of sub-scenario B2

(graphic: own work, 2024)

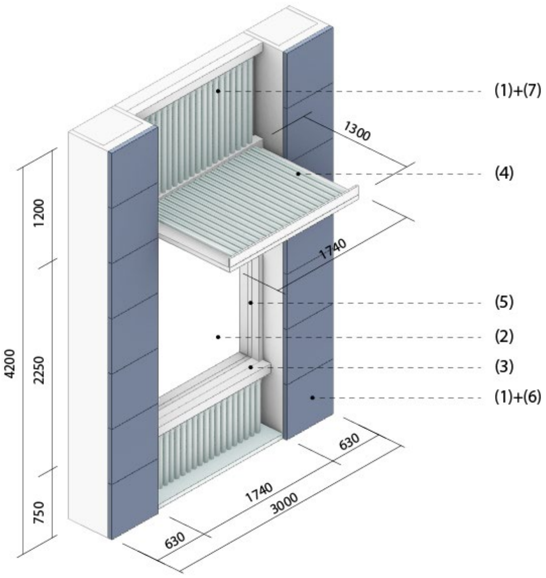


Figure 3.74 Façade module of sub-scenario B3

(graphic: own work, 2024)

The materials of all the façade modules:

(1) The opaque section – metal cladding	Properties
From outdoor to indoor: Aluminium cladding 5mm with heat-reflective coating EPS expanded polystyrene (standard) 80mm. EPDM water barrier Aluminium cladding 5mm	U-value=0.46 W/m² K (≤0.8 W/m² K max limit)
(2) The transparent section – double glazing	**Properties**
From outdoor to indoor: Generic Low-E glass 6mm 12mm air Generic clear glass 6mm	U-value=1.77 W/m² K (≤2.50 W/m² K max limit) SHGC=0.24 (≤0.24 max limit) Visible transmittance=0.75 (≥0.4 min limit)
(3) The façade frame	**Properties**
Aluminium window frame with thermal break	Thickness: 7mm; U-value=5.014 W/m² K
(4) The fixed shading	**Properties**
Aluminium overhand shading panel combined with evacuated tube collectors	Thickness: 50mm for aluminium panel Thickness: 58mm for solar collectors Efficiency: 65%
(5) The non-fixed sun blind	**Properties**
Concealed toughened blind made in aluminium micro louvre blades with anodised surface	Reference product: Schüco Sun Shading System CTB in Schüco Façade System FWS 50/60
(6) The cladding of Photovoltaic	**Properties**
SW 100 Poly RGP	Efficiency: 13.6%; Thickness: 35mm
(7) The cladding of solar thermal collectors	**Properties**
Evacuated tube integrated cladding components	Efficiency: 65%; Thickness: 58mm

Table 3.13 The materials layer of the façade module for design scenario B

3.7 Design evolution

The figure overviews the design evolution process from base case scenario to design scenario B. (Figure 3.75)

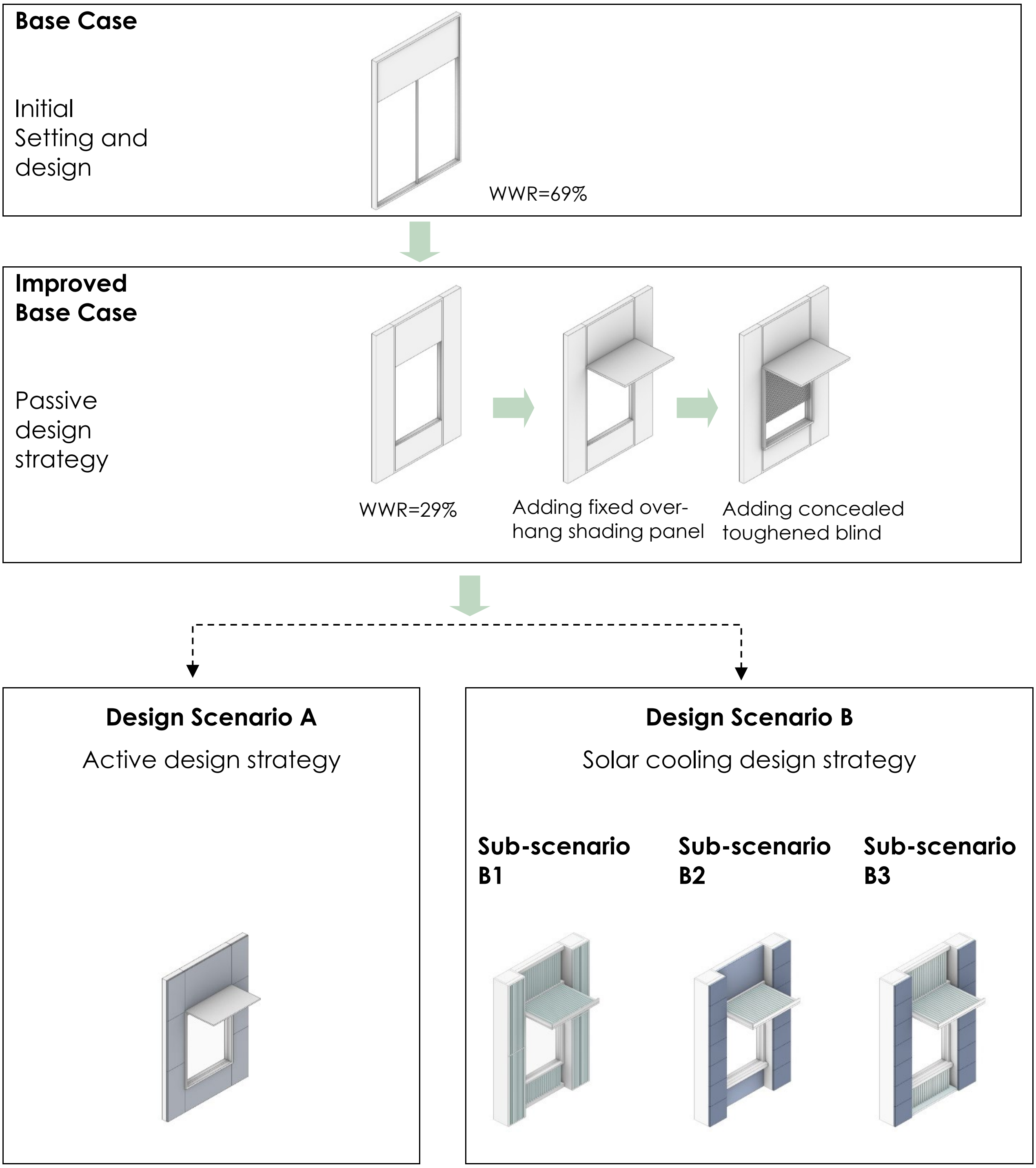


Figure 3.76 Diagram of design evolution

4

DESIGN EVALUATION

4.1 Performance assessment

DesignBuilder v7.2 is used as a performance simulation tool to understand the differences in various scenarios on each parameter input. The parameters, such as primary construction materials, activity settings, opening information (mainly about glazing), are set both in the building and the target room level related to all design scenarios, while the parameters like shading forms, new added-in PV panels and ST collectors, cooling modes, are set for the dedicated scenarios. In all simulations, the weather data of Shenzhen is used as the base climate conditions for all calculations imported to DesignBuilder program.

This design selects the summer design week (Jul 1st-Jul 7th) as the simulation period because this time range represents the harshest weather conditions for cooling in Shenzhen throughout the year. The core results of summer design week simulation for all design scenarios (Table 4. 1):

			Base Case	Improved Base case	Design Scenario A	Design Scenario B		
						B1	B2	B3
Total cooling demand for summer design week		[kwh]	389,10	312,66	293,70	287,76	287,76	287,76
Total cooling demand intensity		[kwh/m²]	3,01	2,42	2,27	2,23	2,23	2,23
Daily cooling demand intensity		[kwh/m²/d]	0,60	0,48	0,45	0,45	0,45	0,45
Electricity end use in cooling		[kwh]	94,01	71,39	67,44	50,70*	82,26*	54,06*
Electricity Intensity in cooling		[kwh/m²]	0,73	0,55	0,52	0,39	0,64	0,42
Total renewable energy generation	**Solar electricity**	[kwh]	-	-	112,67	-	111,20	75,72
	Solar heat	[kwh]	-	-	-	628,72	213,75	365,08
Daily renewable energy generation	**Solar electricity**	[kwh/d]	-	-	22,53	-	22,24	15,14
	Solar heat	[kwh/d]	-	-	-	125,74	42,75	73,02

Table 4.1 The results of summer design week simulation

(* Noted: calculation of cooling electricity consumption for design scenario B1, B2, and B3 could be found in Appendix 1)

4.2 Quantitative evaluation

The simulated results are evaluated quantitatively and qualitatively, seeking to generate the referential assessment, especially to see how each design scenario fares regarding different strategies.

4.2.1 Solar fraction assessment

According to the evaluation methods used by Prieto (2018) and Noaman et al. (2022), the indicator of solar fraction (SF) is used to measure whether a solar-powered cooling system meets the cooling requirements under the corresponding conditions. The SF value can be calculated by the equation below.

$$SF = \frac{Scool\ out}{Cool\ req}$$

Scool $_{out}$ - Cooling effect delivered by the solar cooling system (by calculation)
Cool $_{req}$ - Cooling demand of the target workspace (obtained from DesignBuilder)

The cooling effect (heat removed by the solar cooling system), Scool $_{out}$ is theoretically calculated through the simplified equation below:

$$Scool\ out = Sol\ input * Sol\ array * COP\ solsys * COP\ coolsys$$

Sol $_{input}$ - the availability of solar radiation on a specific location/orientation
Sol $_{array}$ - the area of the solar energy collection (either PV or ST collectors)
COP $_{solsys}$ - the efficiency of the solar energy collection (either PV or ST collectors)
COP $_{coolsys}$ - the coefficient of performance of applied solar cooling systems

This simplified equation does not consider transmission and parasitic losses, nor additional equipment such as storage units, serving a comparative purpose between technical possibilities to assess the broad feasibility of self-sustaining solar cooling facades in different climate contexts. (Prieto, 2018) Therefore, a solar fraction of 1.0 or more means that the system can handle the cooling demands of a given space by itself if all evaluating parameters and conditions are met. If the SF value is less than 1.0, the result is reversed. The assessment will then consider the solar availability and cooling demands for a representative summer design period as a simplified basis for the evaluation. (Prieto, 2018)

For all the façade module proposals of design scenario B, the solar fraction values are the most critical parameters to verify their energy performance. Based on the simulation results of the summer design week for the target room, the SF calculation processes are as follows.

[a] Calculation for sub-scenario B1

Calculation parameters:

Sol $_{input}$	4.96 kwh/m²/day (for tilt angle 0°)		2.41 kwh/m²/day (for tilt angle 90°)	
Sol $_{array}$	2.21 m²/module (for tilt angle 0°)		8.83 m²/module (for tilt angle 90°)	
COP $_{solsys}$	65% (for ST collectors)			
COP $_{coolsys}$	0.72			
Façade modules	6	Active days	5 (weekdays in summer design week)	

Scool $_{out\ B1}$ = 4.96 x (2.21 m² x 6) x 65% x 0.72 + 2.41x (8.83 m² x 6) x 65% x 0.72 = 90.54 kwh/day

$Cool_{req}$ = Total cooling demand in summer design week / active days
= 287.76/5 = 57.56 kwh/day

SF $_{B1}$ = 90.54/57.56 = 1.57	**> 1.0**	**100% cooling demand achieved**

Due to the SF calculation result, the façade integrated LDEVap cooling system not only completely covers the total cooling demand of the target room during the summer design week, but also has a surplus of cooling output, which means that it can even condition a larger given area.

[b] Calculation for sub-scenario B2

Calculation parameters:

Sol_{input}	4.96 kwh/m²/day (for tilt angle 0°)		2.41 kwh/m²/day (for tilt angle 90°)
Sol_{array}	2.21 m²/module (for tilt angle 0°)		8.83 m²/module (for tilt angle 90°)
COP_{solsys}	65% (for ST collectors)		13.6% (for PV panels)
$COP_{coolsys}$	0.72		
Façade modules	6	Active days	5 (weekdays in summer design week)

$Scool_{out\ B2}$ = 4.96 x (2.21 m² x 6) x 65% x 0.72 = 30.78 kwh/day

$Cool_{req}$ = Total cooling demand in summer design week / active days
= 287.76/5 = 57.56 kwh/day

SF $_{B2}$ = 30.78/57.56 = 0.53	**< 1.0**	**53% cooling demand achieved**

As seen in the result, the façade proposal of sub-scenario B2 can only cover 53% of the cooling requirement for the target room during summer design week. In other words, the rest 47% should be supported either by extra solar thermal collectors (e.g. collectors mounted on the roof top) or be satisfied by the conventional A/C systems.

[c] Calculation for sub-scenario B3

Calculation parameters:

Sol_{input}	4.96 kwh/m²/day (for tilt angle 0°)		2.41 kwh/m²/day (for tilt angle 90°)
Sol_{array}	2.21 m²/module (for tilt angle 0°)		3.54 m²/module (for tilt angle 90° for ST)
COP_{solsys}	65% (for ST collectors)		13.6% (for PV panels)
$COP_{coolsys}$	0.72		
Façade modules	6	Active days	5 (weekdays in summer design week)

$Scool_{out\ B3}$ = 4.96 x (2.21 m² x 6) x 65% x 0.72 + 2.41x (3.54 m² x 6) x 65% x 0.72 = 54.74 kwh/day

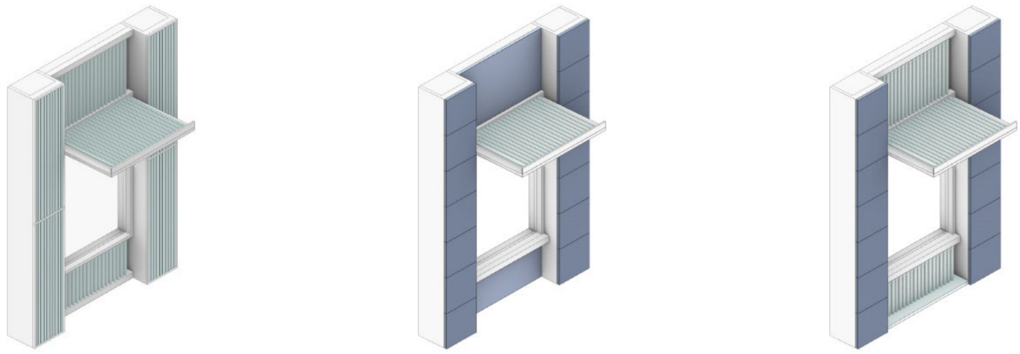
$Cool_{req}$ = Total cooling demand in summer design week / active days

= 287.76/5 = 57.56 kwh/day

SF $_{B3}$ = 54.74/57.56 = 0.95	**< 1.0**	**95% cooling demand achieved**

According to the calculation result, it almost fulfils the total cooling requirements of the target room during the summer design week. Considering the bias in the calculation results and some uncertainties (e.g. the half-occupancy in the room during lunchtime), as well as summer design week representing the most extreme time of the year, an attainment rate of 95% is acceptable.

[d] Comparisons of SF results



SF $_{B1}$ = 1.57 > 1.0	**SF $_{B2}$ = 0.53 < 1.0**	**SF $_{B3}$ = 0.95 ≈ 1.0**
100% cooling demand achieved	**53%** cooling demand achieved	**95%** cooling demand achieved

Figure 4.1 Comparisons of solar fraction values among sub-scenarios B1, B2, B3

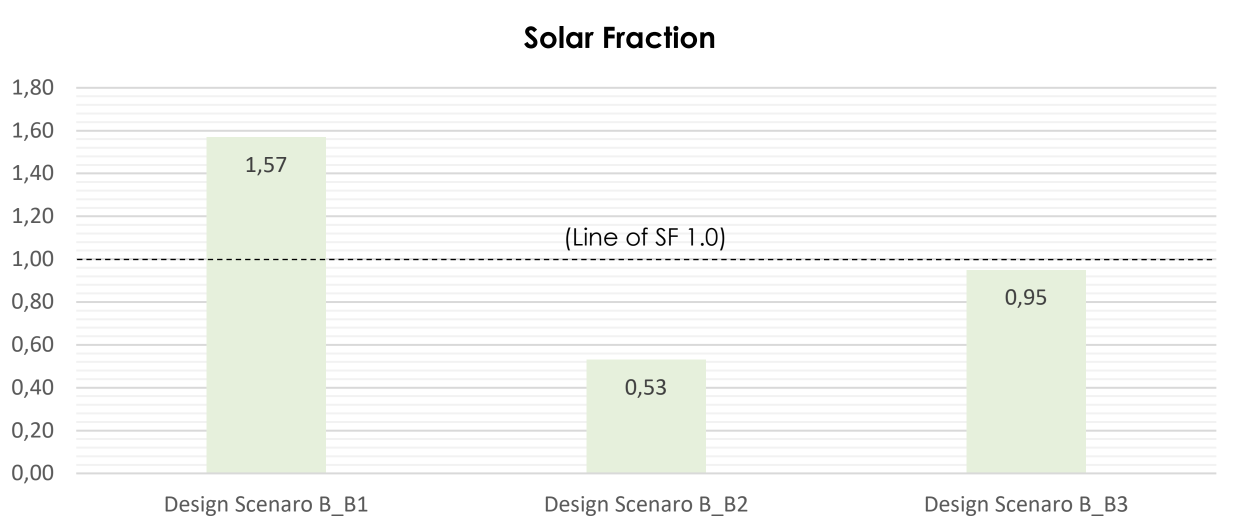


Table 4.2 Comparison charts of solar fraction values

[e] Supplementary Suggestions

There are two supplementary suggestions to optimize the SF values.

Suggestion One:
Improve the $COP_{thermal}$ of the desiccant evaporative cooling. According to Elmer's research, the $COP_{thermal}$ ranges from a minimum of 0.34 to a maximum of 1.26. If the $COP_{thermal}$ reaches 1.26, the SF value can be more likely to exceed 1.0 without adding more ST receiving area.

Suggestion Two:
Enlarge the total receiving area of the evacuated tube solar thermal collectors or change the ST products with higher thermal efficiency. However, the former is subject to the available surfaces' area on the façade module, while the latter is related to product upgrades.

4.2.2 Reduction in cooling demand

Overall, from all simulated results of the west-orientated target room, the cooling demand decreased phase by phase from base case scenario to design scenario B during summer design week. (Table 4. 3)

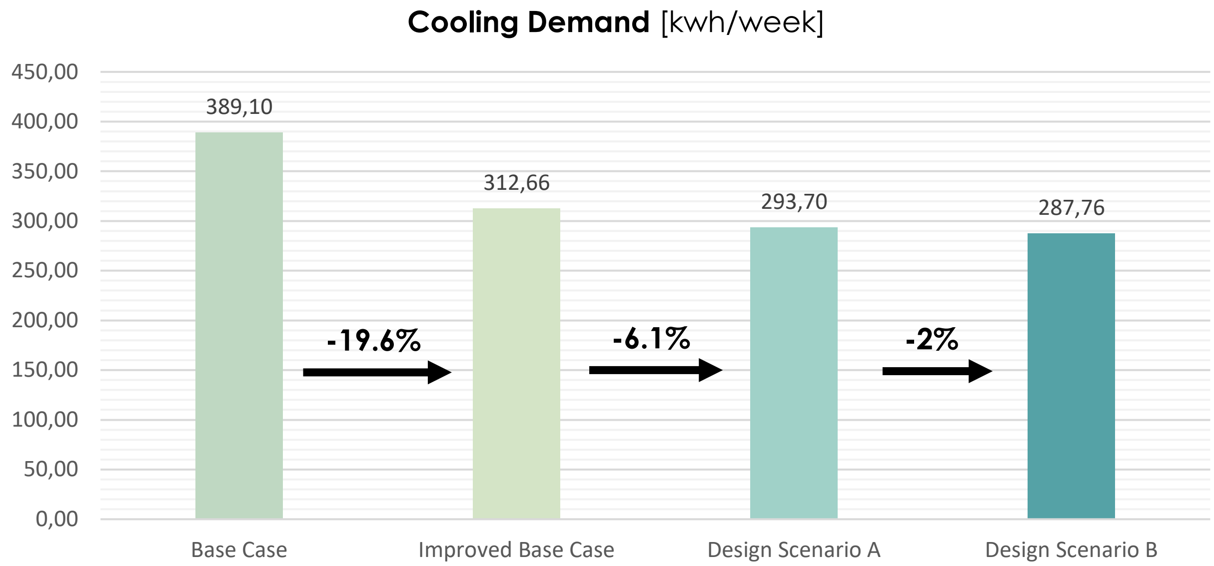


Table 4.3 Comparison charts on cooling demand

As shown in the charts, the most significant drop occurs from 'Base Case' to 'Improved Base Case'. The total cooling demand are reduced by 19.6% (from 389.10 kwh to 312.66 kwh), which indicates that the passive design strategies have had a significant effect in reduction of cooling demand, including lowering WWR to a minimum, improving the insulation performance of the opaque façade components, and the design of external sun shading elements.
From 'Improved Base Case' to 'Design Scenario A' and 'Design Scenario B', The reductions are 6.1% (312.66 kwh to 293.70kwh) and 8% (312.66 kwh to 287.76kwh) respectively. Because the thickness of the façade units for design scenario A and B are both greater than that of improved base case, which enhances their thermal insulation.

Finally, between design scenario A and B, the latter works slightly better with a 2% advantage also due to its thicker dept of the façade unit. Totally, compared to the initial base case design, solar desiccant cooling integrated facade design helps reduce cooling demand by 26%. (389.10 kwh to 287.76 kwh)

4.2.3 Reduction in cooling energy consumption

According to the simulated results, the cooling energy consumption in the target room also shows a dropping trend from base case scenario to design scenario B during summer design week. (Table 4. 4)

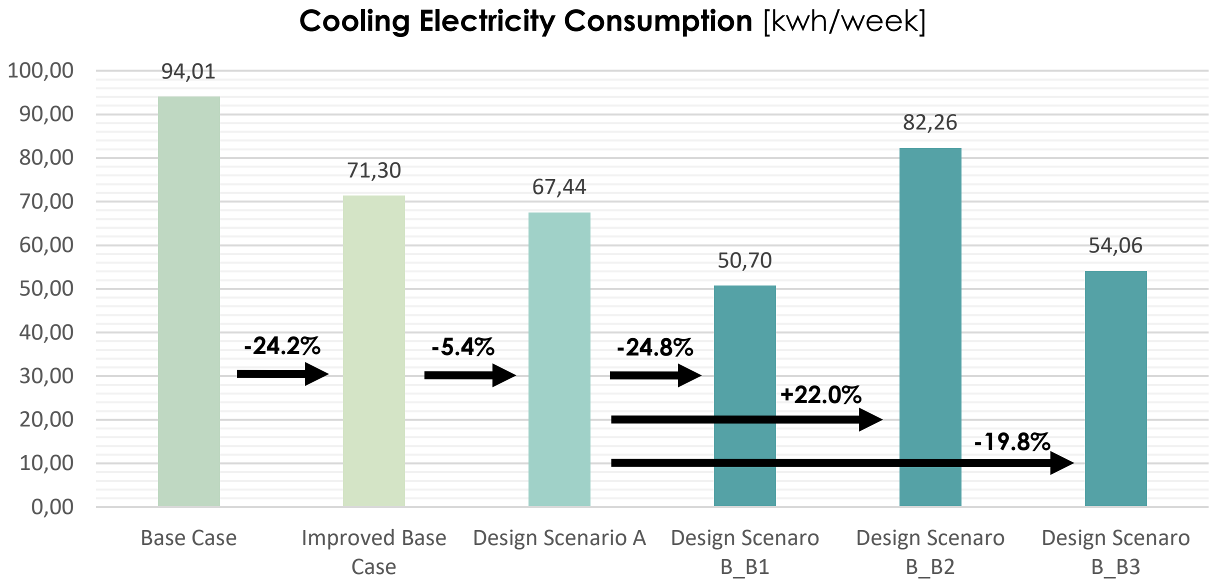


Table 4.4 Comparison charts on cooling electricity consumption

(Note: calculation of cooling electricity consumption for design scenario B1, B2, and B3 could be found in Appendix 9.1)

Similarly, the first and most remarkable change occurs when 'Base Case' gets improved, where cooling power consumption dropped by 24.2% because of the simultaneous decline in cooling demand. In design scenario A, the design continues to help decrease the energy use by 5.4% from the scenario of improved base case.

However, compared with design scenario A, three results of design scenario B indicate variable changes. Sub-scenario B1 and B3 contribute 24.8% and 19.8% to the electricity savings respectively, as both options have enough solar heat to generate cooling output by solar desiccant cooling design.

In contrast, it is reversed in scenario B2. As mentioned previously, this case only satisfies 53% of the cooling demand in the target room by the same desiccant cooling technology, but the remaining 47% is provided by conventional A/C systems. That is the reason for the significant increase in cooling electricity consumption in sub-scenario B2. As shown between Design Scenario A and Design Scenario B2, the rate of change is 22% increase, which also implies that the inadequate solar heat input in the design will not be able to provide the required cooling output but request supplementary electricity from the grid to produce extra cooling service.

Compared to the base case conditions, design scenario A with FIPV design results in a 28.3% decrease in cooling electricity consumption, while design scenario B1 and B3 contributes to a reduction of 46.1% and 42.5% respectively.

4.2.4 Capacity of renewable energy generation

In design scenario A and B, the renewable electricity is all produced through the PV panels integration, while the solar heat is generated through solar thermal collectors. Considering the efficiencies of 13.6% and 65% for PV and ST collectors, respectively, the bar charts show the yield of renewable energy between design scenario A and B (including B1, B2, B3). (Table 4.5)

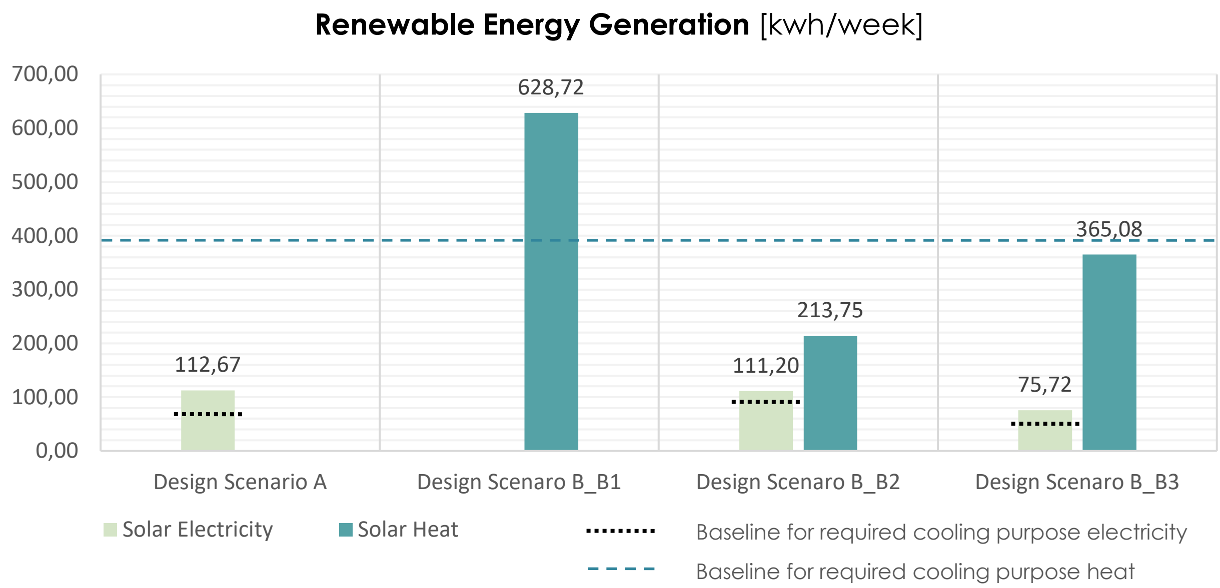
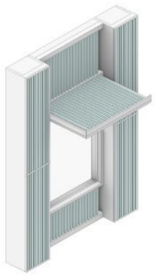
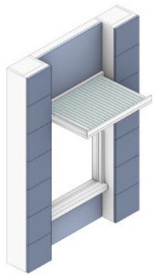
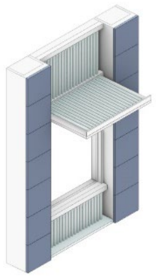


Table 4.5 Comparison charts on renewable energy generation

For the yield of solar electricity, proposal of design scenario B2 has almost the same output as that of design scenario A, as they both have 100% PV coverage on façades apart from the opening parts. For design scenario B3, it has less PV surfaces so that only 75.72 kwh of electricity was produced during summer design week. For design scenario B1, it ends up with zero production due to its out-of-PV integration. However, in terms of the energy payback, the cooling electricity consumption in design scenarios A, B2, and B3 can all be compensated by their on-site yield, whereas the case in design scenario B1 still requests electricity from the utility.

For the yield of solar heat, design scenario B1 converts the most thermal energy (628.72 kwh) depending on its 100% ST coverage. B3 ranks second with 365.08 kwh, while B2 generates the least with 213.75 kwh. According to the requirement of solar heat for cooling output for the target room (287.76 kwh / 0.72 = 399.67 kw), the thermal yield of scenario B1 can completely fulfill the demand even with surplus. At the same time, there is a little production gap of about 31.69kwh (399.67kwh -365.08 kw) in scenario B3.

4.3 Qualitative evaluation

<table>
<tr><th colspan="2">Design proposal of solar liquid desiccant cooling Integrated façade (Design Scenario B)</th><th>Applications of design strategies</th></tr>
<tr><td colspan="2">Design Scenario B1  Design Scenario B2  Design Scenario B3 </td><td>[a] Passive design strategies including WWR values adjustment, external wall insulation materials setting, sun shading elements design.

[b] Active design strategies mainly about FIPV and FIST design.

[c] Solar cooling strategies including LDEVap cooling units' integration, FIST design and multi-system merge.</td></tr>
<tr><td>Criterion</td><td>Pros.</td><td>Cons.</td></tr>
<tr><td>Integration feasibility</td><td>High feasibility in façade integration, regarding the compact size of the core cooling units.

High possibility and more space efficiency in multiple systems merges.</td><td>The extra hot water cylinder takes more façade internal space, and the weight of water tank is another issue. Due to the safety consideration, the load of water tank needs to be taken by the building's structure.</td></tr>
</table>

Energy performance	The high capacity in cooling and dehumidification of a single cooling unit and the maximal cooling service range are subject to the number of integrated coolers. Refrigerant-free system, water as the coolant without environmental harmfulness Considerable solar energy yield from PV and ST elements.	Fully achieving energy autonomy still depends on the improvement of COP_{elec} of the LDEVap cooling units. The area of ST collectors is limited, due to the available space on façade module. The higher efficiency of PV and ST collectors depends on the product upgrades.
Assembly and maintenance	Compact outline size with 3000 (w)x 4200(h)x500(d) mm, prefab unitized façade units in module and easy for delivery and assembly All the cooling units can be maintained from the interior space, easy for daily cleaning and Inspection.	Maintenance of solar panels must be carried out outdoors, but this depends more on the product's life cycle.
Design aesthetics and space efficiency	The metal frame-shaped facade is visually technological. Decentralized cooling systems save the internal height in working space, including the ducts and the pipes' space.	Due to the large number of PV panels covering the building, the color tone of the façade is dark, and it has Lower transparency and lightness in vision compared to a fully glazed building.
Other uncertainty		Due to the uncertainty in the materials price in the market, and the manufacturing quality, the first cost of facade investment is unknown.

Table 4.6 Qualitative evaluation

4.4 Design review and decision

Through the performance assessment, it is clear to find out that the effective area of the solar thermal collectors exposed to the sun is the most critical parameter without upgrading the products' efficiency. Therefore, out of the three proposals in design scenario B, B2 converts too little of the solar heat required for cooling output as it contains a minor solar thermal receiving area. As a result, it can only satisfy 53% of the cooling demand for the target room if there is no continuous supply of additional energy. However, the design proposal of scenario B1, even though it converts the most solar heat to provide the cooling, could not be regarded as a better solution because it does not generate electricity, but the auxiliary systems such as fans and pumps still require electrical power to operate, therefore the extra power still needs to be supplied by the grid. This is inconsistent with the goals of the study. Finally, there is B3, which has a hybrid configuration of PV and ST. The surface area for collecting solar energy is evenly distributed. It produces solar heat and solar electricity simultaneously and almost meets the full cooling demand (95% achieved), as well as achieves energy autonomy without the supporting from the utility, therefore the design solution for sub-scenario B3 deserves further development.

Additionally, compared with the design proposal in design scenario A, solar desiccant cooling integrated façade systems (design proposal of B3) not only achieve less cooling demand (2% in reduction) and electricity consumption in cooling (19.8% less use), but also provide the refrigerant free cooling which is much more environmentally friendly and sustainably. Furthermore, even if the conventional centralized cooling system like the vapor compression A/C are still in need for other non-office space such as the ground floor lobby, the lift hall, some plant room like CCTV room, the size of selected A/C systems can also be reduced.

In summary, considering all the above comparisons, **the design proposal of sub-scenario B3 will be developed in the next stage**, which is also used as a baseline direction for the design finalization. (Figure 4. 2)

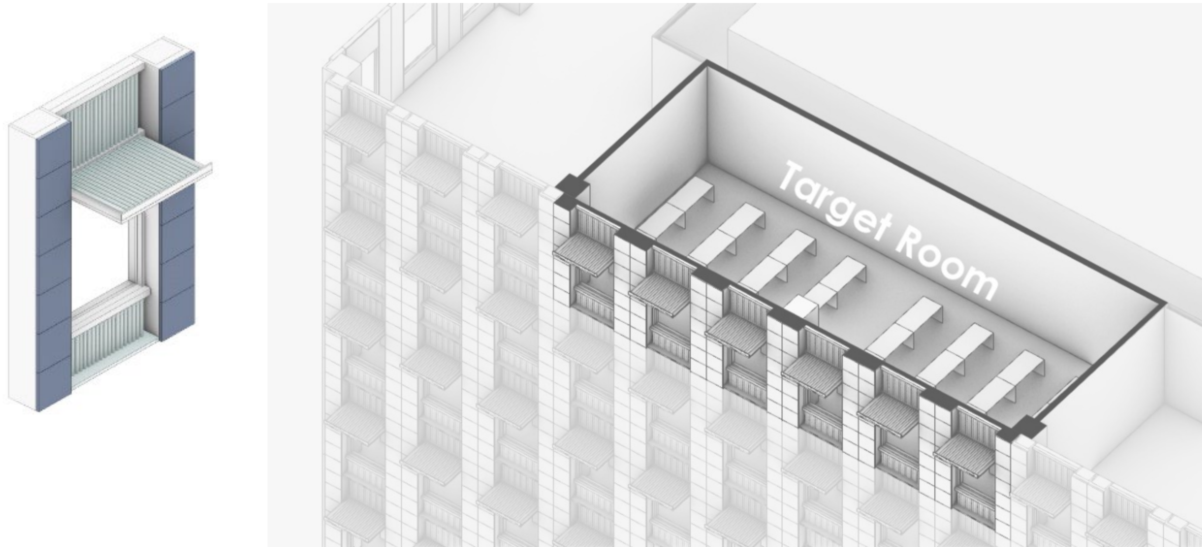


Figure 4.2 Further design direction based on sub-scenario B3 for the target room

5

DESIGN FINALIZATION

5.1 Façade components design

5.1.1 Multiple systems design

[a] Air circulation system

According to the experimental conclusions by Elmer et al. (2016), the dehumidifier, the evaporative cooler and the regenerator require different airflow sources as design criteria. The diagram (Figure 5. 1) shows the various airflow in the circulation.

For the dehumidifier, the outdoor fresh air with high temperature and high level of relative humidity is recommended. For the evaporative cooler, a mixed airflow including the outdoor fresh air and the indoor returned air (warm but dry) is recommended. For the regenerator, the indoor returned air with warm temperature but dry humidity level is recommended.

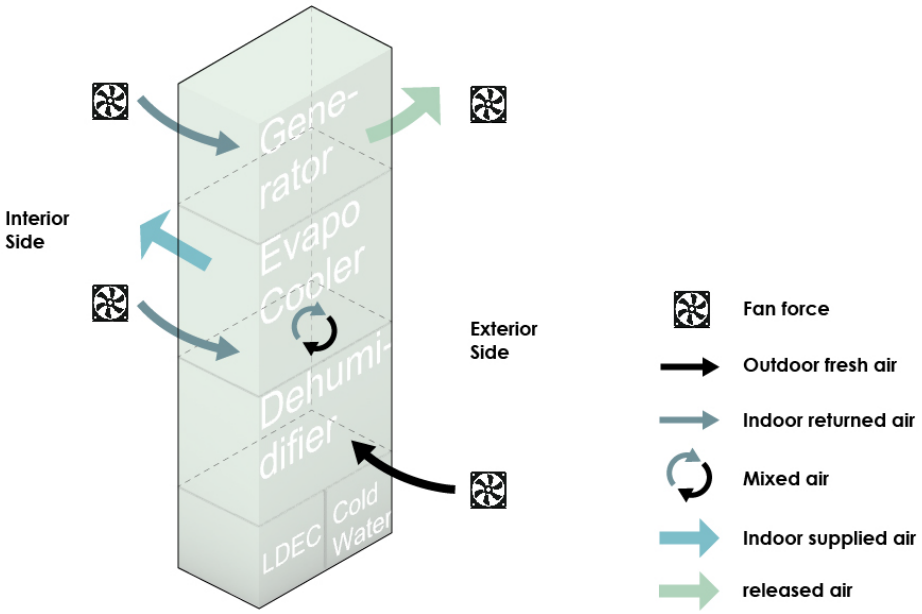


Figure 5.1 Airflow sources criterion for the LDEVap cooling unit

(graphic: own work, 2024)

For feasibility purposes, the design attempts to use the same equipment that was used in Elmer's experiment, or devices with similar properties. Based on the equipment list mentioned in Chapter 2 (as shown in Table 2. 4), the first task is to calculate the cross-section size of the air ducts.

According to the data of daily cooling demand in summer design week (57.56 kwh/d) and the average cooling capacity of the LDEVap cooing unit (1.1 kw), taking 9 operational hours (9:00-18:00) per day into account, the number of integrated coolers for the target room is calculated as follows:

Average hourly cooling load = 57.56 kwh / 9h= 6.40 kw
Number of the required coolers = 6.40kw / 1.1 kw = 5.82 $\approx$ 6

Therefore, at least six sets of LDEVap cooling units must be evenly installed into the current six façade modules of the target room; in other words, each façade module requires one set of cooling units. (Figure 5. 2)

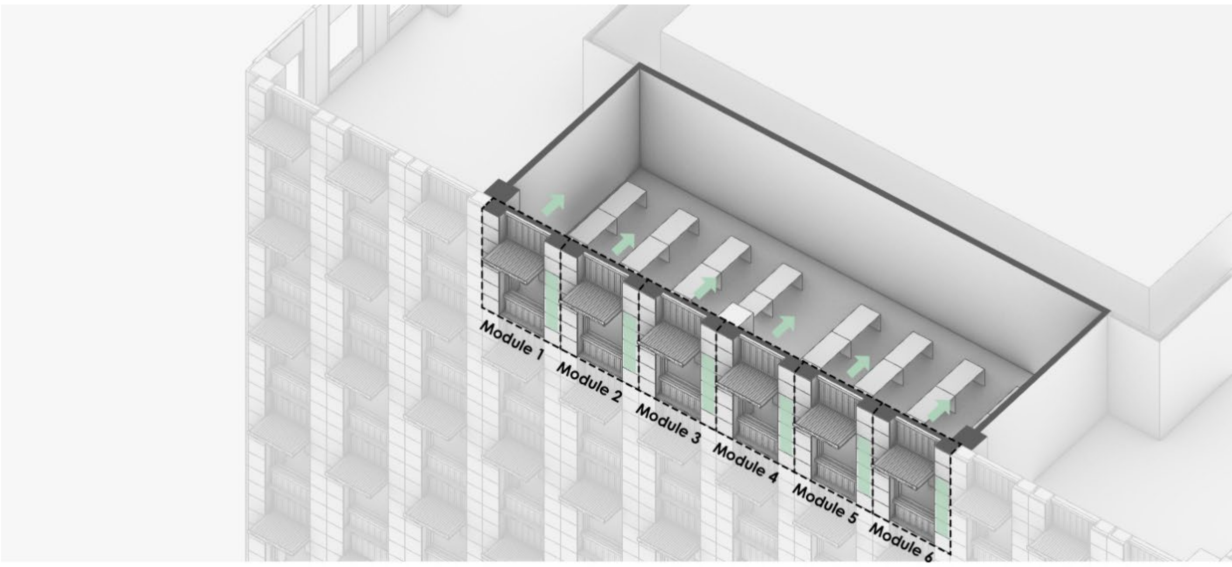


Figure 5.2 LDEVap cooling units integrated into all façade modules for the target room

Calculation parameters:

Room area	129.14 m^2	data used in DesignBuilder program
Room volume	129.14 x 4.2(h)=542.39 m^3	
ACH	3	
Volume of the air to be conditioned	542.39 x 3 = 1627.16 m^3	Air to be conditioned in the target room per hour
Max. indoor airflow velocity	0.8 m/s	the upper limit to air speed for office for operative temperatures above 25.5°C by ASHRAE standard

It is assumed that every cooling unit of façade module has one indoor supplied air outlet, so in total there are six air outlets for cooling output. Hence, the hourly air output of every air outlet is equivalent to:

$V_{\text{per outlet}}$ = 1627.16m^3 / 6 = 271.2 m^3/h = 0.075 m^3/s

Minimum of cross-section area for every air outlet = 0.075 m^3/s / 0.8 m/s = 0.094 m^2

Assuming to design a strip vent (diffuser) for the indoor supplied air, the possible dimensions: 0.4m(w)x 0.25m(h)=0.1 m^2 (> 0.094 m^2)

In addition, regarding the sizing of the return air ducts for the evaporative cooler and the regenerator system, as well as the outdoor air inlet (for fresh air input) and outlet (for released air), it is assumed to use the same products' sizes as those used in Elmer's experiments, which are galvanized steel spiral tube ducts with 125mm diameter for each. The airflow circulation is driven by three axial fans connected with every circular duct. (Figure 5. 3)

Figure 5.3 Vents, ducts and axial fans

[b] Water circulation system

Figure depicts the water circulation within LDEVap cooling unit. Cold water (liquid temperature at 20 °C) is pumped up from the bottom water tank and sprayed down through the chamber of the evaporative cooler by a nozzle. Similarly, the desiccant solution is pumped up, going through the space where the regenerator is located, and then sprayed down through the dehumidifier core. At the same time, hot water flow (liquid temperature at 60 °C) is provided to the regenerator through the copper pipes by a 120L hot water cylinder as an extra auxiliary heat source. (Figure 5. 4)

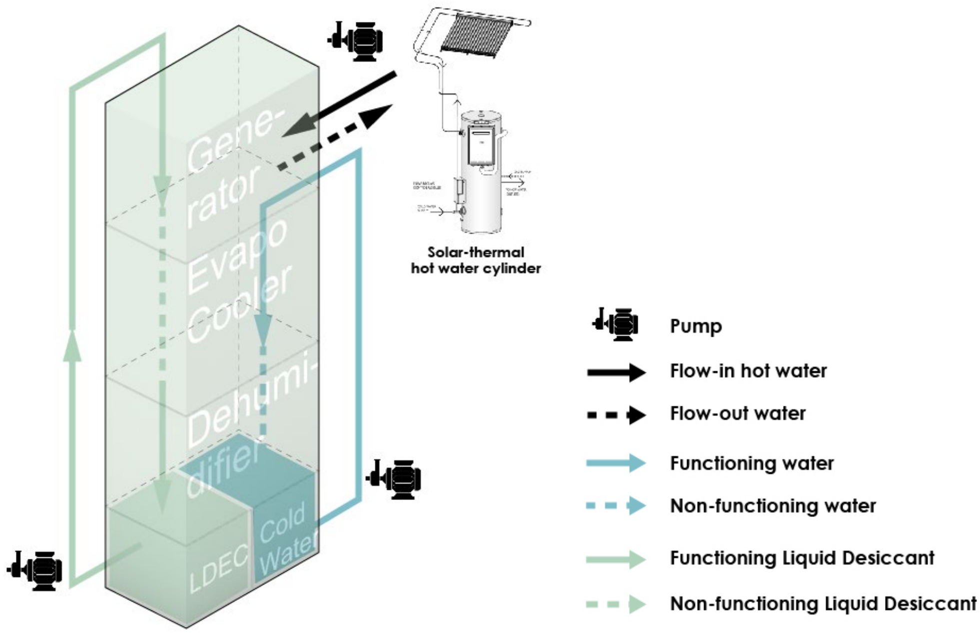


Figure 5.4 Waterflow circulation criterion for the LDEVap cooling unit

(graphic: own work, 2024)

The following graphic shows the indirect evaporative cooling and dehumidification process happening in the core of LDEVap cooling units. (Figure 5. 5) The dehumidifier removes the moisture from the outdoor fresh air in the film channel of liquid desiccant, while the evaporative cooler cools the dehumidified air in the water film channel. Eventually, the temperature of the dry air will drop significantly. Finally, the conditioned air (cool and dry air) will be supplied to the room.

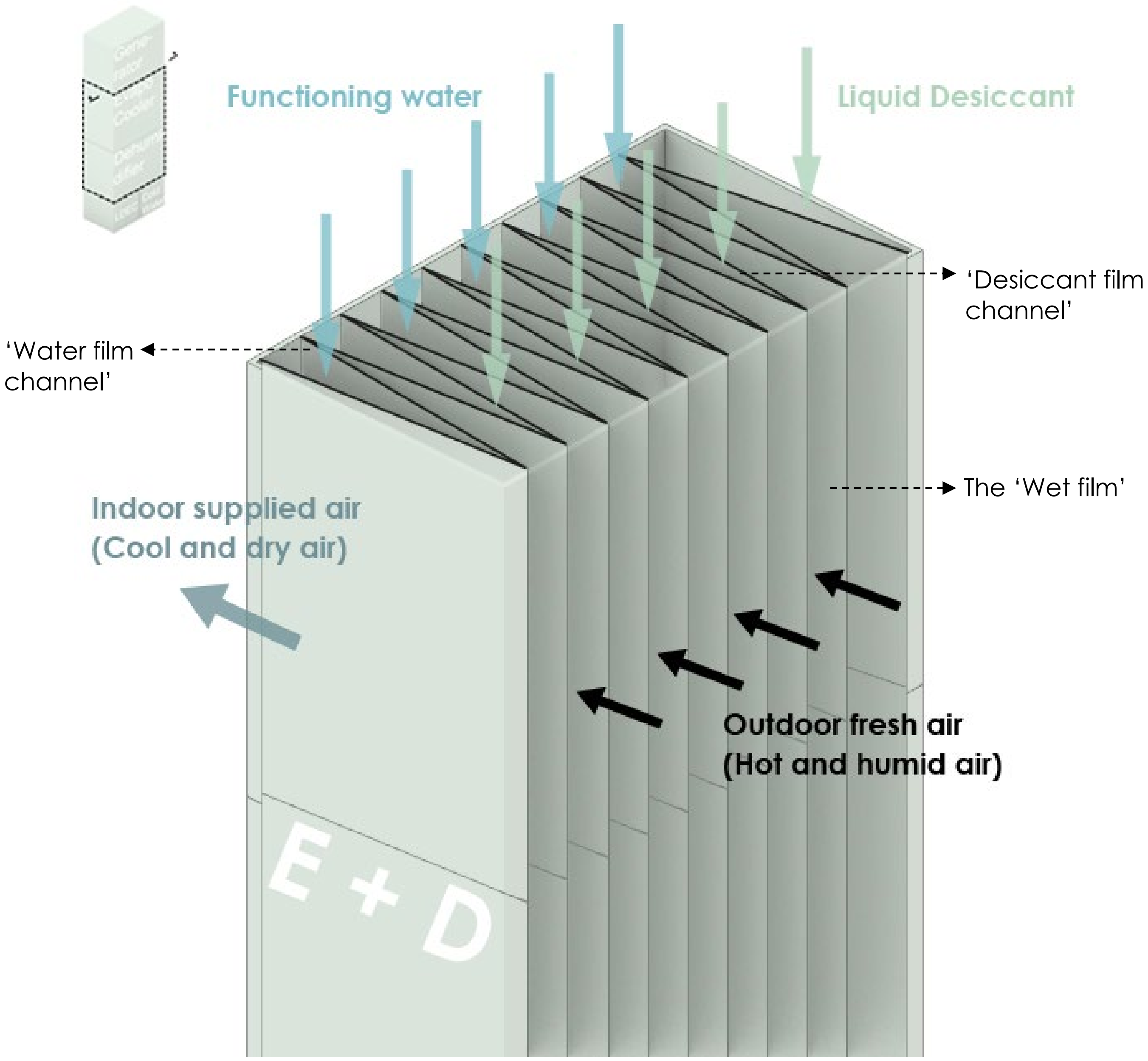


Figure 5.5 Cross section of the dehumidifier and evaporative cooler in

For feasibility purposes, it is assumed to use several referential products as the auxiliary components for the water circulation system. (Table 5. 1) The principles for products selection are to have the same technical data as those used in Elmer's experiment. (Refer to Table 2. 4)

Auxiliary components		Functioning	Key technical data
	Solar thermal hot water cylinder (Reference to the British product of Mixergy Solar X Direct Slimline. Product code: MX-120-ELE-479)	To provide the regenerator with heat source for 'drying up' the saturated desiccant solution	Number: 1 Capacity: 120L Dimensions: 1240mm height 479mm diameter Electrical support: 16A, 230 - 240 V
	Circulating pump (Reference to the German product of Wilo Star-Z 25/6-3)	To circulate the hot water between the hot water tank and the regenerator	Number: 1 Max. power consumption: 99W 230V AC Dimensions: 101mm(w) x 180mm(h)
	Single phase centrifugal magnetically driven pump (Reference to the German product of Burkle magnetic centrifugal pump 15 Watt)	To pump the cold water to the evaporative cooler, and the liquid desiccant solution to the dehumidifier and the regenerator	Number: 2 Max. power consumption: 15W Max. liquid flow rate: 1-12 L/min 230V AC
	Copper hot water pipe with fittings	To circulate the hot water	Counted in length Ø 22 mm x 2mm (thickness)
	PVC-U plastic pipe with plastic fittings	To circulate the functioning cold water and desiccant solution	Counted in length Ø 20 mm x 1.5 mm (thickness)

Table 5.1 List of the auxiliary components for the water circulation system

[c] System merge

Within a façade module, the whole cooling systems can be stacked and merged in a limited space. Considering the weight of hot water cylinder, it is placed on the lower position with the piping connection to both the evacuated tubes collectors and the re-generator of the cooling unit. The cooler is installed above the hot water tank, supplying the conditioned air at a higher level just right below the clear height line of the indoor space. In addition, all the piping systems are powered by pumps, while all the ducts are driven by electrical fan force. The diagram of Figure 5. 6 shows the concept of multiple systems merge through the sectional view. Figure 5.6 and Figure 5.8 illustrate the main components involved in one façade module.

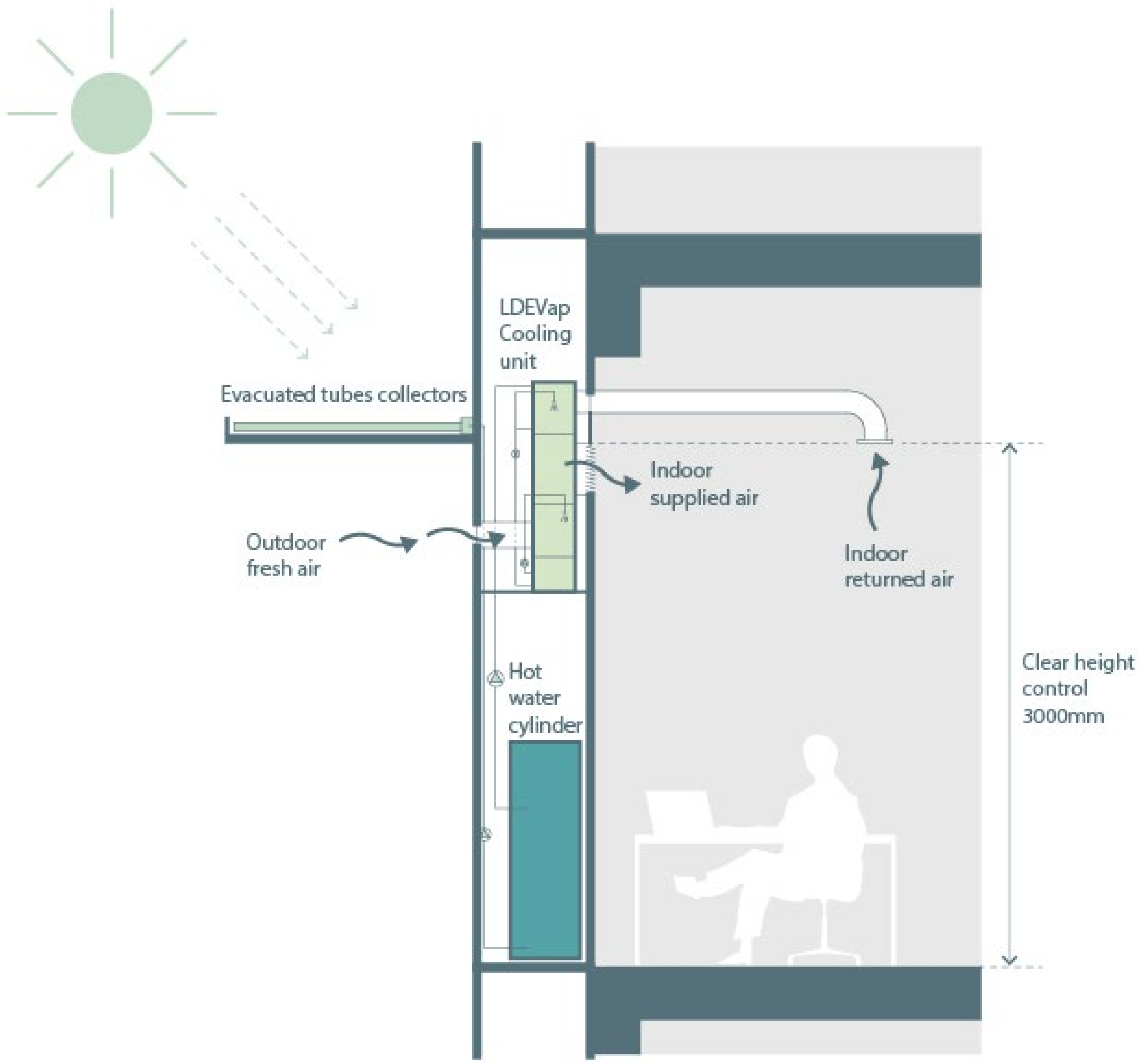


Figure 5.8 Concept of multiple systems merge

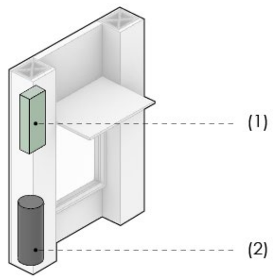


Figure 5.9 The basic principle on how the cooling components placed

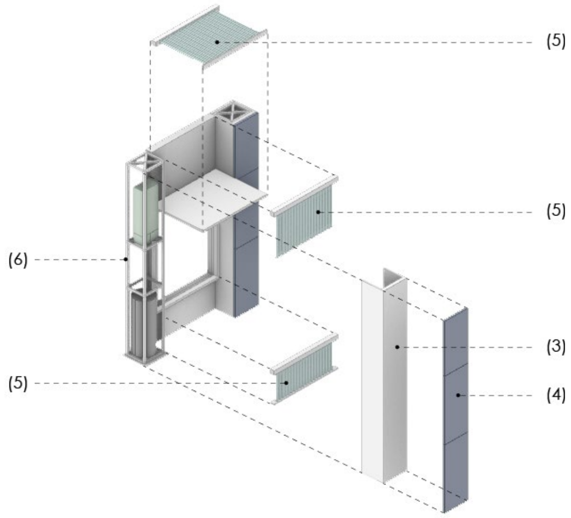


Figure 5.10 The main components involved in one façade module

Main components involved:

(1) LDEVap cooling unit
(2) 120L hot water cylinder
(3) Aluminum cladding panel
(4) Photovoltaic panels
(5) Evacuative tubes collectors
(6) Sub-structural frames in steel

[d] Re-sizing of the façade module

To accommodate the cooling unit and its auxiliary components, the internal room of the façade module should be re-sized. Figure 5.11 shows the axonometric view of the façade module, and Figure 5. 10 show the clear dimension of the equipment space - 528mm(w)x 520mm(d)x4200mm(h), which well fits the sizes of all cooling devices.

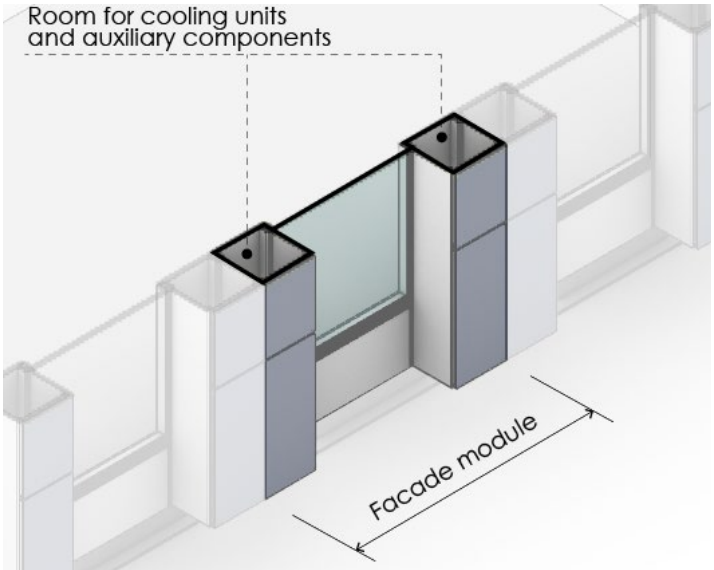


Figure 5.12 Axonometric view: room for the cooling units and its auxiliary components

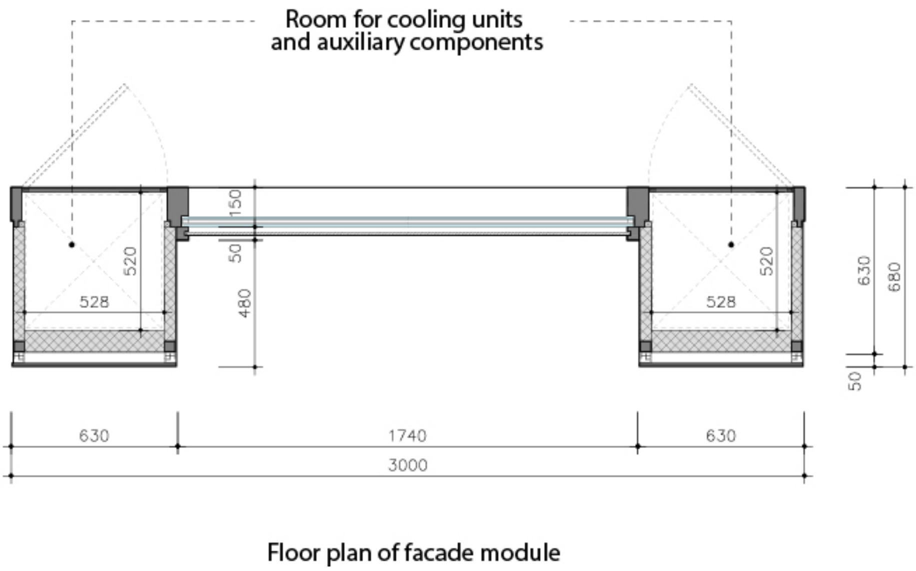


Figure 5.13 Floor plan re-sizing of the façade module

[e] Air-in and air-out design

Error! Not a valid bookmark self-reference. shows the outdoor air inlet and outlet design. The general idea is to utilize the surfaces on both sides of the glazing panel. The air outlet for the released air from the regenerator system is placed on a higher level above the overhand shading panel, and the air outlet to absorb the outdoor fresh air is arranged under the shading element.

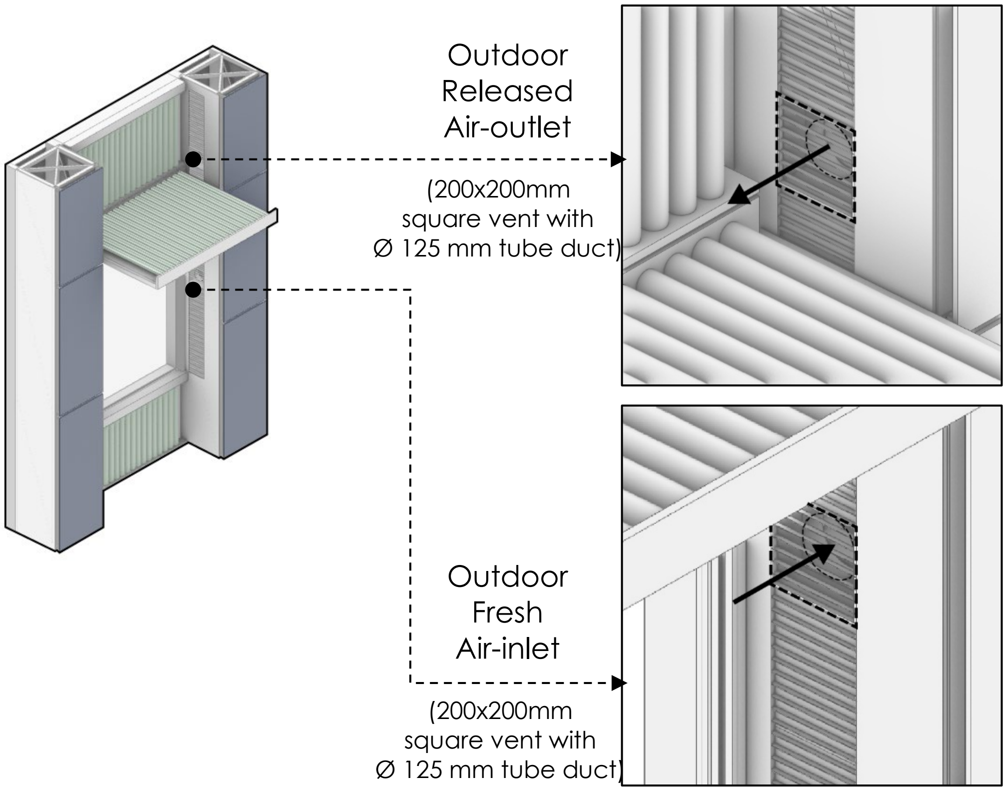


Figure 5.14 Outdoor air inlet and outlet design

For the exterior side, the opening sizes of the air inlet and outlet are based on the given data from Elmer's experiment - Ø 125 mm tube pipes connecting with the 200 x 200 (mm) metal square vents. The conditioned air is supplied to the workspace through a strip vent (520x250 mm) with a top height of 3m from the floor. The indoor returned air is absorbed by a circular exhauster connecting with the evaporative cooler and regenerator through the same size tube duct. (Figure 5.15)

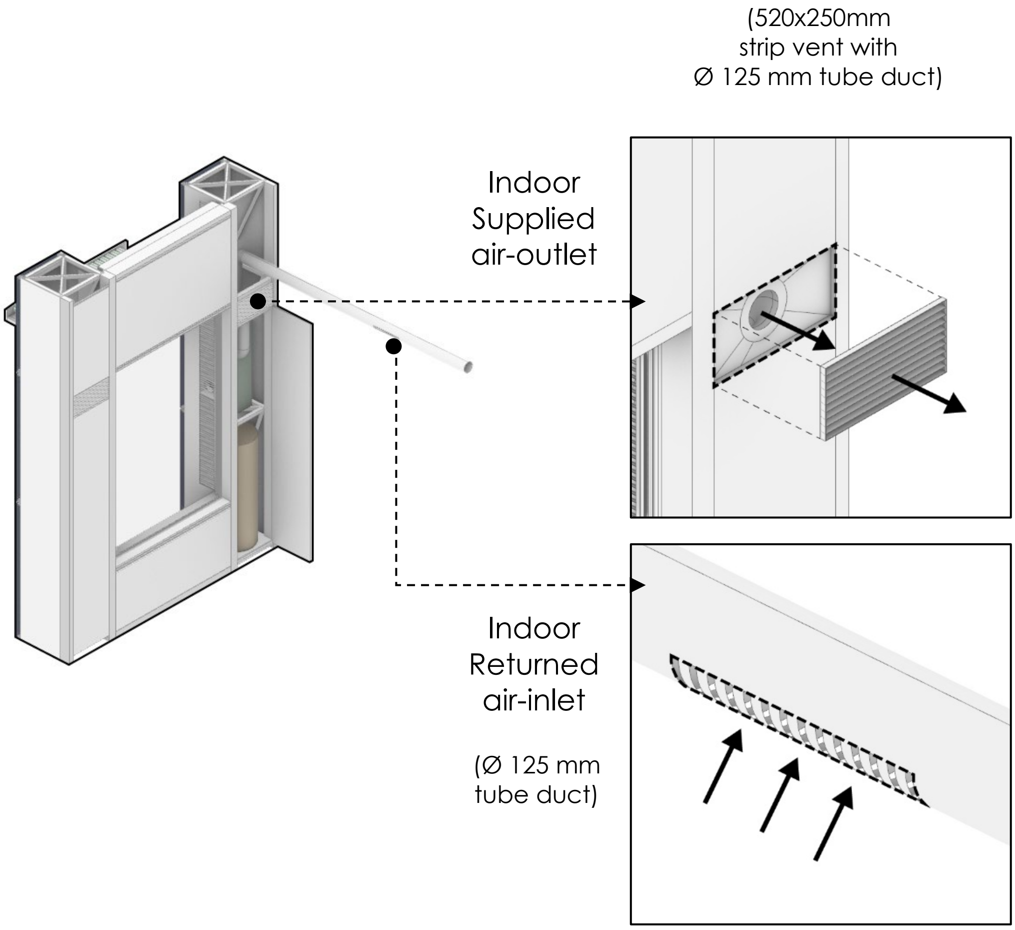


Figure 5.16 Indoor air inlet and outlet design

Figure 5.17 View from interior

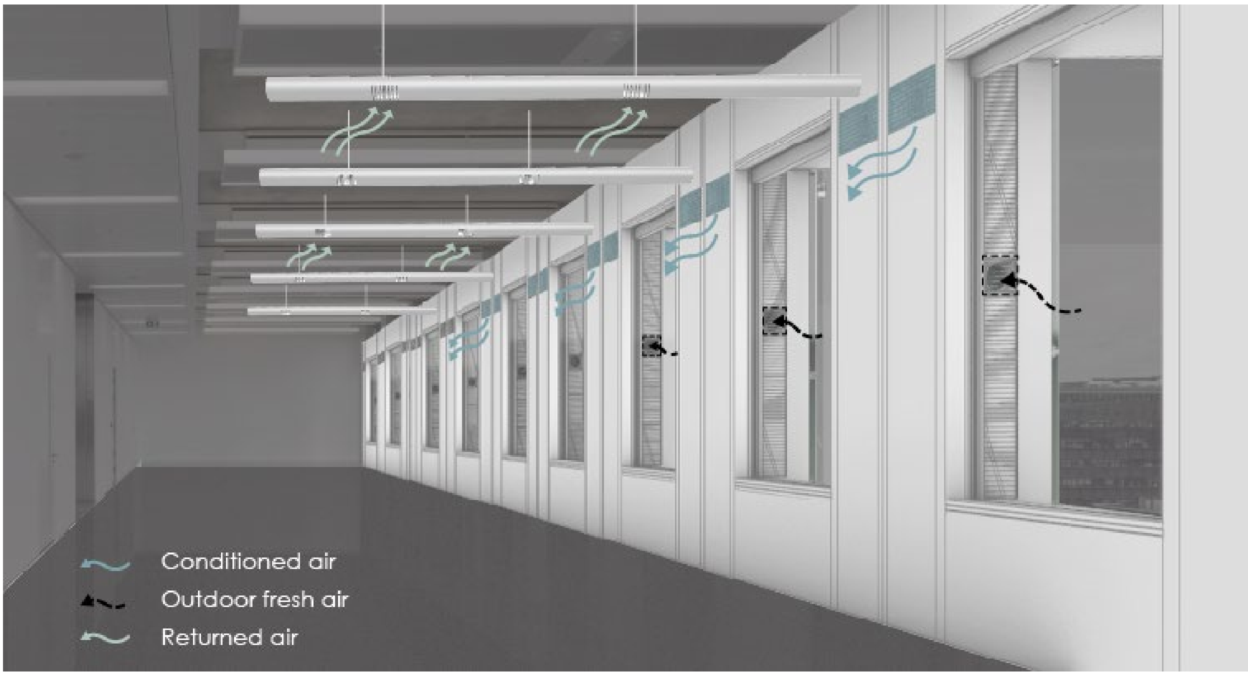
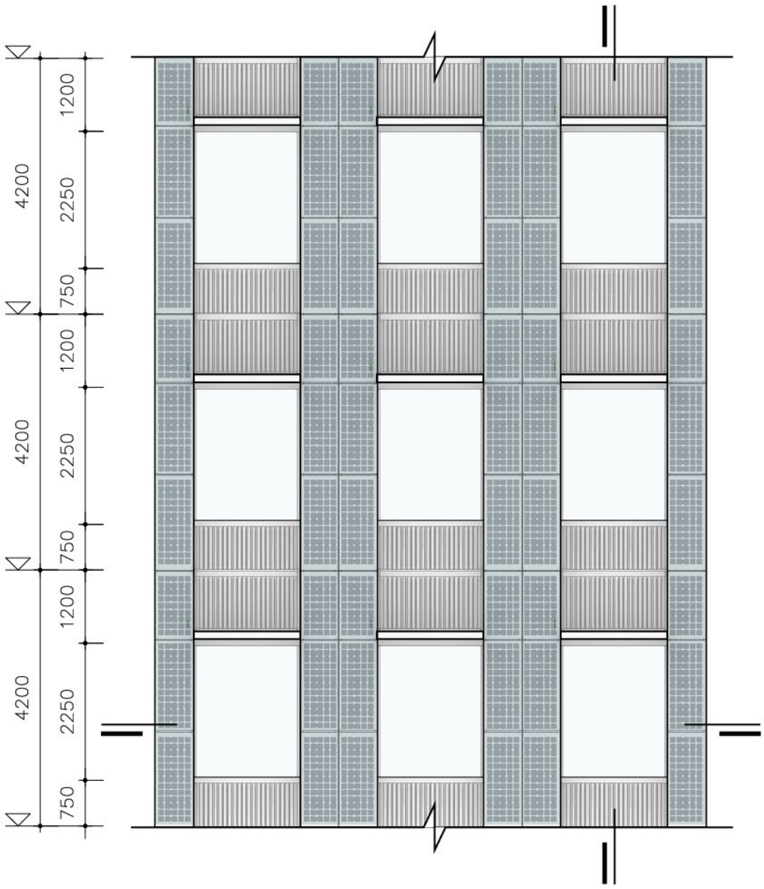


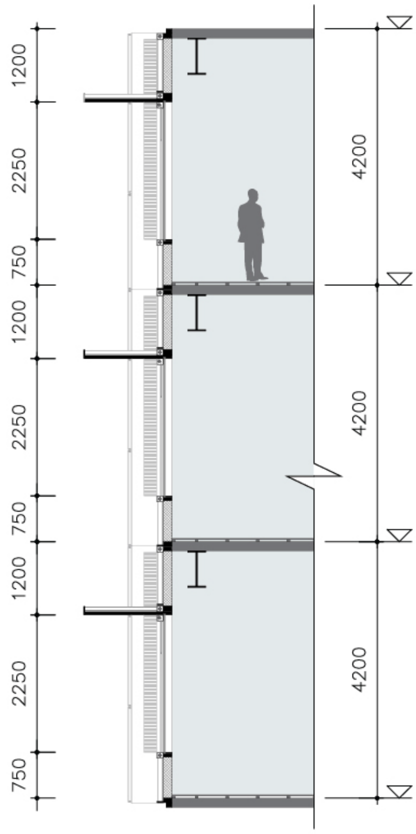
Figure 5.18 3D view of the cooling service principle

5.1.2 Components and details design

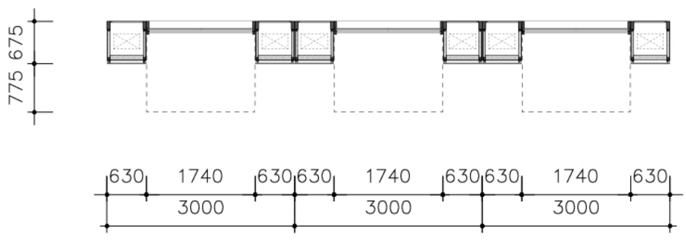
[a] Façade 2D drawings



Typical elvation



Typical façade section



Typical façade plan

Figure 5.19 Typical 2D façade drawings – plan, elevation and section

[b] Typical detains drawings

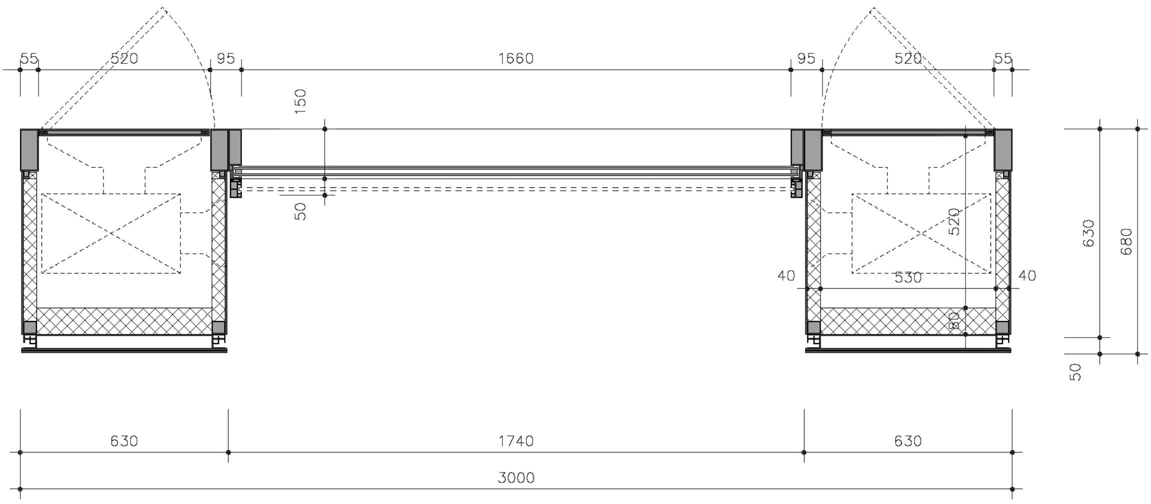


Figure 5.20 Façade module zoom-in floor plan

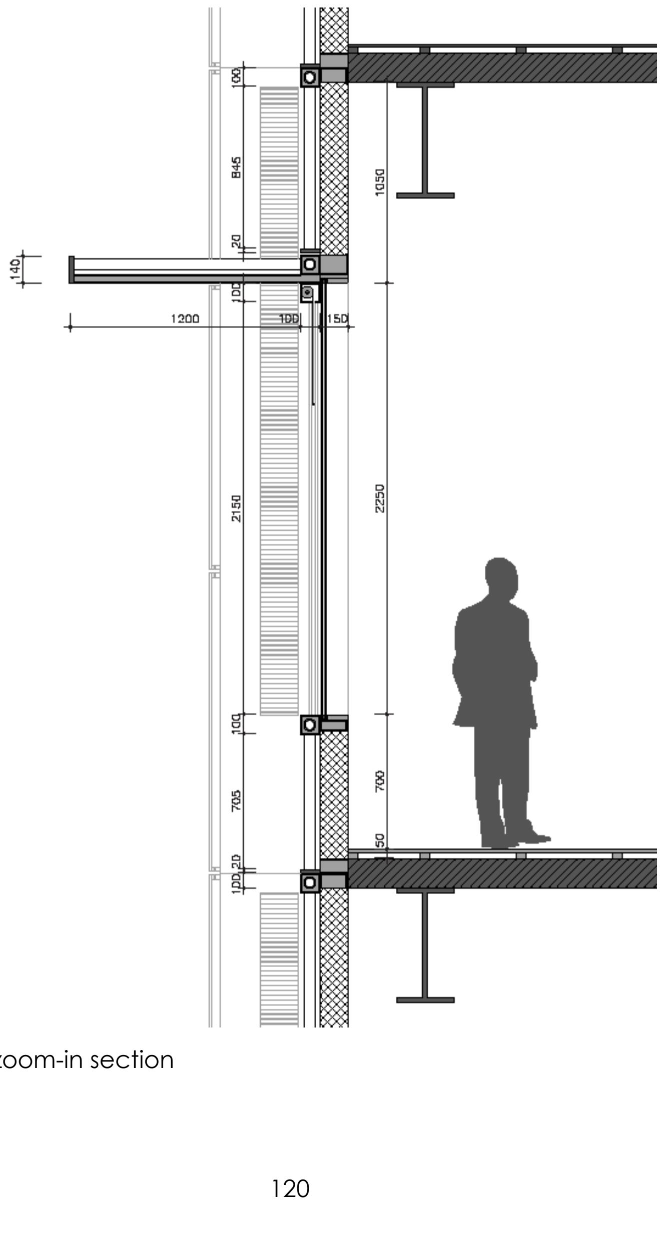


Figure 5.21 Façade module zoom-in section

5.2 Façade assembly process

This section describes the general composition of a single prefabricated facade module and the overall sequence of assembly. All elements were pre-assembled by the façade builder in their factory and brought to the site. Once on site, each façade block was connected to the main structure of the building.

5.2.1 Assembly process in the factory

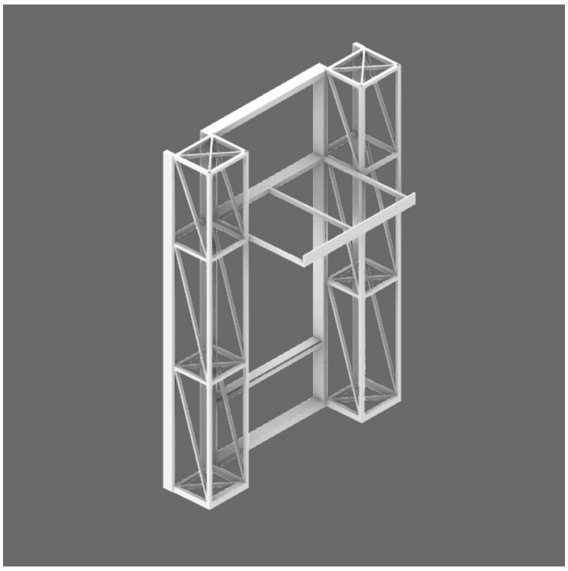


Figure 5.22 Factory assembly step one

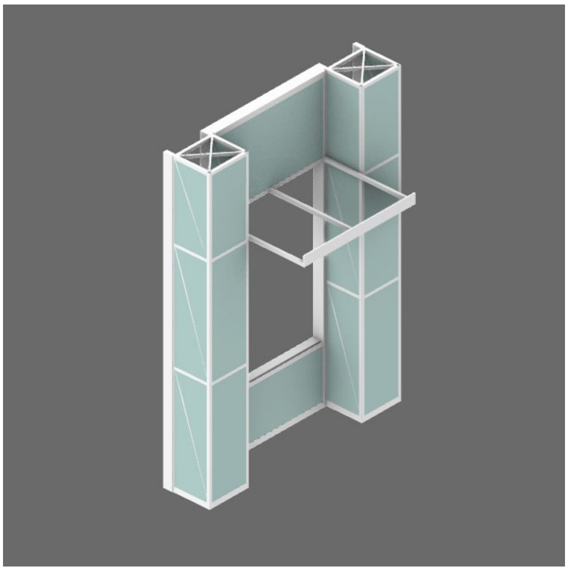


Figure 5.23 Factory assembly step two

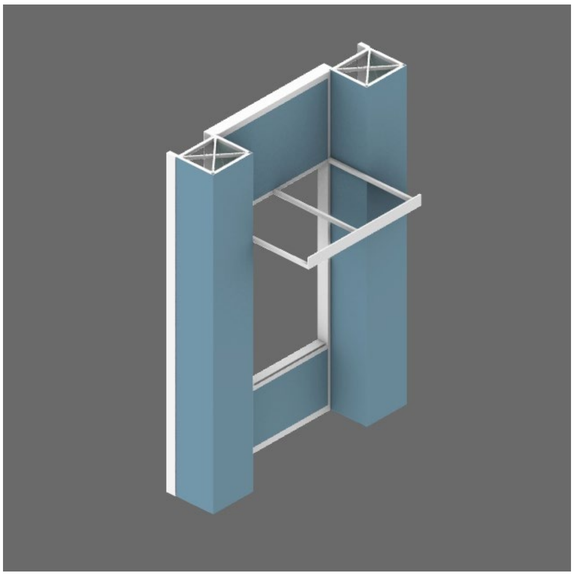


Figure 5.24 Factory assembly step three

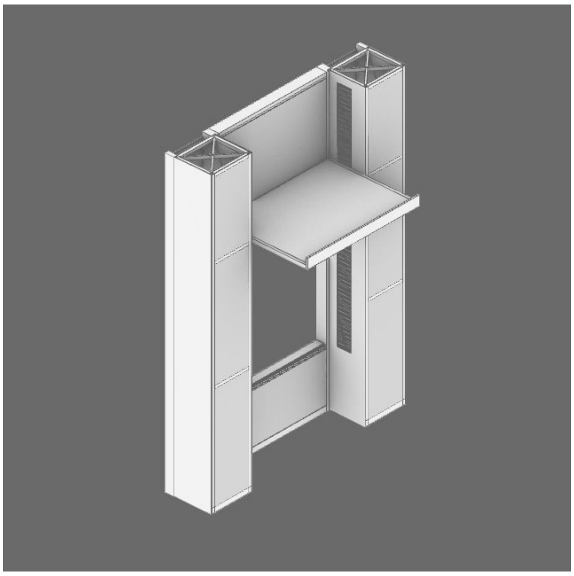


Figure 5.25 Factory assembly step four

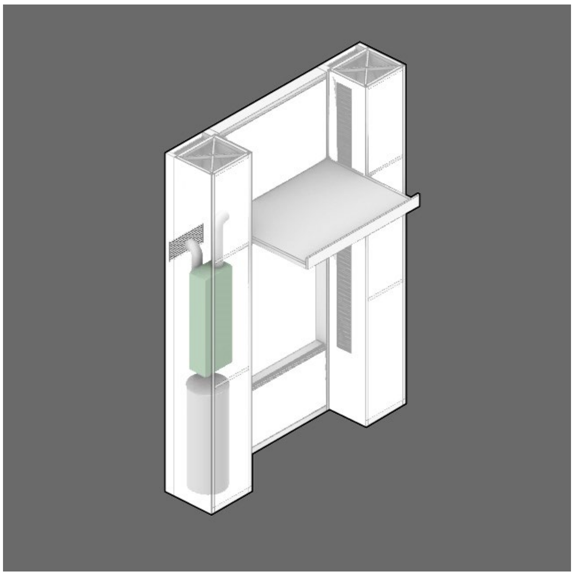


Figure 5.26 Factory assembly step five

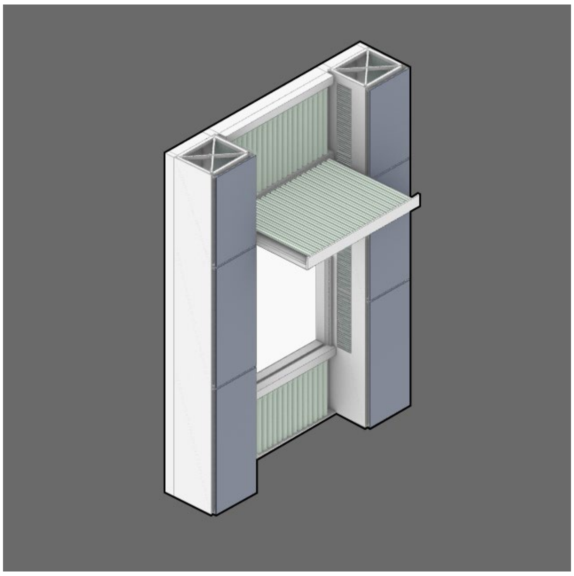


Figure 5.27 Factory assembly step six

There are six main procedures involved in the assembly process in the factory:

Step one – Assembling the framework
Step two – Wrapping the Insulation layers (EPS expanded polystyrene)
Step three – Adding the water barrier layers (EPDM water barrier)
Step four – Mounting the cladding systems (aluminum plate, glazing panel, …)
Step five – Installing the cooling systems and connecting all the auxiliary components
Step six – Installing the solar energy systems (PV, ST, extra sun blind, …)

5.2.2 Assembly process on site

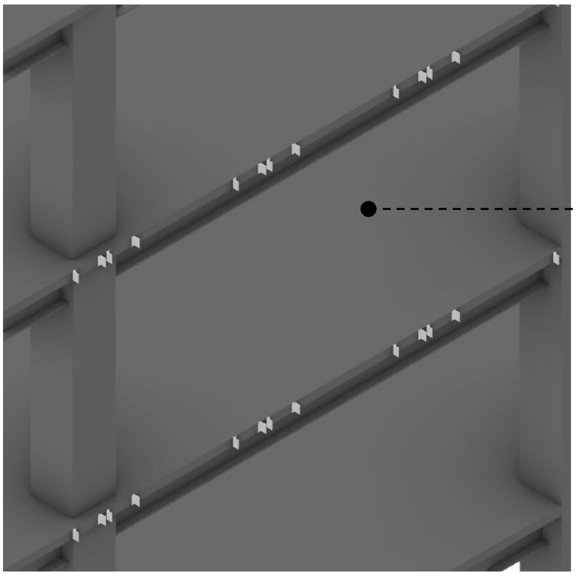


Figure 5.28 On-site assembly step one

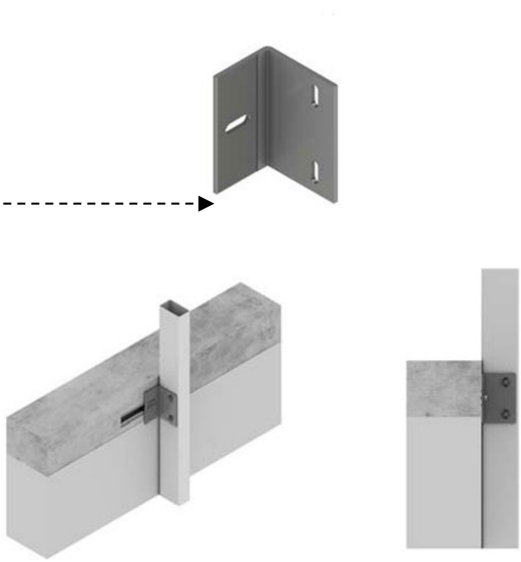


Figure 5.29 The fixing components – L-shape bracket

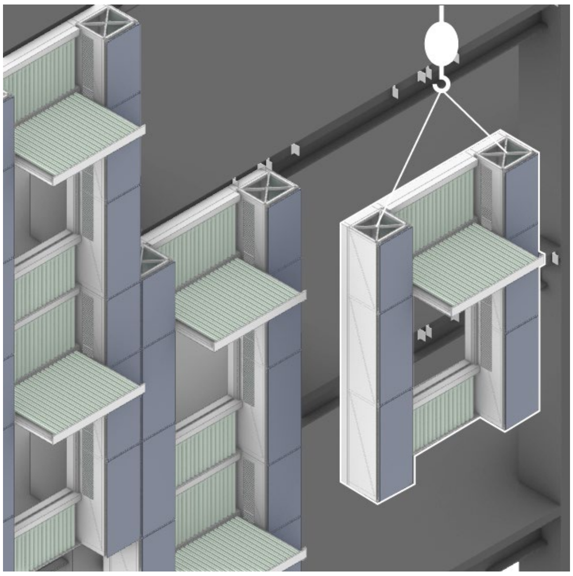


Figure 5.30 On-site assembly step two

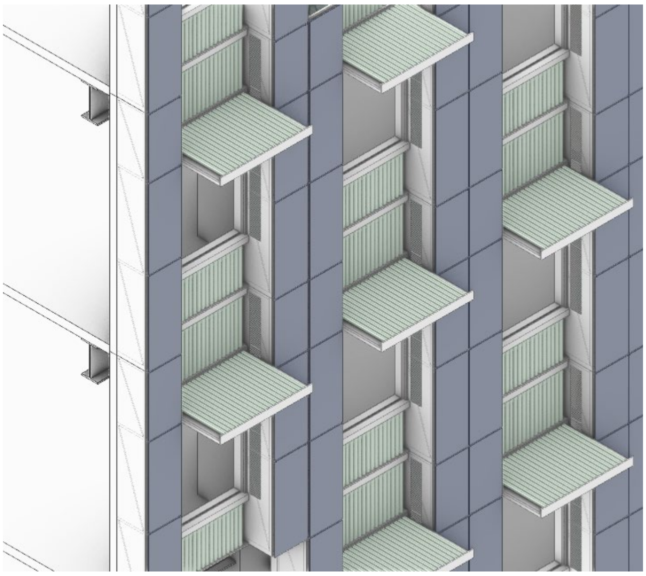


Figure 5.31 Factory assembly step three

There are three main procedures involved in the assembly process on site:

Step one – Pre-embedding the fixing systems (L-shape supporting bracket)
Step two – Mounting the façade modules
Step three – Adjusting the tolerances and installing the fittings for the cooling systems (ducts and pipes)

6
CONCLUSION

6.1 Conclusion on research questions

In general, this graduation project demonstrates that it is not sufficiently dependent on only one specific technology to design a façade system that promotes the reduction of the cooling demand and energy consumption of a high-rise office building in Shenzhen's hot and humid climate, but it is necessary and useful to integrate multiple design strategies. In this design, passive cooling, active cooling, and liquid desiccant evaporative cooling strategies are used to achieve the study's objectives. Each strategy is applied and analyzed in different design scenarios to determine the final design solution.

6.1.1 Conclusion on main research question

The main research question:
"**In hot-humid climate, how can the design application of solar cooling integrated facades minimize the cooling energy consumption for office buildings and optimize the indoor thermal comfort?**"

To answer this question, it is necessary to compare all the key results generated in performance assessments.

In energy performance, compared with the scenario of base case, the cooling demand of the target office room dramatically drops by **26%** during summer design week when solar cooling integrated façade design is adopted. At the same time, the corresponding cooling electricity consumption even decreases by **over 40%**. (by 46.1% in design scenario B1 and by 42.5% in design scenario B3)

In terms of design strategies, the biggest changes occurred in the processing from the basic case to the improved base case when applying passive design strategies. By lowering the WWR value, adjusting the insulation materials of the opaque cladding panels, and adding external sun shading elements, the cooling demand of the target office room dramatically drop by 19.6%, and the corresponding cooling electricity consumption even decreases by 24.2%. That is because lower WWR value avoids more solar heat gain, while a suitable shading design effectively blocks much solar radiation.

In terms of renewable energy generation, solar cooling integrated façade systems provide on-site energy production of both solar electricity and solar heat. This advantage allows for self-sufficiency in cooling energy, and the excess yield of energy can be fed back into the building's requirements. For instance, in design scenario B3 (as seen in Table 4. 5), the major cooling output is generated by the self-produced solar heat (up to 365.08 kwh/week), while the extra electricity use is also covered by its own energy production (up to 75.72 kwh/week). In other words, solar desiccant cooling integrated façade minimizes the end use of electricity by achieving the energy autonomy in cooling.

In contrast, although the FIPV design represents design scenario A, which also has a good performance in terms of solar electricity production (up to 112.67kwh per week), it is not an environmentally sustainable strategy considering that the converted electricity is still used in the conventional A/C systems, which continue to use chemical refrigerants.

Regarding the optimization of indoor thermal comfort, liquid desiccant cooling technology controls both the indoor temperature and relative humidity at a stable level. According to the high dehumidification ability of liquid desiccant $CHKO_2$, under the air intake condition of 29 °C (average temperature) and 79% average relative humidity, the conditioned air provided by the evaporative cooler stays between 22-26 °C. The indoor humidity is controlled at the range of 38-60%, which meets the standard of indoor comfort zones in Shenzhen. (The above data refer to similar air intake conditions and experimental results of Elmer et al., 2016)

Finally, as a refrigerant-free system, the solar desiccant cooling integrated façade uses cold water as the coolant, not only reducing the cooling demand and energy consumption in office buildings in the hot-humid climate but also mitigating the harmful effects of traditional refrigerant systems imposing on the environment.

6.1.2 Conclusion on sub-questions

[a] Sub-questions about design factors and adjustable parameters:

"What are the specific design factors and adjustable parameters that enable to affect the design process of solar cooling integrated facades?"

In total, three significant systems need to be considered when designing the solar cooling integrated facades, including solar energy system, cooling system, and façade system.

Regarding solar energy systems, the key design factor is the energy harvest system which determines the type of energy output, either solar electricity or solar heat. Because the cooling systems mentioned later need to be driven by different types of energy respectively. Along with it, the efficiency of the Photovoltaic or solar thermal collectors is the most significant parameter which directly determines its performance level.

Regarding cooling systems, the key design factors mainly consist of cooling generators, cooling distributors and cooling delivery elements, among which the cooling generators have the most significance. Because the designer needs to select the most suitable solar cooling technology as the core technology of the generator according to the climatic conditions and the project situation. In this research, liquid desiccant cooling technology has been chosen as the core technology of cooling generator just because it can control both the temperature and relative humidity. In addition, the most critical parameters are the COP of the cooling units, the capacity of dehumidification and cooling, as well as the typology of the desiccant materials.

Regarding façade system, there are five primary design factors, such as structural components, fixing system, cladding components, shading systems and ventilators (if available). In terms of adjustable parameters, window-to-wall ratio, glazing types, thermal properties of the insulation materials, sun path and shading angles, are the most significant input data that critically affects the façade design performance.

Other parameters from the specific climate conditions are also important, such as the available solar radiation load, the sunlight hours, the wind conditions, the discomfort zones for a city, the yearly harsh time for cooling, and so on.

[b] Sub-questions about design solutions:

"In terms of the performance, to what extend the solar cooling facade design solutions can reduce the cooling energy consumption and how to evaluate it?"

According to the performance tests in design scenario B, the design proposal of solar desiccant cooling integrated façade achieves over 40% reductions in cooling energy consumption during summer design week (up to 46.1% decrease in design scenario B1 and 42.5% in design scenario B3).

In this research project, the simulated design results will be evaluated quantitatively and qualitatively. One of the methods for quantitatively evaluating the design performance was based on the approach used by Prieto (2018) and Noaman et al. (2022) in their corresponding research projects, i.e. comparisons of solar fraction (SF) of the system. Meanwhile, some important numbers like cooling demand, the amount of energy consumption, and the yield of renewable energy are also to be the comparative criterion.

The qualitative evaluation results are evaluated from five angles: integration feasibility, energy performance, assembly and maintenance, design aesthetics and space efficiency, and other uncertainty. These angles are derived from the study by Prieto (2018), who assessed and discussed his research results by checking the identified main barriers to façade integration.

[c] Sub-questions about design guides:

"Based on the design factors, parameters and evaluation results, how to generate a design guide for solar cooling integrated façade system?"

This question can be translated into another way of asking what to consider when designing a solar cooling integrated facade. There are several steps to follow:

Step One: check the background conditions

The first chapter refers to the vicious circle of cooling demand due to overheat gain and overuse of air-conditioning, and this type of façade is one of the products that would have been regarded as an effective alternative product that integrated the solar cooing technology. This is related to the location of the target project; if a place has abundant solar energy resources, long sunshine hours and buildings are all in high cooling demand, then the solar cooling integrated façade can be one of the suitable solutions. If other energy sources are dominant, such as wind, geothermal, or tidal, this technology somehow is not the most appropriate option. Therefore, the first step is to figure out whether a target place with its climate conditions fits before planning decisions.

Design factors to consider:
Climate zone (Koppen climate zones or ASHRAE climate zone), local weather data including CDD (Cooling Degree Day), mean temperature and humidity, wind and precipitation, monsoon season, availability of solar energy, and so on.

Design tools to recommendation:
Climate Consultant, System Advisor Model

Step Two: define cooling strategy

In this research project, cooling strategies are classified into three categories passive cooling design strategies, active cooling strategies and solar cooling strategies. In building design level, passive strategies can be applied to the façade system first because the goal is about heat prevention. Active strategies and solar cooling design strategies are mainly about heat modulation and dissipation. Therefore, once the target location and its climate conditions have been confirmed, choose the most suitable cooling strategies. For example, FIPV technology and desiccant enhanced evaporative cooling technology are the selected options especially for Shenzhen projects. If the target location has an acid-dry climate, then the absorption or adsorption technology might be a good choice.

Design factors to consider:
Most suitable solar cooling technologies (Themo-electric, Sorption, or Desiccant cooling)
Most suitable active cooling technologies (air-conditioning cooling, water cooling, fan cooling, plant cooling, PV/ST driven cool
Most suitable passive cooling technologies (building orientation, WWR, glazing type, sun shading, thermal mass, night ventilation, natural ventilation, etc.)

Step Three: design the core systems

Three systems including solar energy system, cooling system and façade systems are the core systems to be well designed. As introduced in the previous sections, each system consists of a series of key design factors, i.e. for cooling systems, cooling generators, distributors and deliveries are the main design factors. And for façade systems, sizing the components that could contain so many cooling systems is a significant task. Hence, decompose these systems and fully design them.

Design factors to consider:
Solar energy system (types of solar energy collectors), cooling system (the cooler design), façade system (all façade components)

Step Four: define design scenarios (optional)

This step is optional. In this research project, it starts from an assumed generic office building, four design scenarios are set up to compare their performance in the reduction of cooling demand and energy consumption. Different strategies are applied in each scenario, and the simulation and evaluation work are monitored at scenario level. However, for the universal case, follow the exact scenario the design proposal will serve, for example, a project with a very clear energy saving target, or a renovation project to improve its energy performance, etc.

Design factors to consider:
Specific design conditions in different scenarios

Step Five: assess the performance of the design proposal

Model validation with some simulation program, the aim is to assess the performance of various design proposals. This step helps you test tour design results and make the design decisions.

Design factors to consider:
Simulation parameters inputs

Design tools to recommend:
DesignBuilder, Ecotect, or other EnergyPlus engine program.

Step Six: Evaluate the simulated results

Evaluate the design results quantitatively and qualitatively.

Design factors to consider:
Data performance, cost estimation or market investigation, etc. for quantitative evaluation; other influential elements for qualitative evaluation (Integration feasibility, Energy performance, Assembly and maintenance, Design aesthetics and space efficiency, etc.)

Step Seven: Finalize the design proposal

Finalize the design proposal based on all the simulation and evaluation results obtained. Take all feedback into account, develop the components details and think about the assembly process.

6.2 Future development

6.2.1 Cost estimates

As mentioned in the qualitative evaluation stage, cost is one of the most significant issues to research in the future. Despite the reduction in the cooling demand and energy consumption, several other fields may increase the overall cost, which may arise from the material price and manufacturing spend. Further research on cost estimates is necessary.

6.2.2 Difference in desiccant materials

This research mainly focuses on liquid desiccant materials, which are subject to the specific climate conditions of Shenzhen and other considerations in façade integration, like the compact size of cooling units and the ability and durability of liquid desiccant solution. In the future, this research is open to any possible desiccant materials, maybe the solid materials mentioned previously or even other new types.

6.2.3 Study on other solar energy systems

Currently, Photovoltaic panels and solar thermal collectors are the most used solar energy products, based on their mature market. However, there are several other solar energy systems noteworthy, for example, the parabolic solar thermal collectors and the solar battery systems in building applications.

6.2.4 Various façade typology

This design has only studied the more common and standard unitized aluminum-glass curtain wall system. Still, in the future, some other types of facades combined with solar cooling technology are also worth studying, such as double-skin curtain walls and closed cavity façade, or even plants façade, etc. These façade systems have excellent thermal performance, and it is believed that the research would also be valuable when integrated with SCT.

6.3 Experimental design guide

Step One	Check the background conditions	
Key consideration factor	**Sub-factors**	**Tools**
Specific climate zones by exact project location	Temperate climate Subtropical climate Tropical climate	Koppen climate classification
Local weather conditions	CDD (Cooling Degree Day), Temperature and relative humidity, solar load, wind and precipitation	Climate Consultant program, System Advisor Model
Step Two	**Define cooling strategy**	
Key design factor	**Sub-factors**	**Parameters**
Passive cooling strategy	Building orientation, Window to wall ratio Glazing type, Sun shading, Thermal mass, Night ventilation, Natural ventilation	Solar load data by orientation, WWR value, U value and g value, Data of sun shading charts
Active cooling strategy	Air-conditioning cooling, Water cooling, Fan cooling, Plant cooling, PV/ST driven cooling	Efficiency of A/C system, Efficiency of water evaporative cooling, airflow velocity, Efficiency of PV/ST, Receiving area of PV/ST
Solar cooling strategy	Themo-electric, Sorption, Desiccant cooling	Materials characteristics
Step Three	**Design the core systems**	
Key design factor	**Sub-factors**	**Parameters**
Solar energy system	Energy harvest system Energy storage system	Refer to **Error! Reference source not found.**
Cooling system	Cooling generators Cooling distributors Cooling delivery	Refer to **Error! Reference source not found.**
Façade system	Structural components Fixing system Cladding system Shading system Ventilators	Refer to **Error! Reference source not found.**
Step Four	**Define design scenarios (optional)**	
Key design factor	**Sub-factors**	**Parameters**
Various design scenarios	Different design proposals Potential users Design period Benchmark project or base case Comparative design results	Depend on various design conditions

Step Five	Assess the performance of the design proposal	
Key design factor	**Sub-factors**	**Parameters**
Energy simulation	Dedicated design period simulation (e.g. typical design period, summer design week, monsoon season, etc.), Annual simulation	Simulation parameters input based on the various design conditions' setting
Step Six	**Evaluate the simulated results**	
Key design factor	**Sub-factors**	**Parameters**
Quantitative evaluation	Solar fraction value Cooling demand Electricity consumption (in cooling) Renewable energy payback First investment cost	Based on the simulation results
Qualitative evaluation	Integration feasibility, Energy performance, Assembly and maintenance, Design aesthetics and space efficiency	Based on the simulation results
Step Seven	**Finalize the design proposal**	
Key design factor	**Sub-factors**	**Parameters**
Design feasibility issues	Depend on things learnt and summarized by previous steps	Based on the results of performance assessment

Table 6.1 Table of experimental design guide

7
REFLECTION

7.1 Purpose of the reflection

The primary purpose of this reflection is to show the lesson and learn in the whole process of the graduation project, including all the available experiences in topic selection, research, design, and conclusion phases. Also, through this reflection, the aim is to figure out how to move on for future work.

7.2 Topic selection

My research topic, solar desiccant cooling integrated façade design, aims to explore the design and development potential of solar desiccant cooling technology integration in façade systems, particularly for high-rise office buildings located in the hot and humid subtropical climate zones.

The selection of topic came initially from the needs. Buildings consume tremendous energy, and many are used for air conditioning. This situation is dire in the vast, hot-humid Southern China, the world's top energy consuming country and the top seller of air-conditioning equipment. Proposing alternatives to conventional air-conditioning systems through building product design is a significant motivation for choosing this topic, as this need is imminent. Furthermore, to what extent the design solution contributes to minimizing cooling energy consumption is also critical to know.

From the perspective of my personal growth, having been born in a hot and humid subtropical climate, I am very familiar with the impact of air conditioning on people's daily lives under such weather conditions. (Figure 7. 1) I also see the technical and social significance of this subject very clearly. This is why I chose this topic in the first place: I wanted to understand the technology and the logic behind it. However, as my studies progressed, if it could be developed into a full-fledged product that would enter the market, it would have a positive effect on the technology of the industry. In conclusion, studying this topic has multiple implications.

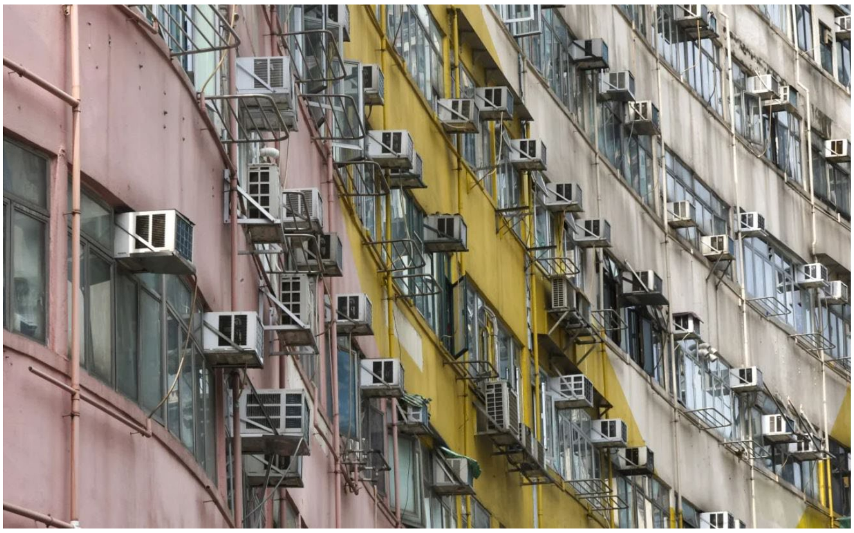


Figure 7.1 The air-conditioning life in hot-humid climate regions

7.3 Reflection on the research phase

The study began with two research gaps. Through extensive literature review and case studies, the two gaps in this field are lack of commercial maturity in the market and identified guides in the design practice. Hence, what's missing helps generate the initial statement of the problem, meanwhile, it pushes me to explore the possibilities to narrow those gaps.

The overall experience is that this is multi-disciplinary research. As the study continues, more and more knowledge of specific technologies has been obtained, such as the expertise of solar energy systems, various solar-driven cooling technologies, the knowledge on the conventional A/C systems with regular cooling modes, and the skills to simulate and evaluate the energy performance of building facades, etc. Of course, in the process of climate study, I have also received numerous useful information about climatic-responsive design approaches that I applied to the further design, like the passive and active cooling design strategies.

Technically, the most interesting findings are all about the desiccant enhanced evaporative cooling technology. Through some studies on experiment projects, I eventually understand why the desiccant evaporative cooling so well-fits the hot-humid climate conditions, that is because it utilizes the water evaporation effects to absorb the heat instead of environmentally harmful refrigerants to cool the air, it also effectively controls the air humidity in a constant level in terms of its high capacity of moisture removal by desiccant solution. Additionally, the finding of micro-porous membrane materials is also incredible. It makes the process of dehumidification easier and more economic.

This exploration process is exciting. I even went to search a lot of information about evaporative cooling to deepen my understanding; for example, there are a lot of DIY evaporative cooling air conditioning experiments on the Internet, as well as some desiccant evaporative cooling air conditioning products' videos, all of which make me deepen my interest in this technology.

Finally, another significant work of the research phase is that the study attempts to propose a holistic research framework about what to consider when designing a solar cooling integrated façade system. This framework consists of three core systems – solar energy systems (working as a power source), cooling systems (working as a cooling source) and facade systems (working as a multi-systematic vessel). Within each system, there are several different design factors and adjustable parameters. All these subdivisions are instrumental in the following design phase.

7.4 Reflection on the design phase

The entire design process consists of the pre-design stage mainly for climatic analysis, the design implement phase, and the design assessment phase. It is full of joy and challenges.

[a] Significant assistance by the design tools

Learning some new software helped me a lot during the design process in my design research. For example, learning to use the Climate Consultant software allowed me to clearly understand the climate characteristics of a city through visualization information, and the climate strategy provided by this software guided me well in the following design, such as the guidance of shading maps for shading device design. Another example is learning to use Ladybug, which can be converted into a visualization of solar radiation graphics; the user is conducive to reading the data and as a basis for design decisions. Of course, the simulation software design-builder is also very challenging, as it tests whether each design solution achieves the desired energy-saving effect.

All in all, through learning this new software, I have gained a lot of additional skills, but they also become an effective way to review their design results.

[b] Experience in different design scenarios

In the base case scenario, through the process of establishing a generic office building model, the most crucial gain is to have a deeper understanding of the relevant national and local design regulations, for instance, the limitation about WWR and WFR, and a series of design standards for office buildings in Shenzhen.

In the scenario of improved base case and design scenario A, the application of passive and active cooling strategies brings a lot of Unexpected Outcomes that somehow affects the design results. For example, when designing the sun shading elements, differences from façade orientations, seasons, solar radiation loads and even the peak time hours all have their impacts on the design decisions. What's more, in terms of FIPV design research, the area of PV on façade module varies that affect the generation of solar electricity, furthermore, the solution does not only depend on the surface area but also need to take the cost and aesthetical issues into account.

In design scenario B (including three sub-scenarios), when integrating the liquid desiccant evaporative cooling devices and solar thermal collectors into façade modules, there are many data constraints from those laboratory cooling devices. For example, some parameters from Elmer's equipment are missing, like the actual size of wet channels insider the dehumidifier and evaporative cooler, and some key parameters like the airflow rate of the supplied air, the Wet bulb effectiveness, the mixed processing air ratio, etc. All these missing data affects the calculation results of system performance.

The following diagram shows the design evolution among all scenarios. (Figure 7. 2)

Another critical limitation of design is that the existing evaporative coolers and dehumidification systems are fixed in form and do not allow various explorations—specific geometry results from different experiments with specific performance data. If multiple forms and sizes of evaporative coolers could be tested, more design options could be considered. However, this is totally beyond the scope of the façade design track and requires assistance from a multidisciplinary field.

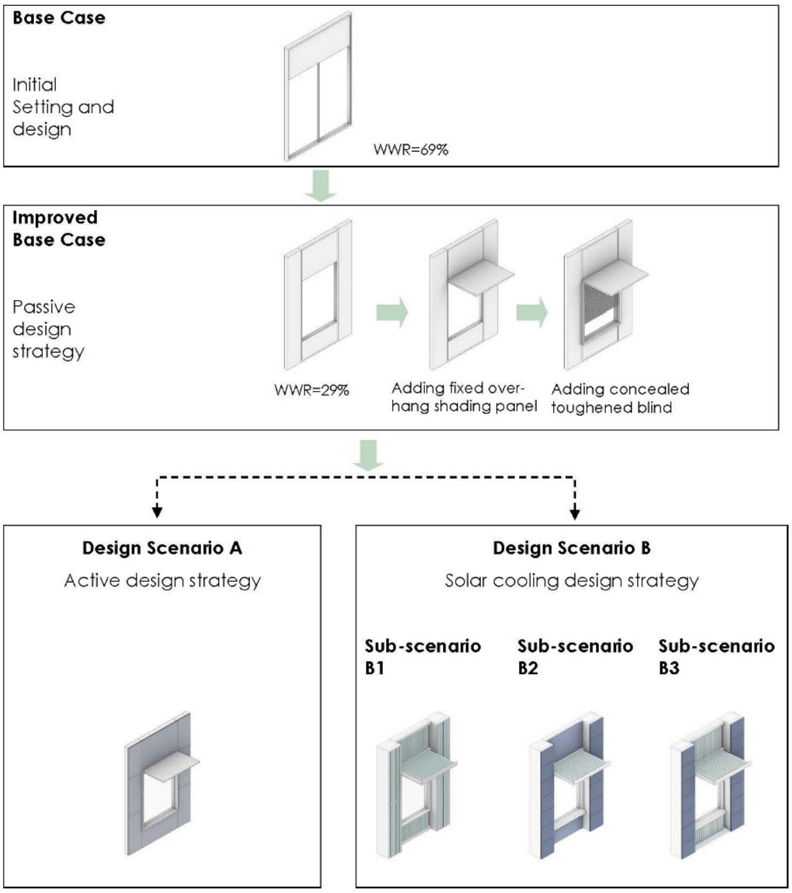


Figure 7.2 Roadmap of design evolution

7.5 Reflection on the performance assessment phase

[a] Simulation iteration: a good way to test the design results.

In the design assessment stage, simulation work is paramount when designing a novel type of facade and intending to test its performance. Using DesignBuilder v7.2 to simulate every design option provides data-driven insights that inform design choices and identify the issues that occurred in the design stage. For example, cooling demands simulation could show the cooling load reduction by different solutions, like lower WWR value, choosing the higher thermal resistance insulation materials, or even offering the higher heat-reflective coating to façade cladding, etc.

[b] Design evaluation: a good way to review the design results.

Design evaluation is an excellent process for reviewing the design. One hand, through quantitative evaluation, it is possible to know precisely how well the design results are performing, e.g., which design strategy is most helpful in reducing cooling demand, etc. For instance, it allows me to figure out how the size of the shading measures affects the building's thermal protection by simulation data. This process also makes it possible to see where the defects and constraints are clearly and to think about how to solve them.

On the other hand, qualitative evaluation gives me a holistic understanding of what I have learned and designed. It allows for an understanding of design results by considering aspects that quantitative measures might overlook. For example, regarding the design aesthetic aspect, it somehow influences the design decisions from a subjective point of view, e.g. façade proportions, or the impact of color poses on architectural features, etc.

7.6 Reflection on the mentorship

The most rewarding part of the months-long graduation design journey was getting to know several of my mentors. I want to express my sincere gratitude and respect to them. They provided me with varied, well-directed and instructive help and advice from their respective fields of study.

Professor T. Konstantinou is my first mentor whose major fields are in façade technology and energy engineering. Throughout the research and design process, she helped me a lot, especially on vital issues, and gave me specific directions. For example, during the literature review stage, she advised me to keep digging into what was already there in the research, what was missing, and what was particularly needed for in-depth research. As a result, two research gaps were identified during my research.

In addition, she suggested that I should think about how to apply the available lessons learnt from the literature review and case study, such as different design strategies, design factors to be considered and adjustable parameters, etc., to the subsequent design. As a result, I have planned several design scenarios, and for each of them, I decided to use different design strategies, to check whether those design results are as I expected. Obviously, the process is full of joy because I'm applying what I learnt in the research phase to the design practice process. Moreover, Professor T. Konstantinou also suggested me to treat this research project similarly as an ongoing façade product development, and to consider what the clients want. This direction really makes me think more about the technical feasibility aspects.
Professor E.R van der Ham is my second mentor who specializes in climate design and building physics. What is impressive is that he has given me a lot of specific perspectives on thinking during many exchanges. For example, at the early stage of design, he guided me on how to compare the energy consumption of centralized air-conditioning with that of separate air-conditioning using solar energy, and he suggested me to keep in mind that whether this technology would bring extra heat to the city and to the atmosphere. That's why he recommended me to read some of the urban heat island effect research.

Furthermore, Eric gave me lots of study “tips” which make me have deeper understanding with some knowledge. In this research project, he mainly helps me solve the problems on the climatic design and some HVAC engineering issues. For example, he suggested me to watch a video about an experimental liquid desiccant cooling installation, showing the tools preparation, working principle and the entire cooling process, and so on. That video gave me an extremely Intuitive Impressions on these technical logics. What's more, he also told me to learn some useful program tools, like showing me how to use the miller-diagram tool, a variant of the psychrometric chart, to understand the changes in temperature and humidity that occur in each process of evaporative cooling technology. All in all, I also learnt a lot of new skills from discussing with Eric.

PhD student H.Hamida is my third mentor who has a similar research topic to me. We talked a lot, as we often met at faculty. Since he was also involved in similar research, he frequently shared his research experience with me and told me about problems I might encounter. For example, the climate conditions with hot but dry in his research location is much different than mine, so he applied solar sorption cooling technology rather than desiccant technology. Hence, the different conditions gave rise to different design reactions. Regarding this directional difference, he often shares some relevant paper or other reading materials with me, which helps me effectively.

Moreover, He has been a great help to me in terms of software learning and academic writing. For instance, I am a green user of DesignBuilder program. To help me understand it systematically and efficiently, we met every week or two; he taught me some skillful techniques about how to 'well play' with this program and recommended I watch some tutorial videos so that I could master it in a short time. Besides, He gave me a lot of advice on writing academic thesis, such as adjusting the structure of contents and using academic writing terminology, and so on. All these details are helpful and appreciated.

In short, I had a great time with all three teachers because they are very enthusiastic and sincere, and I gained a lot from them.

7.7 Reflection on the self-discovery journey and the future development

Finally, I'd like to talk about my journey of self-discovery. This research topic was challenging, because there was a lot of knowledge and content that I was not familiar with, such as desiccant cooling technology, such as solar energy transition systems, etc. So, within a lot of times, I was on a journey of self-discovery.
I went through a lot of study material, read a lot of papers on the subject, and even found lecture notes and videos I had studied on the climate design course to review. I made numerous notes during this process, and it was very touching to look back at them again. Because this is also a process of discovery that fills my knowledge gaps.

In the process of designing, I also made many sketches that quickly translated my design ideas into some concrete concepts. Furthermore, sometimes I double-checked the accuracy of some simulated data by manual calculations, which made this journey a training exercise for me.

Parts of the notes and sketches are shown in Figure 7. 3

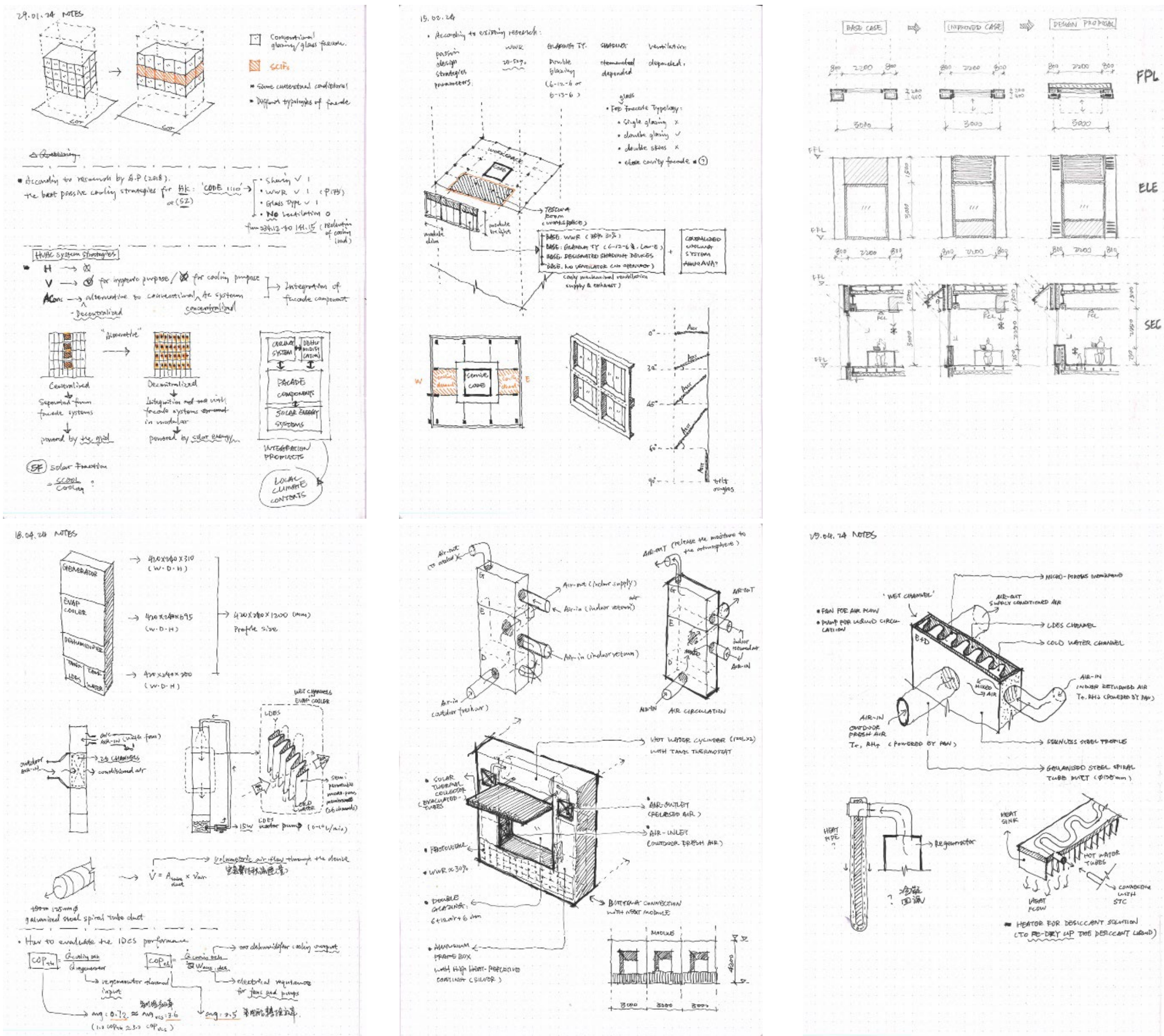


Figure 7.3 Notes and sketches for research project

For future research, I'd like to expand the scope of research in the following areas.

First is about cost estimates. There is no way that products and technology can be separated from cost considerations. I was wondering how costly the design proposal would be if it goes towards the manufacture and construction phase, because I do understand the material prices, implementation feasibility, and market acceptance are partially subject to the economic conditions.

Second is various façade typologies. This research project has only studied the more common and standard unitized aluminum-glass curtain wall system. Still, in the future, some other types of facades combined with solar cooling technology are also worth studying, such as double-skin curtain walls and closed cavity façade, or even plants façade, etc. These façade systems have excellent thermal performance, and it is believed that the research would also be valuable when integrated with SCT.

Finally, is to research other types of solar cooling technologies, such as the other four most promising SCT mentioned in this thesis. And meanwhile, I will keep on eye on this field to expect more new and sustainable technologies coming.

For my personal future, I am willing to continue to work on this topic and field on façade technology. It would be fascinating to see the technology I've been working on one day become a marketable, manufactured, and built technology. It is one of the sustainable façade technologies that has positive implications for building performance and the built environment.

8
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APPENDIX

Appendix 1

Calculation of cooling electricity consumption for design scenario B1-B3

Constant calculation parameters:

Electrical equipment for one cooling unit	Max. power consumption	Description
Fan 1	23 W	Axial fan for dehumidifier
Fan 2	23 W	Axial fan for evaporative cooler
Fan 3	23 W	Axial fan for regenerator
Pump 1	15 W	Pump for cold water circulation
Pump 2	15 W	Pump for desiccant solution circulation
Pump 3	99 W	Pump for hot water circulation

(The table data above are based on the equipment list shown in Table 2. 4)

Other parameters	Value	Description
Operation hours per day	8.5 h	8h full load (working hours) with 1h half load (lunchtime)
Active days per week	5	Weekdays in the summer design week
Number of cooling unit	6	Align with the number of façade modules for the target room
Cooling electricity intensity by conventional A/C	0.52 kwh/ m^2	Data refer to Table 4. 1
Room area	129.14 m^2	Calculated area of the target room (data used in DesignBuilder program)

[a] Calculation for sub-scenario B1

Cooling electricity consumption by fans:
23w x 8.5h x 3 = 586wh $\approx$ 0.59 kwh/d

Cooling electricity consumption by pumps:
15w x 8.5h x 2 + 99w x 8.5h = 1096wh $\approx$ 1.10 kwh/d

As B1 can achieve 100% cooling demand of the target room, therefore the total cooling electricity consumption during the summer design week is equal to:

(0.59 kwh/d +1.10 kwh/d) x 5d x 6 = **50.7 kwh**

[b] Calculation for sub-scenario B2

As B2 can only achieve 53% cooling demand of the target room, but the rest 47% is assumed to be covered by the conventional A/C system, therefore the total cooling electricity consumption during the summer design week is equal to:

50.7kwh + 129.14 m^2 x 47% x 0.52 kwh/ m^2 = **82.26 kwh**

[C] Calculation for sub-scenario B3

As B3 can only achieve 95% cooling demand of the target room, but the rest 5% is also assumed to be covered by the conventional A/C system, therefore the total cooling electricity consumption during the summer design week is equal to:

50.7kwh + 129.14 m^2 x 5% x 0.52 kwh/ m^2 = **54.06 kwh**