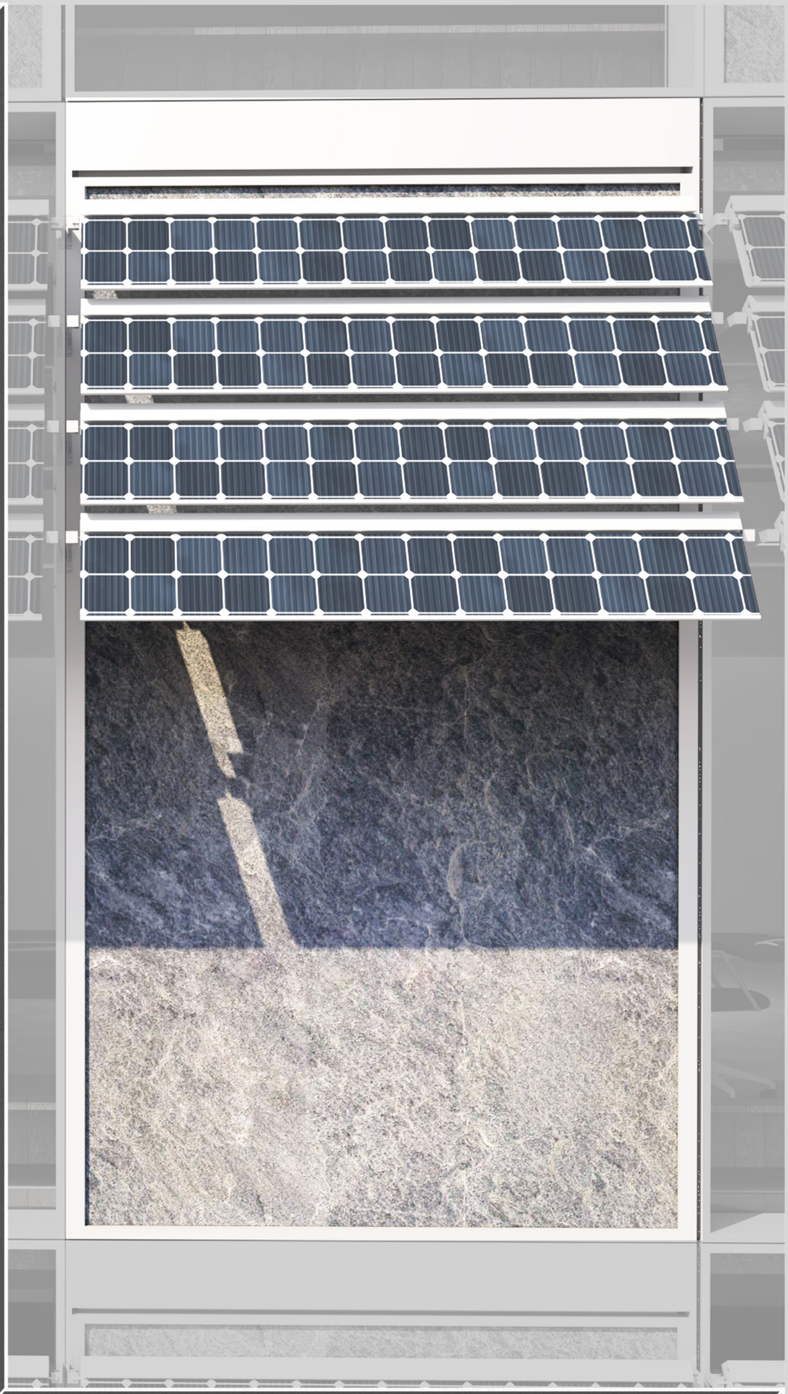
TE INTEGRATED FACADE



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JULY 2019

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TE integrated facade

Design of an integrated facade for a typical office building in the semi-arid climate of Tehran using thermoelectric technology powered by PV panels for space heating and cooling.

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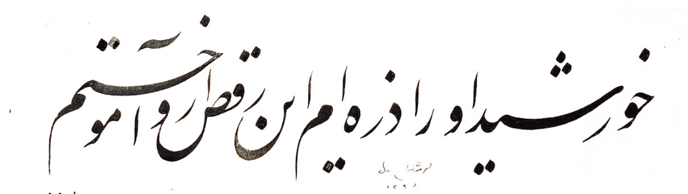

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Abstract

Building industry consumes around 50% of the world's electricity consumption and space heating and cooling plays an important role in ozone depletion and global warming potential. Solar cooling technologies promise more sustainable approaches with reliance on solar energy as a renewable energy source. Thermoelectric technology is a promising solar cooling technology that is powered by electricity from PV panels and has been researched in recent years for investigation of potentials for building and façade integration. These small devices create a temperature difference between the two sides when applied to electricity and therefore, can be used in generating both cold and heat for conditioning of spaces. As an example of arid to semi-arid climates, Tehran has been selected as the context of this project. This graduation project focuses on designing an integrated façade product that uses thermoelectric technology for providing cooling and heating demands of an office building in Tehran. One of the main challenges of this design was the low performance of the TE system that could be increased in a few ways among which decreasing the temperature difference created at the two sides is the most crucial.

An office building was initially selected to represent typical offices in Tehran and a few passive strategies including reductions in WWR, changing glazing type, applying insulation and reducing infiltration rate as well as using natural ventilation were implemented on this office model. The implementation of these passive measures leads to a decrease of 55 percent in the annual heating and cooling loads and 39 and 49 percent in the heating and cooling design capacity, respectively. Having this passive model, a ventilation integrated active cooling and heating system was developed that functions like a heat recovery system and uses extracted ventilation air to cool down the temperature of the hot side in summer. Fresh conditioned air is provided in this system through the cold side of the façade via an underfloor air distribution system. A unitized façade product was then developed to accommodate this integrated concept and it this TE system was proved to be flexible in terms of design and integration.

To evaluate the performance of this façade, a comprehensive model was developed, and a code was written in EES to solve the equations simultaneously. A baseline model was set to simulate a summer peak situation and as a result, COP, electricity consumption, and temperature difference values were obtained. Next, all the variables in the model were studied and optimized to obtain the best results for every time step of the year. The annual simulations showed that average COP of 1 to 1.3 and 2.1 to 3.0 could be obtained for summer and winter conditions. Feasibility aspects of this façade unitized system were then studied and compared to other solar cooling technologies to obtain a better understanding of limitations and promises of this façade. It was found out that although in terms of performance and cost the TE façade can compete with other solar cooling technologies, issues such as weight, size requirements, and noise might affect its application in some cases.

Acknowledgment

I am truly grateful for the opportunity I was given to study in such a great environment with so many talented, hardworking, and inspiring people. The last two years past in a blink and yet memories of it will remain for years to cherish. I became a stronger person who although still struggling, have begun to believe in herself.

I want to express the deepest gratitude to my supervisors, Alejandro and Eric, who have been among the kindest and most caring mentors I have had. They have helped me through my confusions and excitements to become a better designer and put more effort into what I want to achieve.

I am the luckiest to have the best friend, best supporter, and the best husband, Mohamad by my side, without whom I would not be here today.

I would like to thank my parents, who made me the person I am, my dearest and youngest brother, Alireza who has always been there to talk to me and my mother and father in law, who truly believed and trusted in me. I would also like to thank my friends in Iran and the new one I made here in the Netherlands. I have been blessed not to spend all my joyful times here alone.

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1 Introduction

Throughout history, buildings have intended to provide people with thermal comfort by using passive strategies and available resources. With advances in chemistry in the 19th century the first air-conditioning units were introduced and ever since there has been a growing demand for heating and cooling as comfort standards have increased, financial capabilities have grown and more activities are included in our lives partly due to economic growth(Eicker et al. 2015; IEA 2018). Our role as architects and building engineers gains more importance as today, we face disastrous consequences of wasteful management of resources, the careless release of greenhouses gases and ozone-depleting chemicals into the environment. The building sector plays an inevitable role in the prevention of global warming. In this field, controlling the heating and cooling demands of buildings and providing them with the renewable resource as energy input could play a key role in assuring an existing and safe planet.

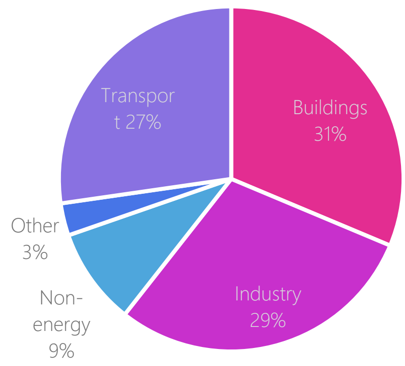


Figure 1 Share of building industry in energy consumption (IEA 2018)

1.1 Background

Around 30 percent of the world delivered energy the and more than half of the electricity consumption was in the building sector in 2015 of which 18% to 73% is consumed by heating and cooling (Urge-Vorsatz et al. 2015). As reported by the International Energy Agency (IEA 2018), energy efficiency in heating and cooling can save up to 25 and 20 percent of the energy consumption in the building sector by 2040 respectively.

In a country like Iran, rich with natural gas and oil reservoirs and being the 8th producer of CO2 in the world (IEA 2018), it is not surprising to find out that 35.8% of energy consumption was in the building sector in 2013 (Affairs 2013). The authorities in Iran have tried to reduce the energy consumption in the building sector by assigning the 19th issue of National codes to Energy efficiency in buildings in 1991.

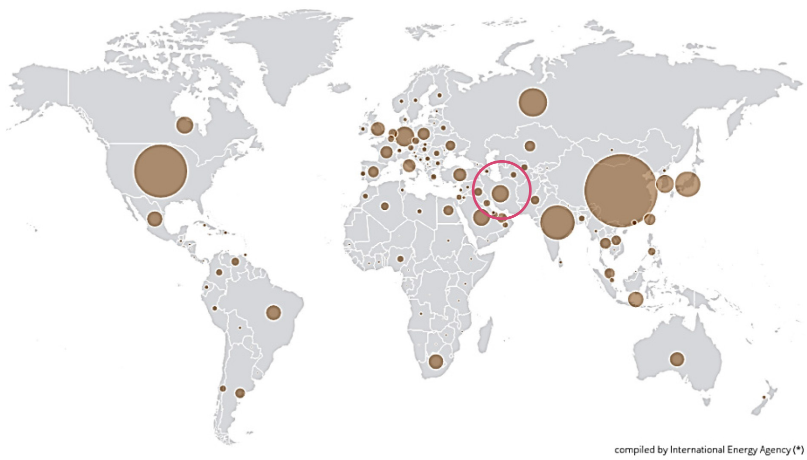


Figure 2 Global CO2 emissions from fuel combustion in 2016, for Iran it is 563.4 MtCO2. (Source: http://energyatlas.iea.org/#!/tellmap/1378539487)

Despite efforts to reduce energy demands, there is a growing concern about energy consumption in Iran which is mainly due to economic growth, poor resource management, substantial subsidy programs offered by the government and lack of awareness. Moreover, the growing trend in the peak hour demand imposes enormous investment costs on building new power plants to overcome the power outage during peak hours.

Iran's construction market is expected to continue relatively steady growth at annual growth rate (CAGR) of 6.1% from 2016 to 2020 and according to Iran investment monthly magazine, 54 percent of the houses in Tehran in 2015 were buildings under five years of age. Therefore, new buildings offer a lot of room for improvements and energy-oriented designs to reduce the energy consumption of heating and cooling and offer opportunities for the utilization of renewable resources.

The government of Iran has shown interest in renewable resources as a more reliable source to improve energy security and meet the growing electricity demands since the 1950s. According to Tavanir, Power Generation, Transmission, Distribution, and Management Company, Iran had plans in 2016 to generate 10 percent of its electricity demands from renewables within five years. Hydropower, wind power, and solar power are recognized as the most promising alternatives for fossil fuels in this country.

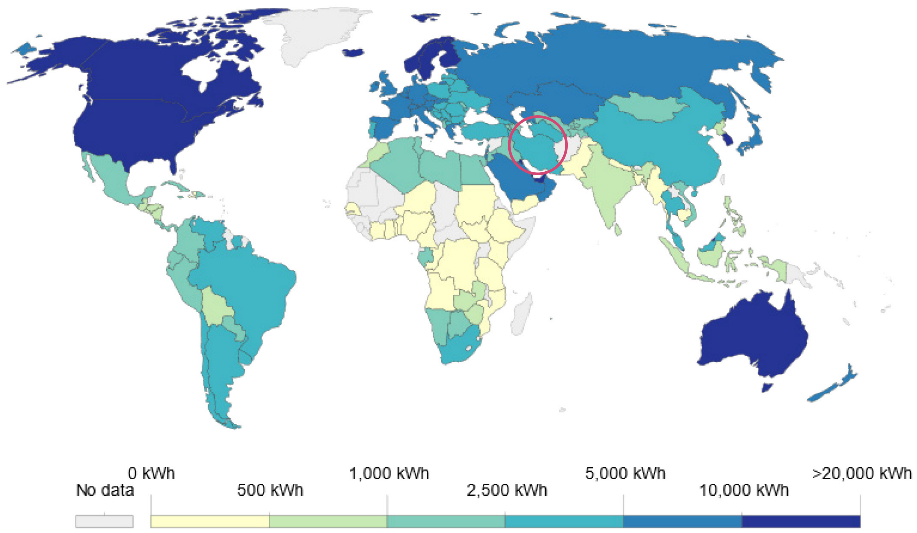


Figure 3 Electrical power consumption per capita, measured in kilowatt-hours (kWh) per capita. This is calculated as national electricity availability (production plus imports minus exports and transmission losses) divided by the population (not the population with access to electricity) in 2014, which is 2985(kWh) for Iran. (Source: http://data.worldbank.org/data-catalog/world-development-indicators)

Among renewable resources to minimize reliance of gas and oil for space heating and cooling, solar energy displays a very good potential considering the high amount of solar radiation that hits this region. This gains more favor when noting that peak hour demands for cooling coincide with a peak in electricity generation of PV panels.

Thermoelectric (TE) technology has the advantage of being very compatible with PV panels and easily switchable between cooling and heating and being refrigerant free depicts a promising potential for application of this technology in the building industry. Moreover, its silent, flexible, and compact natures make it very suitable for façade application as an active system to obtain indoor thermal comfort.

1.2 Problem statement

The main problem that this research is aiming to solve is to find out whether an integrated façade powered by PV panels can cover the space heating and cooling loads of a typical office building located in the semi-arid climate of Tehran implementing Thermoelectric technology. The outcome of this project is with current efficiencies of commercially available TE and PV technologies which are subject to advancements in future, and better upcoming efficiencies will contribute to higher chances of this system to compete with conventional heating and cooling systems.

1.3 Main objectives

The main objectives of this graduation project are as following:

- Development of a typical office model in Tehran based on the current trends in architectural practices, the climatic conditions, indoor thermal comfort, and municipality guidelines. This typical office model then can be further optimized to lower the heating and cooling demands by implementing certain passive measures that may also have an impact on the performance of the active system.
- Developing an integrated façade system using TE modules powered by solar cells that provide the building with enough heating and cooling. Improving the efficiency of this system by enhancing the performance of the module itself, and establishment of its relation to the façade and the ventilation system of the building could make a step in proving the feasibility of such solar-driven technologies.
- Although the main evaluation goal of this study is the performance, other aspects such as feasibility could be studied to examine the potentials and drawbacks of this system.

1.4 Boundary conditions

The climatic conditions of this study are limited to cold semi-arid climate as Tehran has been selected to analyze heating and cooling loads. For the selection of TE modules, commercially available ones are selected due to availability on the market and designing of the TE module itself is limited to selection of the product, system sizing, number of the required modules, electrical connections, applied power voltage, and intensity. Prototyping and testing in real conditions are out of the scope of this research.

1.5 Research question

The main research question is: "How could an integrated façade with TE active heating and cooling powered by PV panels be designed to cover the heating and cooling loads of a typical office building in a cold semi-arid climate like Tehran?"

1.6 Sub-questions

The sub-questions follow as:

- What is the minimum cooling/heating loads in a typical office building in the semi-arid climate of Tehran to achieve thermal comfort?
- What is the state-of-the-art advancements in Thermoelectric technology in the built environment, and what are the criteria that would affect the performance of the thermoelectric cooling/heating system?
- How could the performance be enhanced by the arrangement of the TE module itself, with the façade and in a more integrated system with the whole building?
- How building and façade passive strategies such as s utilizing the ventilation system of the building can be applied to increase the efficiency and accommodate meeting peak hour demands?
- What are the most effective passive measures that help in reducing the cooling/heating loads? And which of them would have a positive impact on the performance of the active cooling system?

1.7 Approach and methodology

The graduation project starts with literature studies on Thermoelectric technology, climatic conditions, thermal comfort criteria, and passive measures to reduce heating/cooling demand.

The design process then starts with developing a typical office in Tehran based on case studies, accordance with National codes and municipality guidelines and optimization of this model with selected passive measures that also contribute to better efficiency in the active heating and cooling.

The reduced cooling/heating loads will be calculated using commercial software, considering the acceptable indoor comfort range. Conceptual design of the active system would revolve around the design of the thermoelectric module itself, its relationship with the façade design and PV panels, implementation of other elements such as PCM and with the building such utilization of the ventilation system to increase the efficiency. Case studies and simulations would be used to measure and implement these façades and building strategies.

Finalization of the design concept requires closer studies in sizing, detailing, and other design specification. Evaluation based on certain criteria could help to measure the performance, feasibility, and sustainability of this technology.

Table 1 Approach and methodology used in this project for research, design, and evaluation stages.

Research	Design	Evaluation
Thermoelectric technology	Baseline model	Simulations/comparison
PV technology	Optimized model	Performance
Climatic conditions	Load reduction	Energy consumption
Thermal comfort criteria	Active cooling/heating	Feasibility
Typical office model	On façade level	Cost-effectiveness
Passive strategies:	TE module design	Building integration
WWR	PCM integration	Availability
Shading	Facade integration	Now or the future?
PCM	Heat sink	Sustainability
Ventilation	PV integration	Embodied the energy
Night ventilation	On building level	Life cycle analysis
Thermal insulation	Ventilation	
	Delivery system	

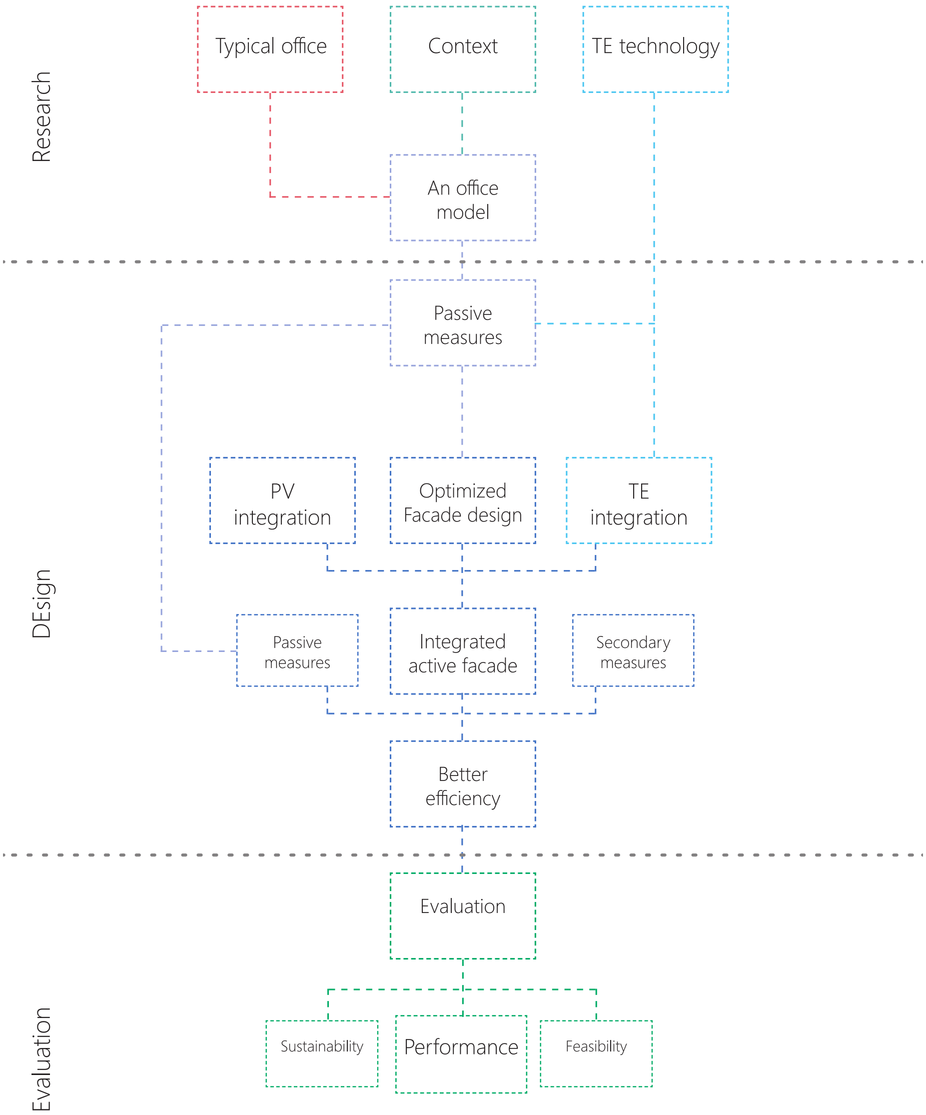
1.8 Relevance

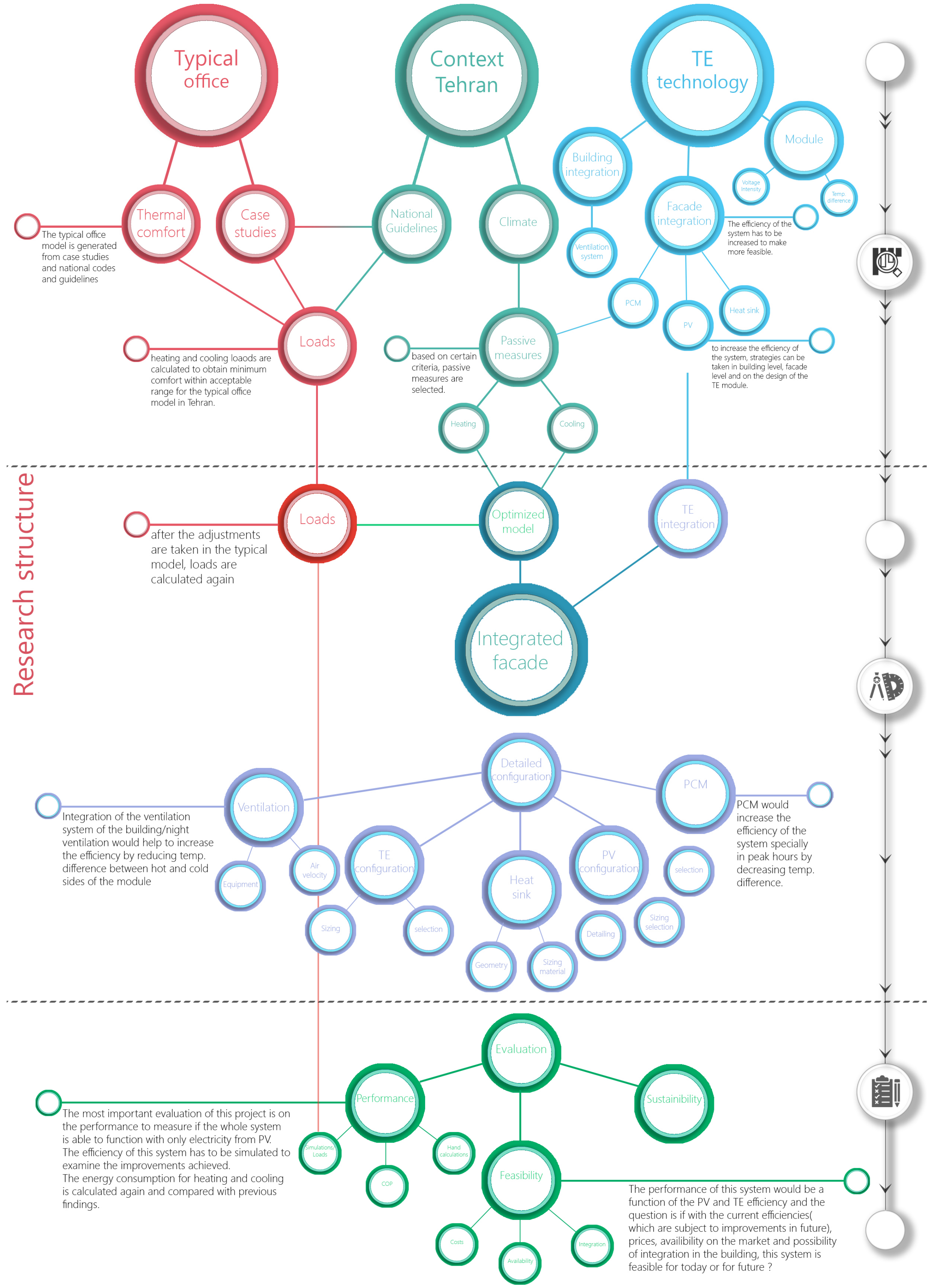
The goal of this project is to cover as much heating/cooling loads as possible with solar energy by implementing Thermoelectric technology on the façade of an office building in Tehran.

Although this research is bounded with a semi-arid climate and as a worst-case scenario office building, if proven to reduce energy consumption, reliance on non-renewable resources, the outcome could be extended to all building types in similar climatic conditions.

1.9 Research structure

This graduation project consists of three steps of research, design, and evaluation, as shown in the following schemes.





Research structure
Typical office
Context Tehran
TE technology
Building integration
Module
Voltage Intensity
Temp. difference
Facade integration
The efficiency of the system has to be increased to make more feasible.
Ventilation system
Thermal comfort
Case studies
National Guidelines
Climate
The typical office model is generated from case studies and national codes and guidelines
PCM
PV
Heat sink
Loads
heating and cooling loaods are calculated to obtain minimum comfort within acceptable range for the typical office model in Tehran.
Passive measures
based on certain criteria, passive measures are selected.
to increase the efficiency of the system, strategies can be taken in building level, facade level and on the design of the TE module.
Heating
Cooling
Loads
after the adjustments are taken in the typical model, loads are calculated again
Optimized model
TE integration
Integrated facade
Detailed configuration
Ventilation
Integration of the ventilation system of the building/night ventilation would help to increase the efficiency by reducing temp. difference between hot and cold sides of the module
PCM
PCM would increase the efficiency of the system specially in peak hours by decreasing temp. difference.
Air velocity
Equipment
TE configuration
Sizing
selection
Heat sink
Geometry
Sizing material
PV configuration
Detailing
Sizing selection
selection
Evaluation
Performance
Sustainibility
The most important evaluation of this project is on the performance to measure if the whole system is able to function with only electricity from PV.
The efficiency of this system has to be simulated to examine the improvements achieved.
The energy consumption for heating and cooling is calculated again and compared with previous findings.
Simulations/ Loads
COP
Hand calculations
Feasibility
The performance of this system would be a function of the PV and TE efficiency and the question is if with the current efficiencies(which are subject to improvements in future), prices, availibility on the market and possibility of integration in the building, this system is feasible for today or for future ?
Costs
Availability
Integration

2 Contextual Study-Tehran

2.1 Cold semi-arid climates

Semi-arid climates are characterized by the low levels of precipitation (not as low as in deserts) that they receive during a year. Based on the Köppen climate categorization, Tehran is classified as Cold semi-arid, BSk.

Cold semi-arid climates are located further from temperate zones and usually border humid continental or Mediterranean climates. People living in these climatic zones experience hot and dry summers and despite hot semi-arid climates cold winters with chances of snowing. Another specific characteristic of cold semi-arid climates is the large temperature swings between day and night, dry summers, relatively wet winters, and even wetter springs and autumns.

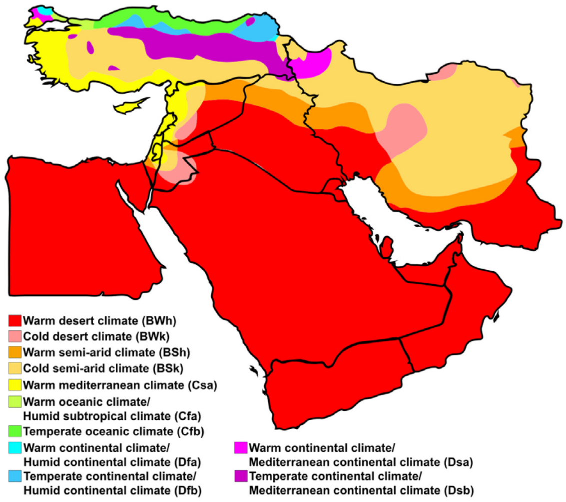


Figure 4 Middle East map of Koppen climate classification.

2.2 Climatic characteristic of Tehran

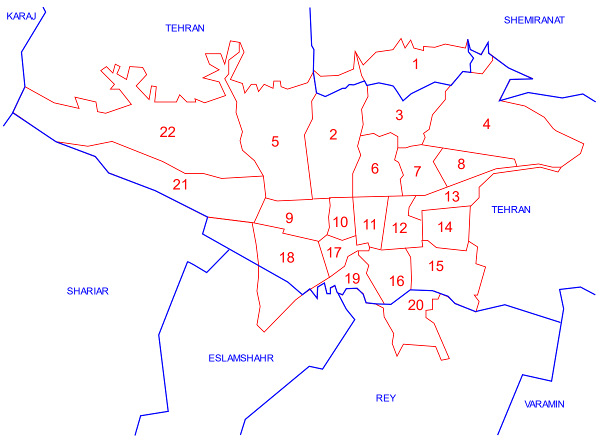


Figure 5 Administrative 22 divisions of the city of Tehran. In blue: Limits of the counties. In red: Limits of the municipal districts.

Iran is in Southeast of Asia, the Middle East with an Area of 1628763 km2. The capital is Tehran with 8.69 million populations. Tehran as the second-largest metropolitan area in the Middle East consisting of 22 districts.

According to climatic records, Tehran is a four-season city that portrays mild springs and autumns, long, hot and dry summers and short but cold winters. With different altitudes in the city, northern and southern parts experience different microclimates, with higher altitudes being slightly colder.

The average annual rainfall is not higher than 230 millimeters, and during dry hot summer days, the average maximum and minimum temperatures are 29.8degC and 16.5degC with highest values in July. The coldest month is January with an average minimum and maximum of 0degC and 8degC, and winters are during the three months of December, January and February with a minimum average of 1.6degC and a maximum average of 9.6degC. The Mean maximum temperatures of summer and winter are 2degC and 10.6degC respectively, and the Mean minimum temperatures of summer and winter are 16.5degC and 2.3degC respectively.

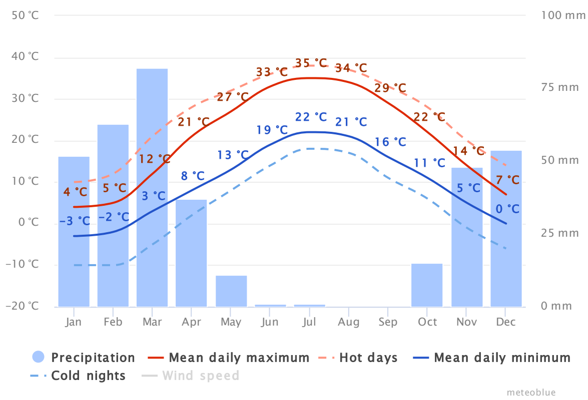


Figure 6 Average annual temperatures and precipitation levels of Tehran, source:meteoblue.com

As shown in Fig 7, the greatest number of days in which temperature falls below 0degC and above 30degC is in January with 15 days and July with almost 21 days respectively.

March is the wettest month with 85mm of rainfall, and the highest relative humidity values are in January with 63% and the lowest in June to September with 22%.

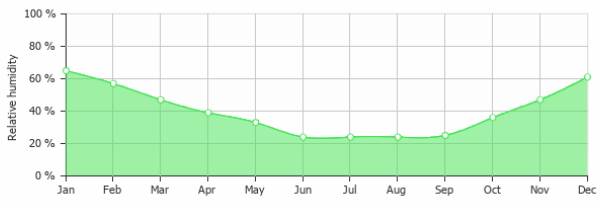


Figure 7 Average relative humidity in Tehran, source: www.weather-and-climate.com

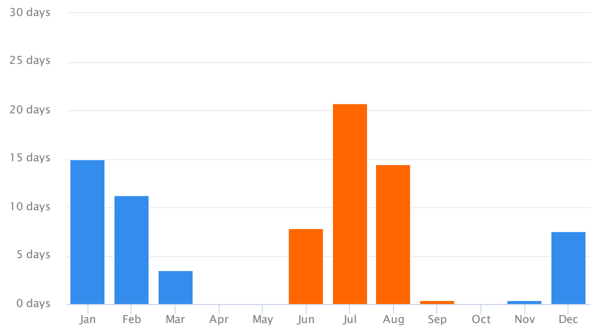


Figure 8 Number of days below 0 and above 30 degree of Celsius in Tehran, source:meteoblue.com

Availability of sun during a year is relatively high; the mostly sunny days are in June to September with 26 to 28 days. Moreover, as depicted in Fig. 9, the wind rose diagram shows the prevailing wind is from the South and the windiest month in May.

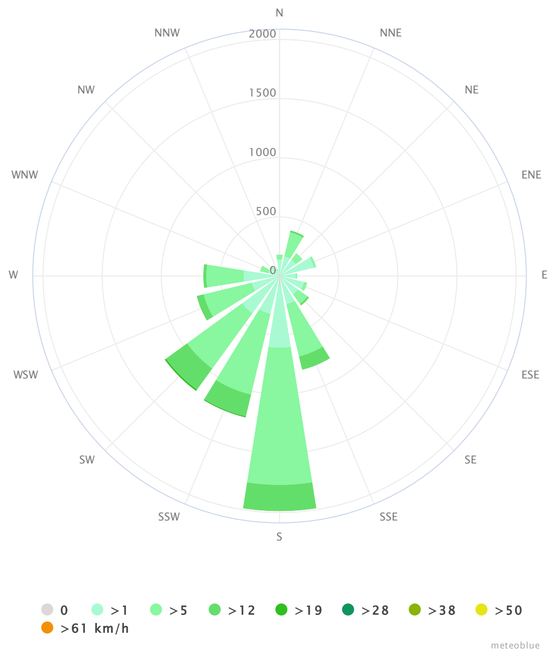


Figure 9 The wind rose diagram showing the prevailing wind direction in Tehran, source:meteoblue.com

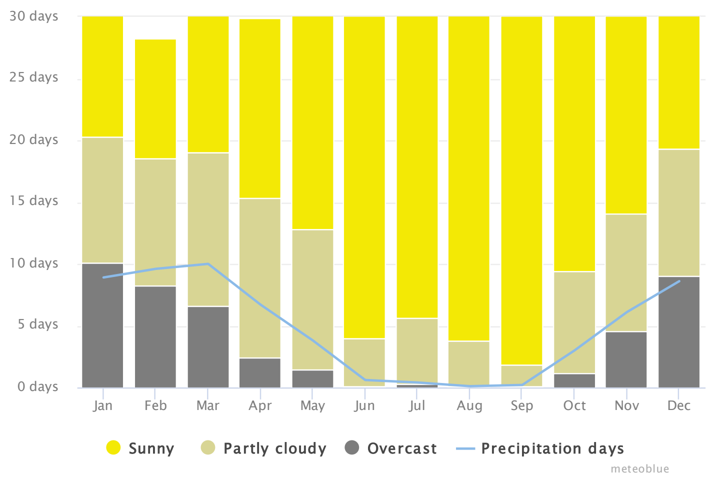


Figure 10 Cloudy, sunny, and precipitation days in Tehran, source:meteoblue.com

The annual global radiation shows good potential for harvesting solar energy on South-West and South-East, especially in summer.

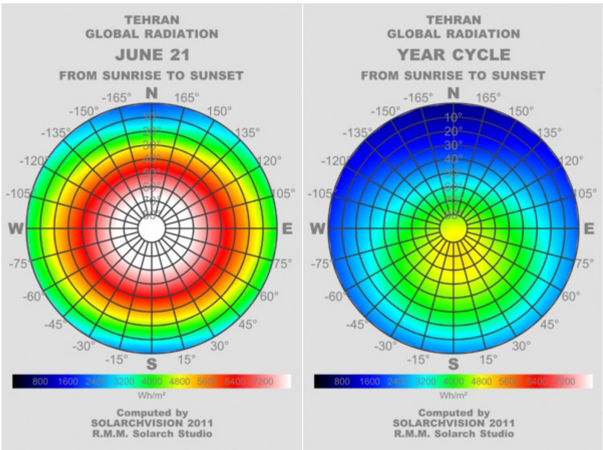


Figure 11 Left: Total Solar Radiation on Different Directions and Slopes in June and right: Yearly Solar Radiation on Different Directions and Slopes.

2.3 Energy consumption: heating and cooling in Tehran

Iran holds about 17.8% of the world's total reservoirs of Natural gas, which ranks as the second country after Russia. Per capita consumption of natural gas, oil and petroleum product in 2013 were 5.9 and 1.6 times the building industry and 1.8 times higher than that of global average consumptions and considering the growth of 2.9 from 2012 to 2013 in per capita energy consumption, it is expected to be a growing concern (Iran and World Energy Facts and Figures, 2013)

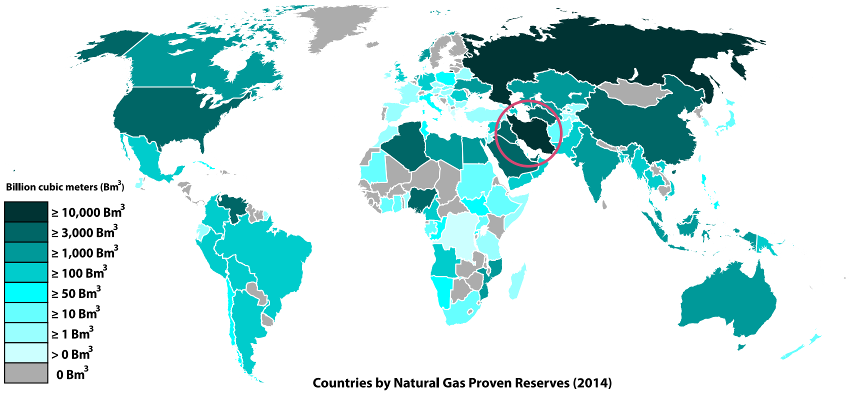


Figure 12 Iran's place among other countries by natural gas proved reserves (2014) source: https://en.wikipedia.org/wiki/Natural˙gas˙by˙country

2.4 Building regulations and codes

The Ministry of roads and urban development of Iran have published 22 chapters on codes and regulations for buildings of which chapter 19th is on energy conservation. In addition, chapter 13, 14 and 18 representing electrical equipment, mechanical equipment and sound and thermal insulation respectively may be found useful in the context of this study being related to façade, passive measures to reduce the energy consumption of cooling/heating equipment.

Moreover, the municipality of Tehran has published guidelines for façade design that has to be studied where modeling a typical office in Tehran. These guidelines may differ for each city.

An overview of these regulations is presented in chapter 5 and 6, and references will be made to them in the design stage if necessary.

3 Thermoelectric technology

With the discovery of thermoelectricity at the beginning of the 19th century by Thomas Seebeck, it was proved that when two different electrical conductors have different temperatures at their junctions, there will be an electrical current produced to maintain the temperature difference. Later French physicist Jean-Charles Peltier showed the opposite; by applying the electrical current difference in temperature will be created across the two junctions. By 1950s thermoelectric technology started its rapid development by employing semiconductors when the basic science of thermoelectric materials became well-established (Cosnier, Fraisse, and Luo 2008).

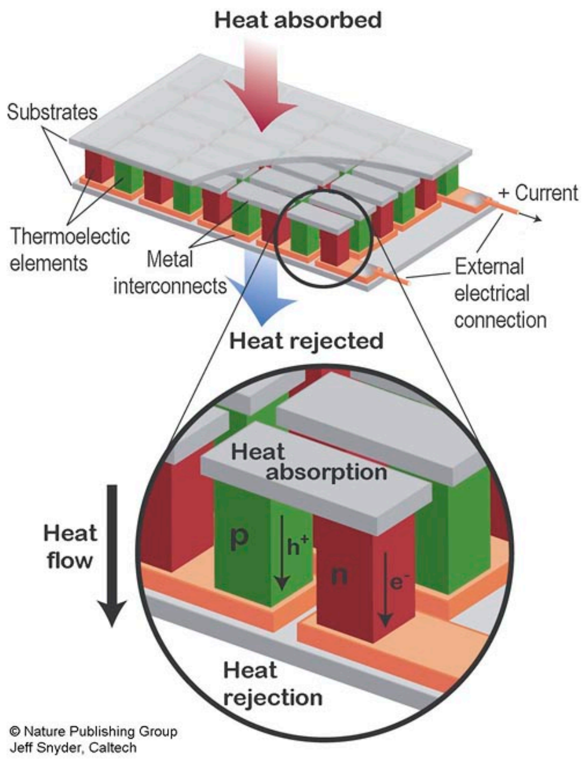


Figure 13 An overview of TE technology, source: http://thermoelectrics.matsci.northwestern.edu/thermoelectrics/engineering.html

3.1 Why thermoelectric?

Following the ambition of developing sustainable solar cooling/heating with minimum reliance on fossil fuels, thermoelectric technology is regarded as one of the most promising technologies while it has been commercially and widely available in consumer goods for decades such as portable camping coolers, electric iceboxes, dish warmers and computer CPU coolers, in the military sector and NASA. However, building and especially façade applications are still limited to a few prototypes (Prieto et al. 2017; Cosnier, Fraisse, and Luo 2008).

In this section, a few of the reasons for the selection of this technology are reviewed, and reasons are provided for second thoughts on applications in the built environment.

3.1.1 Advantages-disadvantages

There are many advantages to this technology that make it favorable for further exploration in the field of the built environment. One of the main advantages is the absence of mechanical moving parts and working fluids, which make it free of noise, harmful refrigerants, and reliable. Since they are powered by direct current, no converters are required if the source of electricity is PV panels making this technology a good potential for BIPV integration. Simplicity in operation and compact sizes both contribute to flexibility of the technology, rendering it as a good candidate for façade integration (Zhao and Tan 2014; Prieto et al. 2017; Cosnier, Fraisse, and Luo 2008; Prieto et al. 2018).

On the other hand, a certain drawback is a low efficiency especially compared to vapor compression air conditioners in addition to high costs. Heating COP, however, is higher than cooling, which promotes its application in heating-dominated climates (Zhao and Tan 2014; Riffat, Ma, and Qiu 2004).

As presented by (Prieto Hoces 2018) in the following figure, technical feasibility, physical integration, durability, and easy maintenance are three most important factors that make this technology a promising substitute for conventional cooling/heating. Whereas, performance as the worst drawback besides aesthetics and availability are the main issues that have caused thermoelectric technology to suffer from lack of attention in the building industry.

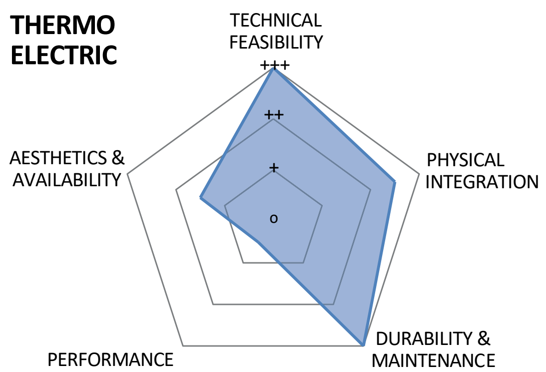


Figure 14 Qualitative assessment maps for the facade integration potential of selected solar cooling technologies. (Prieto Hoces 2018)

3.1.2 In this climate

The idea of implementing solar technologies for cooling of buildings is favorable since the peak hours coincide with the electricity generation peak. In Tehran, the annual solar radiation is around 6500 MJ/m2 (Nejad 2015), which indicates a good potential for PV installations.

According to a research done by (Prieto et al. 2018), one of the recommended cooling solar technologies is thermoelectric cooling in climates similar to Tehran with dry summers, such as Athens and Lisbon (Prieto et al. 2017). Furthermore, since heating is as important in the climate of Tehran as cooling, thermoelectric technology seems like a suitable candidate since it can switch to heating easily by changing the direction of the current.

Finally, the efficiency of the thermoelectric heating/cooling system is the result of the efficiency of the thermoelectric modules and PV panels, which is very likely to improve by future advancements in these technologies. Some papers suggest with a breakthrough in thermoelectric materials this technology will gain an advantage over conventional vapor compression techniques. Therefore, this research will seek to examine the current and future possibilities offered by employing this system, which is very promising by far.

3.2 Mechanism

3.2.1 Overview

When electrical current is applied to two dissimilar metals, a temperature difference will develop across the two junctions, and this makes one junction cold and the other hot. The working mechanism of this system is very simple; when electricity is applied to a typical thermoelectric module made of an array of Bismuth Telluride thermocouples connected electrically in series and thermally parallel, one side of the module absorbs heat, and the other side releases heat. By switching the current, this mechanism is reversed and therefore, cooling and heating are both achievable (Zhao and Tan 2014).

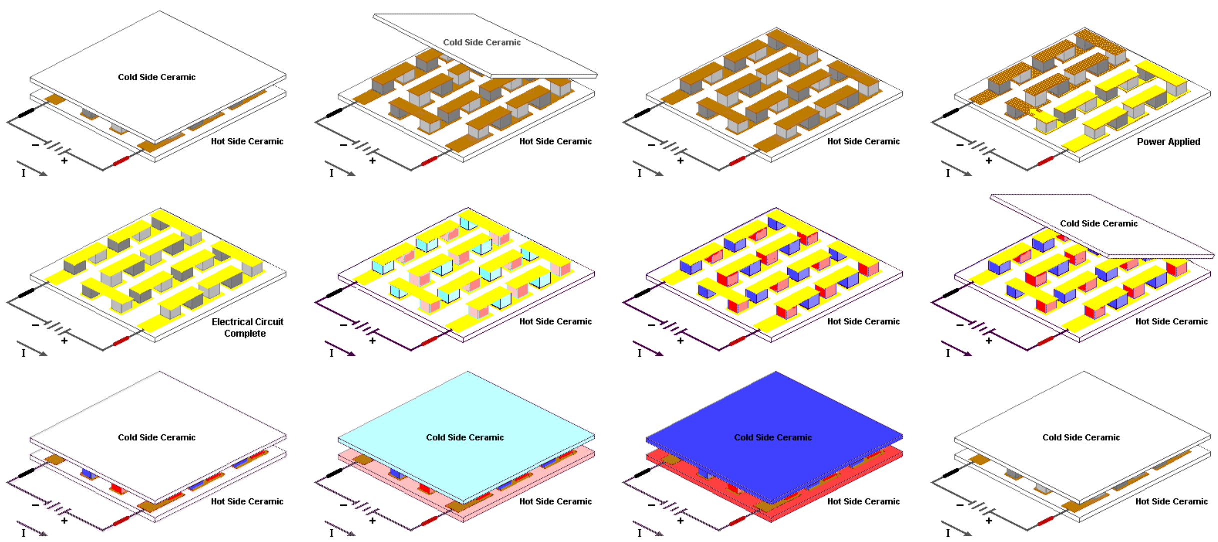


Figure 15 Step by step mechanism of TE technology, source: https://www.electracool.com/moduleworking.htm

3.3 Increasing the performance

The COPs reported for thermoelectric refrigerants are usually less than 0.5 with a temperature difference of 20-25degC and to be able to compete with vapor compression air-conditioners with COP of 2.6-3.0 the performance has to the increase (Zhao and Tan 2014).

As evident from the following formula, COPmax of the thermoelectric modules where the maximum efficiency is reached is a function of hot side and cold side temperature and ZTm. Therefore, the efficiency of the system is mainly a function of two factors: temperature difference and material of the semiconductors (Zhao and Tan 2014).

$$(\mathrm{COP})_{c,max} = \frac{T_c}{T_h - T_c} \frac{\sqrt{1 + ZT_m} - \frac{T_h}{T_c}}{\sqrt{1 + ZT_m} + 1} \qquad (1)$$

In which ZTm is the thermoelectric material figure-of-merit at average hot and cold side temperature Tm, Tc is the temperature on the cold side, and Th is the temperature on the hot side.

3.4 Increasing the efficiency

3.4.1 Thermoelectric module design

One way to increase the performance of TE modules is an advancement on the ZT value. Current materials used are based on N-type or P-type semiconductors, including Bi2Te3. Some studies have shown ZT of 2.4 at 300 K which have not been commercialized yet. Therefore, no materials have been manufactured yet to compete with Bi2Te3 (bismuth telluride) and Sb2Te3 (antimony telluride). One of the main obstacles in producing materials with higher ZT values is that the value of Z increases when electrical conductivity increases and thermal conductivity decreases and that is against the inherent property of materials that are usually good electricity conductors when are good conductors of heat (Bell 2008; Steven Brown and Domanski 2014).

Furthermore, other design factors that contribute to better system efficiency in the thermoelectric module include thermoelement length to cross-sectional ratio and slenderness ratio (Zhao and Tan 2014). Since these variations cannot be altered in this study and commercially available thermoelements are going to be selected, further analysis is not provided.

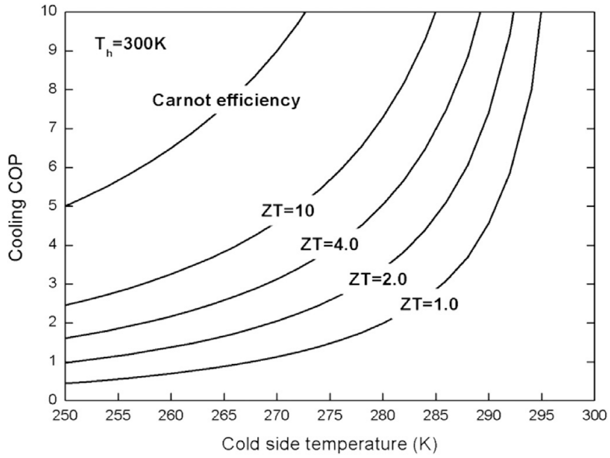


Figure 16 Cooling COP of a thermoelectric module under optimum electrical current with fixed hot side temperature of 300 K (Zhao and Tan, 2014).

3.4.2 Selection of current intensity and voltage

As can be seen in Fig. 16, the selection of the current plays an important role in the performance of the system. The current should not be larger than 0.7 times Imax, which is a value stated by the manufacturer. By applying appropriate electrical intensity, higher COPs can be achieved (Cosnier, Fraisse, and Luo 2008). It has been proven in studies that lower voltages may work better for cooling purposes than heating (Ibañez-Puy et al. 2017).

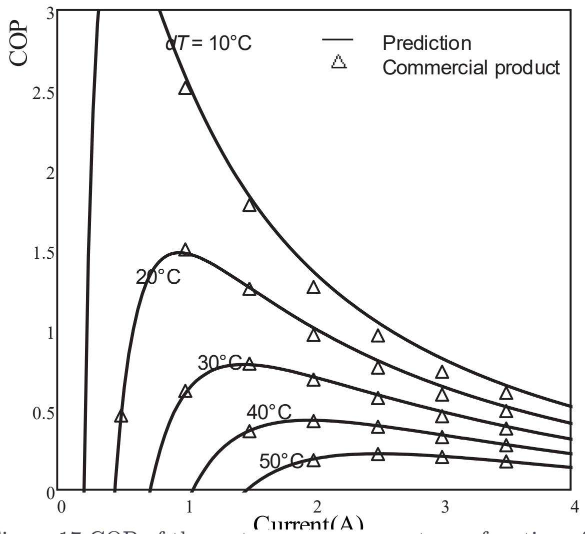


Figure 17 COP of the system versus current as a function of temperature difference (Lee, Attar, and Weera 2015).

3.4.3 Decreasing temperature difference

There is a trade-off in the thermoelectric modules between the maximum heat pumping capacity and the temperature difference. Meaning that by an increase in the temperature difference between hot and cold sides, the COP will drop (Lee, Attar, and Weera 2015).

3.4.3.1 Heat sink design

Heat sinks are designed to decrease the temperature at the heat disposal surface by dissipating heat to the surrounding. Therefore, the design of the heat sink includes factors that provide lower thermal resistance path for heat dissipation (Khire, Messac, and Van Dessel 2005). The efficiency in the design of the heat sink greatly influences the COP of the system. Selection of materials with low thermal resistance is crucial.

Based on a model developed by Khire et al., 2005, Resistance of the heat sink is a function of the base and fins' resistance. Fins providing extra surface area for heat transfer represent a few factors including width, thickness, and length of the fins that affect the overall performance of the heat sink.

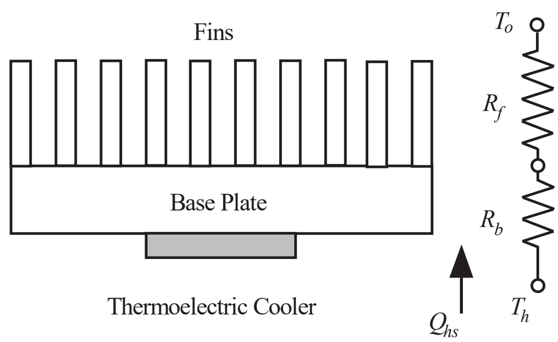


Figure 18 Cross-section of a heat sink (Khire, Messac, and Van Dessel 2005)

3.4.3.2 Maximizing heat transfer

Examples of techniques used to enhance the heat dissipation of the heat sinks include air and water cooled heat sinks, and heat sinks integrated with heat pipe, heat sinks with Nanofluid, heat sinks with synthetic jet and microchannel for heat removal (Zhao and Tan 2014). Moreover, the cross flow and counter flow air streams with forced convection have been used to enhance heat dissipation at the heat sink (Cosnier, Fraisse, and Luo 2008) in addition to natural convection systems(Xu, Van Dessel, and Messac 2007).

3.4.3.3 Utilizing PCM

In several studies, phase change materials have been used to maximize heat transfer on the hot side of the module (Riffat, Ma, and Qiu 2004). Employing thermal mass in such a system provides better distribution of the delivered cold/heat to the conditioned space throughout the day and night, especially because sunlight for electricity production is not available at nights (Xu, Van Dessel, and Messac 2007).

3.5 Case studies-façade integration

There are a few studies done on design possibilities of using thermoelectric cooling, mostly oriented towards increasing the efficiency of the system.

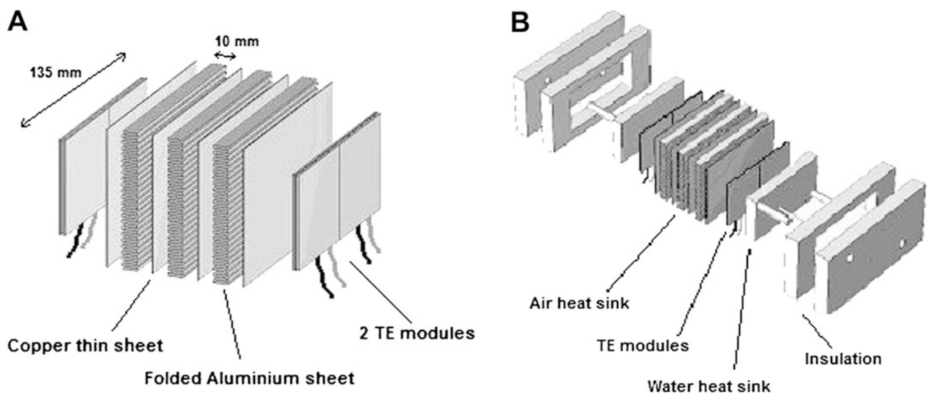


Figure 19 (A) Compact fin heat sink and TE modules and (B) experimental assembly (Cosnier, Fraisse, and Luo 2008)

3.5.1 Airflow and water flow at heat sinks

Cosnier et al., 2008 developed an experimental model for heating and cooling using four thermoelectric modules attached to heat sinks that accommodate an airflow on one side and water box heat exchangers on the other. The study was concluded with promising results of COP for cooling and heating functions. COPs of 1.5 and higher were reached for air cooling and near 2 for air heating modes for electrical intensities between 4-5 A and temperature difference of maximum 5-10degC. According to their results, the cooling power of 50W per module could be achieved (COP of 1.5-2) with an electrical intensity of 4A and temperature difference of 5degC.

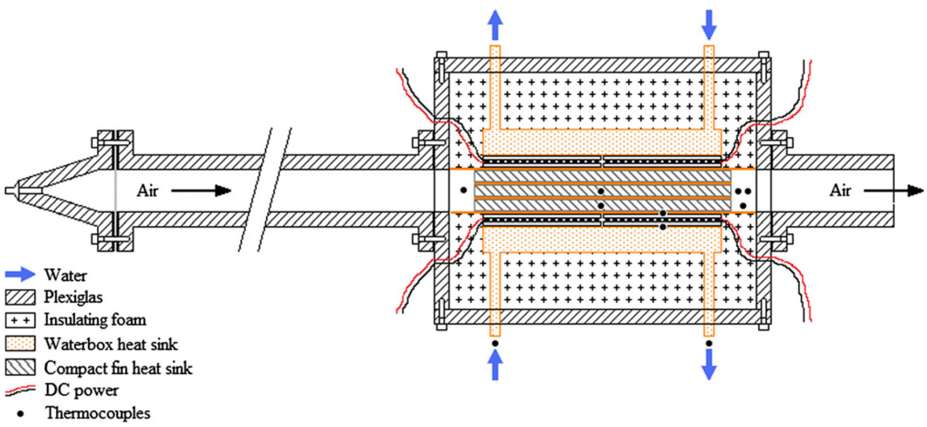


Figure 20General view of the experimental setup (Cosnier, Fraisse, and Luo 2008)

3.5.2 ABE window-system with water as thermal storage mass

Xu et al., 2007 developed an active window system with BIPV that utilized eight TE modules placed on both sided of the façade and mounted on two aluminum tubes, connected to external heat sinks. The aluminum tubes incorporate thermal insulation and water as thermal mass.

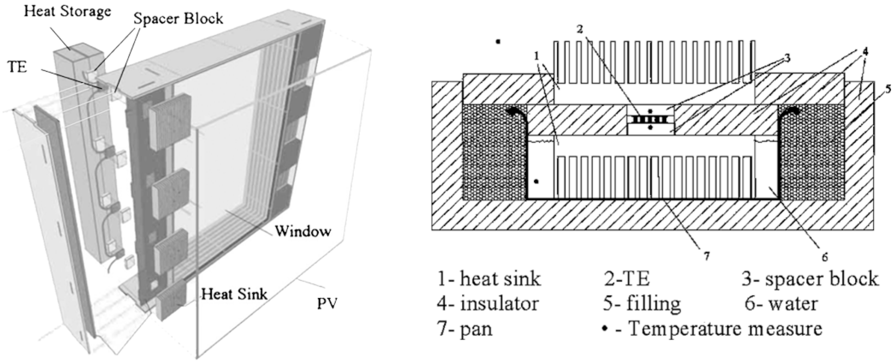


Figure 21 ABE window-system, (Xu et al., 2007).

In this study, the connection of TE units was also tested, which proved that having two parallel connected arrays of four modules connected in series is better in performance than all the eight units connected in series. Since different voltages for two types of TE modules were tested for both heating and cooling it is concluded that the heating mode can provide enough heating for the tested enclosure for both modules at any of voltages 3, 5 and 7 V. In the cooling mode PT4-12-40 type module was proved to perform better at 5 V.

3.5.3 A heating cooling system prototype with forced convection

The TE modules incorporate in an active façade system by Ibañez-Puy et al., 2017, as shown in Fig. 22, which consists of 8 thermoelectric modules with a maximum capacity of 51.4 W connected in series and aluminum heat sinks on both sides.

The results of this experiment depict that the heating COP is higher than cooling, even for the same temperature difference due to the Joule effect. Also, it has been concluded that having more density in cells and applying lower voltages, which results in lower intensity in the cells may result in better efficiency. The obtained COPs from this experimental study is from 0.75 to 0.78 for 7.2 V, which includes the fans in calculations as well.

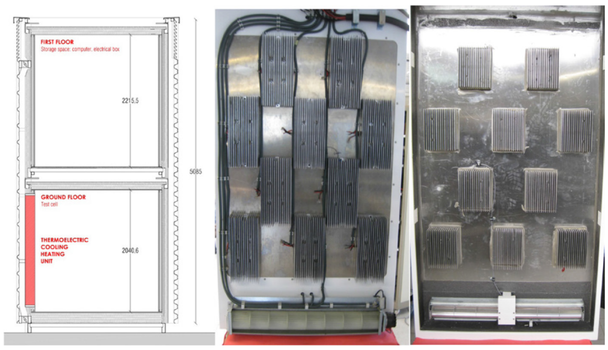


Figure 22 A heating cooling system prototype with forced convection Ibañez-Puy et al, 2017

3.6 Conclusion

Thermoelectric technology is a simple process of turning electricity into temperature difference between two sides of a module. Although it benefits from advantages of being silent, compact, compatible with PV panels, free of refrigerants and other working fluids, durable and reliable which makes TE technology very suitable for façade integration, low efficiency and high costs have stopped it from being used widely. Increasing the COP of this system would help to make it competitive with conventional heating and cooling systems and ease its way to building and façade application as a clean and solar driven sustainable air-conditioning system.

The efficiency of this system is a function of two main factors; design of the TE module itself and Decreasing the temperature difference between the cold and hot sides. Regarding the module design, different power intensities and voltages can be applied, and adjustments can be made to the number of TE modules, connections of them (parallel or in series), etc. The temperature difference between the hot and cold sides can be decreased by the heat sink design, providing lower thermal resistance and better heat dissipation on the base and fins. Strategies such as using the buildings ventilation system to reduce temperature difference contribute to better integration of the TE modules with the façade and the whole building.

As far as the scope of this graduation project allows, configurations will be made with commercially available products in the building and façade level to enhance the performance of the system and cover the whole cooling/heating loads if possible, with the electricity generated by PV panels.

4 Development of a typical office

An initial step in the design of an integrated façade was establishing a realistic context in which a typical building is being designed. This model is assumed as a representation of typical buildings that are in the design stage and considerations of passive heating and cooling as well as active heating/cooling must be considered.

In this chapter, firstly case studies are done to get an insight into how typical office buildings look in Tehran and what trends are being practiced in terms of form, material, façade type, interior planning, shading etc. Municipality guidelines will be then discussed to get an overview of the constraints that apply to building design. A typical office model is then developed which is a simple representation of typical offices in Tehran. This model will be used later to simulate the cooling and heating loads in order to obtain minimum comfort in the acceptable range of temperatures defined in this chapter.

4.1 Case studies

When choosing a type of building to develop a typical model for calculation of design loads, office buildings were studied since they impose more loads for cooling and heating in summer due to equipment and a larger number of occupants. This does not mean that using such systems integrating TE modules is restricted to office buildings, but this typology is taken as the worst case scenario.

Figure 23 Examples of governmental office buildings located in Tehran.

When defining "typical office type" we face two different office types in Tehran. One that is mostly designed and constructed by the governmental sectors for central bank offices, ministry buildings, public buildings, shopping malls, governmental business headquarters etc. and another that is usually owned by private sectors for headquarters and private office from small to medium scales. The first type is usually owned, funded, designed and constructed directly or indirectly by governmental sectors, and therefore information on these buildings are rather confidential and not publicly published.

They are mostly high-rises, located in low-density urban areas and big plots that are less constraint and therefore possess more freedom with form and façade design. The earlier modernist style witnessed in these buildings showcases glazed facades with minimum thoughts on energy consumption and even comfort which is observed to change later in the most current high-rises being more considerate in use of transparent facades.

However, although these high-rise buildings play a key role in the building industry in Iran, they own a small share in the number of buildings that are being built. Most offices in Tehran are small to medium-sized and located within the dense urban fabric of Tehran. Offices located in the denser urban areas, restricted by the small to medium sized plots that they are situated in often have two to three available facades and are what constitute the majority of offices built in Tehran.

Figure 24 Small to medium sized offices in Tehran

These buildings are usually low rises located in areas with easy access to highways and main streets of the city. The form and orientation are often limited by the site and general orientation of the building is mostly towards South-North tilted to the West and East depending on the location.

Since the second type of office buildings are more commonly built and obtaining information about them is easier due to publicity, for this thesis these small to medium sized buildings are chosen to be studied.

Figure 25 Map of the orientation common in Tehran.

4.1.1 Small to medium-sized offices

The office that is selected as case studied is designed by architectural design studios that are rather well-known and have published their work online, therefore obtaining at least basic information about these projects is possible.

These ten cases studied are built between 2004 to 2016 and are from 5 to 9 floors depending on the district that they are located on average 6.8 floors. In 90 percent of the time they are facing South-north and the average plot size is 430 m2. Most of these buildings are simple extrusions from the plot due to the preciousness of land in Tehran. It is evident that architects exploring different concepts put efforts on playing with the façade to compensate the restrictions and imposed simplicity on the form. The figure below provides an overview of these case studies.

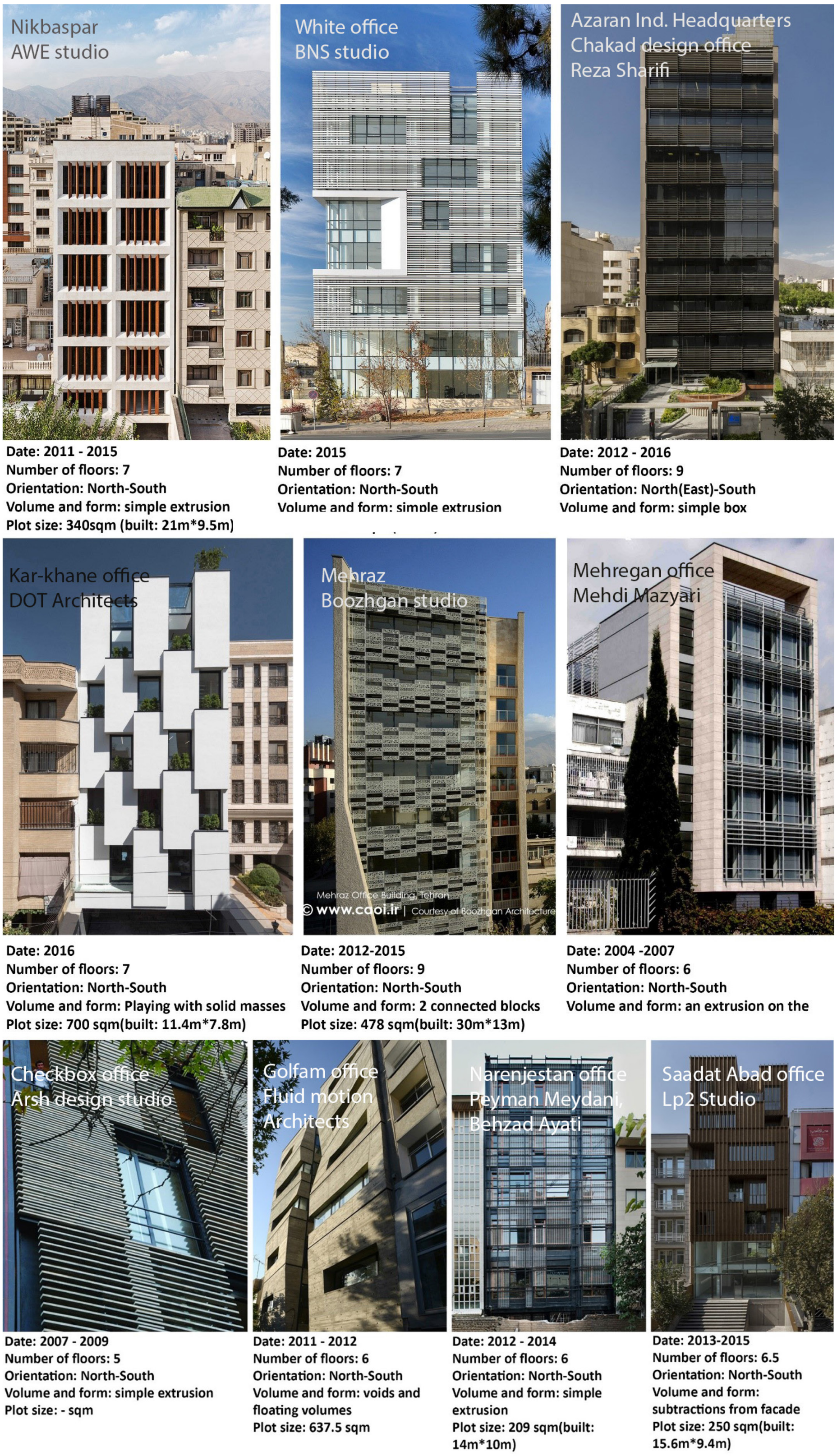


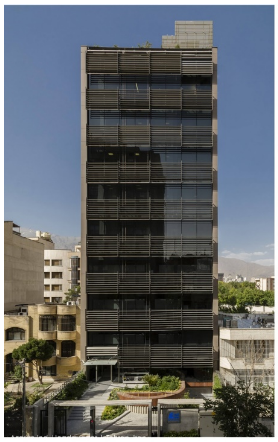
Figure 26 Various cases studied as small to medium offices in Tehran.

4.1.2 Façade

Due to restrictions that apply on the form of buildings, facades are taken as opportunities to establish architectural concepts and exploration.

The façade type used in these buildings is mostly masonry probably due to lack of skilled labors, knowledge or technology required in curtain wall facades. 8 out of 10 of these buildings have shadings including vertical, horizontal, perforated and movable shadings. This proves that there is an ongoing trend in having shadings on the façade either due to raised awareness in energy consumption or because it gives more design opportunities to be creative on. The average window to wall ratio is 54.3 percent which is lower than the limit of glazing percentage defined by the municipality i.e. 60%.

This may also be since these offices are mostly located in residential areas where privacy is an issue. Therefore, except for the interior planning and circulation, these offices are not easily distinguished from residential buildings.

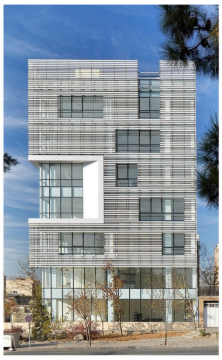


Façade type: Curtain wall
balconies, or additional elements: sustainable approaches
Window to wall ratio:95%
Number of materials used:2
Materials: Stainless steel, laminated double glazing, sintered ceramic for the façade
Shading type: vertical louvres
Form and cantilevers:-a very minimalistic approach
Following a grid: yes

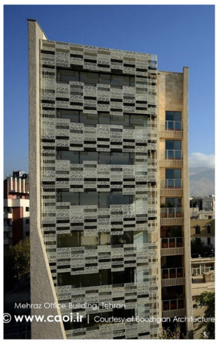
Façade type: masonry
balconies, or additional elements:
Window to wall ratio: 40%
Number of materials used:3
Materials: Stone, wood and glass
Shading type: Horizontal movable louvres
Form and cantilevers:-intelocking shading louvres
Following a grid:

The materials used include wood, aluminum, cement, concrete and stone and on average three different materials are used on each building. It is also evident that most of these facades follow grids on their facades. The figures below showcase the façade of these buildings and more details about them.

Façade type: Masonry
balconies, or additional elements:-
Window to wall ratio: 44%
Number of materials used: 3
Materials: stone-wood-aluminum frames and glass
Shading type: wooden vertical louvers
Form and cantilevers: recessed windows
Following a grid: yes



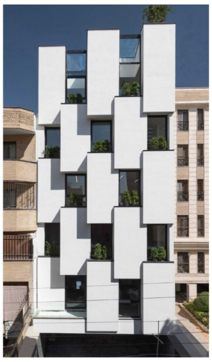
Façade type: Curtain wall- double skin facade
balconies, or additional elements: Green elements
Window to wall ratio:60%
Number of materials used:3
Materials: Aluminum panels- Aluminum sections, aluminum frames and glass
Shading type: Horizontal Aluminum sections
Form and cantilevers: subtractions from the second skin
Following a grid: yes



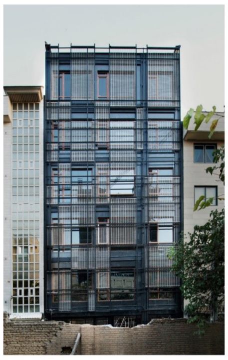
Façade type: Masonry
balconies, or additional elements: balconies-a skin wrapped around two separated blocks
Window to wall ratio: 50%
Number of materials used: 4
Materials: cement, stone, perforated steel, aluminum windows and glass
Shading type: CNC-milled flat sheets
Form and cantilevers: The facade wrapes the building and covers its transparency
Following a grid: yes

Façade type: curtain wall
balconies, or additional elements:-
Window to wall ratio: 70%
Number of materials used: 3
Materials: stone, aluminum louvers, aluminum profiles and glazing
Shading type: adjustable aluminum louvers
Form and cantilevers: extrusion on a part of facade
Following a grid: yes

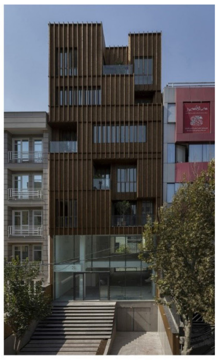
Façade type: masonry
balconies, or additional elements: maximizing natural ventilation and light
Window to wall ratio: 40%
Number of materials used: 3
Materials: concrete, wood, glazing and aluminum frame
Shading type: -
Form and cantilevers:-dynamic movements
Following a grid: -



Façade type: masonry
balconies, or additional elements: canteliveres, flower boxes with automatic irrigation system using the grey water, skylights
Window to wall ratio: 30%
Number of materials used: 3
Materials: U steel profiles (reducing risk of cracks on cement), white cement, aluminium frames and glass
layer of anti-static material on the cement reduces absorption efficiency and pollution.



Façade type: Masonry
balconies, or additional elements:-
Window to wall ratio: 50%
Number of materials used: 3
Materials: stone-wooden frames and glass, aluminum sections
Shading type: wired screens
Form and cantilevers:-
Following a grid: yes a grid drawn from neighboring buildings



Façade type: Masonry
balconies, or additional elements: balconies formed by subtractions from the facade
Window to wall ratio: 46%
Number of materials used: 2
Materials: wood, aluminum frames and glazing
Shading type: adjustable vertical wooden louvres
Form and cantilevers: facade is reccessed at some points.
Following a grid:-

4.2 Municipality guidelines on facades

The municipality of Tehran has published a set of guidelines and rules for the façade design to accommodate the growing demand in the building industry with more harmony in the whole city. Therefore, these standards evolve around maintaining unity and coherence in each area, district, and in the whole city. The important factors of a façade for which guidelines are provided include materials, entrance, openings, cantilevers, roof terrace, and skyline. These guidelines are listed as follows:

- Avoiding fully glazed or full metal facades, i.e., the glazing ratio of the façade should not exceed 60%.
- Avoiding using unusual or heterogeneous colors
- Avoiding usage of multiple materials (maximum of four)
- Avoiding using irregular forms
- Avoiding usage of hazardous materials
- It is necessary to use durable materials against weathering and pollution
- The façade should be in harmony with the neighboring buildings in terms of overall design language; form, color, materials, and height.
- Using multiple colors on the façade should be avoided
- Materials used on the ground floor should be washable
- Using bricks, cement, stone, and a combination of these materials are recommended.
- Using local materials is suggested.
- It is prohibited to display any mechanical equipment on any façade of the building. This includes any split units, ducts, cables, gutters, etc.
- It is recommended to design flowerpots and green facades if safety and health criteria are met.
- It is recommended to have green roofs while providing safety and proper detailing.

4.3 A typical office-definition

For this graduation project of which the aim is experimenting the potential of thermoelectric cooling and heating running by renewable resources, a typical office model must be developed to experiment reductions of loads and system COPs on it. Therefore, one of the studied offices, Azaran Ind. Headquarters has been selected as a typical office model to analyze further and study.

The reason for selecting this office is that firstly it is a good representative of offices in Tehran. It is a simple extrusion of the plot, facing South-North with horizontal louvers. It is a newly built building and the façade type is curtain wall which makes it easier further adjustments. Moreover, its simplicity in concept and design makes it a better typical experimental façade. In other words, architectural concepts will not affect the design of the heating and cooling system.

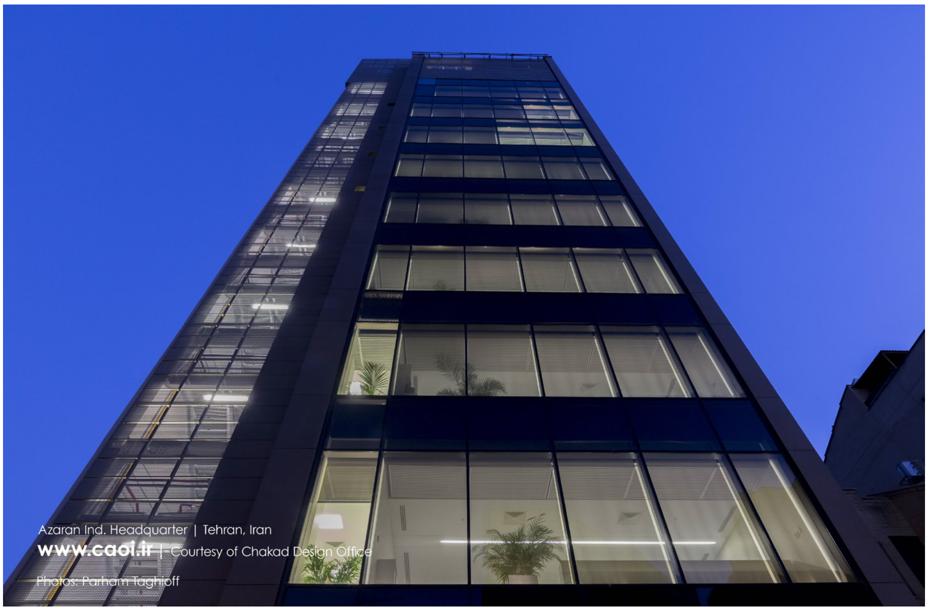


Figure 27 North-East façade, source:www.caoi.ir

4.3.1 Architectural concept

- Name: Azaran Ind. Headquarter
- Architecture firm: Chakad Design Office + Reza Sharif Tehrani
- Date: 2012 - 2016
- Site area: 610 m2
- Built area: 6350 m2

The concept behind this building is maintaining a simplistic and harmonious language with the urban fabric. This simple approach in designing a humble and minimal building, as stated by the architects helps in establishing a good relationship with the whole neighborhood. Maximizing natural light entering open office spaces has led the design of the façade to be as transparent as possible while adding the horizontal louvers controls the amount of light entering the building to avoid glare and overheating in summer. The architects and mechanical engineers have tried to adapt the building with sustainable approaches such as having solar collectors on the roof to provide hot water and a heat recovery system to minimize energy losses.

The building is in a busy Northern district of Tehran where many offices, shopping malls, and headquarters are located. The orientation of the block is North-East-South-west and the built area dimensions are 26.6*15.2.

Figure 28 South-west façade, source:www.caoi.ir

Figure 29 Location of the office building in Tehran.

The Azaran headquarters office, a relatively new building, consists of 5 typical floor plans and 13 floors from which four floors are basements and parking areas. Two different types are floors plans are presented in the above figures. The office area comprises of two different types of working paces, more flexible and public and the other more private and smaller. Services and a small lobby with a secretary office are located on each floor, and the more general service areas such as a dining area are located on the basement floor. In this section, the location of a skylight on the 8th and 9th floor and a roof terrace are evident.

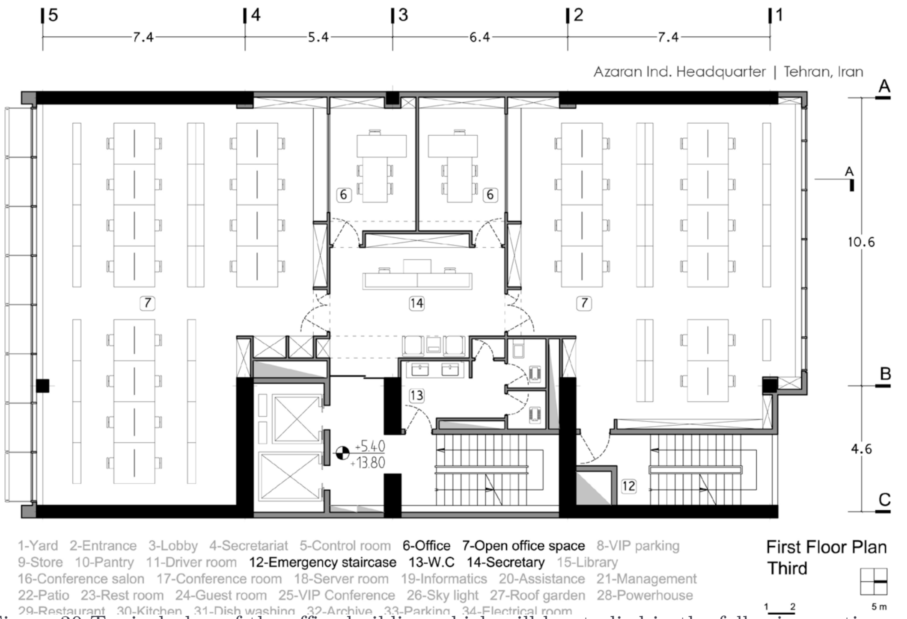


Figure 30 Typical plan of the office building which will be studied in the following sections.

4.3.2 Façade details

The southern façade of this project is a curtain wall with horizontal louvers connected to it. The system used is as witnessed from the drawings and pictures a stick system. The Northern façade has details different to that of the South façade.

Figure 32 Facade and interior perspective of the selected office building.

The details provided by the architect for the façade of this project presented in the following figures will be used as a baseline to design a new system with a modular unitized façade.

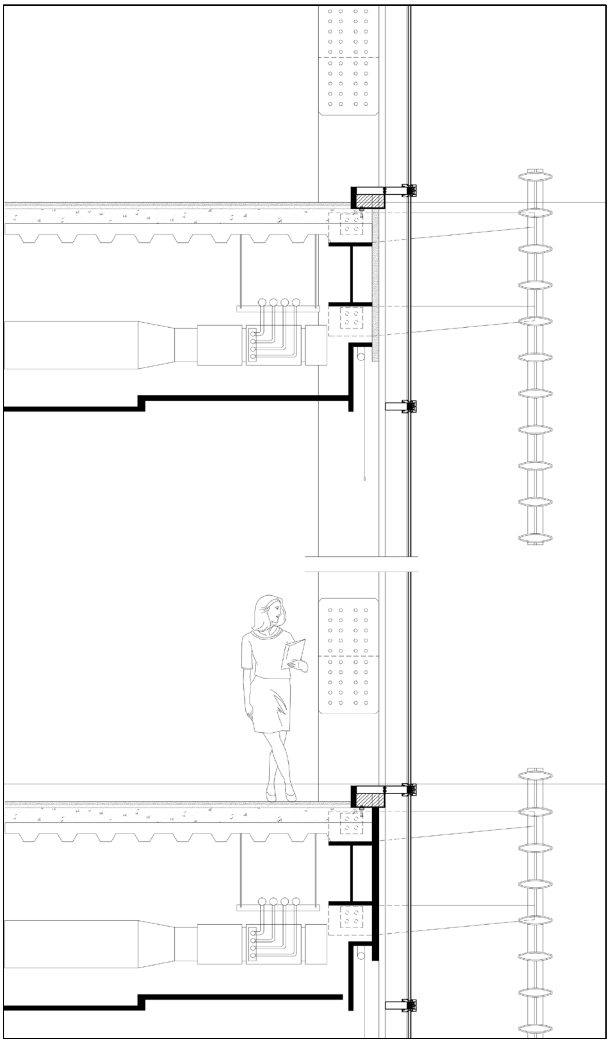


Figure 31 Section through the South facade showing facade connections to the main structure. source:www.chakadoffice.com/en/projects/azaran.html

4.4 Thermal comfort criteria

Thermal comfort (Hensen 1991) is achieved in a condition where there is no driving force to change and correct the environment. This condition, which is a state of mind in which we are satisfied, may differ from one person to another depending on the mood, culture, and other individuals, organizational, and societal factors. Six factors determine thermal comfort, including air temperature, air velocity, relative humidity, mean radiant temperature, clothing insulation, and activity level (Djongyang, Tchinda, and Njomo 2010). However, to determine comfortable indoor climatic conditions, two approaches are taken to define standards that result in the establishment of a temperature range in which at least 80 percent of the Occupants are comfortable.

4.4.1 The rational approach

The rational approach or the heat balance approach uses data from experimental chambers to validate the findings driven from heat-balance equations. Thermal comfort standards use the PMV model to recommend acceptable thermal comfort ranges based on the response of a large group of people according to ASHRAE thermal comfort sensation scale (Djongyang, Tchinda, and Njomo 2010; Nicol and Humphreys 2002).

According to Djongyang et al.,2010 for a relative humidity of 50%, a mean relative velocity lower than 0.15 m/s, a mean radiant temperature equal to air temperature and a metabolic rate of 1.2 met and clothing insulation defined as 0.9 in winter and 0.5 in summer, thermal comfort's acceptable range is between 20degC to 23degC in winter and 23degC to 26degC in summer.

As some experts criticize this approach for lacking consideration of real contextual factors, adaptive approach is introduced to provide a more comprehensive understanding of the comfort range as a result of behavioral, physiological and psychological adaptation (Djongyang, Tchinda, and Njomo 2010).

4.4.2 The adaptive approach

The adaptive approach, which is a method based on field studies in normal conditions with actual buildings and real occupants, is claimed to provide more realistic numbers for thermal comfort range.

Case 1 - Kalgoorlie-Boulder in the desert area of Western Australia

Based on a study by (Cena and de Dear 2001) on 22 office buildings, for similar climatic conditions to that of Tehran, thermal neutrality was obtained at 20.31degC in winter and at 23.31degC in summer.

The field study was in a condition as follows:

Located in the desert area of Western Australia with mean minimum winter and summer temperature of 9.61 degC and 16.71 degC and mean maximum temperatures of the winter and summer sample periods of 18.51 degC and 30.71 degC respectively.

Case 2 - Free-running buildings based on outdoor temperature

Although the comfort conditions suggested by (Nicol and Humphreys 2002) based on the mean of the outdoor temperature is for free-running buildings, the findings could provide a comparison to put the chosen thermal comfort range in a logical range of numbers. Therefore, the table below presents comfort temperature based on the formula provided by (Nicol and Humphreys 2002) for a non-heated and cooled building in the climate of Tehran.

$$T_{comfort} = 13.5 + 0.54T_0 \quad (2)$$

In Table 1 and 2, thermal comfort ranges are drawn from formulas (Nicol and Humphreys 2002) based on outside temperature for winter and summer.

Table 2 Thermal comfort ranges for winter in Tehran.

WINTER	October	November	December	January	February	March	Winter-Mean
Mean max	22degC	14degC	7degC	4degC	5degC	1 degC	10.6degC
Mean min	11degC	5degC	0degC	-3degC	-2degC	3degC	2.3degC
T_0	16.5degC	9.5degC	3.5degC	0.5degC	1.5degC	7.5degC	6.5degC
$T_{comfort}$	22.4degC	18.6degC	15.4degC	13.7degC	14.3degC	17.5degC	17.0degC

Table 3 Thermal comfort ranges for summer in Tehran.

SUMMER	April	May	June	July	August	September	Summer-Mean
mean max	21degC	27degC	33degC	35degC	34degC	29degC	29.8degC
mean min	8degC	13degC	19degC	22degC	21degC	16degC	16.5degC
T_0	14.5degC	20degC	26degC	28.5degC	27.5degC	22.5degC	23.2degC
$T_{comfort}$	21.3degC	24.3degC	27.5degC	28.9degC	28.3degC	25.6degC	26.0degC

4.4.3 National codes

Based on chapter 19th of National codes of Iran (ministry of roads and urban development, 2011) on energy conservation, the indoor temperature should be kept at a maximum of 20degC in winter and 28degC at summer time. Although this provides a large range in which the thermal comfort should be kept at, it can be taken as a good reference based on the climatic conditions, cultural, psychological and physiological condition of people living in Iran.

4.4.4 Conclusion

Two approaches of obtaining thermal comfort as well as National guidelines, chapter 19th were briefly studied in this section to obtain a range of temperature in which most Occupants feel comfortable. This range will later be used for calculations and simulations to obtain heating and cooling loads of the typical office building. Based on the obtained values 24.7degC and 20.4degC can be taken as acceptable temperature for summer and winter respectively. The minimum and maximum acceptable temperatures are 20degC and 28.9degC in summer and 13.7degC and 26degC in winter respectively.

Table 4 An overview of thermal comfort ranges of different methods for summer in Tehran.

Summer	Rational	Adaptive-1	Adaptive-2	Chapter 19th	Total
Minimum	20degC	-	21.3degC	-	20degC
Maximum	23degC	-	28.9degC	-	28.9degC
Average	21.5degC	23.31degC	26.0degC	28degC	24.7degC

Table 5 An overview of thermal comfort ranges of different methods for winter in Tehran.

Winter	Rational	Adaptive-1	Adaptive-2	Chapter 19th	Total
Minimum	23degC	-	13.7degC	-	13.7degC
Maximum	26degC	-	22.4degC	-	26degC
Average	24.5degC	20.31degC	17.0degC	20degC	20.4degC

5 Implementing Passive measures

In this section the heating and cooling strategies that are claimed to be the most effective ones in this climatic condition based on reviewed papers are going to be examined. Although some of these factors will alter the appearance of the façade, the effort will be to remain the initial concept of the architectural design. It should be noted that this is only a preliminary stage in designing the active air-conditioning system and not the main goal of this practice and therefore, as crucial as this stage is, only a few scenarios will be examined for each strategy to come up with the best configuration and detailing for the design of an integrated façade with energy consumption reductions.

Also since as seen later from the simulations, the cooling loads are much greater than the heating loads especially considering the building type, and on the other hand, it is known that the COP of heating is in most cases higher than COP of cooling, the method in choosing one strategy over the other will be with the priority of cooling load reduction. This will hopefully lead to better distribution of energy consumption over the year and lowering the system sizing.

5.1 Establishing goals

5.1.1 Reducing peak loads

Realizing that the cooling and heating system sizing is based on the peak hours loads, it can be pointed out that the most outcome of implementing passive strategies should be firstly reducing the peak loads. This will lead to a more efficient and cost-effective design that is able to cut down on excess capital investments as well as wasting of materials. The immediate consequence of reducing the design capacity will be reducing the number of thermoelectric modules, heat sinks and therefore, the weight, initial cost and weight of the system.

On the other hand, as explained before, these increasing peak demands are forcing governments to build new power plants only to cover these shortages of electricity during peak hours. The electricity distribution companies in Tehran have therefore set tariffs on electricity price based on peak and non-peak consumption to deal with this growing concern and every year citizens in bigger metropolitan areas would have to suffer from electricity outage especially during summer when it is most needed. Therefore, reducing these loads is expected to decrease not only the capital costs associated with cooling and heating system sizing but also on a bigger scale, reducing investments on power plants and energy losses due to excess electricity production during non-peak hours.

5.1.2 Reducing annual heating and cooling consumptions

The second criteria that must be met as an outcome of applying these passive strategies is reductions in the annual heating and cooling demand. It is obvious that at most occasions these two criteria are going to be in the same direction, and one will result in another. However, the first selection criteria of different scenarios of each strategy will be based on reductions on peak demands.

5.1.3 Recommended reductions of annual consumptions

In order to set a goal on how much reductions should be achieved in this stage an aim should be set. This is a necessary stage because as explained before the main goal of this step of design is to reduce the loads to a certain point. Further reductions are very likely to occur if optimizations and possibly other methods are applied which is out of the scope of this project.

The implementation of the TE modules itself does not impose a great limitation on the system mainly because it is very small in size and for bigger loads a greater number of modules can be integrated within the system. The only component that imposes a restricted limitation on the system is the PV panels, that can produce a certain amount of electricity in a year. It is very likely that in future PV panels will have more efficiency that they have today but for this research the highest efficiency PV panel is selected to provide a starting point.

At this point a COP of 1 for cooling and 1.5 for heating is selected based on a rough average obtained from papers to have a fair comparison between electricity demand and production by PV.

The highest efficiency PV panels available on the market are those of 21% efficiency with Monocrystalline type of cells. A product of SunPowerff X-Series Residential Solar Panels — X21-335-BLK — X21-345 has been selected with the following properties.

Table 6 Product specifications of SPR-X21-345 provided by the manufacturer, source: https://us.sunpower.com/solar-panels-technology/x-series-solar-panels.

Nominal Power	Avg. Panel Efficiency6	Rated Voltage (Vmpp)(V)	Rated Current (Impp) (A)	Open-Circuit Voltage (VdegC) (V)	Short-Circuit Current (Isc)(A)	Maximum Series Fuse (A)	Temperature (degC)	Weight (kg)
335 W	22.00%	57.3 V	5.85 A	67.9	6.23	15	−40 to +85	18.6

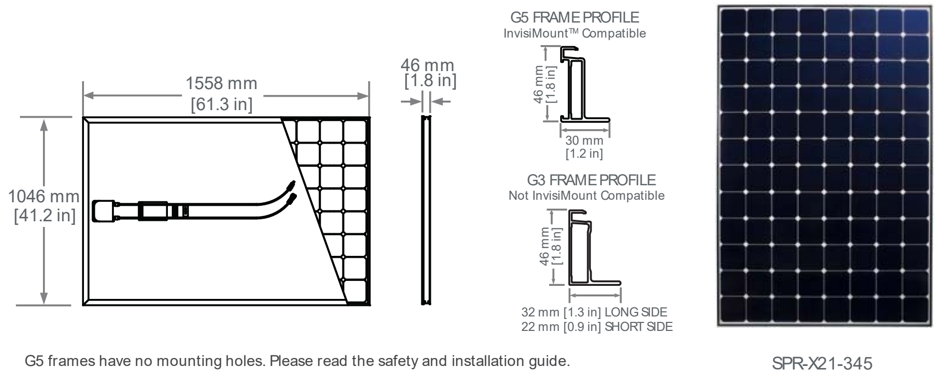


Figure 33 Appearance and details of SPR-X21-345 provided by the manufacturer, source: https://us.sunpower.com/solar-panels-technology/x-series-solar-panels

5.1.3.1 Area available for PV panels

PV panels can be located on the roof and on the façade of this nine story building. Since the intention of this design is to make as small changes to the appearance of this building as possible it is decided that the shading devices designed by the architects of this project remain on the south façade. Because of this decision the PV panels cannot be located on the south façade as they will be shaded by the vertical louvers and therefore are located on the shading devices of the South façade. By making some changes to the shading device available area is increases and the risk of casting shadows on one another is reduced. The pictures below depict a new shading dimensions and areas are as following:

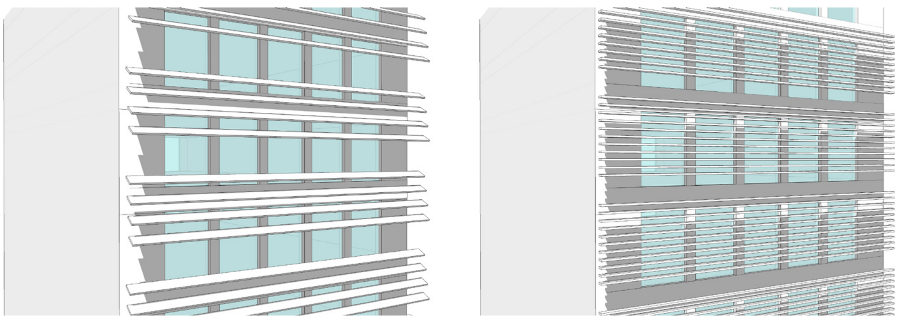


Figure 34 Right: the original design of the shading devices on south. Left: the design suggested by the author to maximize area.

The new shading dimensions and areas are as follows with the total roof area is 148 m².

Table 7 The designed shading dimensions.

Length (m)	Depth (m)	number	Effective area	Total effective shading area (m2)
15.33	0.5	4x9	80%	275.94

5.1.3.2 PV production

The total nominal power is calculated as below:

$$\text{Installed power roof in kWp} = \text{Roof Area} \times \text{nominal power} \tag{3}$$

An online program called pvPlanner from Solargis is used to calculate the annual and monthly average electricity production of PV panels. The advantage of this program is that the specific location and site elevation and direction is selected, and the tilt is considered. The following inputs were inserted into the program.

Figure 35 Site location inserted into the pvPlanner program, source: https://solargis.info/pvplanner.

Site information which will be filled automatically in by the selection of location:

- Site name: Tehran, Iran
- Coordinates: 35° 41' 21.11" N, 51° 23' 20.31" E
- Elevation: 1171 m
- Slope inclination: 2°
- Slope azimuth: 190° south

5.1.3.3 PV system

- Installed power roof (kWp): 91.96
- Installed power facade (kWp): 60.70
- Type of modules: crystalline silicon (c-Si)
- Mounting system: fixed mounting, building integrated or fixed mounting, roof installed
- Azimuth/inclination: 220° (southwest) / 30° or 224° (southwest) / 26°
- DC / AC losses: 5.5% / 1.5%
- Availability: 99.0%

Therefore, in total **27664 kWh** electricity per floor is generated yearly by installing PV panels on the roof and shading devices of the façade and having all the passive measures taken by the end of this chapter, heating and cooling electricity consumption should be at maximum equal to the total electricity produced by PV panels.

5.1.4 Recommended reduction on peak demand

In order to compare the summer design day demand and PV production. First, the electricity produced by PV panels on this day had to be calculated. From DesignBuilder solar radiation on the roof and shading surfaces was obtained and then from these formulas, E was calculated.

$$E = A \times r \times H \times PR \tag{4}$$

With E is energy (kWh), A is total solar panel Area (m2), r is solar panel yield or efficiency (%), H is average solar radiation on the panels, and PR is the performance ratio as the coefficient for losses. The performance ratio is obtained from simulations of pvPlanner and is as following for the month of July:

- On the south façade: 0.715
- On the roof: 0.725

The total produced electricity is therefore calculated to be 58.92 kWh during the summer design day. This finding indicates that if the design capacity obtained from simulations after taking all of the passive measures is able to meet this number, then with a COP of 1 during peak, the peak loads can be covered only with PV panels and without relying on electricity from the grid.

5.2 The method of implementing passive measures

The simulation phase taken in this chapter consists of four chapters through which the initial design of this typical façade evolves, and the annual and peak loads reduce. in order to have a good comparison between different scenarios, it is better to compare them in terms of electricity consumption. Therefore, from simulations where heating and cooling loads (kWh) are obtained, COPs of heating and cooling are taken into consideration to obtain electricity consumption (kWh) from the following formula.

$$\text{Electricity consumption } (\text{kWh}) = \text{ heating and cooling loads } (\text{kWh}) \,/\, \text{COP} \tag{5}$$

It is obvious that by increasing COP electricity consumption decreases, and the system has a better performance. Moreover, simulation results of annual consumptions are going to be evaluated based reductions on heating, cooling and electricity consumption. This is the simplest method of measuring the effect of taking one decision in all relevant aspects. For instance, reducing the window to wall ratio will probably reduce the cooling loads by reducing the heat gains through window, however it will have an adverse impact on heating and electricity consumption. Only strategies will be selected where their overall saving in three aspects is positive.

At the initial stage, every single chosen passive strategy is applied individually, and a thorough examination of these measures, the best scenarios are selected. This first step of simulations itself has a few sub-phases that help to ensure that the results are reasonable and in line with expectations.

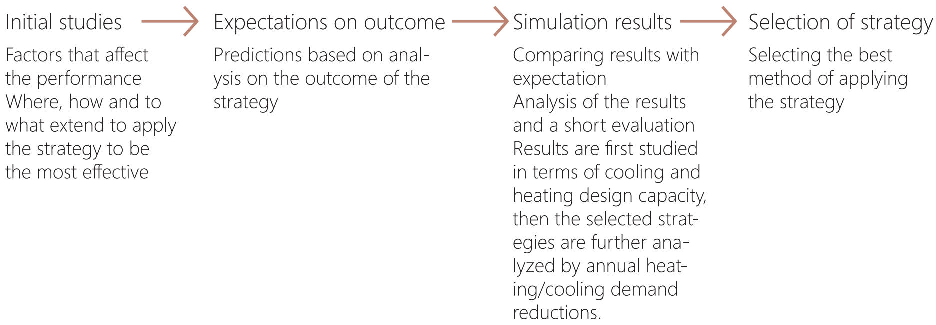


Figure 36 sub-stages of the first step is explained.

At the second stage, all these methods are adding into a single model, and simulations are done to measure the effect of these applications on the overall energy performance. During the next stage, some of the so-called in this thesis secondary measures are taken in order to reduce the peak and annual loads further. these secondary measures include having natural ventilation with temperature control systems and reducing the infiltration rates.

As expected, some of these strategies are overlapping and therefore in the fourth stage, these strategies are one by one excluded from the model containing all the passive measures and then the effect of not having a single strategy while having all the others is studied. At the end of this step some of these passive measures can be left aside from the final model. Finally, a completed model is built, and the final results are obtained.

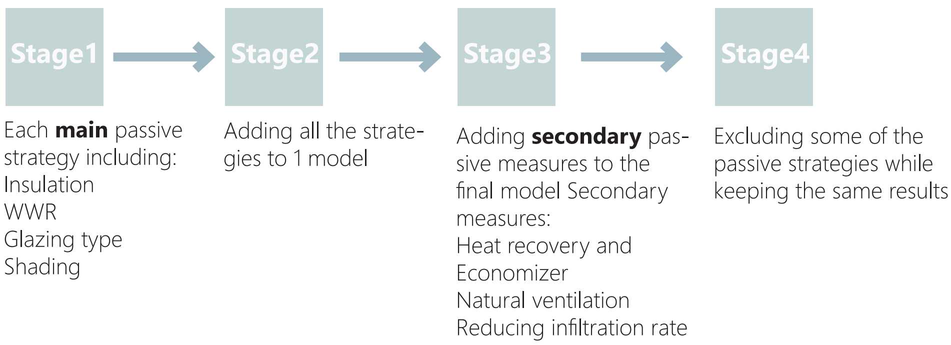


Figure 37 Overview of the four simulation stages.

5.3 Cooling and heating strategies

5.3.1 Selection criteria

As explained in earlier chapters, in this climatic condition, where heating and cooling are both required, matters regarding the selection of passive strategies get more complicated. This is mainly because in passive heating the main focus is on minimizing losses and maximizing gains whereas on the contrary, with passive cooling avoiding gains and removing of heat becomes crucial (Tejero-Gonzalez et al. 2016).

5.3.1.1 Passive cooling

The selection criteria here between all the measures that can be taken in order to reduce cooling loads as categorized by (Prieto et al. 2018), i.e. shading, glazing size, and type and ventilation is based on effectiveness in the first place. As categorized by (Santamouris and Asimakopoulos 1996) passive cooling techniques fall into three main categories of Solar and heat protection techniques, i.e. shading, window to wall ratio, heat modulation techniques such as using PCM and thermal mass, heat dissipation and heat amortization techniques such as night ventilation. Strategies discussed in this section only refer to the façade design or techniques that can be implemented on the façade as an integration of the whole building.

As concluded by (Prieto et al. 2018) based on obtained results of reviewed papers, in warm-dry climates ventilation strategies and window to wall ratio and shading are respectively the most effective techniques in reducing cooling loads. In the simulations, however, done by the same authors in a climatic condition in summer similar to that of Tehran (Athens) up to 70 percent of energy consumption reductions were achieved by a combination of adjustments in glazing size, ventilation, and shading in one scenario and glazing type, ventilation and glazing size in another. In a study by (Solgi, Fayaz, and Kari 2016), 47% energy reduction were obtained with a combination of PCM and night ventilation in the desert city of Yazd.

Also, there are some guidelines provided by the ministry of roads and urban development that drive architects, mechanical and electrical engineers as well as construction companies to follow some rules in order to be granted with building permission. Since 1992 with the publication of the first edition of the energy chapter, which was mostly on insulation properties of the building envelope, authorities have tried to reduce the energy demands in the building industry.

In 2003 the second edition of the 19th chapter was published with further suggestions on mechanical and lighting equipment in addition to insulation. This chapter now includes calculations on U values of different building materials, suggestions for the optimum angle and position of shading devices in different cities, guidelines for calculations of cold bridges, suggestions of mechanical and lighting equipment that would help in reducing energy demands.

the passive strategies that chapter 19th offers are to increase reliance of natural resources and reduce energy consumption of buildings and they fall into seven categories from which some recommendations are not applicable in this specific case study. It is suggested by these guidelines that special attention should be paid to transparency of the façade. Because besides material properties, reduction of thermal bridges and infiltration, safety etc., the percentage of glass is of critical importance in facades. As the window to wall ratio decreases, the façade obtains a better insulating performance. Therefore, this ratio should be carefully selected in order to minimize heat losses while providing enough sunlight. It is recommended that this ratio is more on the southern façade and reduces to minimum sunlight provision on other less desirable facades.

Also, some suggestion is given in designing of shading devices and awnings and some angles and positions are provided for different locations of Tehran. It is suggested that awnings are designed in such a way that during hot seasons, the window will be shaded to reduce direct sunlight penetration while in winter sun rays will be able to pass to the indoor spaces.

Table 8 The optimum angles for shading devices in different locations of Tehran, MS: Movable shading covering the whole window.

Tehran	North		East		South		West	
-	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Park-shahr	-	70°W	70°	-	60°	-	-	M.S
Doushan-tape	-	62°W	60°	-	60°	-	-	M.S
Saadat abad	-	-	-	-	72 °	-	40	-
Mehrabad	-	65°W	70°	-	60 °	-	-	M.S
Narmak	-	80°W	83°	-	70 °	-	20	-
Namayeshgah		82°W	-	-	70 °	-	20	-

Table 8 presents the optimum angles for vertical and horizontal shading devices in different locations of Tehran. In this table, for example, W indicates that the shading should be located on the West side of the window.

Furthermore, the usage of natural ventilation is recommended to lower the demand for mechanical ventilation.

What can be concluded in this section is that use of shading, proper glazing type, glazing size, and natural ventilation can have the most beneficial impact on energy consumption reductions of cooling.

5.3.1.2 Passive heating

Since as weather data shows, the main concern of this climatic condition is not heating but cooling, only a few basic strategies will be implemented to reduce the heating demands. some of the most effective ways in reducing heat losses are applying proper insulation thickness on the exterior walls of building construction as well as reducing infiltration rate by reducing thermal bridges in façade.

5.4 Baseline model and steady-state validation

In this section, firstly the baseline model is described with its construction specification in DesignBuilder. Then, results are validated for a specific time step in the simulation with manual steady-state calculations.

5.4.1 Baseline model

The baseline model is a simplified version of the typical office as described in earlier chapters.

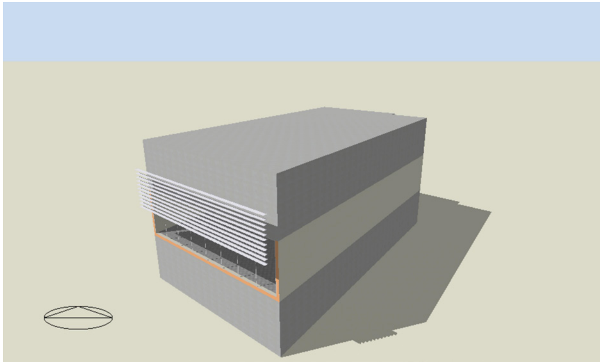


Figure 38 The appearance of the baseline model in DesignBuilder software

Construction specifications used in the software, are listed as follows in the table.

	North facade	West and east facades	South facade
Layers			
U-value (W/m^{2}K)	1.60	1.62	1.60
WWR	90%	0%	100%

The infiltration rate in this model is 0.7 ac/h, and the glazing type has the following properties with aluminum frames filled with thermal break:

Table 9 Properties of glazing type

Glazing	No. of layers	Outer pane	Inner pane	Window gas	Total solar transmission	Light transmission	U-value (W/m^{2}K)
Generic glazing	2	Generic 3mm clear glass	Generic 3mm clear glass	13mm air	0.69	0.74	1.96

Table 10 Specifications of interior zones for usage in the DesignBuilder software.

Zone	Open office-south	Open office-north	Meeting room1,2	lobby	Circulation	Emergency stairs	toilet
Occupants density (people/m^2)	0.111	0.111	0.1221	0.1008	0.1173	0.1173	0.112
Min. fresh air (L/s/person)	10	10	10	10	10	10	12
Office equipment power density (W/m^2)	11.77	11.77	11.77	6.19	1.85	0	5.48
Lighting control	on	on	off	off	off	off	off
Target illuminance (lux)	500	500	400	200	100	100	200
Office schedule	6 days/ week, 8-18		6days/week, Occasional	6 days/ week, 8-18			

The shading device originally designed by the architects was simplified into louvers in DesignBuilder having 11 blades with 0 degrees of tilt and vertical spacing of 300mm. Also, an interior shading was added to the model as a medium translucent shade roll.

5.4.2 Results

The cooling and heating design capacities are the cooling and heating load during the peak design day multiplied by a design margin of 1.15. This capacity is used for sizing and cooling of the HVAC systems as it represents the maximum required capability.

Table 11 Portions of electricity consumption of heating, cooling, and lighting.

Specification	Cooling load (kWh)	Cooling Electricity (kWh)	Heating load (kWh)	Heating Electricity (kWh)	Lighting Electricity (kWh)
Design capacity	55.02	55.02	39.17	26.11	-
Design capacity/m^2	0.37	0.37	0.26	0.18	
Annual consumption	49261.07	49261.07	10115.11	6743.40667	11153.44
Annual consumption/m^2	332.84	332.84	68.345	45.56	75.36

As can be seen in Fig. 39, the biggest portion of electricity consumption is dedicated to cooling.

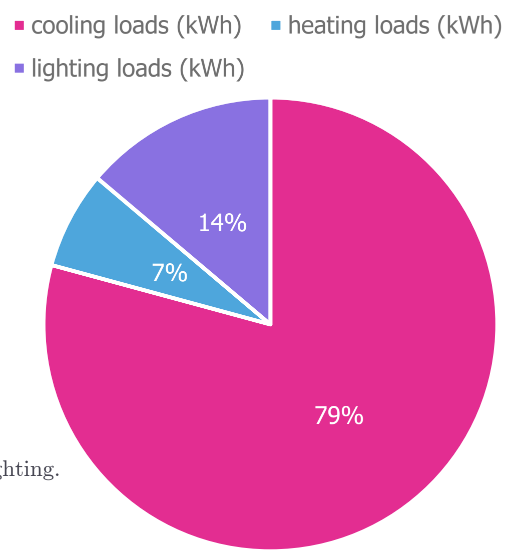


Figure 39 Annual electricity consumption of cooling, heating and lighting.

5.4.3 Validation of results

At this point it is necessary to validate the results obtained from simulations before going further with implementation of passive schemes. For this reason, a summer design day is chosen from calculations and results from steady-state manual calculations at 10 A.M are compared to results from Designbuilder simulations.

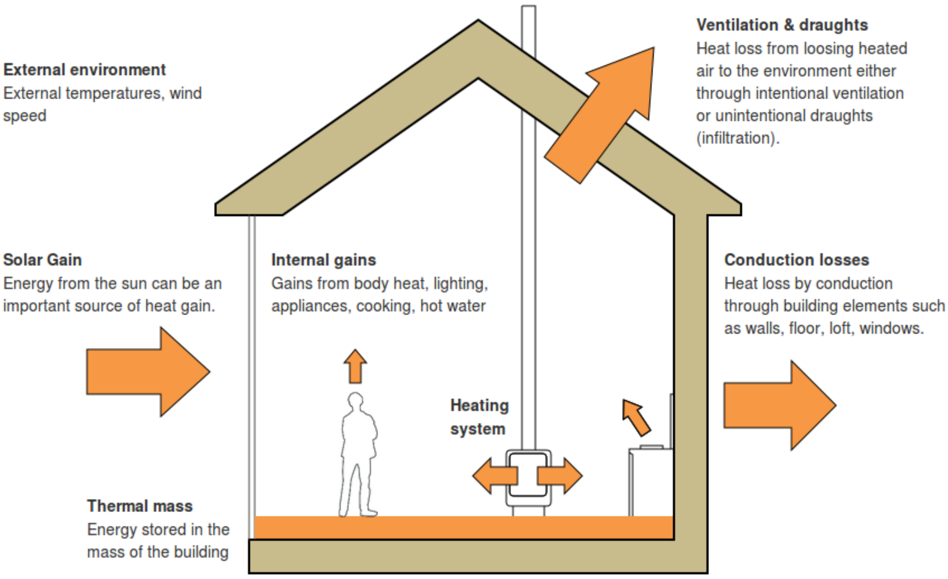


Figure 40 Heat balance of a typical building source:https://learn.openenergymonitor.org/sustainable-energy/building-energy-model/readme

The following heat gains and losses would occur at this typical office building:

5.4.3.1 Transmission

Q transmission, the heat that is transferred through the building envelope is obtained from the following formula.

$$Q\ \text{transmission} = \Sigma U \times A \times (T\ \text{Outside} - T\ \text{inside}) \tag{6}$$

Where U is thermal transmittance of the wall [W/(m2-K)], A is the area of the wall [m2], T outside is outside temperature [degC or K], and T inside = inside temperature [degC or K].

Therefore, the transmission through walls of this building are obtained as in table below when the inside temperature is 25.4 degC and outside dry bulb temperature is 36.24 degC:

Table 12 Q transmission through walls of the selected building.

	Area (m2)	U-value W/(m2·K)]	Q transmission(W)
North wall-glazing	50.93	1.96	1082.079152
North wall-solid	10.35	1.59	178.38
East and west walls-glazing	212.4	1.61	3706.88976
South wall-glazing	55.6	1.96	1181.29
South wall-solid	5.6	1.6	97.12

Hence, Q transmission is computed as 6.24 kW.

5.4.3.2 Ventilation

Q ventilation is the controlled air exchange of a room, and the following formula is used in obtaining results:

$$Q\ \text{ventilation} = V\ \text{ventilation} \times n \times \rho \times cp \times (T\ \text{outside} - T\ \text{inside}) / 3600 \tag{7}$$

In which, V ventilation is the volume of the room [m3], n is air change rate [1/hr], ρ is the density of air [kg/m3], cp is heat capacity of air (at constant pressure) [J/(kg-K)], T outside is outside temperature [degC or K], and T inside is inside temperature [degC or K].

The ventilation gains/losses are calculated having V ventilation of 592 m3, the air change rate of 3 (1/hr) and ΔT of 10.84 degC: Q ventilation= 6.41 kW.

5.4.3.3 Infiltration

Q infiltration is the unwanted airflow through crack and openings in walls and windows and the following formula is used in obtaining results:

$$Q\ \text{infiltration} = V\ \text{inf} \times n \times \rho \times cp \times \left(T\ \text{outside} - T\ \text{inside}\right) / 3600 \tag{8}$$

Where V inf is the volume of the room [m3]. The infiltration heat transfer is calculated having air change rate of 0.7 (1/h), volume of 592 m3 and ΔT of 10.84 degC: Q infiltration= 1.50 kW.

5.4.3.4 Sun

Q sun, is the gains from solar radiation through transparent surfaces of the building which is obtained from the following formula:

$$Q\ \text{sun} = A\ \text{glass} \times q\ \text{sun} \times G\ \text{value} \tag{9}$$

In which, A glass is the area of the glass [m2], q sun is the intensity of the solar load on the glass [W/m2], and 'ZTA' = solar factor (SF, Dutch: ZTA) or g-value according to EN 410 [-]. The solar gains are then calculated having G-value of 0.62, q sun of 0.1, and A glass of 106.53 m2: Q sun= 6.60 k.

5.4.3.5 Internal

Q internal, is the heat that is originated within one space from people, lighting and equipment. With having the data in the below table it can be calculated. It is obtained as Q equipment= 8.47 kW

Table 13 Data for computing the internal load.

1	No. of people	Heat per person (W/person)	-	Q_{people} (kW)
	30	100	-	3
2	Lighten floor percentage	Total floor area (m^2)	Light power (W/m^2)	Q_{light} (kW)
	80%	148	15	1.77
3	Equipment power (W/m^2)	Total floor area (m^2)	-	$Q_{equipment}$ (kW)
	25	148	-	3.7

5.4.3.6 Total load

From the following formula we can obtain the total cooling load.

$$Q\ \text{cooling} = Q\ \text{transmission} + Q\ \text{infiltration} + Q\ \text{ventilation} + Q\ \text{sun} + Q\ \text{internal} \tag{10}$$

Q cooling=29.24 kW at 10 A.M of 15th July.

The results from simulation show a sensible cooling load of 31.53 kW, and it is slightly higher than the manual calculation. This is because there are some minor effects like the transmission between different floors have not been taken into consideration. However, the results are in good agreement and therefore the simulated model is acceptable for further stages.

Temperature and Heat Gains - Untitled, Building 1

EnergyPlus Output

15 Jul (Zone conditions reported for occupied periods, defined by schedule), Sub-hourly

Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00
Air Temperature (°C)	29.66	29.56	21.62	22.06	22.40	22.51	22.25
Radiant Temperature (°C)	29.37	29.37	29.00	28.76	28.37	28.37	28.74
Operative Temperature (°C)	29.51	29.46	25.31	25.41	25.39	25.44	25.49
Outside Dry-Bulb Temperature (°C)	30.20	29.52	29.52	32.21	36.24	39.04	40.50
Glazing (kW)	-0.66	-0.76	1.29	8.23	4.53	4.46	5.76
Walls (kW)	4.07	3.40	6.75	3.76	3.51	3.60	3.92
Ceilings (int) (kW)	-2.12	-1.84	2.38	1.39	2.34	1.67	-0.18
Floors (int) (kW)	-1.45	-1.02	3.00	3.47	3.41	1.33	-2.35
Partitions (int) (kW)	-0.23	-0.03	5.76	0.40	0.34	0.02	-0.17
External Infiltration (kW)	0.14	-0.02	2.24	2.86	3.85	4.55	5.01
External Vent. (kW)	0.00	0.00	0.00	1.17	6.41	7.60	6.28
General Lighting (kW)	0.00	0.00	0.00	1.87	2.09	2.82	2.96
Computer + Equip (kW)	0.19	0.19	0.19	3.38	3.60	3.60	3.60
Occupancy (kW)	0.00	0.00	0.00	0.75	2.97	2.94	2.23
Solar Gains Exterior Windows (kW)	0.00	0.00	11.63	9.17	5.95	6.99	14.11
Zone Sensible Cooling (kW)	0.00	0.00	-29.85	-34.25	-31.53	-31.89	-35.26
Sensible Cooling (kW)	0.00	0.00	-29.85	-35.46	-37.98	-39.47	-41.50
Total Cooling (kW)	0.00	0.00	-29.85	-35.46	-37.98	-39.47	-41.50
Relative Humidity (%)	23.04	23.14	37.65	37.21	37.93	38.77	39.83
Direct Normal Solar (kW)	0.00	0.00	0.34	0.73	0.83	0.86	0.84
Diffuse Horizontal Solar (kW)	0.00	0.00	0.05	0.10	0.11	0.12	0.11
Mech Vent + Nat Vent + Infiltration (ac/h)	0.70	0.70	0.68	0.95	1.77	1.77	1.49

Figure 41 Results from DesignBuilder showing system loads and gains.

5.5 Stage 1, applying strategies individually

In this stage each of the four main strategies are applied individually and the results are compared with baseline model to obtain the reductions or increase in the loads. A short analysis is provided on how this tactic works in reducing the loads and what can be expected in different scenarios. Then results are obtained from simulations and it is studied if the results are in a good agreement with the expected outcome. The iterations of each strategy with an overview of the four stages is shown in the diagram below.

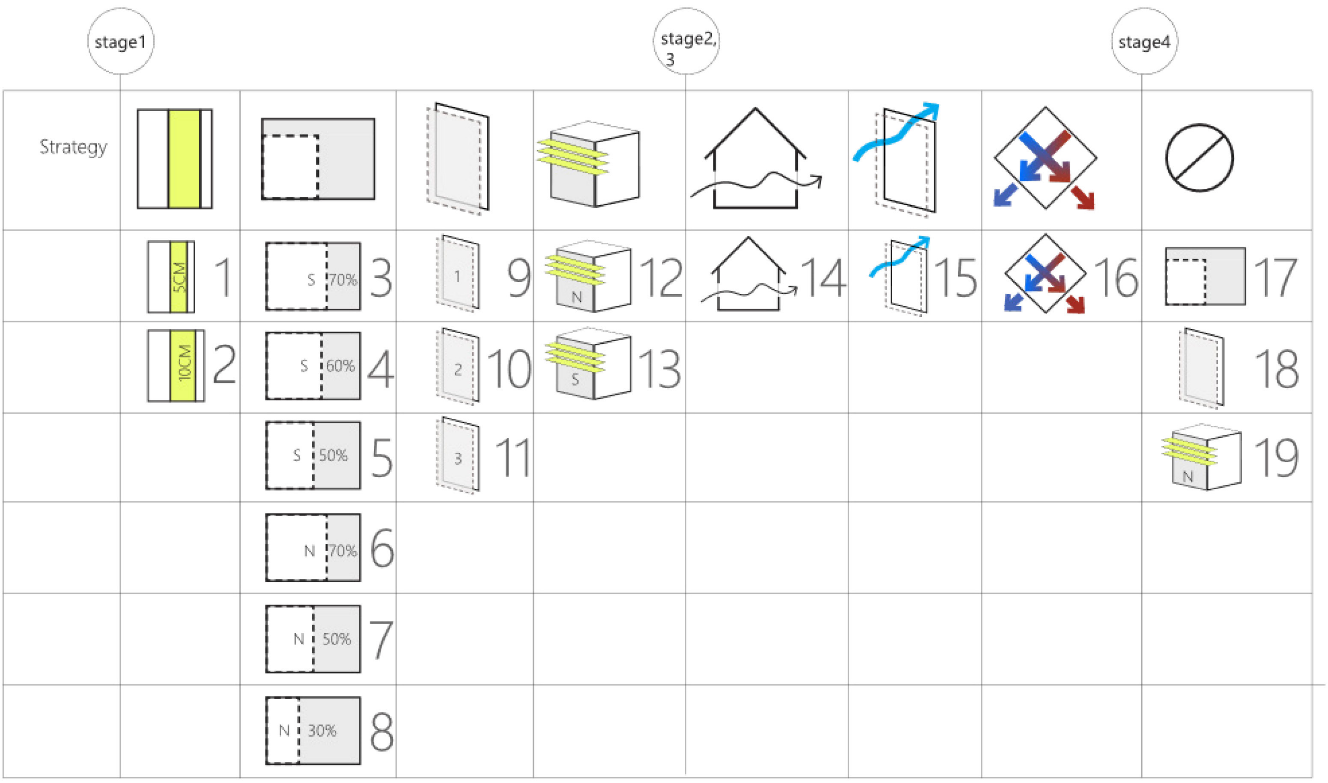


Figure 42 Four stages of reduction in the loads.

5.5.1 Insulation

As seen in the baseline model simulations, lack of insulation in facades and a high U value contributed to the heating and cooling loads. A well-insulated façade is expected to increase the energy performance of the building dramatically. There are two different thicknesses of 50mm and 100mm of R-10 glass fiberboard insulation examined in this study. A relatively good insulation with a high R-value is chosen but the study is limited in terms of material selection to this extent only. This material was chosen because of its availability in building construction in Iran.

It was expected that by doubling the in insulation thickness the R-value would double, however the convection resistance of air which contributes to the overall R-value of wall does not change. Furthermore, it is very unlikely for the heating loads to halve by doubling the thickness of insulation because the infiltration losses and heat losses through conduction of cold bridges are not necessarily decreased. the results are presented as following.

5.5.1.1 50 mm thickness

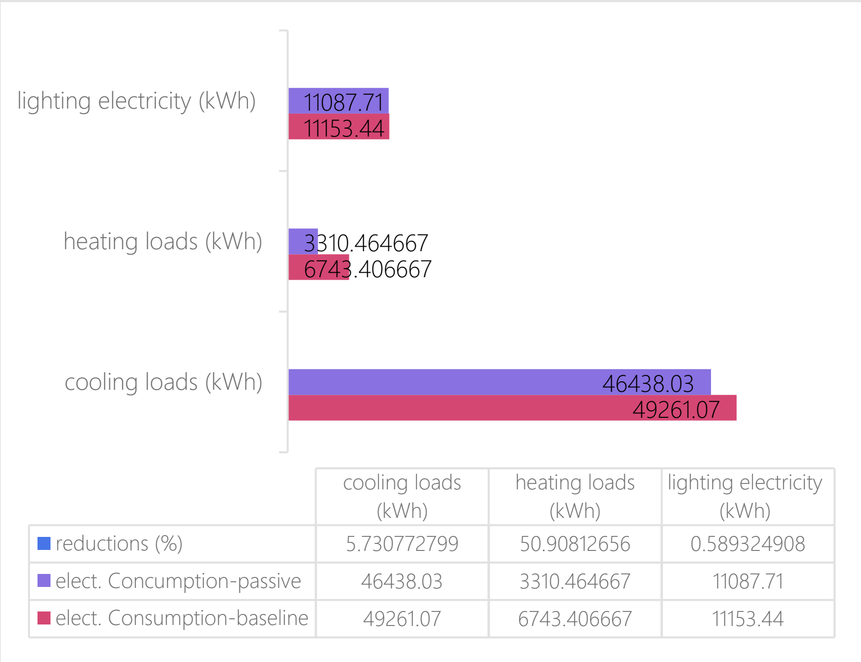


Figure 43 DesignBuilder simulation results depict reductions in annual heating and cooling loads for 50mm insulation thickness.

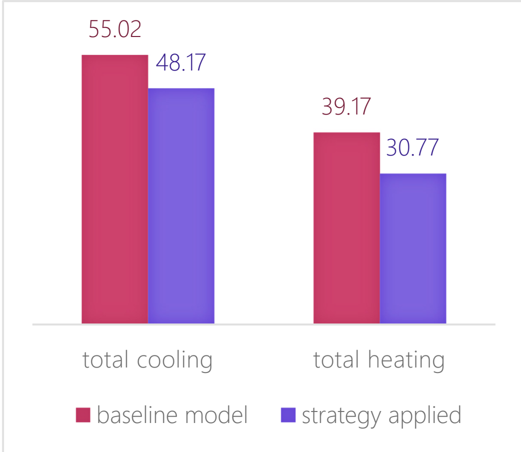


Figure 44 Comparison of the cooling and heating design capacity before and after applying the 50 mm insulation with results taken from DesignBuilder

As can be seen from these graphs the heating design capacity reduced by 21.4 percent compared to the baseline model and the cooling design capacity also decreased by 12.4 percent. The annual cooling and heating loads were reduced by 5.7 and 51 percent respectively. As evident the insulation has more positive impact on the heating loads than the cooling loads.

5.5.1.2 100 mm thickness

The results show a 15.5 and 26 percent reductions in cooling and heating design capacities respectively. The annual heating and cooling loads decreased by 61.1 and 7.3 percent respectively.

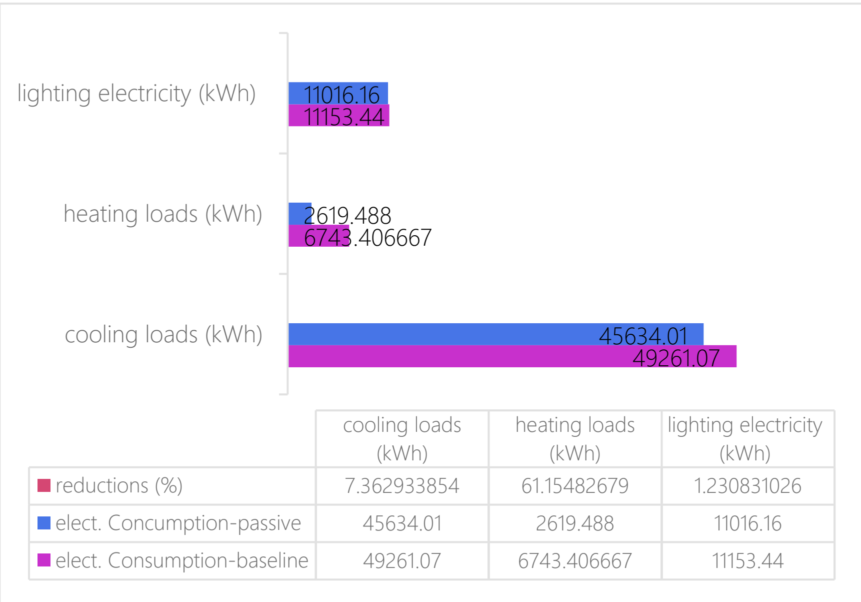


Figure 46 DesignBuilder simulation results depict reductions in annual heating and cooling loads for 100mm insulation thickness.

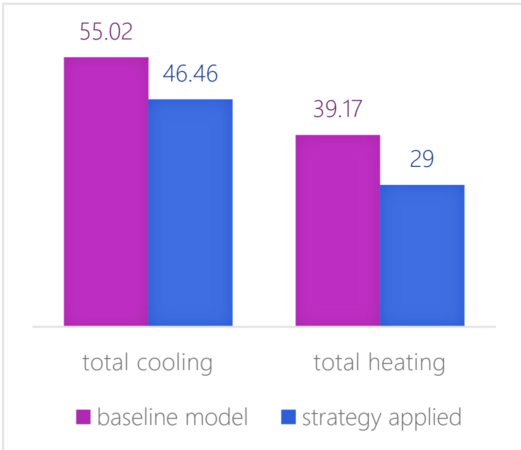
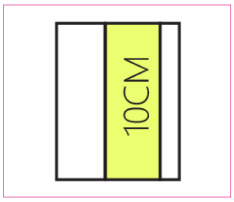


Figure 45 DesignBuilder simulation results depict reductions in annual heating and cooling loads for 100mm insulation thickness.

The decrease in cooling and heating annual and peak loads agrees with the expectations and has not doubled. The U-value decreased from 1.60 W/m2K to 0.3 W/m2K.

5.5.1.3 The chosen scenario



A proper cost analysis in choosing the optimum insulation thickness and material was out scope of this project, therefore as the best results were obtained from 10mm thickness of insulation, this is chosen as the best scenario. 100 mm of R-10 fiberboard insulation then will be applied on all the facades of this building. This strategy will have a 11.74 percent overall annual saving for this building which is a considerable amount of reduction.

5.5.2 Glazing size

The window to wall ratio of a façade indicates the percentage of transparency and changing it hold some basic consequences. By increasing the size of windows in a façade, firstly the total transmission heat transfer through the façade is increased because even the best available glazing types usually have lower R values compared to well-insulated wall constructions and they have more potential for thermal bridges than solid constructions. On the other hand, by increasing the glazing ratio, the solar heat gains through windows are increased. Moreover, it will lead to less electricity consumption for lighting. Therefore, if a façade contributes to reducing the heating loads such as the south façade in this location, increasing the WWR will probably be more beneficial in winter than summer because the cooling loads will be increased.

It must be kept in mind that in this special case as explained before, the cooling loads are of more concerns than the heating loads. Moreover, since the cooling loads are much greater than heating loads in the overall saving calculated, every 25 percent of reduction in heating load in this case leads to 2.5 percent increase in the overall savings. A shading study is therefore done in order to have a better understanding of how each of north and south facades may contribute to heating, cooling and lighting loads.

5.5.2.1 Shadow analysis

The buildings in Tehran are typically only available for windows placement of south and north facades. It can be seen from the graphs that in a summer design day, the south façade is exposed to solar radiation from 11 A.M afterward and this is when the peak loads start to begin. Therefore, as expected increasing WWR on this façade will lead to increase in cooling design capacity. The north façade, however, is exposed to sun only in early mornings in summer where the solar loads are high as well. Therefore, raising the glazing ratio on this façade will also result in higher cooling loads but the effect may not appear as dramatic as on the south façade.

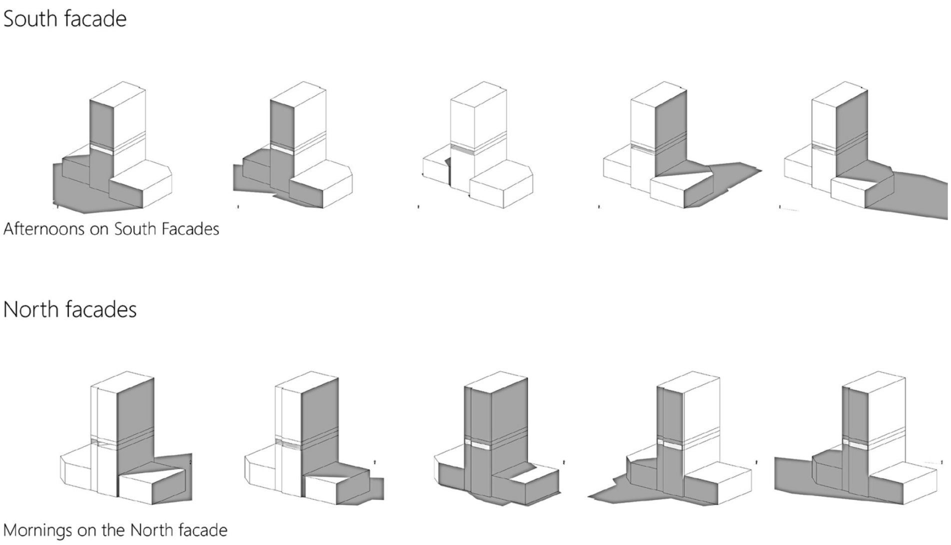


Figure 47 Shadows on south and north facades in summer design day.

The winter shadow analysis however shows that the south façade is more exposed to solar gains than in summer and this agrees with previous assumption that southern facades are beneficial for reducing heating loads. what can be seen on the north façade is that it barely experiences the solar arrays in winter and therefore increasing the WWR on north is not expected to contribute to dropping heating and lighting loads in winter.

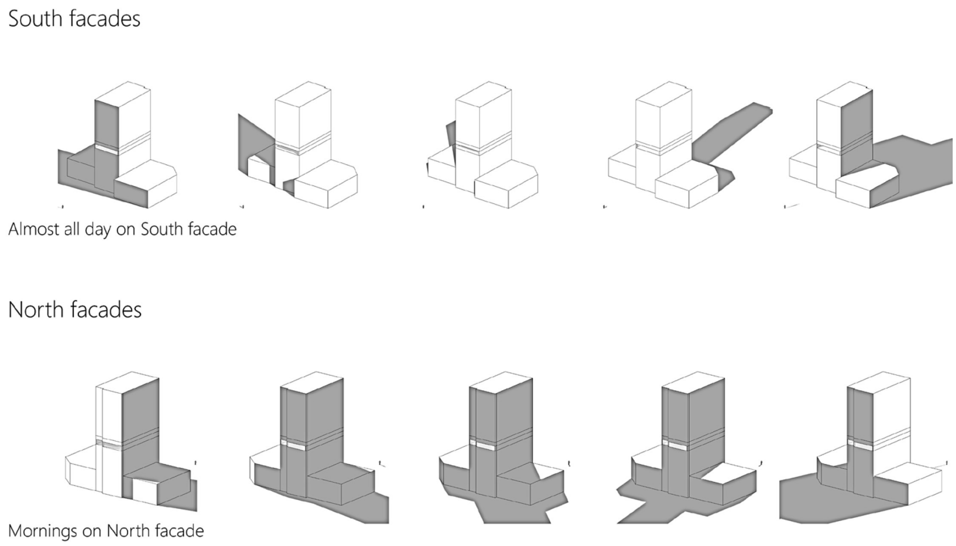


Figure 48 Shadows on south and north facades in winter design day

5.5.2.2 South façade WWR: 70%, 60% and 50%

The results from DesignBuilder for heating and cooling design capacity shows a 4.5 percent increase in the cooling design capacity and a decrease of 25.9 percent in the heating design capacity for the 70% glass setting replacing the glazing with insulated walls. The results are still not positive for cooling design capacity in the 60% WWR scenario and this is not in agreement with the initial expectations and this is probably because the role that lighting power plays in increasing the cooling loads is neglected. This means that 30 percent less glazing has

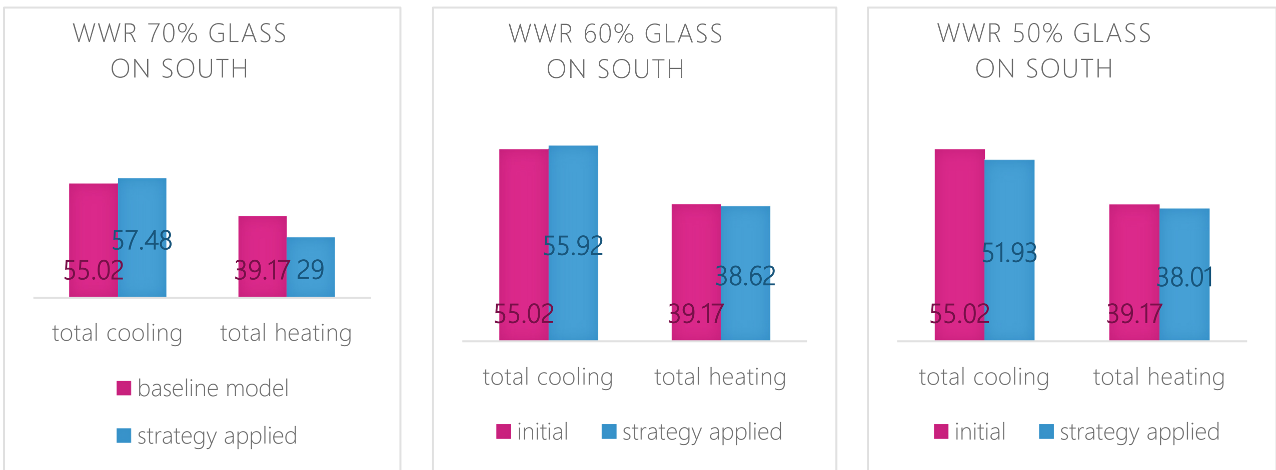
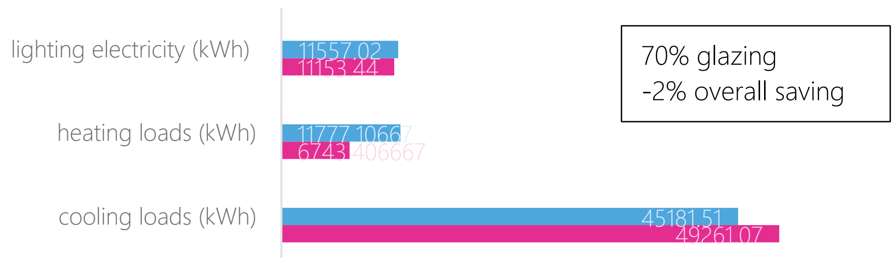


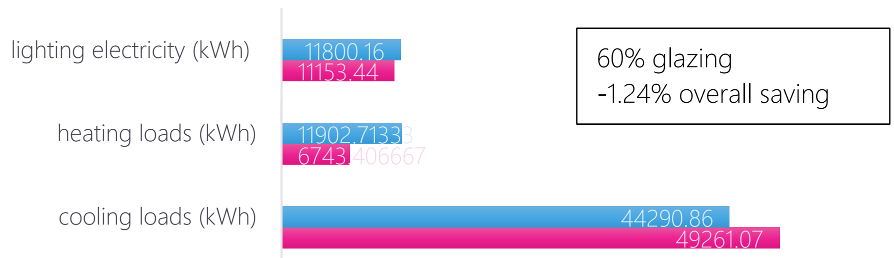
Figure 49 DesignBuilder results of South showing the cooling and heating design capacity in comparison with the baseline model.

A lower contribution in reducing solar heat gains than the increased cooling loads caused by the heat produced by growth in artificial lighting requirements. In the last setting where WWR is 50 percent there is 5.6 and 3 percent reduction in cooling and heating design capacities and what can be perceived here is that only from 50% glazing the reductions in solar heat gains can compete with the increase in internal heat gains due to lighting power.

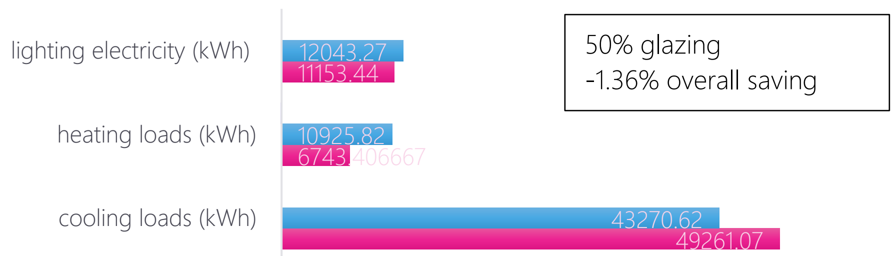
The annual simulations of 70% setting show an 8 percent reduction in cooling loads but a 75 and 3.6 percent increase in heating and lighting loads respectively. The overall saving is a negative 2 percent which makes this setting not a very suitable scenario. The loads do not change significantly from 70 to 60 percent glazing and the annual savings rate remains negative in 60% glazing setting as well. In 50 % glazing the heating loads savings improve slightly and the annual overall savings become 1.3 percent.



	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	8.281509111	-74.64624705	-3.618435209
elect. Concumption-passive	45181.51	11777.10667	11557.02
elect. Consumption-baseline	49261.07	6743.406667	11153.44



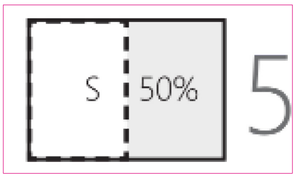
	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	10.08952911	-76.50890598	-5.798390452
elect. Concumption-passive	44290.86	11902.71333	11800.16
elect. Consumption-baseline	49261.07	6743.406667	11153.44



	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	12.16061689	-62.02226175	-7.978076719
elect. Concumption-passive	43270.62	10925.82	12043.27
elect. Consumption-baseline	49261.07	6743.406667	11153.44

Figure 50 DesignBuilder simulation results depict reductions in annual heating and cooling loads for 70%, 60%, and 50% WWR on South.

5.5.2.2.1 The selected scenario



As seen in these simulations, changing the WWR on south façade does not have a very positive influence on the energy performance of this building. This is probably because the openings on this façade contribute a lot to the passive heating and providing natural light for the interior spaces. However, since the active façade located on this façade occupies a percentage of the opaque façade, 100% glazing is not available for this façade and 50% glazing is chosen for this envelope.

5.5.2.3 North façade WWR: 70%, 50% and 30%

The results of design capacity simulations show positive impacts for reducing the glazing ratio of the 95% transparent façade of north. This façade does not contribute a lot to the passive heating of interior spaces and lighting and therefore by reducing the WWR the heating design capacity is also decreased. however, since in summer this façade has a positive impact on providing natural lighting it can be seen that the cooling design capacity is increased slightly compared to the baseline model in 70% glazed setting.

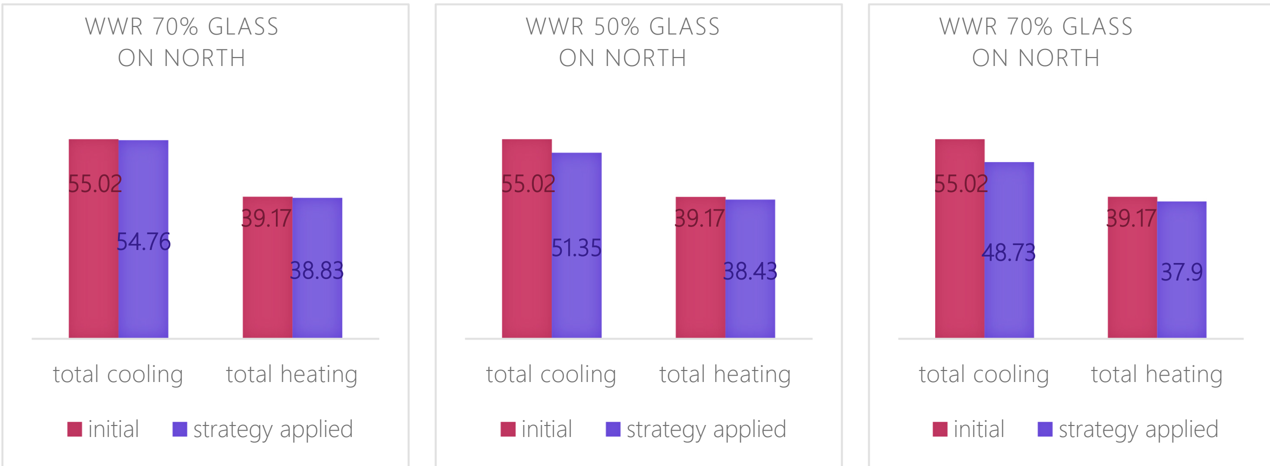
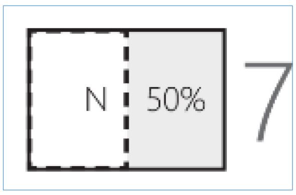


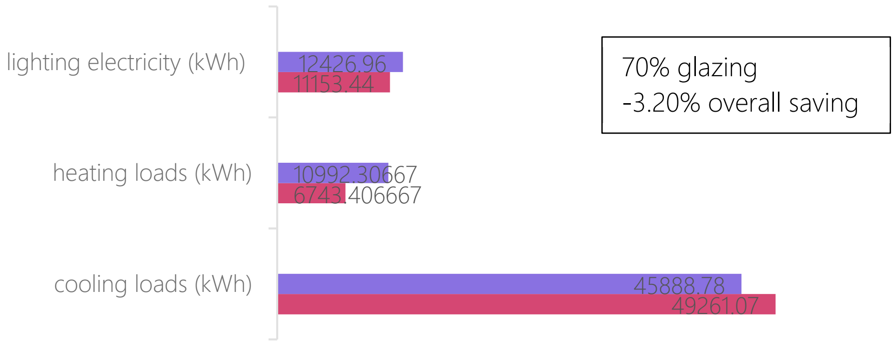
Figure 51 DesignBuilder results of North showing the cooling and heating design capacity in comparison with the baseline model.

The annual energy consumptions, however, show that by reducing the glazing ratio on this façade the heating and lighting loads drop so significantly that the annual overall saving in all 3 settings is either negative or only slightly positive. This means that the slight morning sun rays that drop on this façade help significantly in reducing the heating loads annually.

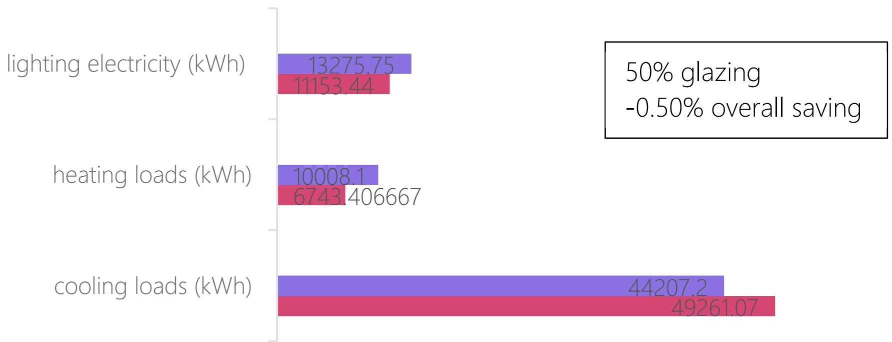
5.5.2.3.1 The selected scenario



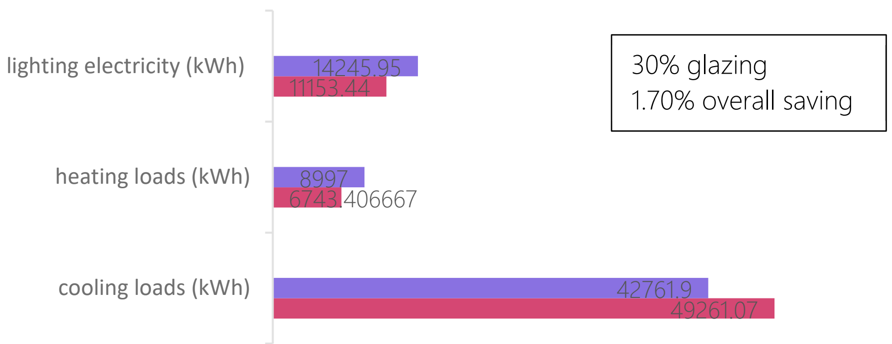
As explained before the main goal of this passive applications are reducing firstly the cooling design capacity. therefore, even though reducing the WWR on this façade is not very beneficial in overall, the 50% glazed setting is selected.



	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	6.84575061	-63.00821247	-11.4181813
elect. Concumption-passive	45888.78	10992.30667	12426.96
elect. Consumption-baseline	49261.07	6743.406667	11153.44



	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	10.25935896	-48.41311661	-19.02829979
elect. Concumption-passive	44207.2	10008.1	13275.75
elect. Consumption-baseline	49261.07	6743.406667	11153.44



	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	13.19331878	-33.41921146	-27.72696137
elect. Concumption-passive	42761.9	8997	14245.95
elect. Consumption-baseline	49261.07	6743.406667	11153.44

Figure 52 DesignBuilder simulation results depict reductions in annual heating and cooling loads for 70%, 50%, and 30% WWR on North

5.5.3 Glazing type

In choosing the proper glazing type two main factors should be considered which are the Spectrally Selectivity of the glazing and its U-value. It is expected that by having Low-E windows with high visible transmittance and low solar transmittance the natural lighting effect of the window is not reduced but excessive heat gains are. On the hand this leads to increasing of the heating loads because heat gains through windows in winter are reduced, but since the U value of the new glazing is probably lower, the performance of the glazing in the cold season is expected to remain almost the same. Applying Low-E coatings with high visible transmittance to solar transmittance ratio would be especially effective on the south façade which contributes significantly to the cooling loads.

Table 14 The specification of glazing that have been applied in this study.

	Outermost Layer	Gas layer	innermost layer	Visible transmittance	Solar transmittance	U-value (W/m^{2}K)	Outside emissivity	Inside emissivity
Glazing 1	Low-E	10mm Ar gas	Clear float glass	0.76	0.37	1.40	0.84	0.04
Glazing 2	Low-E	10mm Ar gas	Clear float glass	0.71	0.27	1.36	0.84	0.02
Glazing 3	Low-E	10mm Ar gas	Clear float glass	0.35	0.15	1.38	0.84	0.03

5.5.3.1 Glazing type 1, 2 and 3

The VT/ST of these three glazing types that are applied on both south and north facades are 2.05, 2.63 and 2.33 respectively. The results from heating and cooling design capacity at peak summer and winter days in simulations show 18.1, 24.3 and 25.2 percent reductions in cooling design and 3.5, 3.7 and 3.6 percent decrease in the heating design capacity respectively. As evident from the graphs the type of glazing is more beneficial for summer situation than winter especially because the interior zones will benefit less from solar gains in winter although heat losses are reduced due to lower U-values.

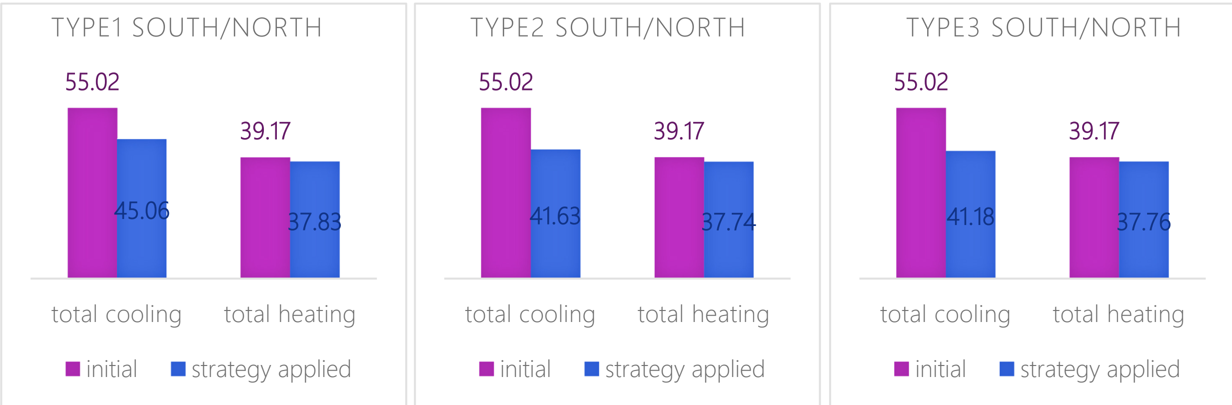
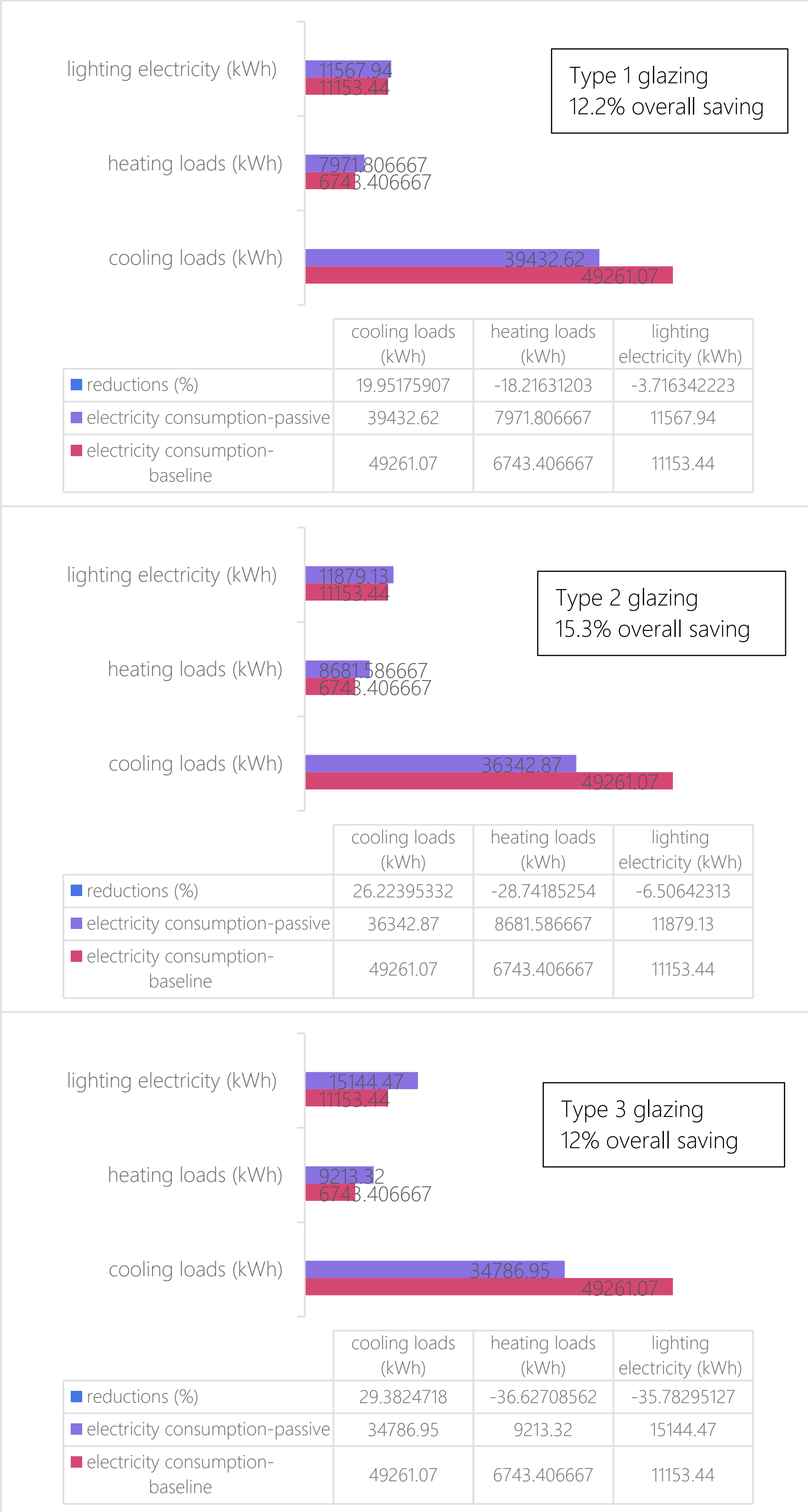


Figure 53 DesignBuilder results showing the cooling and heating design capacity in comparison with the baseline model for various types of glazing.

The annual simulation results show a reduction of 12.2, 15.3 and 15.1 percent in the overall electricity consumption of heating, cooling and lighting. The simulations prove that changing the glazing type in a building as such is a very beneficial strategy in reducing energy demands.



	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	19.95175907	-18.21631203	-3.716342223
electricity consumption-passive	39432.62	7971.806667	11567.94
electricity consumption-baseline	49261.07	6743.406667	11153.44

	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	26.22395332	-28.74185254	-6.50642313
electricity consumption-passive	36342.87	8681.586667	11879.13
electricity consumption-baseline	49261.07	6743.406667	11153.44

	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	29.3824718	-36.62708562	-35.78295127
electricity consumption-passive	34786.95	9213.32	15144.47
electricity consumption-baseline	49261.07	6743.406667	11153.44

Figure 54 Comparison of the results obtained from changing the glazing type.

5.5.3.2 The selected scenario

The most beneficial scenario amongst the three types of glazing applied in this building is Type 2 with the highest visible transmittance to solar transmittance ratio. The third type of glazing has slightly a higher decrease in the cooling design capacity however the annual saving of this type is much lower compared to type 2.

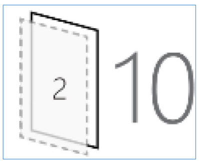


Table 15 Results obtained from changing the glazing type

	Type 1 reduction%	Type 2 reduction%	Type 3 reduction%
Cooling design capacity	18%	24.5%	25%
Heating design capacity	3.5%	4%	4%
Annual cooling demand	20%	26%	30%
Annual heating demand	-18%	-29%	-37%
Annual lighting elec. demand	-4%	-6.5%	-36%
Overall saving	12.2%	15.2%	12%

5.5.4 Shading

The existing shading device that is design by the architects of the project are vertical louvers attached to the façade with a gap of 90cm and attached to beams stretching out from the structural beams. However, as the following graphs show the north façade has a peak rise at around 7 AM, when the sun is rising and shining on the North façade. A proper shading device can help to reduce the peak loads caused by this façade.

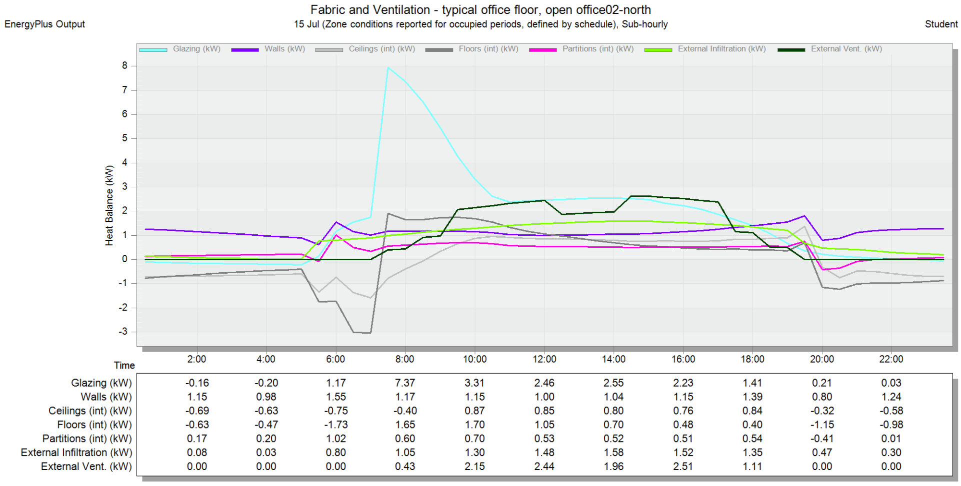


Figure 55 DesignBuilder simulation results show the peak loads caused by glazing on the North façade in the early hours of the day.

5.5.4.1 North shading

This façade is exposed to solar radiation in early mornings of summer and therefore the solar gains are high in summer. However, in winter this façade is never exposed to sun and this simplifies application of sunshades. It is obvious that this façade preventing the sunrays in early morning in summer from East has to be vertical due to solar altitude and azimuth angles.

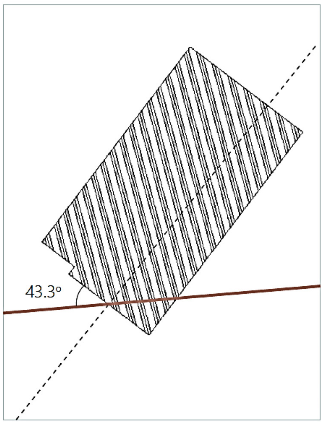


Figure 56 Determining the angle of the shading device based on solar azimuth angle

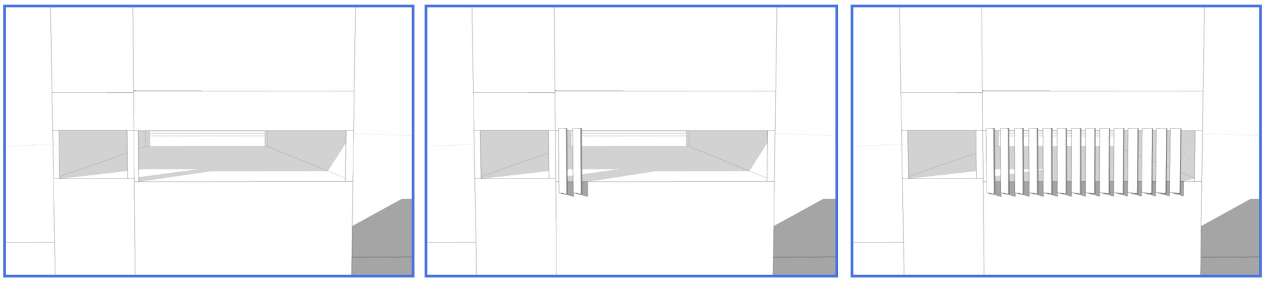


Figure 57 The effect of applying shading on the Northern façade

According to calculation the best angle for shading devices on the North glazing is 43.3 deg considering the solar azimuth degree of 85 deg at around 7 in the morning and a tilt of the façade according to north of 37.2 deg. this façade was implemented with a depth 50 cm of vertical louvers and in the shadow analysis it is evident that it blocks all the direct sunlight from entering the northern zones.

Simulations in DesignBuilder show promising results as well. 11.6% reductions are achieved in the cooling design capacity and no reductions are apparent the in the cooling design capacity.

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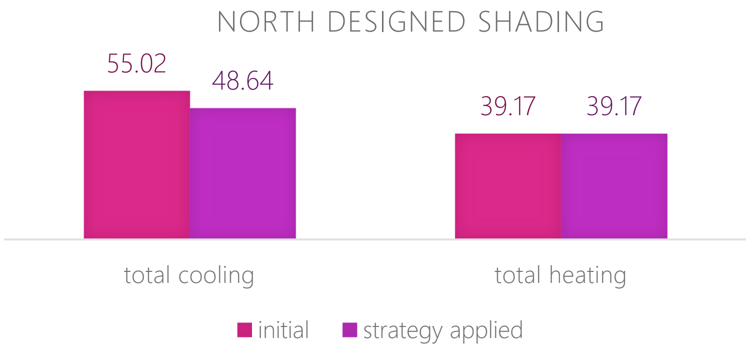
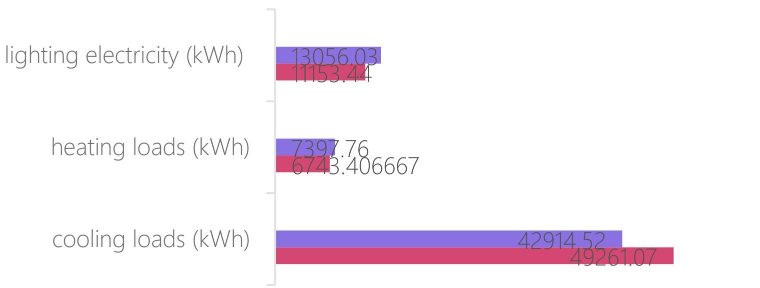


Figure 58 DesignBuilder simulations showing reductions in heating and cooling design capacities for North designed shading.

The annual results show an overall saving of 5.6% on the heating, cooling and lighting electricity consumption. The cooling loads are reduced by 12.9 and heating loads by 9.7 percent. The lighting electricity consumption, however, is as expected increased by 17 percent.



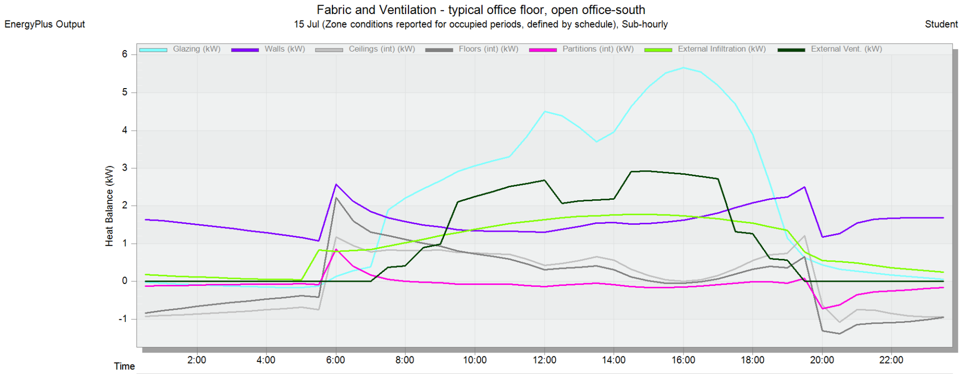
	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	12.88350009	-9.703601839	-17.05832461
electricity consumption-with	42914.52	7397.76	13056.03
electricity consumption-without	49261.07	6743.406667	11153.44

Figure 59 Comparison of the results obtained from applying the shading on north.

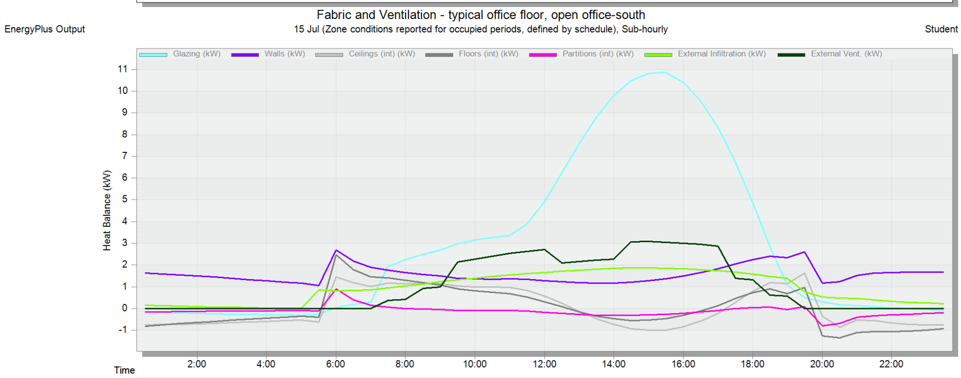
Overall the shading device on north seem to be a moderate way in decreasing the annual and peak loads and this is mainly because the savings in the cooling loads is being overwhelmed by the increase in lighting electricity consumption.

5.5.4.2 South shading

The existing shading device on the South as seen in the graphs is decreasing the peak loads in the summer design day in the south office zone by almost half and it proves to be a very effective tool in reducing the peak loads. The advantage of this shading device is that although it prevents most of the solar radiation from entering the southern spaces, it does not block the view of people working while walking and being sited.



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Glazing (kW)	-0.09	-0.15	0.14	2.20	3.06	4.50	3.96	5.67	3.89	0.43	0.17
Walls (kW)	1.51	1.28	2.58	1.58	1.34	1.30	1.55	1.63	2.09	1.18	1.67
Ceilings (int) (kW)	-0.87	-0.75	1.18	0.82	0.75	0.42	0.56	0.01	0.55	-0.63	-0.85
Floors (int) (kW)	-0.67	-0.47	2.22	1.11	0.73	0.31	0.31	-0.05	0.32	-1.32	-1.09
Partitions (int) (kW)	-0.10	-0.07	0.85	0.00	-0.07	-0.14	-0.09	-0.15	-0.02	-0.72	-0.25
External Infiltration (kW)	0.11	0.06	0.80	1.02	1.38	1.64	1.77	1.73	1.54	0.55	0.36
External Vent. (kW)	0.00	0.00	0.00	0.41	2.25	2.69	2.19	2.85	1.27	0.00	0.00



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
Glazing (kW)	-0.23	-0.28	0.04	2.26	3.15	4.92	9.80	10.39	4.87	0.30	0.03
Walls (kW)	1.50	1.28	2.69	1.65	1.37	1.29	1.18	1.50	2.25	1.16	1.66
Ceilings (int) (kW)	-0.70	-0.59	1.46	1.15	1.00	0.58	-0.74	-0.84	0.78	-0.36	-0.66
Floors (int) (kW)	-0.64	-0.44	2.47	1.30	0.82	0.31	-0.47	-0.31	0.73	-1.25	-1.06
Partitions (int) (kW)	-0.13	-0.10	0.90	0.01	-0.09	-0.17	-0.31	-0.21	0.05	-0.79	-0.29
External Infiltration (kW)	0.09	0.03	0.82	1.04	1.40	1.66	1.85	1.83	1.60	0.53	0.33
External Vent. (kW)	0.00	0.00	0.00	0.42	2.28	2.71	2.27	3.01	1.33	0.00	0.00

Figure 60 Designbuilder simulations showing the reductions in peak of internal gains by glazing

Therefore, the southern shading devices besides contributing to the architectural intentions of the architect, help significantly in reducing the peak and annual loads and therefore, this shading will remain on the south for this design. However, the form and configuration of this shading device has to undergo a few changes in order to be able to accommodate PV panels on it. The details on the new design of the shading will be provided later in the design stage, but to assure that enough area is provided for the PV panels, some basic specifications are presented in this section.

The number of shading louvers in the new design is reduced to 4 with a 30o angle and the depth is increased to 50 cm to prevent over shading of the louvers on each other as well as providing maximum area. More studies need to be done on the shading and how distant they are from each other in order to avoid shading one another.

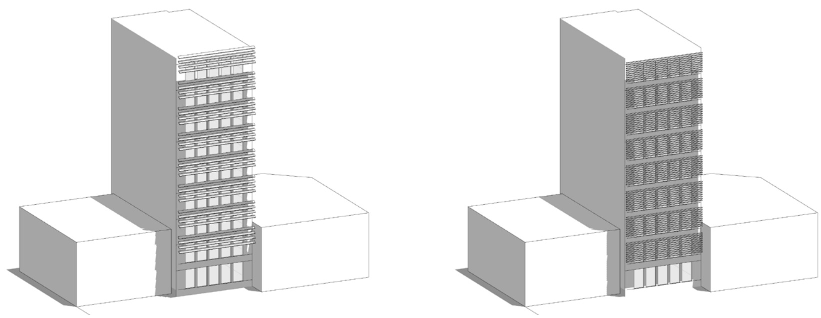


Figure 61 The adjusted (left) and the original design of the shading devices on the South façade.

5.6 Stage 2 and 3, Adding all the main and secondary strategies

In this stage when finally, all the different scenarios of passive strategies were examined, all of them are added to one model including the secondary strategies being natural ventilation and reduced infiltration rate. It is important to note that using a heat recovery and an economizer would have also helped in reducing the loads further. However, since the active TE cooling system will act as a heat recovery in using the exiting ventilated air to reduce the ΔT, this passive strategy will not be considered in this stage. The reason why some of these strategies are referred to as secondary is that they were not as deeply studied as the previous strategies were and they were implemented in this model in the simplest way.

The infiltration rate was reduced from 0.7 to 0.1 which is a good value for newly built buildings. In the design of the façade a special attention must be given to detailing and airtightness of the façade to achieve this value.

Natural ventilation in this design is not expected to help with reducing the peak demand because the wind speed during a design day in summer is negligible as in figure 53. Also, during peak-hours, natural ventilation would not be useful due to very high outside temperature. But it can help in reducing the annual cooling consumption.

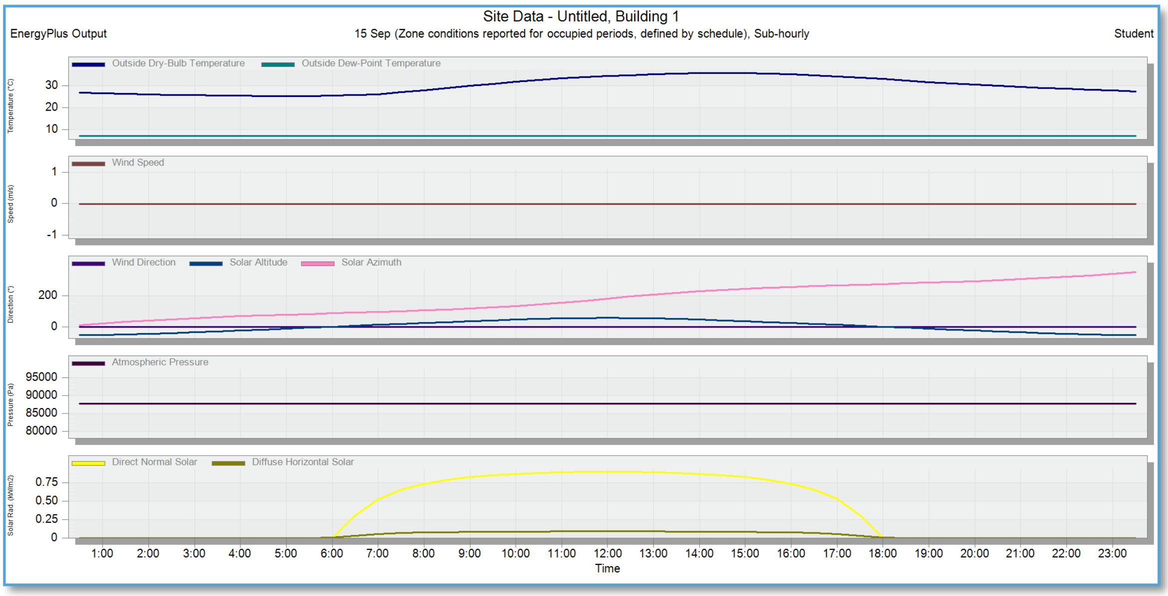


Figure 62 DesignBuilder graph showing no air movement during design day

The final results of simulation in this stage prove that some of the strategies are overlapping or adversely affecting the results of one another. However, the promising outcome of implementing these passive strategies is 49 and 51 percent reductions in the cooling and heating design capacities respectively.

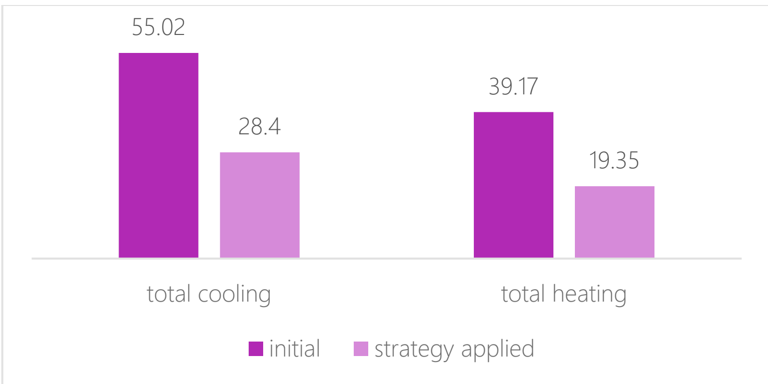
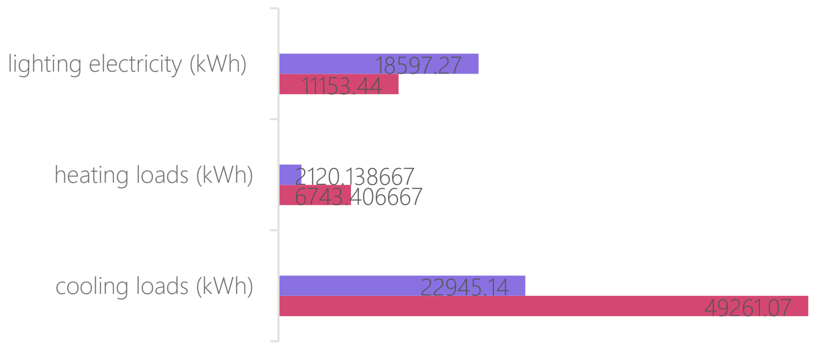


Figure 63 reductions in cooling and heating design capacities

The annual electricity consumption results however are significantly affected by 67 percent increase in the lighting electricity consumption. The annual cooling electricity consumption is reduced by 54 percent while the heating electricity loads are decreased by 69 percent. However, an annual overall saving of 35 percent is achieved at this stage.



	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	53.4213528	68.55982782	-66.74021647
electricity consumption-with	22945.14	2120.138667	18597.27
electricity consumption-baseline	49261.07	6743.406667	11153.44

Figure 64 annual savings in the electricity consumption of heating, cooling and lighting.

5.7 Stage 4, excluding the overlapping strategies

As explained before, it is obvious that some of the strategies would be overlapping each other, for instance glazing type, reduction in the window to wall ratio and shading devices are all contributing to reducing peak loads imposed by the windows, some by reducing the solar heat gains and others by reducing losses through windows or both.

In this section each of the strategies were excluded from the developed model in previous sections and the increase in the loads as a result of this change is simulated. This means that all the main and secondary strategies applied to the main model are excluded from the model to measure the effect of this exclusion. The ones with the least impact on the overall results can then be excluded from the final model since it proves that it has insignificant effect on reducing the loads. DesignBuilder simulation results are presented in the following table.

Table 16 simulated results from excluding each of strategies from the final model

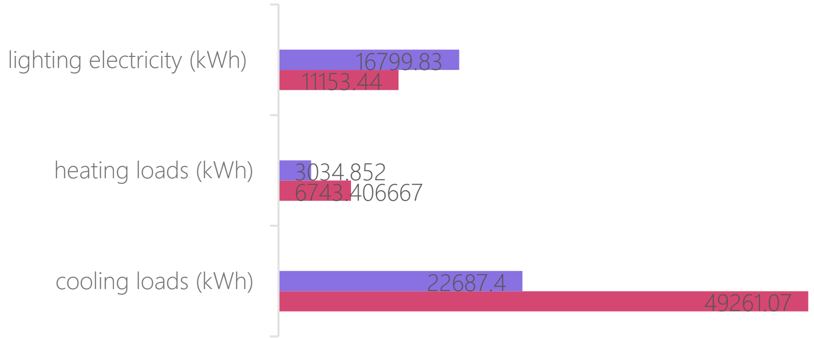
Removing/ changing	Shading Device			Glazing Type			WWR(100% north/ 70% south)		
increase (%)	cooling	heating	overall	cooling	heating	overall	cooling	heating	overall
North-annual	1.58	0.85	1.38	12.95	6.81	2.47	2.47	66.70	2.57
North-Design capacity	0.13	0	-	6.64	1.75	-	3.18	3.72	-
South-annual	-	-	-	22.93	-40.6	3.12	-1.65	69.34	1.35
South-Design capacity	-	-	-	23.01	2.22	-	2.43	2.86	-

As seen from the results the shading device on north has the least impact on the design capacity and annual reductions of cooling and heating, and therefore it can be removed from the final model without imposing significant changes on the final results.

5.8 Conclusion

5.8.1 Annual electricity consumption and PV production

The final scenarios implemented in this stage of the design to reduce the cooling and heating design capacities as well as annual heating, cooling, and lighting consumption are as shown in the following diagrams.



	cooling loads (kWh)	heating loads (kWh)	lighting electricity (kWh)
reductions (%)	53.94456515	54.99526945	-50.62465033
electricity consumption-with	22687.4	3034.852	16799.83
electricity consumption-baseline	49261.07	6743.406667	11153.44

Figure 65 Annual demands simulated with the final model

The annual results show an overall decrease of 37 percent in the cooling, heating and electricity consumption. It is necessary to note again that these percentages are based on electricity consumption that is calculated assuming a cooling COP of 1 and heating COP of 1.5. Later more exact calculations are driven, these results could be updated with actual COP values to investigate the actual reductions in electricity consumption. As can be seen from the following graph only a very small portion of electricity demand is dedicated to heating and this is partly due to higher COP of heating.

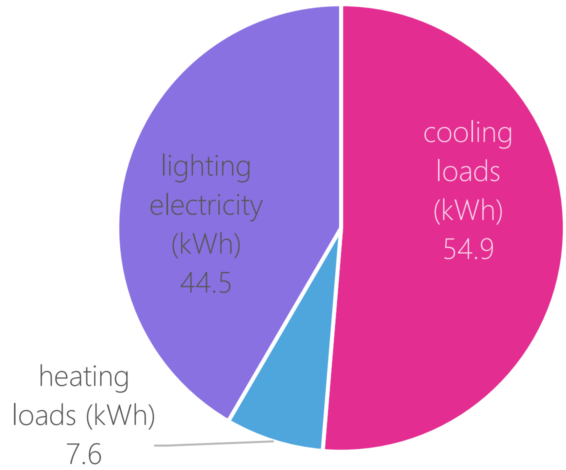
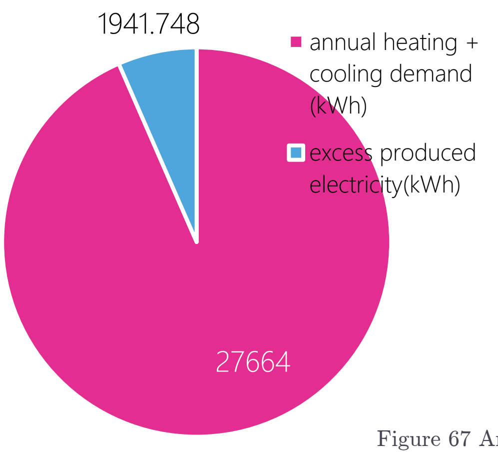


Figure 66 Reduced annual cooling, heating and lighting electricity consumption per m2



The main concern of this design, therefore, is to enhance the performance of the cooling system to help decrease the cooling loads and to reduce the lighting electricity demand there are some strategies available such as using smart systems.

Figure 67 Annual electricity consumption of heating and cooling vs PV production (kWh)

As seen from graph 66, the PV production can cover the heating and cooling loads with COP of 1.5 and 1, and there will be some excess production as well. However, the lighting loads will not be covered by PV panels. For this building to rely entirely on solar energy and cover all electricity consumptions such as domestic hot water and equipment as well as lighting, more PV panels should be placed at nearby places. In the next section, there will be an effort in increasing the COPs and reducing the electricity consumption to help in decreasing the annual energy demand of this building.

5.8.2 Cooling and heating design capacity and PV production during peak

As shown in the following graph, the passive measures taken as explained in previous sections have resulted in 49 and 50 percent reductions in the cooling and heating design capacity respectively.

The cooling design capacity is still more than the heating design capacity, and this is not considering the COPs of system. this means that in terms of design capacity it is best to design the system sizing based on the cooling loads since the COP is lower and the loads are higher.

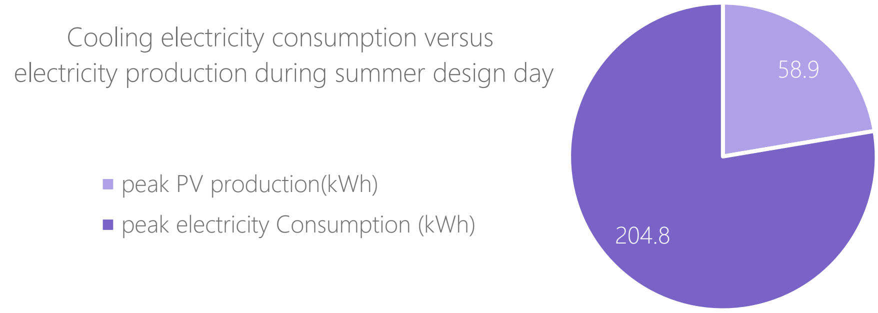


Figure 69 Cooling electricity consumption vs electricity production by PV panels per floor

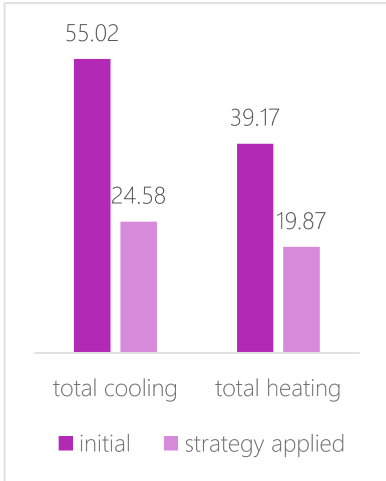


Figure 68 Final simulations showing the reductions in the design capacity

The comparison between the electricity consumption and production by PV during the summer design day, assuming a COP of 1 for cooling shows that the electricity produced by PV panels is only able to cover a small portion of the peak day consumption and only an average COP of 4.5 is able to make these two values meet. This means that being able to design a system where no electricity from the grid necessary to provide cooling in a peak summer design day is very unlikely.

Final simulation results are presented in the following table in short:

Table 17 Overview of the results obtained by implementing passive strategies

	Cooling(kWh)	heating(kWh)	lighting(kWh)	Cooling design capacity(kWh)	Heating design capacity(kWh)
Load-No passive	49261.0	10115.1	-	55.0	39.2
Electricity-No passive	49261.0	6743.4	11153.4	-	-
Load-all passive	22687.4	4552.2	-	24.58	19.9
Electricity-all passive	17974.3	3034.8	16799.8	-	-
Reduction (%)	54	55	-50.6	49	39

6 Active system design

In this section design of the active system that provides heating and cooling requirements of one floor of the office building described in previous section is explained. Since the cooling design capacity of this building is around 1.2 times higher than the heating design capacity and also the COP of cooling is as a general rule higher than the COP of cooling, it is obvious that the cooling system design of this building is more challenging than its heating design. The cooling design is therefore what will be the base of all calculations in this section assuming that if cooling design capacity is covered with a certain COP, the heating design capacity will be covered with a higher COP.

Figure 70 diagram showing that Qhot and therefore COP of heating is always higher than Qcold and cooling COP

6.1 Introduction

Like any other cooling system, the main goal of this thermoelectric cooling system is to firstly cover all the required cooling design capacity, in other words as the main provider of cooling for the room being capable of providing thermal comfort even in a day with highest cooling demands or the cooling design day. The second goal is to have as high as COP as possible to minimize the electricity consumption of the system while minimizing the consequences such as higher initial investment costs.

In this thermoelectric cooling design as will be shown later there are many criteria that have simultaneous effect on each other. Since the most important criteria in the design process was to determine the loads for which the active system is designed, a room model is explained in short firstly, and then the initial step would be to select the most proper thermoelectric module from ranges of thermoelectric modules available commercially to cover the cooling demands. Selection of the most proper heat sink will help in the cost analysis in the next stage which helps in determining the number of TE modules. As the number of modules are determined, a certain COP will be expected from the TE system which will be discussed at the end of this chapter.

6.2 A thermodynamic room model

It is important in this stage to have an overview of the stationary heat balance model of the spaces for which cooling is provided. The results presented here are the outcome of the Designbuilder model, and therefore this is where the cooling system design gets synced with the results of passive strategies provided by simulations in previous sections. From this stage separate models, estimations and later a parametric solver will be developed for the active cooling system.

As seen in this model, the $Q_{total\ cooling}$ that has been used in the passive stage and will be used in the active system design is a load that covers all the heat gains during peak of cooling consumption. Therefore, this is the overall cooling load that the TE system has to cover to provide minimum fresh air and thermal comfort for the room.

It is important to note that having a heat recovery that lead to reductions in $Q_{ventilation}$ are not taken into account here because the thermoelectric system itself works as a heat recovery that uses the cold air extracted from indoor spaces to reduce the temperature difference between hot and cold sides.

In Eq. 11, $Q_{total\ cooling}$ is 24.58 (kW) as the result of taking all the passive strategies, as explained in chapter 5.

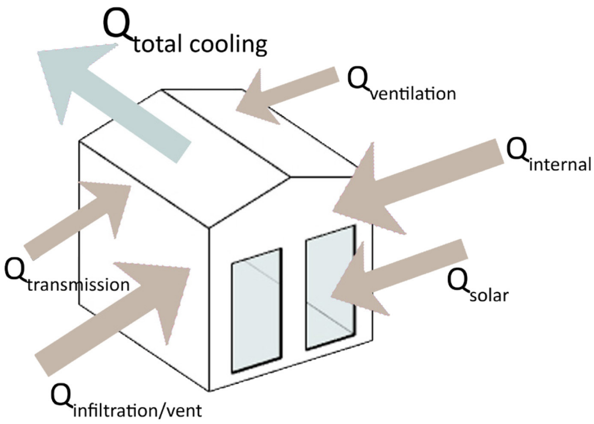


Figure 71 Stationary office model provided by Designbuilder

$$Q_{total\ cooling} = Q_{infitrationventilation} + Q_{transmission} + Q_{Solar} + Q_{internal\ gains} + Q_{ventilation} \quad (11)$$

6.3 Selection of Thermoelectric module

The initial step in the design of this system is to define which thermoelectric module with what maximum cooling capacity must be selected. Several TE modules available on the market from QUICK-OHM in Germany were compared here. As it is observed this technology is going through rapid developments, and at the time of this project the highest cooling power of TE modules was Q_{max}=430 W, the results of these simulations is subject to change with a different TE module selection but the methodology used will remain the same.

6.3.1 Introduction

For every TE module, the manufacturer provides specifications that are important in the calculations that follow. An example is provided here to show what information is provided by QUICK-OHM for a certain product.

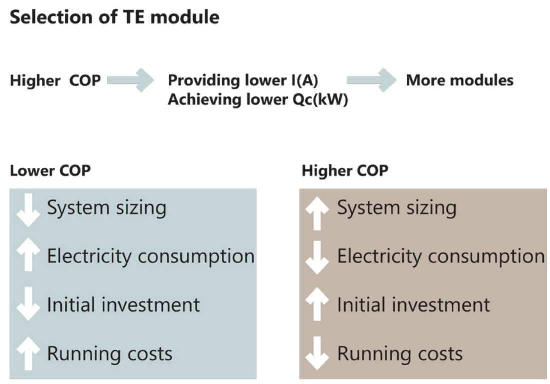


Table 18 Performance data of TE module QC-71-2.0-15.0M

I_{max} (amps)	12
V_{max} (volts)	8.3
ΔT_{max} (°C)	71
Q_{max} (W)	63.8
AC resistance (ohms)	0.56
Number of couples	71
Dimensions (mm)	40*40*3.8

6.3.1.1 Performance graphs

The performance of modules is different for every T_h which is the hot side's working temperature, and as seen in graphs the performance is better in conditions with higher hot side temperature. This is due to increase in the Seebeck coefficient and changes in Thompson coefficient as a temperature dependent variable.

The following graphs provided by the manufacturer are at a T_h=25°C

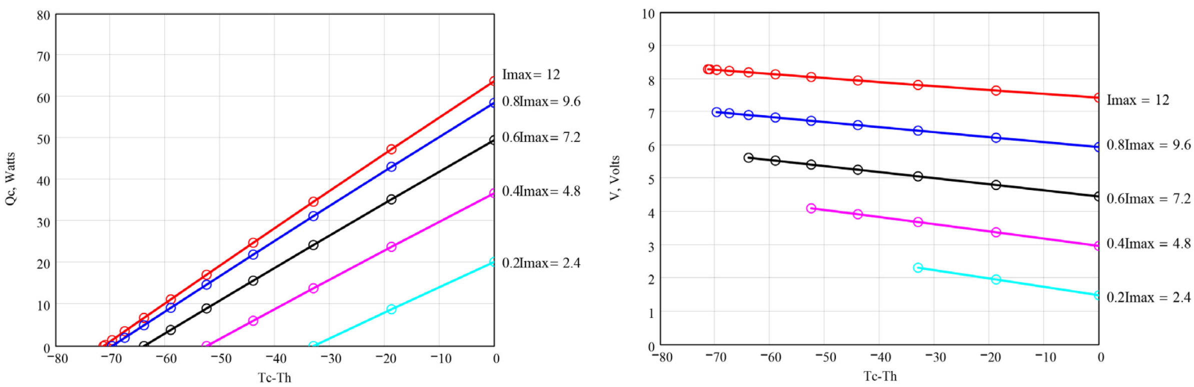


Figure 72 Performance graphs of TE module QC-71-2.0-15.0M provided by QUICK-OHM, source: https://www.thermo-management.com/peltierelemente/peltier-elemente˙einstufig/peltier-elemente-standard.html

Based on these graphs for a constant ΔT, Q_c(W) and V(v) can be extracted for ranges of electrical current I(Amps) and therefore COP graphs can be drawn for a constant ΔT and different I(Amps) from the following formulas for constant ΔT:

$$Q_w = V \times I \quad (12)$$

In which V is the required voltage, and I is electric current in Amperes, and therefore cooling COP can be calculated as follows:

$$COP_{cooling} = Q_r \, / \, Q_W \quad (13)$$

In which Q_c is the cooling load provided by manufacturer in performance graphs. Therefore, for every range of electrical current I, with an assumption of ΔT=10°C, Qc is obtained, and the number of modules necessary to cover the $Q_{total\ cooling}$ is calculated from the following formula.

$$N = Q_{total\ cooling} \, / \, Q_C \quad (14)$$

$$\text{Cost} = N \times (\text{price of each module}) \qquad (15)$$

Having the number of modules, N the cost for each selection of TE module with a corresponding I(A) can be obtained.

Several modules are compared based on their COP and cost at a constant ΔT of 10°C and in different electric current ranges. It is shown in the following graphs how COP can determine system sizing and number of modules and consequently the overall cost of the system.

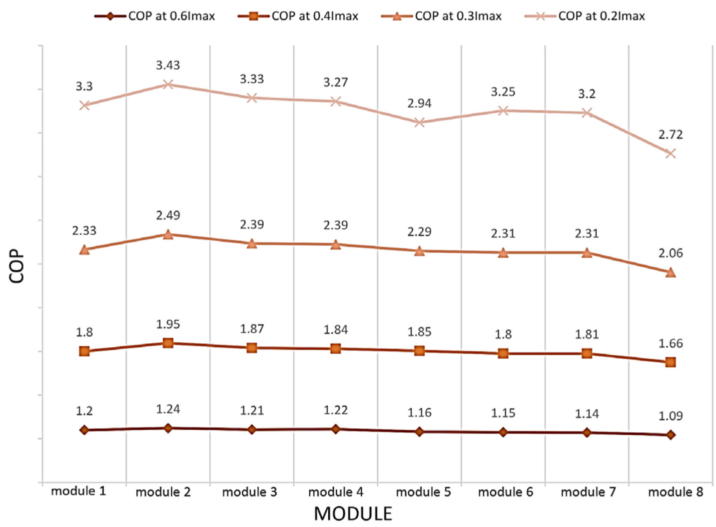
6.3.2 Selection of TE element and specifications

8 modules in this section are compared in terms of cost and the COP that enables them to cover the $Q_{total\ cooling}$ obtained from Designbuilder simulations. Table below presents the eight examined modules in short:

Figure 73 Effect of COP on the design

Table 19 comparison of modules studied to be later selected

	Module1	Module2	Module3	Module4	Module5	Module6	Module7	Module8
Qmax(W)	20.7	63.8	78	135.4	142	165.3	247.5	430
Imax(A)	8.5	12	15	15	8.5	15	15	28
Price per module (EUR)	18.8	30	30.5	39.4	45.1	41.4	46.3	47.8
Dimension(mm)	30*15*3.4	40*40*3.8	40*40*3.6	50*50*3.8	55*55*3.4	40*40*3.3	50*50*3.8	50*50*3.3



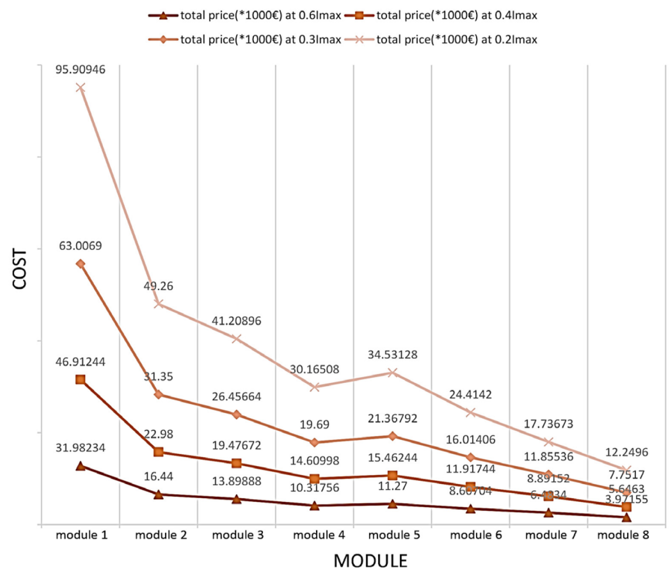


Figure 74 Comparison of the 8 modules in terms of COP and cost

As evident from these graphs module, 8 has the lowest price of all the 8 modules in every scenario of electric current, while it has the lowest COP almost in all the scenarios. However, what can be seen is that the difference in COP value between modules is not as significant for the same I/I_{max} value and their cost and the differences get smaller as the electric current is increased. Therefore, since cost is a more important factor in determining the suitable module, it seems that module 8 is the most proper module to select. This module has the highest Q_c and the highest I_{max}, the dimensions compared to the module 1 with smallest Q_c are not significantly bigger, and the price for each module is only about 2.5 times higher whereas the Qc is about 21 times bigger.

The specifications of TE module QC-241-1.6-28.0M are as follows:

Table 20 Performance data of TE module QC-241-1.6-28.0M

I_{max} (amps)	28
V_{max} (volts)	27.7
ΔT_{max} (ºC)	66
Q_{max} (W)	430
AC resistance (ohms)	0.87
Number of couples	241
Dimensions (mm)	50*50*3.3

6.4 Selection of heat sink

Selection of heat sinks with lowest possible resistance values R is crucial because as seen in the following sections, enhancing heat dissipation, reduction in ΔT and obtaining better COP values depend significantly on the heat sink resistance. In this section, 2 commercially available heat sinks with lowest resistance values are presented. Heat sinks are selected from Cool Innovations Inc. a company based in Canada that produces all ranges of heat sinks.

One of the problems associated with selection of heat sinks with low R values is their increase in size and weight because two heat sinks are needed for each TE module one for each side. The following data provides an overview of the properties and footprint of the heat sinks, assuming 180 TE elements, 360 heat sinks per floor and 72 per façade.

Table 21 Properties of the two heat sinks in terms of resistance, size, and footprint.

Heat sink	R(ºC/W) at 250CFM	Height(m)	Weight per HS (kg)	Total weight in each TE façade (Kg)	Area per HS (m2)	Total area in each TEF (m2)
3-985025RFA	0.033	0.0635	2.657	191.304	0.031	1.13
3-989825RFA	0.020	0.0635	5.286	1902.96	0.071	2.55

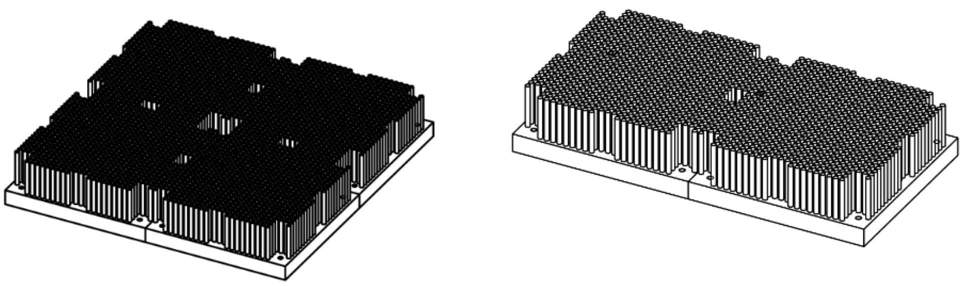


Figure 75 Selected heat sinks' appearance. Left is 3-985025RFA and right is 3-989825RFA source:http://www.coolinnovations.com/products/high-power-fan-sinks/data-sheets/

The available area for each TE façade module is assumed to be around 9 m^2, and therefore sufficient area is available for both of these heat sinks. Since the role of the heat sink is crucial in this study, the second heat sink with lower thermal resistance is selected. It is, therefore, necessary to conduct further studies on how the same or lower resistance can be achieved with lower weight.

6.5 Number of modules and COP during peak demand

In appendix 12-2 two method used for calculations of Q_c, Q_h, V_{req}, and COPs are explained in brief, and both are compared and validated with the performance graphs provided by the manufacturer. These calculations will be used in this section to draw a cost analysis and select the number of modules and later in section 9 in the parametric model development.

As evident from calculation in the second method, the hot and cold temperatures sides play an important role in the system COP besides ΔT and in this method calculation of Seebeck coefficient as a temperature dependent value helps in obtaining more realistic results, especially when developing the parametric model in the following sections.

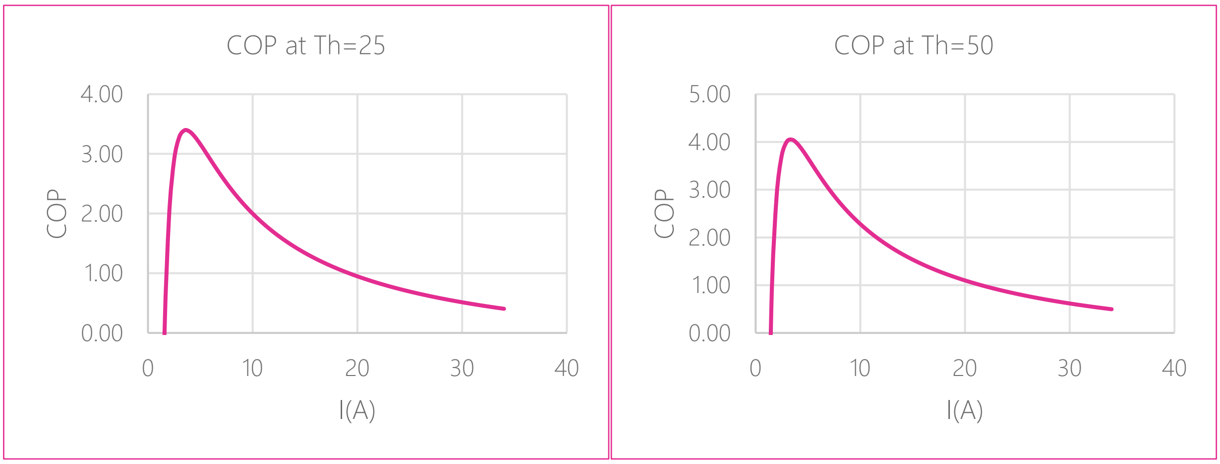


Figure 76 Graphs presenting COPs obtained at different working temperatures in ΔT=10oC with increasing I(A).

Based on the results from the second method, maximum COPs of around 3.4 and 4 can be obtained at T_h of 25 and 50 accordingly at ΔT=10^{o}C.

The number of modules that will be selected in this selection is a very important factor in determining the COP of the system as explained before because it is in direct relation with the Qc and I. It is unfortunate and controversial that in order to obtain higher COP, a lower Qc must be selected and therefore the number of modules increase. On the other hand, the number of modules will affect the overall weight of the system and cost.

6.5.1 Control system

The graphs below of a typical thermoelectric module show the effect of I on COP and Q_c.

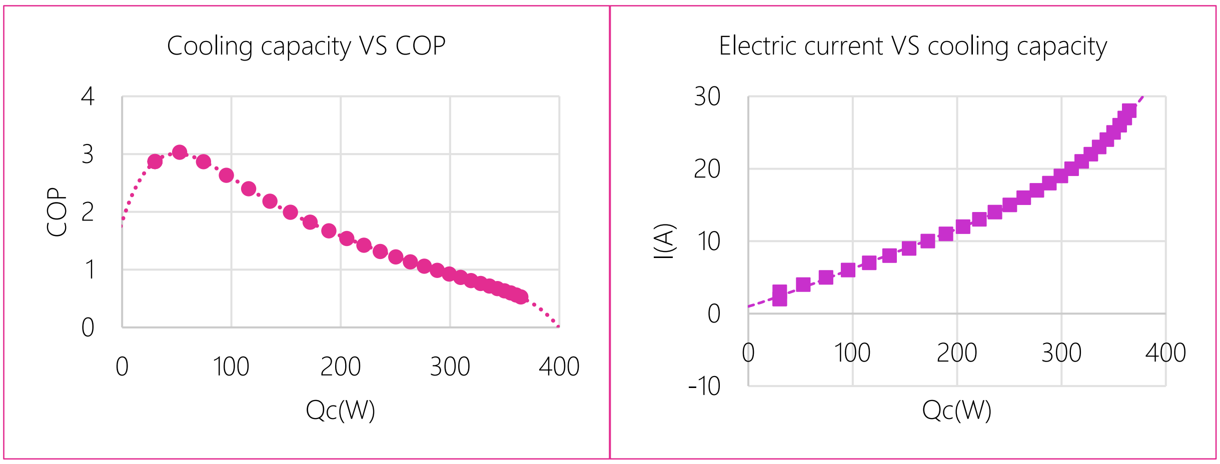


Figure 77 effect of electric current on COP and cooling capacity

It is observed that there is a value for Q_c and I where COP has a peak at each ΔT, and by reducing I to a certain value, different for each TE module, the highest COP can be obtained. However, by reducing the electric current, lower cooling capacity is obtained, and in order to cover the loads, more number of modules have to be used.

As seen in the graphs for electrical current lower than the corresponding I for peak COP, the COP drops rapidly, therefore it seems that a range should be defined for electrical current and the lowest value for this should be the corresponding I for the highest COP which is in this case around 4 (A). this value, called I_p has a corresponding cooling capacity called Q_p, and for loads lower than this value, a separate controlling system has to be designed to avoid overcooling of spaces.

The controlling system of this TE air conditioning system requires more attention than the scope of this project, and it could be used as an approach in optimizing the system, reducing cooling and heating loads of the building and increasing the overall COP especially during peak. It is suggested in a paper by Astrain et al., 2012 that TE systems should not be turned off at nights mainly because these very conductive small portions of façade work as thermal bridges when they are not working, and this new arrangement may lead to 40% reduction in electricity consumptions. The second advantage of having such control system that never turns off is using this cooling power in non-working hours to precool or preheat the zones and reduce the loads during peak hours. It has to be measured however, if the reduction in loads during working hours and reduction in heat losses is enough to compensate for the energy consumption of TE modules working full-time.

A possible way to avoid having COPs that are caused by loads lower than Q_p, the controlling system could be designed in such a way that it reduces the number of modules involved in cooling or heating the room and increases the loads assigned to each module.

An overview of how the system provides thermal comfort at the conditioned zone is shown in figure below.

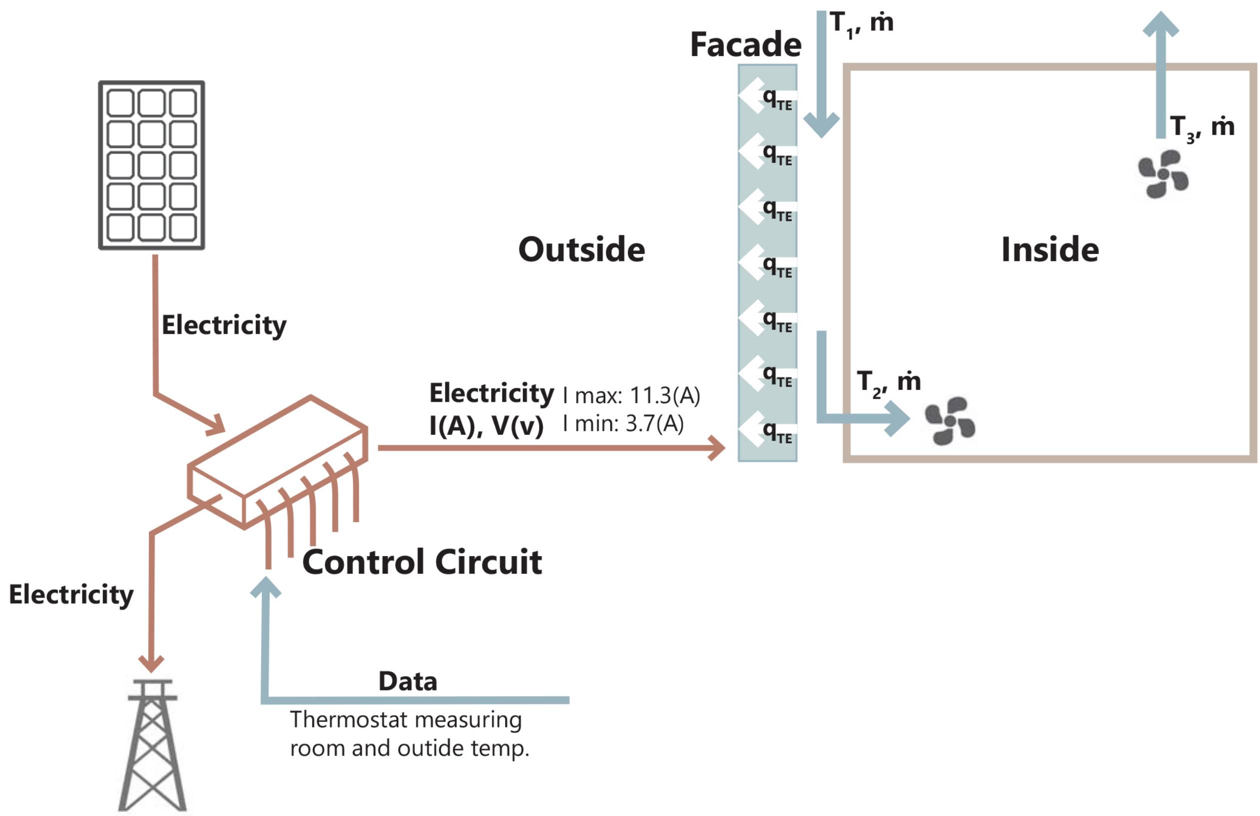


Figure 78 An overview of the system and how it is controlled and connected to the grid and PV panels.

As seen in this diagram, controlling the system is managed by a control circuit attached to each TE module that at each time step defines the required I and V based on calculations explained in previous sections and results of optimizations. If the required electricity is higher than that produced by PV panels, the system will take electricity from the grid and otherwise when loads and electricity consumption is lower; the control circuit redirects the produced power by PV to the electricity grid. The system has to be updated with the outside and inside temperatures as well as the predicted cooling or heating loads in each time step which the proper I.

6.5.2 Method of comparison

In order to determine a proper number for the modules, the effort in this section was to find an optimum arrangement and a good balance between COP and number of modules. A cost analysis may be the best way to define this since at the end the cost determines the feasibility of this façade. It is, of course, possible to reach the highest COP if temperature difference of 10°C or lower is obtained by having around 315 modules. However, as the initial investment costs of TE modules and heat sinks increases significantly with the increase in the number of modules, it is essential to measure whether the decrease in electricity consumption due to higher COPs will compensate this initial investment increase or not.

Therefore, the main comparison factor between different numbers of modules is the total cost associated with each selection. In order to take into account, the running costs associated with every arrangement, the electricity or operation costs of each arrangement has to be calculated. And since the minimum life span of these thermoelectric modules is assumed to be between 20 to 30 years, the electricity costs are calculated in 20, 25 and 30 years and added to the initial investment costs as in the following formulas.

$$\text{total cost in 25 years} = \text{investment costs} + \left(\text{electricity cost of 1 year} \times 25\right) \tag{16}$$

The investment cost of this system is basically the cost paid for the number of TE modules required for the system, but since for each module there is a heat sink that is attached to it, the number of modules also affect the cost associated with heat sinks.

$$\text{investment costs} = N \times \left(\text{price of 1 module}\right) + 2 \times N \times \left(\text{price of 1 heat sink}\right) \tag{17}$$

And the electricity cost in 1 year obtained from the following formulas:

$$\text{electricity cost} = \text{electricity consumption} \times \text{electricity rate} \tag{18}$$

Electricity consumption is denoted by Q_w; therefore, for every time step in the year, Q_c or Q_h has been extracted from Designbuilder and multiplied by a design margin of 1.3, then by obtaining Q_w as explained in previous sections, average COP can be obtained for each time step.

$$COP_{average} = Q_c / Q_w \text{ or } Q_h / Q_w \tag{19}$$

And therefore, average values of COP can be obtained for summer, winter and the whole year. The reason why the design margin is 1.3 is because in these calculations the total cooling loads are including the minimum fresh air amount during peak hours. However, later it might be concluded that the fresh air amount must be more in order to meet design requirements of TE modules.

The assumption made in this section that ΔT is a constant value might lead to error in obtained results because the temperature difference created at the two sides of the modules is in direct relation with the cooling loads and by reducing the number of modules and increasing the loads on each module, the temperature difference created on the two sides of module will definitely increase. On the other hand, for peak conditions, the obtained ΔT may be higher than 20 depending on how the heat sink performs.

Also, what is neglected by assuming constant temperature in these calculations is the effect of temperature on the Seebeck coefficient and COP. By increasing the working temperatures, the COP of the system increases due to increase in S, and therefore, it is expected that the heating and cooling COPs will be higher than expected in these calculations. In conclusion, the accuracy of the values obtained here need a more precise study and may require a more dynamic model when the overall model is developed. Later the effect of increasing the number of modules in COPs will be studied.

6.5.3 Final number of modules and expected COPs

In this section the results of plotting total costs in 20, 25 and 30 years against number of modules are presented, on the same graph, the corresponding annual COP

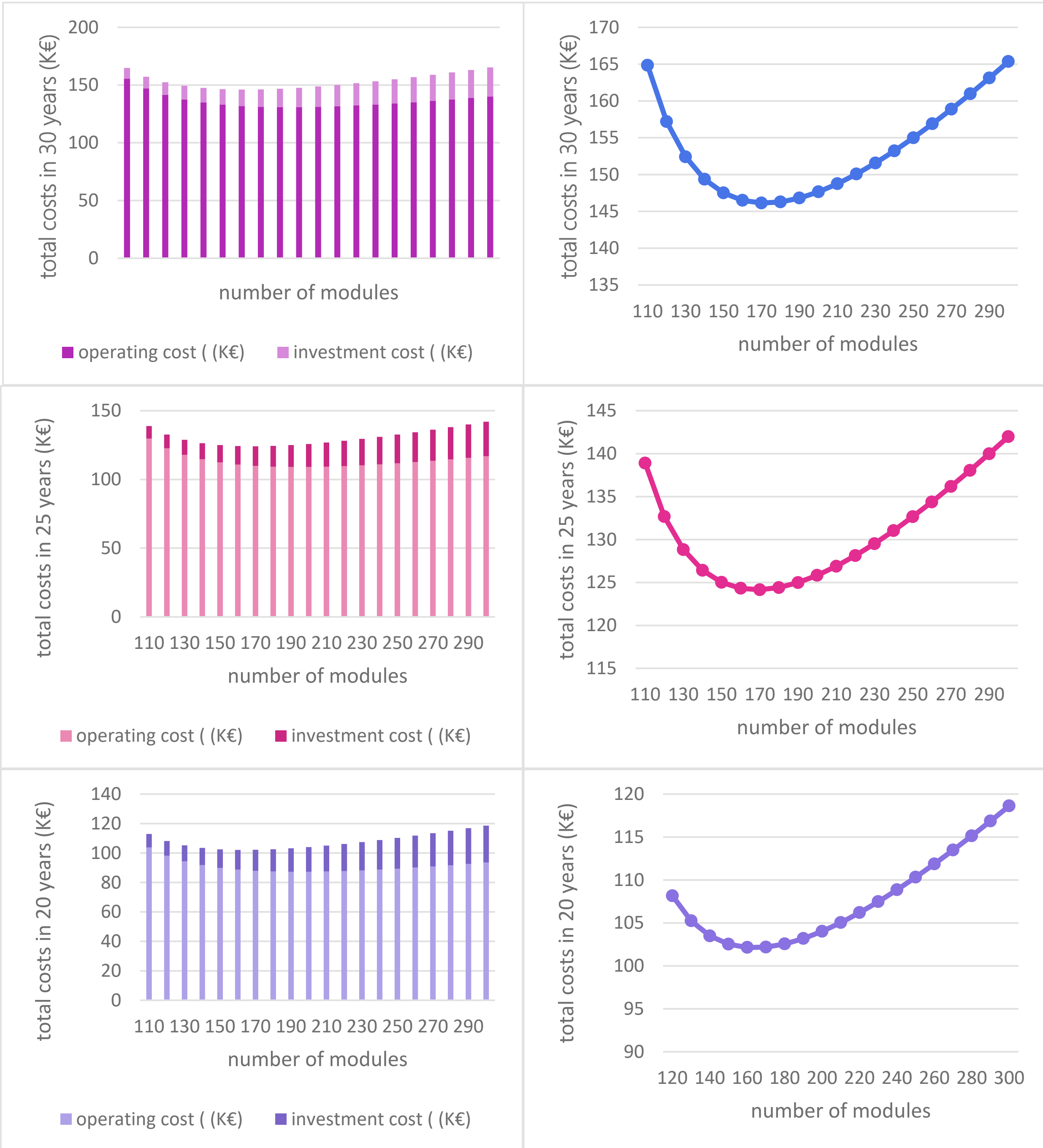


Figure 79 Total costs in 30, 25, and 20 years as a function of number of modules

The results show that in almost all combinations having 160 to 180 TE elements will result in the lowest total operating and investment costs. The following graph shows that increasing the number of modules will make a peak in the annual COP and then gradually decrease the it.

This means that increasing the number of modules will not always be beneficial in terms of efficiency and the highest COPs will be obtained by having around 200 modules.

The outcome of this section was firstly selecting the most proper TE element that would provide enough cooling capacity with the lowest number of modules and costs. Then a heat sink with lowest value for thermal resistance was selected which being attached to each side of the Peltier elements would help in decreasing the temperature difference between the two sides and increasing efficiency. then a precise method of calculating cooling capacity and electricity consumption and therefore COP of TE elements and at the end, it was found out that 180 modules would result in the lowest running and investment costs in 20 years.

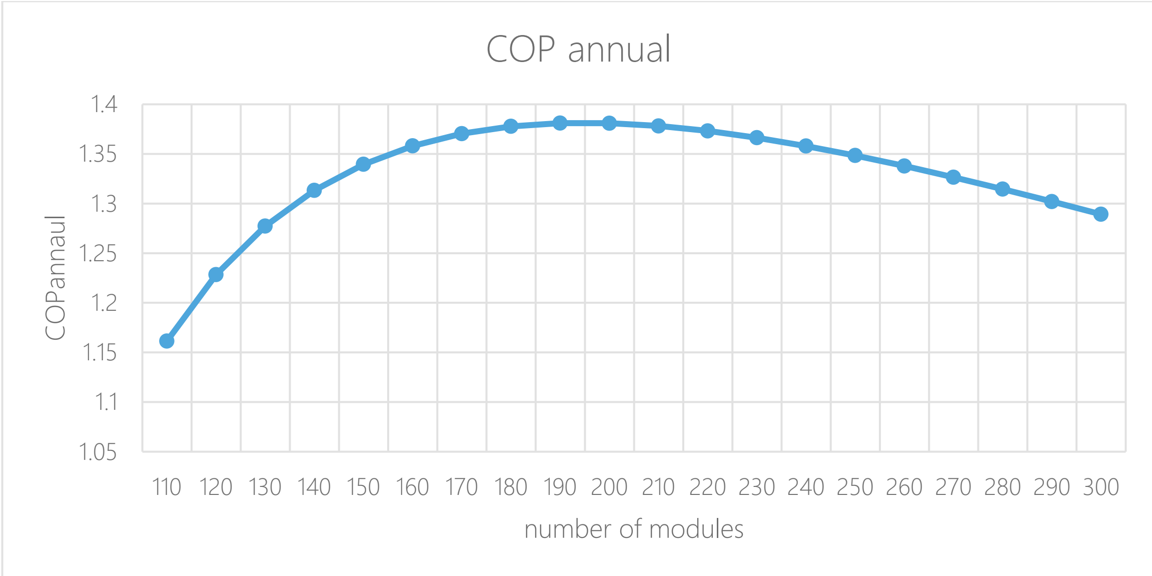


Figure 80 Number of modules vs. annual COP

It is expected from simulations of the second method for every cooling and heating load in each time step of the year that having 180 modules and ΔT at a constant value of 20°C will result in the following COP values.

- $COP_{cooling} = 1.37$
- $COP_{heating} = 1.47$
- $COP_{annual} = 1.38$

This is provided that the maximum temperature difference is 20°C in average and therefore the role of the façade and its building and ventilation integration becomes crucial in reducing and maintaining the ΔT as low as possible.

6.6 Reducing ΔT and ventilation integration

As explained in the previous sections obtaining the COP calculated with these formulas is only possible if the maximum value of temperature difference between the hot and cold sides of thermoelectric module, ΔT is 20°C. when the thermoelectric module is connected to electricity, based on the amount of electric current I that is being fed to the system, a temperature difference will be created along the two sides of the module. On the one hand, the heat moved from the cold side to the hot side has to be removed immediately and on the cold side, some heat has to be added or cold has to be removed to create the lowest degree of temperature difference.

6.6.1 Concept

What defines the temperature difference, therefore, is, on the one hand, the N, I, and Qc and on the other hand the temperature and mass flow rate of hot and cold side streams. The first criterion was defined in previous section when the number of modules was defined, while its effect on the ΔT was not considered and should be integrated in a more complete model developed in the following sections. In this section factors related to the second criteria that is related to the façade and overall building design is discussed.

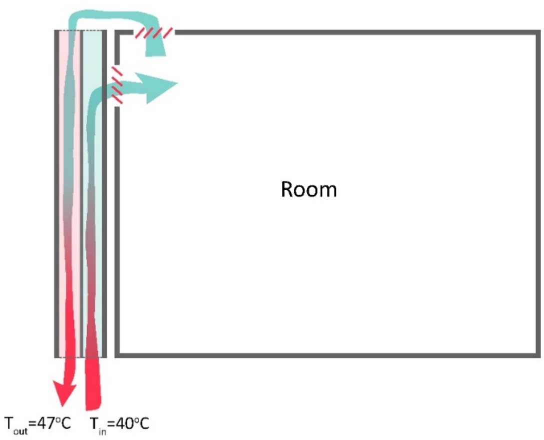


Figure 81 Diagram showing the function of TE facade as a heat recovery system

The concept developed in this section is derived from the fact that the ΔT at hot and cold sides of TE modules has a significant impact on the COP of the system. Integrating ventilation system into the active TE system will help in decreasing this temperature difference while it acts as a heat recovery system that minimizes energy losses. This means that the exiting air from the cold side of modules always have a temperature more than the entry temperature because the ventilated air has been used to cool or heat the TE elements of façade as shown in figure below

In a paper recently published by (Liu et al. 2019), a similar system is used and called "thermoelectric heat pump recovery system," as shown in figure below:

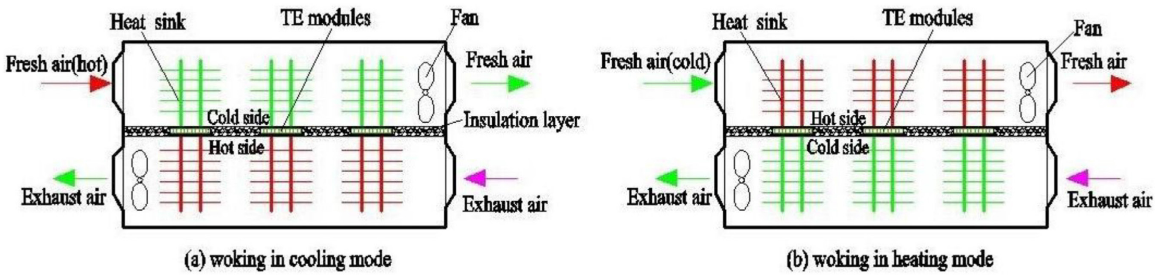


Figure 82 Working principle of thermoelectric heat pump recovery system, (Liu et al., 2019)

As it is observed from Designbuilder model having a ventilation system is a requirement for this climate since in summer there is almost no natural ventilation due to low wind speeds. Therefore, integrating these two systems seems essential to minimize ductwork and also to provide cooling and heating for every zone in the floor and not only those next to the façade with TE system. A decentralized ventilation system is then used for every floor of the office building that is integrated with the active TE system on the façade.

How the inlet temperatures at the hot and cold sides of the modules can affect the temperature difference at the two sides is described in the following graph. The reason why air flow in these arrangements are co-flow is due to hot air's tendency to go upwards and cold air to go downwards and to help reduce loads on fans.

These diagrams show rough estimations of how ΔT is formed on the two sides during peak hours with the air streams passing through them when the outside temperature is 40°C and inside temperature is 25°C.

The first scenario uses the outside air to cool down the hot side while the inside air is recirculated to be cooled and fed to the room. In the second scenario inside air is used to cool the hot side while outside air passes through the cold side and is provided to the room. In the third scenario where the lowest ΔT is achieved, the inside cold air is mixed with air passing through both the hot and cold sides to reduce ΔT. This is a conceptual and very simplified model that shows using the cold ventilated air that has to be replaced by fresh air can be used in enhancing the system efficiency by decreasing the temperature difference.

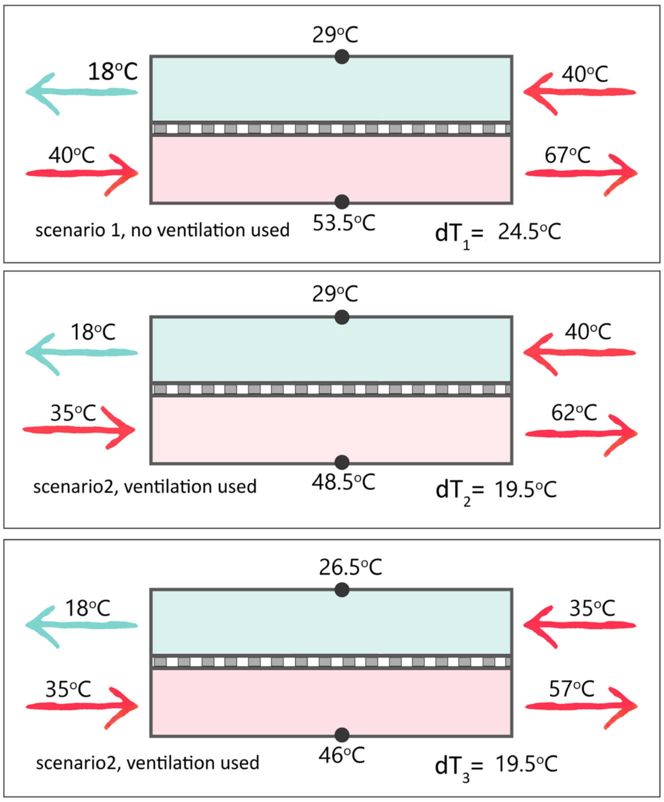


Figure 83 conceptual diagram showing how ventilation integration reduces temperature difference

6.6.2 Integration with ventilation system

Integrating the ventilation system into the TE active system as explained before both has advantages and is inevitable. In this concept, the extracted air from the room which is a cooled air is used to decrease the temperature of air streams entering both the hot and cold sides. the fresh air entering the room is added to a portion of extracted air that is being redirected into the room, cooled to a certain degree and provided to the room. The amount of air that enters the building can be more than the minimum fresh air requirement which leads to an increase in the air flow rate exiting through the hot side and help it further with the cooling process.

In this scenario what makes it more complicated is that the performance of TE model can be significantly improved if the amount of fresh air is increased, while on the other hand this increases the room load and lead to creating a higher ΔT. In this scenario, the amount of fresh air can affect the performance of TE modules in 2 ways, firstly affecting ΔT and secondly affecting room load.

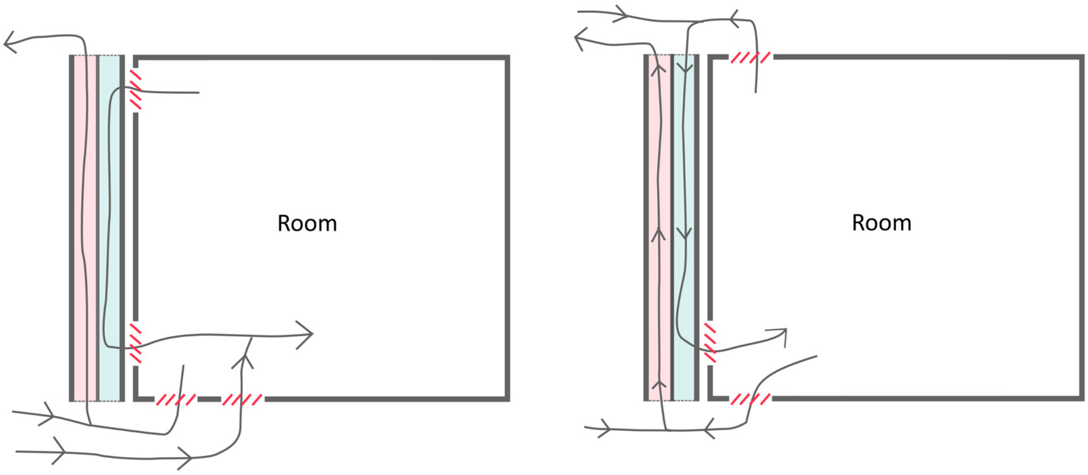


Figure 84 A non-ventilation integrated TE system(left), the proposed ventilation integrated TE system (right)

Compared to a system where the fresh air is taken in a separate way, and the ventilated air is not used in the TE system as shown in the following graph it can be proved that this system is capable of reducing ΔT depending on how much fresh air intake further than a normal system nonintegrated system.

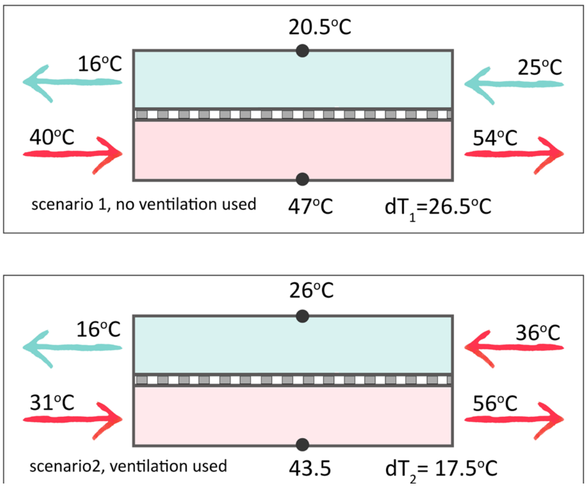


Figure 85 Non ventilation integrated TE system (up) ventilation integrated TE system (down).

To conclude, this concept is expected to help the system increase its efficiency by using the cold air exiting the building to reduce ΔT on the two sides of the modules and therefore increasing the efficiency. In the next chapters, this concept is first developed in the context of the façade and then examined in a more comprehensive model to validate if the expected enhancement in COP are achieved.

7 Facade design

Figure 86 Render showing replacement of the facade with TE facade modules.

7.1 Introduction

In this stage of this facade design, goals must be established as the first step to clarify the direction of design and later evaluate the concept based on these criteria. One of the main goals of this facade design was to achieve a facade product that is not specific to only this building but is capable of being applied on every other building in the same climatic conditions. Therefore, a unitized facade type is preferable to make it more universal and applicable. Another important role of this facade beside other functions that any facade would normally have is reducing the temperature difference between the hot and cold sides of the thermoelectric module. Following the same criteria, integration of this facade with the ventilation system becomes crucial.

Figure 87 renders showing the TE facade module next to glazed modules

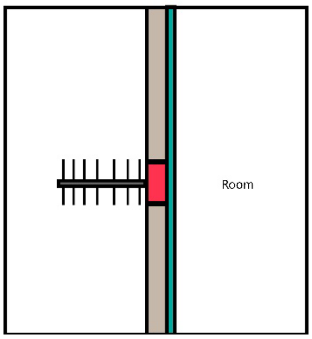
7.2 Integration of Peltier elements and heat sinks

Two of the important components of this system is thermoelectric elements and heat sinks attached to them to dissipate heat on the hot and cold sides. In different published studies various configurations of thermoelectric modules and heat sinks within facade have been proposed. A small study is done in the following section to obtain a better understanding of possibilities of integration this cooling system components in the facade.

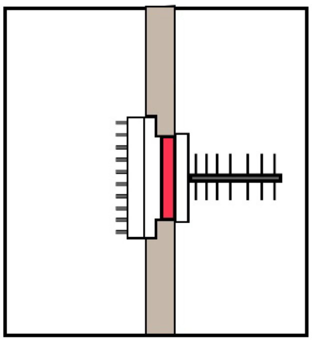
7.2.1 Case studies

In this section, some of the proposed TE facades will be studied with focus on integration of Peltier element and heat sinks. The different configurations are shown in the following diagrams.

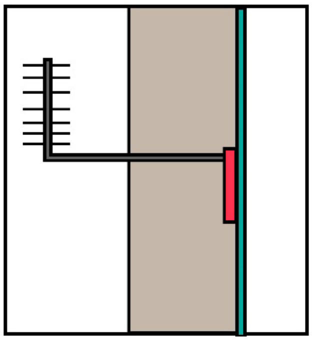
Configuration 1 (Liu et al. 2019)



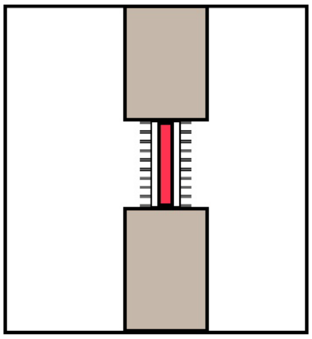
Configuration 2 (Riffat, Omer, and Ma 2001)



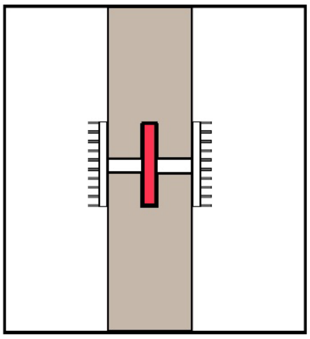
Configuration 3 (Ibáñez-Puy et al. 2015)



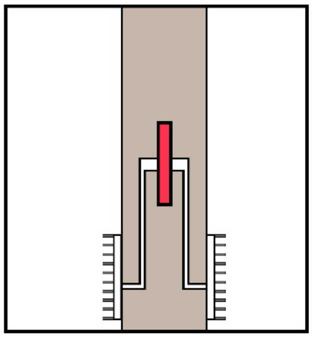
Configuration 4 (Aksamija et al. 2019)



Configuration 5 (Aksamija et al. 2019)



Configuration 6 (Aksamija et al. 2019)



It has to be noted that increasing the thickness of the insulation layer, on the one hand, increases the thermal resistance between the hot and cold sides and therefore prevent heat from moving to the cold side and on the other hand increases the resistance between the heat sinks and TE modules, therefore increases ΔT and will result in a lower COP. Therefore, there has to be balance between increasing the thermal resistance between the hot and cold sides and increasing the resistance between the heat sink and the TE modules. Also, more thickness on this insulation layer leads to increasing the width of the facade module which must be prevented.

As seen in the diagrams some of these proposals use radiant walls to condition the room which is not the chosen strategy in this thesis. Configuration 1 and 4 do not seem to have a potential in this facade design one due to too little thermal resistance and the other due to low contact with the ventilation air. Configuration 3 and 6 possessing the thickest layer on insulation would result in increasing ΔT and, therefore, configuration 2, and 5 seem to be most suitable ones for this facade.

7.2.2 Development and application

As explained before, the most important criteria in integration of TE elements and heat sinks is to firstly prevent heat transfer between the hot and cold sides and the two heat sinks and secondly to enhance the contact by decreasing the thermal resistance between the heat sinks and the TE modules they are connected to. Therefore, inspired by the case studies the following concept was developed.

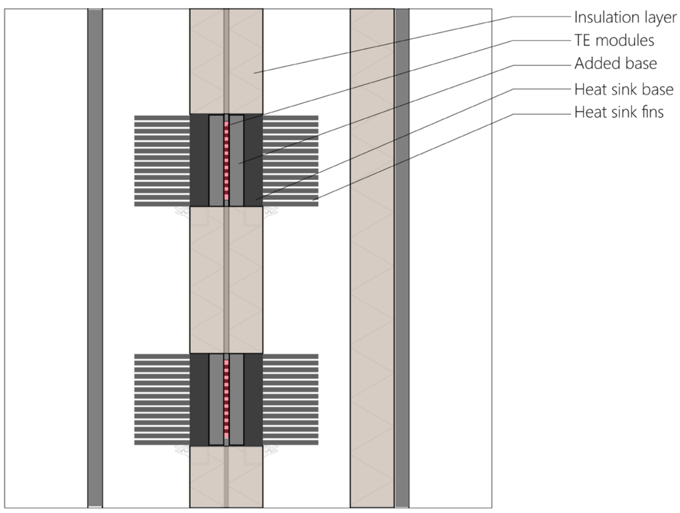


Figure 88 initial idea of TE and heat sink integration

As the size of the heat sinks increased, the base merged with the added aluminum plated to form one shape connected to the TE elements. Also, a secondary structure is designed to support the heat sinks. The fins of the heat sink have the highest contact with the air passing through the channels in this design, and this helps to increase the contact between the air and heat sinks.

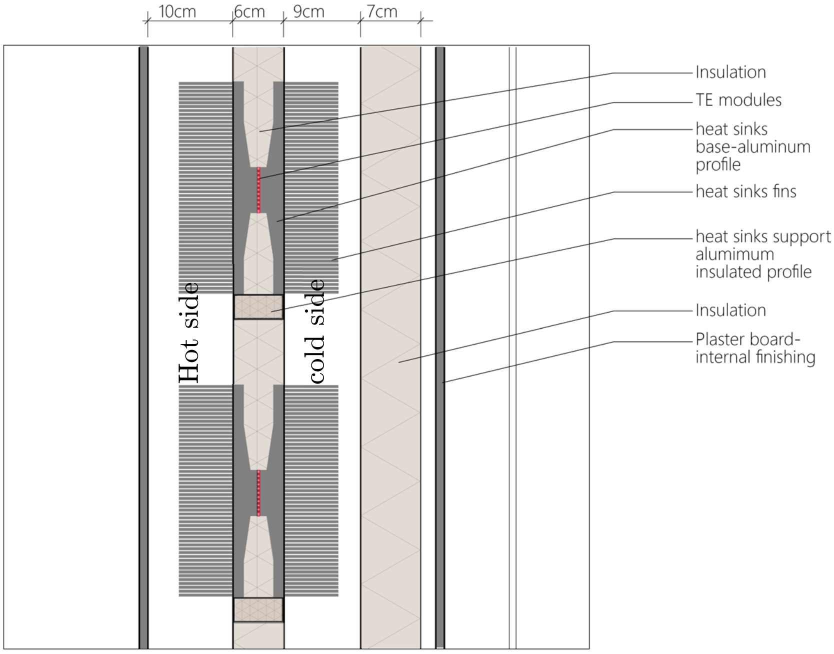


Figure 89 The concept used in TE and heat sink integration

The 60mm insulation layer of foam board R-10 reduces the U value to nearly 0.5 W/m²K. This means that for the 10 m² of the facade module, 5 W heat will be transferred to the other side. Although the value is not significant, with better insulation, the thickness can be reduced while remaining the thermal resistance to enhance conductivity between heat sinks and their TE modules. Aluminum profiles supporting the heat sinks would create small thermal bridges which would be minimized by using insulated profiles.

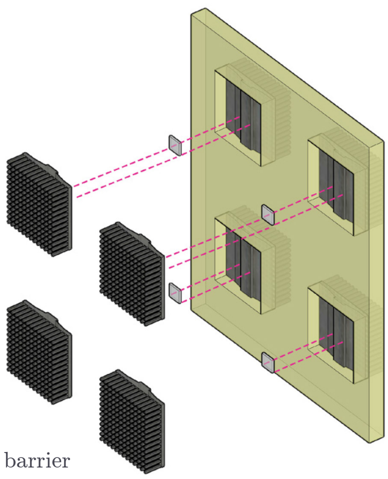


Figure 90 Integration of TE and heat sinks and the thermal barrier

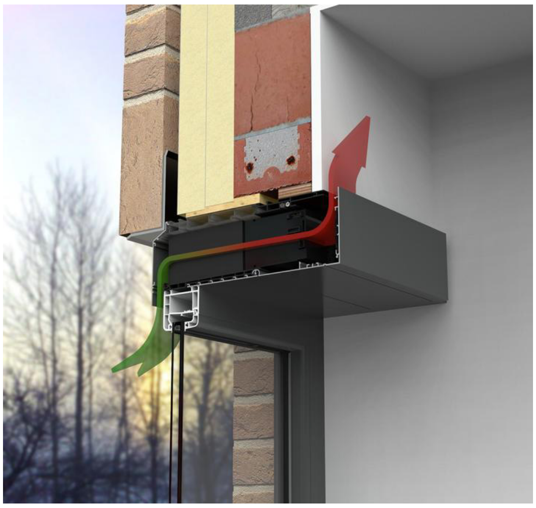
7.3 Integration of ventilation system

A proof of concept was provided in previous sections that showed integrating ventilation system with the TE cooling and heating system and using cool and hot ventilated air may be an effective way to reduce the temperature difference between the two sides of the modules. The essential components of this ventilation system will include fans, dampers, and ducts for each module in each floor to distribute and collect back the ventilated air in a decentralized system.

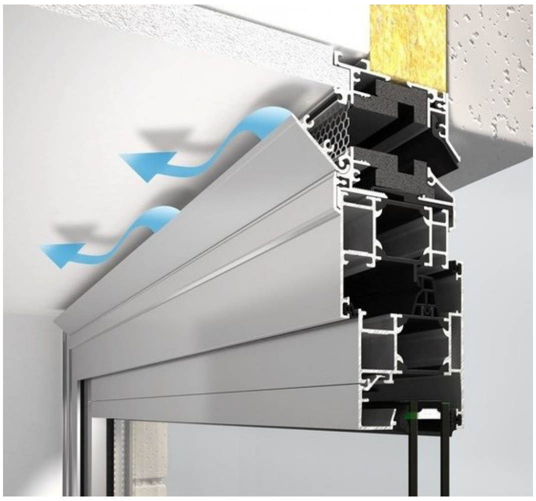
Some of the commercially available decentralized facade integrated ventilation systems are shown in the next section.

7.3.1 Case studies

1- Endura Twist, Renson
Source : https://www.renson.eu/de-de/producten-zoeken/ventilatie/



2- Schuco Ventilation System VentoAir
Source: https://www.schueco.com/web2/de-en/fabricators/products/ventilation˙systems/



The first case study which is a ventilation cooling/heating system incorporates a fan box with a series of fans that extracts, condition and feed the air to the zones. The hidden air intakes in the Schuco air Vento product provides better aesthetic properties for the facade and also opening and closing the vents will be possible with the moving profile.

7.3.2 Concept

As explained the previous chapters and shown in the following graphs with winter and summer conceptual schemes of how the system works, there are three air intakes in this system. One that takes fresh air to the cold side, one that takes fresh air to cool the hot side and one that takes ventilated hot air to the outside.

Conceptual Summer scheme

Conceptual Winter scheme

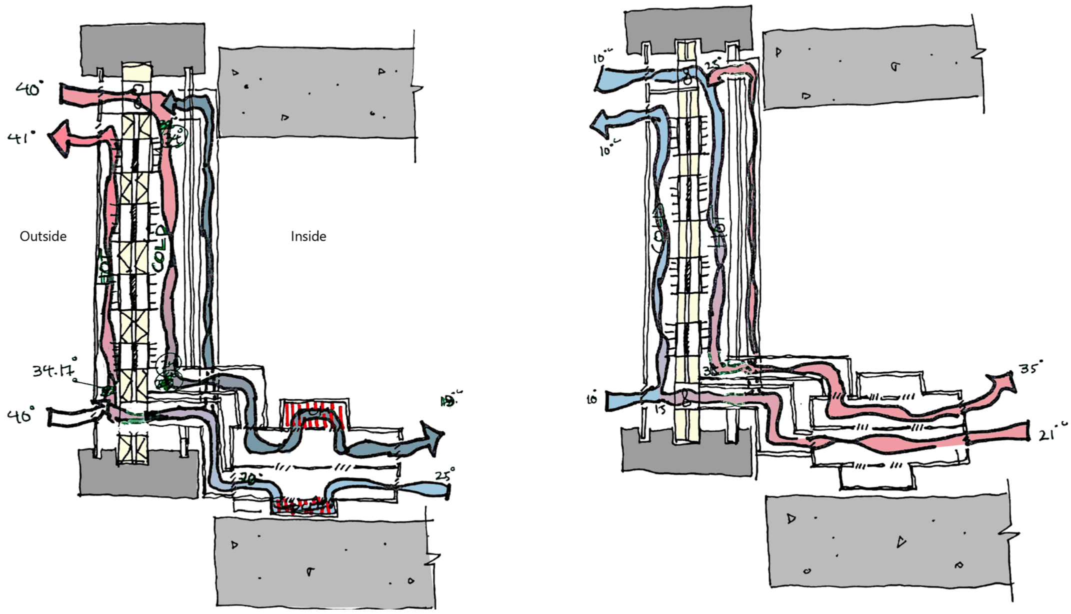


Figure 91 conceptual schemes of ventilation integration and system operation in summer and winter

As noted in the graphs, the position and design of the air inlet and outlets leads to creation of short circuit and unwanted extraction of hot side's exiting air in the fresh air intake. Therefore, a new concept is developed in which the hot side is cooled through vertical air vents instead of horizontal ones. The cooled air is distributed under the floor through the zones and air extraction happens from the ceilings. In this way as air flows naturally upwards after it has been heated it gets extracted as shown in the following figure.

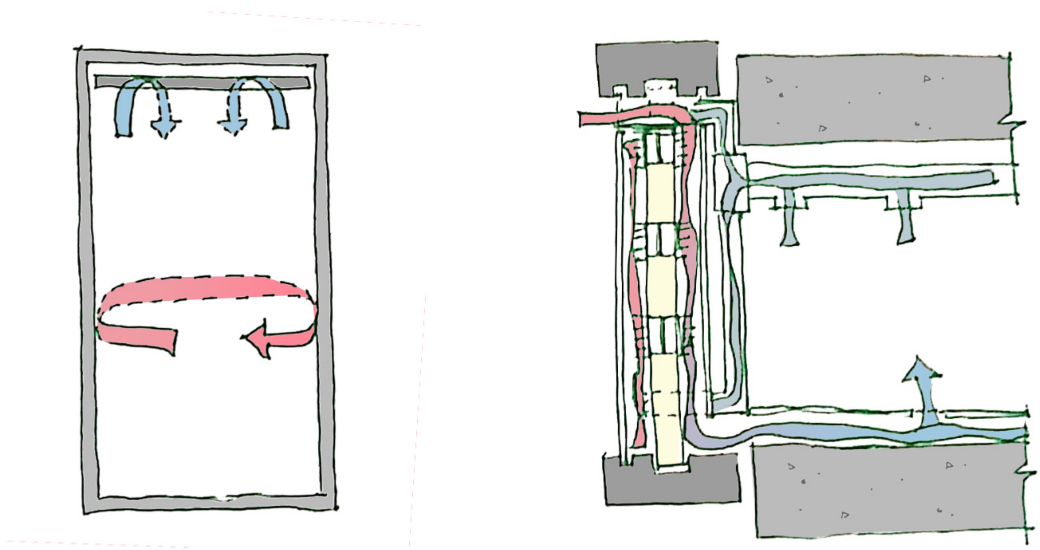


Figure 92 conceptual diagram showing the final concept of ventilation integration

In this concept which will be further developed in the following sections, due to the distance between the inlet and outlet air vents, there is less chance of formation of short circuits.

Due to size limitation in this facade, axial fans with maximum 100mm diameter has to be selected. The selected fan can provide 0.1 m^3/s air and based on this value and the required air flow rate in the facade, the number of fans will be calculated in the following sections.

The material of the fan has to be able to undergo an operating temperature between -10°C to 60°C which is the temperature created by the TE elements.

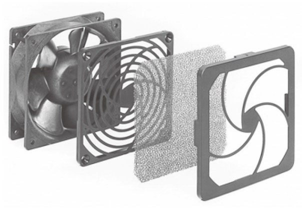


Figure 93 the selected facade blower, source: http://www.nidec-servo.com/en/digital/g˙fab/index.html

Table 22 product specifications of the selected fan

Product code	Size (mm)	Max. air flow rate (m3/min)	Max. static pressure (Pa)	Noise (dB)	Operating temp. range (°C)	material
G0938B48B9ZP-00	92×38	6.3	415	64	-20 - 60	Aluminum

Due to high air flow rates required in this TE ventilation system, the whole facade will be used the air channel both on hot and cold sides. Also, to control the air flow rate that passes through each channel other than the max flow rate provided by fans, dampers have to be used.

7.4 Final facade design

Figure 94 Interior view of the office with TE and glazed facades

As this integrated concept developed, the design as presented in this section was finalized. The development phase included a few alternatives that lead to evolutions in the final product, which will not be further explained in the thesis, but was an important stage of the design process.

7.4.1 Details of the design

The final details of the facade are presented in the following graphs. In this 3D-section the ventilation system, underfloor air distribution and delivery of cold air through the façade are evident.

Figure 95 Render showing a vertical section through the TE facade module

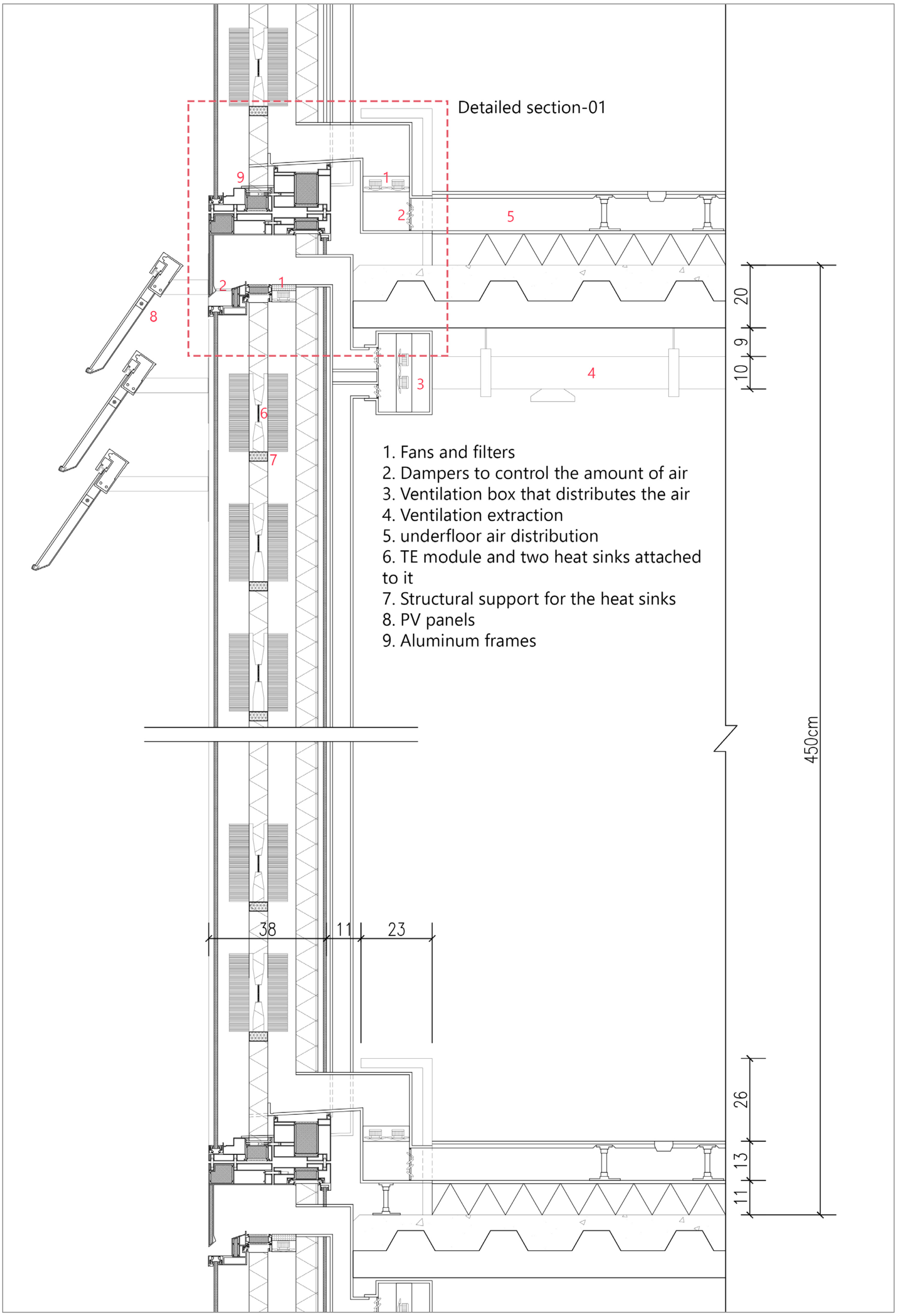


Figure 96 Vertical section of the TE facade module in connection with another TE module

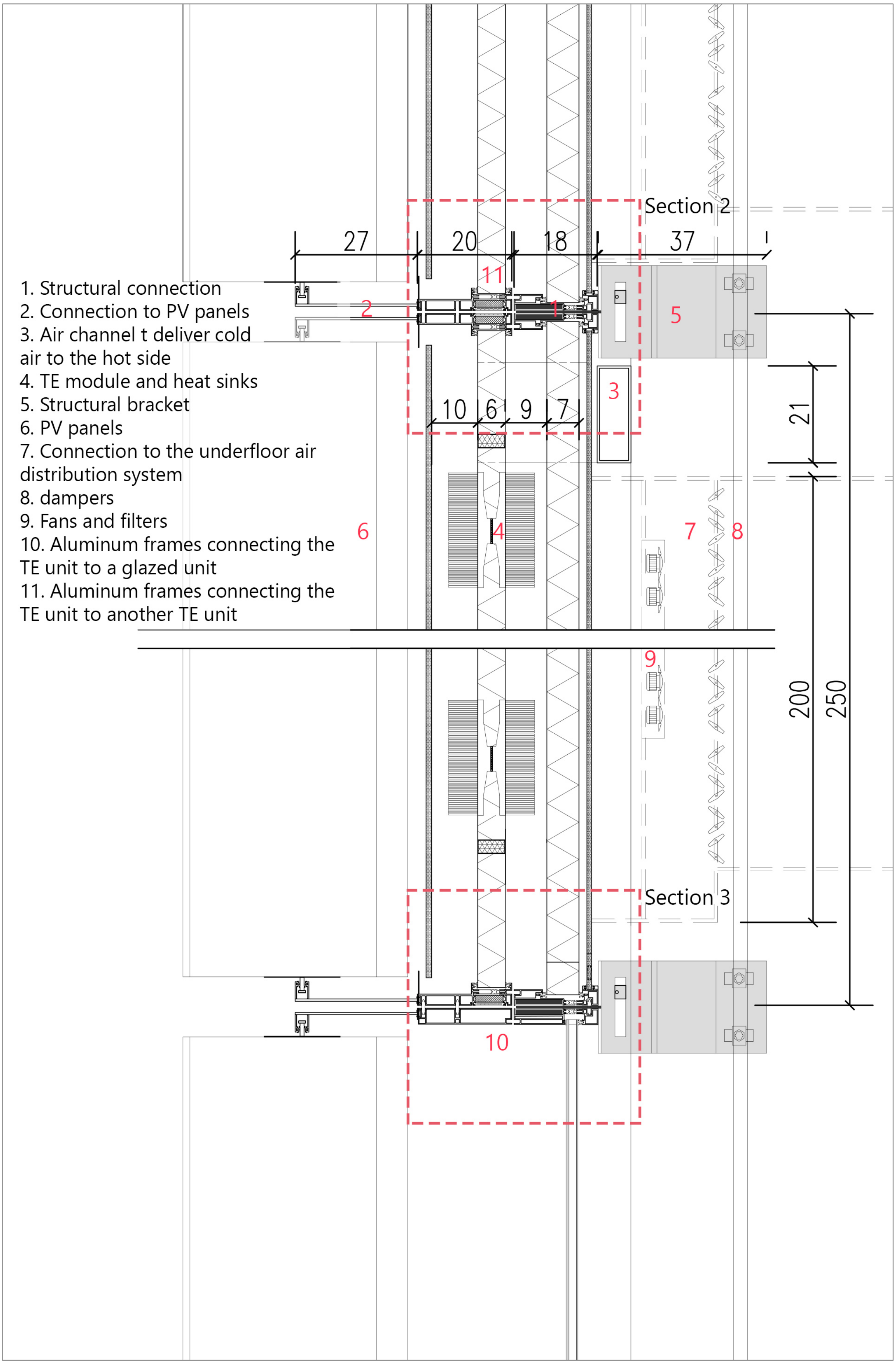
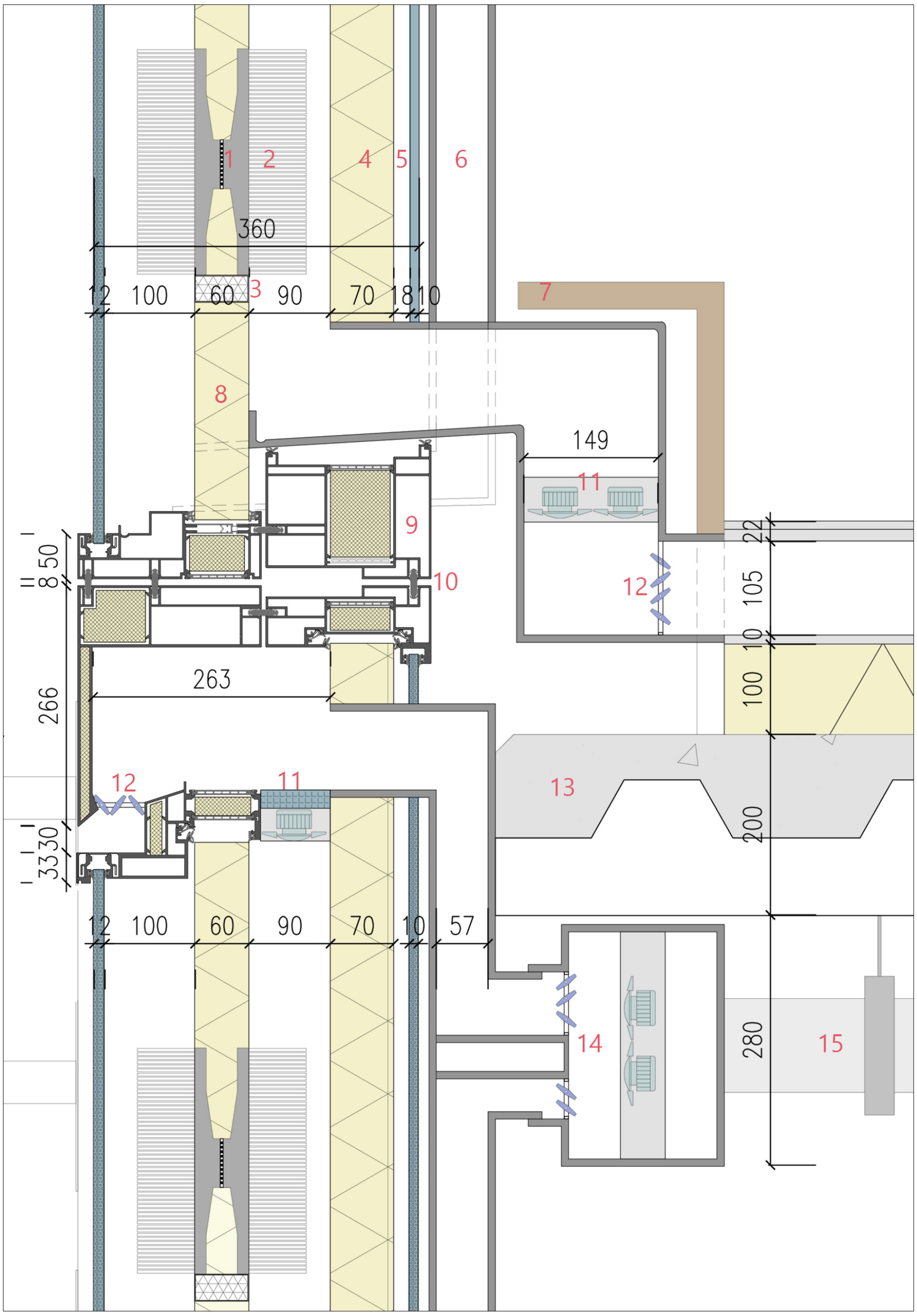


Figure 97 Horizontal section of the facade



1. TE element in contact with heat sink
2. Heat sinks
3. Aluminum frames supporting the heat sinks
4. Insulation-mineral wool
5. Gypsum board
6. Air channel
7. Wooden board
8. Insulation-mineral wool
9. Insulated aluminum frame
10. Gaskets
11. Fans and air filters
12. Dampers
13. Floor structure
14. Ventilation box
15. Extraction channels

Figure 98 Section 1- vertical detail

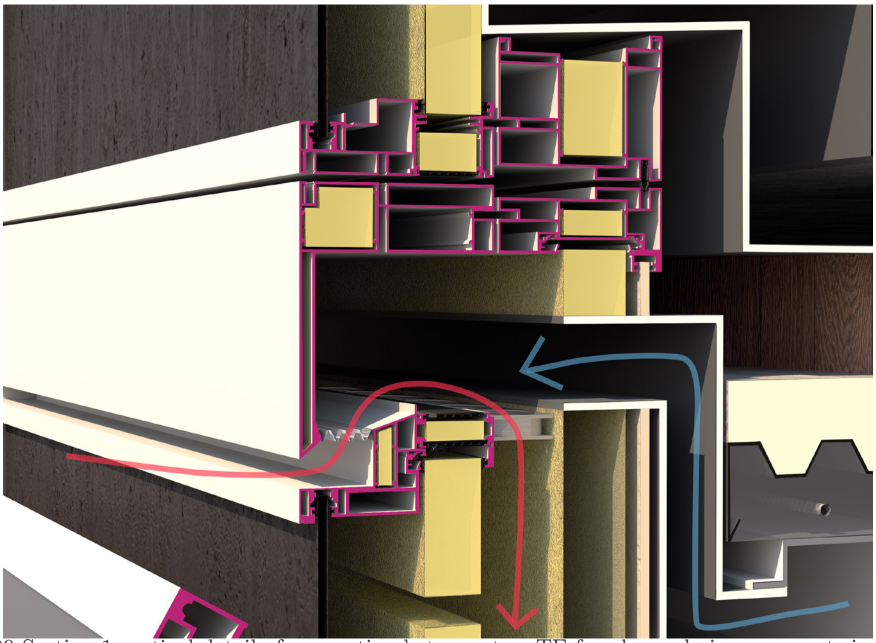


Figure 99 Section 1 vertical detail of connection between two TE facades and air movements in summer

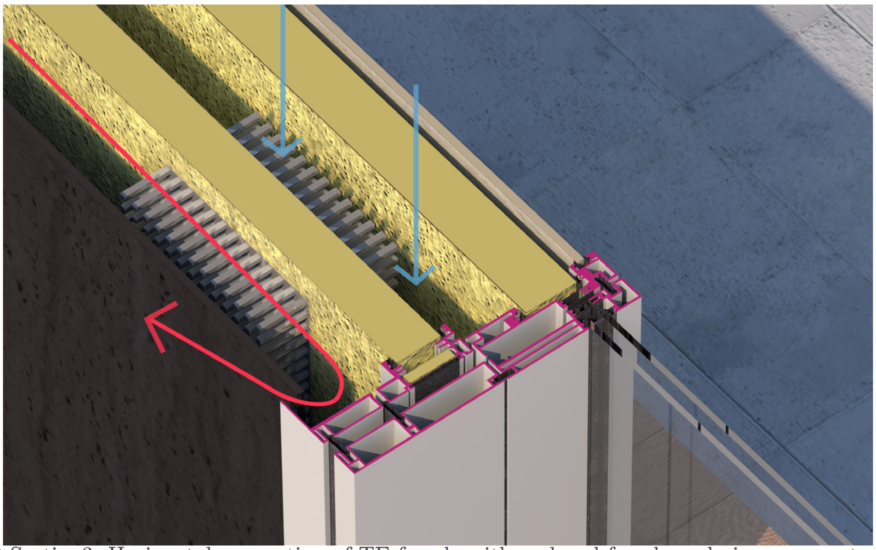


Figure 100 Section3- Horizontal connection of TE facade with a glazed facade and air movements in summer

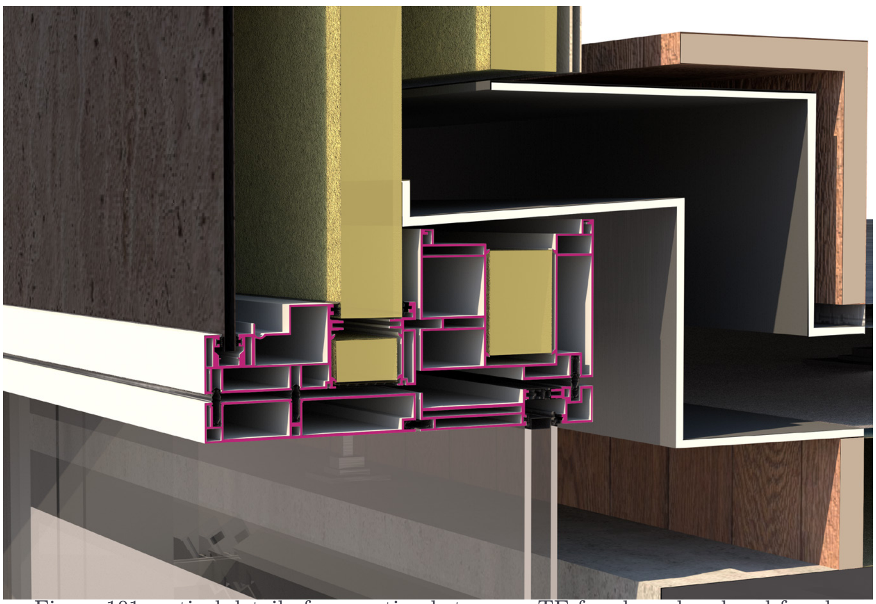


Figure 101 vertical detail of connection between a TE facade and a glazed facade

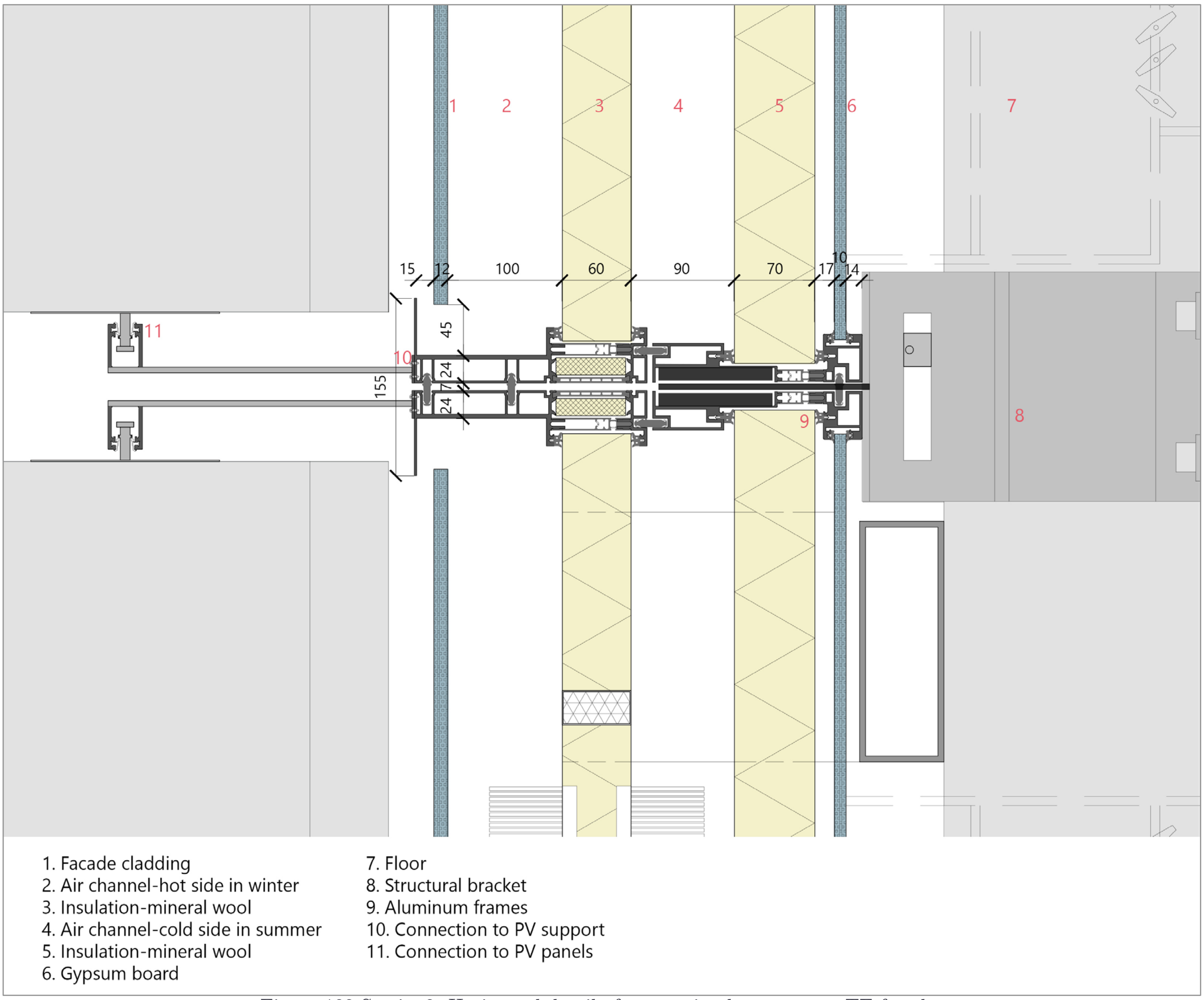


Figure 102 Section2- Horizontal detail of connection between two TE facades

As the facade design developed, it went through changes that were applied with active system design principles. The facade has three air vents, two taking air in and one taking it out. The cooling and heating function of the facade and how it performs will be shown in the next sections.

7.4.2 Assembly sequence

Assembly in factory

the TE façade is a unitized system that consist of components essential for a functional façade as well as components that provide heating and cooling via ventilation system. The assembly of the TE façade in factory is as shown in the following diagrams.

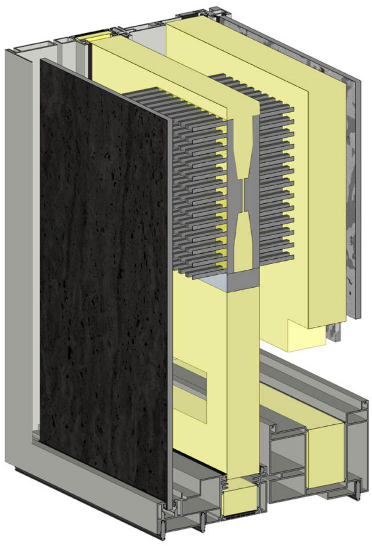


Figure 103 Assembly of TE facade in factory

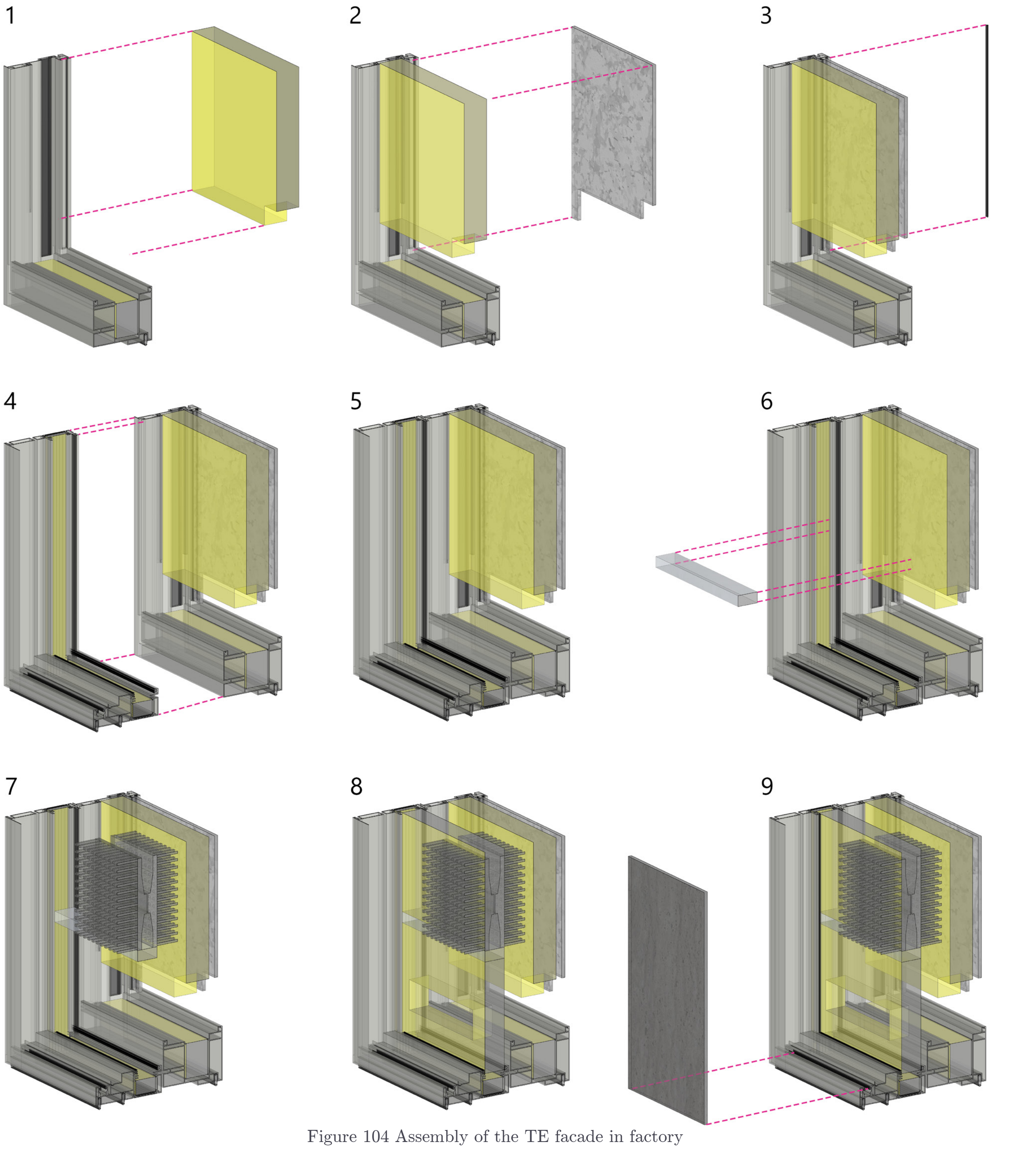


Figure 104 Assembly of the TE facade in factory

On site assembly

One the primary functions of this facade is being capable of transferring the loads to the office's structural components. The facade bracket in this design consists of two vertical supports that are connected to the bracket fixed to the floor. This structural element supports the width of the whole facade which is around 37cm while providing enough room for tolerances in assembly as well as possible movements. The overall weight of this facade is probably more than other façade types of the same size given that it is a multifunctional integrated facade providing heating, cooling and electricity production. Compared to a non-integrated facade, heat sinks and TE elements as well fans, dampers and ducts are added to this facade which would result in making it significantly heavier. Therefore, in a more extended study, the structural stability of this facade has to be examined.

The following graphs represent the sequence in which the facade panels are connected to the structural bracket.

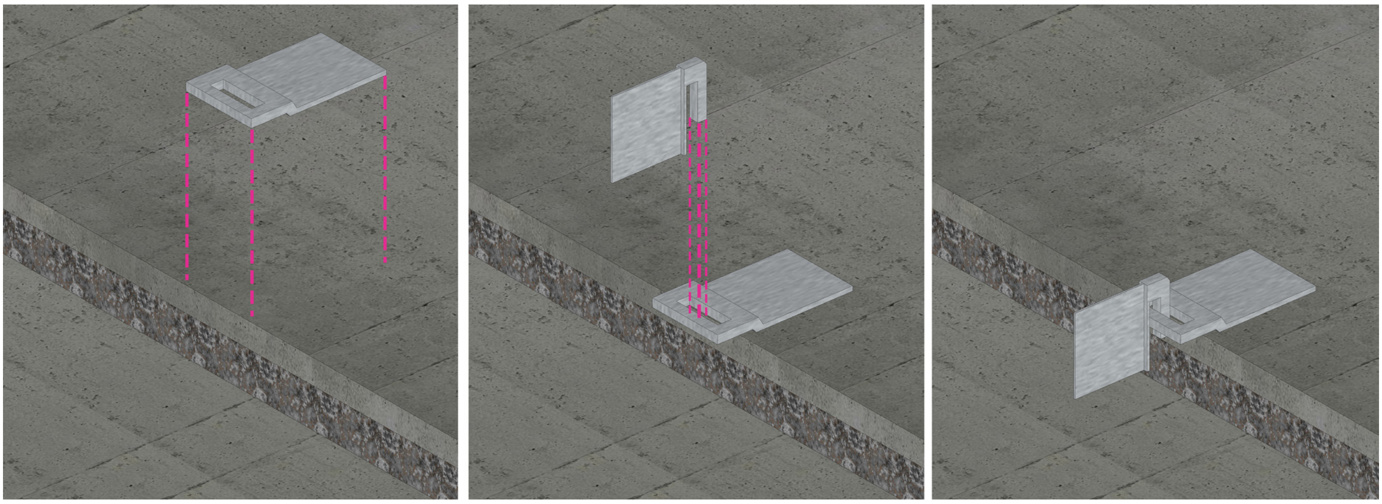


Figure 105 Installation of the structural bracket

The units are brought to site and are installed by crane as shown in the following diagram.

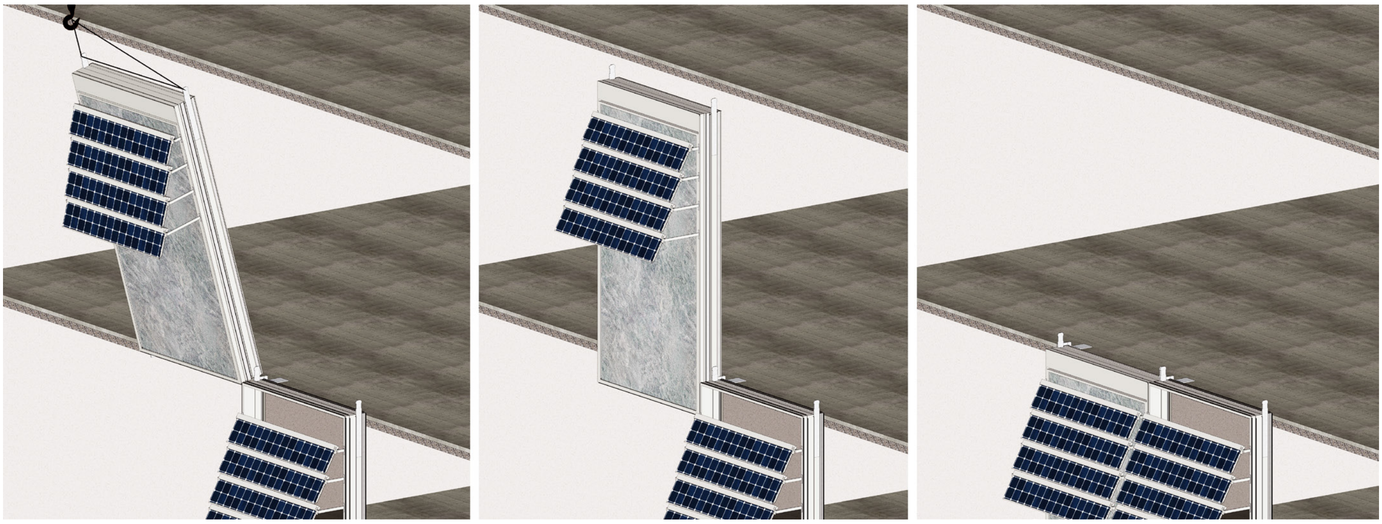


Figure 106Assembly of the unitized facade

Then the support connecting the facade units to the bracket is connected and fixed with bolts.

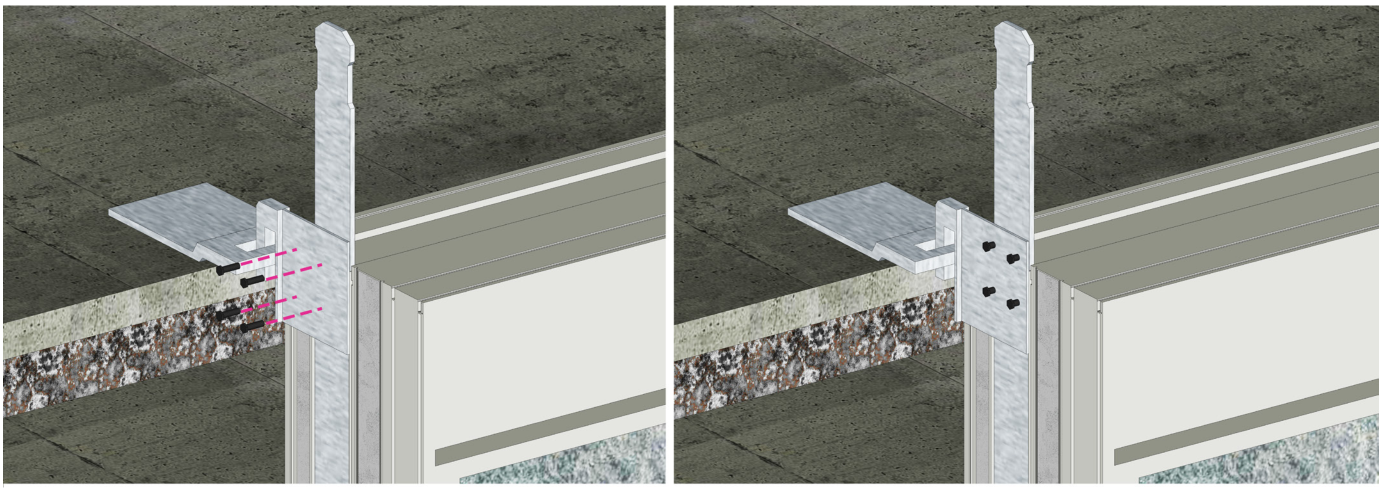


Figure 107 Bolts connecting the TE facade to the structural brackets

After installation of the TE modules, the flooring layers including insulation, cement and finishes are constructed. After installation of the insulation layer, the ventilation ducts must be connected to the TE façade and the underfloor air distribution layer is connected to these channels as seen in the following graphs.

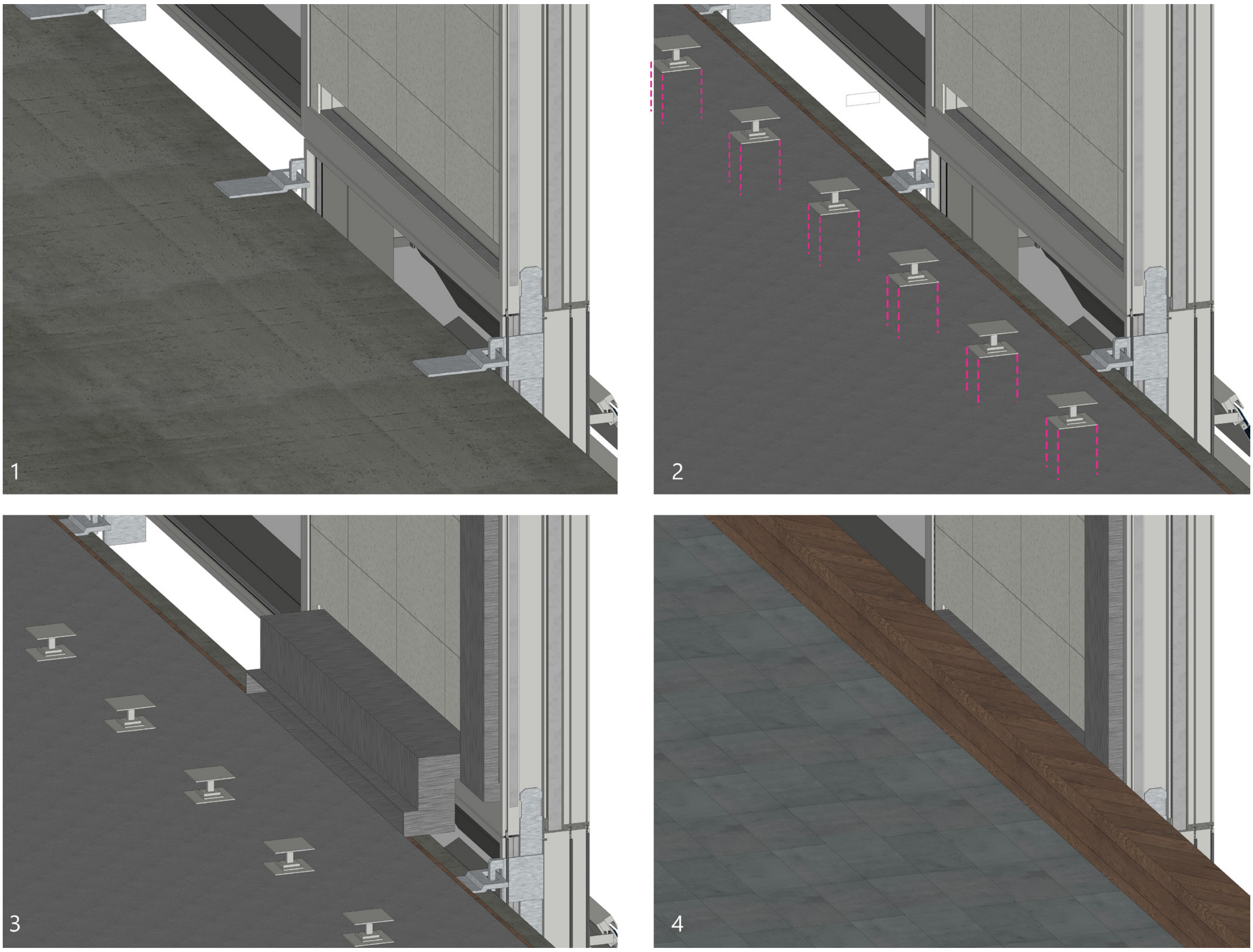


Figure 108 Assembly of ventilation system on site

7.4.3 Tolerances and movements

The advantage of this support type is that it provides enough possibility for tolerances and therefore simplifies site assembly. How the tolerances are incorporated in the design are shown in the following graphs.

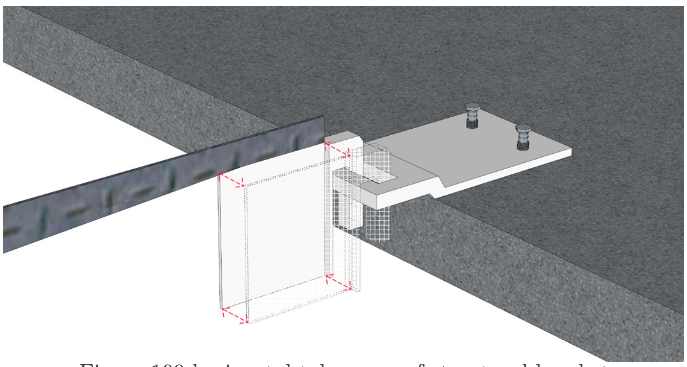


Figure 109 horizontal tolerances of structural bracket

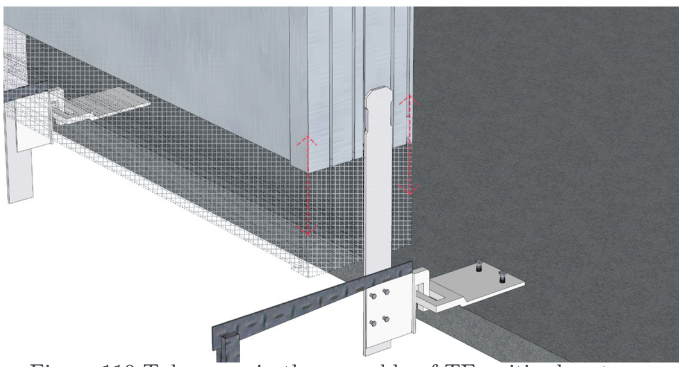


Figure 110 Tolerances in the assembly of TE unitized system

7.4.4 Materials

In the following graph, the materials selected are shown. The choice of materials can be further researched for sustainability and life cycle assessment.

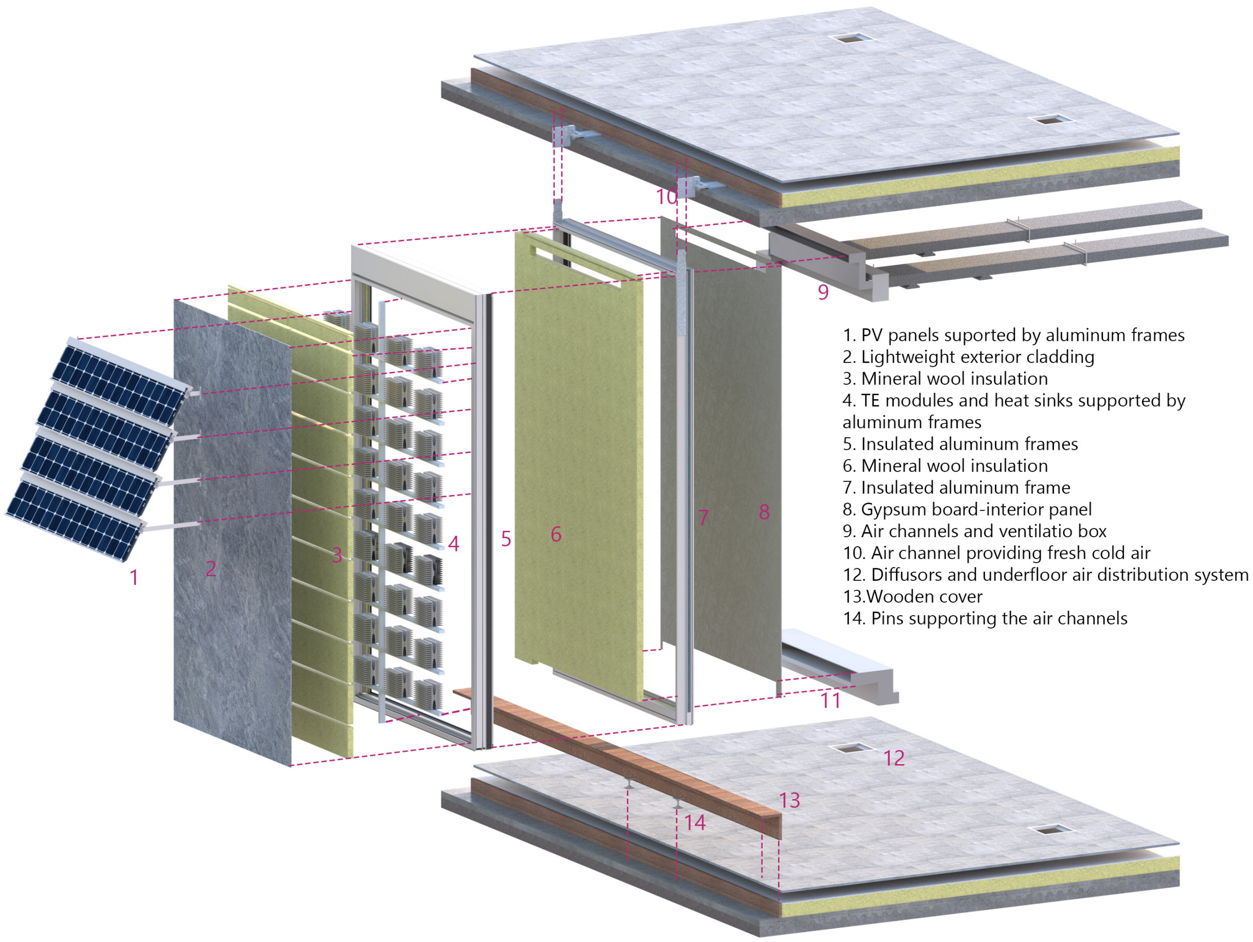


Figure 111 Materials shown in a exploded view

7.4.5 Lines of defense

There are two insulation lines in this facade, one dedicated to the TE system that prevents heat from transferring from the hot to the cold side and the other, providing the main insulation barriers from the outdoor environment to the indoor. It can be seen in the section that ventilation integration in the facade causes thermal breaks where the air inlet and outlets are located. Although air provides insulation in these insulations gaps, to prevent creating cold bridges the ventilation ducts and boxes, have to be insulated, and the damper have to close automatically when the system is not functioning.

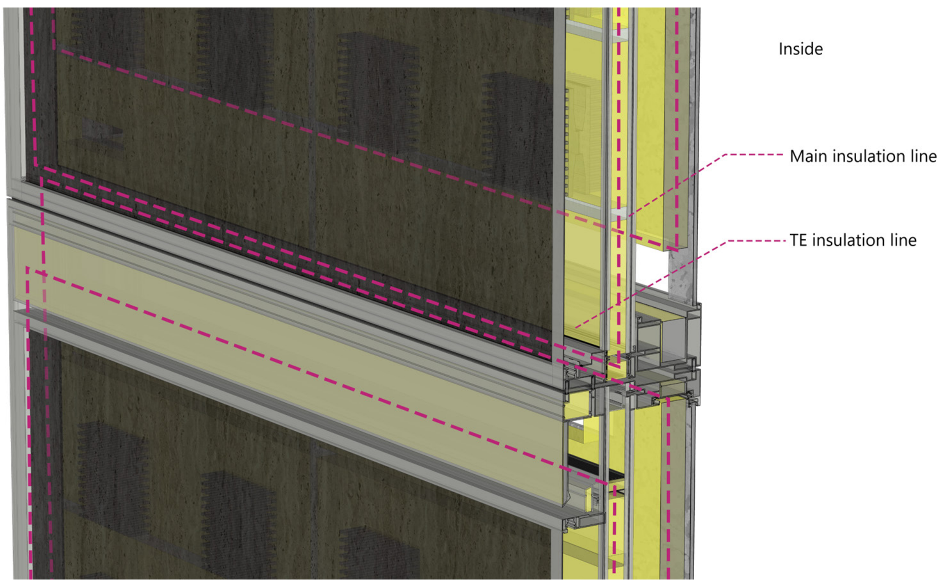


Figure 112 Figure 56 diagram showing the insulation lines in the TE facade

The water tightness in this facade is provided by two lines shown in the graph. The facade finishes and the sloped facade profiles, as well as pressure caps and gaskets, prevent the water from entering the first line. The gasket between profiles and the waterproof insulation on the second line ensure that water does not enter the building.

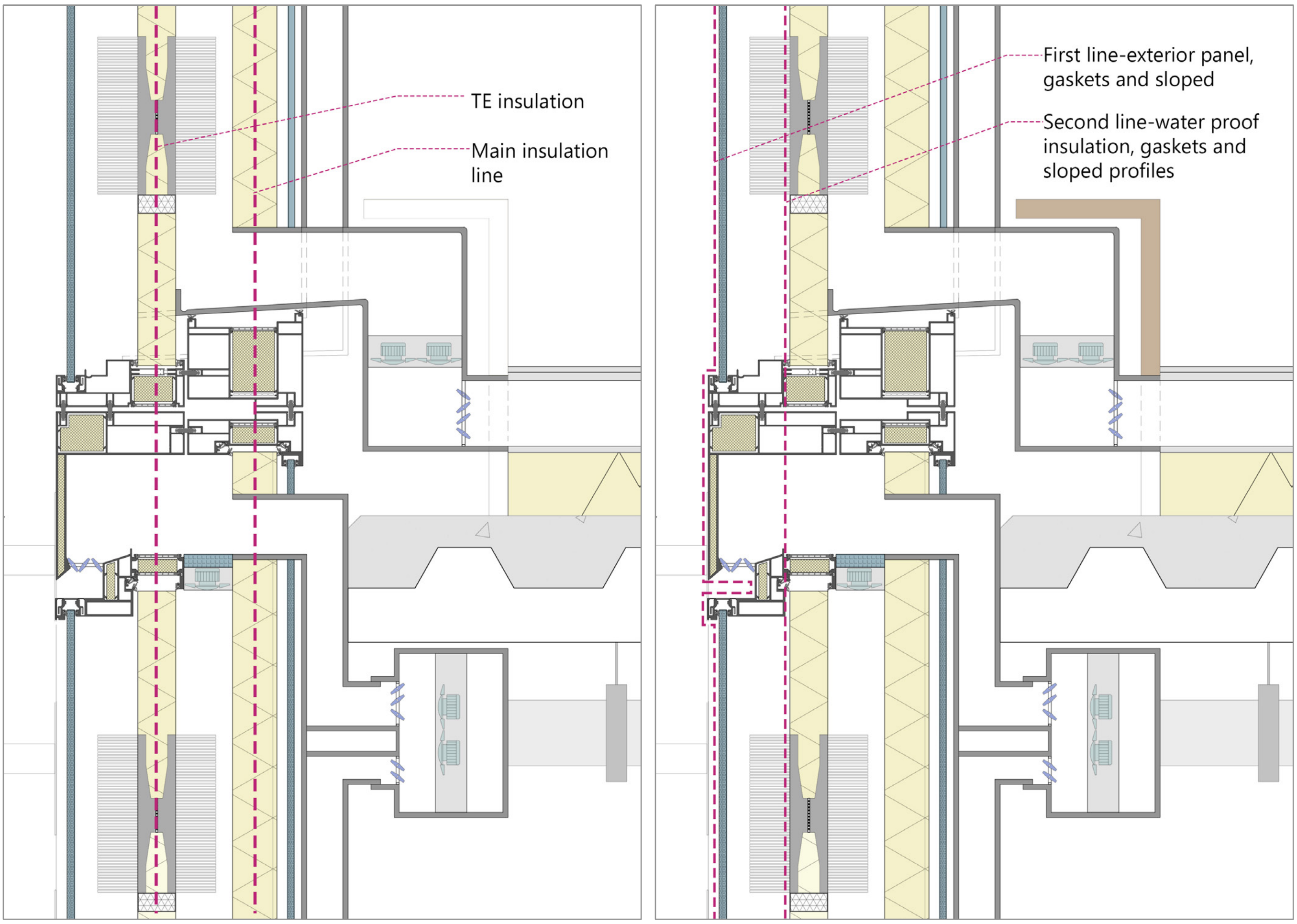


Figure 113 Vertical section showing insulation and water tightness lines in the facade

On the other hand, the heat sinks have a high potential in reaching the dew point and forming frost. The sloped profiles lead the water to the outside, and a drainage system is needed to collect this water.

7.4.6 PV panels, connections and characteristic

The PV panels are structurally connected to the façade aluminum frames via a secondary structure and this makes the maintenance of the PV panels easier. The following diagrams show the connection between PV panels and TE façade.

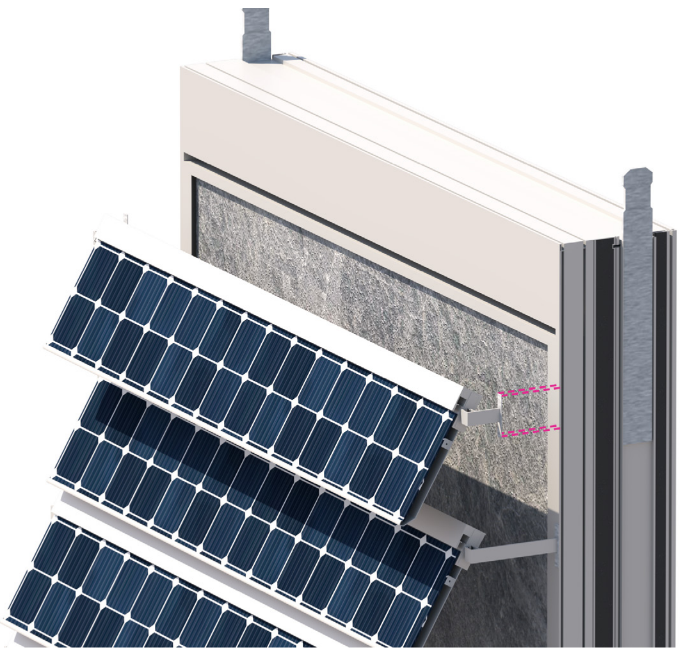
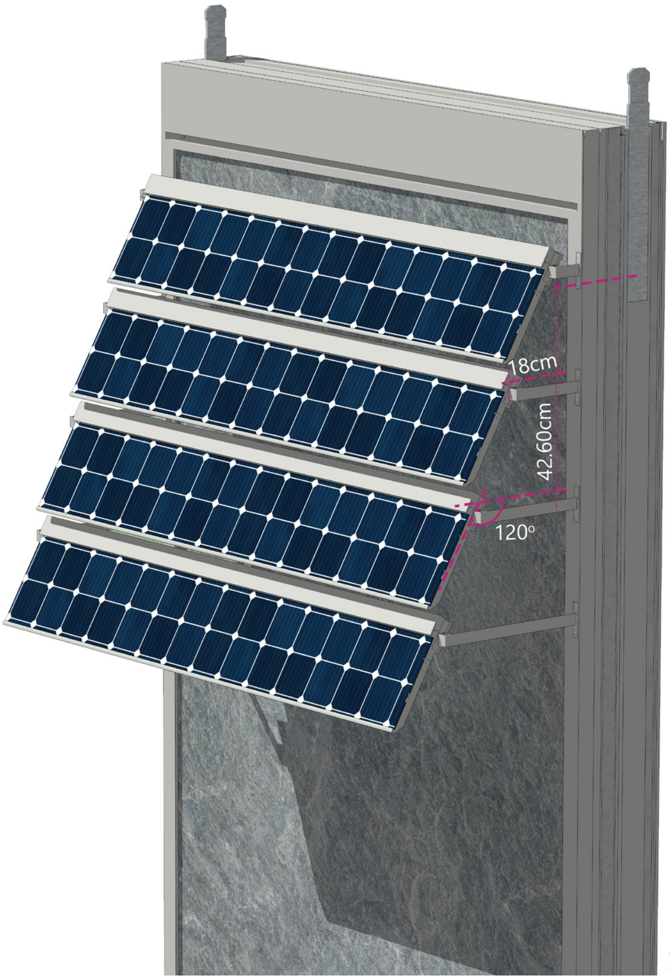


Figure 114 Connection of the PV panel with the TE facade



A shadow analysis using the exact location of the office building is conducted to find out the proper distance and angle between the PV modules and the façade to prevent shading of the PV panels on each other. The following diagrams shows shadows casted in different times of day in summer and winter and how overcasting is prevented.

Figure 115 Distance and relation between PV panels

July-7:00pm July-2:00pm January-11:00am

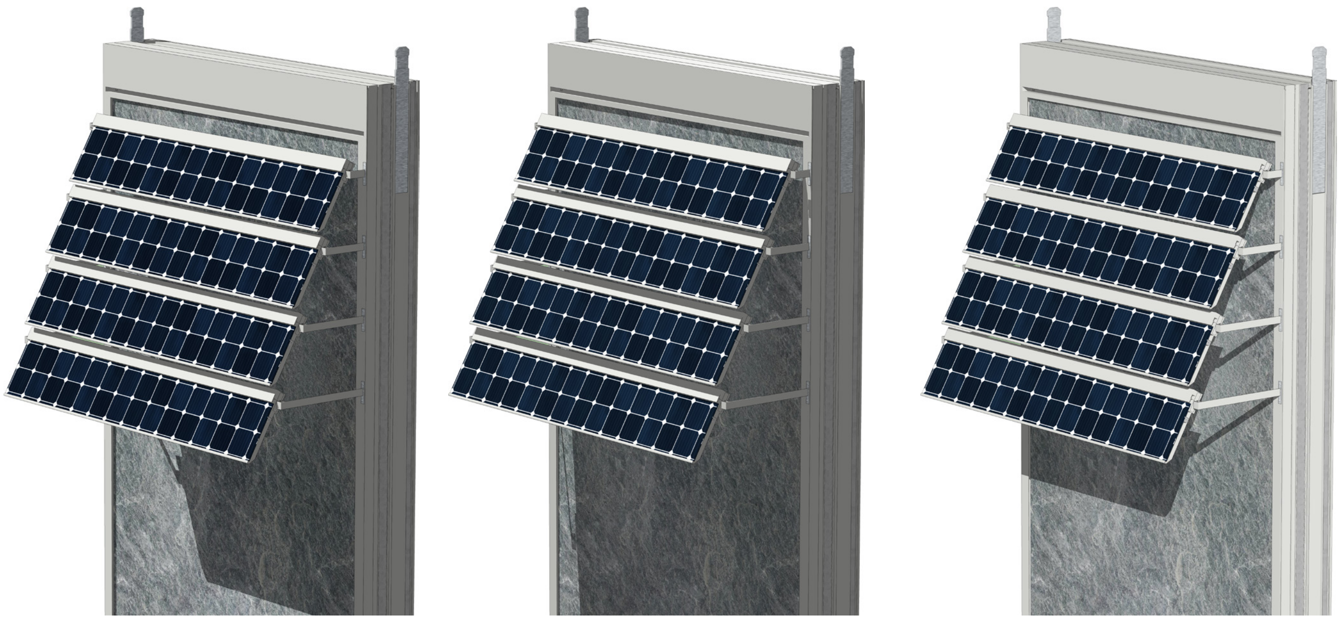


Figure 116 Shadow analysis of the PV panels on different times of the day in summer and winter

7.4.7 Active TE cooling and ventilation functions

In the active TE cooling/heating system as explained before the whole facade on each side of the module acts as a duct and provides the cooled or heated air to the room. The ventilated air is taken to the outside through the hot side of the facade. This system is reversed in winters, and hot and cold heat sinks change places. How the system works in summer is shown in the following diagrams. In winter the cold air channels become hot and the ones cold since the cold and hot side of the TE modules switch.

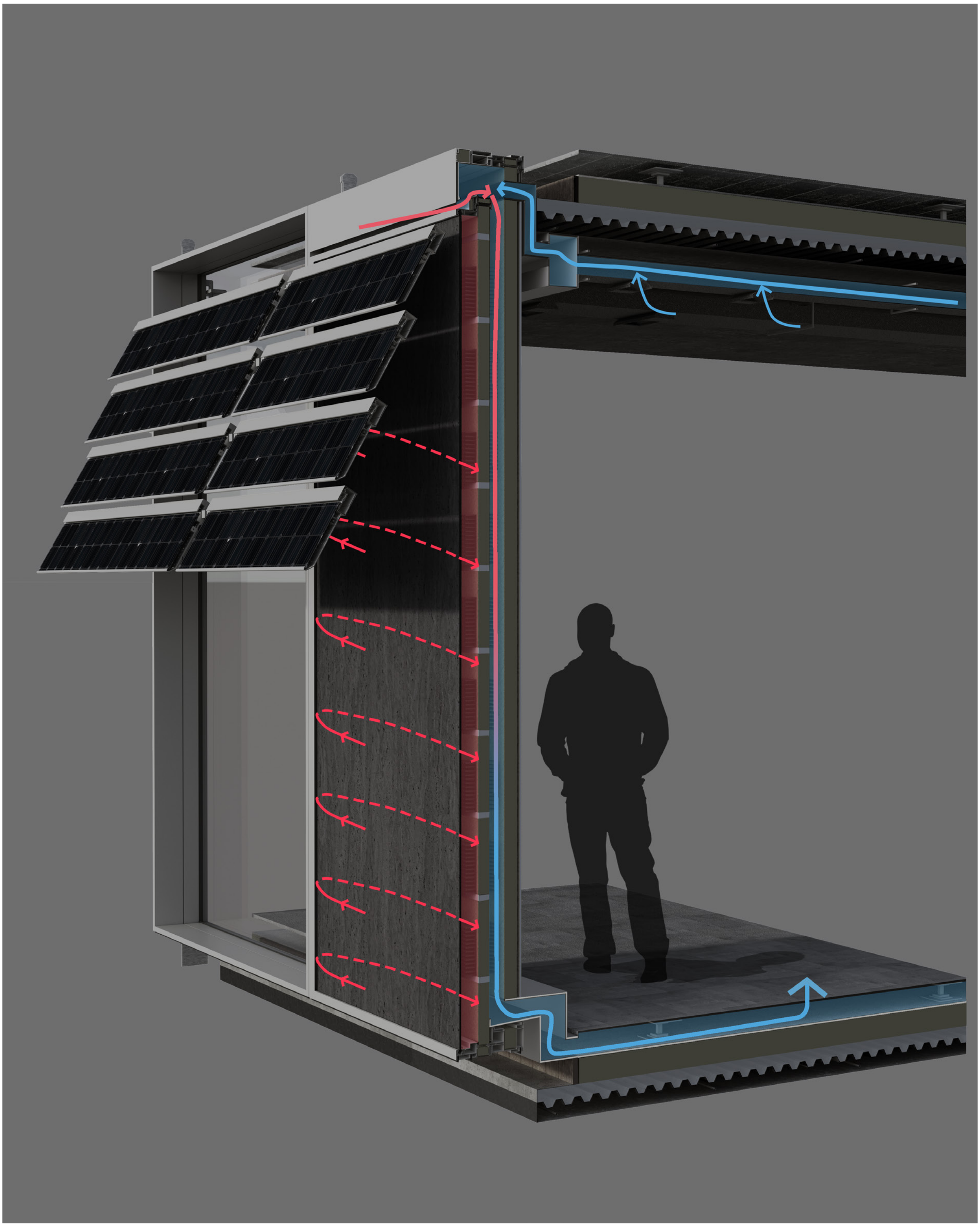


Figure 117 Diagrams of the facade's section showing air flows in the facade in summer

7.5 Alternative designs

Integration of Peltier elements with façade provides a rather significant flexibility in design. in this section a set of alternative designs are provided which have not been studied in detail and are conceptual. The goal is to present a range of possibilities with other approaches in design.

Figure 118 Possible alternative designs with TE integrated active system

8 Thermal design and performance assessment

8.1 Introduction

The whole TE ventilation systems evolves around how ΔT created on the two sides affects the performance of TE elements. However, as seen in previous diagrams, the room loads may also be subject of this reductions in temperature difference. Therefore, a comprehensive model has to be defined to examine the effect of various parameters on the system performance. This model includes on one hand, the thermal model of thermoelectric elements and calculations based on the temperature-dependent method and on the other hand the ventilation system and room loads. These two models are simultaneously affecting one another, and this is why a universal model is developed in this section.

This chapter begins with explanations on development of this comprehensive model. The most important criteria in this study is then defined as COP_{system} and a baseline model for summer peak situation is developed to which further studies are compared to. In the next stage, the variables that affect the performance of the system are studied individually to help gain a better understanding of the whole system and its optimization. Then an optimization is run for the peak situation to obtain the best values for each of the parameters. This will lead to the best COPs in the peak hour which should be the lowest performance of the system, and it can be shown later in this chapter that non-peak conditions will lead to better system efficiencies.

In these calculations the goal is to first evaluate if ΔT created is sufficiently reduced by using this ventilation integrated concept and since all the calculations in previous sections were based on reaching a ΔT of 20 °C, it can be assessed in this section if the predicted COPs can be achieved with the same number of TE modules estimated in the cost analysis.

The second goal is to propose operating conditions in which the overall COP of the system and not only the thermoelectric performance is maximized. To this end, the summer peak situation is first studied as an indication of the most extreme condition with highest cooling loads and outside dry-bulb temperature.

At the end of this chapter, an optimization is run for every time step of the year. Conclusions can then be drawn along with calculations of the annual electricity consumption of this ventilation integrated cooling and heating system to estimate if the system is efficient enough to cover the annual consumption with electricity provided by PV panels. Moreover, Suggestions will then be made with potential integration of PCM to improve further the performance of this system, especially in summer.

8.2 Mathematical formulations and modeling of the system

Although the model developed in this section takes into account many of the aspects that affect the performance of the system including the fans consumption, thermoelectric calculations and heat sink resistance varying with wind velocity, many of other criteria are not taken into consideration. These aspects that require more attention include heat transfer between air channels and neighboring spaces, heat transfer to the air streams from the fans, CFD model of air streams and how it flows in the channels and through the heat sinks, pressure drops to calculate exact SFP value, etc. Therefore, in a more extended research, further improvements of this model is required.

8.2.1 Cooling and ventilation loads

As explained before in the beginning of chapter 6, the ventilation load is already calculated in $Q_{total\ cooling}$, however, since we are integrating ventilation in the active cooling system, it is required to exclude the ventilation loads from the room loads and include them in the TE ventilation thermal model in an effective way.

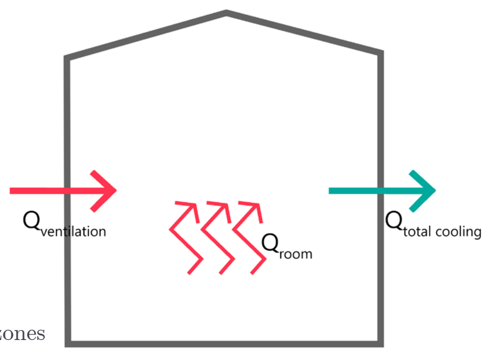


Figure 119 load streams entering the conditioned zones

Q_{room} refers to loads of the room excluding ventilation loads, we have:

$$Q_{Room} - Q_{TotalCooling} - Q_{Ventilation} = 0 \tag{20}$$

In which

$$Q_{Ventilation} = \dot{m}_{FreshAir} C_p \left(T_2 - T_1\right) \tag{21}$$

Where T_1 is inside temperature and equal to 25°C, and T_2 is outside temperature and equal to 40°C in summer peak condition. Furthermore, $\dot{m}_{FreshAir}$ is the total mass flow rate of ventilated air and can be obtained from the following equation:

$$\dot{m}_{FreshAir} = (\text{no. of people}) \times (\text{minimum fresh air rate per person}) \times \rho_{Air} \tag{22}$$

The minimum fresh air required per person is considered to be 10 [l/s] and assuming 30 people in this office floor, the required mass flow rate to provide minimum fresh air is then calculated via Eq. (9.3) to be 0.29 [kg/s], and then $Q_{Ventilation}$ = 4.53 [kW] from Eq. (9.2).

Finally, Q_{Room} can be calculated from the formula (9.1), having the cooling demand simulated by Designbuilder in previous sections to be 24.58 kW during peak in summer as Q_{room} = 24.58 – 4.53 = 20.05 [kW]. This load together with inside and outside temperatures are the inputs of the peak situation as independent variables.

8.2.2 Thermal calculations for each facade module

For each TE thermoelectric module, the following energy balance equations can be written for the hot and cold air streams with the terminology shown in the figure below.

$$\dot{m}_1 C_p T_1 + q_h - \dot{m}_1 C_p T_2 = 0 \tag{23}$$

$$\dot{m}_2 C_p T_3 - q_c - \dot{m}_2 C_p T_4 = 0 \tag{24}$$

In which $\dot{m}_1$ and $\dot{m}_2$ are the mass flow rate on the hot and cold sides of the modules, T_1 to T_4 are the temperatures of the air entering and exiting the modules on both sides and q_h and q_c are the values of heat added to or taken from the modules.

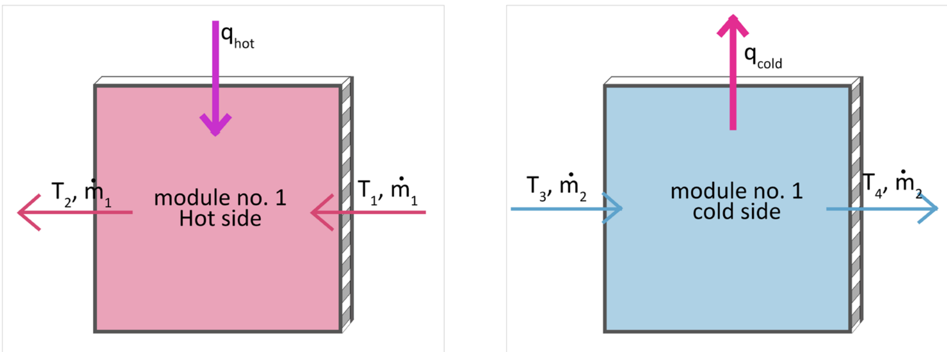


Figure 120 Airflow scheme at the cold side of the TE

On the other hand, we know the relationship between q_h and q_c as following:

$$q_h = q_c + q_w \tag{25}$$

Where q_w is the electrical power consumption by the TE module, and as explained in of chapter 6 in details, following equations based on method 2 and calculation of Thompson coefficient are used to calculated q_c and q_w:

$$q_c = S_{T_c} I T_c - 0.5 I^2 R - K \left(T_h - T_c\right) + 0.5 \tau I \left(T_h - T_c\right) \tag{26}$$

$$q_w = \left(S_{T_h} T_h - S_{T_c} T_c\right) I + I^2 R - \tau I \left(T_h - T_c\right) \tag{27}$$

In which I is the electrical current in Amperes, T_c and T_h are the cold and hot sides temperature of the TE module in Kelvin, R and K are electrical resistance and thermal conductivity of the TE that are assumed to be constants, S_{Tc} and S_{Tc} are the Seebeck coefficient on the hot and cold sides that are estimated by the following linear interpolations using the values of that at 323 and 298 Kelvin:

$$S_T = (S_{323} - S_{298})(T - 298) / 25 + S_{298} \tag{28}$$

Where T can be T_c or T_h to obtain the Seebeck coefficients at that temperature. Thomson coefficient is computed using its definition as following:

$$\tau = 0.5(T_c + T_h)(S_{Th} - S_{Tc}) / (T_h - T_c) \tag{29}$$

Temperature at the surface of the TE is connected to the hot and cold side air flows utilizing heat sink thermal resistance as given below:

$$T_h = R_h q_h + 0.5(T_1 + T_2) \tag{30}$$

$$T_c = R_c q_c + 0.5(T_3 + T_4) \tag{31}$$

In which R_h and R_c in [W/K] are total thermal resistance of the heat sinks at hot and cold sides. The procedure to calculate the thermal resistance of the selected heat sinks are explained in the next section.

The set of inputs in this problem are on the one hand the indoor and outdoor temperatures and mass flow rates on the hot and cold sides on the other. Therefore, what can be concluded is that by changing 4 variables here, different results can be expected in ΔT on the two sides of modules. These variables including $\dot{m}_1$, $\dot{m}_2$, T_1 and T_3 will be studied in the following sections.

It should be noted that when the input temperatures of streams at cold and hot sides are given, by using the presented formulations in this section, one can compute the outlet temperatures as well as the electrical energy consumption of the TE, its temperature difference (ΔT=Th-Tc), the removed energy at the cold side qc and released energy at the hot side q_h, and cooling COP of that TE via COP=q_c/q_w.

Now, it is assumed that there are n columns and m rows of the TE elements modules at each facade module with total number of n × m TE elements and hence the total number of TEs is equal to Nfm (Number of facade modules) × (n × m).

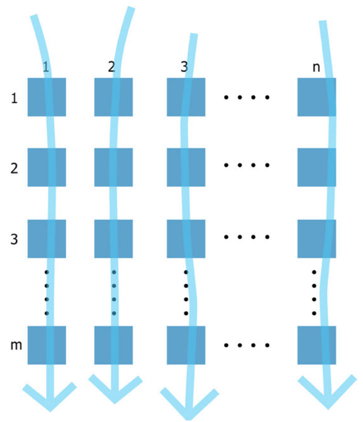


Figure 121 Arrangement of TE modules on each of the hot and cold sides

For each facade module, we assume that the conditions of ΔT is equal for elements on the same row, i.e. in row m, all the modules from 1 to n will experience the same thermal input conditions. Therefore, the set of equations will be solved in one-dimensional for rows 1 to m by assuming n TEs at each stage. The formulations of the problem have been carried out in the EES software of which the code is attached to this report.

8.2.3 Electricity consumption of fans, air velocity, and mass flow rate

The number of facade modules that integrate TE elements, provide heating and cooling and their size defines how much of volume flow rate would be dedicated to each module as seen in the following formula:

$$\dot{V}_{total} = \dot{V}_{module} \times Nfm \tag{32}$$

With Nfm stands number of facade modules. This means that each facade module will contribute to 1/Nfm of the overall air flow rate entering the zones. Also, for every certain volume flow rate, certain duct area and air velocity are required which can be calculated from the following equations

$$\dot{V} = V \times A \tag{33}$$

where $\dot{V}$ is the volume flow rate (m^3/s), V is the air velocity (m/s), and A is the cross-section area (m^2).

Calculation of air velocity is important since it defines the resistance of the heat sink and as seen in the following graphs, resistance would decrease by increasing the air velocity.

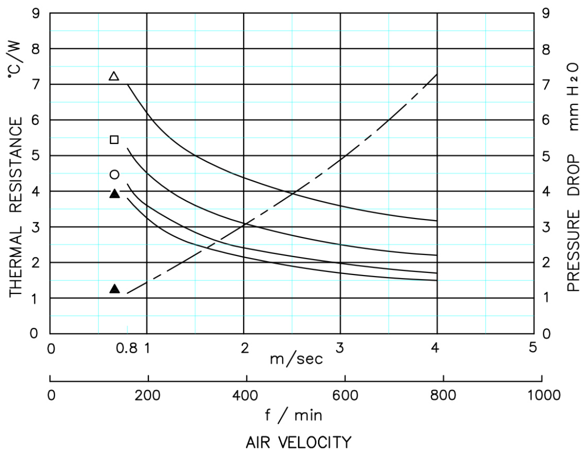


Figure 122 diagram showing decrease of thermal resistance with increase of V for different heat sink products. http://www.alphanovatech.com/en/cat`te.html

The area A is constraint by the available area for ducts on each of the hot and cold sides. To maximize this area, the length of every facade module is considered to be 2.5 m, available length for the duct to be 2.2 m, and a width of 0.1 m is assumed.

$$A = L \times W \tag{34}$$

Where W is width of the channel (m), L is length of the channel, and A is obtained as 0.22 m^2. Therefore, for every volume flow rate, the air velocity and its effect on the heat sink resistance can be studied.

The fans provide enough mass flow rate and velocity in the air channels and consume electricity. Therefore, in the final model, the energy consumed by fans and their effect on the overall system COP must be considered.

In order to calculate the energy demand of fans, an SFP must be assumed for the system, and it should be noted that in a more complete model this value has to be calculated for the actual pressure drops and fan efficiency of this system. The value of SFP is important since it defines the weight of fans consumption in the overall system COP and with lower values, more fan power can be used to reduce ΔT. In this study, values of 1 and 2 kW/(m3/s) for SFP are assumed to examine the fans efficiency and reducing pressure drops on the overall system efficiency.

The energy consumption of fans is therefore calculated as follows:

$$P_{fans} = SFP \times \dot{V} \tag{35}$$

With SPF stands Specific fan power demand (kW/(m3/s))

8.2.4 Resistance of heat sinks

The heat from the cold side which leads to increasing of the hot side temperature has to be removed as quickly as possible to reduce the ΔT. As seen from the equation below with the relation between R, Q, and ΔT, having lower resistance leads to lower values of temperature difference having the same load Q.

$$Q = \Delta T / R \tag{36}$$

Although the role of having a good performing heat sink is crucial, design of the heat sink is out of the scope of this project. The heat sink selected before with the lowest resistance as presented below will be applied in this thermal model.

Table 23 properties of the selected heat sink

Heat sink	R(ºC/W) At 250CFM	Height(m)	Weight per HS (kg)	Total weight in each TEF(Kg)	Area per HS (m2)	Total area in each TEF (m2)
3-989825RFA	0.020	0.0635	5.286	1902.96	0.071	2.55

The selected heat sink in this study has a certain resistance that is influenced by the factor of air velocity. It is therefore essential to predict the effect of air velocity in the overall COP of the system since more electricity consumption of fans will not only effect on the mass flow rate but also the resistance of heat sinks. In other word, increasing the volume flow rate $\dot{V}$, will on the one hand increase the fans energy consumption and on the other hand decrease the resistance of heat sinks, increase the mass flow rate and contribute to better heat dissipation.

To calculate the resistance of heat sinks the following formula can be used (Nellis and Klein 2009):

$$h_{air} = 10.45 - V + 10V^{1/2} \tag{37}$$

In which A_f is fins contact area in m^2, A_{nf} is the area of heat sink excluding fins' area in m^2, η is the efficiency of fins, and h_{air} is convective heat transfer coefficient of air (W/m2ºC).

The following equations are used to calculated A_f, A_{nf} and h_{air}. The fins efficiency is usually a number between 0.7 to 0.95 and in this case, based on data provided by the manufacturer is assumed to be 0.9.

$$A_f = \left(\pi D_{fin} L_{fin} + (\pi D_{fin}^2 / 4)\right) N_{fin} \tag{38}$$

In which D_{fin} and L_{fin} are the fins' diameter and length and N_{fin} is the number of fins, which are values provided by the manufacturer and are as follows.

- D_{fin} = 0.0032 (m)
- L_{fin} = 0.0635 (m)
- N_{fin} = 56*56 = 3136

Also,

$$A_{nf} = L_{hs} W_{hs} - A_f \tag{39}$$

In which L_{hs} and W_{hs} are the length and width of the heat sink's base as $L_{hs} = W_{hs} = 0.25$ (m). For heat transfer convection:

$$h_{air} = 10.45 - V + 10V^{1/2} \tag{40}$$

It is important to note that the air velocity V could be different value for the hot and cold sides and therefore two set of calculations for the resistance R needs to be driven.

8.2.5 Ventilation thermodynamic model

The following diagram represents the thermal scheme of the concept presented in chapter 6 and shows how the ventilation air divided between TE facade modules and is used in each to cool down the hot side and precool the incoming air.

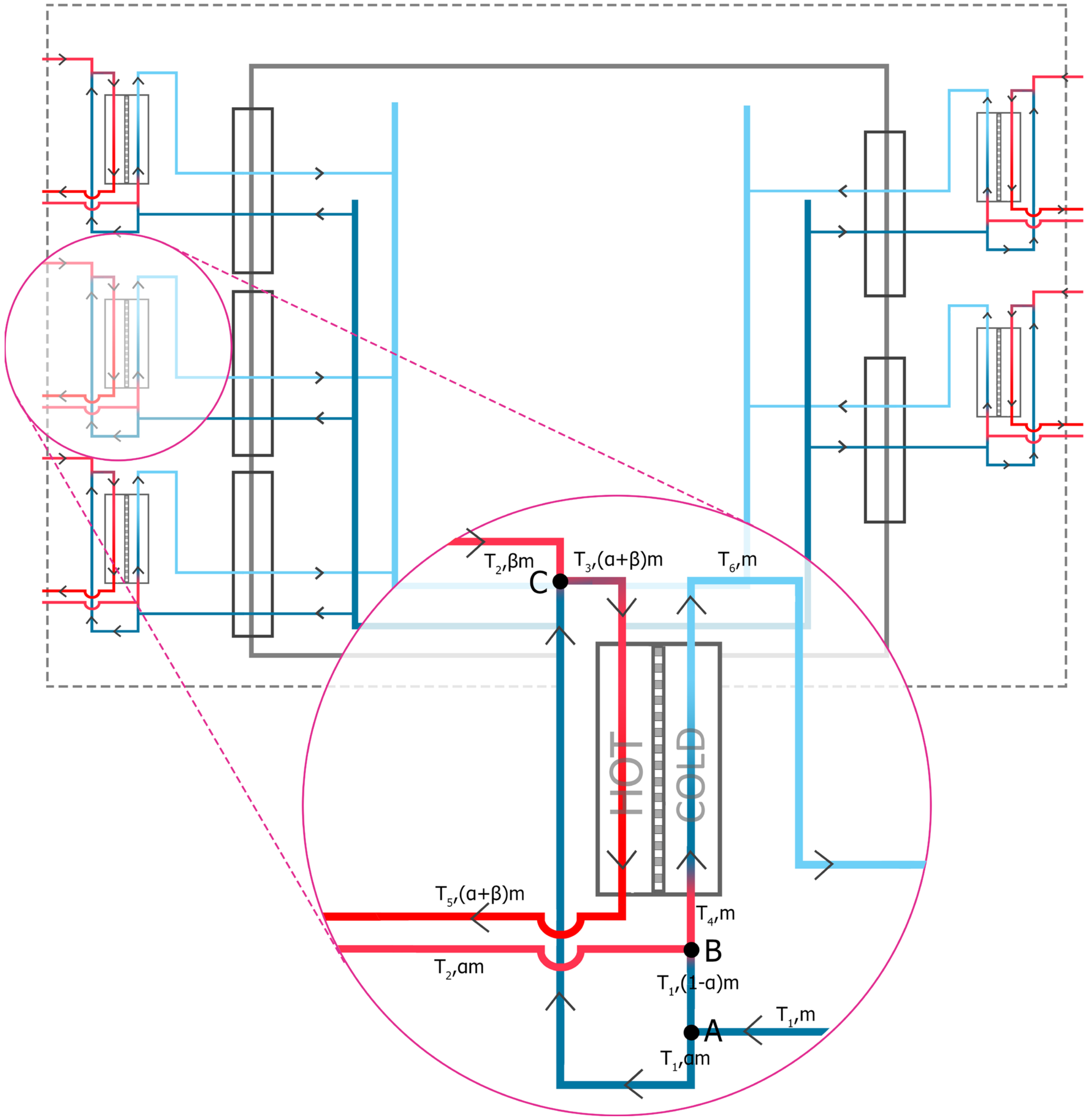


Figure 123 Thermal scheme TE facades on one floor of the office and focus on one of the TE modules

The air flow starts from the room where air is extracted with a mass flow rate of $\dot{m}$ and temperature T_1, then it gets divided in point A, where α portion of $\dot{m}$ goes through the hot side of the TE facade and the rest through the cold side.

The mass balance in point A can be written then as follows:

$$\text{Point A:} \quad \dot{m}CpT_1 - \alpha\dot{m}CpT_1 - (1-\alpha)\dot{m}CpT_1 = 0 \tag{41}$$

The return air from point A towards the room gets mixed up with fresh air that is equal to the amount of air that is exiting the system, $\alpha\dot{m}$

This amount of air must be at least meet the amount of fresh air necessary for ventilation of the office and could be more to decrease the ΔT of TE modules.

$$\text{Point B:}\quad (1-\alpha)\dot{m}CpT_1 + \alpha\dot{m}CpT_2 - \dot{m}CpT_4 = 0 \tag{42}$$

The air going through the hot side then gets mixed up with outside fresh air in point C to increase the air mass flow rate and therefore improve the heat removal process.

$$\text{Point C:}\quad \alpha\dot{m}CpT_1 + \beta\dot{m}CpT_2 - (\alpha+\beta)\dot{m}CpT_3 = 0 \tag{43}$$

After points B and C, air gets heated or cooled through the TE elements, and either is ventilated to the outside or provided to the room delivering the required fresh air.

The temperature of the exiting air, T_6, will be determined by the solver based on how much the total Q_h is and how much of it has been transferred to the air via the heat sinks with certain thermal resistance. On the other hand, the temperature of the air that feeds the room, T_7 is determined by the total cooling load of the room, which is the total amount of Q_{room} plus the ventilation load as explained before and shown in the following formula.

Heat balance of the room:

$$Q_{room} + \dot{m}C_pT_6 - \dot{m}C_pT_1 = 0 \tag{44}$$

Therefore, the setup of the model should be in such a way that defines the necessary electric current, I for the TE system to be able to provide T_7 as an output of the cold side. The calculation related to the TE system are explained in previous section, and by solving these set of equations, ΔT, I and Q_w can be calculated for each TE element in order to fulfill the room thermal comfort requirement.

Therefore, having all these equations including the room heat balance, the ventilation equations and TE calculations a complete room model is obtained. In order to solve these set of equations, engineering equation solver, EES has been used. This parametric model can be used both to improve and optimize the COP of this system and to assess the expected results from previous calculations.

Now that the thermal model of this ventilation integrated TE system is developed, a baseline scenario must be defined on which the variables could be studied individually. The model is verified in appendix 1 in simple system scheme.

8.2.6 Overall system efficiency

As seen in the previous section the actual required cooling load in this ventilation integrated system considering the minimum fresh air requirement in peak is $Q_{total\ cooling} = 24.58$ kW.

For the system to have a lower ΔT and a higher COP value, it may be necessary to add more fresh air to the system. This will cause an addition to the overall cooling load as well as electricity consumption. If the addition in electricity consumption is lower than that of cooling loads, the COP will increase.

A COP value can then be defined that both integrates the overall loads including the additional fresh air loads and the electricity consumption of fans as well as TE modules.

$$COP_{overall} = Q_{total} / \left(P_{fans} + P_{TE}\right) \tag{45}$$

In which Q_{total} is the total cooling load including the added fresh air required for the TE system.

However, this value may not be a good indication of the system performance because higher COPs may be achieved while increasing the total electricity consumption. Therefore, it seems that introducing a new COP is necessary which is defined as follows.

$$COP_{system} = Q_{total,\ cooling} / P_{total} \tag{46}$$

Where

$$P_{total} = P_{fans} + P_{TE} \tag{47}$$

In this COP the $Q_{total\ cooling}$ is assumed to be the load including only minimum fresh air as an output of Designbuilder simulations and the rest of the added load is not considered since it is only an addition because of the TE performance. This value will be used in the next section to optimize and compare results of studying variables.

8.3 Baseline model, validation and optimization

The variables of this thermal model are listed in the table 24.

Table 24 list of variables in the model

Category	≠	parameter	Description	Constraints	value
Air movement and flow rate	1	$\dot{V}$	Volume flow rate of office (m^3/s)	Fan consumption and avoiding discomfort	Studied for each condition
	2	α	% Fresh air-cold side	Min value of $\alpha\dot{m}$ should be 0.18	Studied for each condition
	3	β	% outside air-hot side	Fan energy consumption	Studied for each condition
	-	A_{duct}	Duct area (m^2)	Facade dimensions	A = 0.22 m^2
	4	SFP	specific fan power	Pressure drops and fan efficiency	1 and 2 kW/(m3/s)
TE elements within facade modules	5	N_{tot}	Total number of modules	Min 110, refer to chapter 6	180
	-	Nom	Number of facade TE modules	Maximum 6, WWR	5
	-	n	Number of TE columns in each facade module	-	4
	-	m	Number of rows in each columns, n	M = N_{tot}/m*Nom	9
Operating conditions at peak	-	T_1	Indoor air temperature	Thermal comfort range	25 °C summer, 21oC winter
	-	T_2	Outside air temperature at the peak time	Independent value	Differs for each time step
		Q_{room}	Cooling load excluding ventilation	Obtained from Designbuilder simulations	Differs for each time step

Some of these variables related to the TE elements arrangement within the facade modules including number of columns, n, and number of rows, m will not be studied in this section due to calculation complications, and their effect is assumed to be insignificant. Also, the operating conditions for each time step is constant. The heat sink resistance is calculated as explained in previous sections for every airspeed for the selected heat sink. Therefore, the variables studied in this section are five variables including the number of TE elements, N_{tot}, Volume flow rate of office, $\dot{V}$, α, β and SFP.

8.3.1 Baseline model- summer peak condition

Since as explained before, the summer peak is expected to have the lowest COP, the effect of each variable on improving this condition should be studied. For each variable, the baseline value is set as in the following table, where 180 TE elements are used based on the cost analysis in chapter 6. In the peak scenario, the $Q_{total\ cooling}$ is equal to 24.58 (kW), and therefore COP_{system} can be obtained as

$$COP_{system} = 24.58 / P_{total}$$

Moreover, $\alpha\dot{V}$ should at least be the minimum amount in summer equal to 0.30 (m^3/s).

Table 25 Inputs of the baseline model, air movement and operating conditions

Category	≠	Input	explanation	Value
Air movement and flow rate	1	$\dot{V}$	-	2 (m^3/s)
	2	α	To provide minimum fresh air of 0.3 m^3/s	0.15
	3	β	-	1
	4	SFP	-	2 kW/(m3/s)
operating conditions	7	T_1	Indoor air temperature	25ºC
	8	T_2	Outside air temperature at the peak time	40ºC
	9	Q_{room}	Room cooling demand excluding ventilation load	20.05 (kWh)

Also, the following results are obtained from EES by having these values as input.

Table 26 results of simulations in EES with the baseline model

Output	Description	Obtained value
COP_{system}	COP of the system including consumption of fans	0.57
$COP_{TE\ system}$	COP of the thermoelectric system	0.73
$\Delta T_{average}$	Average temperature difference obtained at the two sides 2of TE modules(ºC)	38.51
$T_{required}$	Required temperature entering the room (ºC)	16.45
$I_{required}$	Required electric current to provide enough cooling power by TE (A)	14.42
V_{hot}	Air velocity of the exiting air (m^3/s)	2.1
R_{hot}	Heat sinks resistance on the hot side (ºC/W)	0.023
V_{cold}	Air velocity of the air entering the room (m^3/s)	1.81
R_{cold}	Heat sinks resistance on the cold side (ºC/W)	0.024
P_{TE}	Electricity consumption of TE system (kWh)	34.73
P_{fans}	Electricity consumption of fans (kWh)	8.60
P_{total}	Total system electricity consumption(kWh)	43.33

As evident from the simulation results, the obtained COP is 0.57 for the whole system, and a peak COP of around 0.73 is obtained for the TE elements in the peak conditions and the integrated configuration of the ventilation system has helped to reduce the ΔT to around 39 ºC, which is still a high value and should be further reduced. The expected COP and ΔT values estimated from the costs analysis are still not achieved and therefore studying the variables and optimizations are required.

In the next section each variable will be studied individually to measure its thresholds and effectiveness in the overall COP.

8.4 Studying variables

Now that an optimized baseline model has been developed and verified as explained in the appendix A for the peak condition, each of the parameters can be studied and compared to the baseline results while all the other variables are constant to gain a better understanding of the factors that influence the performance of this system. As the first variable, number of modules has been examined to measure the effect of increasing the number of TE elements on the overall performance.

8.4.1 Number of modules, N

It is expected that the thermoelectric system COP would experience a peak at 190 modules as seen in chapter 6 and then drop gradually. While with the same air flow rate the system COP would as well undergo a peak and gradual drop.

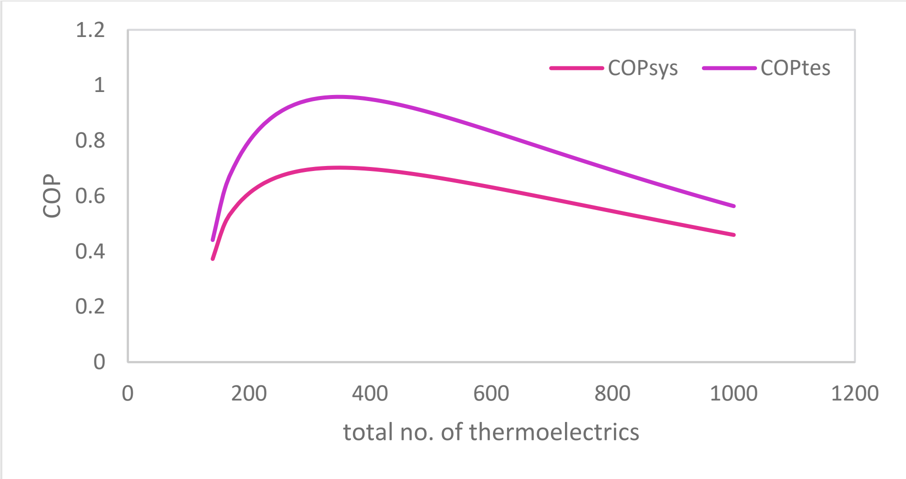


Figure 124 effect of number of TE elements of system and TE efficiency

As seen in these graphs the COP of both the whole system and TE increases until It reaches 320 modules, then remains constant till 380 modules and then slowly decrease although ΔT continues to gradually decrease. The increase in the COP_{system} in these situations is by 0.3 from 160 to 300 modules, and this proves that increasing the number of TE elements will not lead to a great rise in the COP at least in the peak situation.

8.4.2 Percentage of fresh air, α

This value defines the portion of the total ventilated air from the conditioned zone that is outside fresh air. This is also the volumetric flow rate of cool air that passes through the hot side and cools it down. Therefore, on the one hand increasing this value will help the TE system to decrease ΔT and on other, it increases the total cooling load due to added ventilation loads and leads to increase in ΔT. Therefore, an optimum value should exist to obtain a balance between these two extremes. The minimum value for $\alpha\dot{V}$ as explained before should be 0.3 m^3/s to provide the minimum fresh air requirement and therefore, $\alpha_{minimum} = 0.15$.

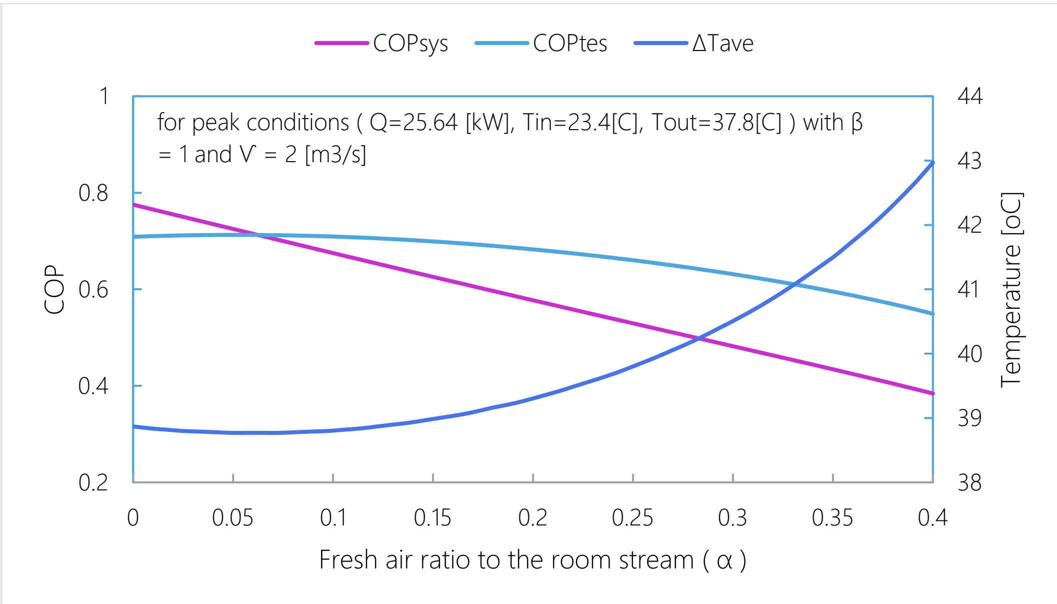


Figure 125 simulation results showing COP with varying α values

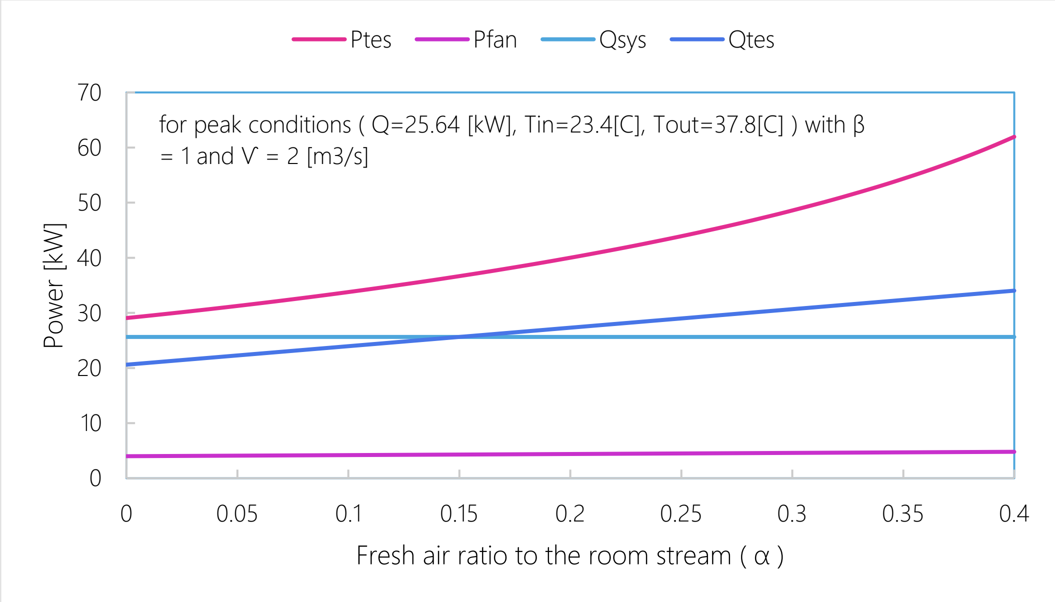


Figure 126 Simulation results showing electricity consumption with varying α values

As seen from these graphs, increasing the fresh air intake will gradually decrease the COP of both the overall system and the TE, this is especially significant in the system COP. This can be due to the high outside temperature during the peak which will not help in decreasing the temperature difference ΔT as seen in the graphs. For **α** more than 0.4, ΔT reaches more than 66ºC which is the maximum ΔT possible for TE elements. Therefore, it seems that during peak hours, value of **α** should be kept at a minimum value only needed to provide fresh air. For other conditions than the peak, it should be studied if increasing this value would help the system to boost the efficiency.

8.4.3 Percentage of fresh outside air at the hot side, β

As **α** portion of $\dot{V}$ heads to the hot side of the TE system, it gets mixed with $\beta\dot{V}$ air flow rate and the volume flow rate that passes through the hot side at the end is $(\alpha+\beta)\dot{V}$. This is expected to increase the performance of the TE system by increasing the mass flow rate at the hot side and decreasing ΔT as well as decreasing the heat sinks resistance on the hot side. However, by increasing this value power consumption of fans is increased and therefore there should be an optimum value for where the fans electricity usage will weigh more than its contribute to a better COP.

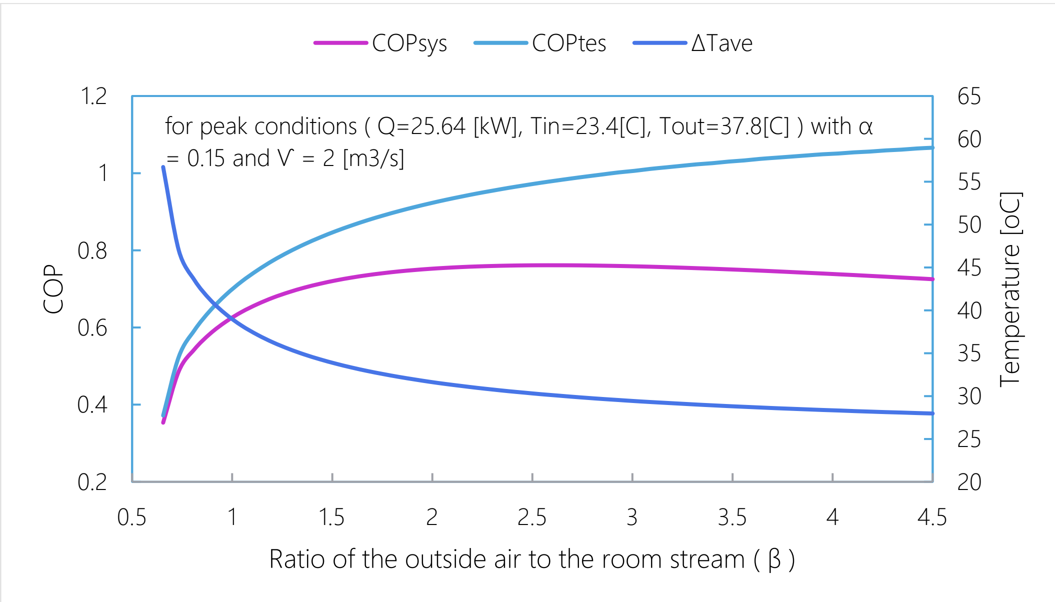


Figure 127 simulation results showing COP with varying β values

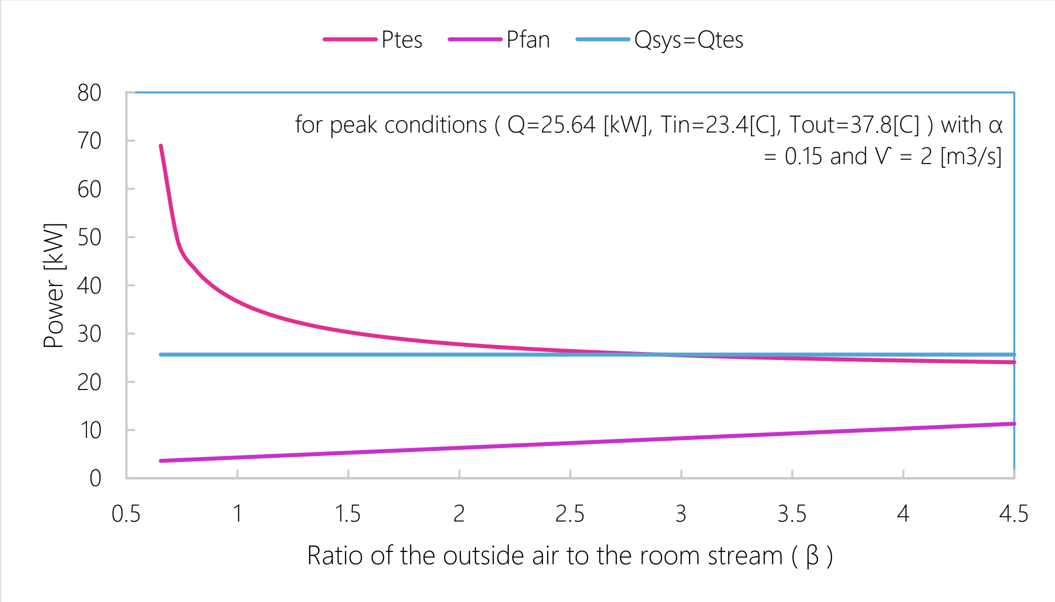


Figure 128 simulation results showing electricity consumption with varying β values

As it can be seen from the graphs, the increase in the amount of air that passes through the hot side will lead to an increase in the system COP until values of around 2 which leads to COP_{system} of 0.75 and COP_{TE} 0.92. Therefore, considering the maximum allowable β, 1.5 seems to be the best value.

8.4.4 Volume flow rate

Increasing this volume flow rate which is the total air stream extracted from the room is expected to lead to better efficiency since it increases the mass flow rate in air channels and therefore enhances heat dissipation also by decreasing the thermal resistance of heat sinks. Since it was proved in previous studies that increasing α is not beneficial for the system, in the examination of $\dot{V}$, α is kept at the minimum value.

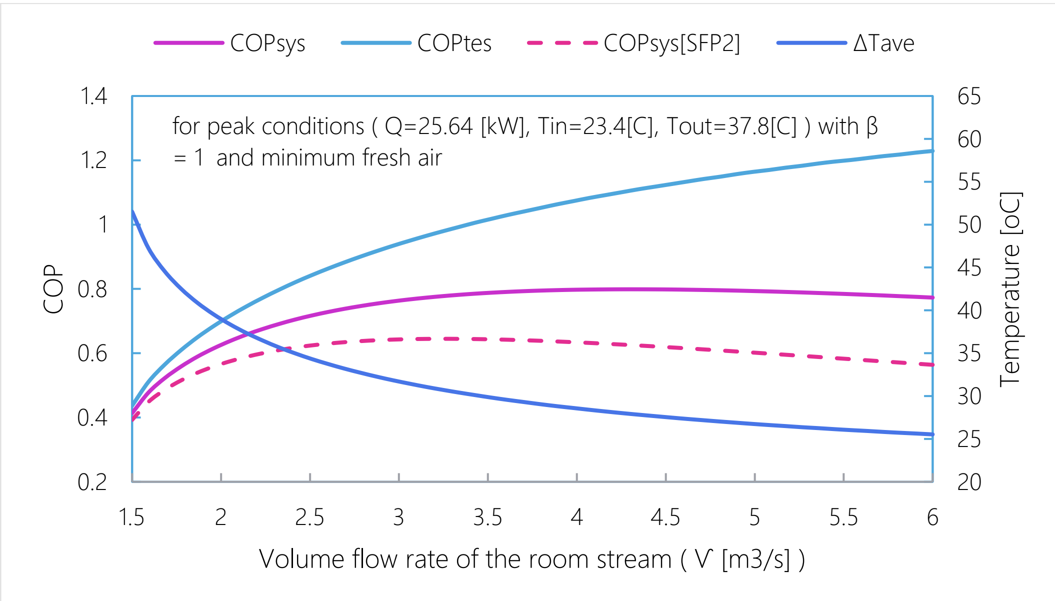


Figure 129 simulation results showing COP with varying air flow rates

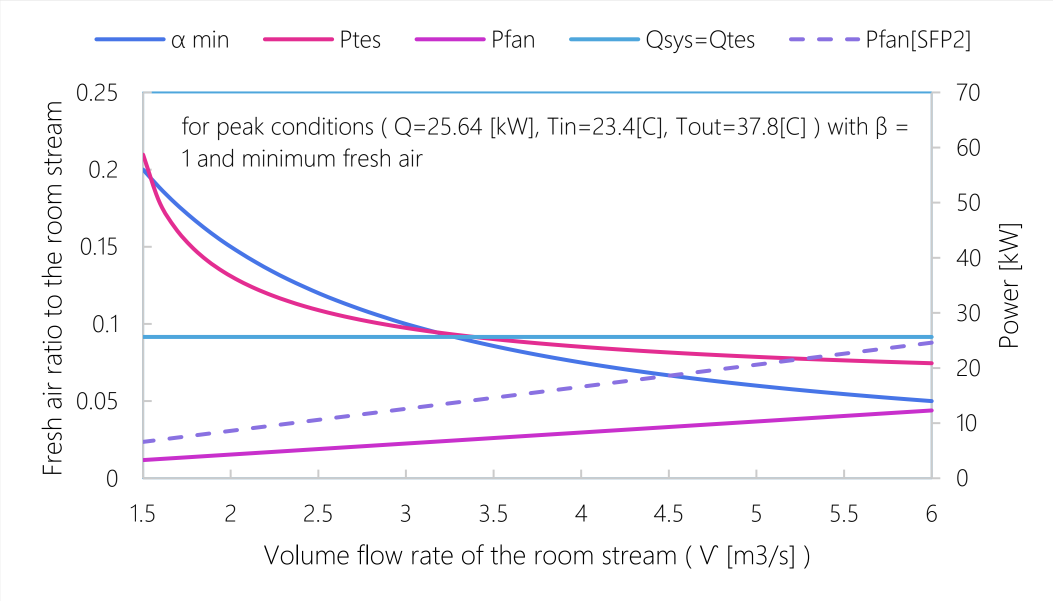


Figure 130 simulation results showing loads and electricity consumption with varying air flow rates

It is evident from simulation results that by increasing $\dot{V}$ the fans consumption increases gradually until the system reaches a COP of around 0.78 and then the system efficiency decreases with a gradual slope. It is also evident in this diagrams that using efficient fans and minimizing pressure drops helps in increasing the COP by almost 0.2.

8.5 Optimization

The engineering equation solver program, EES can run optimizations to maximize the selected values. In this study the goal was to maximize the system COP which includes the fans electricity consumption as well as TE system. The reason why this value is selected to be optimized is because increasing the air flow rate in the channels will end up increasing the TE system's performance by decreasing the temperature difference; however, it will reduce the overall system performance by increasing the fans energy consumption as seen in previous simulations.

8.5.1 summer peak condition

The following tables presents the optimized values of $\dot{V}$, α and β for SFP values of 1 and 2 kW/(m3/s) to observe the effect of specific fan power on the COP values.

It can be observed that without optimizing the system reducing the SFP value to 1 kW/(m3/s) will increase the COP_{system} to 0.71 which is a result of reducing the fans consumption only and not improving the TE system efficiency. However, due to limitation in the air velocity in channels increasing the value of air flow rate is not possible and further optimization of COP is not entirely possible.

Table 27 Results of the optimization for peak conditions.

Category	≠	Input	Value for SFP = 1 kW/(m3/s)	Value for SFP = 2 kW/(m3/s)
Air movement and flow rate	1	$\dot{V}$	4.26 (m^3/s)	2.76 (m^3/s)
	2	α	0.07	0.11
	3	β	1.19	1.15
Environmental conditions	7	T_1	25°C	
	8	T_2	40°C	

Table 28 Obtained optimization values for the peak condition.

(Q=25.64 [kW], Tin=23.4[C], Tout=37.8[C])			
Output	Description	Obtained values for SFP = 1 kW/(m3/s)	Obtained value for SFP = 2 kW/(m3/s)
COPsystem	COP of the system including consumption of fans	0.80	0.65
COPTE system	COP of the thermoelectric system	1.14	0.94
ΔT average	Average temperature difference obtained at the two sides of TE modules(oC)	27.09	31.63
Irequired	Required electric current to provide enough cooling power by TE (A)	11.72	12.88
Vhot	Air velocity of the exiting air (m/s)	4.9	3.14
Vcold	Air velocity of the air entering the room (m3/s)	3.9	2.51
Ptotal	Total system electricity consumption(kW)	32.07	39.75

As evident from the calculation, with more efficient fans not only the fans consumption drops but also it helps with reducing the TE system consumption by decreasing ΔT. The optimization helped in improving the COP to 0.65 and 0.8, increasing the TE efficiency to almost 1 in both cases.

It can be concluded that with 180 modules the maximum COP that can be reached is no more than 0.8 provided that SFP of 1 kW/(m3/s) is achieved. Implementing better heat sinks will also result in better COPs. In order to deal with high air velocity in ducts, sound insulation properties of the facade must be studied.

8.5.2 Non-peak summer condition

As seen from the following diagram which presents the frequency distribution of each cooling load, highest cooling loads of between 22.5 to 25.5 kW occur for only 49 hours of the year. Moreover, most of the loads are between 10 to 19 kW having a frequency of 890 hours. Frequency of loads lower than 10 kW is also significant.

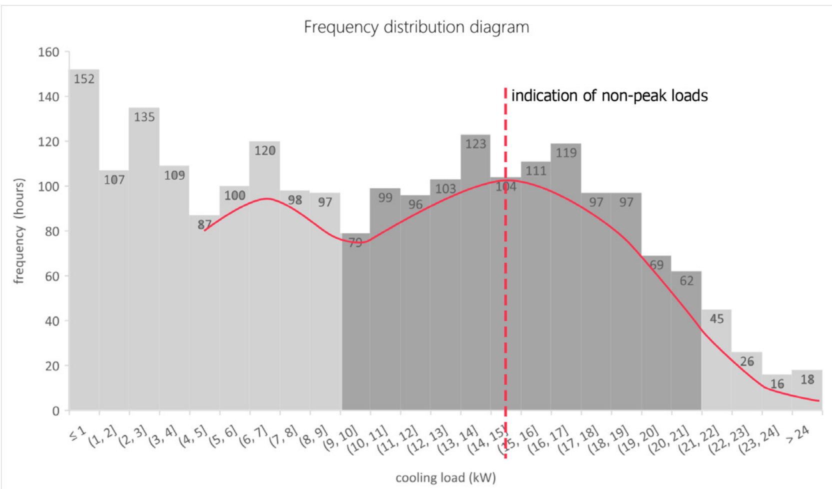


Figure 131 Designbuilder simulation showing the frequency distribution of loads during a year

An average of value of 14.5 kW is taken as an indication of a non-peak summer situation because when too high and too low loads are filtered loads around 14 to 16 become good representatives of a typical situation. In one example of such load, the cooling load in a time step with exclusion of fresh air and ventilation loads when outside temperature is 30.8°C and 10 l/s of fresh air is required is around 2.76 kWh in 18/6 at 6 PM. In this case, the system COP is obtained from the following formula.

$$COP_{system} = 14.50 / P_{total}$$

It has to be noted that in order to obtain the best COP values for each time step an optimization is required in this system for every cooling load because the values of volume flow rate, alpha, and beta should be different for each scenario and SFP value. Having the following inputs, optimization is run in order to obtain the best value for COP_{system}.

Table 29 Results of the optimization for non-peak conditions

Category	≠	Input	Value for SFP = 1 kW/(m3/s)	Value for SFP = 2 kW/(m3/s)
Air movement and flow rate	1	$\dot{V}$	2.1(m^3/s)	1.35 (m^3/s)
	2	α	0.15	0.22
	3	β	1.0	
Environmental conditions	7	T_1	25°C	
	8	T_2	30.8°C	

Table 30 Obtained optimization values for the non-peak condition

Output	Description	Obtained values for SFP = 1 kW/(m3/s)	Obtained value for SFP = 2 kW/(m3/s)
COP_{system}	COP of the system including consumption of fans	1.27	1.0
$COP_{TE\ system}$	COP of the thermoelectric system	2.1	1.67
$\Delta T_{average}$	Average temperature difference obtained at the two sides of TE modules(°C)	17.4	20.85
$I_{required}$	Required electric current to provide enough cooling power by TE (A)	6.43	7.1
P_{total}	Total system electricity consumption including fans (kWh)	11.44	14.68

This shows that in a non-peak situation a COP of 1.27 is obtained for the system which is a promising value more than the assumed cooling COP of 1 in previous chapters.

8.5.3 Peak winter condition

During the peak of winter consumption where the outside temperature is -2°C, and the indoor thermal comfort is obtained at 21°C., the total heating load is 14.74 kW and considering the ventilation loads providing fresh air the value for Q_{room} can be calculated.

Since the loads in winter are lower than that of summer and the expected COP is definitely higher, reducing the number of TE facades activated during winter should be reduced to obtain better results. Therefore, two facade modules are activated in winter to provide heating and fresh air to all the conditioned zones in south and north.

It was observed in the simulation results that the optimum air flow rate of β in the winter condition has to be zero to obtain the best COP_{system} and COP_{TE} as a result of minimum ΔT. On the other hand, it was evident that amount of flow rate $\dot{V}$ should also be kept at a minimum value for all winter conditions to meet the minimum fresh air requirements. This means that α should be set to 1 as the maximum value and the air vent that takes outside fresh air in summer to cool down the hot side should be closed during winter and all the ventilated inside air should go only through cold side while fresh outside air removes heat from the hot side and delivers it to the conditioned zones. The following results are obtained from optimization simulations.

Table 31 Results of the optimization for peak winter conditions

Category	≠	Input	Value for SFP = 1 kW/(m3/s)	Value for SFP = 2 kW/(m3/s)
Air movement and flow rate	1	$\dot{V}$	0.3 m^3/s)	
	2	α	1.0	
	3	β	0.0	
Environmental conditions	7	T_1	21°C	
	8	T_2	-2°C	

Table 32 Obtained optimization values for the peak winter condition

Output	Description	Obtained values for SFP = 1 kW/(m3/s)	Obtained value for SFP = 2 kW/(m3/s)
COP_{system}	COP of the system including consumption of fans	2.01	1.9
$COP_{TE\ system}$	COP of the thermoelectric system	2.25	
$\Delta T_{average}$	Average temperature difference obtained at the two sides of TE modules(°C)	23.89	
$I_{required}$	Required electric current to provide enough cooling power by TE (A)	10.23	
P_{total}	Total system electricity consumption including fans (kWh)	7.17	7.77

It is evident from optimization results that COPs of 1.9 to 1 are obtained for the heating system including the fans power consumption and COP_{TE} reaches around 2.3.

8.5.4 Calculation the annual optimized COP

Now that all the possible configurations of the system were examined, by running optimization for every time step of the year, the annual electricity consumption of the system can be simulated. It has to be mentioned that this electricity demand is including the fans consumption in contrast with previous simulations from Designbuilder which only comprised energy demands. The performance of the system can now be evaluated to see if providing heating and cooling to this office building is possible by only relying on solar energy.

Table 33 overview of the results obtained from annual EES simulations

	Summer		Winter		Annual	
	SFP = 1 kW/(m^3/s)	SFP = 2 kW/(m3/s)	SFP = 1 kW/(m3/s)	SFP = 2 kW/(m3/s)	SFP = 1 kW/(m3/s)	SFP = 2 kW/(m^3/s)
Electricity consumption (MWh)	17.81	23.47	1.51	2.14	19.32	25.61
Total load (MWh)	22.69		4.55		27.24	
COP	1.27	0.97	3.02	2.13	1.41	1.06

The annual power consumption of this system is simulated to be 19.32 - 25.6 (MWh), and it is lower than the electricity production of PV panels calculated in previous sections, i.e., 27.66 (MWh). Therefore, it is proved that the system designed is efficient enough to cover the annual loads with PV only.

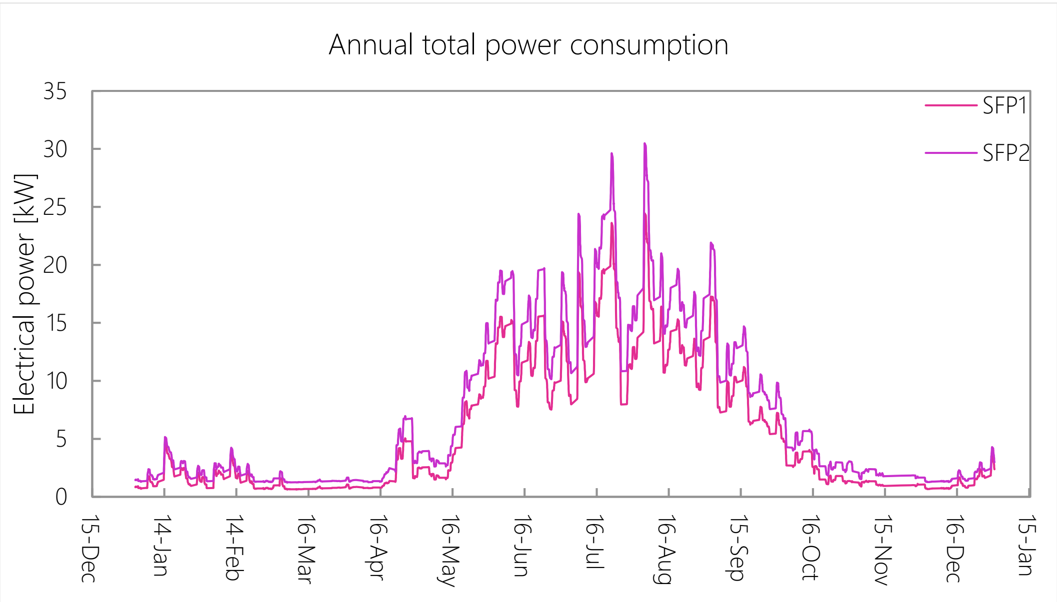


Figure 132 annual power consumption of TE system simulated by EES

The graph presenting the monthly average electricity consumption of the system for both SFP values shows that the peak of the loads is significantly bigger and are during five months of summer. In the rest of the year, the electricity demand remains relatively low due to lower loads and higher COPs.

8.6 Conclusion

In this chapter first, a comprehensive model was developed to help in simulating the behavior of TE elements in integration with the ventilation system. Then a baseline situation was defined based on which variables in this problem were studied.

It was concluded from the parametric studies and later optimization results that although fresh air intake helps in improving the system efficiency in summer by reducing ΔT, increasing this amount to more than required minimum fresh air will not be beneficial for the system in any condition including peak and non-peak. On the other hand, in summer introducing an addition of fresh hot air to pass through the hot side called β was proved to be beneficial for the system, helping in enhancing the efficiency.

It was measured that the highest COP that the system could achieve in summer design day which represents only about two days of the year cannot be more than 0.8 with 180 modules. Moreover, as seen in the following graph showing the annual electricity consumption vs PV production, the system needs to rely on sources other than PV panels during summer.

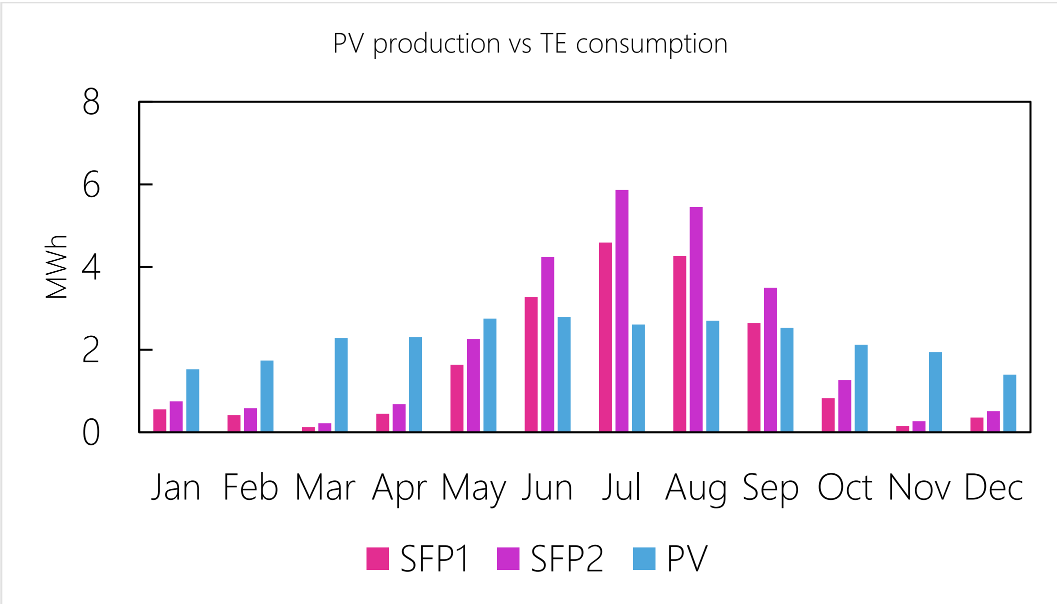


Figure 133 Annual electricity consumption having SFP of 1 and 2, vs PV production

Winter optimizations showed a reverse behavior for the system which indicated that minimum air flow rate should enter the building while all this air is ventilated out and replaced by fresh air, heating the cold side. Also, despite summer where β was beneficial for the system, it was observed that for winter it should be zero. It was as expected shown that efficiency of the system was higher in every case of winter than summer.

It was shown that even with SFP value of 2 kW/(m3/s) the system can meet the requirements set by PV electricity production. Higher SFP values make the system more efficient, however due to high air velocities caused in the air channels would lead to high noise levels and many fans. it should be studied for each case whether this increase in the air flow rate would be compensated by the achieved higher efficiency.

8.7 Improving the performance

As seen in previous sections, although the system meets the initial goal of this project which is covering the annual consumption of heating and cooling with electricity only produced by PV panels, the peak performance is not very efficient. In order to enhance the performance of this system during peak and reduce reliance on non-renewable resources, there are a few strategies that can be implemented.

First, the heat dissipation in this facade can be enhanced by improving the performance of heat sinks or using other working fluids with higher heat capacity and heat transfer coefficient like water instead of air to reduce ΔT. Since water scarcity is a serious issue in the arid context of this project, alternative ways of cooling the facade can be using the facade TE system in providing the required domestic hot water. Also, PVT systems can be implemented to help in reducing ΔT.

Secondly, by future enhancements in TE technology, it is expected that higher COPs can be obtained. This will lead to increase in peak and annual efficiency while maintaining a reasonable investment cost. Furthermore, it is predicted that developments in PV technology will increase its efficiency and therefore with higher yield of solar energy reliance electricity from the grid will decrease.

The third method relies on managing the loads lower that Q_p where the COP drops dramatically. It was explained in chapter 6 where controlling systems were introduced that dealing with these low cooling and heating demands through suggested methods will help in increasing the overall COP.

Another way of increasing the performance of the system in summer is using PCM materials to precool the air streams that enter the hot and cold sides during peak demand. PCM is capable of absorbing heat during peak loads and releasing it at nights where the temperature drops. This is especially a good strategy in a climate like Tehran where the diurnal temperature difference is almost 10°C which helps in discharging PCM.

PCM can be implemented in 2 different ways, first to precool the incoming air and second to cool the air after being cooled to a certain temperature by TE elements. The scheme in which PCM can be used is shown in the following diagram where points A to D are possible places where PCM can be integrated within the system.

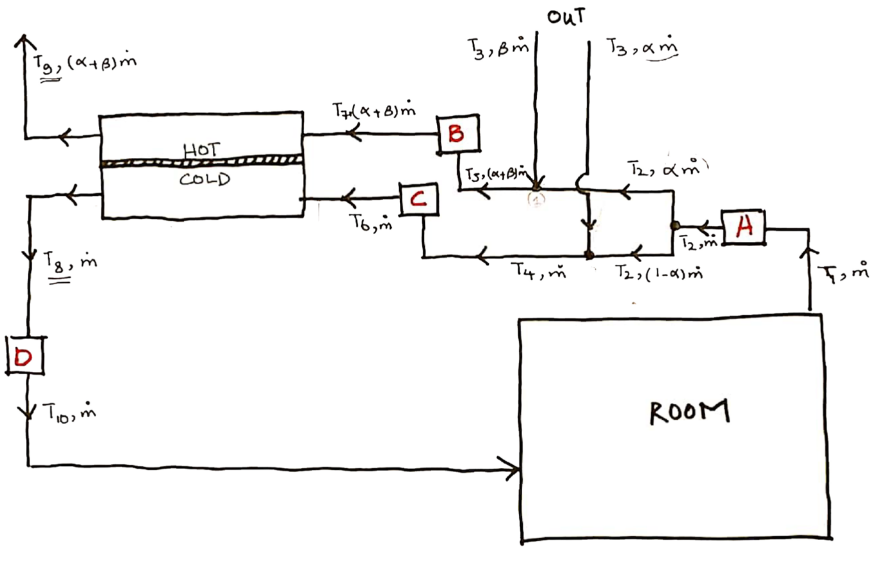


Figure 134 diagram showing possible integration of PCM in points A to D

In point A, PCM will precool both air streams going through hot and cold sides, and it will help in decreasing the temperature difference and therefore enhances the thermoelectric system's efficiency. This will also reduce the cooling loads due to reduction in ventilation demand. Addition of PCM in point D helps in post cooling the air stream entering the conditioned spaces, and it helps in increasing the performance by decreasing the cooling demand.

This concept can be integrated in facade vents where the ventilation air enters as well as in ventilation boxes. Furthermore, TE system can be used in non-working hours to cool and discharge the PCM and by doing this the peak loads during the day can be shifted to nights where the demand is much lower, and COP is high.

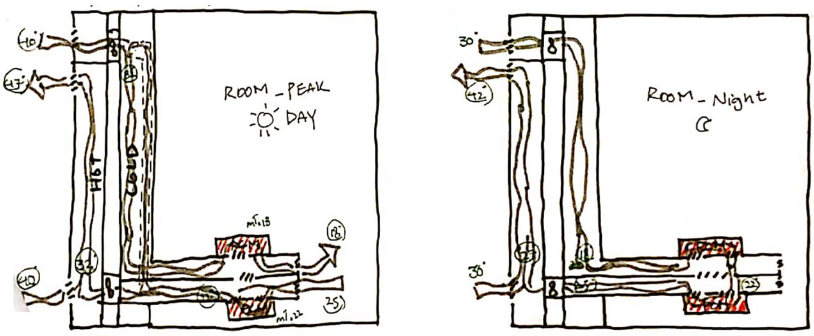


Figure 135 PCM used in the facade in point A and D to precool and post cool the ventilated air during day and night

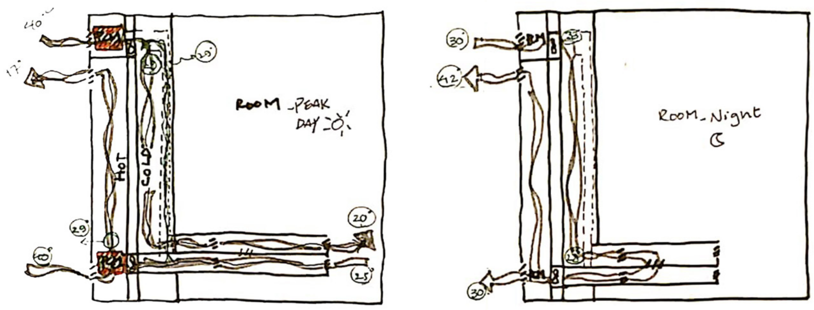


Figure 136 PCM used in the facade in point B and C to precool the air passing through hot and cold sides

Implementing PCM can be a very efficient passive or active way of enhancing the COP of system especially during peak hours. However, the effectiveness and consideration such as PCM type, amount, enthalpy, melting temperatures and so on should be studied.

9 Feasibility analysis

In this section, the aim is to examine the facade in a few terms that can help in reaching a conclusion about how feasible this facade is at the end. Some of the most important factors that play a role in application and further development of this cooling/heating facade include economic feasibility, integration and performance analysis.

9.1 Basic cost analysis

In this section, firstly, a rough estimation of this heating/cooling TE system per kW is drawn and then comparison is made with other cooling systems to position this system within the range of other solar cooling technologies as well as estimated goal of these systems. This will lead to a conclusion of whether this system is too expensive or within a reasonable range.

It should be explained here that the estimated cost only includes the heating and cooling function of the facade and not the extra components and materials imposed on the facade design because of this special design such as the extra layer of insulation, extra structural elements and added materials in the aluminum frames.

Moreover, comparison of the associated costs is drawn between the available systems based on cooling operation only. The TE system can provide heating and cooling and this makes it more feasible than many other air-conditioning systems.

9.1.1 Cost estimation of the cooling/heating system

In order to estimate the costs associated with this ventilation integrated thermoelectric heating/cooling system, some assumptions are made. Firstly, these calculations exclude installation costs which may differ from country to country and may play an important factor in the determination of costs. Secondly, there are components for which no cost estimation could be drawn in this short analysis and for a better understanding of costs a more extensive study and possible prototyping is required. Also, in a more comprehensive research the payback time of this design should be estimated to gain a better understanding of the feasibility.

9.1.1.1 The cost associated with fans

In order to estimate the cost imposed by the fans, the number of fans required to provide the required volume flow rate for every air flow has to be estimated separately. There are 4 positions where the fans are applied on this ventilation system and for those located on the facade especially there is a limitation of size. For the fans located on the ventilation boxes on the floor and on the ceiling these restrictions are not as severe, therefore, bigger fans with higher capacities can be selected. This helps in reducing the number of fans and lowering the associated costs.

The table below presents the calculated number of fans for 2 scenarios of low and high air flow rates which at the end leads to higher or lower COP, as explained in previous sections. These calculations are based on the worst case in summer peak demand and in other situations some of the ventilators can be turned off.

$$\text{Number of required fans} = \text{volume flow rate} / \text{air flow rate per fan} \quad (48)$$

In which volume flow rate is obtained from values of α, β and $\dot{V}$ in previous sections.

For fans with 0.105 (m^3/s) of air flow rate 50 EUR and for fans with 0.28 (m^3/s) 100 EUR is assumed. These are assumption based on the prices on Farnell company.

Table 34 Estimation of costs associated with fans

Scenario 1 Lower COP	Location	Volume flow rate(m^3/s)	Air flow per fan(m^3/s)	Number of required fans	Total Cost (EUR)
Return air-hot stream	Ventilation box	0.3	0.105	3	150
Fresh air-hot stream	Facade	3.13	0. 105	30	1500
Return air-cold stream	Ventilation box	2.44	0.28	9	900
Fresh air-cold stream	Facade	0.3	0.105	3	150
total	-	-	-	45	2700
Scenario 2 higher COP	location	Volume flow rate(m^3/s)	Air flow per fan(m^3/s)	Number of required fans	Total Cost (EUR)
Return air-hot stream	Ventilation box	0.3	0.105	3	150
Fresh air-hot stream	Facade	5	0. 105	48	2400

Return air-cold stream	Ventilation box	3.9	0.28	14	1400
Fresh air-cold stream	Facade	0.3	0.105	3	150
total	-	-		68	4100

As seen in the calculations the cost of fans depending on the air flow rate of the system varies between 2700 to 4100 EUR for every floor of this office building. This means that for every kWh of cooling 135 to 205 EUR has to invested on the fans to provide the required circulation of air.

9.1.1.2 The costs associated with PV panels

Taking into account that this TE system falls under the solar cooling category in many of the studied literature, the costs associated with PV panels has to be taken into consideration. Based on a master thesis by (Paardekooper 2015) the net cost of solar panels available in the market excluding the installation costs range between 0.80 to 1.00 (EUR/Wp). This means that for the selected solar panels in this study with a peak production of 220 (W), the cost of solar panels per m^2 is approximately 176 (EUR). Therefore, the total cost of PV panels is 13552 (EUR) considering 77 m^2 of solar panels per floor.

9.1.1.3 Total cost of the TE system

Other essential components of this system including TE elements and heat sinks are selected and explained in previous chapters and are presented in the following table to show their weight in the overall cost of the TE cooling/heating system. since the cost of the selected heat sinks could not be obtained it is assumed to be 18 EUR per heat sink. Other components of this system could not be included in the cost calculations because they are too specific for this facade like the custom-sized dampers and some of the electrical equipment like the control circuits etc.

Table 35 Estimation of the cost of cooling/heating system

TE cooling/heating	Number	Price per component (EUR)	Total cost (EUR)
TE elements	180	47.85	8613
Heat sinks	360	18	6480
Fans	45-68	50-100	2700-4100
PV panels	-	-	121968
total	-	-	31345- 32745
Total cost per kWh of cooling	-	-	1563-1634

As seen in the table the total cost to provide 1 kW of cooling is around 1550 to 1650 EUR. PV panels contributes to around 43 percent of the overall cost of this system and this shows that economic advancements in PV technology will lead to making such systems more feasible.

9.1.2 Feasibility of costs

In this section, estimated costs of TE cooling system is compared with conventional and solar cooling technologies. This will help in positioning this technology in the range of other solar cooling technologies.

Table 36 comparison of cost of solar cooling technologies with TE integrated system

System number	Type	Cost of complete kit (EUR/kW)	Resource	Remarks
	General target price for small to large scale	Small scale: 3000 Large scale: 1000-1500	Stryi-Hipp, G. (Ed.). (2015)	
	Conventional vapor compression chillers	500-1000	Stryi-Hipp, G. (Ed.). (2015)	
1	H2O–LiBr absorption cooling system with FPC	1500–2000	Ghafoor, A., & Munir, A. (2015)	By 2014
2	NH3–H2O absorption cooling system with ETC	2500–3000	Ghafoor, A., & Munir, A. (2015)	
3	Adsorption chiller using FPC	2000–2500	Ghafoor, A., & Munir, A. (2015)	
4	Desiccant evaporative cooling system with FPC	3000–4000	Ghafoor, A., & Munir, A. (2015)	
5	Small scale solar cooling technologies	4500	Stryi-Hipp, G. (Ed.). (2015)	By 2012
6	Large scale solar cooling technologies	2250	Stryi-Hipp, G. (Ed.). (2015)	By 2012
7	Solar cooling technologies in Europe	3100-6200	Montagnino, F. M. (2017)	In 2005
8	Solar cooling technologies in Europe	2000-6000	Montagnino, F. M. (2017)	In 2012
9	Ventilation integrated TE system	1550-1650	-	In 2019

Comparison of the costs associated with this TE system with other solar cooling technologies shows that it falls within the most economical ones like absorption cooling. This system is 1.6 to 3.2 times more expensive than conventional vapor compression cooling systems but it is in an acceptable range below the target cost per kW as stated by (Stryi-Hipp 2016).

9.2 Performance comparison

In this section, a short comparison is drawn between the performance of thermoelectric heating/cooling system with other solar cooling technologies. It is important to mention that the COP is an indicator dependent on the environmental conditions like the outside temperature and the design capacity. This study, however, may be useful in showing the range of COP of other solar powered cooling technologies. The following table presents a few of these technologies as well as the reported COP of conventional and most common cooling system; vapor compression.

Table 37 Performance comparison of solar cooling technologies with vapor compression and TE system

Type of cooling technology		Capacity(kW)	COP	resources
Conventional vapor compression chillers		-	3.1-6.2	Baskaran, A., & Mathews, P. K. (2012)
Solar cooling technologies	Absorption chillers	4.5-17.6	0.63-0.77	Ghafoor, A., & Munir, A. (2015)
	Adsorption Chillers	5-430	0.6-0.7	Stryi-Hipp, G. (Ed.). (2015).
		-	0.1-0.59	Sarbu, I., & Sebarchievici, C. (2013)
		0.03-20	0.15-0.2	Al-Alili, A., Hwang, Y., & Radermacher, R. (2014)
	Liquid sorption	10-350	0.5-1.0	Stryi-Hipp, G. (Ed.). (2015).
	Desiccant and evaporative cooling	6-300	0.5-1.0	Stryi-Hipp, G. (Ed.). (2015).
		-	0.5-0.74	Sarbu, I., & Sebarchievici, C. (2013)
	Thermos-mechanical cooling/steam ejector	-	0.1-0.85	Sarbu, I., & Sebarchievici, C. (2013)
		1-100	0.1-0.53	Al-Alili, A., Hwang, Y., & Radermacher, R. (2014)
	Ventilation integrated TE system	20	Summer: 1.06-1.41 Winter: 2.13-3.02	

as evident from the table, comparison of reported COP shows that the designed integrated TE system stands in a higher range than other solar cooling technologies, but lower than conventional vapor compression system. This performance indication of the TE system is the average obtained COP in summer and winter from the optimization phase for the 2 scenarios of lower and higher air flow rates. Liquid sorption, desiccant and evaporative cooling barely reach COP of 1 in the studied resources. This proves that in terms of performance, this system is promising compared to other solar systems, but requires better performance to compete with mature technologies like vapor compression.

9.3 Facade and building application

In order to gain a better understanding of viability of facade integration of this TE technology, some of the aspects that might affect its feasibility are shortly studied here. This study is an open discussion that intends to expose the limitations and considerations that need to be considered when choosing this technology and this designed facade over other solar cooling techniques. This might be useful in deciding where this technology can be applied and where the limitations restrict its application.

Since the performance and cost indicators have proven this facade in a feasible range, this study may draw a broader image of promises and limitations of this product.

9.3.1 noise levels

one of the main challenges with this design is the noise created by the fans and by the movement of air through the channels. According to the manufacturer of the fans, the level of noise created is 64 dB while the acceptable noise level for offices is between 40 to 50 dB. This means that the materials used as insulation and the gypsum board should be able to reduce this noise to an acceptable range. Moreover, as seen in the diagram, due to high air velocity in this design that ensures heat dissipation at the heat sinks, the corners of air channels and diffusers at the underfloor air distribution system are subject to creating unwanted noise, which can be reduced by applying suitable materials, noise damper and proper design of the channels.

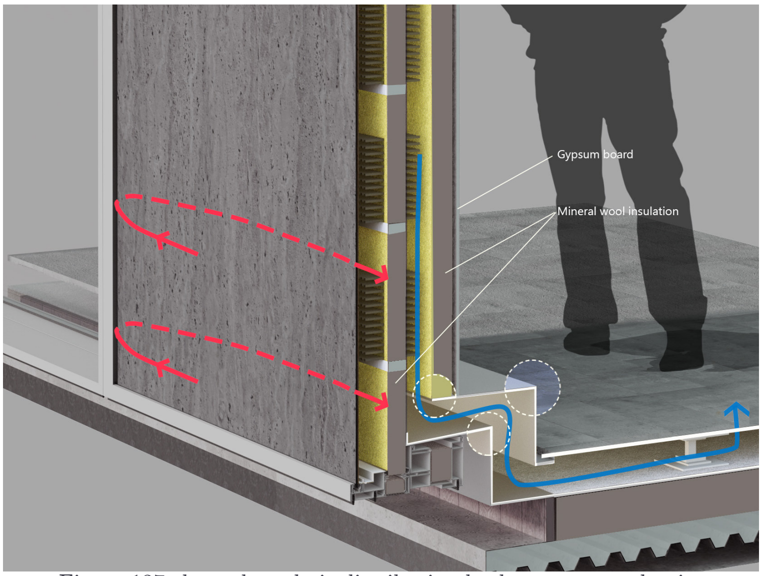


Figure 137 channels and air distribution leads to unwanted noise

The table below shows air velocity values in the two scenarios with lower and higher air flow rates that circulate in the facade having the area of 0.22 m2 in the channels on the hot and cold sides.

Table 38 Air velocity created in channels

	$V_{hot\ side}$ (m/s)	$V_{cold\ side}$ (m/s)
Scenario 1-lower COP	3.14	2.51
Scenario 1-higher COP	4.89	3.87

This high air velocity might be more problematic on the cold side since it is closer to the indoor. The noise problems of this facade design have to further studied and cautiously analyzed specially in situations where having a quiet indoor environment is necessary.

This values for the air velocity can be reduced if more of these TE facade modules are applied on each floor and thus the volume flow rate is divided between a greater number of modules. Also, increasing the width of the facade leads to an increase in the cross section of air flow and reduces the air velocity and might help in mitigating noise related issues.

9.3.2 Air circulation and number of fans required

as explained in the previous sections there are 45 to 68 fans of two different sizes required for each floor of this building, 9 to 14 for each facade module. Fans and filters in this system require maintenance and replacement more frequently than other components such as heat sinks. This imposes extra maintenance costs and effort on the cooling system. On the other hand, one of the features is connection to the ventilation system that marks it as an independent cooling system and might be problematic for many of applications specially in renovation projects, where there is an existing provision of fresh air.

The section shows how the TE facade is connected to the floor and ceiling of the office, where air circulation is used for better performance.

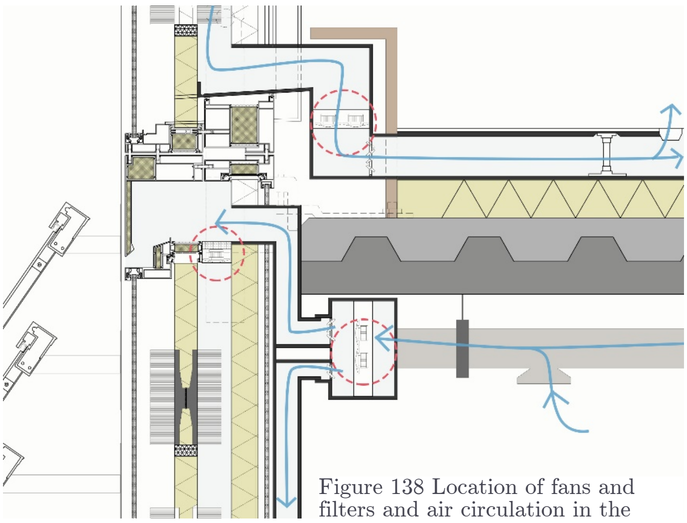


Figure 138 Location of fans and filters and air circulation in the

9.3.3 Sizes and dimensions

The whole facade on each side of the TE modules is an air channel and therefore, the cross section of the facade determines the air velocity. Therefore, on each of the hot and cold sides a certain depth has been assigned and this has contributed to a rather wide facade module of 37.7 cm.

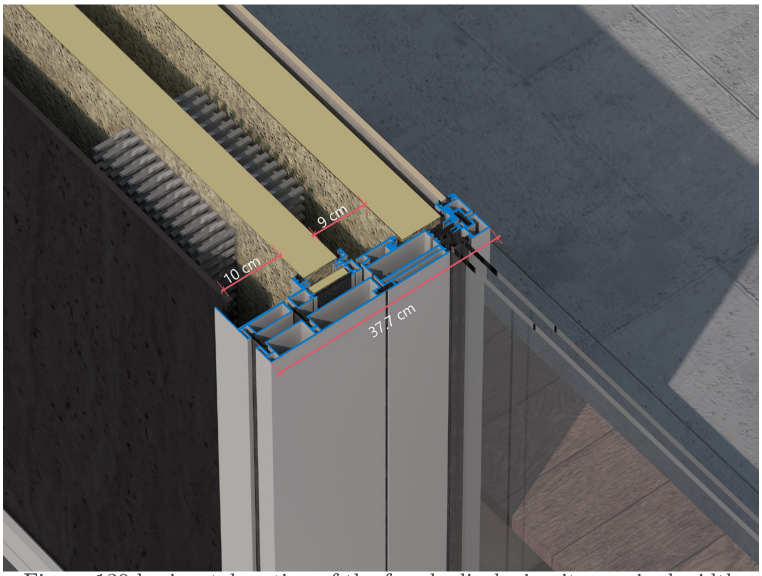


Figure 139 horizontal section of the facade displaying its required width

On the other hand, the overall width of the facade module has to be enough to provide the same cross section of 0.22 m². In this case, a width of 250 cm per facade module is assumed. The height of this facade would affect the pressure drops of the air flow but does not directly affect the air velocity and it might vary per project and floor to floor height of the building.

Figure 140 overall width of the facade

It should be mentioned that the overall sizes of such product can vary per project with the specific requirements and design criteria such as cooling and heating demand and outside temperature, as well the building plot and available facade area.

9.3.4 Weight

Due to the extra components of this facade, it is expected that one of the main issues would be cause by the heaviness. In this section by calculating and comparing the weight of this TE facade and comparing it to other opaque and non-opaque facades, its feasibility in terms of weightiness can be concluded.

The following table presents calculations of the mass of different components of this TE facade which leads to the overall mass of the product. A double-glazed facade of the same size has been modeled and its weight is calculated. The opaque facade calculated includes insulated aluminum frames and a light to heavy exterior facade panel.

As seen in the table, the heaviest component of the TE facade is heat sinks with a considerable mass of 380 (kg), and the overall weight is 2.6 times heavier than a double-glazed facade. Compared to an opaque facade of the same size with light to heavy exterior panel, the TE facade is 3.3 and 1.6 times heavier.

Table 39 comparison of the weight of TE integrated facade

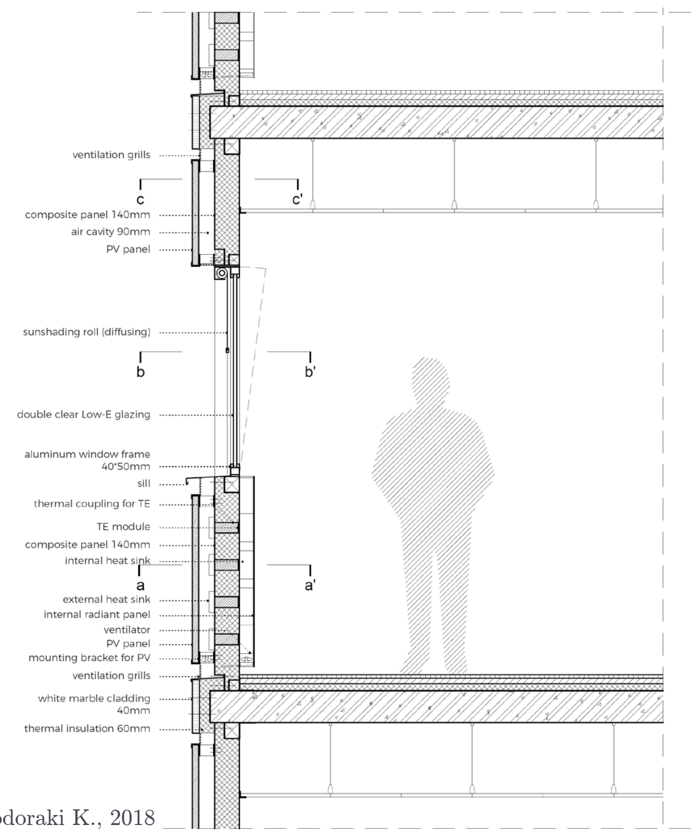
Facade type	components	Mass (kg)	Total weight	Relation to TE facade
TE facade	Aluminum frame	143.9	699.2	-
	Insulation-mineral wool	119.9		
	Heat sinks	380.5		
	Exterior panel-light weight	2.57		
	Interior panel-gypsum board	52.2		
Double glazing facade	Aluminum frame	50.4	267.9	2.6 times
	Glass-4 mm	217.5		
Opaque facade-light to heavy	Aluminum frame	88.0	213.2-444.7	1.6-3.3 times
	Insulation-mineral wool	70.5		
	Light-heavy exterior panel	2.57-234.0		
	Interior panel	52.2		

Comparison of the mass shows that the TE facade is heavier than other facade types but fall in an acceptable range. However, this must be noted specially in renovation projects where the structural elements may not have the required stability for such extra weight.

9.4 The alternative solution

While the focus of this graduation thesis is on the integrated TE system explained in the previous chapter, there might be situations where this integration is not possible due to limitations imposed by the building design or in some renovation projects. This alternative design as proved previously is expected to have a lower performance due to higher temperature difference created on the two sides and is not going to be examined in the following sections in terms of performance. In a thesis developed by (Theodoraki 2018) the concept of a non-integrated thermoelectric facade is developed. As seen in the diagram, this system is an independent system that cools the hot side with outside air and provides cooling for the interior adjacent zone by means of forced convection via the cold side.

While the performance of this design has not been estimated by the author, the discussed issues including weight, required dimensions and noise problems of the ventilation integrated system may lead some of the case to implementing this system instead. This facade integration of TE elements could be especially useful in small renovation projects with where each zone can be conditioned with one of these facade modules, or in bigger projects as a secondary cooling system.



141 Figure A TE facade by Theodoraki K., 2018

9.5 Conclusion

In this chapter, some of the feasibility aspects of the developed facade product in this thesis report were studied. It was concluded that although the facade has an acceptable performance compared to other solar cooling technologies, the issues associated with its high level of noise caused by the high air flow rates in the hot and cold sides, heavier mass compared to other facade products and restriction due to size and required dimensions and necessities related to the number of fans and filters and associated maintenance requirements, might limit its application in many projects. Reviewing and highlighting some of the advantages and disadvantages of the TE facade in this section would provide an overview on the specific point that one should note when choosing this technology over others.

9.5.1 Pros

1. A sustainable operation: one of the main advantages of this technology in general is the fact that it does not need any working fluids when operating and this makes it environmentally friendly with no global warming and ozone depletion potential.
2. A relatively good performance: the COP of this facade as proved in the previous section is a good range among other solar cooling technologies.
3. Minimum and easy maintenance: the maintenance of this facade does not require advanced knowledge due to its simplicity and this makes it easy to keep. While the maintenance of this facade is not as little as expected due to high number of fans required, easy access to these components can make it more feasible.
4. Flexible and suitable for facade integration: Thermoelectric technology can be considered as one of the best solar technologies in terms of facade integration, due to small sizes, simple connections and the flexibility offered in design. As explained in previous chapters, there are many possibilities and design approaches than can be taken while implementing this technology and this makes it a suitable technology for complicated or special facade concepts.
5. Summer and winter operation: the fact that this TE facade is able to provide both heating and cooling with only a switch that changes the current makes it very suitable for regions like Tehran with four seasons. The performance of this system is better in winter with higher average COP where some of the TE modules can be turned off during winter operation.
6. Control over ventilation air: integration of ventilation system and providing it through the facade makes control over the quality of air like CO2 monitoring easier.

9.5.2 Cons

1. Difficulty in heat dissipation: one of the main factors that limits the performance of this facade is the high temperature difference created on the two sides of the modules. Therefore, while it is not required as a part of the operation, it seems inevitable to use means of heat dissipation such as forced convection to obtain the required performance. this makes it despite what the literature indicated a possibly noisy operation.
2. Releasing hot air to the environment: as mentioned before, without combining this system with heat exchanger to make use of the released hot air in summer, the system has a disadvantage of contributing to heat island effect.
3. Low COP at peak and reliance on grid electricity: like any other systems during peak demand, the performance of the TE facade drops and although the annual net energy consumption is covered by PV panels reliance on the grid electricity still remains.
4. High air flow rates: for this system to obtain higher COP, high volume flow of air is required to circulate in the facade, this leads to extra costs, noise and maintenance issues as explained earlier in this chapter.
5. Weight: the load of the cooling/heating system as explained before is imposed on the facade and might be as issue in many cases such as some renovation projects.

9.5.3 Removing boundaries and future advancements

Some of the factors that might have a positive impact on removing the boundaries in development and widespread application of this project will be noted. Some of these criteria is related to the technology itself and the advancements that can lead to better performing and more feasible facade application.

Improvements in the TE technology are mainly characterized by ZT factor which has a direct influence on the performance of these elements. On the other hand, it was shown in previous chapters that production of TE elements with higher cooling capacity makes it more feasible for facade application due to reduced costs. Also, with higher capacity the number TE elements and consequently the number of heat sinks can be reduced to lower the cost and weight of the system. Developments in this field require more studies and launching of prototypes both in areas of TE technology and its facade integration with other measures to improve its efficiency such as ventilation and PCM integration.

On the other hand, more research is required on improving the heat dissipation of the TE elements. Special designs should be developed to remove the heat and cold produced on the hot and cold sides, which leads to considerable improvements on the performance of this system. while special attention should be payed to the mass of the heat sinks and its effect on the feasibility and final realization of this facade.

On a higher level, increasing the knowledge of designers and engineers in the field of solar technologies and assigning subsidies for application of these products in the building industry are among effective measures that can be taken. It must be noted that in future where energy becomes more expensive and precious than it is today, feasibility of such cooling and heating systems powered by renewable resources grows.

10 Conclusions

Figure 142 Final TE facade design

10.1 General conclusion on research questions

The main goal of this graduation project was designing an integrated facade that provides heating and cooling using thermoelectric technology that only relies on PV electricity production for annual energy demands.

In the initial step of the design progress, a typical office model was developed as a representative of office buildings in Tehran. The heating and cooling loads were simulated in Designbuilder, and as the next step, passive measures including changing glazing type and size, improving insulation, using shading devices, natural ventilation and reducing infiltration rate were applied and studied to reduce the design capacities as well as the annual demands of heating and cooling. As a result of these strategies 54 and 55 percent reduction were achieved in annual cooling and heating loads as well as 49 and 39 percent decrease in the cooling and heating design capacities. These reductions in design capacity helped in reducing the sizing of the system and making a more feasible active cooling and heating system.

In the next step of the design, an active ventilation integrated facade concept was proposed with a focus on reducing the temperature difference created at the two sides of TE elements. This was the central concept developed in this graduation project that was expected to result in better COP of the system with integration of ventilation and utilizing the ventilated air in reducing ΔT. A facade design was then developed to accommodate the requirements of the proposed active system.

In the last chapter, a model was developed with various thermal considerations that were used to study the different parameters of this concept and optimize the values to obtain the best possible COP for the whole system as well as TE elements in summer peak and non-peak situations as well as a winter condition. The annual COP and electricity consumptions were also obtained by optimizing the parameters for each time step of the year.

As the last step, a feasibility analysis was conducted to examine the facade product in different aspects such as cost and integration. The facade was proved to be feasible in some aspects, while a few considerations were pointed out to be taken when designing with this facade.

The outcome of this graduation project is an integrated unitized facade module that provides heating, cooling, and ventilation for the conditioned zones in the office building in a sufficiently efficient way. The performance evaluation proves that the annual cooling, heating and ventilation demands can be covered by electricity only from PV panels.

10.2 Conclusion on performance evaluation

It was concluded by optimization and simulations in the EES model that seasonal COP of 0.97-1.27 for summer and 2.13-3.02 for winter were obtained for the whole system including fans power consumption. It was proved that the annual electricity consumption was 19.32 (MWh) with SFP 1 kW/(m3/s) and 15.61 (MWh) with SFP of 2 kW/(m3/s), values lower than the annual PV production of 27.66 (MWh). Therefore, the annual heating and cooling electricity consumption of the designed ventilation integrated TE facade including the fans energy demand is covered by the electricity by PV panels.

However, it was observed that the COP that can be reached in summer design days cannot be covered with PV electricity only and reliance on the grid electricity or batteries remains. Suggestions were made in order to improve the COP of the peak at the end of chapter 7.

The Thermoelectric efficiency in this facade concept was enhanced to 1.7-2.2 in summer and 2.2 to 3 in winter.

10.3 Conclusion on feasibility analysis

The feasibility of the application of TE facade was studied in this section, considering factors such as cost, facade and building integration and performance. In the cost analysis, first the cost of each component was estimated and then a comparison was made with other solar cooling technologies. The cost analysis in this section showed that the TE cooling system applied in this integrated facade falls in a good range compared with other solar cooling technologies. However, it is still more expensive than a conventional vapor compression system.

Next, performance of the cooling system was compared with other solar cooling technologies as reported in literature. It was concluded that the TE cooling system has a performance higher than most of the other technologies while being still very far from vapor compression cooling. This proves that this system is capable of competing with other cooling systems of the same category.

Facade and building integration of this system can be restricted and challenged from a few factors. Noise created by air movement as well the increased number of fans required in providing enough air flow rate, are two of the main issues of this facade. On the other hand, the increase in the weight of this facade which is around 2 to 3 times more compared to a normal facade of the same size, as well as the dimensions of facade imposed by the active cooling system and ventilation integration, might restrict the application of this product in many cases. To this end, an alternative integration of TE cooling/heating was suggested which could be more suitable specially in renovation and small-scale projects or as a secondary cooling system.

At the end of this chapter, advantages and disadvantages of this facade product were reviewed to make decision making in terms of TE facade integration easier.

10.4 Further developments

The areas where future research is required in this facade product can be divided into four categories of reducing ΔT and enhancing the performance, controlling strategies, management of ventilated heat and facade studies.

- Obtaining better COP values and decreasing ΔT: While the proposed facade can be improved by designing better heat sinks and enhancing heat dissipation using working fluids other than air as well as improving SFP to reach values near 1 by minimizing pressure drops and implementing efficient fans, other additional methods like integration of PCM should also be studied specially to improve COPs obtained at peak. Also, a CFD analysis is required to obtain a better understanding of the working fluid's behavior in the channels in contact with heat sinks. As explained in previous chapters, the parametric model developed in this thesis needs advancements in many aspects and could be used as a base model for more comprehensive studies.

- Controlling system, user control and management of lower loads than Q_p: As explained in chapter 6 there are several ways in which the system can be controlled to maintain the minimum loads at the maximum possible COP. Also designing a proper system can result in providing the users with some control over the system.
- Heat recovery and using the excess heat in summer: As seen from the simulations the hot air ventilated out of the facade can reach up to 50°C in summer design days. This heat can be used to provide hot water for the building or can be stored in an underground aquifer to be used in winter and prevent adverse effects of this released heat in the urban context such as heat island effect.
- Facade development: In more extensive research the facade of this product should be studied structurally due to the weight of the TE system. Reducing materials used in this facade, replacing heat sinks with more efficient ones and reducing sizes would also contribute to a better facade design.

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12 Appendix

12.1 Parametric model validation

Now that the baseline model has been obtained a simple system energy balance can be assumed to verify the results obtained from simulations in EES. The following diagram shows the simplified system with energy inputs and outputs.

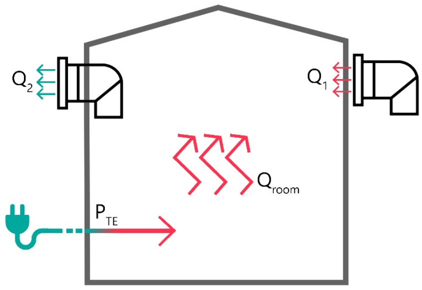


Figure 143 schematic diagram of the energy input and output of the TE integrated system

In which Q_1 is the air cooled by TE modules containing fresh air and Q_2 is ventilated air. P_{TE} is a value obtained from simulations in this model and represents the electricity consumption of Peltier elements.

The energy balance can be written as:

$$Q_{room} + Q_1 - Q_2 + P_{TE} = 0$$

In which

$$Q_1 = (\alpha + \beta) C_p T_2$$

$$1 - Q_2 = (\alpha + \beta) C_p T_5$$

Where $Q_{room} = 20.05$ kW, $T_2 = 40^oC$, $T_5 = 60.32^oC$, and T_2 is the outside temperature and T_5 is an output of simulations which is the temperature of the air stream exiting the last row of TE elements in the facade.

And P_{TE} is calculated from the thermoelectric calculations and equals to 34.73 kW. Since the energy balance in equation one is verified and results in 0, the model is validated.

12.2 Thermoelectric calculations

12.2.1 Method 1- temperature independent Seebeck coefficient

Based on a paper written by Chen and Snyder, 2013 the following equations can be used to obtain Qc, the cooling power of any thermoelectric module. This equation is a non-temperature dependent approach and therefore is subject to error when compared to performance graphs provided by the manufacturer. The cooling capacity Q_c is calculated from the following formula.

$$Q_c = SIT_c - K\Delta T - 0.5RI^2$$

As seen from the formula Seebeck coefficient S, thermal conductance K and electric resistance R can be calculated from the following equations:

$$K = \frac{Q_{max}}{\Delta T_{max}}, R = \frac{2Q_{max}}{I_{max}^2}, S = \frac{2Q_{max}}{I_{max}(T_h - \Delta T_{max})}$$

Moreover, knowing values of Q_{max}, ΔT_{max}, and I_{max} from data sheets and assuming Th=25°C, ΔT=20 °C, values of K, R and S are calculated as followed.

$$K=6.515 \text{ W/K}, \quad R=1.097\ \Omega, \quad S=2.04 \text{ V/K}$$

In which S is the Seebeck coefficient, R electric resistance, and K thermal conductivity.

However, to be able to calculate the electricity consumption of this TE module the required voltage has to be calculated from the following formula:

$$V = S\Delta T + RI$$

And

$$Q_w = VI$$

Therefore, COP can be calculated from the following formula:

$$COP_{cooling} = Q_c / (VI)$$

In order to calculated Q_h and COP in heating application, as explained before the following formula can be used.

$$Q_h = Q_c + Q_w$$

And

$$COP_{heating} = Q_h / (VI)$$

It is obvious that under any circumstances COP of heating is higher than cooling COP. The results of this method will be compared to the performance graphs in the following sections.

12.2.2 Method 2- temperature dependent Seebeck coefficient

In order to improve the results obtained from these calculations, an improved simplified model with Thompson coefficient can be written as follows (Zhao and Tan, 2014).

$$Q_c = \mathbf{S_{Tc}} I T_c - 0.5 I^2 \mathbf{R} - K(T_h - T_c) + 0.5\tau I (T_h - T_c)$$

Thompson coefficient in these formulas itself is a temperature dependent variable that can be calculated from the following equation.

$$\tau = T_{average} (S_h - S_c) / (T_h - T_c)$$

In this equation, S_h and S_c and from the previous equations R and K are unknown values. In order to obtain these values, data from the manufacturer needs to be used. Therefore, for a few conditions the values are extracted from performance graphs as follows:

1	Th=Tc=298 K	I = 28 A	Qc = 430 W
2	Th=Tc=323 K	I = 28 A	Qc =500 W
3	Th=Tc=298 K	I = 11.2 A	Qc = 244 W
4	Th=323 K, Tc=298 K	I = 28 A	Qc = 337 W

For these conditions, there are four unknowns, and the following values are obtained:

S298	0.087494 [V/K]
S323	0.088461 [V/K]
R	0.76637 [Ω]
K	3.89431 [W/K]

In this problem R and K values are considered constant and temperature independent, however, for every temperature Seebeck coefficient is estimated as below assuming a linear relation between S values at two temperatures of 298 K and 323 K.

$$S_T = \frac{S_{323} - S_{298}}{323 - 298}(T - 25) + S_{298}$$

Therefore, values of Thompson coefficient and qc can be calculated for every temperature difference. By calculating electricity consumption from the following formula, COP can be calculated for every condition.

$$Q_w = (S_c T_h - S_c T_c) I + I^2 R - \tau I (T_h - T_c)$$

12.2.3 Discussion and Validation of results

The two methods that were used in section, one non-temperature dependent and another using temperature dependent Seebeck coefficient, S, ended up in different results that can be compared with manufacturer performance curves. Validation of results obtained from method one with the performance graphs from manufacturer are presented in the following graphs.

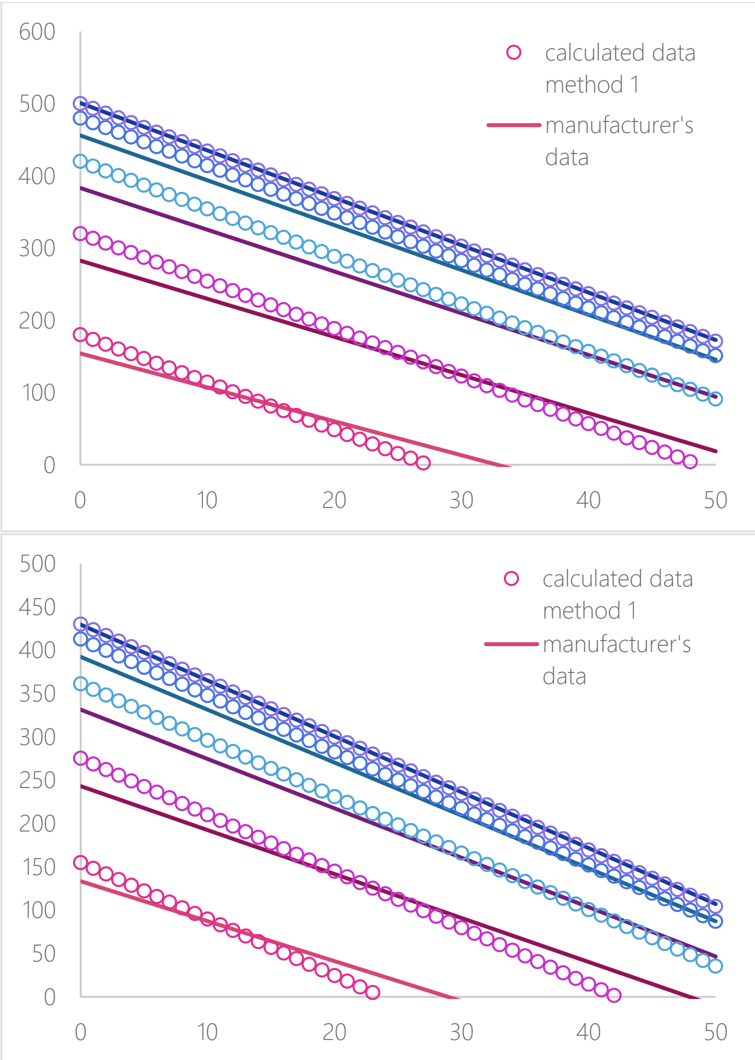
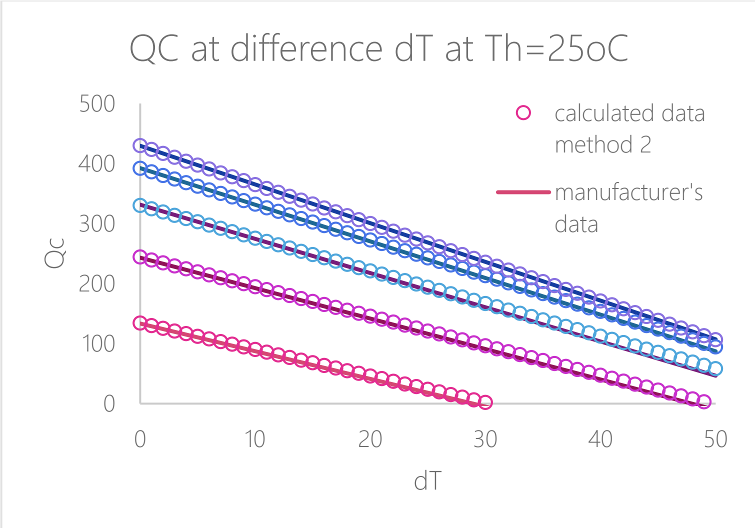


Figure 144 comparison of results obtained from method 1 with manufacturer's performance graphs at Th 25 degC (up) and Th 40 degC (down)

The importance of developing the second method is evident from the following graphs, and it is proved that the results obtained from this method are reliable especially in calculating COPs.



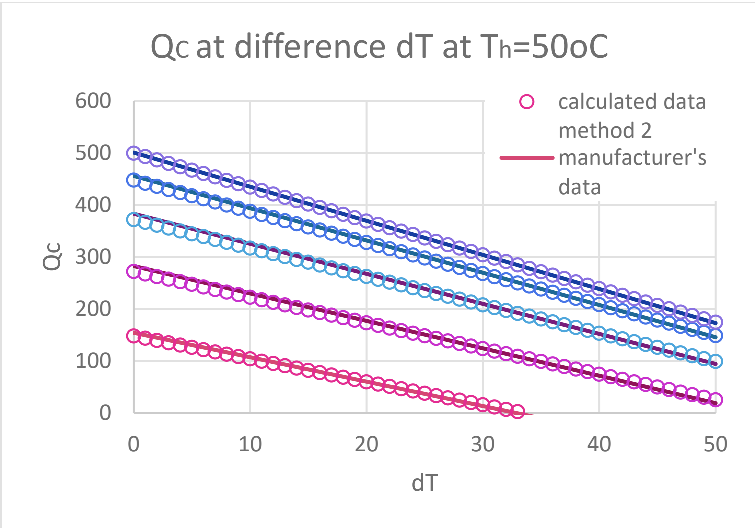


Figure 145 comparison of results obtained from method 2 with manufacturer's performance graphs

12.3 EES script for summer peak simulation

```
"thermoelectric facade configuration"
nfm =5 "number of facade modules, nom"
nnn = 5* ( 4 * 9 ) "total number of TE elements"
nte = nnn / nfm  "number of TE elements in each facade module"
n = 4 "number of columns of TE elements in each facade module"
m = nte / n "number of rows of TE elements in each facade module"

"thermoelectric properties"
S25 = 0.087494   "Seebeck coefficient at 25 [C]"
S50 = 0.088461   "Seebeck coefficient at 50 [C]"
R =0.76637           "electrical resistance"
K = 3.89431          "thermal conductivity"

"heat sink resistance at the hot and cold sides"
Lfin= 63.5e-3 [m]  "FinHeight"
Dfin = 3.2e-3[m]   "FinDiameter"
nfin = 56 * 56
Afin = ( 3.14 * Dfin * Lfin  + 3.14 * Dfin^2 / 4 ) * nfin

"heat sink dimensions"
```

```
HSL = 250e-3 [m]     "heat sink length"
HSW = 250e-3 [m]  "heat sink width"
Anf = HSL * HSW - nfin * 3.14 * Dfin^2 / 4

"thermal resistance at the cold and hot side"
haircold = 10.45 - Vaircold + 10 * Vaircold^(1/2)
hairhot = 10.45 - Vairhot + 10 * Vairhot^(1/2)
eta = 0.90
Rctot = 1 / ( eta * haircold* Afin + haircold * Anf )
Rhtot = 1 / ( eta * hairhot* Afin + hairhot * Anf )

"inside and outside temperatures"
T1 = 23.4 [C]
T2 = 37.8 [C]
Q= -25.64[kW]

"Fan electricity consumption"
SFP = 1000 [W-s/m^3]

"Volume flow rates of recirculated air for the room"
Vdot = 0.0031*Q^2-0.0738*Q+0.3304       "------SFP1"
{Vdot = 0.0021*Q^2-0.0435*Q+0.2695       "------SFP2"}

"controlling parameters for the usage of the outside air"
alpha * mdot = mdot_freshair

beta =  -0.0014*Q^2-0.0725*Q+0.2541       "------SFP1"
{beta =  -0.0019*Q^2-0.0903*Q+0.0756       "------SFP2"}

"cooling load of the room"
Qtotal = Qroom + Qvent
Qtotal = -Q*1e3

"heat capacity and density of air at 300 K and 1 atm "
Cp = 1005 [J/kg-C]
Rho = 1.16 [kg/m^3]

"minimum fresh air ant its load"
NOP = 30 "no. of people"
MFAP = 10e-3 [m^3/s] "volume rate of minimum fresh air per person"
mdot_freshair = NOP * MFAP* Rho
Qvent = mdot_freshair * Cp * ( T2 - T1 )

"mass flow rate of recirculating air"
mdot = Vdot * Rho

"energy balance at point B"
( 1 - alpha ) * mdot * Cp * T1 + alpha * mdot * Cp * T2 - mdot * Cp * T4 = 0

"energy balance at point C"
alpha * mdot * Cp * T1 + beta * mdot * Cp * T2 - ( alpha + beta ) * mdot * Cp * T3 = 0

"energy balance of the room "
Qroom + mdot * Cp * T6 - mdot * Cp * T1 = 0

"incoming air temperature and mass flow rates at the hot and cold sides of each facade module, in case of
summer they are as following"
Th[m] = T3 "inlet temperature of hot side channel"
Tc[0]  = T4 "inlet temperature of cold-side channel"
mdoth = ( alpha + beta ) * mdot / nfm
mdotc = mdot / nfm

"duct geometry of each facade module at the cold and hot side"
Lhot = 10e-2 [m] "length of the duct"
Lcold =10e-2 [m] "length of the duct"
Whot = 2.2     [m]   "width of the duct – hot side"
Wcold = 2.2     [m]   "width of the duct – cold side"
```

```
"cross section area for intaking air at the cold and hot side"
Ahotside = Lhot * Whot
Acoldside = Lcold * Wcold

"air velocity calculations at the cold and hot sides"
Vairhot = ( ( alpha + beta ) * Vdot / nfm ) / Ahotside
Vaircold = ( Vdot / nfm ) / Acoldside

Pfans =( Vdot + ( alpha + beta ) * Vdot ) * SFP

"TE calculations for each facade module "
Duplicate j = 1, m
   Thot[ j ] = qh[ j ] / n * Rhtot + 0.5 * ( Th[ j ] + Th[ j - 1 ] )
   Tcold[ j ] =0.5 * ( Tc[ j ] + Tc[ j - 1 ] ) - qc[ j ] / n * Rctot

   Sc[ j ] = ( S50 - S25 ) / ( 50 - 25 ) * ( Tcold[ j ] - 25 ) + S25
   Sh[ j ] = ( S50 - S25 ) / ( 50 - 25 ) * ( Thot[ j ] - 25 ) + S25
   Tave[ j ] = 0.5 * ( Thot[ j ] + Tcold[ j ] ) + 273.15
   tau[ j ] = Tave[ j ] * ( Sh[ j ] - Sc[ j ] ) * ( Thot[ j ] - Tcold[ j ] ) / ( ( Thot[ j ] - Tcold[ j ] )^2 + 1e-20 )
   dTw[ j ] = Thot[ j ] - Tcold[ j ]

   qc[ j ]= ( Sc[ j ] * I * ( Tcold[ j ] + 273.15 ) - 0.5 * I^2 * R - K * dTw[ j ] + 0.5 * tau[ j ] * I * dTw[ j ] ) * n
   qw[ j ] = ( ( Sh[ j ] * ( Th[ j ] + 273.15 ) - Sc[ j ] * ( Tc[ j ] + 273.15 ) ) * I + R * I^2 - tau[ j ] * I * dTw[ j ] ) * n
   qh[ j ]  = qc[ j ] + qw[ j ]

   qh[ j ] + mdoth * Cp * Th[ j ] = mdoth * Cp * Th[ j - 1 ]
   mdotc * Cp * Tc[ j - 1 ] = mdotc * Cp * Tc[ j ] + qc[ j ]

   COPcooling[ j ] = qc[ j ] / qw[ j ]
   COPheating[ j ] = qh[ j ] / qw[ j ]
End

"results of the TE calculations"
dTave = SUM( dTw[1..m] ) / m
Pelec = SUM( qw[1..m] ) * nfm
Qctotal = SUM( qc[1..m] ) * nfm
{Qhtotal = SUM( qh[1..m] ) * nfm}

"outlet temperature of TE heat exchanger, in case of summer they are as following"
T5 = Th[ 0 ]  "exiting air from hot side"
T6 = Tc[ m ]  "exiting air from the cold side"

"total performane parameters"
Ptotal = Pelec + Pfans
COP_TES_COOLING = Qctotal / Pelec
COP_SYS_COOLING = ( Qroom + Qvent ) / Ptotal
```

12.4 Ventilation type

There are two types of ventilation used in buildings, including constant volume and constant temperature. In the first type, mass flow rate remains constant and the variable to obtain thermal comfort in conditioned spaces is via changing the air temperature whereas in the second system, the temperature remains the same, and the mass flow rates determines the indoor obtained temperature.

Varying temperature

Type 1- Constant volume

$$\text{Supply Airflow} = \frac{Q_{room}}{\text{Constant} \times (T_{space} - T_{supply})}$$

$$\text{Supply Airflow} = \frac{11{,}724\ \text{W}}{1{,}210 \times (23.9°\text{C} - 12.8°\text{C})} = 0.87\ \text{m}^3/\text{s}$$

Varying volume

Type 2-Constant temperature

$$\text{Supply Airflow} = \frac{11{,}724\ \text{W}}{1{,}210 \times (23.9°\text{C} - 12.8°\text{C})} = 0.87\ \text{m}^3/\text{s}$$

$$\text{Supply Airflow} = \frac{5.86\ \text{W}}{1{,}210 \times (23.9°\text{C} - 12.8°\text{C})} = 0.43\ \text{m}^3/\text{s}$$

Since the way we can control this TE system is via changing the temperature; therefore, the first type seems to be more suitable. The mass flow rate in this design will be a constant value and the required cooling or heating loads of the spaces will be provided by adjusting the temperatures obtained at the hot or cold sides of TE modules. User control, however, can be provided by having three growing values to adjust the indoor conditions.