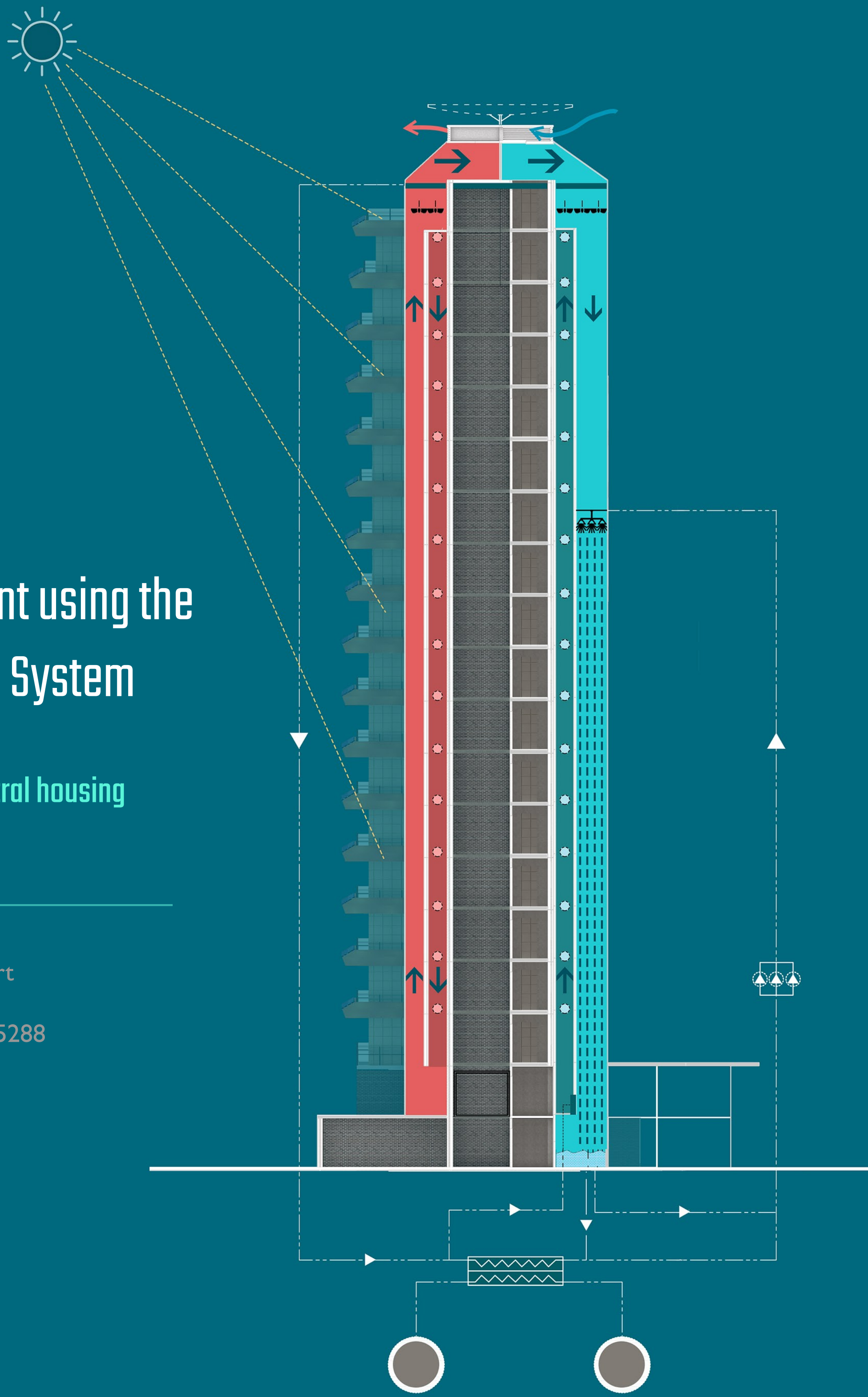
Housing refurbishment using the Earth, Wind & Fire System

Towards a nearly energy neutral housing in the Netherlands



Graduation report

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Abstract

In the Netherlands, the residential buildings consume the highest percentage of primary energy among the various building sectors. With around 80% of the Dutch housing built before 1995 a huge portion of the energy share is tapped in the old housing stock. While new housing constructions had to be nearly energy neutral as of 2020, a large portion of the existing housing stock has a higher relative energy consumption. The old housing stock thus needs urgent energy-retrofitting that is instrumental in reaching the goals targeted by the Dutch government by 2050. The Earth, Wind & Fire (EWF) system developed by Dr. Ben Bronsema (2013) during his PhD research can play an effective role in this aspect. Therefore, the research focussed on investigating the applicability of the Earth, Wind & Fire system for the Housing buildings in terms of energy-efficiency and thermal comfort potential. A case study building is selected to carry out the said investigation. Several design strategies were incorporated for the case study building to design the EWF system with highest technical performance. The study also incorporated dynamic simulations to evaluate the energy performance of the building after installing the EWF system. The study concluded that the integration of the Earth, Wind & Fire system has a great potential to reduce the energy consumption of the apartment buildings and improve the indoor comfort of the building and thus is a highly effective energy-retrofitting system for the housing buildings. The efficiency of the EWF system in improving the performance of the apartment buildings is thus highlighted. The effectives of the EWF system in reducing the energy consumption is dependent on the existing façade of the apartments and thus it is essential to refurbish the poor-performing façade to maximise the benefit. Thus, the study also concluded that apart from the installation of the EWF system several more improvements are needed in the existing buildings to achieve the goal of a nearly energy-neutral design.

Keywords: Earth, Wind & Fire system, energy neutrality, housing refurbishment, nearly energy neutral design, indoor comfort, energy efficient buildings

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Earth
Wind
Fire

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1. Introduction

Climate change is one of the biggest threats to our planet and is an issue of concern throughout the world today. The global temperature has increased by 0.9 ˚C since 1884 and is expected to rapidly rise in the near future as per the Climate change data published by NASA. Greenhouse gas emissions is the vital cause behind Climate Change and the building industry has a huge share in the emissions. In the European Union (EU), Buildings are accountable for nearly 40% of energy consumption and 36% of CO_2 emissions, making them one of the biggest energy consumers as compared to the other sectors (Energy Performance Of Buildings Directive (EPBD) - BIBM). The growing awareness of climate change has resulted in various policies in different countries throughout the world. In the recent Climate Agreement in 2019 in the Netherlands, the Dutch government has set a goal to reduce the greenhouse gas emissions by 49% by 2030 and 95% by 2050, when compared to 1990 (IEA, 2020). Moreover, the Dutch government envisions to achieve 100% sustainable energy by 2050.

To achieve the vision of a sustainable built environment, the industries are working towards reducing the energy consumption of the buildings. Looking at the sector-wise energy consumption across Europe for 2017, the residential sector accounts for around 27.2% of the total energy consumption and the non-residential sector accounts for 14.5% resulting in nearly 41% of the total energy consumption by the buildings (Eurostat). Among the various building sectors, the Housing stock in the Netherlands has a major share accounting for around 62% of the total building area. Figure 3 gives an overview of the Dutch housing sector based on the period they were built. It is evident that almost 80% of the housing stock is built before 1995 tapping a large portion of the energy share.

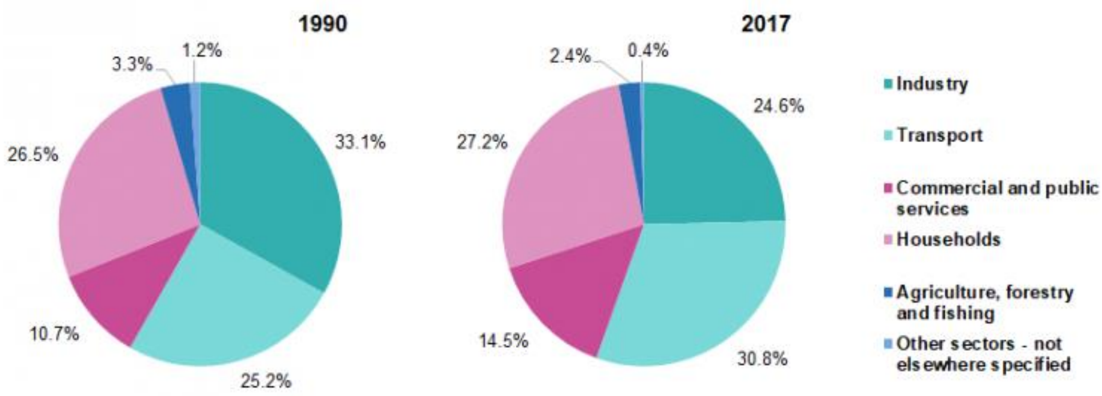


Figure 1: Final energy consumption, by sector, EU-28, 1990 and 2017 (%). Source: Eurostat

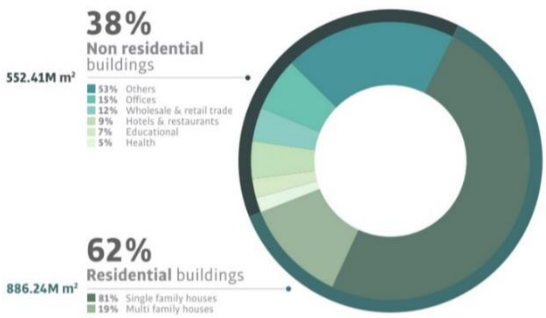


Figure 2: Breakdown of the building stock in the Netherlands. Sources: CBS, EU Building Observatory

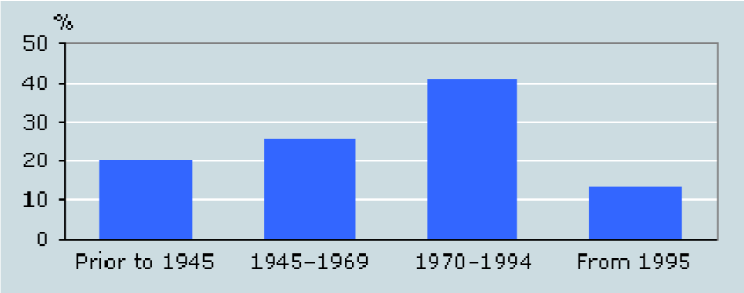


Figure 3: Dutch housing stock by building period (2007). Source: CBS

While new housing constructions have to be nearly energy neutral as of 2020, a large portion of the existing housing stock has a huge share in the energy consumption and have a worse energy label of D or lower in the rating scale from A to G (Oorschot et al., 2016). In a research conducted by Agentschap NL in 2010, the energy efficiency benefits of new buildings have been compared with the renovation of older buildings and the research concluded that the renovation of older buildings show higher energy saving potential. Older buildings have higher relative energy consumption due to lesser strict codes at the time and higher energy usage by the occupants (Sauvé, 2019). The existing stock is thus in need of urgent energy-efficient refurbishment. The European commission has published a new strategy called 'Renovation wave' aiming to double the energy renovation in the next ten years (European Commission, 2020). Energy renovation is instrumental in reaching the goals targeted by 2050. In the Netherlands, the government is targeting to convert 300,000 existing homes more energy-efficient every year.

There is a need to upgrade the existing housing stock using a technology which not only provides energy savings but also contributes towards renewable energy harvesting to address the goal of a zero-energy built environment. While various refurbishment techniques are available, there is a need to develop an integrated system that addresses the energy-retrofitting of the building in a holistic manner. The Earth, Wind & Fire (EWF) system developed by Dr. Ben Bronsema (2013) during his PhD research, harnesses the environmental energy of Earth, Wind & Fire through the use of three responsive building elements which can significantly reduce the energy consumption of the buildings thereby also serving as a means to utilize renewable energy sources for energy production. The system functions as a 'climate-machine' bridging the gap between architecture and climate technology through its integrated elements- Climate Cascade, Solar Chimney and Ventec roof. The system ensures natural air-conditioning of the building taking advantage of the gravity forces, positive and negative wind pressures and temperature differences and thus utilizing Earth, Wind and Fire as renewable sources respectively, thereby providing a natural air-flow to the spaces inside the building (Bronsema, 2013).

The EWF concept shows huge potential to reduce the operational energy of the building and achieve a nearly energy neutral building. However, the system has been designed initially for office buildings in the Western European climate and the potential of the system has not been researched in depth for Housing buildings. It is vital to conduct an investigation for the applicability of EWF system in the Housing buildings in terms of its energy-efficiency potential without compromising the indoor comfort for the occupants. According to Ortiz et al. (2020), people spend over 80% of their time in enclosed spaces. Around 60% of the time is spent at homes and the rest of the time at offices, schools, and/or commuting (Ortiz et al., 2020). Low-energy renovation measures sometimes leads to poor indoor environment worsening the IEQ and causing ill-health for the people (Ortiz et al., 2020). Research has also shown that there is an energy performance gap between the expected and actual energy consumption of the renovated housings. This energy performance gap is partially attributed to the comfort parameters of the occupants and building characteristics (Van Den Brom P., 2012). The comfort aspects should thus be an important design parameter to be included in the energy-retrofitting plan serving as an inevitable and essential performance indicator.

The research would thus focus on the integration of EWF in housing buildings with energy-efficiency and indoor comfort as performance parameters. For achieving the desired goal of energy-retrofitting, the system has to be designed carefully taking all the technical aspects into account which calls for a need to define various technical design guidelines.

Considering the aforementioned aspects, the research aims to:

- Investigate the potential of the EWF system as an energy-retrofitting method for the Housing buildings in the Netherlands with indoor comfort and energy neutrality as performance indicators. The energy neutrality goals are formulated based on BENG regulations.
- Designing a refurbishment project by selecting a case study building as a part of the research to find out the design strategies for integration of EWF and evaluate the performance through simulation tools.
- Derive technical design guidelines for integrating the system for the Housing refurbishment in the Netherlands.

The aim of the research paper is thus to answer the following question:

"How can the Earth, Wind & Fire system be integrated in the Housing refurbishment in the Netherlands to achieve a nearly energy neutral design and improve the indoor comfort of the building?"

2. Literature Study

2.1. Earth, Wind & Fire system

This section provides a detailed explanation on the Earth, Wind & Fire system based on the research paper by Bronsema (2013). This section is written in collaboration with two of my colleagues Shriya Balakrishnan and Puji Natadjaja.

2.1.1. Introduction

The Earth, Wind and Fire system is a concept which uses the driving forces of nature to control the indoor climate of the buildings. It utilizes the environmental energy of earth mass, wind and sun to generate and supply energy throughout the building by eliminating the use of HVAC systems, thereby minimizing the total energy consumption of the building and providing a healthy and productive working environment (Bronsema, 2013). This system eliminates the need of an air handling unit, the building functions as a "Climate Machine" with the help of 3 Responsive Building Elements (RBE): The Climate Cascade, Solar Chimney and Power roof 3.0 (Bronsema et al., 2018). The application of the 3 RBE's will be explained in the following sections.

2.1.2. Application of Earth, Wind & Fire system

The air is supplied throughout the building by the climate cascade. The air enters the building via an overpressure chamber and is supplied to the climate cascade. In the climate cascade, the cold water in the water sprinkler is sprayed on the incoming air at a temperature of 13°C (Bronsema et al., 2018). Due to the reduced temperature of the water droplets, the air is cooled down to approximately 18°C in the summers and the air is preheated to approximately 7-8°C in the winters (Bronsema et al., 2018). The cold water is supplied to the top of the climate cascade with the help of a Thermal Energy storage system located underground. The water droplets in the sprinkler form a heat exchanger with a large surface area which enables the system to generate temperature differences between water and air (Bronsema et al., 2018). This heat exchanger produces pressure at the base of the cascade which is used to supply the cooled/warm air throughout the building via the supply shaft.

The water droplets absorb the particulate matter and the pollutants of the outside air which improves the air quality of the supplied air. During summers, the air is comparatively dry due to condensation of water vapour on the cold-water droplets and in winters, the air is humidified again.

The used air from the building is extracted by a shunt/exhaust shaft which is connected to the solar chimney at the bottom. The solar chimney is a structural shaft which consists of solar panels and insulating glass facing the south in order to capture maximum solar radiation. The air in the solar chimney is heated up which pulls the air from the base of the exhaust shaft. The heat from the exhaust air is recovered at the top of the solar chimney by a heat recovery system. This heat is either supplied to the building or transported to the ground to restore the thermal balance and the used air is exhausted from the top (roof) (Bronsema et al., 2018). In order to maintain the air circulation, auxiliary fans are installed which operate on the basis of energy generated by the solar panels on the roof and in the façade of the solar chimney (Bronsema et al., 2018).

* Section 2.1.1 and 2.1.2 have been written by Shriya.

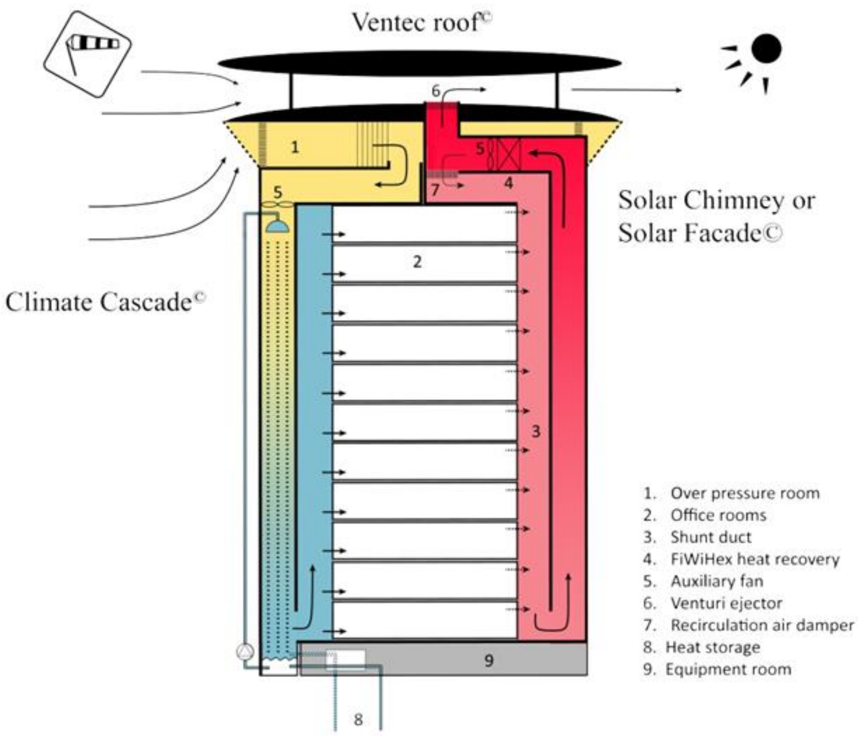


Figure 4: Earth, Wind and Fire Natural Air Conditioning system. Source: Bronsema, 2013.

2.1.3. Utilization of environmental energy

Utilization of environmental energy is an essential strategy to reduce the operational energy consumption of the building and for achieving energy neutral goals. The Earth, Wind & Fire research focuses on passive, active and hybrid systems for the utilization of environmental energy in integrated building concepts (Bronsema, 2013).

Earth

The EWF system utilizes Earth mass through:

- Gravity that causes the water sprayed at the top of the climate cascade to fall down. The momentum of these drops is partially transferred to the air. The suspension of air and water creates a greater density of the air inside the climate cascade as compared to dry air.
- Earth as a source for heating and cooling and for heat/cold storage.

Wind

The EWF system exploits wind through:

- Active energy generation using wind turbines installed in the overpressure chamber of the Ventec roof.
- Wind-driven natural ventilation utilizing the wind pressures for the movement. Climate Cascade provides the supply of Ventilation air using the positive wind pressure whereas the air is extracted via the Solar Chimney utilizing the negative wind pressures.

Fire

In the Earth, Wind & Fire concept, Fire is used as a metaphor for sun utilizing solar energy through:

- Active system in the form of Solar chimney and solar facade and the use of PV foil on the Power roof.

2.1.4. Climate Cascade

The Climate cascade is the heart of the Earth, Wind & Fire system which utilizes gravity for cooling, heating, drying and humidifying the ventilation air, designed as an architectural shaft (Bronsema, 2013). Climate cascade plays a crucial role in achieving the desired indoor temperature. In comparison to traditional cooling batteries, climate cascade offers various advantages as highlighted by Bronsema (2013), such as:

- High heat transfer coefficient between falling water and air to be treated. The temperature difference between air and water can thus be minimal.
- The climate cascade not only cools or warms the air but is also suitable for air treatment in all seasons, such as humidification.
- Air filtering is not required.
- Through varying the spray spectrum, the cooling surface can be increased or decreased.
- No air-side resistance.

The Climate cascade thus plays an important role in reducing the energy consumption and achieving the goal of energy neutral building.

Climate cascade for diabetic cooling

In an adiabatic system, no heat is supplied or removed and the air enthalpy remains constant whereas for a diabetic change of state of a thermodynamic system, it becomes heat exchanged with the environment. With the diabetic process in the climate cascade, the heat is removed by the supply of chilled water which absorbs heat and moisture from the air, causing the air to be dried and cooled and the water temperature to rise (Bronsema, 2013).

- **Temperature trajectory**

A climate cascade can be considered as a direct flow heat exchanger where air and water are in direct contact such that not only heat transfer but also mass transfer can take place. With the diabetic process in the Climate cascade, the heat is absorbed from the air and is transferred to the water, causing the air to be cooled down and rising the temperature of the water. At the inlet, the air is cooled from the cooling water of 13 ˚ C and dried to the outlet condition of 17 ˚ C with 90% RH. After absorbing the moisture in the room, the maximum room condition of 25 ˚ C at 60% RH is reached (Bronsema, 2013).

- **The water/air factor**

The ratio of mass flow of water and air in the climate cascade is an important aspect to determine the energy use of the spray pump.

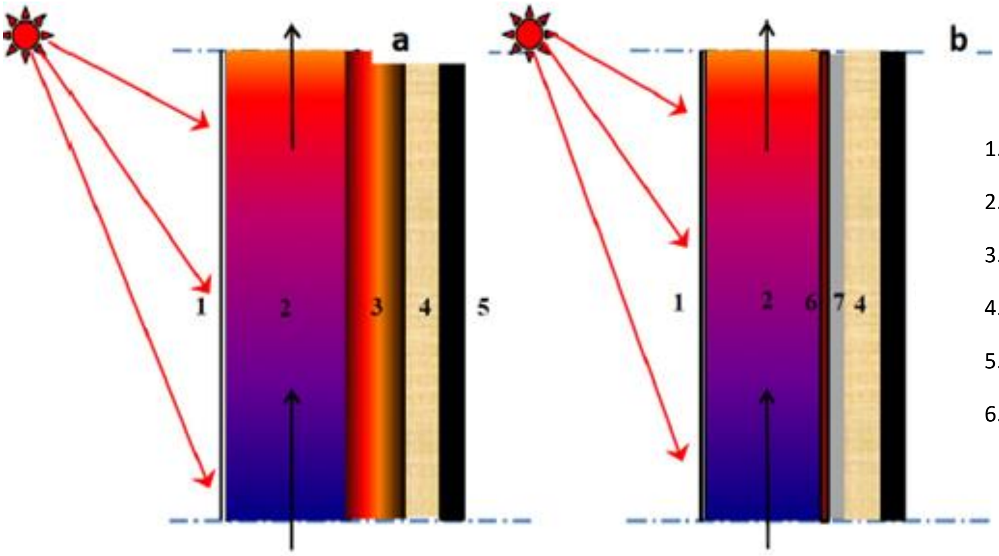
- **Pressure build-up in the climate cascade-**

The Climate Cascade not only ensures that the ventilation air is conditioned, but also shows a positive pressure difference for the air distribution in the connected building. This pressure difference is created by the generated aerodynamic draft, the hydraulic draft and the downward thermal draft (Bronsema, 2013).

The required spray spectrum is mainly determined by the required cooling performance. In higher buildings with a longer contact time between water and air, it is possible with a coarser spray spectrum. The heat transfer in a Climate Cascade is proportional to the heat transfer coefficient with the active surface and it increases with a finer spray spectrum with smaller drop. A choice should therefore be made in order to realize the greatest possible heat transfer for the finest possible spray spectrum (Bronsema, 2013).

2.1.5. Solar Chimney

A solar chimney consists of one vertical shaft on one sensible orientation that is connected at the bottom to the exhaust ventilation system of a building. At the top, the air can escape to the outside. Two things are harvested in the solar chimney: the natural flow of exhaust for ventilation and the collected heat.



1. Insulating glazing
2. Solar cavity
3. Thermally heavy inner wall
4. Insulation
5. Outer wall
6. Thermally light absorber

Figure 5: Principle of Solar Chimney. Source: Bronsema, 2013.

Referring to the above figure, a is the more-common solar chimney with Trombe wall and b is solar chimney with light inner wall. As the energy performance of the latter is better, b type is a preferable design option (Bronsema, 2013). However, for residential buildings where night-time ventilation is essential, type a is preferable.

Parameters for Solar Chimney design

a. Glass wall

The glass wall of the solar chimney should be chosen such that it can yield the best energy performance: highest possible g-value for maximum transmission of the solar radiation and lowest possible U-value to limit the heat loss.

b. Insulation

The inner walls of a solar chimney must be insulated to limit heat loss. The height of the solar chimney, the air flow and the width / depth ratio are important parameters to determine the thickness of the insulation (Bronsema, 2013).

c. The absorber

The surface of the inner wall, the absorber, must maximize the solar radiation absorption and lose as little through emittance. These properties are expressed as the absorption factor α and the emission factor ε respectively; at equal wavelength λ these are equal to each other; in formula:

$$\alpha_\lambda = \varepsilon_\lambda$$

* Section 2.1.5 has been written by Puji.

In which,

α_λ	absorption factor at wavelength λ	[-]
ε_λ	emission factor at wavelength λ	[-]

A solar chimney should ideally be provided with a spectrally selective absorber with the highest possible average absorption factor in the spectrum λ <3 µm, and the lowest possible emission factor in the spectrum λ> 3 µm (Bronsema, 2013). Materials that meet this requirement have been developed for solar thermal collectors and are commercially available.

d. Optimal orientation

In order to optimize the energy performance of the solar chimney, it is important to choose the orientation with the maximum solar radiation.

e. Morphology

For a stable thermal draft in the cooling season, the average chimney temperature during operating hours should be above the outside temperature as much as possible. To ensure this, 4 types of morphology have been analysed by Bronsema (2013).

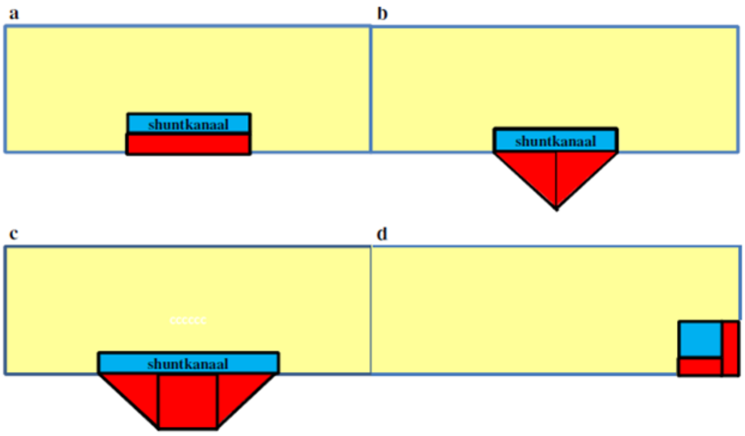


Figure 6: Different configurations for Solar chimney design. Source: Bronsema, 2013.

The facade model (a) is located within the building with the glass wall in the facade line. An orientation to the South provides the greatest benefit. This model has a good energetic performance, but due to the one-sided orientation, the thermal draft is not stable during the day.

The multiple SE / SW oriented pyramid model (b) is a simple and effective solution for the energy yield and stability of the thermal draft. In this configuration, two separate solar chimneys are connected in parallel to one shunt channel.

The trapezoid model (c) is a variant of the pyramid model. By adding a plane south-facing benefits from the high radiation intensity at this orientation.

The angular model (d) can also collect solar radiation at multiple orientations. A SE / SW orientation provides reasonably stable solar radiation for much of the day. For buildings with North / South orientation can also be executed as a twin model on both corners of the south facade.

There are many other possibilities for the architectural integration of a solar chimney in buildings, including the combination with an (emergency) stairwell.

f. Solar façade

A solar façade is a solar chimney covering the façade, which mainly consists of windows that form a direct connection with the outside. The effective surface, and thus the energy performance of the Solar Façade is determined by the size of the window openings. Several conflicting factors are in play e.g., daylight, cooling load, view, costs, and architectural expression. It is therefore an optimization issue based on various other variables that must be solved on a project basis.

g. Shunt channel

The thermal draft of a chimney is proportional to its height. If the extraction ducts on the floors would be connected directly to the solar chimney, the available draft for the higher floors is getting smaller. To ensure that the negative pressure conditions for all floors are approximately the same, a shunt channel is required, shown in (a) below. It also allows for heating recovery to be used outside the operating channel, shown in (b) below.

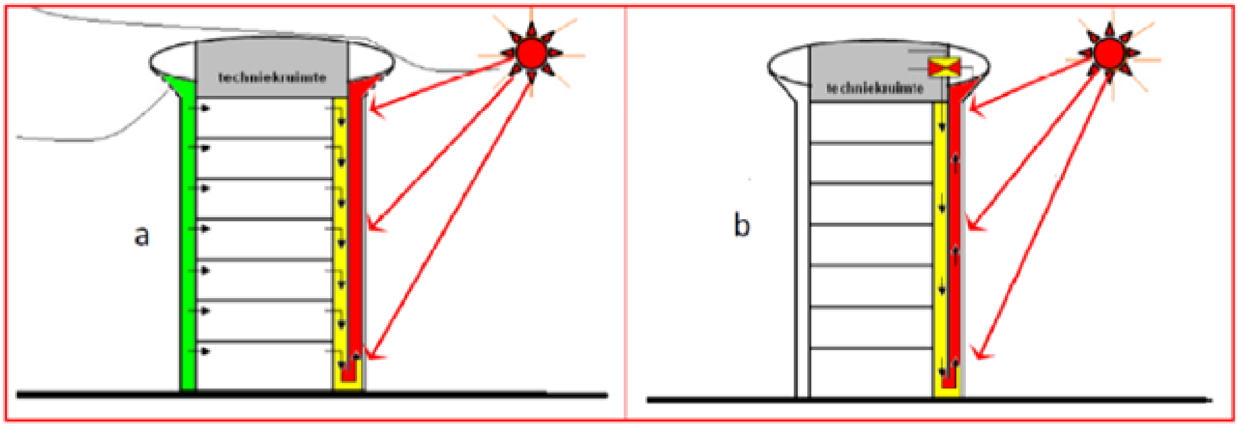


Figure 7: Principle of air extraction and recirculation via shunt channel. Source: Bronsema, 2013

2.1.6. Ventec Roof

The Ventec roof helps in the supply of the fresh air intake into the Climate Cascade by utilizing positive wind pressures via an overpressure chamber. On the other hand, the used ventilation air is extracted from the building through Solar Chimney and venturi ejector by utilizing negative wind pressures (Bronsema, 2013). Overpressure chamber and venturi ejector are important components for the supply and the extraction of the air and are described below.

Overpressure chamber

On the windward side, using the roof overhangs ventilation air is collected and through the positive wind pressure air is transferred to the pressure chamber. The magnitude of the thrust is determined by the local wind speed and the wind pressure coefficient on the relevant facade section. Both normally have the highest value at the top of a building where the air quality is also optimal. The expected wind pressure coefficient at the edge of the roof is approximately 0.8. With a moderate wind of 3 - 4 Bft, wind speed 5 - 8 m/s, overpressures are to be expected at 12 - 32 Pa (Bronsema, 2013).

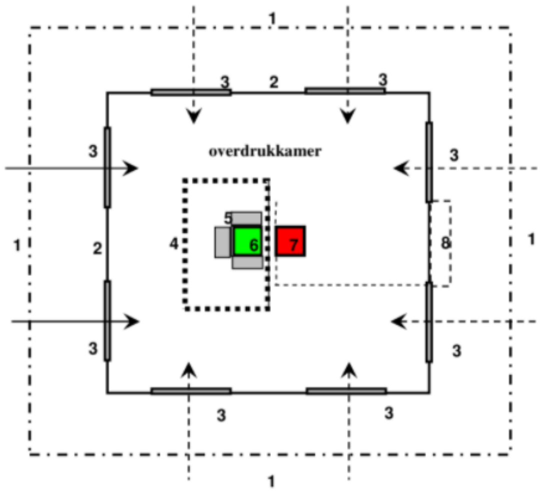


Figure 8: Schematic plan of the overpressure chamber. Source: Bronsema, 2013.

The figure above shows a schematic plan of the overpressure chamber with (1) roof over-cuttings, (2) building facade and air dampers (3)A coarse filter (4) keeps out insects and coarse dirt and also serves to protect any electrostatic filter (5). Furthermore, the Climate Cascade (6) and the mouth of the Solar Chimney (8) in the Venturi ejector (7).

Venturi ejector

The Venturi ejector is the outlet of the central extraction system in the Ventec roof and is also formed by the Solar Chimney and the FiWiHex installation for heat recovery. The pressure loss of the extraction system must be compensated by the thermal draft of the Solar Chimney (Bronsema, 2013). The Earth, Wind & Fire concept makes use of the venturi principle to guide wind through a constriction and to make use of the underpressure generated. Because the venturi gets here used in an open system, it is hereinafter referred to as pseudo venturi (Bronsema, 2013).

2.1.7. Case study: The Four Elements Hotel, Amsterdam

Initially named Breeze Hotel, this 11-story building with 198 ‘zero-energy rooms’, 6 suites, and a total floor area of 9.343 m2, is the pioneer to use EWF in the world. The building is developed by Amstelius/Dutch Green Company in association with Borghese Real Estate, with OZ architect as the project’s architect. The building with its height of 36 meters, consists of the following main elements; a solar chimney, a climate cascade and a power façade.

* Section 2.1.7 has been written by Puji.

Figure 9: Left to right: View from IJmeer Lake, 2 Solar Chimneys on the south façade, huge balcony of the sky-bar on the north facade
Source: OZ Architect, 2019

The EWF here works as follows:

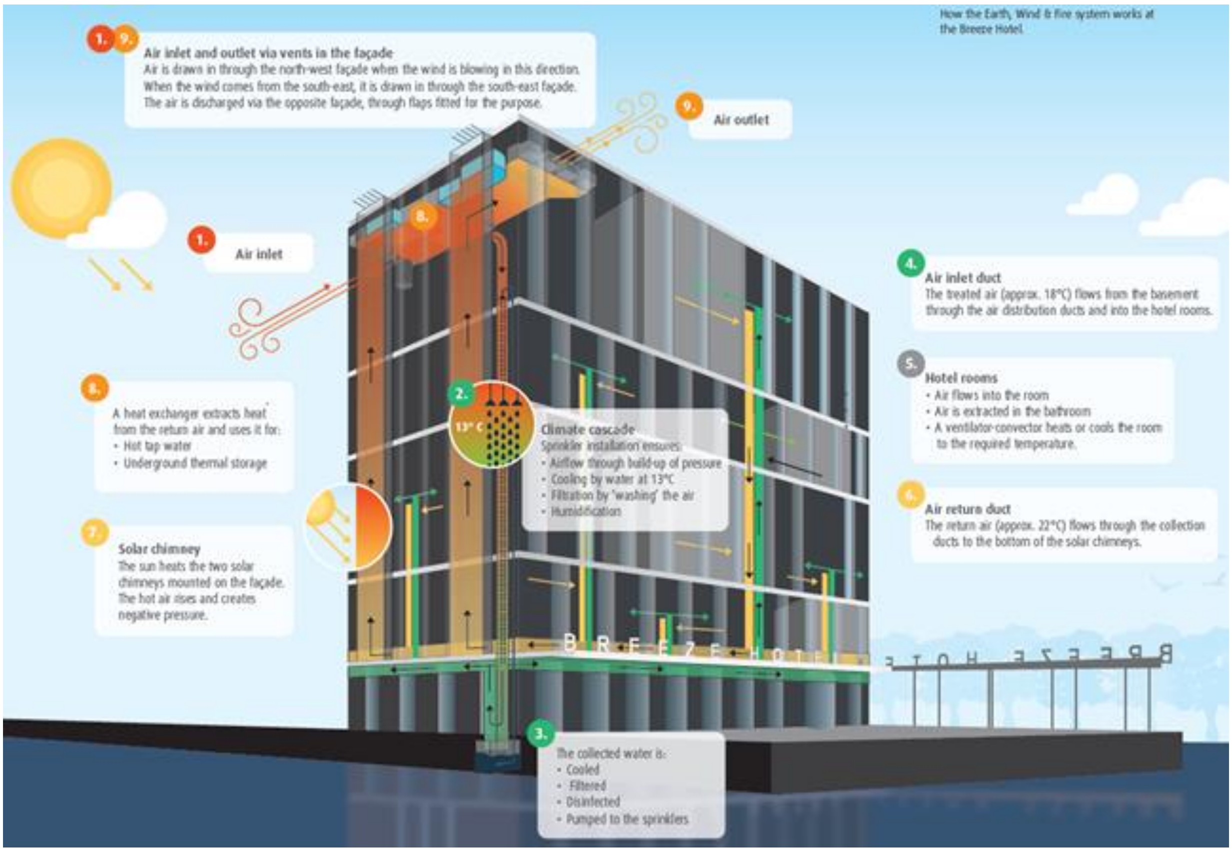


Figure 10: EWF Concept in the Four Elements Hotel. Source: Heirbaut, 2019

The twin solar chimney on the south façade (each 0.65m deep, 3.5m wide) collects heat from the sun. As the air heats up, the weight decrease, causing the warmed air, that can reach 60°C, to ascend in the solar chimney. At the top, the air reaches a heat-recovery system to capture the heat from exiting air to be stored in the underground thermal energy storage. The annual thermal energy yield of the twin solar chimneys is estimated to be 101 MWh (Pearson, 2019).

The captured heat stored in water underground can be used as pre-heated water to then be sent to a heat pump to raise its temperature for domestic hot water (DHW). There is a 10,000-litre DHW storage tank on the 10th floor (Pearson, 2019).

Figure 11: The 9 water spray heads of the Climate Cascade at The Four Elements hotel. Source: Heirbaut, 2019.

To replace the stale air that has been exhausted through the solar chimney, fresh outside air enters the building from the top of the climate cascade. Here, the air is cooled/heated and dried/ dehumidified depending on the season, by 9 water sprays attached to the top of the shaft. The water is extracted from boreholes that extracts water at a relatively constant temperature of 13°C throughout the year. In summer, the water sprays can cool outside air from 28°C to 18°C, and can clean the air by scrubbing particulates from the air. The spray water is collected at the base of the climate cascade and pumped through a water-treatment installation for reuse. As the air cools down, the weight increase, causing it to sink to the bottom of the climate cascade, increasing the pressure. This causes the fresh air to move to the rooms. In winter a heater battery installed at the base of the cascade helps raise the temperature before being supplied to the rooms (Pearson, 2019).

This way, the supply and exhaust of ventilation air is happening naturally. However, both systems are fitted with axial fans to assist the airflow when necessary. As for temperature control, a fan coil unit enables guests to control the temperature and airflow rate in their room. The system is also designed to revert to energy-saving condition when guests leave their room (Pearson, 2019).

When compared to the conventional HVAC, the EWF system integrated into the Four Elements hotel brings the following into perspective.

Table 1: EWF concept in perspective. Source: Bronsema et al., 2018.

Aspect	**Traditional AC**	**EWF Natural AC**
Space requirement plant-room 2 AHU's	220 m² (EN 13779)	50 m²
Cross-section of shafts Air velocity	2,5 m² ≈ 6 m.s-1	2,5 m² ≈ 3 m.s-1
Energy consumption EU 1253/2014-SPFint-limit	50 MWh.a-1 0,8 kW.(m³.s-1)-1	10 MWh.a-1
Maintenance KISS factor - simplicity	Very extensive low	Little extensive high

Average life span	15 to 20 years Mechanical facilities	40 years Architectural facilities
Construction costs Excluding solar chimney	Neutral	

The writer talked to Bronsema (2013) who mentioned that the Power roof could not be realized due to unfeasible cost and were replaced by PV panels on the rooftop, the façade, and at the rear of the solar chimney for energy production. The annual electricity production is 18,000kWh (Pearson, 2019).

To experience the comfort of the EWF system, the writer spent a night at the Hotel in early December 2020. The incoming fresh air was very refreshing and comfortable, as it was not dry. However, the noise, possibly coming from the fan coil, was difficult to ignore.

2.1.8. Conclusion

The Earth, Wind & Fire system functions as a natural air-conditioning system ensuring a good indoor environment and reducing the energy consumption of the building when compared to a typical HVAC system. Through its three integrated elements- Climate cascade, Solar Chimney and Power roof, the system bridges the gap between architecture and climate technology and the building works as a climate machine.

While the system works with the most efficiency when all the three elements are integrated, the elements also show potential to work individually. The Climate cascade being the heart of the system is the most vital element. Solar chimney adds to the functioning of the system and its application is vital for exhausting the air and harvesting the solar heat to meet the heating demands of the building. The Power roof on the other hand maximises the power generation through application of wind turbines. However, its performance majorly depends on the wind speeds and the context in which the building is placed. Attributing to its high financial costs, the system does not show feasibility for every building and its applicability is dependent on various factors. For the housing refurbishment project using EWF, the application of solar chimney and climate cascade shows good potential and shall be researched further during the design phase. The Ventec roof shall not be incorporated in the case study design. However, the design options can have future possibility of Ventec roof integration.

The design of EWF system in the Four Elements Hotel can serve as a source of inspiration and starting point to integrate the EWF system in the Housing refurbishment. The air distribution is designed through the corridors and the air exhaust is planned through the ductworks installed in the bathrooms. This can serve as one of the design aspects for integrating the system during design phase. The provision of two solar chimneys increases the solar heat harvesting potential to meet the heating demand. Another noticeable feature is the provision of air inlet openings in the façade in two directions depending on the prevailing wind direction at the time. In order to maximise the energy production, the entire façade has been designed as a power façade with installation of the PV panels. The Four Element Hotel has proven that the EWF system shows a great potential to transform the building into a nearly energy neutral building.

2.2. Housing Refurbishment

Refurbishment is an upgrading technique which is defined as any work done on the building to make it new again as described by Cambridge dictionary (2018a) (Franx, 2018). The Refurbishment strategy not only focuses on the renovation/modification of the defected components but also outdated components which might be still intact (Giebeler et al., 2009). The refurbishment strategies can be divided into three types: Partial, normal or total refurbishment. The partial refurbishment only deals with one component such as façade, roof etc.; normal refurbishment deals with the building as a whole and total refurbishment deals with large scale work with reducing the structure to only its skeleton (Giebeler et al.,2009). Based on the status of the building and the aim behind the refurbishment, a choice could be made among the three types. For the integration of the EWF which deals with changing the installation for ventilation and adding the solar chimney and solar façade, the normal refurbishment strategy seems to be appropriate. This section provides an overview of the Dutch housing classification to identify the building type suitable for renovation, the different energy-refurbishment strategies and technical parameters related to heating, cooling and ventilation.

2.2.1. Housing classification

The total amount of dwellings in the Netherlands is 7.5 million comprising of approximately 4.5 million owner-occupied homes (60%) and some 3 million rental homes (40% with 8% being privately owned and 32% being owned by housing associations) (rijksoverheid, n.d.). The category of rental housing owned by housing associations is considered as non-profit social housing sector. The social housing sector is more active in energy renovation when compared to owner-occupied sector (Filippidou et al., 2016). In terms of the building typology, the Dutch Housing stock can be divided into Single-family house (semi-detached, detached, terraced) and Multi-family house (common staircase and gallery, common staircase and no gallery). The social housing sector majorly consists of Apartment buildings (with gallery/ with entry hall) and terraced houses. An overview of the statistics of the Dutch Housing stock based on building period, size (no. of rooms), rental/owner occupied and typology can be seen from figure 12.

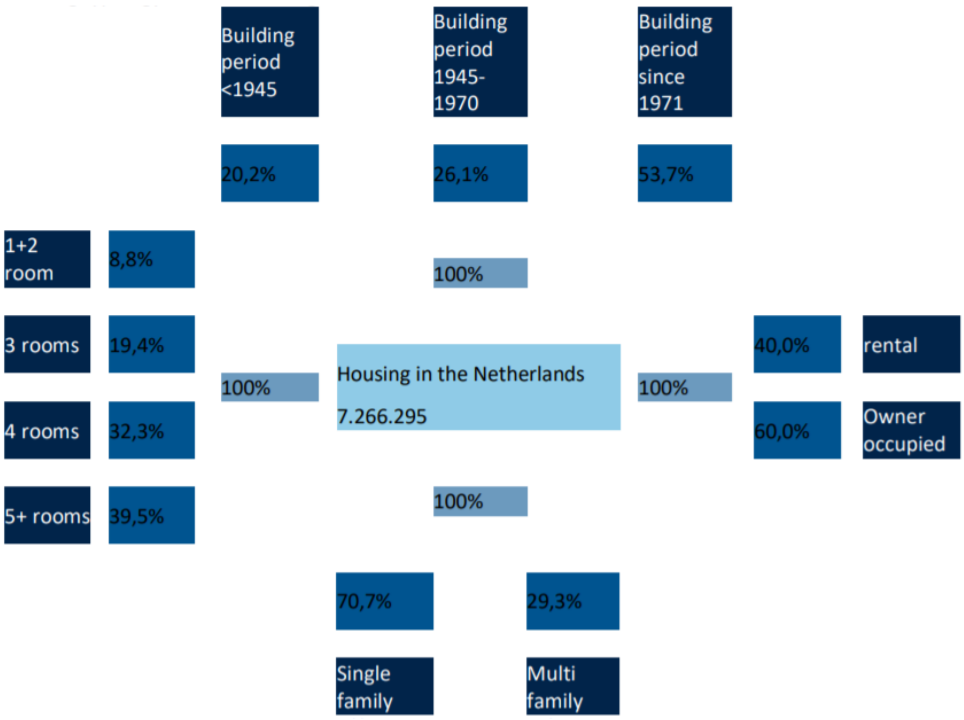


Figure 12: Overview of Dutch Housing stock. Source: Oorschot et al., 2016

There is a relationship between the housing typology, the period in which they were built and the associated energy label. Figure 13 provides an overview of the dwelling type and their assigned energy label whereas figure 14 provides a relationship between the construction period and the assigned energy label of the buildings. It is noticeable that the dwellings with an energy label A are built after 2000 due to introduction of strict energy regulations. However, majority of the dwellings with an energy label of C or below belong to the period 1950-1990. A dwelling belonging to this period from social housing sector needs energy-refurbishment which would result in upgrading the energy label of a huge portion of the housing stock. However, since these dwellings are poorly insulated, upgrading these dwellings is both technologically as well as financially challenging and also require drastic improvement (Oorschot et al., 2016).

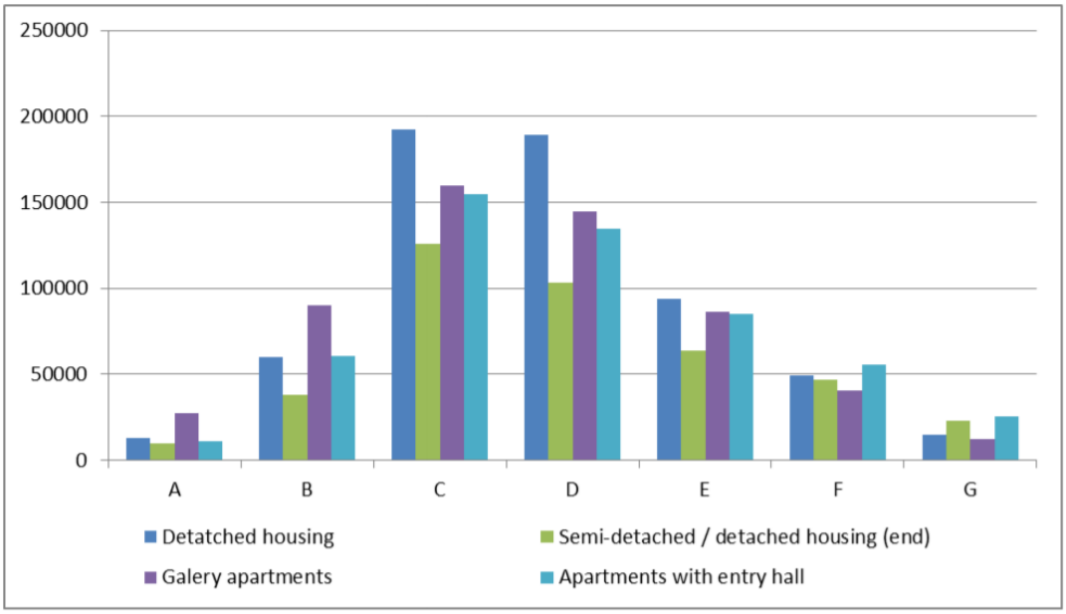


Figure 13:Energy labels classified according to housing typologies. Source: Oorschot et al., 2016

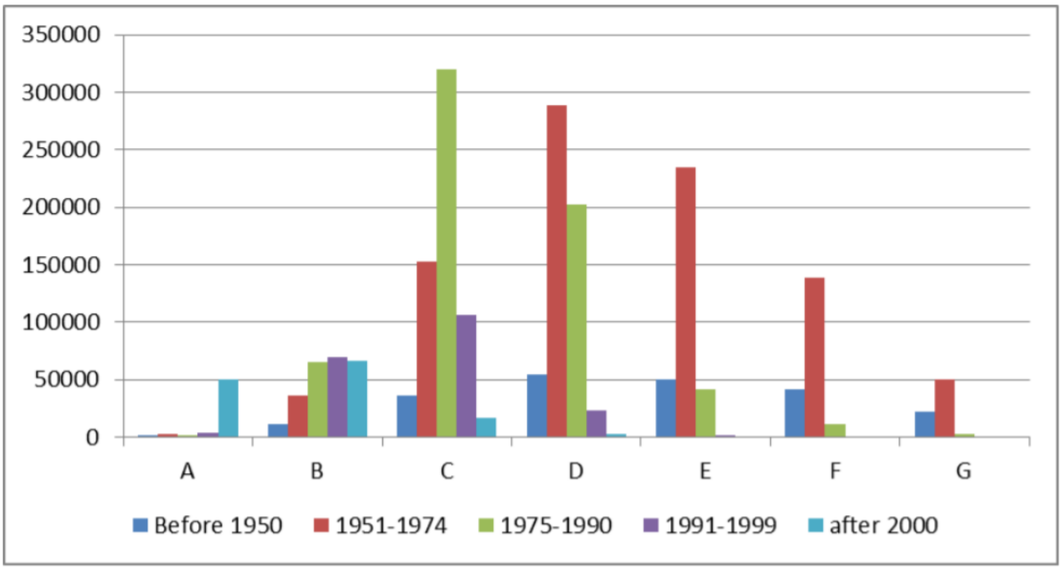


Figure 14: Energy labels classified according to year of construction. Source: Oorschot et al., 2016

2.2.2. Energy-retrofitting

Energy-efficient renovation refers to the renovation of a dwelling with the goal of decreasing its energy use (Sauve, 2019). In the European Union, the final energy consumption in the dwelling is attributed to Space heating, water heating, Lighting and appliances, cooking, other end uses and space cooling in the order of consumption as shown in the figure 15. As evident, the space heating is responsible for almost one-third of the total energy consumption. One of the essential goals of refurbishment is thus to reduce the energy consumption for space heating which can be achieved in a number of ways through the use of efficient heating installations or through improving the insulation of the building envelope to prevent heat loss.

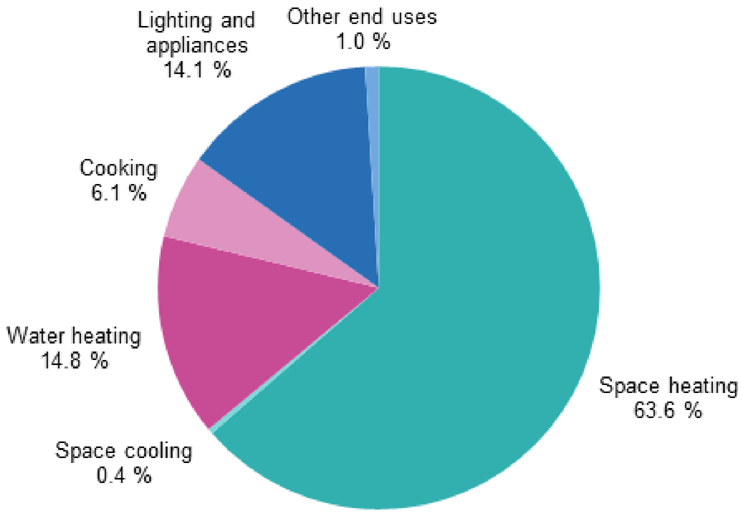


Figure 15: Final energy consumption in the residential sector by use, EU-27 (2018). Source: Eurostat

The energy strategy in the Netherlands is based on Trias Energeticas which is a three-stepped approach. Firstly, reducing the energy consumption of the building by insulating the building, secondly focusing on renewable energy sources instead of fossil fuels and thirdly utilizing the non-renewable sources (if needed) as efficiently as possible by replacing old installations with efficient installations (Franx, 2018). The EWF system is an effective solution to reduce the energy consumption and also utilize the renewable environmental sources as described earlier. Besides the EWF system, additional measures are required to be taken to upgrade the existing poor-performing components of the building having bad/no insulation, ventilation, air-tightness, etc. The improvements of these aspects can contribute towards reducing the energy demand of the building and also provide good thermal comfort in the spaces. Additional installations such as PV panels, solar collector, etc. can be added during the refurbishment process to fulfil the second criteria of Trias Energeticas. The different refurbishment strategies for increasing the energy efficiency of the dwellings are described below.

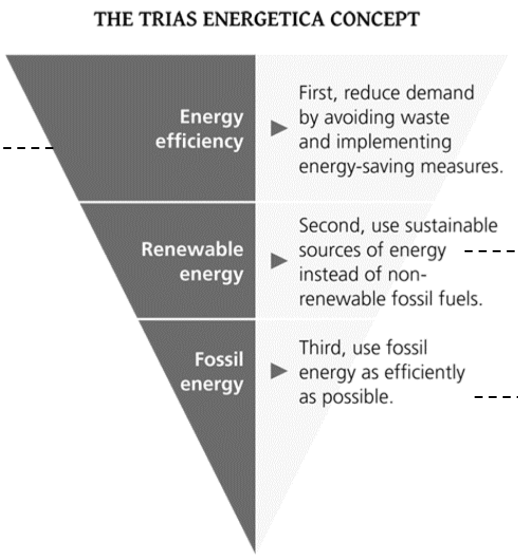


Figure 16: The Trias Energetica concept. Source: Pinterest

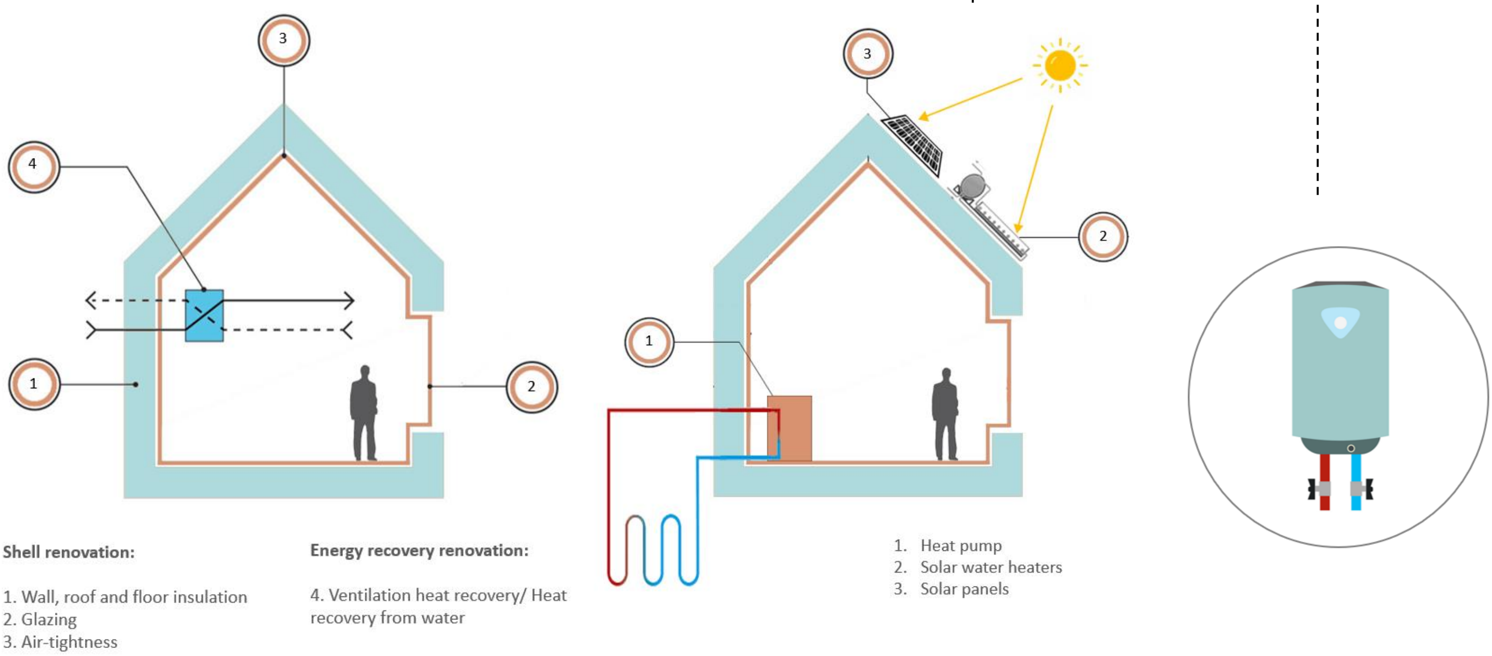


Figure 17: Renovation strategies. Source: Richard Pedranti Architect, PC

The building envelope is one of the major considerations during energy-refurbishments since the envelope can have a drastic effect on the energy use as well as thermal comfort in the building. With a good thermal resistance and air-tightness, the envelope can reduce the heating and cooling demand of the building. As described by Konstantinou (2014), the refurbishment strategies for the envelope can be categorised under five aspects namely replace, add-in, wrap-it, add-on and cover-it that are briefly described below:

Replace: The older envelope is replaced with a new one. This method provides an opportunity to design a new façade which meets all the requirements.
Add-in: Upgrading the envelop from inside.
Wrap-it: Adding a second layer outside the façade.
Add-on: Adding an extra structure to the building. It can be a balcony, extra floors or other elements.
Cover-it: Covering the parts like internal or external courtyards.

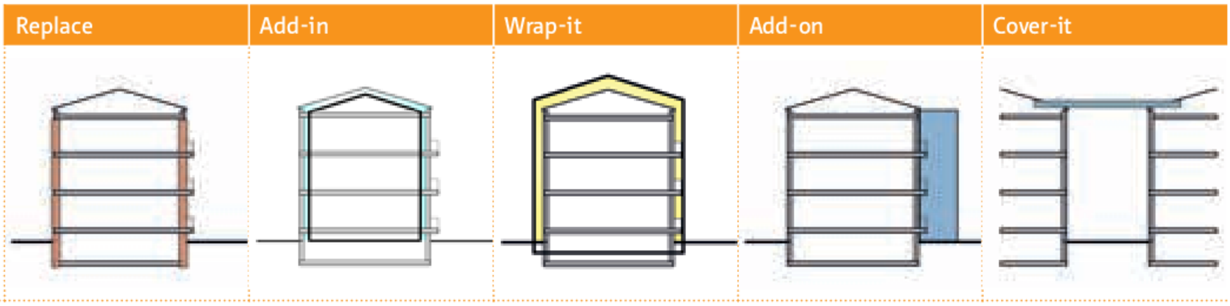


Figure 18: Envelope refurbishment strategies. Source: Konstantinou (2014)

The selection of a particular strategy is dependent on the purpose and goal behind the refurbishment. The Dutch Building Decree - *Bouwbesluit (2012)*, has set boundaries concerning energy efficiency of new and renovated buildings. Considering the insulation requirements of the envelope, *Article 5.1* sets a minimum Rc value of 3.5 m2K/W for the envelope. The maximum heat transfer coefficient (U-value) for windows and doors is set at 1.65 W/m2K.

2.2.3. Heating, cooling & Ventilation systems

Heating system

The heating demand in the Netherlands is met by using gas as a heating-fuel which is much less carbon-intensive as compared to other fuels. Figure 19 shows the schematic gas supply chain to the residential sector. For meeting the heating demand of the houses, the most commonly used system is central heating system using gas-fired boilers. The main source of heat supply to the buildings is the boiler. The heat from the boiler is carried through water flow to the radiators placed throughout the dwellings (Nicolai, 2017). Approximately 38% of the energy is consumed in heating in the Netherlands out of which half of this is used by the residential buildings (Van den Ende, 2017). As per the Energy agenda of 2016, the Dutch government visions to find an alternative to the use of natural gas in order to reduce the carbon emissions. A few alternatives to gas-fuel heating are Electric heat pump, hybrid heat pump and district heating network. This heat is supplied to the rooms through the use of radiators (as shown in figure 20), wall heating or floor heating systems.

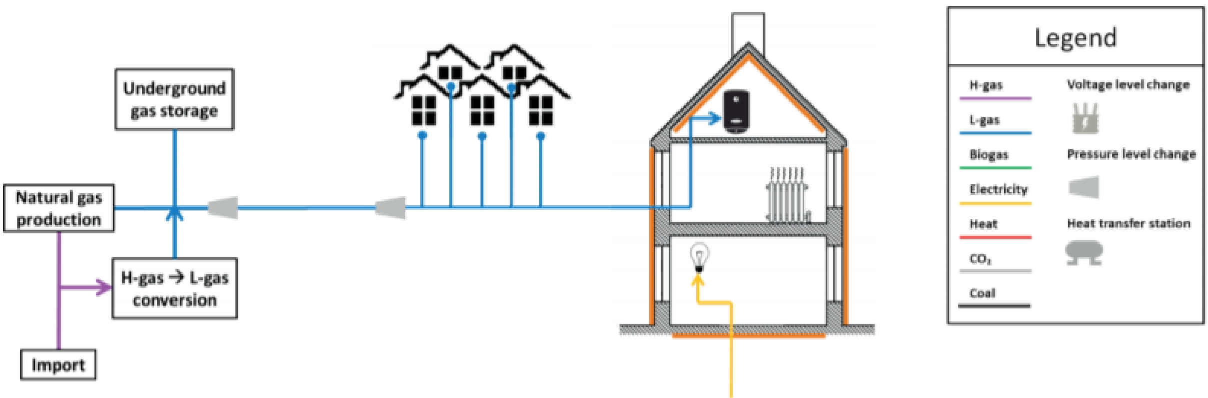


Figure 19: Heat supply chain. Source: Nicolai, 2017.

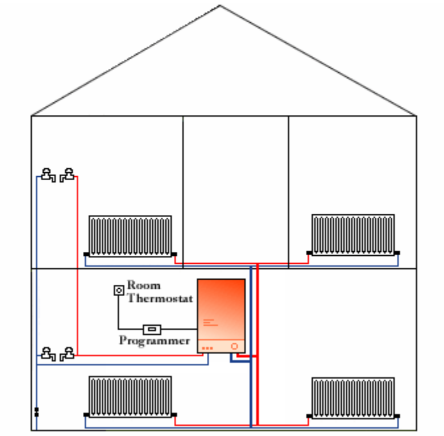


Figure 20: Space Heating. Source: Nicolai, 2017

A possibility to meet some part of the space heating demand with EWF could be explored since the system provides some warmth in addition to ventilation. The potential of Climate cascade to meet the heating demand can be calculated during the simulation phase.

Cooling system

Traditionally, the cooling demand for the Dutch housing is almost negligible when compared to the heating demand. This is due to the fact that Dutch Housing is not installed with air-conditioning or space cooling systems since the number of days exceeding 26˚C is less. However, since past few years Netherlands has experienced heat wave with outdoor temperatures reaching up to 35 ˚C. With no air-conditioning or space cooling systems, occupants in the Dutch housing often face discomfort during hot summer days. On another note, improving the insulation of the building envelope is considered to be an important strategy for reducing the energy consumption of the buildings. While this may be a fruitful strategy during winters, improving the insulation might cause overheating during summers (Ortiz et al., 2020). Since EWF is designed to pre-heat or pre-cool the air before supplying the air to the spaces, the system can help in reducing the discomfort caused during peak summer days.

Ventilation system

The Dutch housing is typically installed with two types of ventilation systems:

- Natural supply and mechanical exhaust ventilation (MEV)

This system has been used in dwelling since 1970s and it uses grilles at the top of the windows for natural supply of ventilation air.

- Mechanical air supply with mechanical exhaust and heat recovery (MVHR)

This system has been used in dwellings since after 2000 and is considered to consume lesser energy when compared to MEV. MVHR has been widely used in the Dutch Housing in the past few years to meet the goal of energy-efficient buildings. However, there are a few shortcomings with this system as highlighted by Balvers et al. (2012) in the research which found that the supply of ventilation air is insufficient a lot of times and doesn't meet the minimum ventilation criteria as prescribed in the Dutch Building code. Other issues faced by the occupants were noise, draught, heat, poor indoor air quality and lack of personal control caused by ventilation system (Balvers et al.,2012).

There is a great need to improve the ventilation system for the Dutch housing which would not only result in energy-efficiency but also provide a better indoor environment. Earth, Wind & Fire system being a natural air-conditioning system has huge potential to replace the existing ventilation systems to improve the energy savings as well as performance for indoor environment. The Dutch Building decree (2012) states the minimum ventilation requirement with an air change rate of 0.9 dm^3 / s per m^2 floor area with a minimum of 7 dm^3 / s. Since the EWF system is initially designed for office buildings which have higher requirement than that for residential buildings, the system shows feasibility for residential buildings.

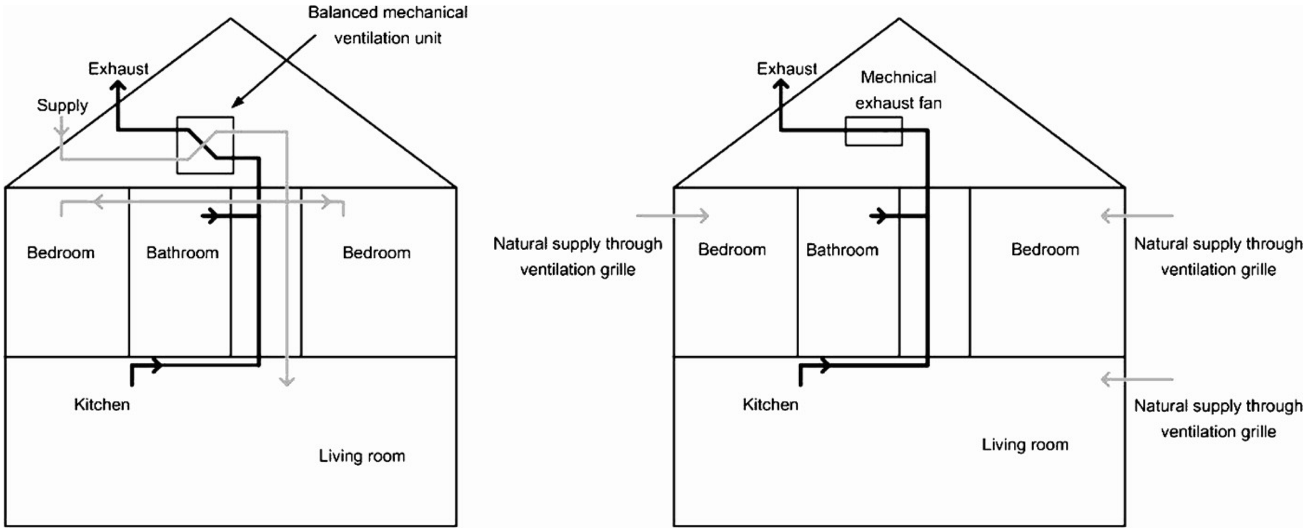


Figure 21: Left: MVHR, Right: MEV. Source: Balvers et al. 2012

2.2.4. Conclusion

Refurbishment of the old dwelling stock plays a crucial role in reducing the energy use in the Netherlands. With around 80% of the dwelling built before 1990 with an energy label of C or below, the refurbishment of the old dwellings shows potential to achieve the energy-efficiency goals.

Various energy-efficient refurbishment techniques are available ranging from small scale refurbishment to deep energy refurbishment. The selection is dependent on the existing issues related to the building. It is highly important to pay attention to the building envelope and improve its insulation, air-tightness and glazing properties to reduce the heat loss or gain from the building resulting in reduction in energy demand. Moreover, renewable energy sources such as heat pumps can be used for producing the required heat demand of the building. The EWF system provides a good opportunity to meet this heating demand through harvesting solar energy inside the solar chimney. The refurbishment solutions for the building envelope or shell have been briefly described in this chapter. With the basic knowledge established, the required R-value for the enclosed parts and U-value for the glazing should be achieved in addition to the installation of EWF system to maximise the energy performance.

The majority of the houses built before 1990 are installed with the Natural supply and mechanical exhaust ventilation which is not highly energy-efficient due to no control over the temperature of the air before the supply and no heat recovery from the stale air. Mechanical supply and exhaust with heat recovery system is more energy-efficient installation. However, this system has majorly been implemented in the houses built in last decade. EWF system can effectively replace the existing ventilation system and meet the ventilation requirements for the habitable spaces. The affect over the indoor comfort should be tested to check the potential of the system when compared to the existing ventilation system.

2.3. Energy Neutrality

The Energy Performance of Buildings Directive (EPBD) defines nearly zero-energy buildings (nZEB) as buildings with a very high energy performance, which make use of renewable energy resources to cover their low energy demand (European Commission, 2010). However, the EPBD does not set any concrete numeric thresholds to define when a building can be considered nZEB. Therefore, the definition of nZEB is not clearly defined and varies from country to country (Mărginean, 2019). On the other hand, the building is termed as a Net Zero Energy Building if the amount of renewable energy harvesting is the same as the total amount of fossil energy consumption during one year (Franx, 2018). The building related energy consumption is through the energy used in heating, cooling, ventilation systems, lighting, and other auxiliary energy that are required for comfort (Klein et. al., 2015). This energy consumption is influenced by occupant behaviour and preferences. User-related energy consumption comprises of appliances, domestic hot-water, cooking etc. (Klein et. al., 2015).

2.3.1. nZEB guidelines

The Dutch government has provided certain guidelines to achieve the energy-neutral goal for the new buildings by 2020. The first National plan of Nearly Energy Neutral buildings (BENG) formulated in 2012, has been sent to the European Commission which is followed in the Netherlands for reaching the energy-neutral goals. In the Netherlands, the energy performance indicator for all the buildings is defined as 'Energy Performance Coefficient' which forms the basis for Energy Performance Certificate. Starting from 2020, all the new buildings in the Netherlands have to comply to BENG regulations and the requirement of EPC shall be eliminated.

Requirements for nZEB

The determination of energy performance of the building is based on three requirements (RVO, 2020):

1. maximum power demand in kWh per m^2 usable area per year
2. the maximum primary fossil energy use, also in kWh per m^2 usable area per year
3. the minimum share of renewable energy in percentages

These are the current requirements of the new construction to be regulated from January 1, 2021 and shall replace the EPC requirement.

BENG indicators

BENG is based on Trias Energeticas strategy as described earlier. Following this strategy, three BENG indicators are identified based on building function (RVO, 2020).

BENG 1 implies a reduction in the primary energy requirement of the building by setting a maximum amount of energy for heating and cooling, expressed in kWh/m2/year. This looks at an optimal quality of the building envelope, in which the window to wall ration, the level of insulation, the degree of air infiltration and the presence of thermal bridges play a role (RVO, 2020). In addition to insulation, the building orientation also plays an important role to limit the energy requirement of building. Calculations are based on an established 'neutral' ventilation system and is calculated by the ratio of the Loss Surface Area (A_{ls}) to the Usable Floor Area (A_{lg}).

BENG 2 implies the maximum allowed primary (fossil) energy use to be used in an efficient way, expressed in kWh/m2/year. The primary fossil energy consumption is the sum of the primary energy consumption for heating, cooling, hot water and ventilation. For the residential buildings, the energy produced by PV panels or other sources is deduced from the primary energy use.

BENG 3 implies the share of renewable energy expressed in percentage which is determined by dividing the amount of renewable energy by the total of renewable energy and primary fossil energy use (RVO, 2020).

Term	Designation
New construction requirements for the maximum energy requirement in kWh per m² usable area per year (kWh / m².yr)	BENG 1
New construction requirements for the maximum primary fossil energy use in kWh per m² usable area per year (kWh / m².yr)	BENG 2
New construction requirements for the minimum share of renewable energy in percentages (%)	BENG 3

Figure 22: BENG indicators. Source: RVO, 2020

Table 2: BENG indicators for the residential apartment function. Source: RVO 2019 adapted and translated from the Dutch version.

Usage function	**Energy requirement (BENG 1)** [kWh/m2. Yr]	**Primary fossil energy use (BENG 2)** [kWh/m2. Yr]	**Renewable energy share (BENG 3)** [%]
Residential building	If $A_{ls} / A_{lg} \leq 1.83$ BENG 1 ≤ 65	≤ 50	≥ 40
	If $1.83 < A_{ls} / A_{lg} \leq 3.0$ BENG 1 ≤ 55 + 30 * (A_{ls} / A_{lg} -1.5)		
	If $A_{ls} / A_{lg} > 3.0$ BENG 1 ≤ 100 + 50 * (A_{ls} / A_{lg} -3.0)		

2.3.2. Renewable energy

There are two parameter which are essential for realizing energy neutrality goals as per the the EPBD Recast (EP and EC 2010), to which the Netherlands also adheres (Bronsema, 2013):

1. Realizing buildings with an energy consumption of *"nearly zero".*

2. *Generating* a very large part of the remaining energy use by *"regeneration", renewable sources, produced on site or nearby".*

The first objective is realized with the Earth, Wind & Fire system through the use of environmental sources and by using low-energy systems for heating or cooling the buildings. The solar chimney plays a significant role in harvesting the solar heat and meeting the annual heat requirement of the building. This is done so by installation of the heat exchanger at the top of the solar chimney which extracts the heat from the hot stale air and stores the heat in the Aquifer thermal energy storage system. Solar chimney thus provides a significant contribution to the second objective and the EWF system as a whole reduces the energy consumption of the building. To meet the remaining energy demand associated to building-related installations (not only auxillary fans and pumps used in EWF but also installations for lighting, heating and other technical facilities), several energy production strategies can be incorporated to meet the goal of energy neutrality.

Photovoltaic energy

The commonly applied concept to convert solar energy directly into electricity through the use of PV cells on building envelope can be implemented for on-site energy generation. Bronsema (2013) also mentioned using PV cells on the rear wall of solar chimney as well as PV foil on the Ventec roof.

Aquifer thermal energy storage (ATES)

ATES is an environmental-friendly system to store energy in the ground and is widely used in the Netherlands to meet the heating and cooling demands of the buildings. In the winter, hot water is pumped up and passed through the heat exchanger where the heat is transferred to the other side serving as heat source for the building. The hot water in the ground size is infiltrated to the other end. The reverse happens during summers when the cold water is pumped up and passed through the heat exchanger where it gets warmer and then infiltrated into the hot source (Sørensen and Nielsen, 2016). This system is environmental-friendly as the heat pump moves heat from the building to the aquifer during summers which acts as a heat sink, whereas the reverse happens in winters as the heat is transferred from the aquifer to the building thus acting as heat source. For the EWF system, the solar chimney harvests the solar heat using a FiWi heat exchanger at the top before exhausting the stale air outside. During the spring, autumn and winter months the heat recovered can be used directly or using a short-term heat storage (RT). However, during summer months the heat is stored in the ATES system to be used again during heating seasons. Moreover, the water used in the climate cascade is also heated or cooled using the ATES system.

2.3.3. Conclusion

The nearly-zero energy buildings have high energy performance which utilize renewable sources to meet their energy demands. The energy demand can be distinguished as building related energy and user-related energy. The refurbishment proposal should at least meet the building related energy demands for heating, cooling, lighting and other auxiliary energy use.

The BENG regulations set certain criteria regarding the energy performance for the building. These regulations shall serve as performance indicators for assessing the potential of the EWF system and the final refurbishment design as an energy-retrofitting system.

The third BENG criteria to have more than 40% share in renewable energy can be greatly satisfied with the EWF system through utilization of environmental sources. If building related energy demand still exceeds by a large amount then other renewable energy systems can be used such as PV panels, Aquifer thermal energy storage, solar water heaters, etc.

2.4.Indoor Comfort

The health and productivity of the people is greatly influenced by the indoor comfort conditions such as:

- Thermal comfort
- Indoor air quality
- Acoustic comfort
- Visual comfort

For the refurbishment of housing buildings using EWF system, thermal comfort and Indoor air quality have a major influence. This section provides an overview of factors that affect thermal comfort and indoor air quality and the criteria for assessing the performance.

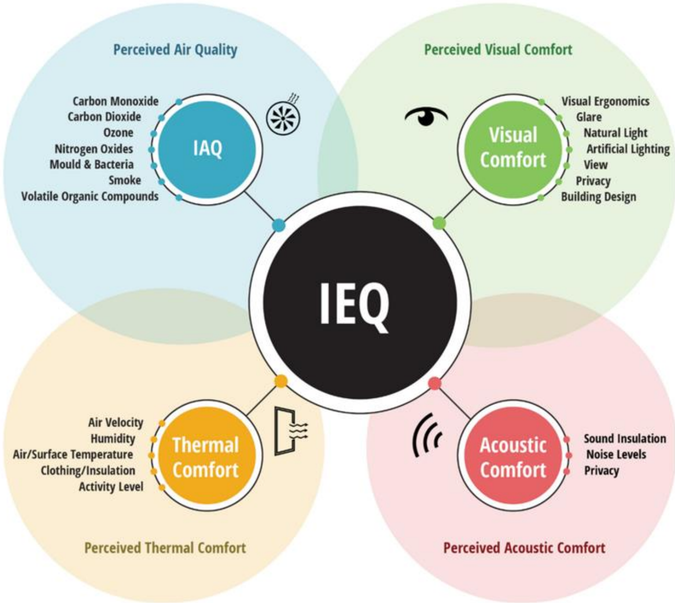


Figure 23: Indoor environmental quality factors. Source: mdpi

2.4.1. Thermal comfort

Thermal comfort is influenced by six factors being both environmental and personal factors. Personal factors such as clothing and metabolic rate are based on individual's personal choice whereas environmental factors could be influenced by the installations. The four environmental factors are air temperature, radiant temperature, humidity and air velocity. HSE states that the relative humidity between 40% to 70% is considered to be comfortable. For the air velocity, Dutch building code suggest the air flow rate of 45 m3 / hour with an air velocity of a maximum of 0.2 m/s for the residential buildings.

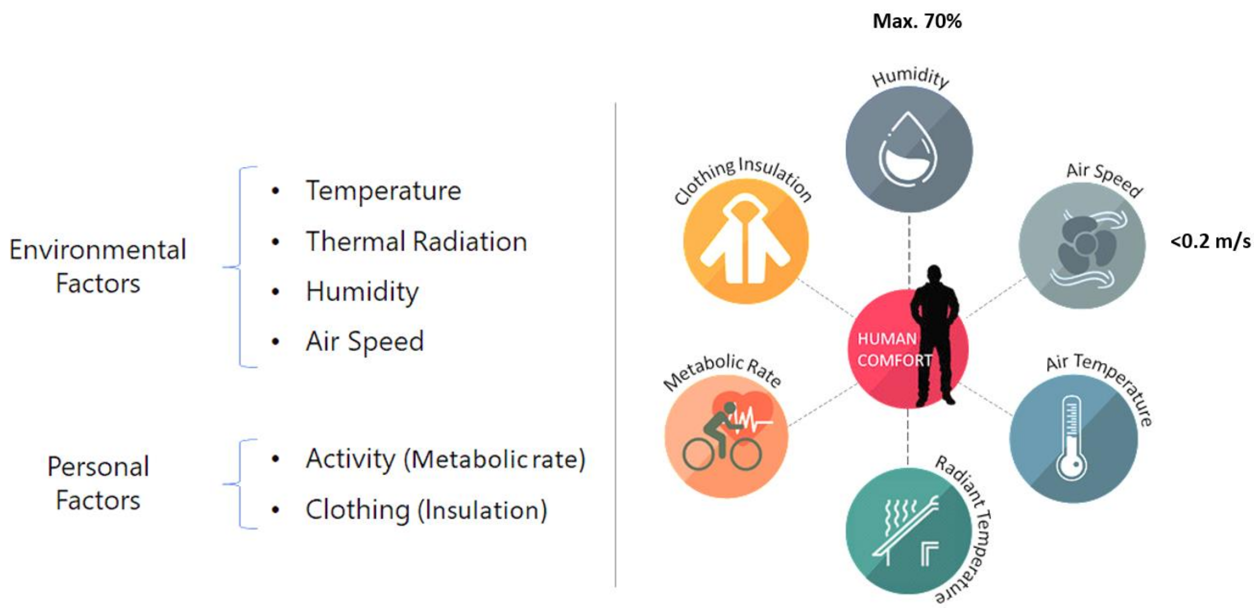


Figure 24: Thermal comfort indicators. Source: Simulationhub

Assessment methods and guidelines

To establish the acceptable thermal comfort range, several assessment models have been made over time which can be categorised under static model and adaptive model (Athienitis & O'Brien, 2015).

- **Static model**

The static model considers a steady-state heat balance equation to determine the thermal comfort of the occupants. The most widely used static model is based on Predicted Mean Vote (PMV) and Predicted People Dissatisfied (PPD) developed by Fanger (Hoof et al., 2010). PPD expresses the percentage of unsatisfied people feeling hot, cold or neutral whereas PMV indicates the average thermal sensation votes of the occupants.

- **Adaptive model**

The static model cannot be applied on naturally ventilated buildings where occupants can adapt to a wider comfort range (Athienitis & O'Brien, 2015). Adaptive model on the other hand, covers a wider comfort range and allows the occupants to control their own environment which has an influence on the health and energy consumption of the building (Athienitis & O'Brien, 2015).

- **Thermal comfort guidelines**

The initial guidelines developed in the Netherlands in the mid-70s is based on static model, PMV-PMD method to predict the thermal comfort (Leitão & Graça, 2017). Over the years, three consecutive methods were developed to assess thermal comfort namely, Temperature Overrun (TO), Predicted Mean Vote (PMV), Adaptive Temperature Limits (ATG) (Leitão & Graça, 2017).

The TO method predicts the number of hours exceeding the temperature of 25 ˚C and 28 ˚C over the entire year. However, this method doesn't provide information on number of hours overheating can last and only considers air temperature. The TO method then evolved into Weighted Overheating Hours (GTO) which was based on PMV-PMD method. The indoor conditions are acceptable if the GTO remains below 150 hours per year. However, this method may not be suitable for buildings where occupants take certain actions to adapt to the environment.

To address the occupant adaptive flexibility, ATG model was developed in 2004 and described in detail in ISSO 74. ATG distinguishes the building into buildings with free cooling providing flexibility to adaptation and sealed mechanically ventilated buildings, identified as alpha and beta respectively. The ATG method was further updated in 2014 which is also the current guideline used in the Netherlands, applicable for new buildings and for refurbishment work. To determine the limits for operative temperature, the buildings should be examined initially based on alpha or beta type and A/B/C/D classification (Boerstra et al., 2015; Leitão & Graça, 2017). The most common target for the new buildings and for the major renovation work is Class B.

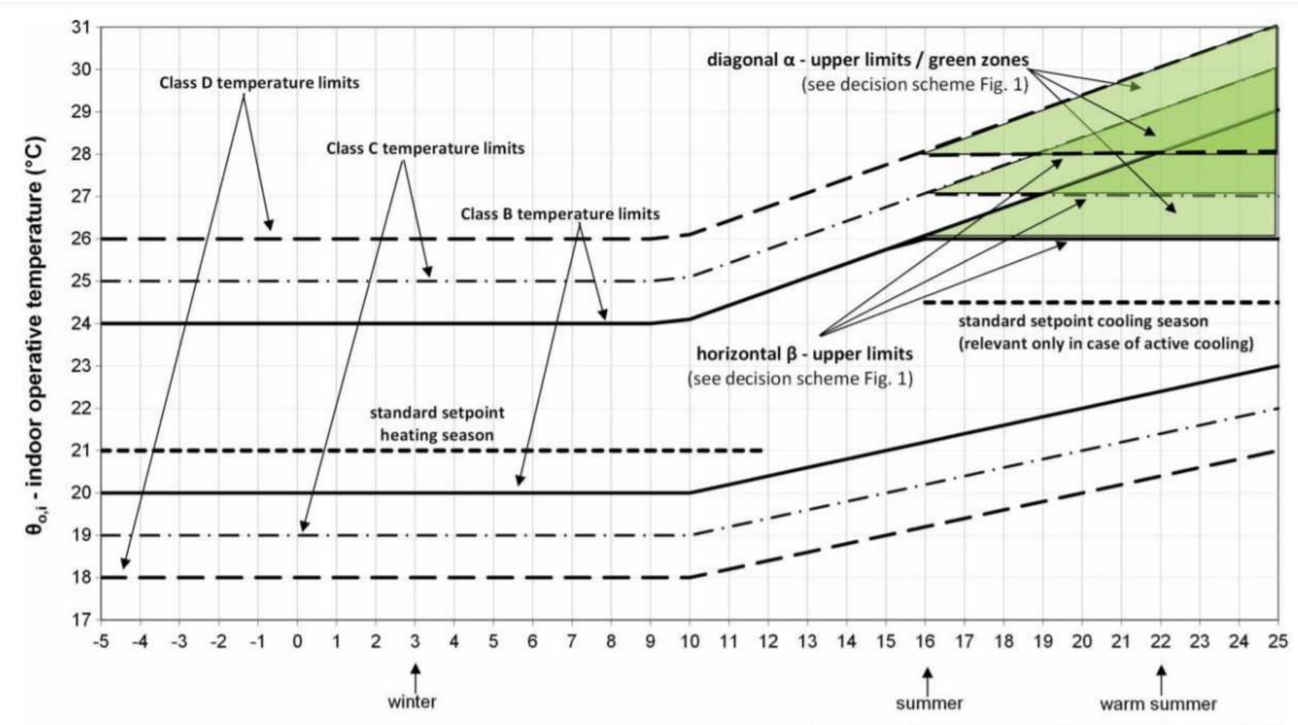


Figure 25: Relation of comfort limits of different class and outdoor running mean temperature for Alpha and Beta Buildings. Source: Leitão & Graça, 2017

Class (bandwidth)	**Requirements indoor operative temperature (°C)**				**Percentage Dissatisfied (%)**	**PMV analogy (bandwidth)**
	Setpoint limit	**Winter**	**In-between-seasons**	**Summer**		
General	Setpoint line	21		24.5		
A	Upper limit	Same as class B (requires options available for occupant control with ± 2 K)			Max. 5%	-
	Lower limit	Same as class B (requires options available for occupant control with ± 2 K)				
B	Upper limit	24	$18.8+0.33*T_{out}+1$	Type β:26 Type α: 18.8+0.33*Tout+1	Max. 10%	-0.5 < PMV < +0.5
	Lower limit	20	$20+0.2*(T_{out}-10)$			
C	Upper limit	25	18.8+0.33*Tout+2	Type β:27 Type α: 18.8+0.33*Tout+2	Max.15%	-0.7 < PMV < +0.7
	Lower limit	19	$19+0.2*(T_{out}-10)$			
D	Upper limit	26	18.8+0.33*Tout+3	Type β:28 Type α: 18.8+0.33*Tout+3	Max. 25%	-1.0 < PMV < +1.0
	Lower limit	18	$18+0.2*(T_{out}-10)$			

Figure 26: Description of the four classification levels. Source: Leitão & Graça, 2017

The ATG model seems to be the most widely used and accepted method for assessing thermal comfort in the Netherlands since it distinguishes into the building types and provides classification levels to determine the operative temperature limits. For the residential buildings where people like to wear comfortable clothing to relax and like to have the flexibility to control their own environment, the comfort aspects differ when compared to office buildings where people want to feel comfortable to be productive and the buildings are usually equipped with central air-conditioning. Since in the residential buildings the occupants have more control by for instance opening windows, the residential buildings are considered as alpha type buildings. On the other hand, Beta type buildings have lesser user control and they mostly have sealed facades (Peeters et.

Al., 2009). Moreover, Peeters et al. (2009) in his paper concluded that the comfort levels vary as per the different zones in the dwellings which can be separated as Bathroom, Bedroom and other living areas.

The Earth, Wind & Fire system usually designed for office buildings has taken the aspects of Beta type buildings since the system provides centralized active cooling. As mentioned earlier, the climate cascade plays an important role in providing a good indoor environment. The study performed by Bronsema(2013) assumes type Beta with a class B with an acceptance rate of 80% categorised as "central classification for a good indoor climate for general application in standard situations".

2.4.2. Indoor Air Quality

Indoor Air Quality (IAQ) refers to the air quality inside and around the buildings, which may have an influence on the health of the occupants (EPA, (n.d.)). Good IAQ is defined as air with no known contaminants at harmful concentrations. The contaminants are usually comprised of gaseous pollutants (such as CO2), volatile organic compounds (VOCs), odours and particulates (Clancy, 2011). The indoor air pollutants can have immediate (dizziness, irritation, etc.) as well as long-term effects (respiratory and heart diseases) on the occupant health. As described by Clancy (2011), the crucial factors determining IAQ are:

- Maintaining fresh air supply rate
- Effective ventilation that removes the pollutants
- Source control (having internal sources with low emission rates)
- Limited external pollution concentrations

Ventilation has a great influence on the IAQ as it can eliminate bad odour, regulate air temperature and remove harmful contaminants from the indoor environment. The air exchange rate is responsible for removing indoor pollutants and replacing it with outdoor air and is achieved through infiltration, natural ventilation or mechanical ventilation.

For the residential buildings, the Dutch Building Decree (2012) provides minimum ventilation rate requirements for different kinds of spaces. The requirements are 0.9 dm3/s per m2 for living areas, 14 dm3/s for bathrooms, 7 dm3/s for toilets, 21 dm3/s for kitchen and 0.5 dm3/s for common circulation areas such as corridors. As described earlier, the EWF system can effectively meet the ventilation requirements for the living areas. However, additional measures should be taken to remove the polluted air from the kitchen and bathrooms to meet the desired ventilation requirements.

2.4.3. Conclusion

Indoor environmental quality is an essential parameter affecting the health and comfort of the occupants. Both thermal comfort and Indoor air quality influence the behaviour of the people as described in this section and should be considered as vital performance indicators for the refurbishment project using EWF. The ventilation greatly influences the indoor air quality and also thermal comfort to a great extent.

For thermal comfort assessment static and adaptive models are available and the Dutch regulations are based on the Adaptive thermal comfort model since it also takes user flexibility into account.

2.5. Building Selection and design criteria

The implementation of EWF in an existing office renovation has been studied by Bronsema (2013) during his PhD research which provided certain parameters and design criteria for implementing EWF into the buildings. This section describes the base parameters firstly for selecting the building type for EWF implementation based on certain building characteristics and secondly the design criteria identified for Solar Chimney, Climate Cascade and EWF system in general.

2.5.1. Case study selection criteria

Context

The building should be considerably higher than the surroundings for the power roof to work. Since the research is not focussing on the Power roof, this is not a major concern. However, having a slightly higher building would also reduce turbulence intensity of the wind and achieve desired pressure difference at the overpressure chamber for air supply and hence can be considered as a parameter.

Building height

The building height should be preferably over 15m to achieve sufficient pressure difference for solar chimney and climate cascade to work efficiently. If the building height is less and if the structure allows for adding more floors at the top, then this could not only be beneficial for the EWF integration but also add more housing spaces which is one of the most crucial problems in the Netherlands.

Structure

The floor height of 3.5m or more is preferable since the duct installations require space and on the other hand, the existing Dutch housings are not installed with any ductwork for ventilation. In terms of the structural system, it is difficult to perform modifications in the post-tensioned concrete slabs during refurbishment.

Façade

Façade type plays an important role in the integration of the EWF elements, specifically Solar chimney. Certain aspects need to be considered before designing the implementation of the EWF system

- If the façade is a load-bearing element, then the integration of EWF might prove to be challenging.
- A demountable façade could make it easy to replace the certain poor-performing parts during refurbishment to improve the thermal performance. Easy disassembly increases the flexibility to integrate the solar chimney, solar façade and also any ductwork for supply or exhaust of the air.

Building typology

The building should preferably be a multi-family building with/without gallery built before 2000. The building with an energy label of D or below would be an ideal case to check the potential of EWF for making the building more energy-efficient.

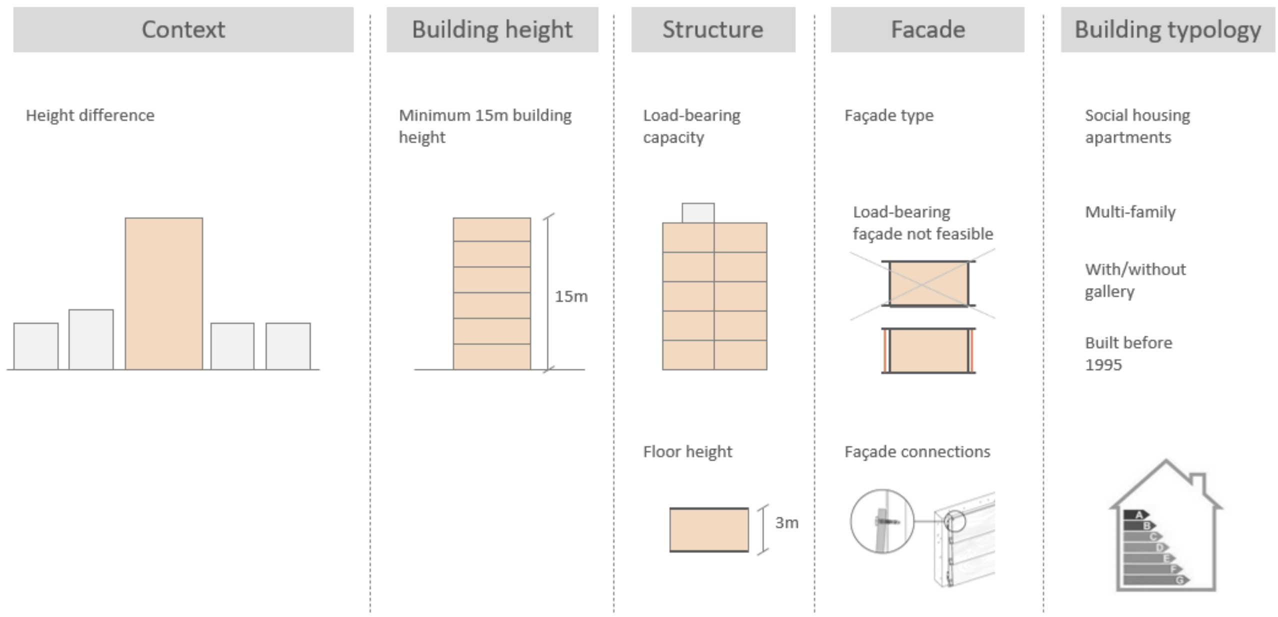


Figure 27: Building selection criteria.

2.5.2. Design criteria

Certain design parameters and possibilities have been identified for designing the EWF system as a whole and the separate components based on the Phd research paper by Bronsema (2013) and through the literature study conducted in the previous sections. These criteria would serve as a starting point for designing the EWF system in the selected case study.

Solar Chimney/ Solar facade

Placement

- To maximize the performance of the Solar Chimney, the preferable orientation should be South/South-East/ South-West. A multi-oriented Solar chimney (Pyramid module/trapezoid module/ angular module) as compared to South facing chimney has higher thermal draft even during summers resulting in better efficiency and thus would be a suitable design aspect.
- Since the solar chimneys could get into the way of achieving required daylight into the rooms, splitting the solar chimneys into multiple could be explored. This could be beneficial for providing sun-shading. However, as mentioned by Bronsema (2013) in his research, one large chimney has better performance than multiple smaller chimneys since the thermal draft increases for a wider chimney thus increasing the performance.

Material/construction

- The outermost glass wall should be selected such that it has highest possible g-value for maximum transmission and lowest possible U-value to limit the heat loss to outside.
- For the rear wall of the solar chimney, the energy performance of light thermal wall is higher than the heavy thermal walls.

- The depth of the solar cavity should be approximately 0.65m for the feasibility of the maintenance. The width of the shunt channel can be designed same as the width of the solar chimney.

Enhancement

- To increase the thermal draft during summers, providing a roof garden could be advantageous although it has no effect during winters. More solutions could be explored to increase the thermal draft during summers.

Climate Cascade

- It is preferable to have it within enclosed walls, however for architectural purpose if it is desired to be exposed using transparent walls, then proper insulation should be provided to avoid any heat loss/gain from outside.
- Desired ventilation capacity and indoor comfort conditions are most important design criteria for climate cascade. Based on the criteria for ventilation capacity and indoor comfort, the climate cascade is dimensioned and the water/air factor, spray spectrum and water temperature are determined (Bronsema, 2013).
- The minimization of water/air factor is a starting point for the excel calculation model for reduction of energy use for spray pump.
- The wind direction should be taken into consideration to design the air inlet for the overpressure chamber.

2.5.3. Conclusion

The criteria for selecting the case study building have been identified which defines the boundary conditions for the applicability of the EWF system. The case study selection criterion consists of the context, building height, structure, façade and the building typology. It is vital to meet this criterion in order to implement the EWF system with its utmost potential.

Secondly, the design criteria and integration possibilities for the climate cascade and the solar chimney have been elaborated for maximising the performance of the system. This would act as guidelines for starting the system design in terms of placement, materiality, dimensioning and integration into the existing building. As a result of the literature study, it has been established that the Ventec roof shall not be implemented during the design phase and therefore the integration criterion only focussed on the Climate Cascade and the Solar Chimney.

3. Methodology

Based on the literature study, the guidelines for energy neutrality and indoor comfort, and the criteria for EWF integration and case study selection has been identified. For the purpose of answering the research question, the study shall follow four main processes: Case study design exploration for integrating EWF into the building, Performance assessment through a simulation software, Final Design and Conclusion.

Case study design exploration

An apartment building which meets the established criteria is selected for case study and the data regarding the existing construction, HVAC system, energy consumption is collected and analyzed to further proceed with the design phase. The refurbishment strategy for the case study building will be identified in order to reach the goal of nearly energy neutral design. Followed by the total refurbishment strategy, different design options for integrating the Climate Cascade and the Solar Chimney shall be explored varying in terms of their architectural and technical parameters. Each design option will vary based on the size, number and the placement of the Climate Cascade and the Solar Chimney. These design options are simultaneously analyzed for their performance using the excel calculation model for the Climate Cascade and the Solar Chimney. The Climate Cascade excel model is developed by Dr. Ben Bronsema (2013) and his research team and the Solar Chimney model is provided by Dr. Reginal Bokel which is further developed by the author. The excel model calculations shall provide results for the energy consumption by the EWF system. The results are then compared to select one design option for further detailing and evaluation.

Performance assessment

The design option will then be simulated through dynamic simulation modelling to calculate the energy consumption performance and thermal comfort using the Design builder software. Different variations shall be carried out in the design to achieve the BENG requirements and Indoor Comfort criteria identified during the literature review. The results of the different design variations shall be compared to the existing building in order to derive the most energy-efficient solution and check the potential of the EWF system to reduce the energy consumption of the existing building. The design variations will also be compared for their thermal comfort performance using the ATG method established during the literature study. The final design variation which meets the requirements shall be selected for further detailing.

Final Design

Followed by the selection of the final design strategy, the refurbishment details shall be carried out for the design of solar chimney and climate cascade elements, and additional details for façade renovation. The final design shall also be evaluated for the BENG assessment criteria to derive whether the refurbished building meets the goal of a nearly energy neutral design.

Conclusions

The final design shall result in formulating case study specific conclusions as well as general technical guidelines for integrating the Earth, Wind & Fire system in the refurbishment of Apartment buildings in the Netherlands. This technical guideline will serve as a starting point for the integration of the EWF system in the refurbishment of apartment buildings in order to maximize the energy performance of the system.

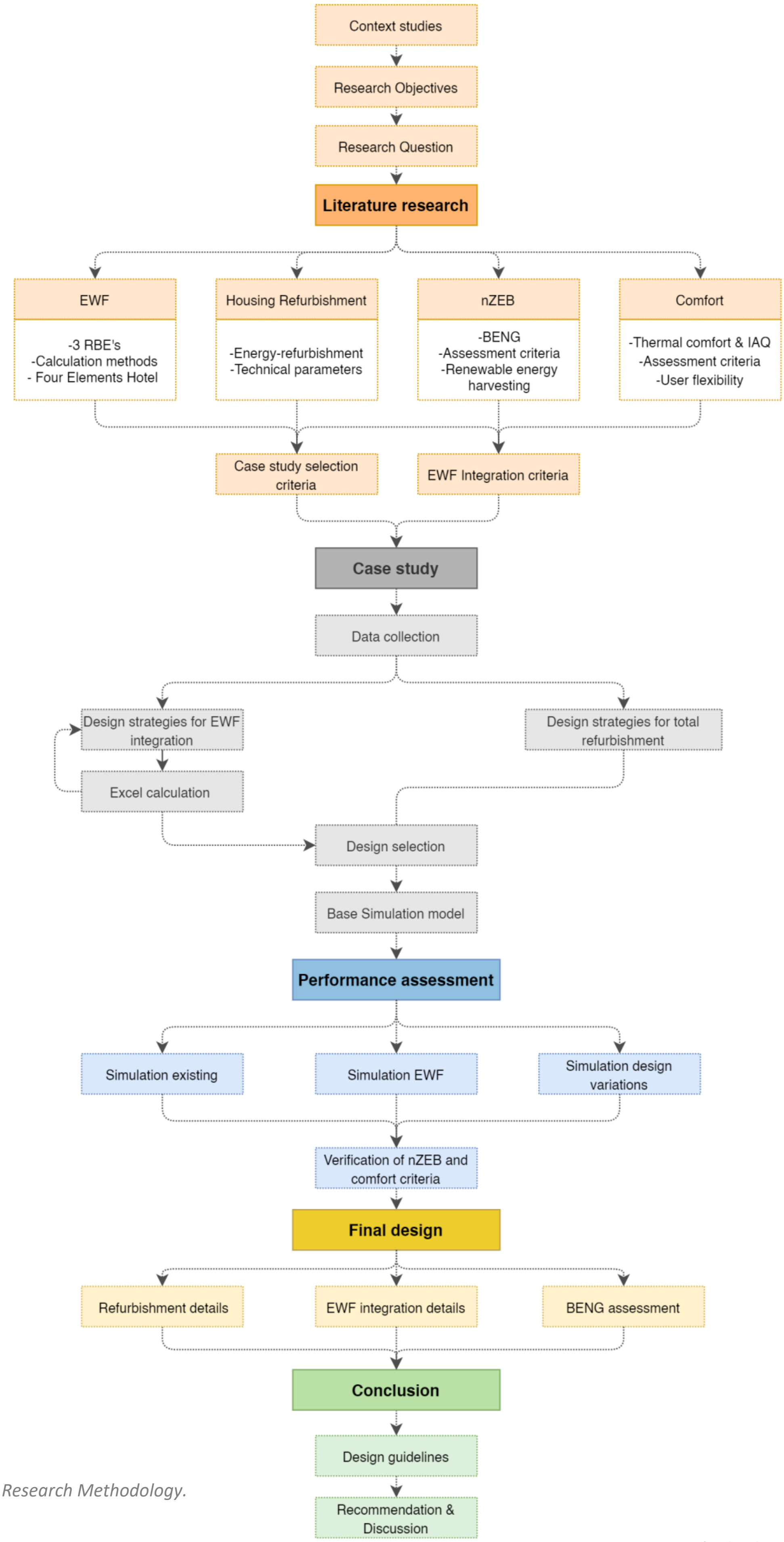


Figure 28: Research Methodology.

4. Case study building

Based on the selection criteria described established during the literature study, a case study building- Arthur Van Schendelplein has been identified. Arthur Van Schendelplein is a multi-family social housing consisting of 198 apartments and was built in the year 1969. The building is located in the Voorhof district in Delft. The Voorhof region, situated in the South Delft, consists of many high-rise residential buildings usually in the form of gallery apartments. The building is a part of three similar residential buildings planned on the Voorhofdreef lane. The adjacent context of the building is mid-rise thus avoiding any obstruction to wind and sun access for the building.

This section provides the information and analysis of the existing state of the building and describing the refurbishment strategy to make the building energy-efficient.

Figure 30: Aerial view of the building context. Source: Heeswijk architecten

Figure 29: Entrance view to the building. Source: funda.nl

4.1.Architectural layout

The building has two blocks joined by a common central staircase and lift block. The taller block has 18 floors with a dimension of 88.5 x 12.85 x 50.36 m with the lower two floors having parking and storage spaces. The shorter block has 10 floors with a dimension of 60 x 12.85 x 28 m with the lower one floor having parking spaces. The central core has a staircase and three lifts providing access to the two blocks. Both the blocks also have an emergency fire staircase at the other ends.

Each apartment has three bedrooms, a living area, kitchen and toilet. The apartments have galleries on both the sides providing ample daylight into the rooms.

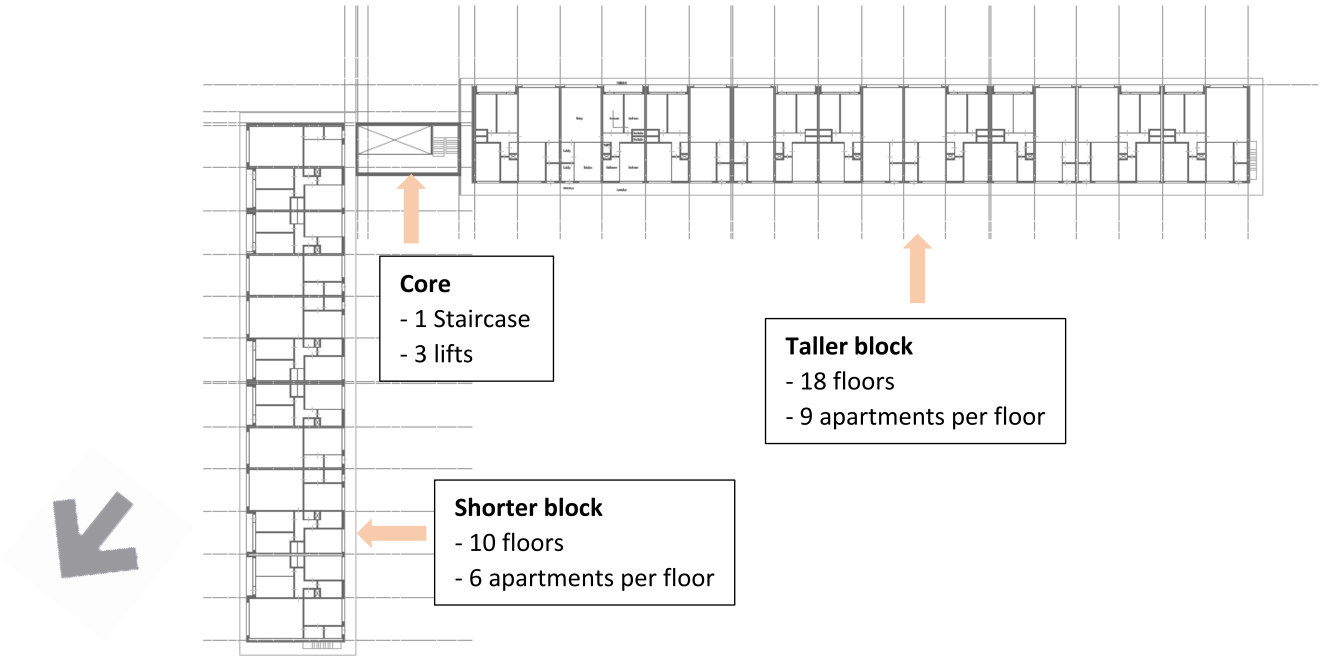


Figure 31: Typical floor plan. Source: author

4.2 Structure

The structure of the building consists of concrete tunnel blocks with a span of 4.8m and 4.63m within a single apartment. This is a typical Dutch housing structure system incorporated in the old housing stock. The tunnel system eliminates the need of having column grid thus the spaces formed are clear from the inside. The floor-to-floor height of the building is 2.8 m which could pose a challenge in incorporating supply and exhaust ducts inside the rooms.

4.3 Facade

The original façade of the building isn't load bearing thus making it feasible to partly refurbish or replace the existing façade. The façade comprises of a cavity brick wall with a total thickness of 270mm having two brick layers of 110mm and a cavity of 50mm. The R-value of the closed parts of the façade is 0.706 m^2 K/W which does not satisfy the Dutch regulation of 4.7 m^2 K/W. The major cause for this is the absence of insulation layer in the facade. The windows are made up of wooden frames and single glazing. Parts of the façade have fixed glazing with a single glass. The U-value of the transparent part of the façade is 6 W/m^2 K. The Bouwbesluit recommends the U-value of the glazing to be 1.65 W/m^2 K or lower. The façade thus does not meet the criteria outlined by the Dutch regulations for reducing the energy consumption of the building. The existing façade thus provides scope to either partly refurbish it by adding insulation and replacing the glazing or completely strip the façade and replace it with an upgraded energy-efficient construction.

Figure 33: View through the gallery. Source: author

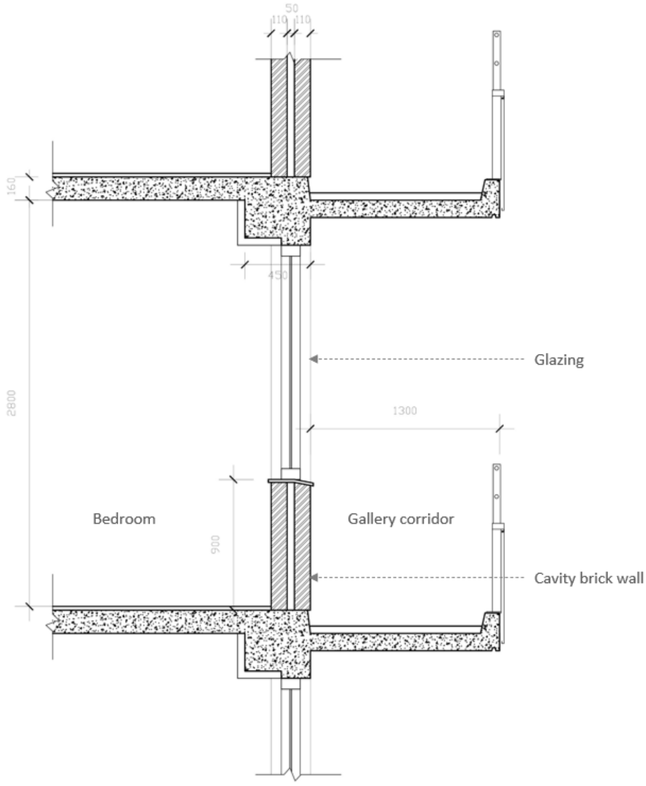


Figure 32: The section through the facade. Source: author

4.4 Heating and Ventilation

The heating of the building is done using the collective heating system through the use of radiators placed on the wall. The hot water demand of the apartments is met by the use of boilers placed on the roof of the building. The building is installed with natural air inlet and mechanical exhaust system from the kitchen and the toilet. The exhaust units are placed on the roof. It is expected that replacing the existing ventilation system with EWF should result in desired indoor comfort and reduce the energy needed for space heating.

A few drawings of the existing building are added in the Appendix A for reference.

5. Refurbishment Strategies for a nearly energy-neutral design

To achieve the goal of nearly energy neutral refurbishment and indoor comfort, the poor performing parts/system of the building needs to be refurbished. This chapter describes the refurbishment strategy followed for the building and the assessment methodology to evaluate the energy performance of the refurbished building to achieve the goal of a nearly energy neutral design.

5.1 Design strategy

In addition to the installation of the EWF system into the building, a total refurbishment model is required in order to satisfy BENG criteria for designing an energy-neutral refurbishment which is carried out in 5 steps:

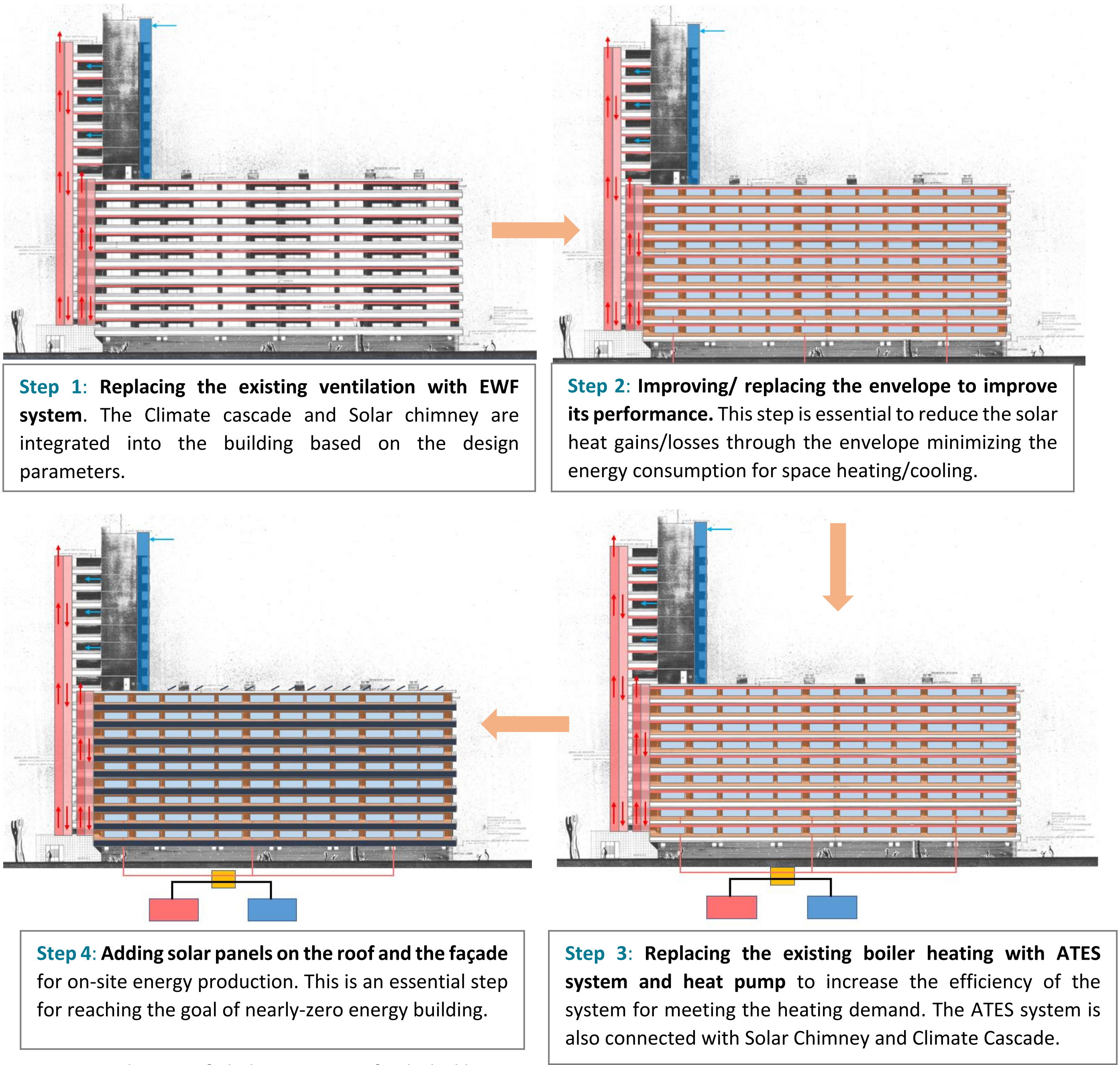
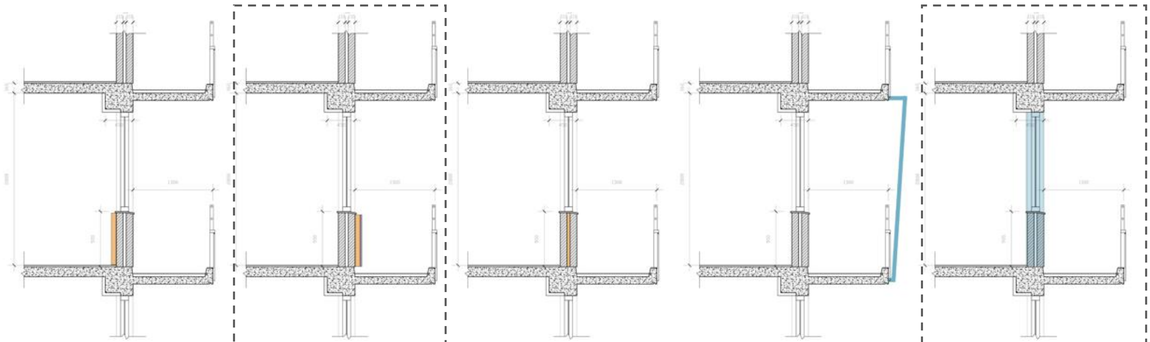


Figure 34: Step-by-step refurbishment strategy for the building.

Design strategies for the façade

Five different strategies for improving the performance of the façade have been compared based on different criteria. These strategies are adding an internal insulation, adding an external insulation, cavity insulation, adding a second skin and replacing the façade. These strategies are derived based on the PhD research by Konstantinou, T. (2014). The level of intervention significantly increases from internal insulation strategy to replacing the façade strategy. The cost estimate plays a crucial role in determining the suitable strategy and thus adding an insulation layer is usually incorporated in the refurbishment projects. However, for the most energy- efficient performance, it is beneficial to replace the façade. Although, this strategy requires huge investment, it is advantageous on a longer run. The first choice for this project is thus adding an external insulation layer and the second choice is replacing the entire façade. During the simulation phase, if the external insulation strategy reduces the energy consumption to a great extent, then this strategy shall be finalized and detailed further.



Strategy	Internal insulation	External insulation	Cavity insulation	Second skin	Replacing the facade
Aesthetics	Unchanged	Changed	Unchanged	Changed	Changed
W/W ratio	Unchanged	Unchanged	Unchanged	Unchanged	Changed
R-value	3.0 - 4.2 m^2 K/W	3.0- 4.2 m^2 K/W	1- 1.6 m^2 K/W (depends on the cavity width)	0.5 m^2 K/W	-
Other benefits	-	Different cladding possibilities	No extra space needed for insulation	-Thermal buffer, unheated space -Solar chimney/ shunt channel integrated - Solar panel integration	New components with better performance
Impact to the residents	High impact	Less impact	Less impact	Less impact	High impact

Table 3:Façade refurbishment strategies (referred from Konstantinou, T. (2014).

5.2 Assessment methodology

With this idea of basic refurbishment, the next step is to design the integration of EWF elements. The design process is carried out together with excel calculation analysis followed by energy simulation. The general procedure would be basic modelling using Excel calculation followed by a dynamic simulation modelling in Design Builder software. The total energy consumption after the refurbishment comprises of energy needed for ventilation, heating, cooling, lighting and domestic hot water. The methodology for calculating the energy consumption utilizes 'excel model' for ventilation and dynamic modelling using 'Design Builder' software for space heating, lighting and domestic hot water energy consumption.

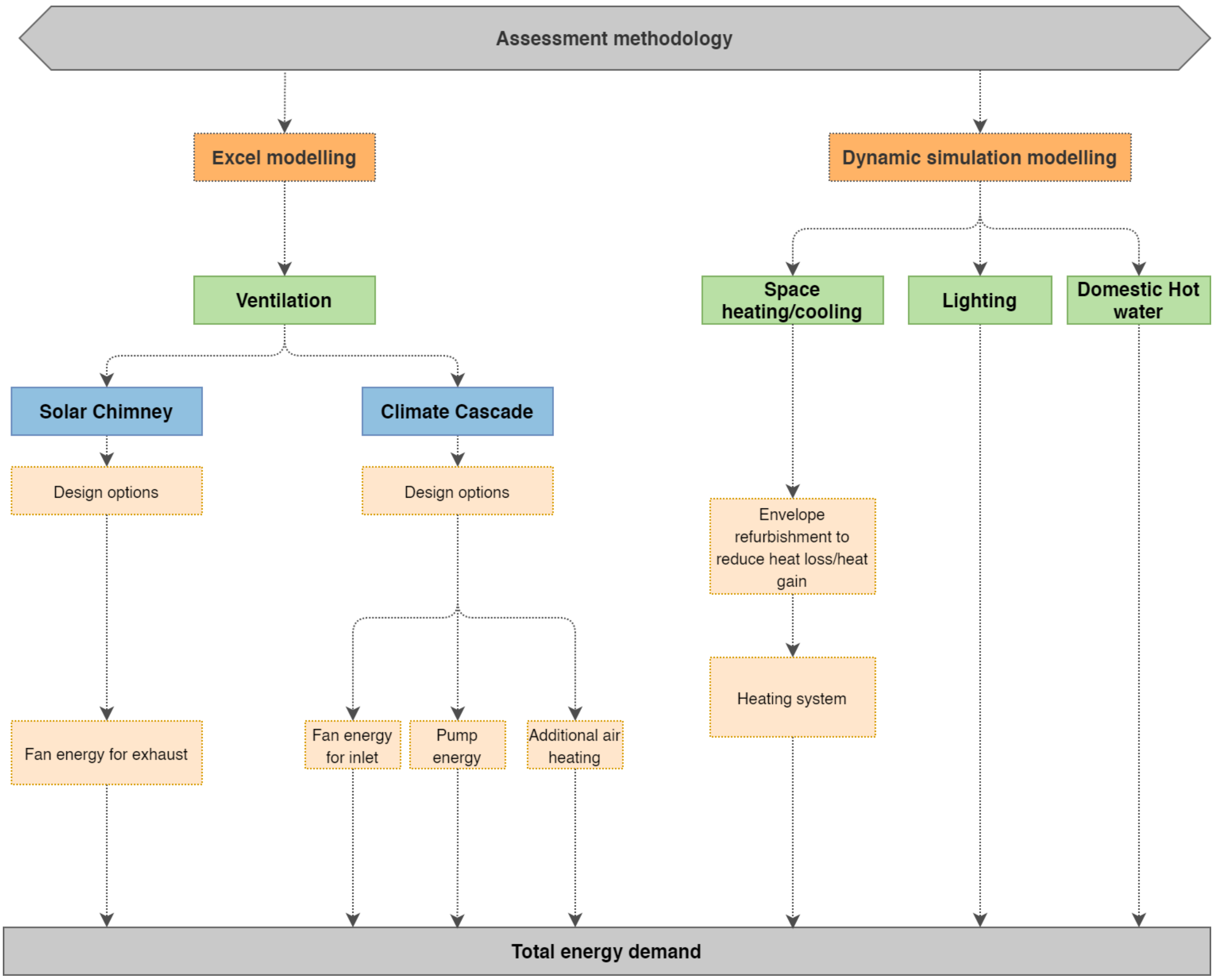


Figure 35: Methodology for calculating energy consumption.

5.2.1 Excel calculation methodology

The excel modelling process includes calculation models which helps in developing the first impressions of the feasibility and potential of the design options (Bronsema, 2013). The excel modelling provides insight on the underlying phenomena of heat transfer and flow and how they work together. This step is done alongside the design phase to simultaneously give an overview of the dimensioning and other parameters for the Climate cascade and the solar chimney. This step will serve as a first quick check to design the system and help with taking certain decisions for the same.

Through excel models for solar chimney and climate cascade, the total annual energy consumption for ventilation can be calculated. This consists of fan energy for exhaust, fan energy for inlet, pump energy for pumping the water till the top of the cascade and additional energy needed for heating the supply air to 18°C. The design options for both solar chimney and climate cascade are explored and optimized based on different parameters and input variables which provides the final energy consumption for all the design options.

The detailed methodology for using excel model is described below:

1. Calculate the **amount of ventilation** for the building.

   The total amount of needed ventilation is 39,600 m^3/h which is calculated as shown below:

Ventilation calculation	
Min. fresh air recommended (Bouwbesluit)	0.9 dm3/s/m2 in all living spaces
Total area (living+ 3 bedrooms) per apartment	59.4 m2
Min fresh air per apartment	53.5 dm3/s ~ 200 m3/h
Total no. of apartments	198
Ventilation for the whole building	39, 600 m3/h
Ventilation for the taller block (144 apartments)	28,800 m3/h
Ventilation for the shorter block (54 apartments)	10,800 m3/h

Table 4: Ventilation requirement calculation.

2. Prepare the **annual climate data** of the Netherlands.

   The climate file consists of hourly data for temperature and solar radiation for the whole year. The climate file for Amsterdam is used for the year 2020.

3. **Design options**

   Different design options for integrating the Climate Cascade and Solar Chimney are generated varying in terms of their placement, size and numbers. These design options are then tested for their energy performance through the use of excel calculation model.

4. **Climate cascade excel model**.

   i. Based on the design options, add the fixed inputs and variable inputs in the climate cascade excel model provided by Dr. Ben Bronsema (2013). Fixed inputs consist of ventilation amount, outside temperature and relative humidity of the outside air. Variable inputs consist of air velocity within cascade, cascade height, no. of nozzles and the spray spectrum from the nozzles.

   ii. Calculate **fan energy** needed for supply air

   Based on the inputs, the excel model provides the hourly values for pressure generated at the base of the climate cascade. When the pressure generated by Cascade is lesser than the pressure loss of the supply system, then a fan is needed to generate that extra pressure for the supply air thus consuming energy which is the output of this step.

iii. Calculate **pump energy**

In order to generate the hydraulic pressure at the base of the Climate Cascade, water nozzles are installed at a certain height in the Cascade. Based on the no. of nozzles and the height, the amount of water used annually is calculated. The output of this step is the annual pump energy needed to pump the water to the top of Cascade.

iv. Calculate the **additional heating energy**

Based on the inputs, the excel model provides the hourly values for the temperature of air coming out of the Cascade. This air needs to be heated till 18°C before supplying it to the rooms which consumes a certain amount of energy annually which is the output of this step.

5. **Solar Chimney excel model**.

i. Based on the design options, add the fixed inputs and variable inputs in the Solar Chimney excel model provided by Dr. Regina Bokel and further developed by the author. Fixed inputs consist of ventilation amount, outside temperature, solar radiation and inlet air temperature. Variable inputs consist of chimney height, air velocity within chimney, chimney depth and chimney wall material properties.

ii. Calculate the **total pressure loss** for the exhaust system

This consists of pressure loss due to friction in solar chimney, shunt channel, bends in the exhaust ducts, external pressure loss, dynamic pressure loss and pressure loss due to heat exchanger.

iii. Calculate the **thermal draft** generated in the chimney

This depends on chimney height, outside temperature and temperature in the cavity. Based on this, excel model provides hourly thermal draft values for the whole year.

iv. Calculate the **fan energy** for exhaust

When the thermal draft is lower than the pressure loss of the exhaust system, a fan is needed. Based on the hourly pressure loss values and hourly thermal draft values, the excel model calculates the fan energy needed for the whole year.

6. Calculate the **total ventilation energy consumption**.

The output of the Climate Cascade and the Solar Chimney consisting of fan energy for inlet, pump energy, additional heating energy and fan energy for exhaust are added together to calculate the total ventilation energy consumption by the EWF system.

5.2.2 Dynamic simulation methodology

The dynamic simulation modelling is done in Design Builder software to calculate the annual energy consumption for space heating, lighting and domestic hot water. Based on the different input parameters, the simulation results also provide the operative temperatures in the rooms which are then used to evaluate the thermal comfort of the building.

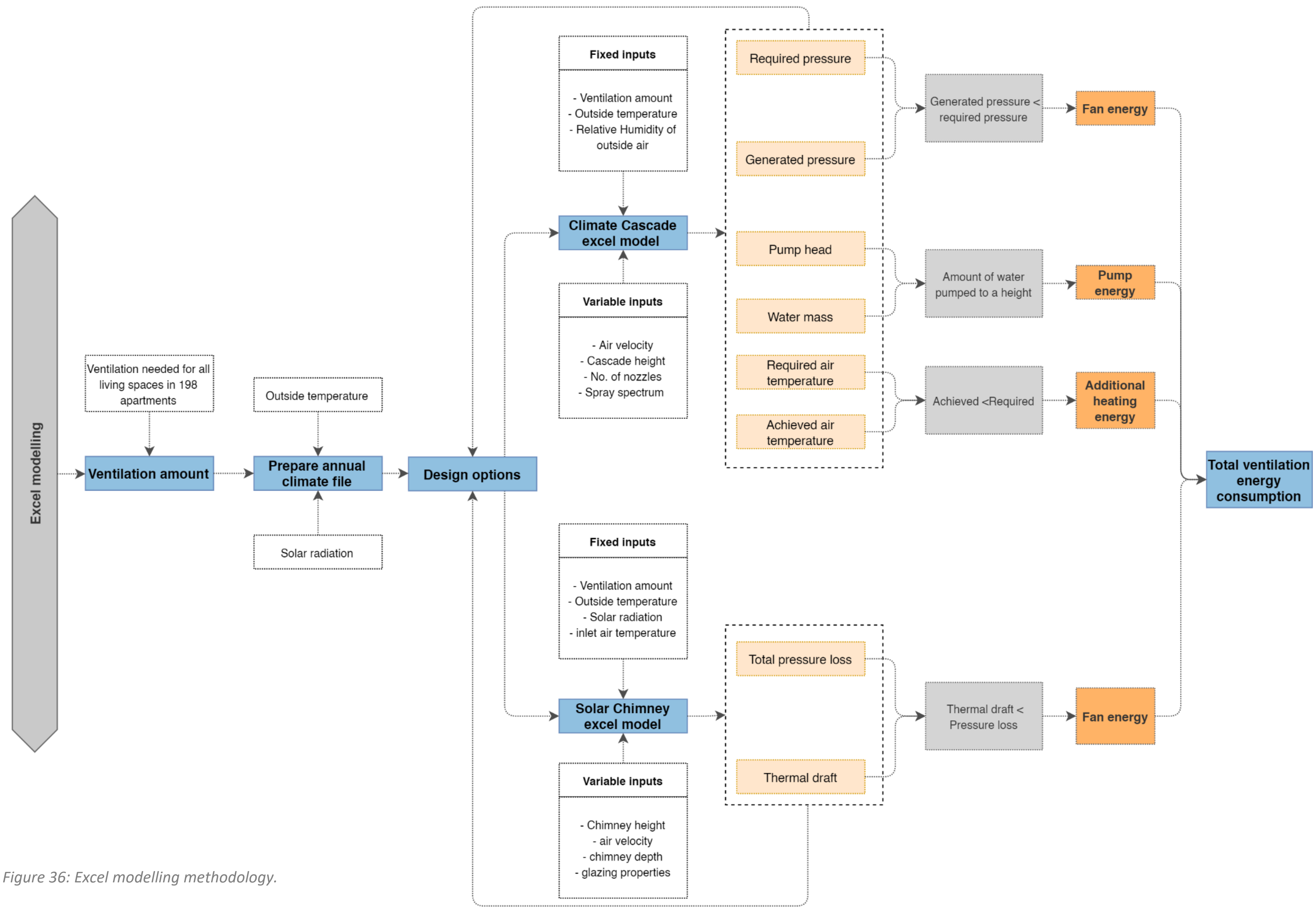


Figure 36: Excel modelling methodology.

7. Application of EWF strategies in the case study building

This chapter describes different design strategies for integrating Solar Chimney and Climate Cascade into the building. The design options were simultaneously analysed and modified using the excel calculation model. Based on the different design parameters and performance criteria, the results obtained using the excel calculation model for all the design options are compared and a final design option is chosen which satisfies the design criteria.

7.1 EWF design options

7.1.1 Site Zoning

The site is oriented at an angle of 20 degrees from the North with the taller block facing South-east/North-west and the shorter block facing North-east/South-west. The placement of climate cascade is independent of orientation and thus it can be placed centrally next to the core serving as a central air supply shaft for both the blocks. The climate cascade can either be placed in front or the back of the core. Since the wind direction is not always constant in the Netherlands, the opening flaps can be located on all the four sides of the cascade to let the air enter from the windward side. The placement of solar chimney on the other hand is dependent on the orientation. The entire South-east and South-west façade is suitable for placing the Solar chimney.

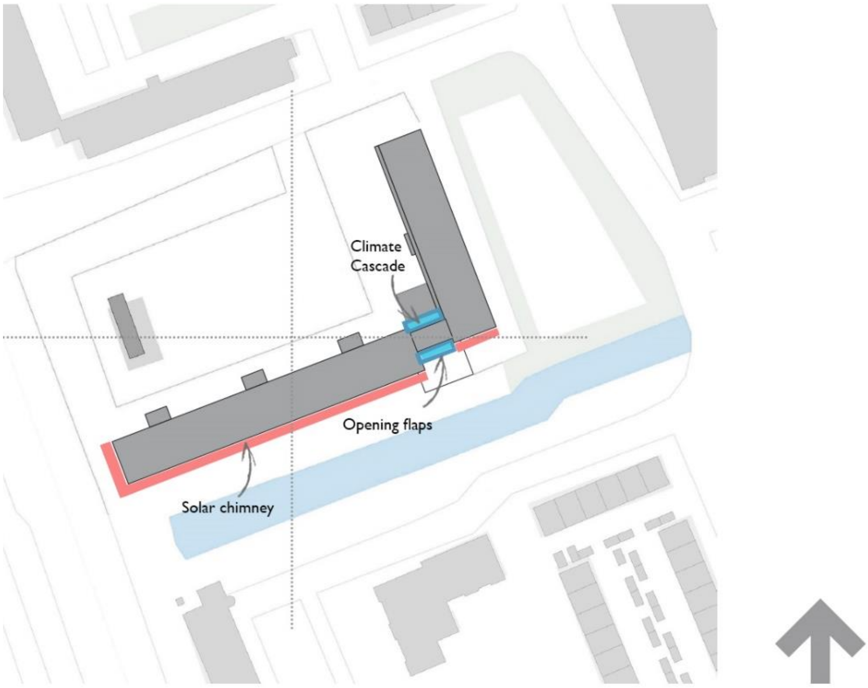


Figure 37: Site zoning for EWF. Site plan source: Heeswijk architecten

7.1.2 Climate cascade and Solar chimney design options

Based on the basic zoning described in the previous section, different design options were explored for both Climate cascade and Solar chimney varying in terms of their placement, size and number. For the apartment building with galleries on both the sides, it is certainly not feasible to provide centralized supply and exhaust system unlike offices where centralized systems can be easily realized. This is due to the division of the apartment building into different zones based on their function living, bedroom, kitchen and toilet. Thus, all the design options discussed in this section have decentralized supply and exhaust layout with supply and exhaust ducts proposed for each apartment.

The central core has three elevators and a staircase leaving no space for accommodating climate cascade in the core. The climate cascade (CC) can thus be placed outside. Similarly, the solar chimney (SC) is designed to be attached to the galleries. On the basis of basic zoning, 5 different options for integrating Climate cascade and Solar chimney are designed which are described below. These 5 design options are analysed for their performance using the excel calculation model. The climate cascade and solar chimney are first separately analysed which is described in the next sections.

Design option 01: 1 Climate Cascade, 1 Solar Chimney

In this design option, 1 Climate Cascade and 1 Solar Chimney are placed centrally next to the core at opposite ends. Since a single chimney is provided catering both the blocks, the size of the chimney is quite big covering the entire backside of the core. The daylight access to the core shall then be provided from the side where climate cascade is placed.

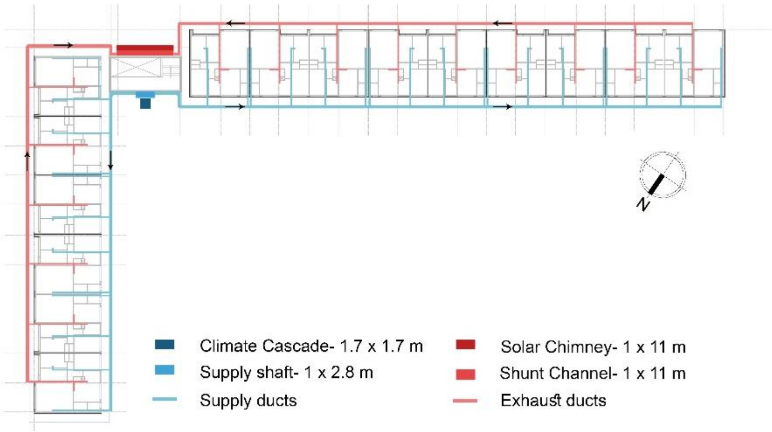


Figure 38: Design option 01

Design option 02: 1 Climate Cascade, 2 Solar Chimneys

In the second option, the Climate Cascade remains the same however each block has its own Solar Chimney. For the taller block, the Chimney cannot be placed centrally at the block since it will block the daylight access into the apartments due to a large chimney size.

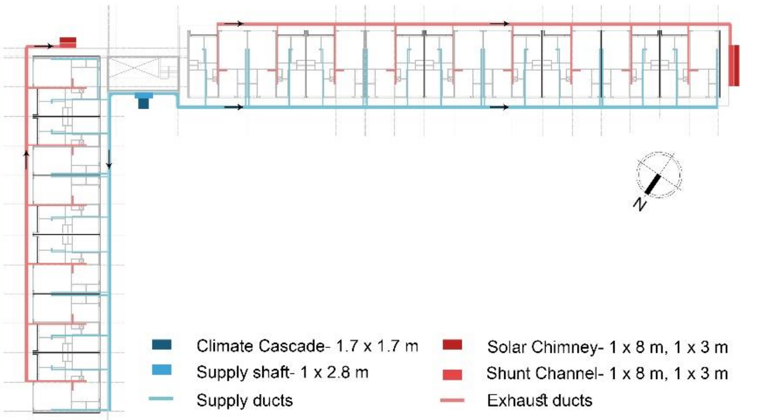


Figure 39: Design option 02

Design option 03: 1 Climate Cascade, 4 Solar Chimneys

For the third option, the Climate cascade is same and 4 solar chimneys are added on the South-east side. Due to smaller chimney size compared to the option 02, the chimneys can be placed in front of the taller block since the daylight access is less hindered.

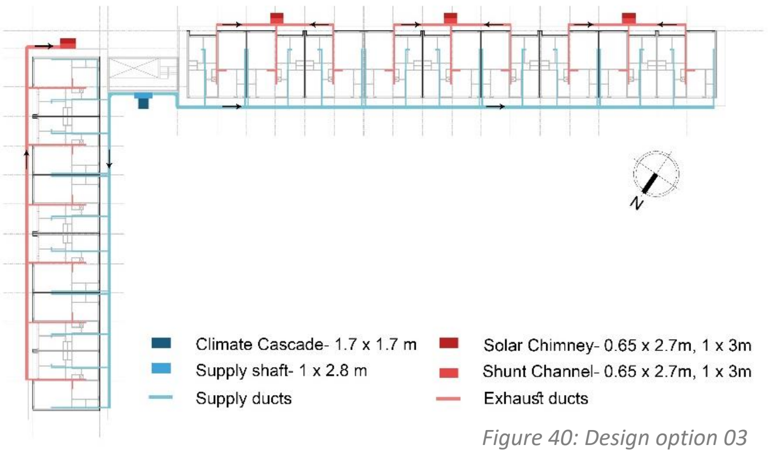


Figure 40: Design option 03

Design option 04: 2 Climate Cascade, 2 Solar Chimneys

In the fourth option, 2 Climate Cascade and 2 Solar Chimneys are provided with each block functioning separately with its own Climate Cascade and Solar Chimney.

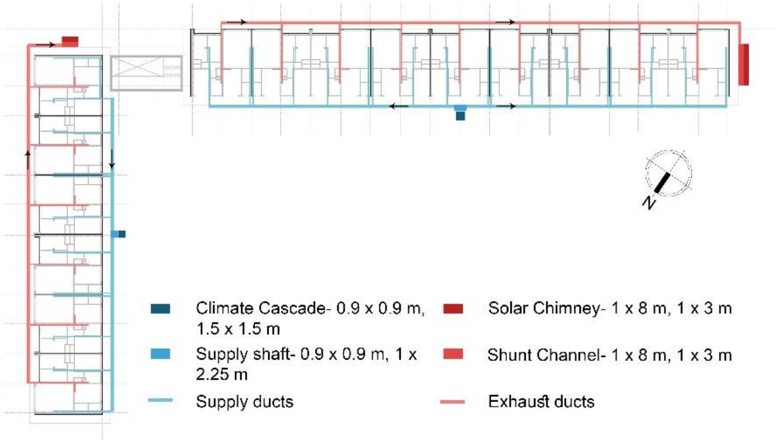


Figure 41: Design option 04

Design option 05: 2 Climate Cascade, 4 Solar Chimneys

For the final option, 2 Climate Cascades and 4 Solar Chimneys are designed which is a combination of option 03 and option 04.

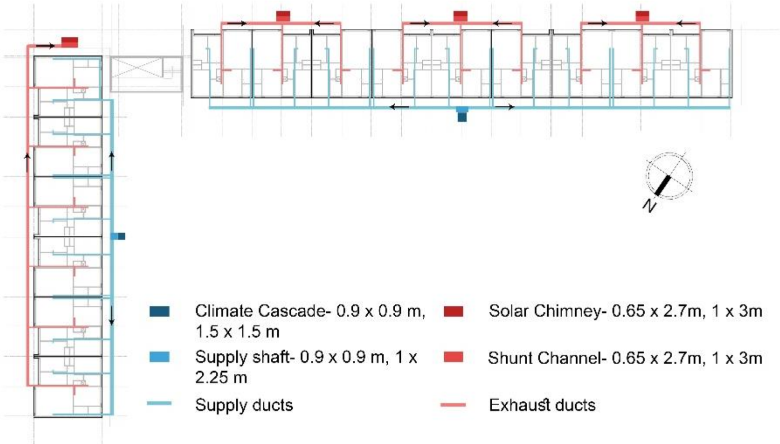


Figure 42: Design option 05

7.2 Climate Cascade

The 5 design options are firstly evaluated in the Climate Cascade model to calculate the energy performance and compare the results in order to find the most favourable design option. This section describes the parameters considered for calculations and the results based on the comparison of these design options.

7.2.1 Design conditions

In order to proceed with the analysis of the design options, firstly it is essential to establish the design conditions describing constants, variables and evaluation parameters.

Design constants

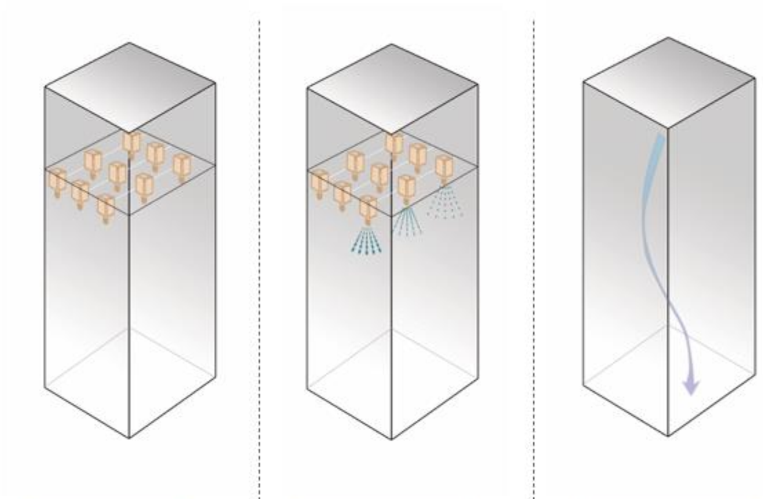
For the design constants, the total pressure loss for the supply system is estimated as 150 Pa which is decided based on the discussion with Dr. Ben Bronsema. This supply pressure loss of 150 Pa is irrespective of the number of Climate Cascade. The desired supply air temperature from the Climate Cascade to the apartments is 18°C throughout the year and the supply water temperature to the nozzles of Climate Cascade is 13°C. These values are decided on the basis of Phd study by Bronsema (2013). The ventilation capacity for the building is 39,600 m3/h as calculated in table 4.

Climate Cascade Design constants				
Supply system pressure loss (Pa)	Desired supply air temperature from CC to rooms (°C)	Supply water temperature to CC (°C)	Ventilation capacity (m^3/h)	Cascade height (m)
150	18	13	39,600	54

Table 5: Design constants

Design variables

The design variables include the no. of nozzles, the spray spectrum and the air velocity in the cascade. These variables affect the pressure generated at the base of the cascade, the air temperature achieved in the Climate Cascade, the relative humidity in the rooms and the size of the climate cascade. As a result, the total energy consumption by the Climate Cascade is dependent on the design variables. Hence the design variables should be carefully selected to achieve the maximum performance with least energy consumption.



Variables	Nozzles	Spray spectrum	Air velocity
Output	Temperature Pressure Amount of water Relative Humidity	Temperature Pressure Relative Humidity	Temperature Cascade size

Table 6: Design variables.

Evaluation parameters

Based on the input provided for design constants and the design variables, the excel model provides the output for each design option. The design option is selected based on the following evaluation parameters:

- Pressure generated in CC should be higher than the pressure loss of supply system (150 Pa).
- Air temperature at the base of CC should be closer to 18 °C.
- Relative Humidity in the room should be between 30-70%.
- The total energy consumption (fan + pump + additional heating) should be low.

7.2.2 Effect of design variables

Before finalizing the design variables, it is essential to understand its effect on the output parameters. The effect of changing the number of nozzles, spray spectrum and the air velocity is described below.

a. No. of nozzles

The number of nozzles used in the Climate Cascade affects the air temperature coming out of CC, the pressure generated at the base of the Cascade and the Relative humidity of the air. The higher the number of nozzles, the more amount of water is used thus increasing the pump energy. It is thus important to reduce the water/air factor (mass of water in kg/ mass of air in kg) resulting in lesser pump energy consumption. The effect of ranging number of nozzles from 2-10 has been studied and described below.

Effect on Air temperature

From figure 43, it can be noted that when the number of nozzles used during extreme summer and winter temperatures is higher, the air temperature coming out of CC is closer to the desired temperature of 18 °C. However, during when the outside temperature is 6 to 18 °C, the number of nozzles does not significantly affect the air temperature. Thus, it is beneficial to use less nozzles during this period in order to reduce the pump energy consumption and more nozzles during extreme summer and winter temperatures.

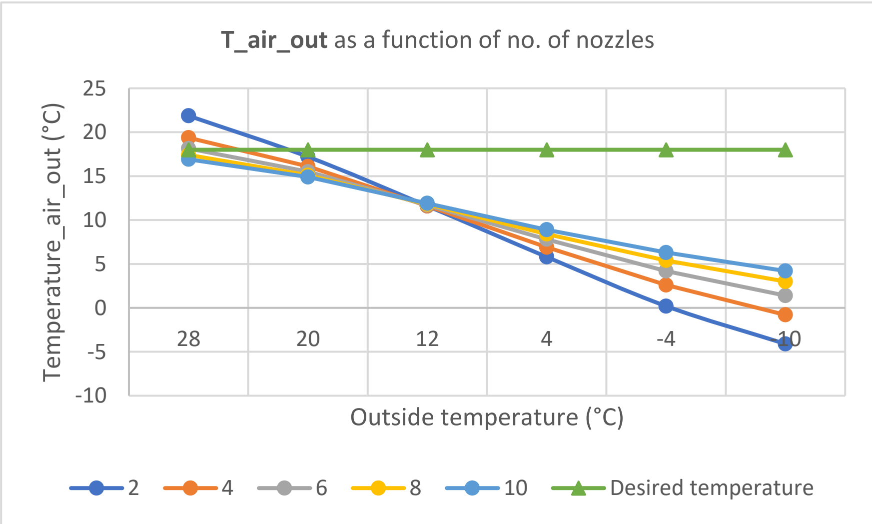


Figure 43: Graph showing T_air_out as a function of no. of nozzles at different outside temperatures.

Effect on generated pressure

From figure 44, it can be noted that the higher the number of nozzles, the higher is the pressure generated at the base of the CC. When the outside temperature ranges from 12 to 28 °C, the number of nozzles can be reduced in order to avoid excessive overpressure at the base of the Climate Cascade.

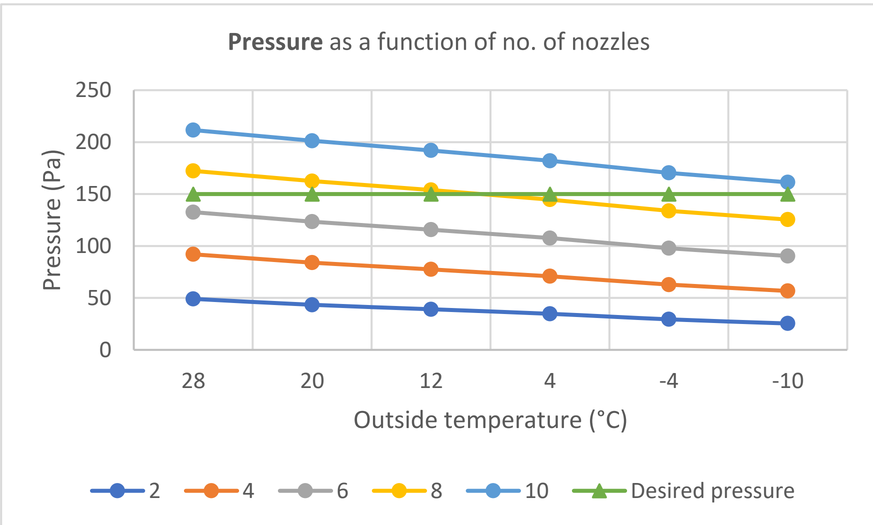


Figure 44: Graph showing pressure generated as a function of no. of nozzles at different outside temperatures.

Effect on Relative Humidity

The figure 45 shows that the Relative Humidity is always within the acceptable range of 30-70 % when the outside temperature is between 4-28°C. However, at lower outside temperatures, the RH achieved in the room is lower than 30% when the number of nozzles is less. Thus, higher number of nozzles are needed during winter months.

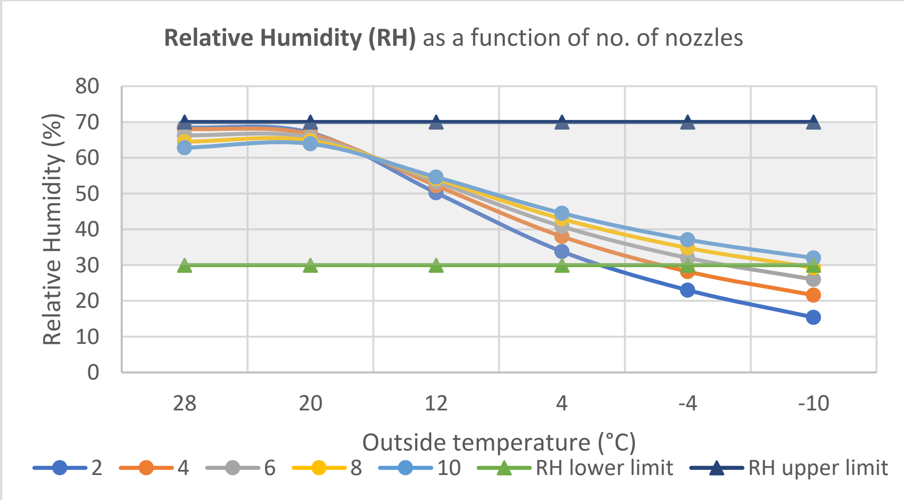


Figure 45: Graph showing Relative Humidity as a function of no. of nozzles at different outside temperatures.

Based on the above factors, **the final number of nozzles used in calculations for all the design options vary between 4 to 10 depending on the outside temperature** in order to keep a balance between the pressure, air temperature and the Relative humidity.

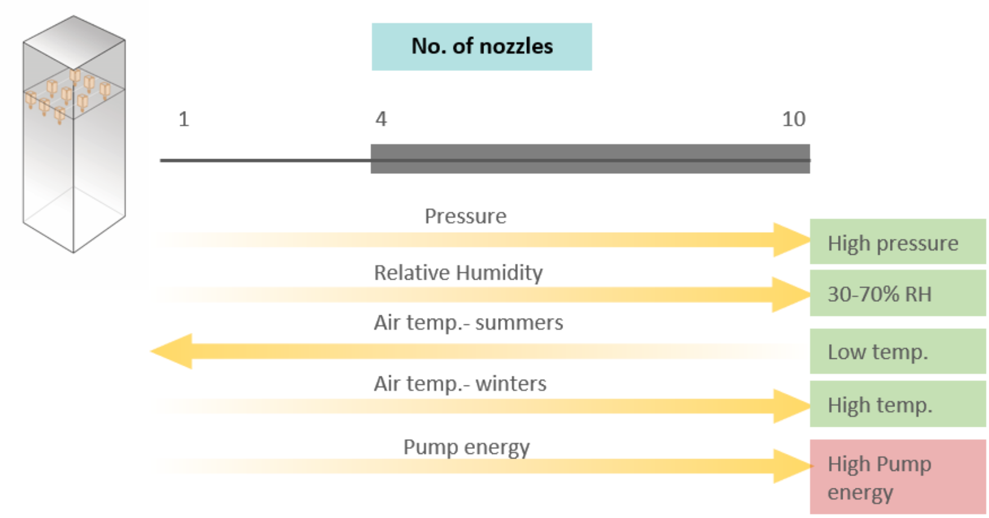


Figure 46: Effect of no. of nozzles.

b. Spray Spectrum

The spray spectrum refers to the characteristics of water droplets in terms of its diameter, surface area, velocity etc. It can range from a course (bigger water droplets) to a fine (smaller droplet size) spectrum. The spectrum used for this analysis ranges from spectrum 2 (coarse spectrum) to spectrum 8 (fine spectrum). The spray spectrum used in the Climate Cascade affects the air temperature coming out of CC, the pressure generated at the base of the Cascade and the Relative humidity of the air. Keeping the water amount same for each spectrum, the effect of varying spray spectrum has been studied and described below.

Effect on Air temperature

Keeping 10 constant nozzles, the effect of changing spray spectrum has been studied for different outside temperatures. Changing spray spectrum does not have a drastic effect on the air temperature as evident from the figure 47. Spectrum 8 however, provides comparatively higher air temperatures during winters which is desirable.

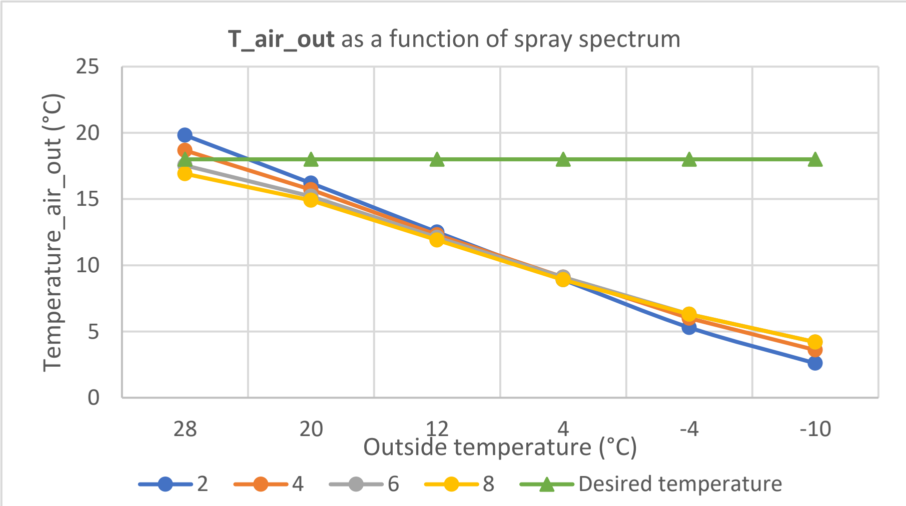


Figure 47: Graph showing T_air_out as a function of spray spectrum at different outside temperatures.

Effect on generated Pressure

From figure 48, it can be noted that the higher the spray spectrum, the higher is the pressure generated at the base of the CC. Spectrum 8 always has higher pressure generated values than the pressure loss (150 Pa) and thus provides desirable results.

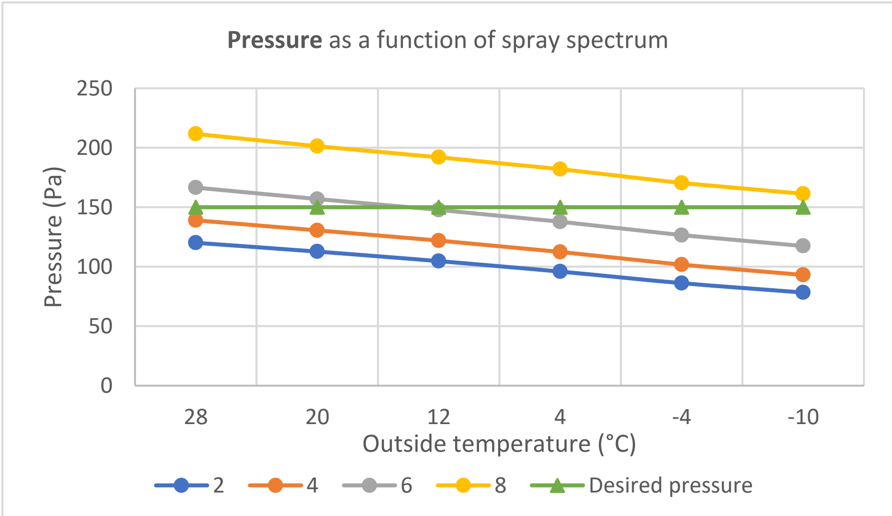


Figure 48: Graph showing pressure generated as a function of spray spectrum at different outside temperatures.

Effect on Relative Humidity

There is not any drastic impact of spray spectrum on relative humidity. It is always within acceptable range of 30 to 70 % except at -10 °C when spectrum 2 falls outside the acceptable range.

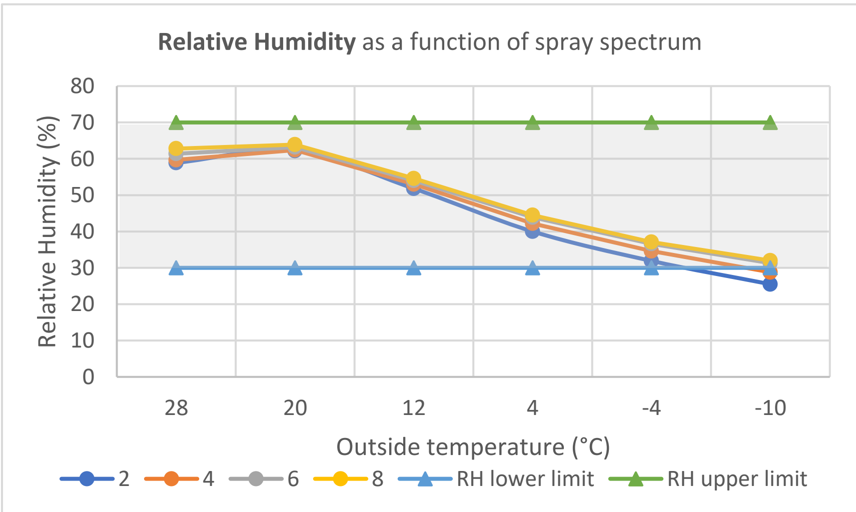


Figure 49: Graph showing Relative Humidity as a function of spray spectrum at different outside temperatures.

Based on the above factors, **spectrum 8 has been selected for all the design options** since it has the most desirable output.

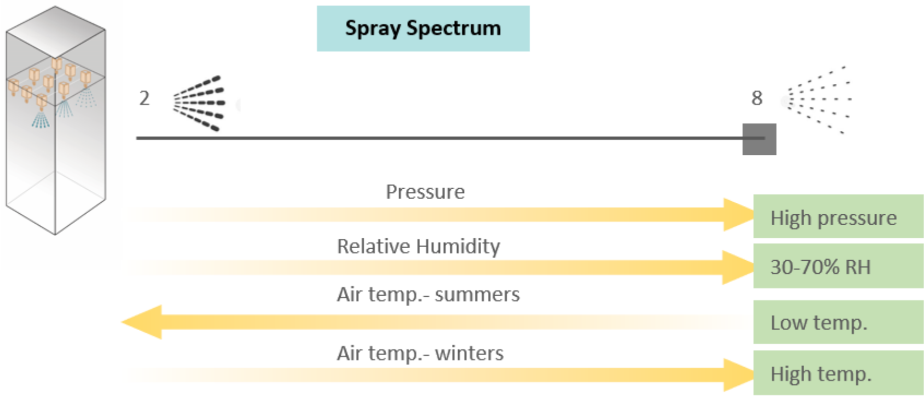


Figure 50: Effect of spray spectrum.

c. Air velocity

The air velocity in the Climate Cascade affects the pressure generated at the base of the Cascade and the shaft size. Relative humidity of the air is independent of the air velocity. The air temperature coming out of the CC is indirectly related to the Climate Cascade such that air velocity affects the size of the cascade which in turn affects the air temperature due to the heat transfer through the walls of the Climate Cascade. The effect on shaft size and the generated pressure is described below.

Effect on shaft size

The shaft size significantly increases on decreasing the air velocity. This may not be a major concern for design option 01,02 and 03 but certainly plays a role for design option 04 and 05 since the bigger Climate Cascade size would block the view and daylight for the apartment in front of which the CC is placed.

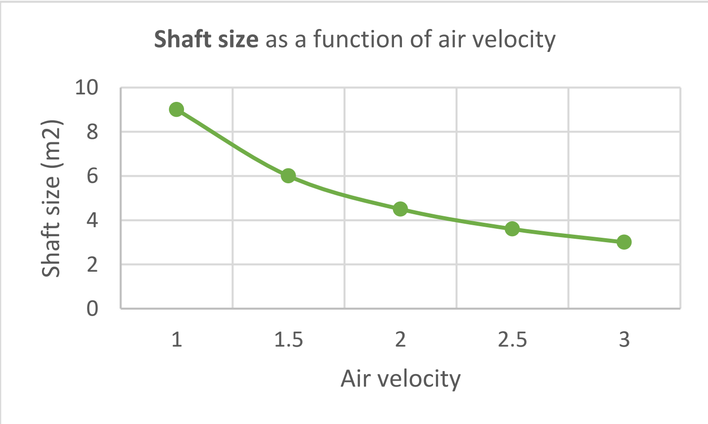


Figure 51: Graph showing shaft size as a function of air velocity.

Effect on pressure generated

The pressure generated increases with the increase in air velocity. At an air velocity of 3 m/s, the pressure generated is always higher than the pressure loss of 150 Pa and thus fits the design criteria.

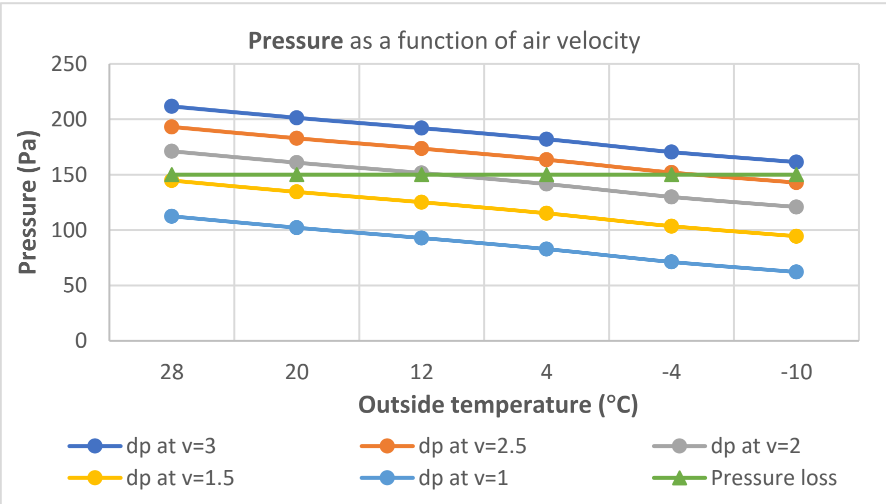


Figure 52: Graph showing pressure generated as a function of air velocity at different outside temperatures.

Based on the above factors, **the final air velocity used in calculations for all the design options is 3 m/s or 3.5 m/s** since it results in desirable pressure values and the shaft size is less.

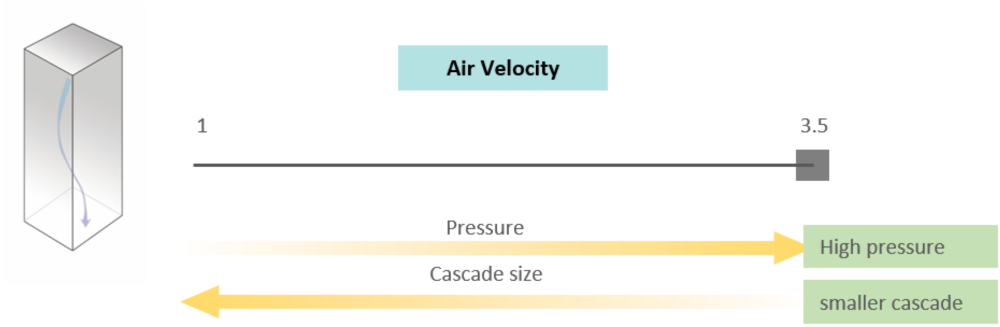


Figure 53: Effect of air velocity.

According to this analysis, the design options shall use **4-10 number of nozzles, spray spectrum number 8 and an air velocity of 3- 3.5 m/s.** However, it is crucial to establish the relation between fan, pump and additional heating energy in order to find out what aspect contributes most in the total energy consumption. And as a result, establish the most important determining parameter among pressure, air temperature or amount of water.

7.2.3 Relation between fan, pump and additional heating energy

Two case scenarios have been analysed in order to find the relation between fan, pump and additional heating energy to derive the biggest contributor to total energy consumption in the Climate Cascade. The input parameters are ventilation amount, needed pressure, number of nozzles and the desired air supply temperature. The output provides results for annual fan, pump and heating energy consumption by Climate Cascade.

Case 1:

Input parameters	
Ventilation amount	39,600 m^3/h
Needed pressure	150 Pa
No. of nozzles	7-10
Desired supply air temp.	18 annually

Output	
Fan energy	0
Pump energy (MWh)	36.7
Heating energy (MWh)	575.5

Table 7: Input parameters and the output for case 1.

The energy calculations are performed using the following equations that were derived from Bronsema (2013) and ABT BV:

$$\text{Fan energy} = \frac{Ventilation\ amount\left(\frac{m3}{s}\right) * (pressure\ needed - pressure\ calculated)(Pa)}{Fan\ efficiency * 1000}$$

$$\text{Pump energy} = \frac{Density\ of\ water\ \left(\frac{kg}{m3}\right) * acceleration\ due\ to\ gravity\ \left(\frac{m}{s2}\right) * Pump\ head(m) * water\ mass\left(\frac{m3}{s}\right)}{Pump\ efficiency * 1000}$$

$$\text{Heating energy} = Ventilation\ amount\ \left(\frac{m3}{s}\right) * air\ density\ \left(\frac{kg}{m3}\right) * (desired\ air\ temperature - achieved\ air\ temperature)(°C) * Specific\ heat\ capacity\ of\ air\ \left(\frac{kJ}{kg°C}\right)$$

Using the above formulas, the energy calculations are performed. The graph below show that the generated pressure is always higher than the needed pressure value of 150 Pa, and therefore a fan is never needed in this case and hence resulting in zero fan energy consumption.

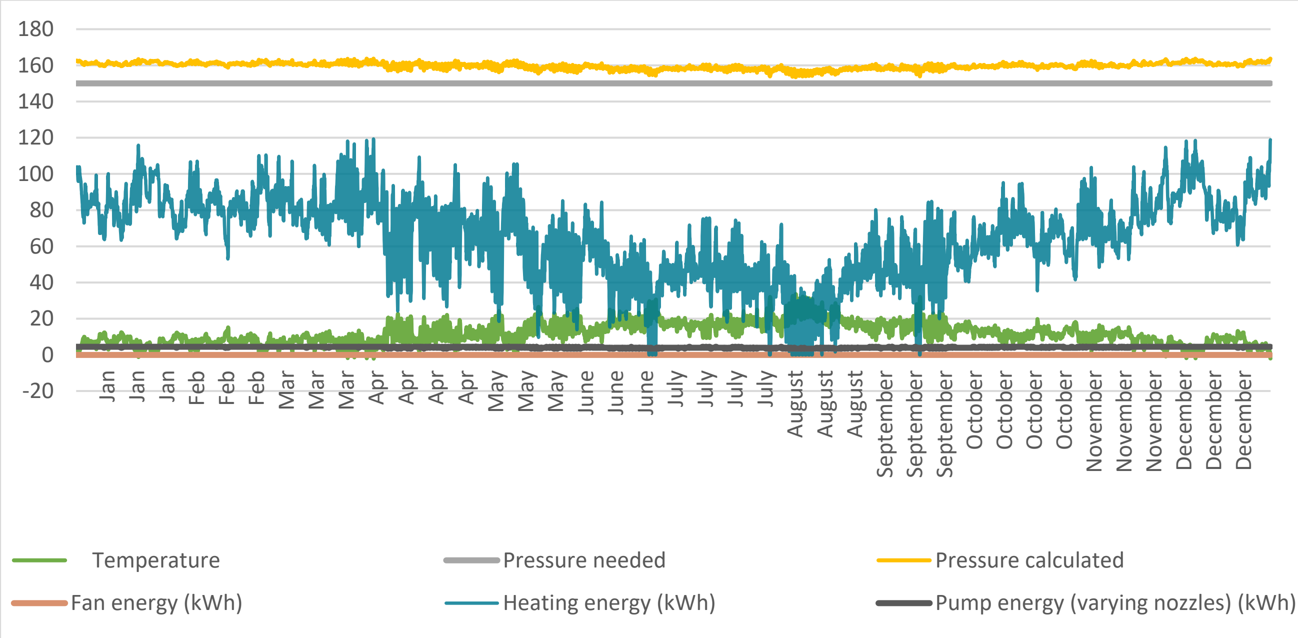


Figure 54: Graph showing results for case1.

From the results we can see that the highest energy consumption is due to heating energy followed by pump energy. Fan energy hardly has any contribution in the total energy consumption. The next step is thus to reduce heating energy for which the system can be designed for **variable air volume** needed depending on the occupancy profile. For a residential function, people usually go for work during day time resulting in lesser need of ventilation. The maximum occupancy is achieved during night resulting in more ventilation need. In accordance with the ventilation amount, the needed pressure also varies on a daily basis. During unprecedented situations such as a pandemic when the residents are obliged to stay at home, the ventilation profile shall not be followed. Hence the system can be adapted based on the situation and the no. of occupants present in the apartments to reduce the energy consumption of the EWF system.

Time	00:00	03:00	06:00	09:00	12:00	15:00	18:00	21:00	00:00
Occupancy	90%	90%	90%	30%	30%	30%	60%	80%	90%
Needed ventilation (m3/h)	35, 640	35,640	35,640	11,880	11,880	11,880	23,760	31,680	35,640

Table 8: Occupancy profile

The above ventilation profile is incorporated in case 2 to check the effect on fan, pump and heating energy.

Case 2:

Input parameters	
Ventilation amount	varies
Needed pressure	varies
No. of nozzles	7-10
Desired supply air temp.	18 annually

Output	
Fan energy	0
Pump energy (MWh)	36.7
Heating energy (MWh)	373.8

Table 9: Input parameters and the output for case 2.

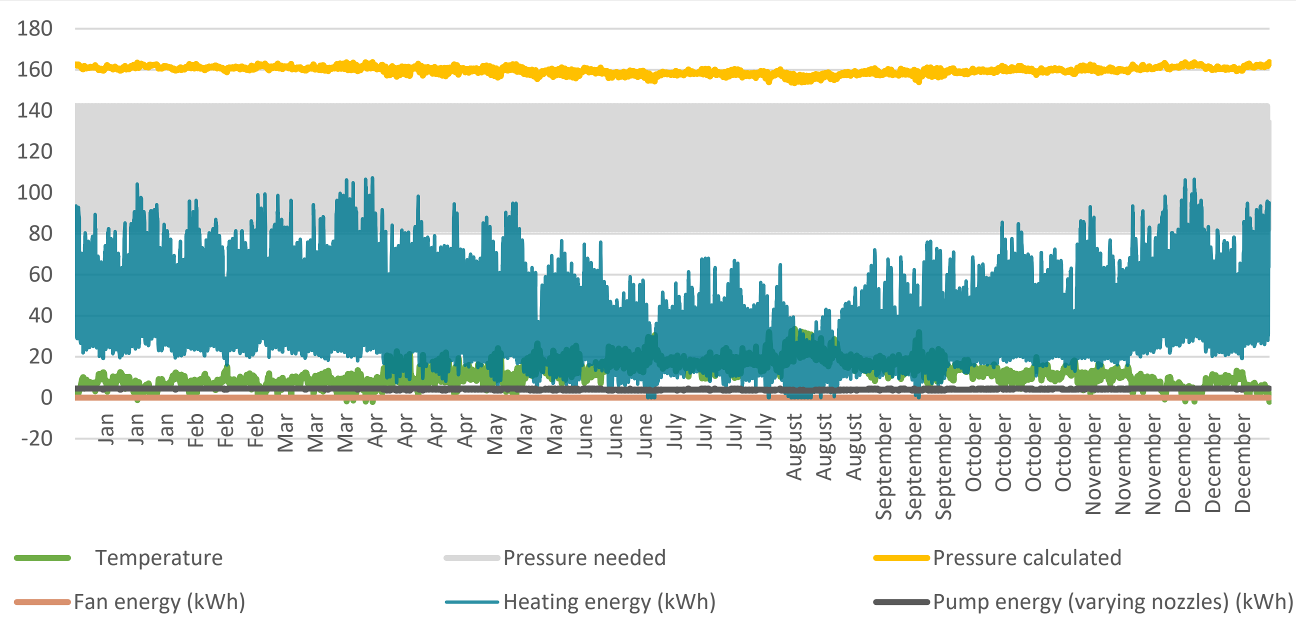


Figure 55: Graph showing results for case 2.

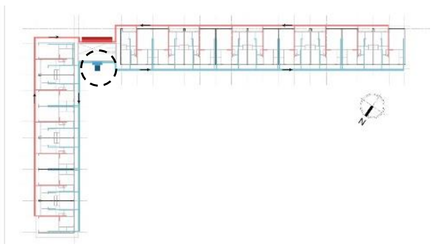
Th results for the case 2 show that the heating energy has significantly reduced as compared to case 1 since the heating system needs less energy to heat less air. The amount of air varies as per the occupancy profile and so does the pressure loss and the heating energy. It can also be noticed from the graph that the heating energy is also consumed during the summer months when the outside temperature is 20 °C and above. This is because of the fact that the air gets cooled to a temperature of 13-15 °C after passing through the water sprinklers during the summers thus resulting in heating energy consumption to again raise the temperature to 18 °C. This leads to unnecessary increase in heating energy consumption. In order to solve this, the number of water nozzles can be reduced to reach the air temperature of 17-18°C instead of 13-15°C when the outside temperature is higher than 20°C. However, on reducing the number of nozzles, the pressure achieved at the base will also decrease thus resulting in some amount of fan energy consumption.

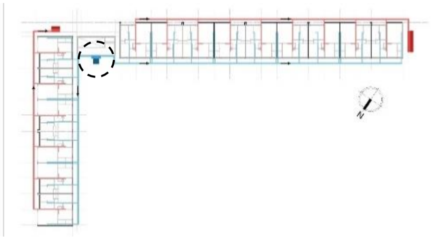
As a result of establishing the relationship between fan, pump and additional heating energy, it is derived that the maximum contribution in energy consumption is through the additional heating energy. It is thus a priority to achieve the air temperature coming out of Climate cascade as close to 18 degrees as possible by changing the variable input parameters.

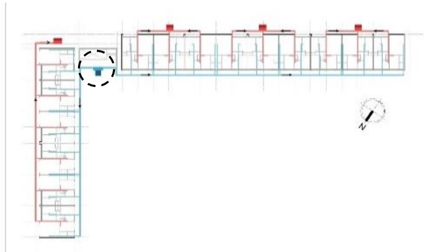
7.2.4 Design options comparison

Using the input parameters established in the previous sections, the 5 design options were then analysed for their performance and compared based on the evaluation parameters defined earlier. Design options 01,02 and 03 have one climate cascade placed next to the core and options 04 and 05 have two climate cascades placed in the middle of both the blocks. Keeping the air velocity and spray spectrum same for all the design options, the major difference is in the placement of the Climate Cascade element and the height and the number of the water nozzles in the cascade since this affects the air temperature and the pressure generated at the base of the Climate Cascade.

Design option 1,2 and 3







Design option 1: Sprinklers (nozzles) shifted at lower level (36m)

- Cascade height- 54m
- Pump height- 36m
- Ventilation capacity- 39,600 m3/h max. following occupancy profile

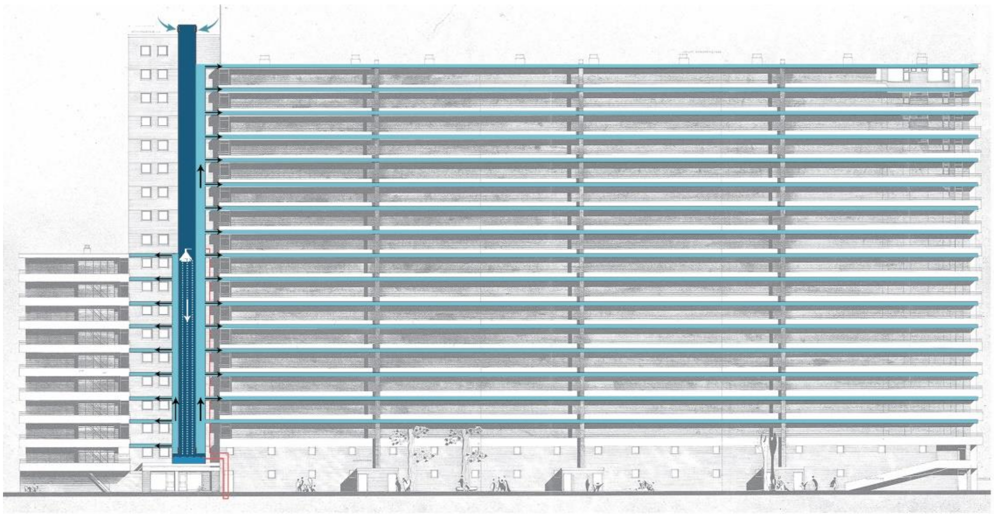


Figure 56: Elevation showing Climate cascade design for design option 1.

Design option 2: Typical climate cascade design

- Cascade height- 54m
- Pump height- 54m
- Ventilation capacity- 39,600 m3/h max. following occupancy profile

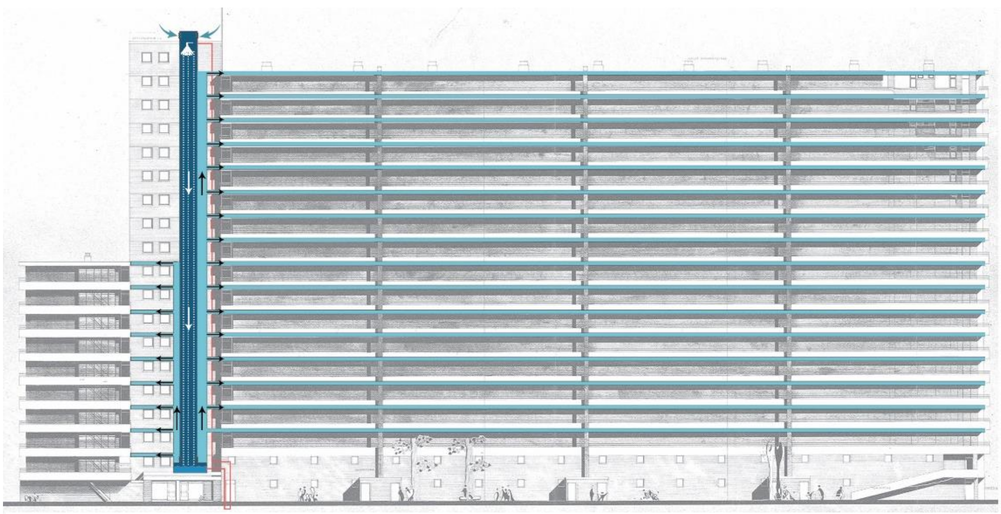


Figure 57: Elevation showing Climate cascade design for design option 2.

Design option 3: Division into two shafts

Top block-

- Cascade height- 27m
- Pump height- 27m
- Ventilation capacity- 14400 m3/h max. following occupancy profile.

Lower block-

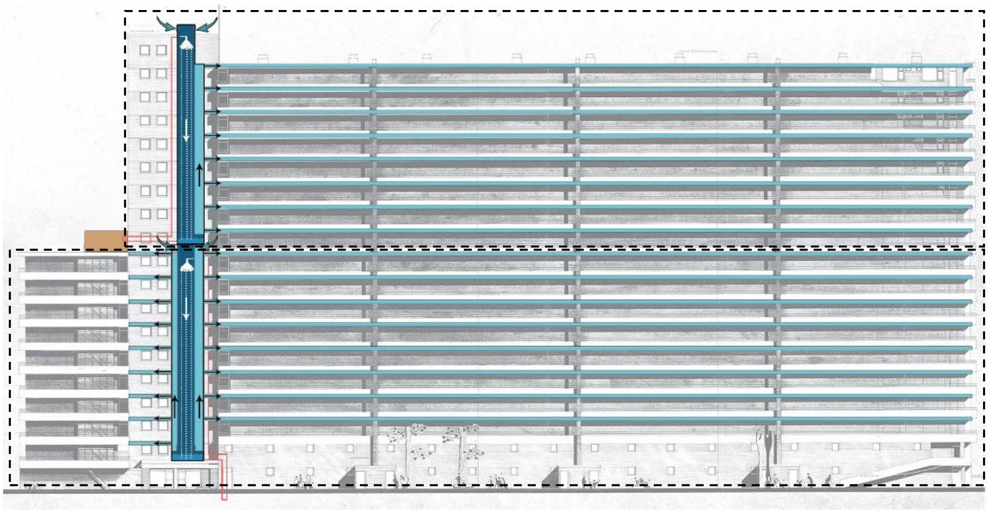
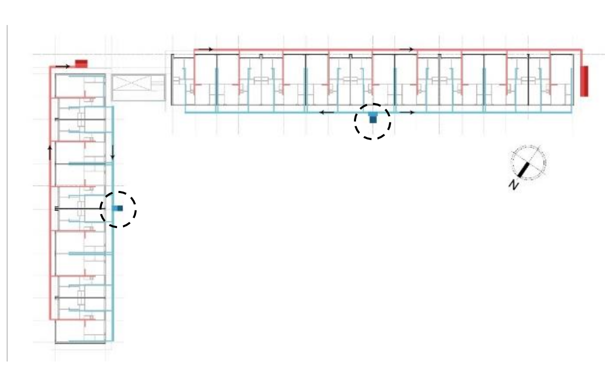
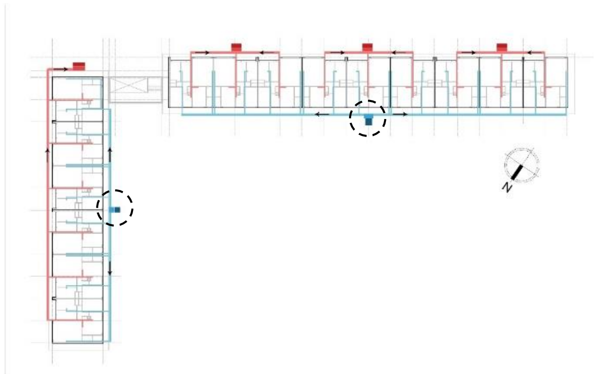


Figure 58: Elevation showing Climate cascade design for design option 3.

- Cascade height- 27m
- Pump height- 27m
- Ventilation capacity- 25200 m3/h max. following occupancy profile.

Design options 4 and 5





Taller block-

- Cascade height- 54m
- Pump height- 27m
- Ventilation capacity- 28,800 m3/h max. following occupancy profile.

Shorter block-

Figure 59:Elevation showing Climate cascade design for design option 4 and 5.

- Cascade height- 27m
- Pump height- 27m
- Ventilation capacity- 10,800 m3/h max. following occupancy profile.

Results

The single and double cascade design options were then compared as shown in the table 10 based on the evaluation parameters- Air temperature, pressure, relative humidity and total energy consumption.

Number of nozzles and pump energy

Among the single cascade design options 01 and 02, the major difference is the height of the nozzles and therefore the number of nozzles used are different throughout the year. For the design option 01 the nozzles are placed at a lower level and therefore the pressure achieved at the base will be very less. Therefore constant 10 nozzles are needed annually to achieve sufficient pressure. On the other hand, for the design option 02, the nozzles are placed at the top of the cascade and thus the no. of nozzles used are lesser during the summer months to avoid unnecessary overpressure at the base and higher during the winter months. The no of nozzles is varied from 7-10. Comparing both of these options, the pump energy for the design option 01 is less since the pump head is less even through it uses more nozzles annually.

For the design option 03, the cascade is divided into two with the top cascade catering less ventilation amount than the bottom cascade. The pump head is same for both the cascades since the cascades have the same height. As a result, the top cascade needs lesser no. of nozzles than the bottom cascade due to lesser ventilation amount and thus lesser shaft size. Moreover the no. of nozzles used in summer months is less as compared to winter months with 5 nozzles in summer and 7 nozzles in winter. However, for the bottom cascade, the amount of ventilation is more thus resulting in constant 10 nozzles annually to achieve sufficient pressure at the base. The total pump energy combining the top and the bottom cascade is similar to that of case 02.

For the double cascade options 04 and 05, the shorter block has lesser ventilation amount thus needing constant 5 nozzles. However, the taller block with more ventilation amount needs 7-10 nozzles. The pump energy is similar to that of design options 02 and 03.

Air temperature and heating energy consumption

On varying the number and the height of the nozzles in the design options, the air temperature achieved at the base slightly differs and as a result the heating energy consumption varies for the design options.

Among the single cascade design options 01 and 02, the air temperature achieved is similar at all the outside temperatures. As a result, the heating energy is also similar.

For the design option 03, the air temperature achieved is higher for the winter months as compared to the design options 01 and 02. As a result, the additional heating energy consumption is lesser as compared to the first two options.

For the double cascade options 04 and 05, the air temperature achieved in the CC follows the similar trend as design option 03. Thus, the additional heating energy is similar to that of design option 03.

The results show that more cascades have a comparatively lesser heating energy consumption than single cascade due to higher air temperature achieved during the winter months.

Pressure achieved and fan energy consumption

On varying the number and the height of the nozzles in the design options, the pressure achieved at the base slightly differs and as a result the fan energy consumption varies for the design options.

Among the single cascade options 01 and 02, the pressure achieved at the base is lesser for design option 01 as compared to the design option 02. Since option 01 has lesser pump head, the hydraulic pressure generated is less even through more no. of nozzles are used for this case. As a result, the pump energy for design option 02 is extremely less as compared to option 01.

For the design option 03, the pressure generated for the top cascade is almost always higher than the pressure loss of 150 Pa. However, for the bottom cascade, the pressure generated is sometimes lesser than the pressure loss. Combining the pump energy for the top and the bottom cascade, the total pump energy for option 03 is higher than the design option 02 and lesser than the design option 01.

Among the double cascade options 04 and 05, the pressure generated at the base follows similar trend as design option 03 and thus the total pump energy for this option is also similar to that of the design option 03.

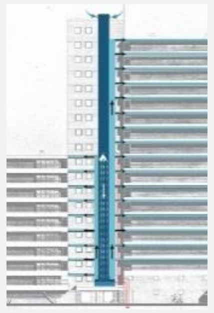
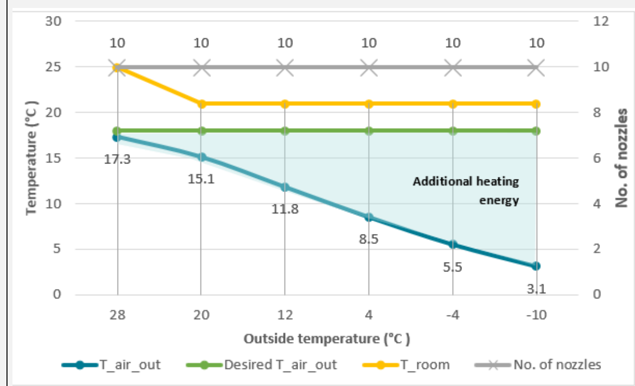
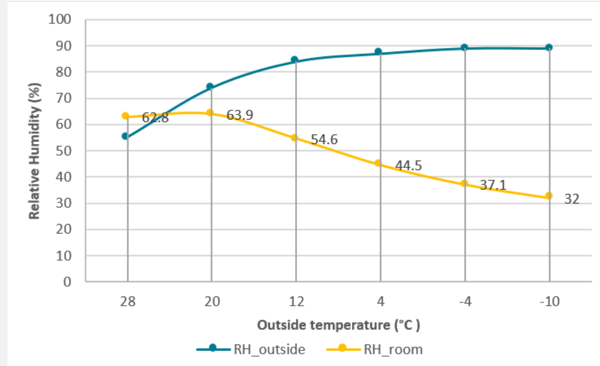
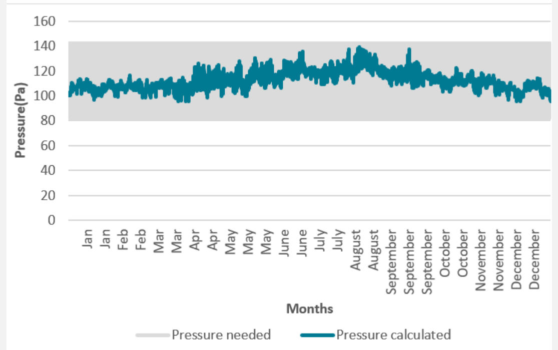
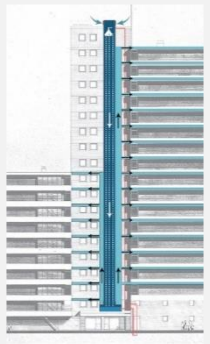
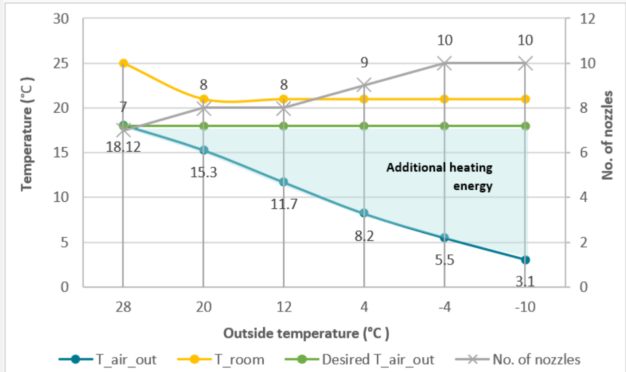
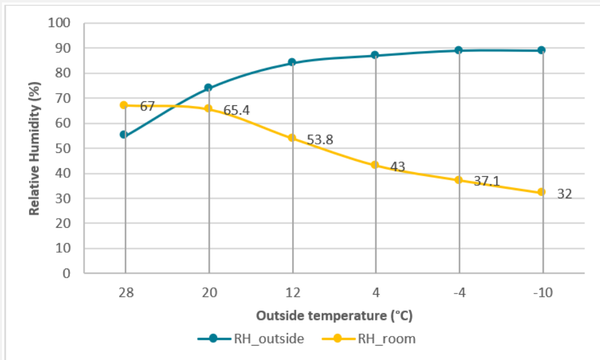
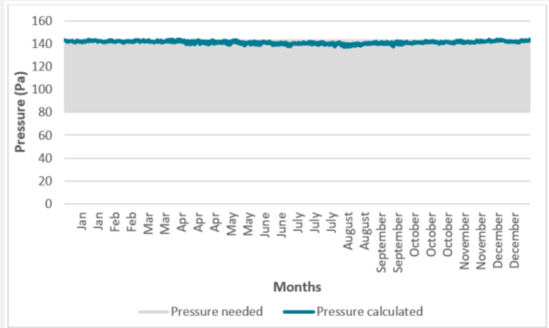
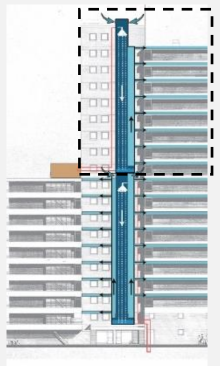
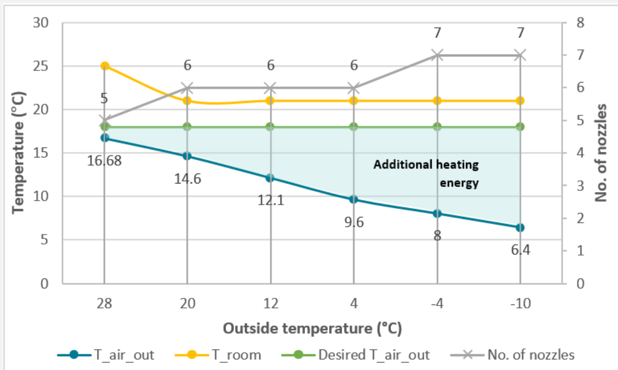
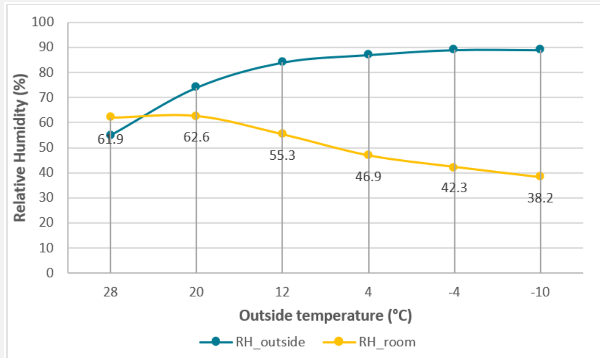
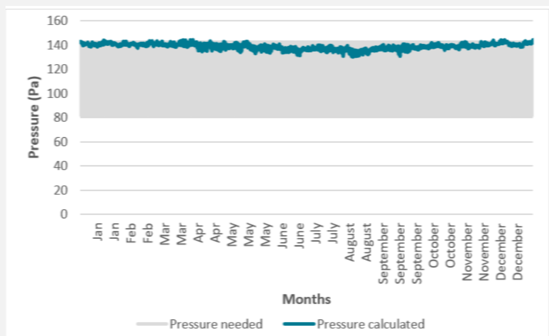
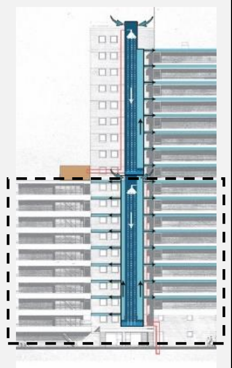
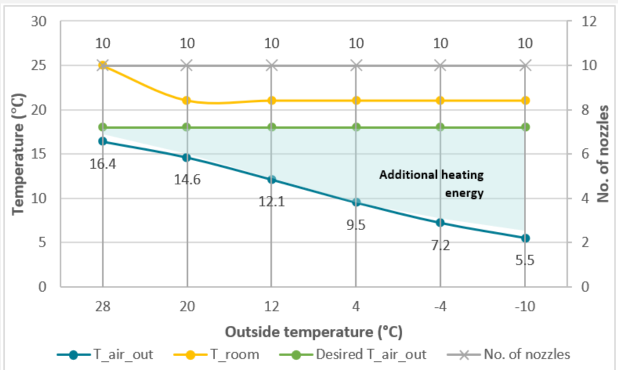
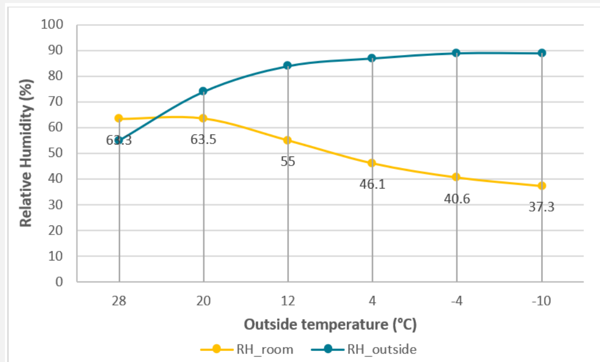
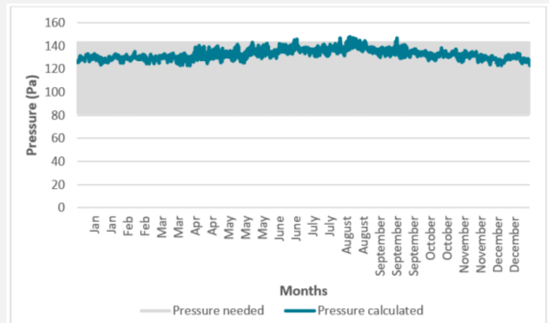
Relative Humidity

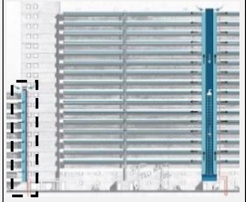
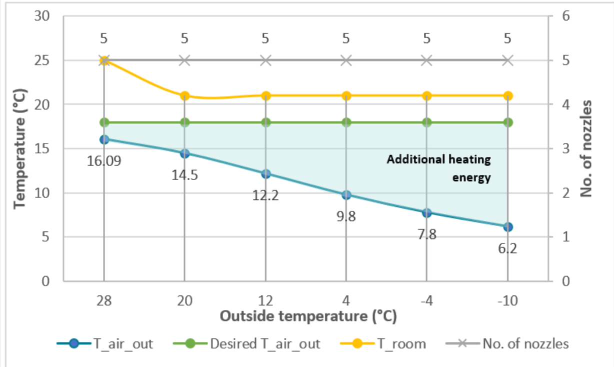
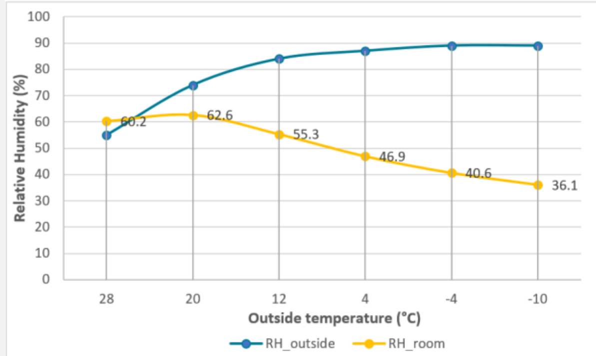
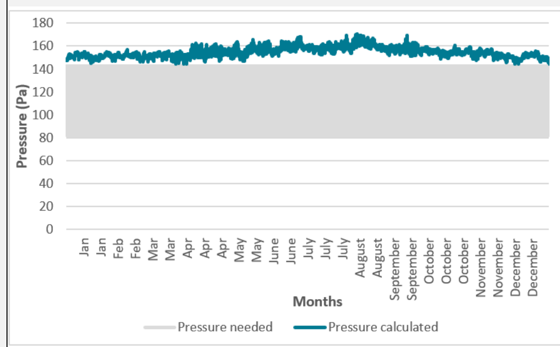
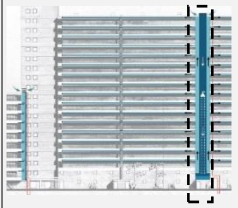
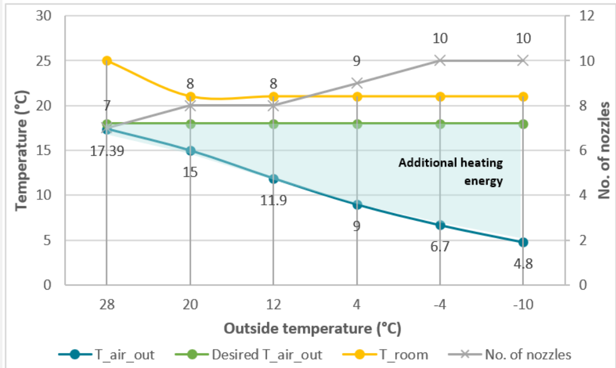
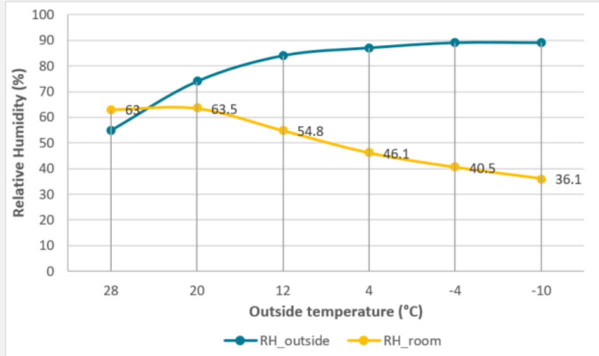
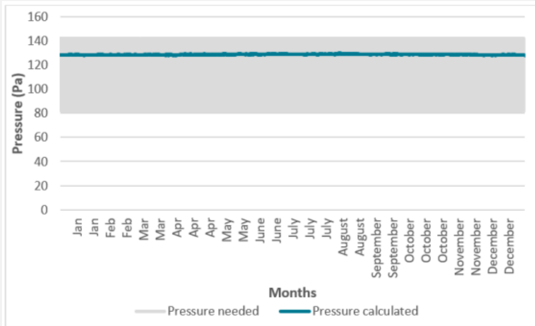
The relativity humidity in the rooms is always withing the desired range of 30-70% for all the design options.

Total energy consumption

Among the design options 01,02 and 03, it is found out that design option 03 with two shafts has the best performance since it has lowest total energy consumption. However, this scenario would need twice the number of installations (2 pump motors, 2 water tanks, etc.) as well as it is slightly impractical in terms of its implementation and feasibility. One reason for this is that the air for the bottom cascade would not get clear access to enter the climate cascade which might result in lesser positive pressure at the inlet of the bottom cascade. Secondly, the calculations performed for the top cascade have the pump head as 27 metres, same height as that of the top Cascade. This would require the placement of the water tank at the roof of the shorter block which results in a complex installation. This option shall thus be eliminated. The second-best option in terms of its performance is the design option 01 with sprinklers shifted at lower level. Although this scenario does not always sufficiently generate the pressure of 150 Pa thus resulting in fan energy, it reduces the pump energy considerably when compared to design option 02. Moreover, fan energy only contributes to 1% of total energy consumption and thus is not a priority. On comparing design option 01 (single cascade) with design options 04 and 05 (double cascades), it is found out that the total energy consumption is lesser for the design options 04 and 05. However, this difference is not large. Thus, **design options 1, 4 and 5 are found out as the most suitable options and the final choice is made after solar chimney analysis and qualitative comparison** which is done in the next sections.

Table 10: Comparative table for Climate cascade analysis

Design option		Visual	Shaft size (m)	Air velocity (m/s)	Evaluation parameters: Air temperature	Relative humidity	Pressure	Water/ air ratio (kg/kg)	Fan (kWh)	Pump (kWh)	Heating (kWh)	Total (kWh)	Total (kWh/ m2)
1 CC, 1 SC	Single- sprinkler in middle		1.7 x 1.7	3.5				0.53	1838	28,924	472,397	503,160	25.9
1 CC, 2 SC	Single- sprinkler at top		1.7 x 1.7	3.5				7 nozzles- 0.37, 10 nozzles- 0.53	43.4	36,724	471,948	508,720	25.7
1 CC, 4 SC	Top block		1.07 x 1.07	3.5				5 nozzles- 0.72, 7 nozzles- 6.4	393.6	34,508	445,741	480,642	24.2
	Lower block		1.4 x 1.4	3.5				0.83					

2 CC, 2 SC	Double		0.9 x 0.9	3.5				0.97	511.4	35,329	448,509	484,350	24.5
2 CC, 4 SC			1.5 x 1.5	3.5				7 nozzles- 0.5, 10 nozzles- 0.72					

7.3 Solar Chimney

Followed by the Climate Cascade analysis, the design options are then evaluated in the Solar Chimney model to calculate the energy performance and compare the results in order to find the most favourable design option. This section describes the parameters considered for calculations and the results based on the comparison of these design options.

7.3.1 Design conditions

In order to proceed with the analysis of the design options, firstly it is essential to establish the design conditions describing constants, variables and evaluation parameters.

Design constants

For the design constants, the total pressure loss for the exhaust system is estimated as 50 Pa which is decided based on the discussion with Dr. Ben Bronsema. This supply pressure loss of maximum 50 Pa is irrespective of the number of Solar Chimneys. The exhaust air temperature from the apartments to the Solar Chimney is taken as 25°C in summer months and 21°C in the winter months. The exhaust temperature values are decided based on the comfort temperature set in the room. The 18°C air supplied by Climate cascade gets warmed up due to space heating in the rooms before entering the Solar Chimney. The ventilation capacity for the building is 39,600 m3/h as calculated in table 4.

Solar Chimney design constants			
Exhaust system maximum pressure loss (Pa)	**Exhaust air temperature from room to SC (°C)**	**Ventilation capacity (m^3/h)**	**Cascade height (m)**
50	Summers- 25 Winters- 21	39,600	50

Table 11: Design constants.

Design variables

The design variables include the air velocity in the chimney and the depth of the chimney. These variables affect the thermal draft generated in the chimney, pressure loss of the exhaust system, air temperature achieved at the top of the chimney and the depth of the chimney. As a result, the fan energy consumption and the temperature of the recovered heat is dependent on the design variables. Hence the design variables should be carefully selected to achieve the maximum energy performance. The graphical representation of the design variables is shown in table 12.

Evaluation parameters

Based on the input provided for design constants and the design variables, the excel model provides the output for each design option. The design option is selected based on the following evaluation parameters:

- The thermal draft generated in SC should be higher than the pressure loss of exhaust system (50 Pa)
- Higher temperature of air coming out of Solar chimney to recover heat efficiently. This recovered heat shall be used to pre-heat the incoming air at the top of the Climate Cascade during winter months.

- Low fan energy consumption.

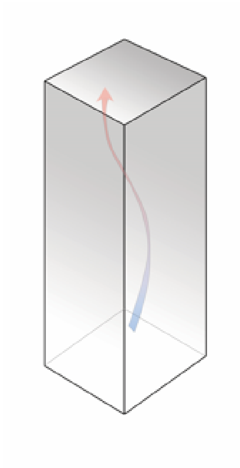
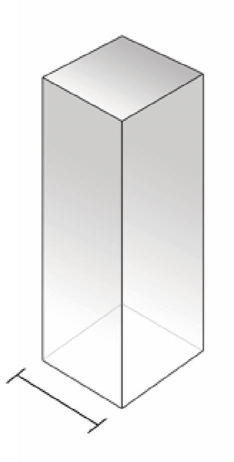
		
Variables	Air Velocity	Chimney Depth
Output	Thermal draft Pressure loss T_out width	Thermal draft Pressure loss

Table 12: Design variables.

7.3.2 Effect of design variables

Before finalizing the design variables, it is essential to understand its effect on the output parameters. The effect of changing the air velocity and the chimney depth is described below.

a. Air velocity

The air velocity in the Solar Chimney affects the thermal draft generated, pressure loss, air temperature coming out of SC and the width of the chimney. The effect of changing air velocity has been studied and described below.

Effect on chimney width

On having a lower air velocity, and considering a depth of 0.65m, the width of the chimney is extremely high. For design options 1,2 and 4 with one and two chimneys, this width is not feasible since only 13 m space is available for placing the chimney. Having a lower width is better in order to occupy lesser area of the façade.

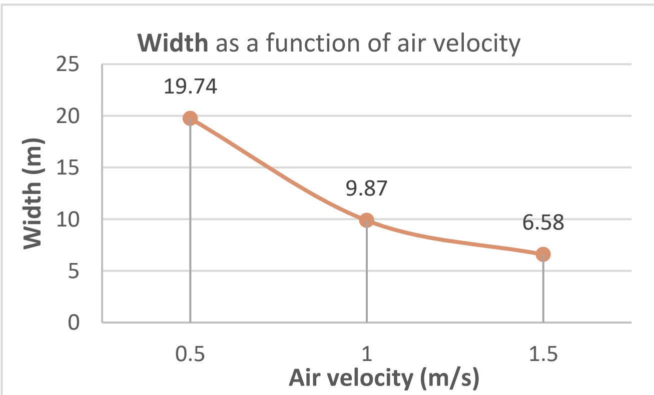


Figure 60: Chimney width as a function of air velocity.

Effect on thermal draft and pressure loss

From figure 61, it can be noted that the thermal draft is higher for lower velocity but as a drawback, the pressure loss increases for lower velocity. For velocity of 0.5 m/s the thermal draft is always lower than the pressure loss when the outside temperature is higher than 2 °C. For the velocity of 1.5 m/s, the performance improves since the thermal draft is lower than pressure loss only when outside temperature is higher than 17 °C. It is thus beneficial to use a higher air velocity in order to reduce the pressure loss of the system.

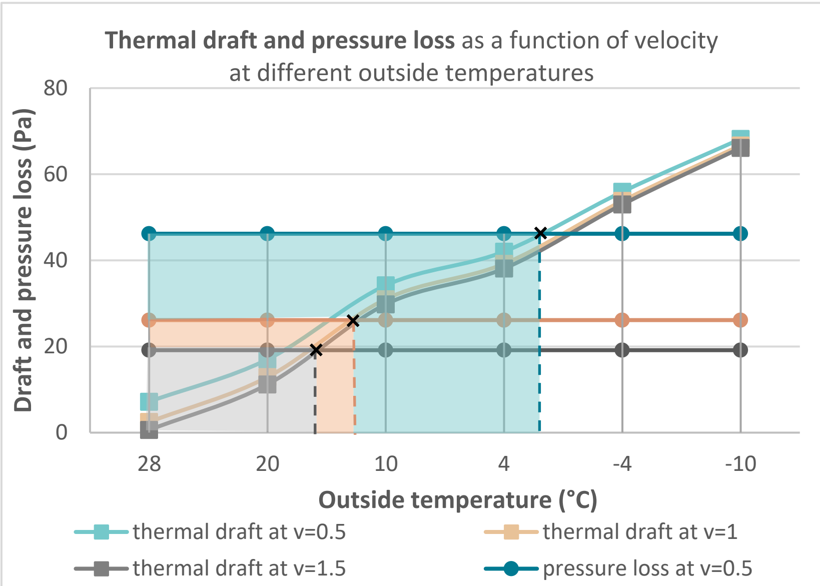


Figure 61: Thermal draft and pressure loss as a function of velocity at different outside temperatures.

Effect on air temperature coming out of Chimney

On reducing the air velocity in the chimney, the air temperature at the top of chimney is higher since the air gets more time to heat up in the chimney.

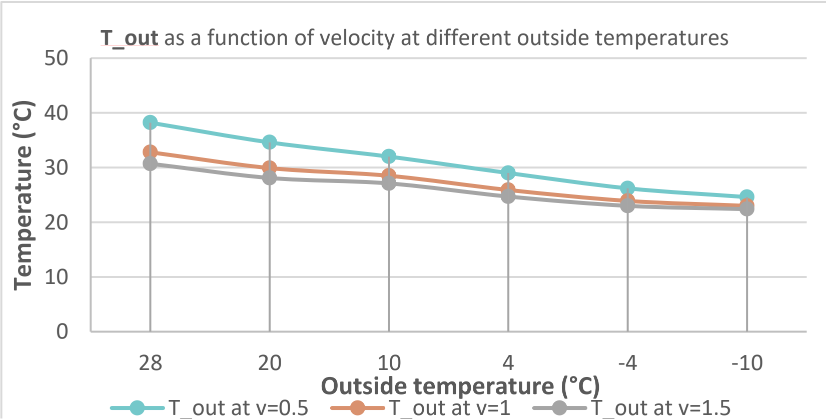


Figure 62: T_out as a function of velocity at different outside temperatures.

As a result, this would result in higher heat recovery value. Moreover, recovered heat of higher temperature is more useful since it improves the COP of heat pumps. Hence, in terms of T_out, using a lower velocity is beneficial. As a result of this analysis, it is found out that the lower velocity has higher thermal draft, higher pressure loss, higher T_out and also big chimney size. **The air velocity of 0.5 m/s is eliminated since it results in huge chimney width. The air velocities of 1 m/s and 1.5 m/s can be explored in the design options to find out the best balance between all the parameters.**

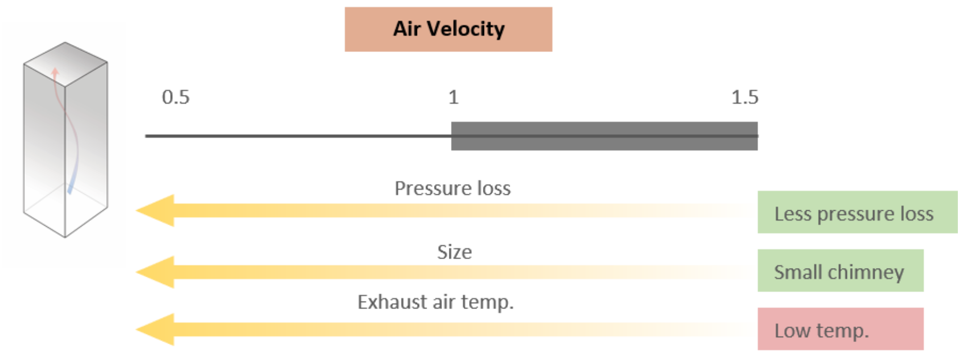


Figure 63: Effect of air velocity

b. Chimney depth

Effect on thermal draft and pressure loss

Chimney depth does not have a drastic impact on the thermal draft and pressure loss when the air velocity is the same. However, it can be noted that the pressure loss is slightly less when the depth is 1 m. Moreover, the chimney would occupy lesser façade area when the depth is 1 m.

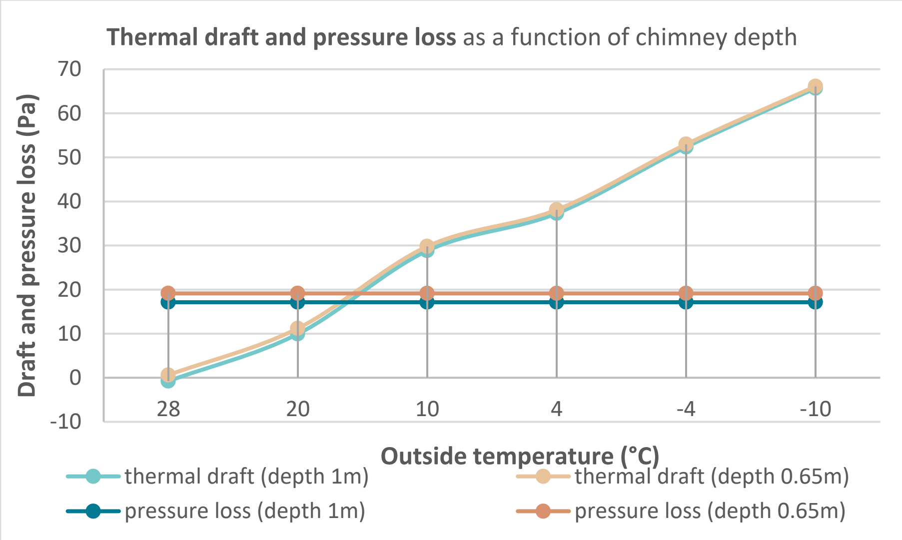


Figure 64: Thermal draft and pressure loss as a function of chimney depth and the air velocity 1.5m/s.

Effect on air temperature coming out of Chimney

The depth of 0.65m achieves higher air temperatures at the top of the chimney thus resulting in higher heat recovery values. The depth of 0.65m is thus beneficial.

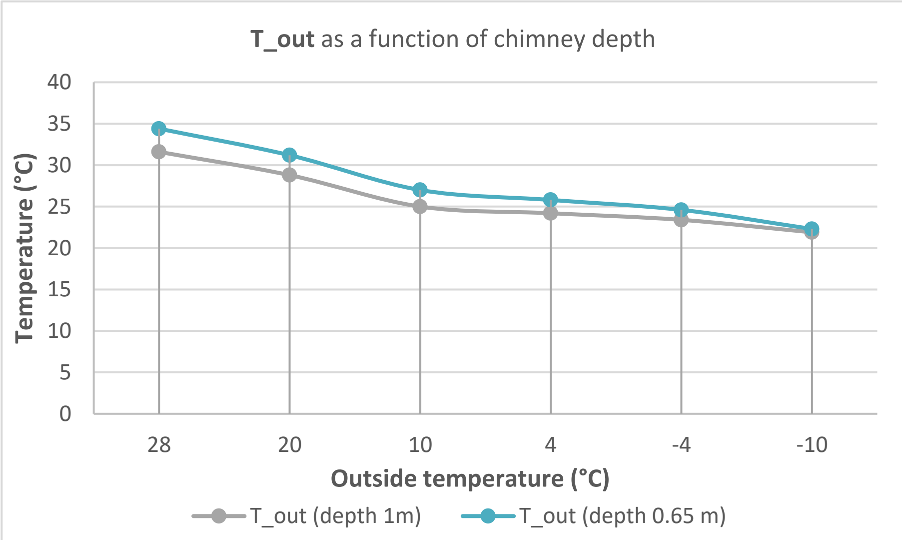


Figure 65: T_out as a function of chimney depth at different outside temperatures at and the air velocity of 1.5m/s.

Based on the above factors, **the depth of the chimney can be taken as either 0.65m or 1m since both have pros and cons**.

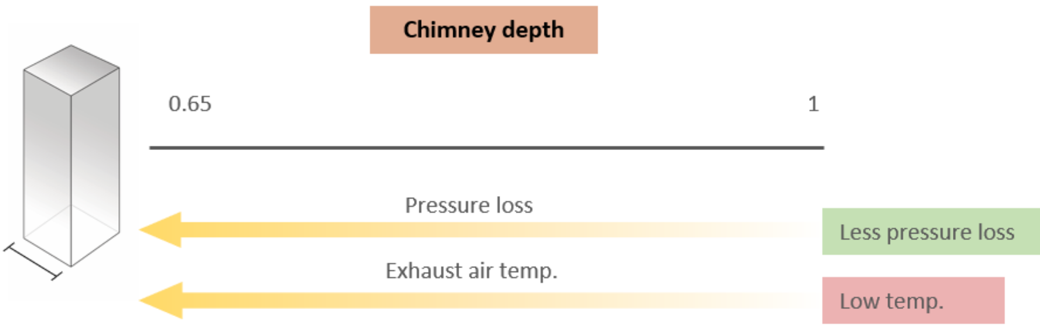


Figure 66: Effect of chimney depth.

According to this analysis, **the design options can have a combination of 1 m/s air velocity with 1m depth or else 1.5 m/s air velocity with 0.65m depth**. The design options with single and double chimneys follow the first combination whereas the design options with quadruple chimneys follow the second combination.

7.3.3 Design options comparison

The five design options are then compared as shown in the table below based on the evaluation parameters- Fan energy and recovered heat energy. The recovered heat energy is calculated using the formula:

Recovered heat = $1.08 * airflow\ (cfm) * (t2 - t1) * efficieny$

Where t2 is the air temperature of the exhaust air before the heat recovery unit (°F)

And t1 is the air temperature of the outside air before the heat recovery unit (°F).

The value is obtained in British Thermal Unit/ hour which is then converted into kWh. The recovered heat value is only calculated to check the potential of the design options for adding a heat recovery system. The temperature of the heat is more important than the amount of the heat which shall be calculated in the next section.

Thermal draft, pressure loss and Fan energy

The air velocity used for the design options 01,02 and 04 is 1 m/s since the chimney is not placed in front of the apartments and thus the size of the chimney can be large. However, for the design option 03 and 05, the chimneys for the taller block use the air velocity of 1.5 m/s to reduce the chimney size since the chimneys are placed in front of the apartments. As a result of these inputs, the design options 01, 02 and 04 with lesser air velocity have higher pressure loss as compared to the design options 03 and 05. However, at the same time, the thermal draft is higher for the design options with 1 m/s air velocity. As a result, the total fan energy consumption does not have a drastic difference.

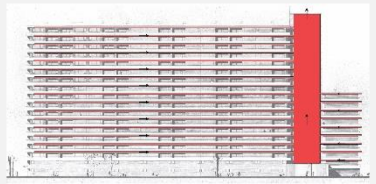
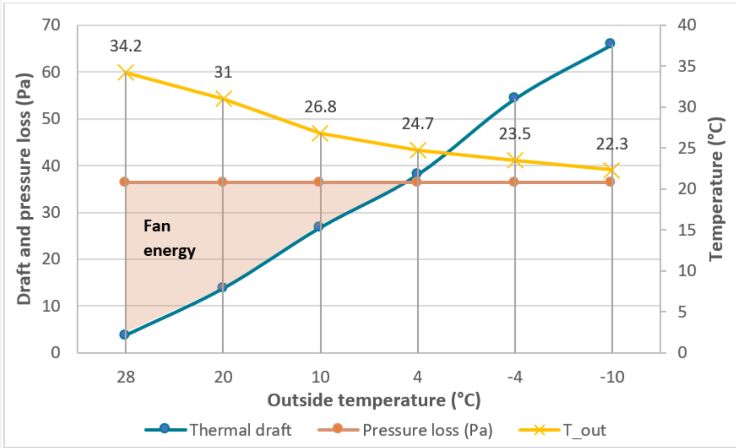
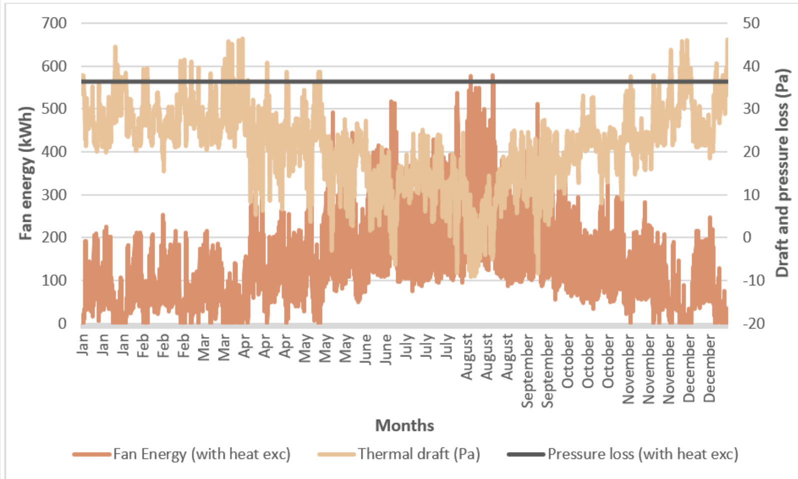
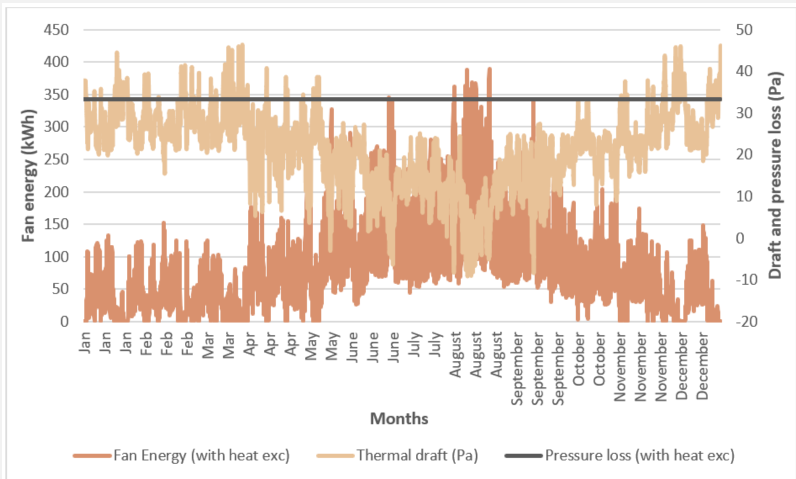
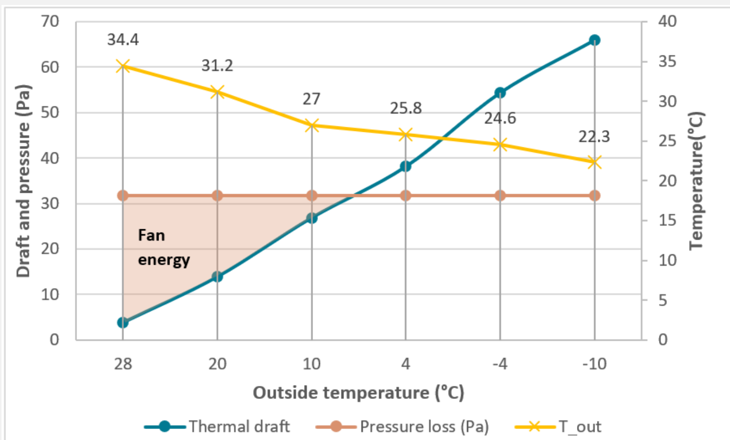
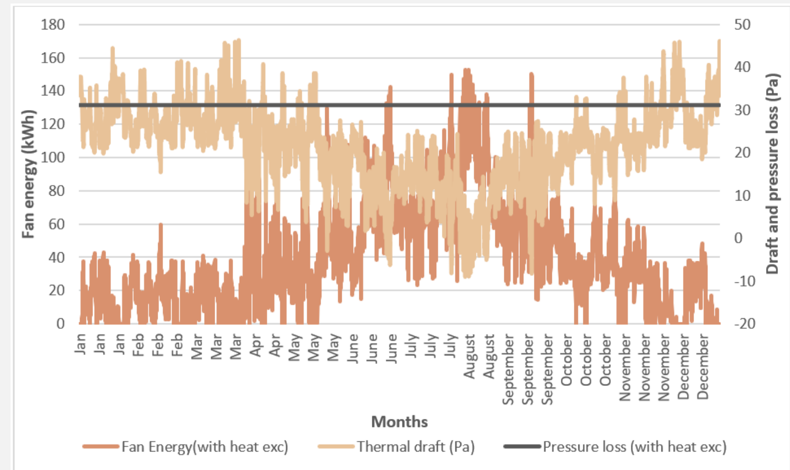
Recovered heat

Since the air temperature values at the top of the chimney are similar for all the cases, the recovered heat values calculated are also same for all the design options.

Conclusion

Based on the comparative analysis, it is found out that there is no significant difference in the energy output of all the five design options. It is to be noted that since the input parameters are decided such that the design option can have a combination of 1 m/s air velocity with 1 m depth or 1.5 m/s air velocity with 0.65 m depth, the difference in the energy consumption is not much. However, if a different combination is used, the results still do not show a drastic difference for the design options. Hence, for all the design options, the values of air velocity and the chimney depth is decided based on the desired length of the chimney since it is one of the important parameters. The final design decision shall be made based on the qualitative analysis described in the next section.

Table 13: Comparative table for Solar Chimney analysis.

Design option			Visual	Shaft size (m)	Air velocity (m/s)	Evaluation parameters: Thermal draft, pressure loss and T_out	Fan energy annual graph	Fan energy (kWh)	Recovered heat energy (kWh)	Recovered heat energy (kWh/m2)
Option 1	**1 CC, 1 SC**	Single		1 x 11	1		 * includes both taller and shorter block due to common chimney	**1280**	**579,730**	29.3
Option 2	**1 CC, 2 SC**	Double		Taller block= 1 x 8 Shorter block= 1 x 3	1		 • only for taller block	Short block= 280 Taller block= 750 Total= **1030**	Short block= 154,510 Taller block= 421,620 Total= **576,130**	29
Option 4	**2 CC, 2 SC**									
Option 3	**1CC, 4 SC**	Quadruple		Taller block= 0.65 x 2.73 Shorter block= 1 x 3	Taller block= 1.5 Shorter block= 1		 • only for taller block	Short block= 280 Taller block= 1080 Total= **1360**	Short block= 154,510 Taller block= 422,164 Total= **576,674**	29.12
Option 5	**2 CC, 4 SC**									

7.4 Qualitative comparison

In the previous sections, the climate cascade and solar chimney have been separately analysed to find out the configuration with highest level of quantitative energy performance. However, there are several qualitative parameters associated with the integrated configuration of Climate cascade and Solar chimney in the five design options that has an impact on the implementation of the system. These comparison of the design options on the basis of the qualitative factors is provided in the table 14 and the description is provided below:

a. **Daylight & clear view to the outside**

Since the Climate cascade and Solar chimney are placed outside, there is a possibility to slightly block the daylight access to some rooms and as a result also hinder the clear visual sight from those rooms. However, this problem only occurs in design options 03,04 and 05 in a maximum of 6 rooms for the entire floor. This criterion thus does not hold high importance.

b. **Effect of duct length**

One of the parameters to improve the performance of the system is to reduce the length of the supply and exhaust ducts. The duct length increases pressure loss as well as influences the temperature of the air. Hence design option 01 and 02 have the lowest score for this criterion and design option 05 has the best score. For design options with 1 climate cascade, the air supplied to the last apartment on the floor might have a higher/lower air temperature than desired. However, if the duct is well insulated then the influence on the air temperature is low. Moreover, with the air velocity of 2.5 m/s in the ducts, the pressure loss is estimated as 0.1 Pa/m (suggested by Dr. Ben Bronsema). Thus, this does not have a high influence on the overall pressure loss of the system. Hence, this criterion also does not hold high importance since the pressure loss is not too high and the temperature influence can be minimized by insulating the ducts.

c. **Feasibility of Ventec roof in future**

The design options are majorly focussing on Climate Cascade and Solar chimney in terms of their performance optimisation, placement, number and size. However, the system is said to perform most efficiently with adding a Ventec roof on the top which helps in extracting the exhaust air from the Solar chimney and also helps in adding extra overpressure for Climate cascade to let air into the cascade. The construction of Ventec roof is however expensive and might not be feasible to implement in the initial refurbishment plan of the apartment buildings. However, the final design can be flexible to accommodate a Ventec roof in the future to improve the performance even further. This is considered as other criteria to evaluate the design options. Design option 01 with 1CC and 1SC scores highest for this criterion since the CC and SC are placed close to each other and can have a common Ventec roof on the top. Options 03 and 05 with 4 Solar chimneys have the lowest score since it would require 4 Ventec roofs on the top of 4 chimneys. Moreover, Climate Cascades are placed far apart from the solar chimneys and thus having a common Ventec roof is thus not feasible.

d. **Sending recovered heat from SC to CC**

The recovered heat at the top of the Solar chimney can be stored in the ATES system during the summer period. However, during winters, it can be supplied to the top of the Climate cascade to pre-heat the incoming air at the top before passing it through the water in the Climate cascade. Design option 01 has the highest score due to relatively lesser distance between the climate cascade and solar chimney and due to the simplicity of design. Design options 03 and 04 with 4 solar chimneys would need more ducting and are more complex to implement, thus getting lowest score for this criterion.

e. Installation/equipment

For multiple number of Climate cascades and Solar chimneys, more machineries and equipment is needed which is usually placed in the technical rooms of climate cascade and Solar chimney. If the design of the system can achieve an efficient performance with less CC and SC, then that would be a desirable solution. With this criterion, the design option 01 has the highest score since it is a simple system with least number of technical rooms and equipment.

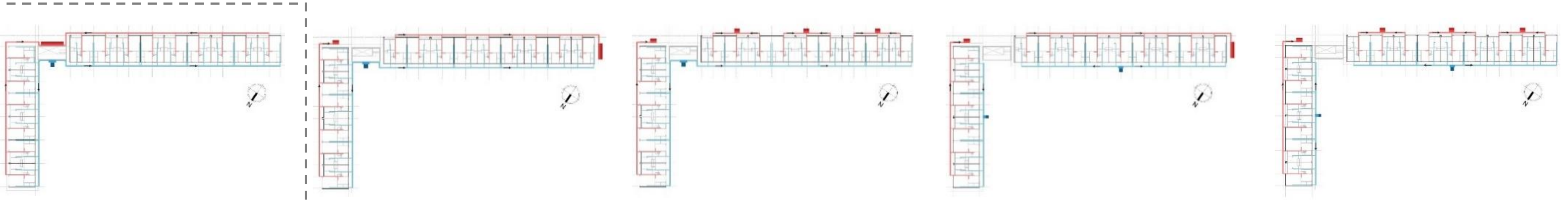
f. Maintenance

This criterion is linked with the installation/equipment criterion since there is a higher need of maintenance to make the system work efficiently when the equipment and the technical rooms are more.

g. Architectural aesthetics

The EWF system is termed as a 'Climate machine' which combines architecture and technology and harness the environmental energy to ventilate the building. The design options have been evaluated for their technical performance, however the architectural aesthetics of the building after refurbishment holds great importance too. Since both the components, climate cascade and solar chimneys are placed outside instead of hiding in shafts or niches, it has a direct influence on the architectural character of the existing building. The design option 01 with single CC and SC placed next to the central core, binds both the building blocks together and acts as a symbol thereby providing an identity to the building. With the addition of Ventec roof in the future, the building would highlight the energy-efficient technology exposed centrally. Thus, this option has the highest score for this criterion. The design options 03 and 05 with 4 solar chimneys have a distribution (placement) of the EWF components making the system visible from all the directions. Thus, both these options take the second place in terms of their architectural appearance. The design options 02 and 04 do not form a clear architectural language or identity for the building and are thus not preferred.

The table with the rating of design options based on these qualitative factors is shown below.



	1 CC, 1 SC	1 CC, 2 SC	1 CC, 4 SC	2 CC, 2 SC	2 CC, 4 SC
Daylight & clear view to outside	★★★★★	★★★★★	★★★	★★★★	★★★
Effect of duct length	★★	★★	★★★★	★★★★	★★★★★
Feasibility of Ventec roof	★★★★★	★★★	★★	★★★	★★
Sending recovered heat to CC	★★★★★	★★★	★★	★★★	★★
Installation/ equipment	★★★★★	★★★	★★	★★★	★★
Maintenance	★★★★★	★★★	★★	★★★	★★
Architectural aesthetics	★★★★★	★★	★★★★	★★	★★★★

Table 14: Rating of design options based on qualitative factors.

7.5 Selected design option

Based on the quantitative as well as qualitative comparison, the design option 01 with 1 Climate Cascade and 1 Solar Chimney is chosen. The Climate cascade shall have sprinklers at a lower level in order to save pump energy. The climate cascade shall be designed with transparent walls with the desire to make the functioning of the system visible to the residents of the building.

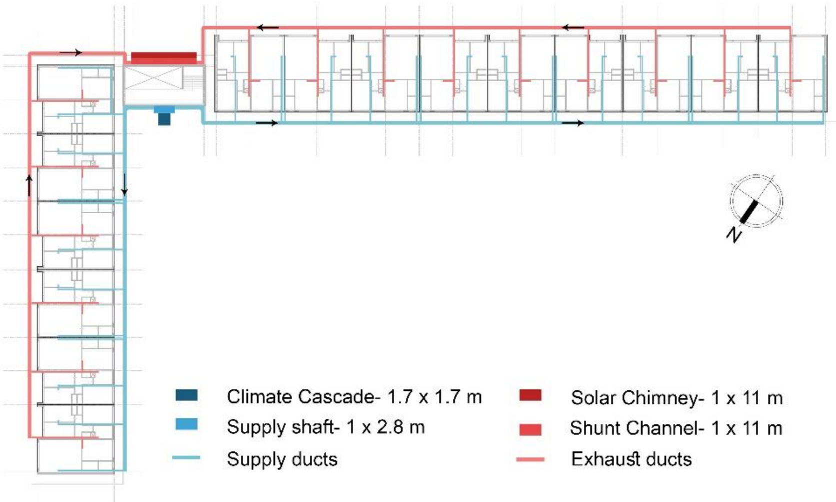


Figure 67: Floor plan of the selected design option.

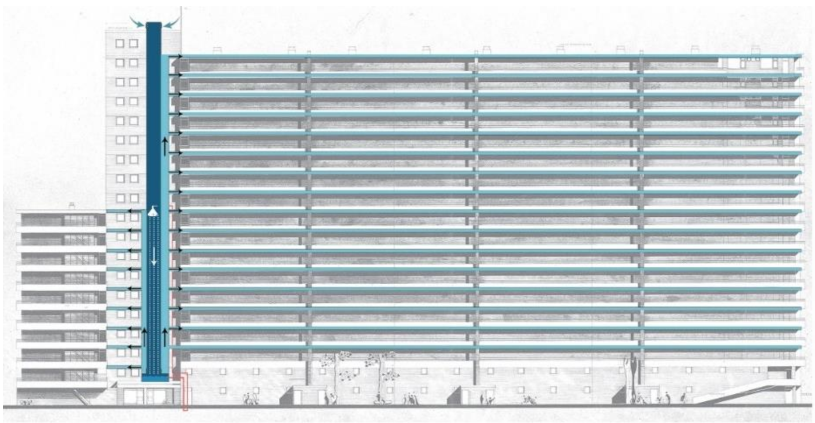


Figure 68: Conceptual section of the selected design option.

Based on the excel calculation modelling, the ventilation energy consumption for the selected design option is calculated in table below:

EWF energy consumed	**Climate Cascade**			**Solar Chimney**	
	Pump energy	Fan energy	Additional heating energy	Fan energy	Total
Energy (kWh)	28,924	1837	472,397	1280	504,438

Table 15: EWF ventilation energy consumption.

7.6 Heat recovery calculation

The heat recovered at the top of the Solar Chimney is used to pre-heat the incoming air temperature at the top of the Climate Cascade during winter months before passing it through the water nozzles for further treatment. This will reduce the pump and the heating energy consumed in the Climate Cascade. The thermal efficiency of heat recovery is calculated using the formula:

Thermal efficiency $\eta = \frac{\theta uit - \theta e}{\theta in - \theta e}$ (Bronsema, 2013)

Where,
ϴuit is the temperature after the heat recovery,
ϴe is the outside temperature
ϴin is the temperature before the heat recovery.

With an efficiency of 70%, the temperature after heat recovery is calculated for all the hourly values for the entire year. The medium used for the exchange is water since it needs lesser space as compared to air to air plate heat exchanger. This recovered heat is passed to the Climate Cascade where second heat exchanger increases the temperature of the incoming air. The heat recovery for pre-heating the incoming Climate Cascade air is only used when the outside temperature is lower than 12 °C. At outside temperature greater than 12 °C, the incoming air gets preheated to 20 °C or more which shall again need cooling till the desired supply air temperature of 18 °C. Thus, when the outside temperature is higher than 12 °C, the recovered heat is transported to the DHW system to help in reducing the energy consumption for hot water heating.

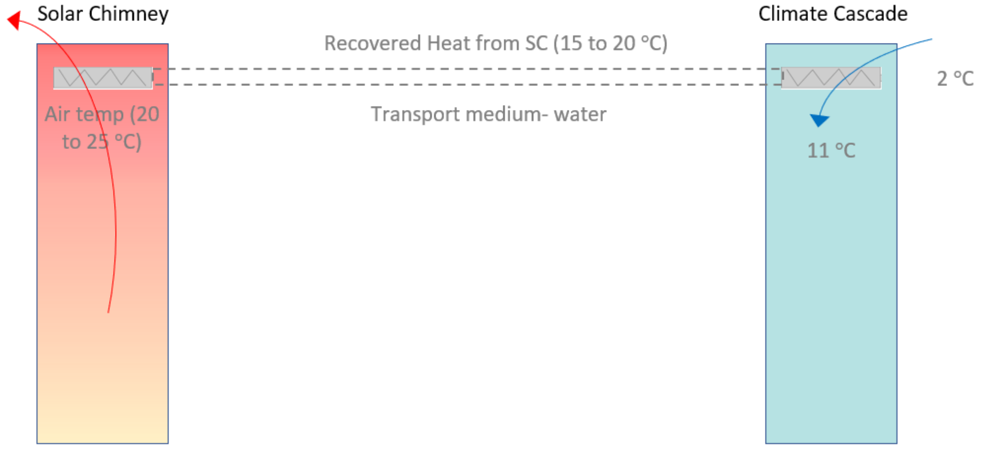


Figure 69: Schematic diagram showing the heat recovery system during the winter months.

Followed by the revised excel model calculation after incorporating the heat recovery system, the total energy consumption for the Climate Cascade reduces by almost 50%. The heating energy consumption tremendously reduces since the air is already pre-heated during winter months. The pump energy also reduces since the water nozzles are designed to be inactive when the outside temperature is between 16-20 °C in order to avoid the unnecessary cooling of the air. This however increases the fan energy by 50% since the pressure generated at the base is insufficient. The overall energy consumption is reduced to a great extent and thus the incorporation of heat recovery adds value to the design. The selected design is then evaluated for the energy and comfort performance which is described in the next section.

EWF energy consumed	**Climate Cascade**			**Solar Chimney**	
	Pump energy	Fan energy	Heating energy	Fan energy	Total
Without HR (kWh)	28,924	1837	472,397	1280	504,438
With HR (kWh)	20,237	3593	237,347	1280	262,460

Table 16: EWF ventilation energy consumption calculation with Heat recovery.

8 Energy & Comfort assessment

The energy and comfort assessment has been done using dynamic simulation modelling with the Design Builder software. This chapter provides information on the energy performance and thermal comfort for the building before and after renovation. Assessment of ISO74 ATG method for thermal comfort has been added to validate the design and justify the extent to which EWF meets the desired goal.

8.1 Calculation Methodology

The energy & comfort assessment follows four steps- Modelling in Design Builder software, providing input parameters, simulating and evaluating the output.

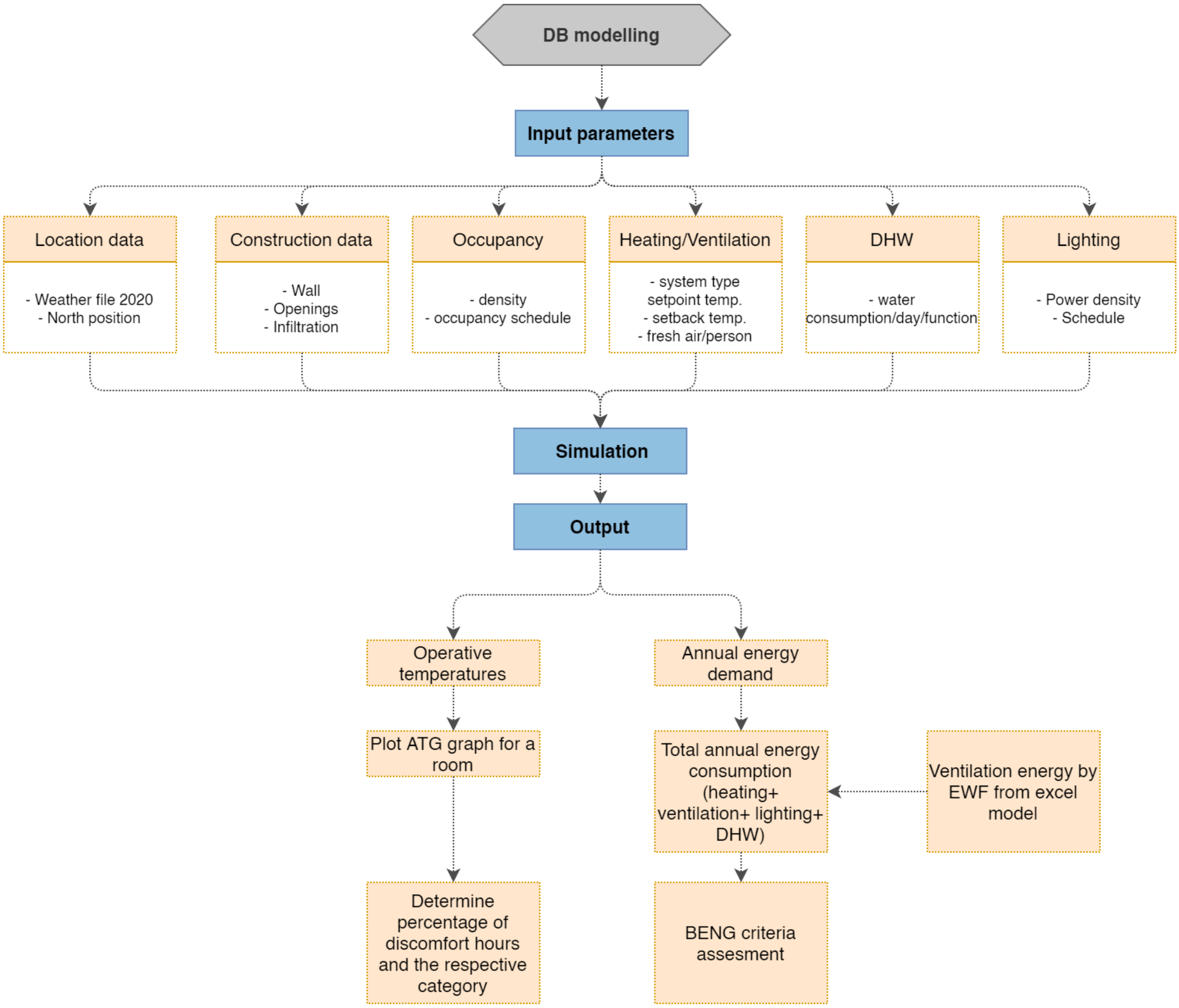


Figure 70: Methodology for dynamic simulation.

Step 1: Design Builder modelling

The first step is to model the 3d of the apartment with all the thermal zones. A single apartment with all the different functions is modelled in order to assign the input parameters based on the function of the zone to get the precise results.

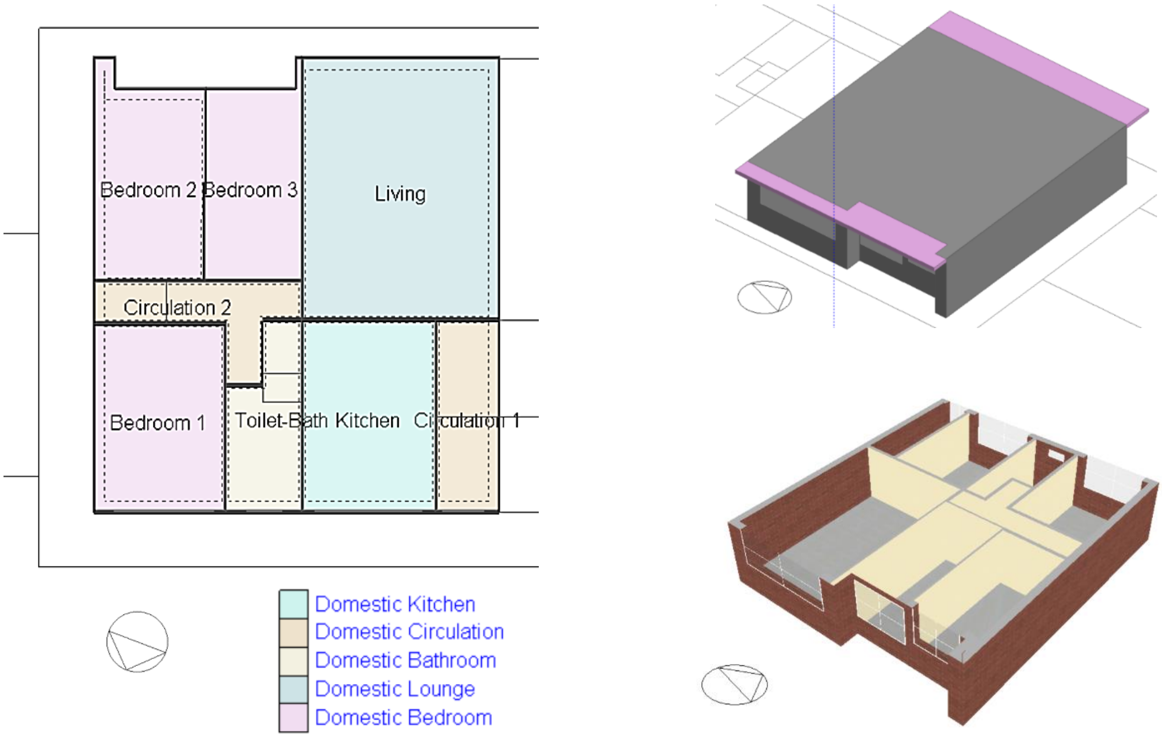


Figure 71: Design Builder modelling.

Step 2: Input parameters-

After modelling the apartment, several input parameters listed below are added into all the spaces as per the function type. The schedule plays an important role in simulations and thus requires attention.

Location data: The default weather file in the Design Builder software is for the year 2002. Since the weather has changed over the years, 'epw' weather file for Amsterdam, year 2020 has been added to the software.

Construction data: The material composition of the envelope and the infiltration rate plays a crucial role in determining the energy demand of the building. From the 'construction' tab, the wall composition and the infiltration rate for the closed parts is defined for both the existing façade and the renovated façade. From the 'openings' tab, the glazing properties are defined with the window to wall ratio.

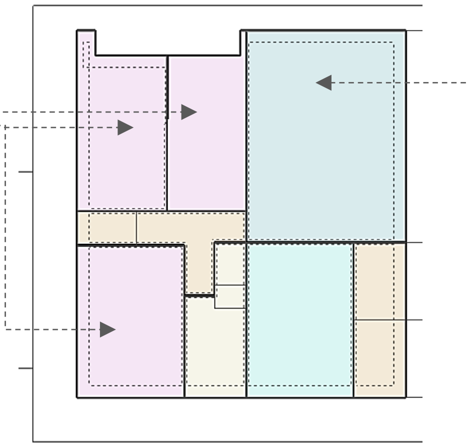
Occupancy data: The occupancy density for each function is based on the floor area such that there is at least one occupant in each zone. The occupancy density is one of the parameters for defining the fresh air supply in each zone which is described in the next step. The occupancy schedule differs for all the zones such that living room has occupants during day and bedrooms have occupants at night.

Heating and ventilation data: The heating and ventilation data is defined by adding a 'detailed HVAC loop'.

The heating system for the existing building and the EWF renovated building is set by adding a gas fired boiler and connecting it to the radiator in the rooms. The setpoint and setback temperatures differ for all the different zones in the apartment. The operation schedule of the radiator plays a crucial role in determining the energy demand of the building. The heating schedule is thus based on the occupancy schedule such that the radiator maintains the setpoint temperature in the presence of the occupants and setback temperature in the absence of the occupants for saving the energy.

The ventilation settings differ for the existing and the EWF renovated case. For the existing case, natural ventilation is provided through the windows. The availability schedule is set as on24/7 for the existing system and the fresh air person rate is dependent on the occupancy density defined earlier. Each bedroom thus has an air supply of 33 m3/h and the living room has air supply of 100m3/h summing up to provide 200m3/h air supply in the apartment.

Bedroom:
Area- 11m2
Occupancy- 0.09 people/m2 (1 people)
Fresh air- 10 l/s/person (33m3/h total)
100m3/h for 3 bedrooms



Living:
Area- 25m2
Occupancy- 0.08 people/m2 (2 people)
Fresh air- 13.8 l/s/person (100m3/h total)

Figure 72: Occupancy and fresh air supply rate for the zones

For modelling the EWF system, certain simplifications are required in order to mimic the system in the software since it's a novel ventilation technique. The climate cascade and solar chimney are thus physically not modelled in the software. With the goal being assessing the effect of EWF on the reduction in the energy consumption, constant air temperature of 18 °C is supplied in the zones. The effect of this 18-degree air supply into the zones is then simulated in the software to find out the effect on annual energy consumption. For doing so, VAV air loop AHU template is added in the HVAC loop with a heating and cooling coil for the air. The air supply output setpoint temperature to all the rooms is set as 18°C annually. This VAV loop air supply is provided to living room and the bedrooms with the operation schedule based on the occupancy schedule such that air is only supplied in the presence of the occupants. The fresh air supply rate is kept same for the existing system and the EWF system for a fair comparison as shown in figure 72. The heating and ventilation loop for modelling EWF is shown in the figure below.

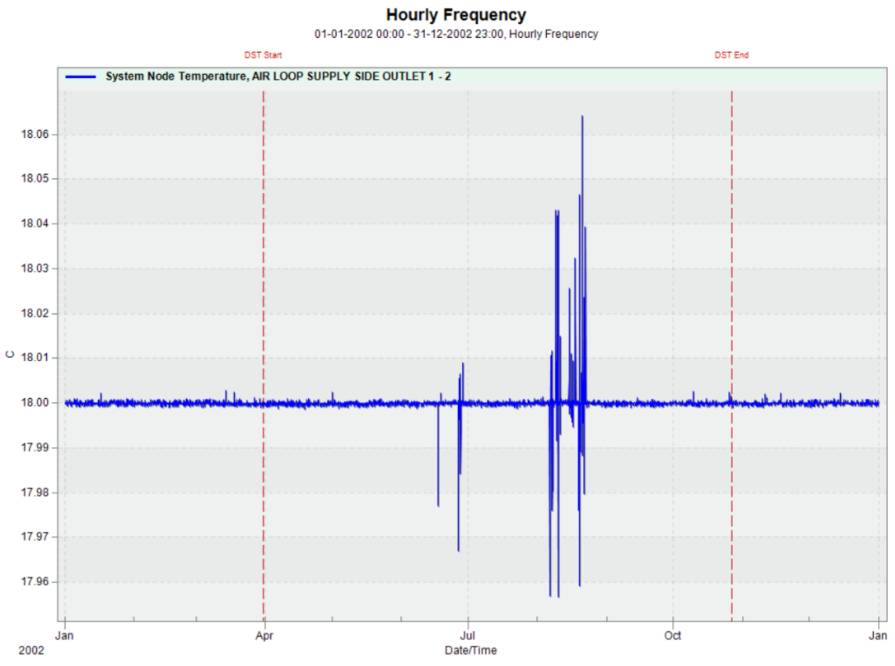


Figure 73: Air supply output in the software.

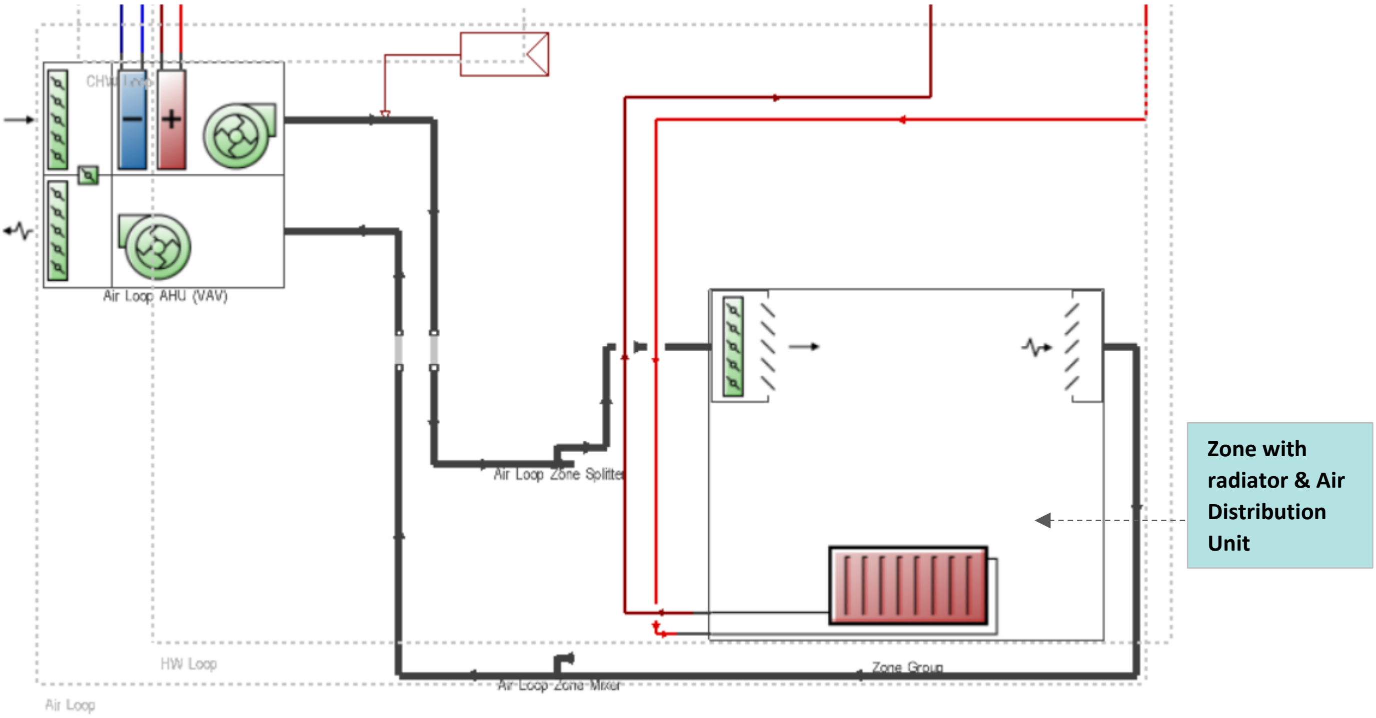


Figure 74: HVAC loop from Design Builder software for imitating the EWF system.

DHW data: The system used for DHW is gas fired boiler and the consumption per apartment is set as 250l/day.

Lighting data: For lighting, LED template is used in the software and the operation is based on occupancy schedule of each function.

For a holistic comparison, the assessment has been performed for six cases:

a. **Case 1: Existing building**- Existing natural ventilation and radiator heating system
b. **Case 2: EWF refurbished building**- EWF ventilation with existing radiator heating system.
c. **Case 3: Façade renovation of existing building**- Façade renovation with existing radiator heating and natural ventilation system.
d. **Case 4: EWF refurbished building with façade renovation**- Façade renovation with existing radiator heating, EWF ventilation system.
e. **Case 5: Façade renovation of existing building variation 2-** Façade renovation with existing radiator heating and controlled natural ventilation system through the use of CO2 sensors such that the windows are shut when the occupants are absent in the zone.
f. **Case 6: EWF refurbished building with façade renovation variation 2-** Façade renovation with EWF system, ATES connected to radiator (with lesser water temperature in radiator), DHW system connected to ground source heat pump.

The input parameters for the six cases are listed in the table 17.

Step 3: Simulation- After properly setting the input parameters, the simulation for annual, monthly, daily and hourly periods are carried out for all the cases to provide the output.

Step 4: Evaluating output- Through the results obtained after the simulation, calculations are performed to tabulate the total energy consumption and assess the thermal comfort of the space. For analysing the comfort performance, living area is chosen since it has the largest area with maximum exposure to South direction. The results after the simulation are multiplied for 198 apartments to get the total energy consumption of the building.

Input parameters			Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
			Existing	**EWF**	**Façade renovation**	**EWF & façade renovation**	**Façade renovation variation 2**	**EWF & façade renovation variation 2**
Construction	Opaque parts (innermost to outermost layer)		110mm Brick, 50mm cavity, 110mm Brick	110mm Brick, 50mm cavity, 110mm Brick	110mm Brick, 50mm cavity, 110mm Brick, 75mm insulation	110mm Brick, 50mm cavity, 110mm Brick, 75mm insulation	110mm Brick, 50mm cavity, 110mm Brick, 75mm insulation	110mm Brick, 50mm cavity, 110mm Brick, 75mm insulation
	R-value- opaque parts (m2-k/W)		0.7	0.7	3.1	3.1	3.1	3.1
	Infiltration (ac/h)		0.7	0.7	0.3	0.3	0.3	0.3
	Openings		6mm clear single glass	6mm clear single glass	6-13-6 mm low-e double glazing with argon gas filling	6-13-6 mm low-e double glazing with argon gas filling	6-13-6 mm low-e double glazing with argon gas filling	6-13-6 mm low-e double glazing with argon gas filling
	U- value of glazing (W/m2-k)		6.1	6.1	1.5	1.5	1.5	1.5
Occupancy	Density (people/m2)	Bedroom	0.09	0.09	0.09	0.09	0.09	0.09
		Living room	0.08	0.08	0.08	0.08	0.08	0.08
Heating	System		Boiler, Water radiator	Boiler, Water radiator	Boiler, Water radiator	Boiler, Water radiator	Boiler, Water radiator	Ground Source Heat Pump, Water radiator
	Setpoint temp.	Bedroom/kitchen	18	18	18	18	18	18
		Living	21	21	21	21	21	21
	Setback temp.	Bedroom/living	15	15	15	15	15	15
		Kitchen	13	13	13	13	13	13
Ventilation	System		Natural inlet, mechanical exhaust	Constant 18 °C air supply	Natural inlet, mechanical exhaust	Constant 18 °C air supply	Natural inlet, mechanical exhaust	Constant 18 °C air supply, natural ventilation in summers
	Setting		On 24/7	Follows occupancy profile	On 24/7	Follows occupancy profile	Follows occupancy profile	Follows occupancy profile
	Fresh air/ apartment (m3/h) (excl. infiltration)		200	200	200	200	200	200
DHW	System		Boiler	Boiler	Boiler	Boiler	Boiler	Heat pump
	Water consumption per apartment (l/day)		250	250	250	250	250	250

Table 17: Input parameters for different cases.

8.2 Results from Dynamic Simulation modelling

8.2.1 Case 1: Existing

Energy performance

Based on the input parameters described earlier, the existing state of the building is simulated. From the analysis, it is evident that the major contribution to the energy consumption is through the space heating load with approximately 70% of the total load. Due to poor façade construction, there is high heat loss through the glazing and the brick wall, resulting in extremely high heating demand for the building. Since the existing case has natural supply through façade and mechanical exhaust through the fans in the toilet and kitchen, the ventilation energy consumption is negligible with only 1% of the total energy demand. Since the simulation software does not provide the ventilation energy consumption, the calculation is done using the formula:

Ventilation energy (kWh) = 0.3 $\left(\frac{kW}{\frac{m3}{s}}\right) * Ventilation\ amount\ \left(\frac{m3}{s}\right) * operation\ hours$ (Van der Spoel, W., 2020)

Ventilation energy (kWh)= 0.3 kW/m3/s * (39600/3600 m3/s) * 8000 s = 26,400 KWh

	Secondary energy	Heating	Ventilation	DHW	Lighting	Total
Existing	MWh	2878	26.4	1058.7	148.8	4112
	kWh/m2	161.5	1.5	59.4	8.4	231

Table 18: Energy consumption results for existing case.

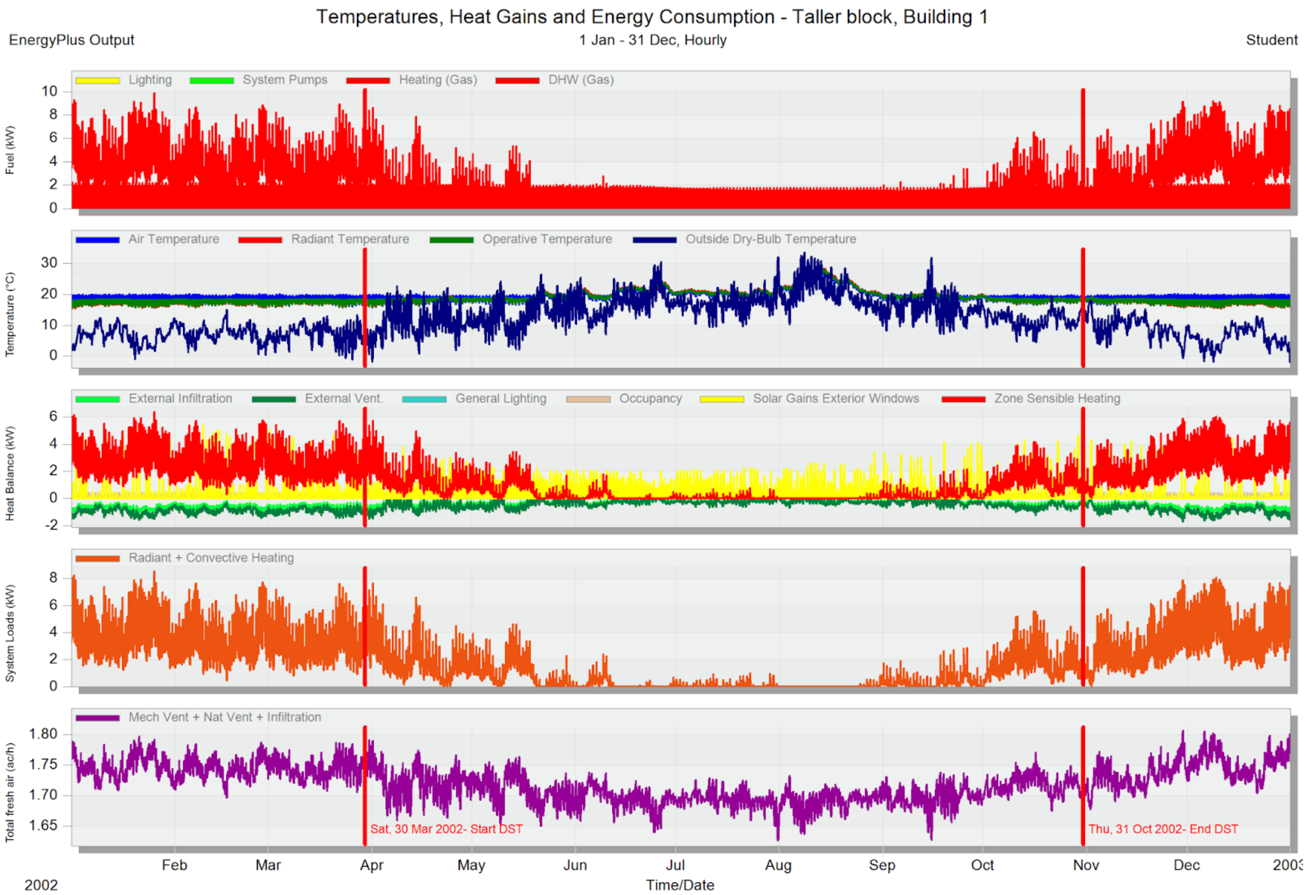
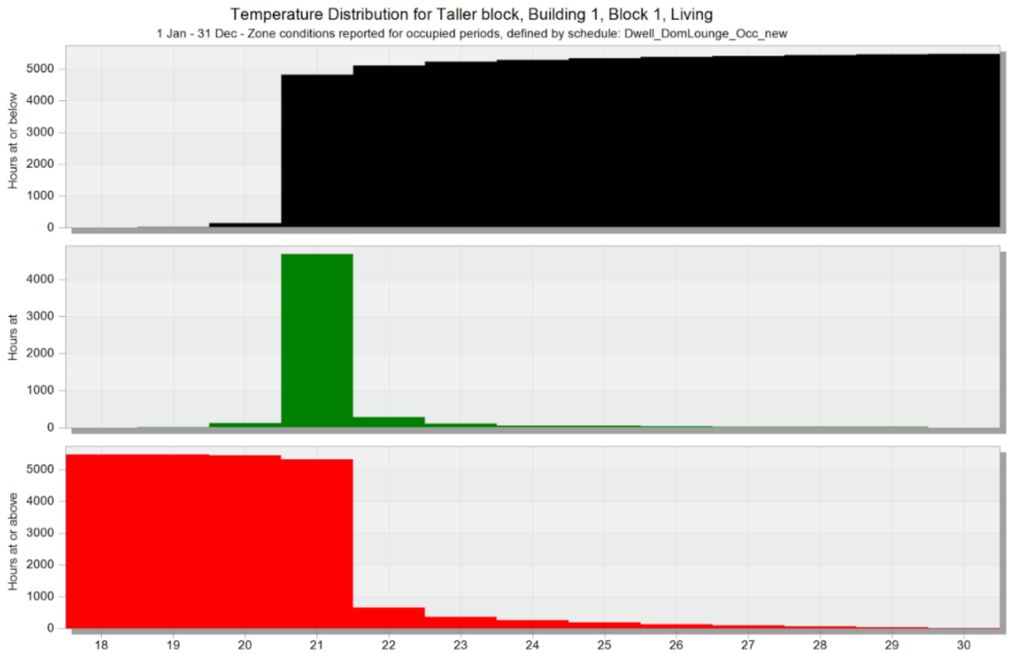


Figure 75: Heat gains and energy consumption graph for existing case.

Since the building solely relies on natural ventilation, occupants have the control to operate the windows. Hence the availability schedule for natural ventilation is provided as on24/7. During the peak summer days, the operative temperatures in the rooms reaches 30 °C due to the absence of active cooling system in the building. During winters, the access to direct cold outside air increases the load on the heating system in order to reach the defined setpoint temperatures in the zones. The graph shows that the heating system is also active during mid-seasons from April to June when the outside temperatures are lower than 15 °C. This is because the radiator always tries to maintain the setpoint temperature of 21°C based on the input setting provided and the user control is not taken into account in the software. The actual heating energy demand should be lesser than the calculated values in the software since the system is controlled by users in reality and the software does not take this into account.

Thermal comfort

The thermal comfort graph below provides the number of hours at the temperature range from 18-30 °C for the living room of the apartment during the occupied periods. The comfort temperature limit for the living room is set as 20-26 °C. The graph shows that 95 hours exceed the comfort limit of 26 °C leading to discomfort in the rooms and the maximum number of hours are at the setpoint temperature of 21 °C with only 15 hours below 21°C. The lower limit is however more flexible since people can adapt their clothing as per their comfort requirement.



	18	19	20	21	22	23	24	25	26	27	28	29	30
Hours at or below	0.3	15.0	139.3	4827.0	5116.8	5228.0	5285.3	5338.0	5379.5	5414.0	5443.8	5470.8	5475.0
Hours at	0.3	14.8	124.3	4687.8	289.8	111.3	57.3	52.8	41.5	34.5	29.8	27.0	4.3
Hours at or above	5475.0	5474.8	5460.0	5335.8	648.0	358.3	247.0	189.8	137.0	95.5	61.0	31.3	4.3

Temperature bins (°C)

Figure 76: Thermal comfort graph for existing case.

These indoor operative temperatures at occupied periods were then plotted in ATG graph for assessing the thermal comfort class of the existing building. The ATG method classifies the building as alpha or beta type and A/B/C/D class. Since the existing building doesn't have active cooling system, it is an alpha category. As per the ATG method, the acceptable discomfort % hours are max. 10% for class B, max. 15% for class C and max. 25% for class D. The graph shows that 69.5% of occupied hours fall under Class B and 30.5% of hours exceed Class B. Hence the space does not satisfy Class B since a maximum of 10% discomfort hours are accepted. 98.5% of hours fall under Class C and only 1.5% of occupied hours have discomfort which is acceptable. Hence the apartment falls under Class C with 1.5% discomfort hours which is classified as 'acceptable' thermal performance. The operative temperatures mostly exceed the lower limit when the outdoor mean running temperature is above 16 °C. However, the operative temperatures do not go below 21 °C and hence theoretically the comfort is acceptable. During the heating seasons, the radiator maintains 21 °C quite sufficiently at the expense of high heating load in order to satisfy the comfort criteria. The heating energy demand can thus be reduced since for the residential spaces people have the flexibility to adapt clothing as per their personal comfort.

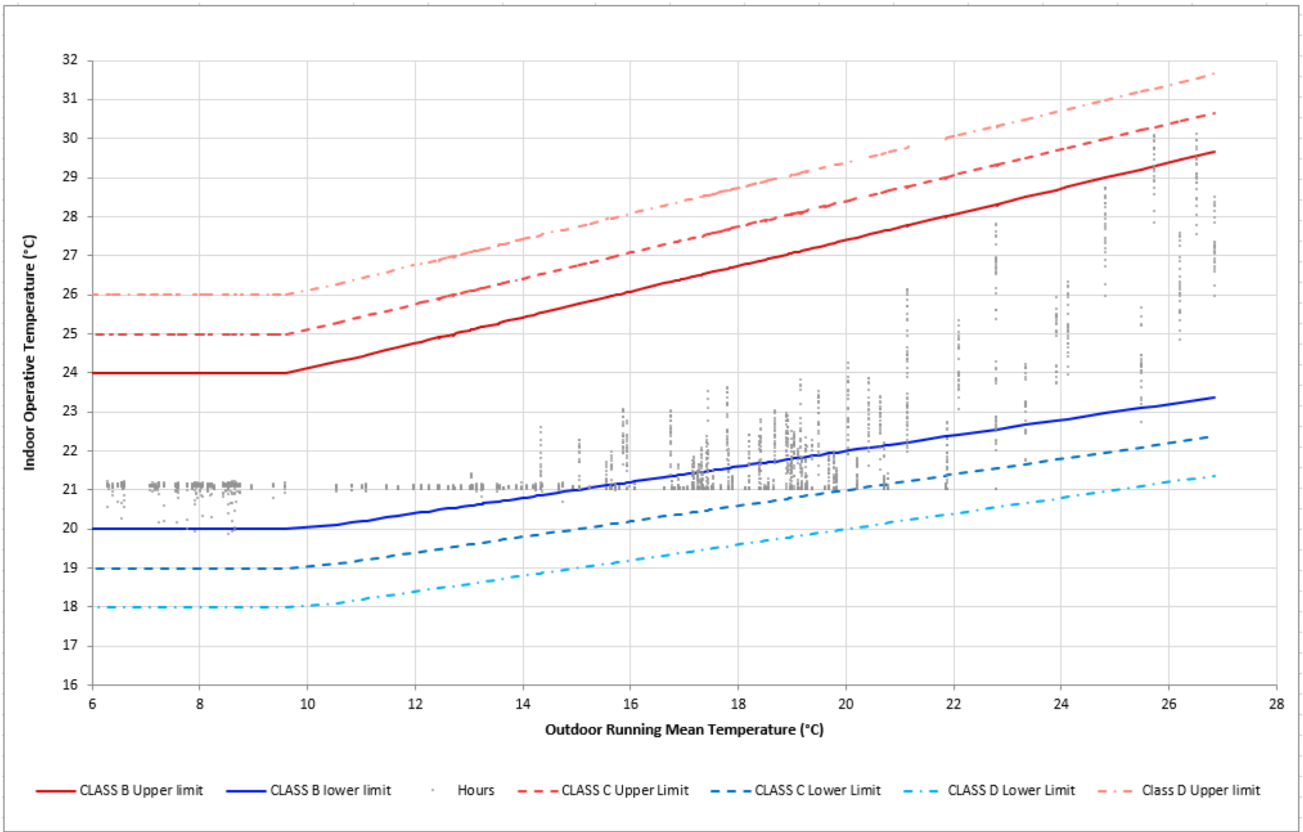
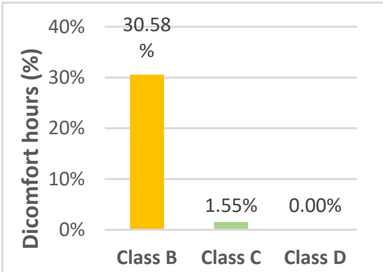


Figure 77: ATG comfort graph for existing case.

Room	Living
Room type	Alpha
Temperature type	Operative
Analysis period	Jan- Sept
Thermal performance	Acceptable
Class	C

Comfort category	No. of discomfort hours	% of discomfort
Class B	1299	30.58
Class C	66	1.55
Class D	0	0



8.2.2 Case 2- EWF

Energy performance

For modelling the EWF system, the natural ventilation is replaced by the EWF ventilation through a constant air supply of 18 °C into the rooms as described earlier in section 8.1. The heating system and the façade construction remain the same as case 1. On comparing the EWF system with the existing case, the space heating load reduces by 27.6% since the only access of cold outside air into the space is through the infiltration. This reduces the load on the heating system to maintain the setpoint temperature of 21 °C. The ventilation however is more for the EWF system since it is a summation of fan, pump and additional heating energy to heat the air till 18 °C as compared to the existing case which only has exhaust fans. The energy consumed by DHW and lighting remains the same as case 1 since no changes were performed for both. The total energy consumed by the EWF system thus reduces by 13.6% as compared to case 1.

EWF energy consumed	Climate Cascade			Solar Chimney	
	Pump energy	Fan energy	Additional heating energy	Fan energy	Total
Energy (MWh)	20.2	3.5	237.3	1.28	262.3

Table 19: EWF ventilation energy consumption from excel modelling.

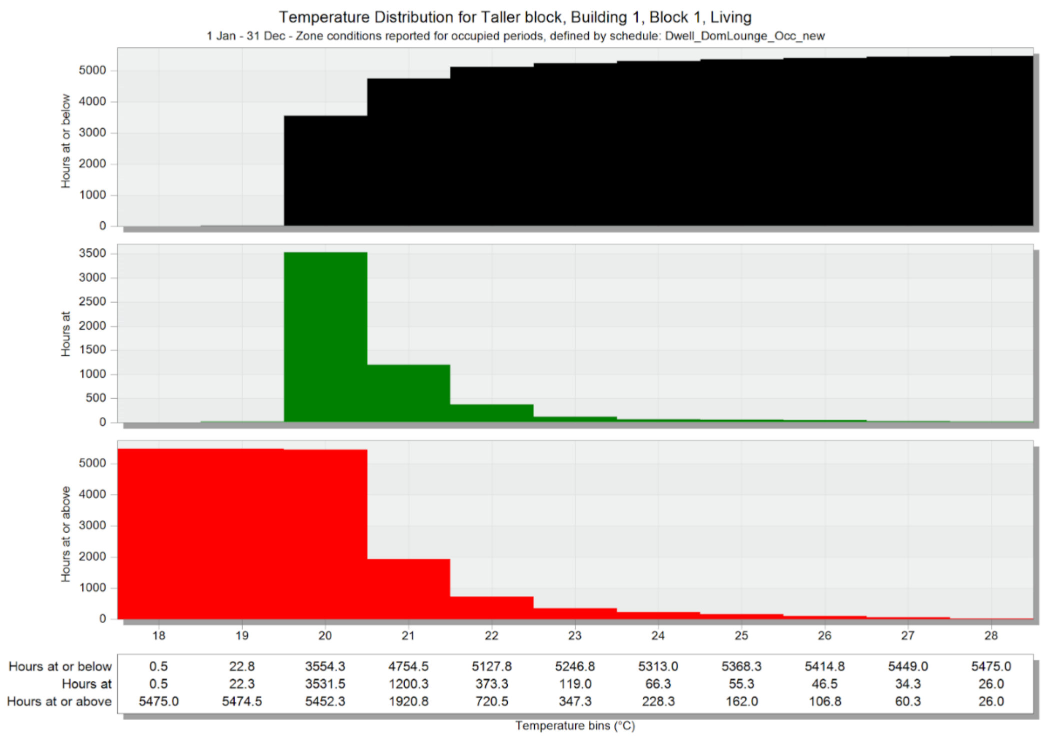
	Primary energy	**Heating**	**Ventilation**	**DHW**	**Lighting**	**Total**
Case 1- Existing	MWh	2878	26.4	1058.7	148.8	4112
	kWh/m2	161.5	1.5	59.4	8.4	231
Case 2- EWF	MWh	2085	262.3	1058.7	148.8	3555
	kWh/m2	117	14.7	59.4	8.4	199
Increase/reduction		-27.6%	+880%	-	-	-13.6%

Table 20 :Energy consumption comparison between existing case and EWF case.

Thermal comfort

Comparing the thermal comfort with the existing case, the thermal comfort during summer months is more pleasant in the EWF refurbished building with 60 hours exceeding 26°C during the occupied periods as compared to case 1 where 95 hours exceed 26 °C. This is due to the cooling effect of the 18 °C supply air.

	Hours above 26 °C
Existing	95
EWF	60



	18	19	20	21	22	23	24	25	26	27	28
Hours at or below	0.5	22.8	3554.3	4754.5	5127.8	5246.8	5313.0	5368.3	5414.8	5449.0	5475.0
Hours at	0.5	22.3	3531.5	1200.3	373.3	119.0	66.3	55.3	46.5	34.3	26.0
Hours at or above	5475.0	5474.5	5452.3	1920.8	720.5	347.3	228.3	162.0	106.8	60.3	26.0

Figure 78: Thermal comfort graph for EWF case.

The ATG graph is plotted for beta type category since there is a cooling effect with the EWF system. Since there is no mechanical space cooling present, the building should ideally fall under a hybrid category, however the ATG model does not have an assessment classification for hybrid systems. The graph shows that 70.8% of hours fall under class B and 29.2% of discomfort hours. The space thus does not satisfy Class B requirements (max. 10% discomfort). 77% of hours fall under class C and only 3% of hours exceed Class C. The space thus falls under Class C with 'acceptable' thermal comfort performance. As explained earlier in case 1, the majority of the discomfort is due to the hours exceeding lower limit which is acceptable.

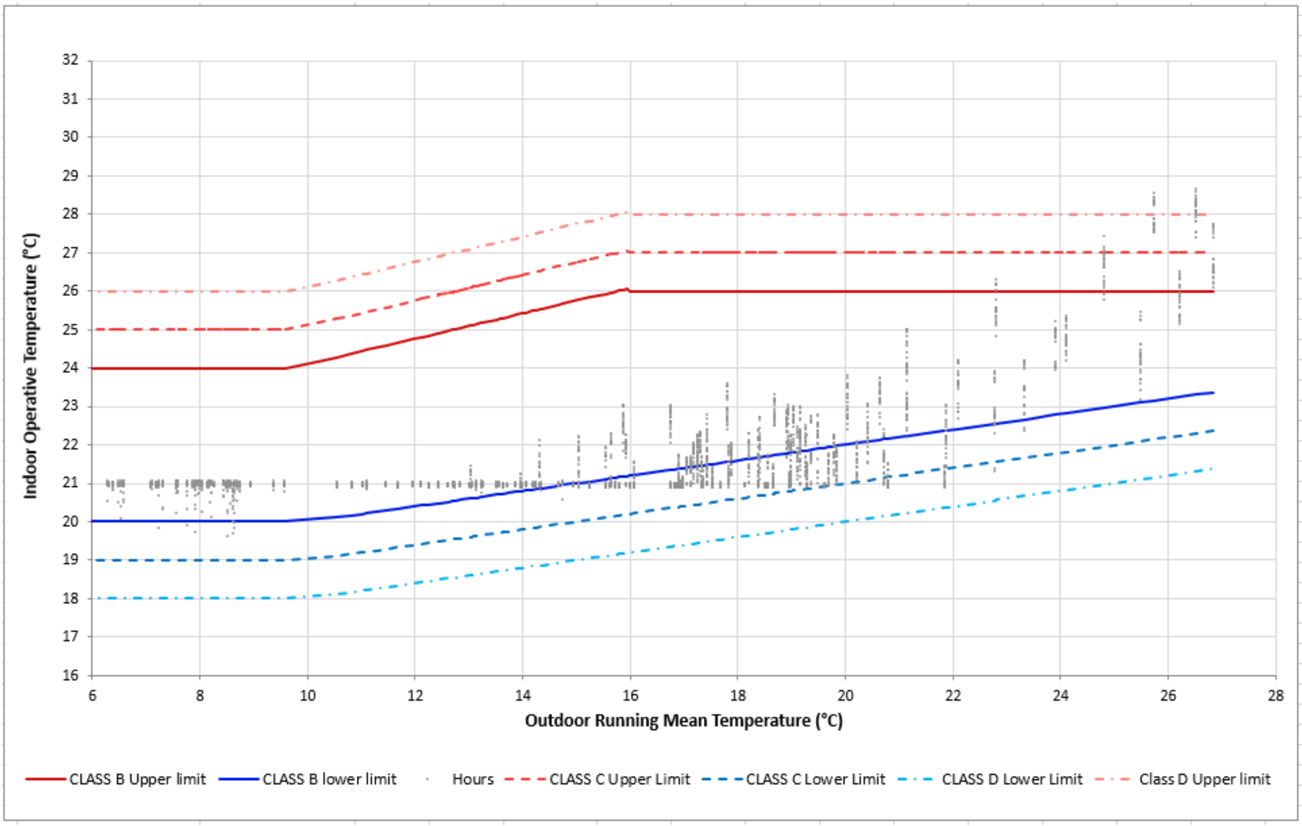
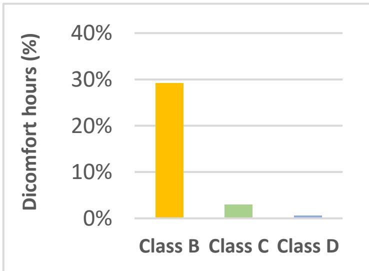


Figure 79: ATG comfort graph for EWF case.

Room	Living
Room type	Alpha
Temperature type	Operative
Analysis period	Jan- Sept
Thermal performance	Acceptable
Class	C

Comfort category	No. of discomfort hours	% of discomfort
Class B	1241	29.2
Class C	128	3.01
Class D	26	0.61



8.2.3 Case 3- Façade renovation

Energy performance

Followed by the façade refurbishment strategies described in the section 5.1, exterior insulation layer of 75mm is added to existing façade and the existing single glazing is replaced by a double-glazing window. The heating system and the natural ventilation system remain the same as case 1-existing building. With the improved façade, the heating load tremendously reduces by 64% as compared to the existing case. This shows that the renovated façade is capable of retaining the heat more efficiently as compared to existing façade. Since the ventilation system is same as case 1 (exhaust fans and natural supply through the facades), the energy consumed in the ventilation remains the same. The total energy consumption thus reduces by 45% as compared to case 1.

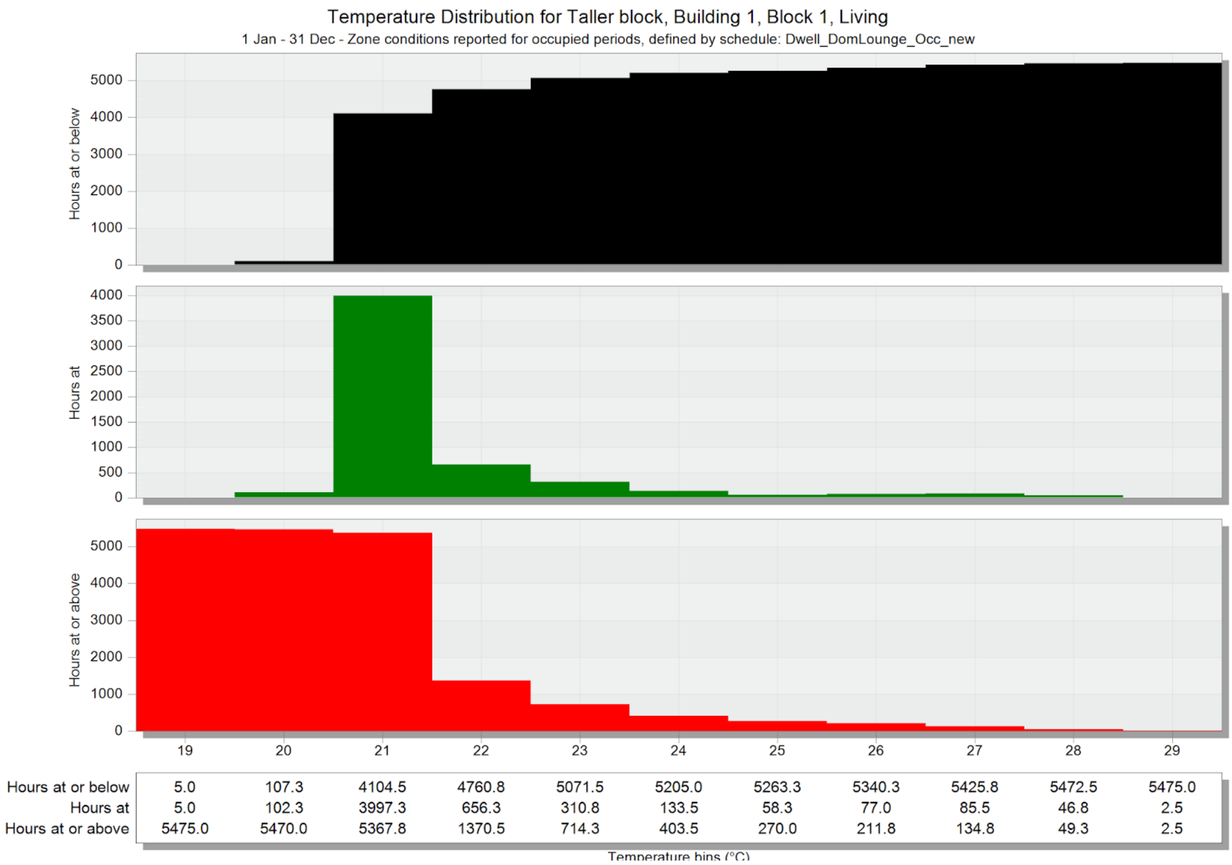
	Primary energy	Heating	Ventilation	DHW	Lighting	Total
Case 1- Existing	MWh	2878	26.4	1058.7	148.8	4112
	kWh/m2	161.5	1.5	59.4	8.4	231
Case 3- Façade renovation	MWh	1032	26.4	1058.7	148.8	2266
	kWh/m2	57.9	1.5	59.4	8.4	127
Increase/reduction		-64%	-	-	-	-45%

Table 21: Energy consumption comparison between existing case and facade renovated case.

Thermal Comfort

Comparing the thermal comfort with the existing case, the thermal comfort increases during winters with barely only 5 hours below 20 °C as compared to case 1 with 15 hours below 20 °C. This difference in operative temperatures is not drastic, however the space heating energy demand is greatly reduced for the renovated façade. So, the similar winter comfort is achieved with lower energy demand for the renovated façade. However, during summers, the renovated façade has more discomfort hours with 134 hours exceeding 26 °C as compared to case 1 with 95 hours exceeding 26 °C. The insulated renovated façade causes overheating in the rooms during summers and the absence of active cooling in the space increases the discomfort. The windows in this case can be installed with solar control shading to reduce the solar gain inside the rooms.

	Hours above 26 °C
Existing	95
Façade renovation	134



	19	20	21	22	23	24	25	26	27	28	29
Hours at or below	5.0	107.3	4104.5	4760.8	5071.5	5205.0	5263.3	5340.3	5425.8	5472.5	5475.0
Hours at	5.0	102.3	3997.3	656.3	310.8	133.5	58.3	77.0	85.5	46.8	2.5
Hours at or above	5475.0	5470.0	5367.8	1370.5	714.3	403.5	270.0	211.8	134.8	49.3	2.5

Figure 80: Thermal comfort graph for renovated facade.

The ATG graph is plotted for alpha category due to the absence of active mechanical cooling. The graph shows that only 10% of hours exceed Class B and thus the space falls under Class B with a ‘good’ thermal performance. The discomfort is only caused due to a few hours exceeding the lower limit which however is acceptable as explained earlier in case 1. During the summer periods, although the total number of hours exceeding 26 °C has increased, the operative temperatures do not reach 30 °C unlike case 1. The thermal comfort has thus improved as compared to case 1.

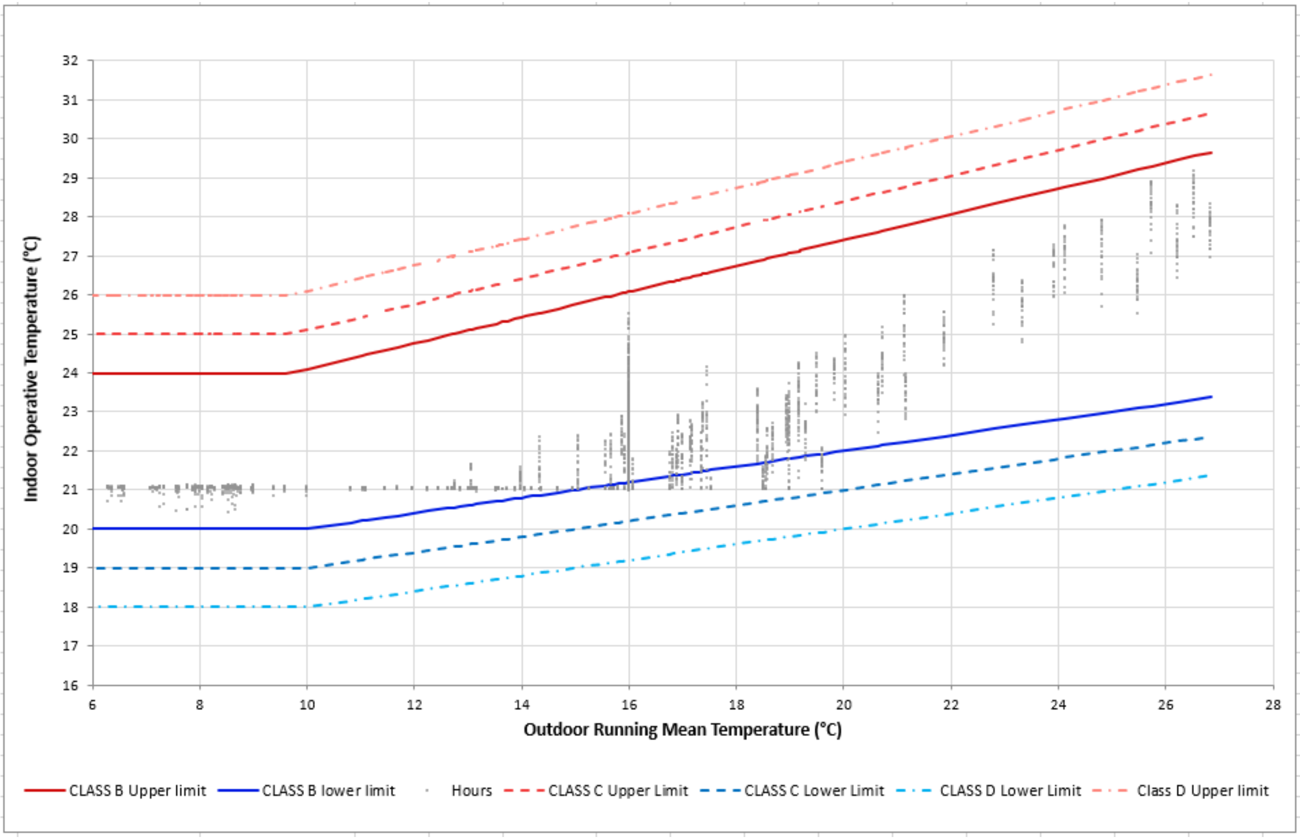
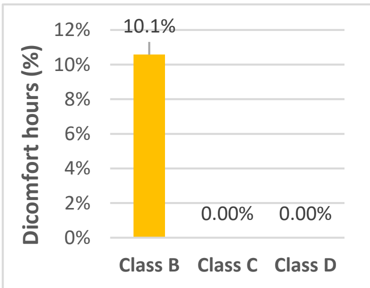


Figure 81: ATG graph for renovated facade.

Room	Living
Room type	Alpha
Temperature type	Operative
Analysis period	Jan- Sept
Thermal performance	Good
Class	B

Comfort category	No. of discomfort hours	% of discomfort
Class B	449	10.1
Class C	0	0
Class D	0	0



8.2.4 Case 4- EWF & Façade renovation

Energy performance

For the case 4, existing ventilation is replaced by EWF ventilation through an air supply of 18 °C and the façade is renovated as described in case 2- façade renovation. The heating system remains the same as the existing case. It is observed that the space heating energy consumption reduces by 89% as compared to case 1 (existing) and 69% as compared to case 3 (façade renovation). The ventilation energy is higher for EWF as compared to existing case and thus the total energy consumption reduces by 56.7% as compared to case 1.

	Primary energy	Heating	Ventilation	DHW	Lighting	Total
Case 1- Existing	MWh	2878	26.4	1058.7	148.8	4112
	kWh/m2	161.5	1.5	59.4	8.4	231
Case 4- EWF & Façade renovation	MWh	319	262.3	1058.7	148.8	1789
	kWh/m2	17.9	14.7	59.4	8.4	100
Increase/reduction		-89%	+880%	-	-	-56.7%
Case 3- Façade renovation	MWh	1032	26.4	1058.7	148.8	2266
	kWh/m2	57.9	1.5	59.4	8.4	127
Case 4- EWF & Façade renovation	MWh	319	262.3	1058.7	148.8	1789
	kWh/m2	17.9	14.7	59.4	8.4	100
Increase/reduction		-69%	+880%	-	-	-21.25%

Table 22: Energy consumption comparison between existing case, facade renovated case and EWF& facade renovation case.

Thermal comfort

Comparing the thermal comfort, the number of hours exceeding 26 °C is similar to case 1 and improved when compared to case 3. The supply of 18 °C has a cooling effect but the insulated façade cause overheating and thus the discomfort hours is similar to case 1.

	Hours above 26 °C
Case 1- Existing	95
Case 3- Façade renovation	134
Case 4- EWF & Façade renovation	95

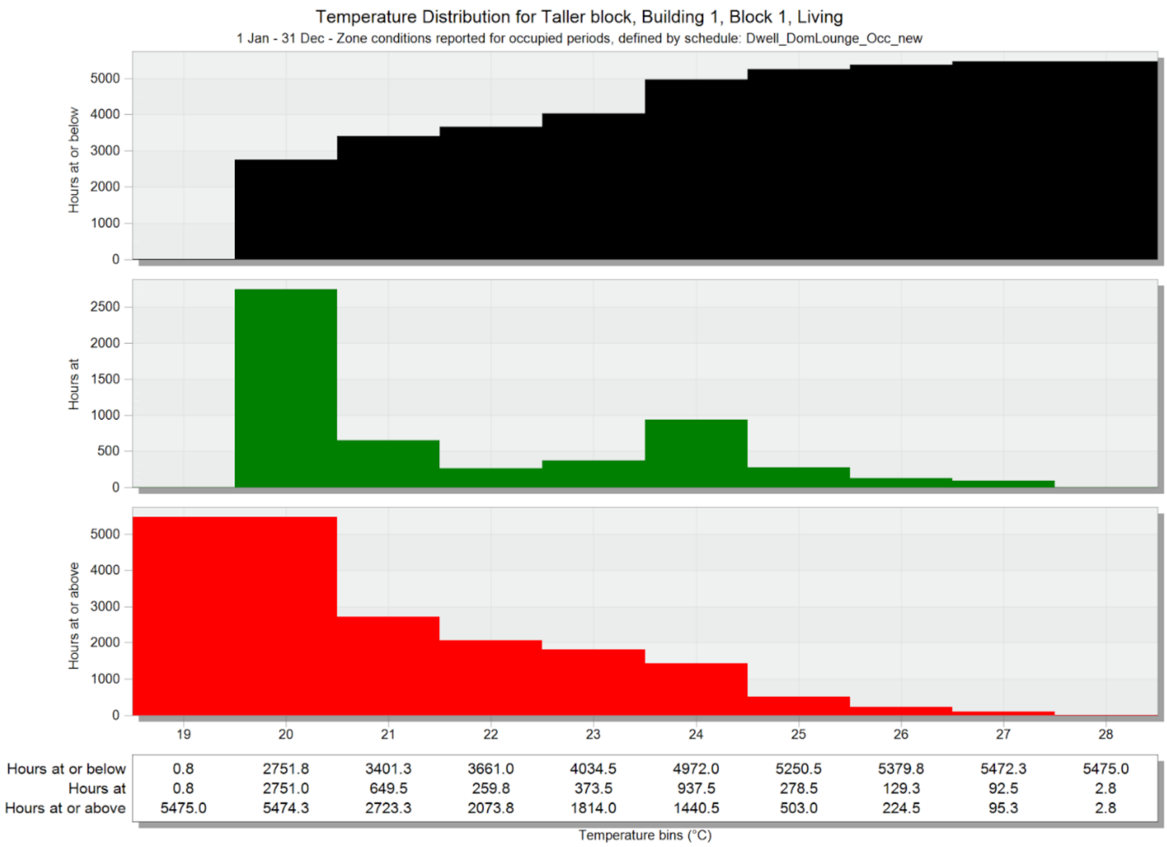


Figure 82: Thermal comfort graph for EWF & Facade renovation case.

The ATG graph shows that only 5.9% of hours exceed Class B and thus the space falls under Class B with a 'good' thermal comfort performance. If the graph is plotted for alpha category, then less than 1% of hours exceed Class B thus the thermal comfort is highly improved for this case. The winter comfort is also improved as compared to case 1 when the operative temperatures were exceeding the lower limit. During peak summers barely a few hours exceed 28 °C thus showing a good thermal comfort for EWF with façade renovation case.

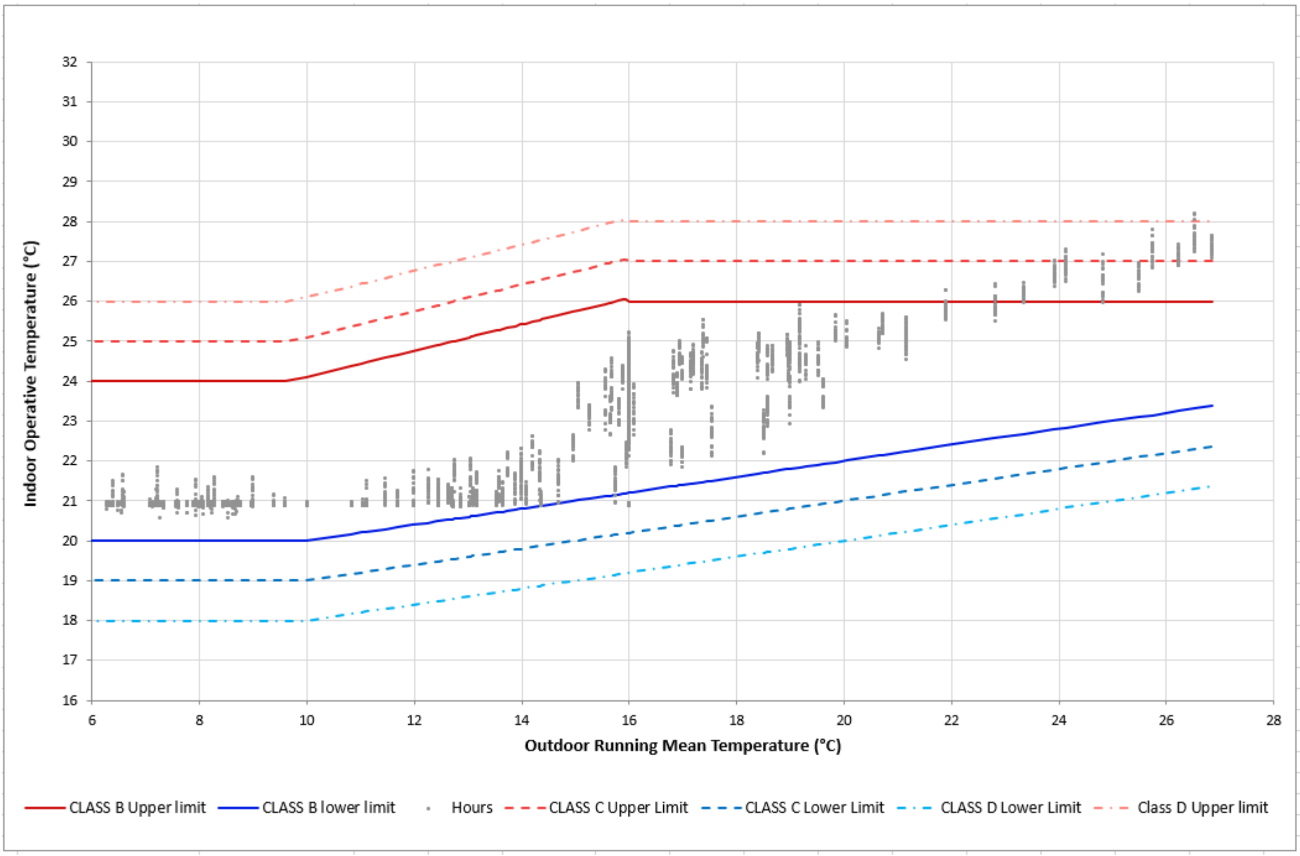
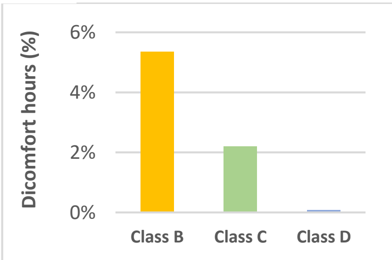


Figure 83: ATG graph for EWF & Facade renovation case.

Room	Living
Room type	Alpha
Temperature type	Operative
Analysis period	Jan- Sept
Thermal performance	Good
Class	B

Comfort category	No. of discomfort hours	% of discomfort time
Class B	227	5.3%
Class C	93	2.19
Class D	3	0.07



8.2.5 Case 5- Façade renovation variation 2

Façade renovation variation case is developed as an improvement to case 3 (façade renovation) through a smart ventilation system with CO2 sensors in the façade such that the natural ventilation is only provided in the presence of the occupants unlike case 3 where the natural ventilation is always kept on24/7. This case is developed to compare the difference in energy consumption as compared to Case 4 (EWF & Façade renovation) to do a holistic comparison for deriving conclusions regarding efficiency of the EWF system.

Energy performance

The results show that the space heating energy consumption is more for case 5 due to access of cold outside air during winter seasons unlike case 4 when 18°C air is supplied into the rooms. However, the total energy consumption only increases by 3% since EWF has more ventilation energy consumption.

	Primary energy	Heating	Ventilation	DHW	Lighting	Total
Case 4- EWF & Façade renovation	MWh	319	262.3	1058.7	148.8	1789
	kWh/m2	17.9	14.7	59.4	8.4	100
Case 5- Façade renovation variation	MWh	595	26.4	1058.7	148.8	1829
	kWh/m2	33.4	1.5	59.4	8.4	103
Increase/reduction		+85.5%	-89.7%	-	-	+3%

Table 23: Energy consumption comparison between EWF& Facade renovation case and Facade renovation variation case.

Thermal comfort

The thermal comfort has decreased for the Façade renovation variation case with 243 hours exceeding 26°C as compared to the façade renovation with EWF system case with 95 hours exceeding 26°C. This is due to the fact that the windows are shut in the absence of occupants thus overheating the space due to reduction of natural ventilation. Case 4 with 'EWF system and façade renovation' is thus more efficient than Case 5 with 'façade renovation and controlled ventilation' since the comfort is improved for the case 4 even though the final energy consumption does not have a major difference for both the cases.

	Hours above 26 °C
Case 3- Façade renovation	134
Case 4- EWF & Façade renovation	95
Case 5- Façade renovation variation	243

8.2.6 Case 6- EWF & Façade renovation variation 2

Case 6 is developed as an improvement to case 4 (EWF & Façade renovation) by replacing the boiler heating system for Space heating and DHW with ATES system. This increases the share of renewable energy and increases the energy efficiency of the building with the goal of achieving a nearly energy neutral design. The Design Builder software does not have ATES system in the HVAC template and thus a Ground Source Heat Pump (GSHP) system is selected as an alternative. The GSHP system works efficiently in connection with low energy heating system such as floor heating which works with a low water supply temperature of 35-40 °C. However, adding a floor heating system to the existing building would mean temporary dislocation of the occupants for a short period of time. This does not satisfy the refurbishment criteria to cause less impact to the residents. The heating system is thus chosen as a water radiator and the supply water temperature is reduced from 75 °C to 50 °C to increase the COP of the GSHP system. The source of DHW is also chosen as GSHP to eliminate the dependence on gas as a source of heating. However, the Design Builder does not have a template to connect DHW with GSHP and thus the final output from the simulation shall be divided by the Coefficient of Performance (3) to get an estimation. For the ventilation system, in addition to EWF (air supply of 18 °C), natural ventilation is added during summers to reduce the overheating of space.

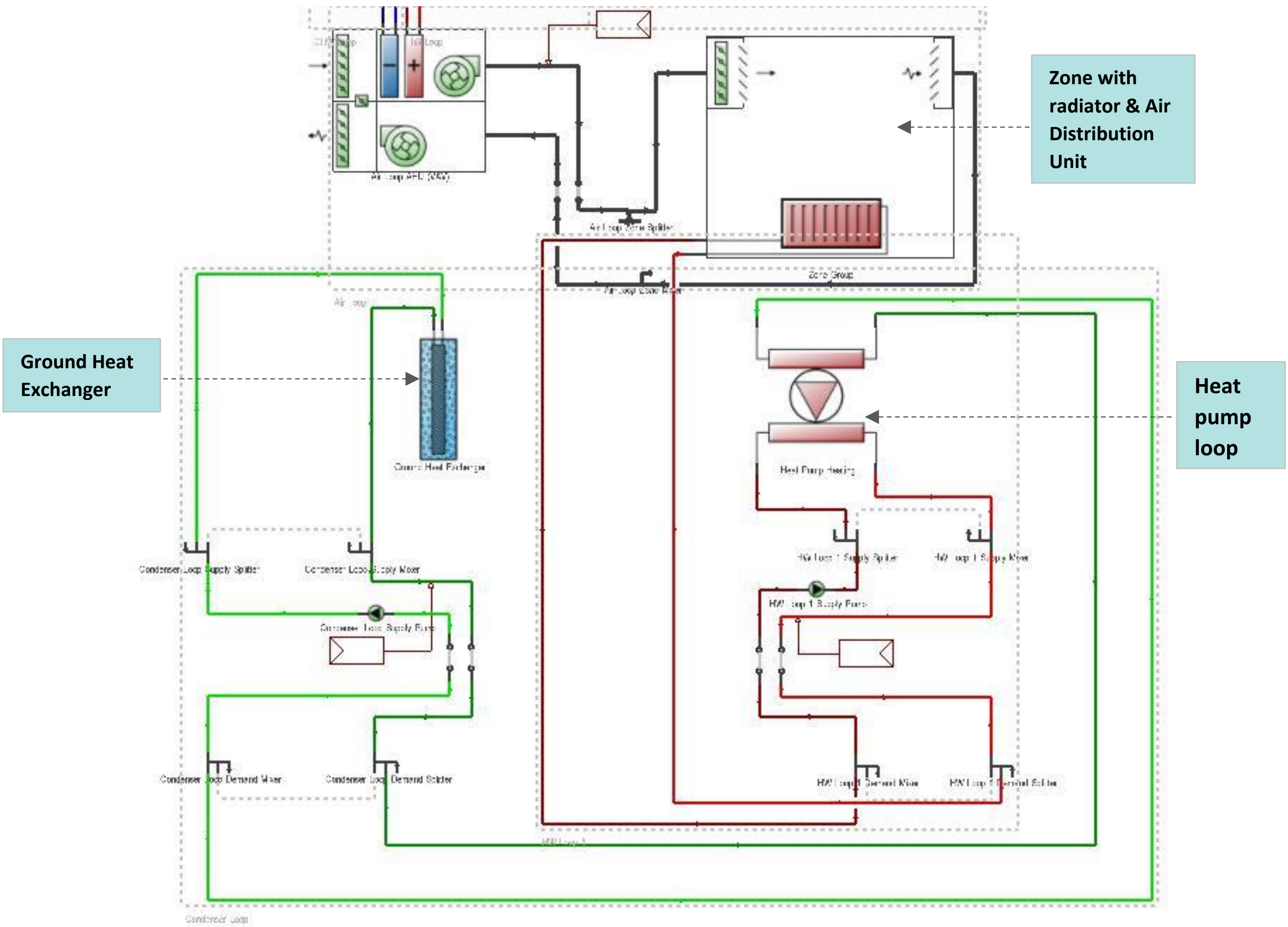


Figure 84: HVAC loop from Design Builder software for case 6.

Energy performance

The case 6 is compared to case 4 (EWF & Façade renovation) in order to find the difference in energy performance. The results show that the space heating load tremendously reduces by 72% for the case 6 since the GSHP system is highly energy-efficient as compared to the gas fired boiler system as a source. On diving the DWH energy consumption by the COP as 3, the DHW energy consumption reduces by 66% and the total energy consumption for case 6 thus reduces by 52%.

	Primary energy	Heating	Ventilation	DHW	Lighting	Total
Case 4- EWF & Façade renovation	MWh	319	262.3	1058.7	148.8	1789
	kWh/m2	17.9	14.7	59.4	8.4	100
Case 6- EWF & Façade renovation variation 2	MWh	89	262.3	352.9	148.8	853
	kWh/m2	5	14.7	19.8	8.4	48
Increase/reduction		-72%	-	-66%	-	-52%

Table 24: Energy consumption comparison between EWF & Facade renovation case, and EWF & facade renovation variation case.

Thermal comfort

For the thermal comfort assessment, case 6 is compared to case 4 and it is observed that the summer comfort improved for case 6 with 47 hours exceeding 26°C as compared to case 4 with 95 hours exceeding 26°C. The overheating of the space is reduced by the provision of natural ventilation during summers in addition to the EWF system. The ATG graph shows that the space falls under Class B with a 'good' thermal comfort performance with only 6.3% of discomfort hours.

	Hours above 26 °C
Case 4- EWF & Façade renovation	95
Case 6- EWF & Façade renovation variation	47

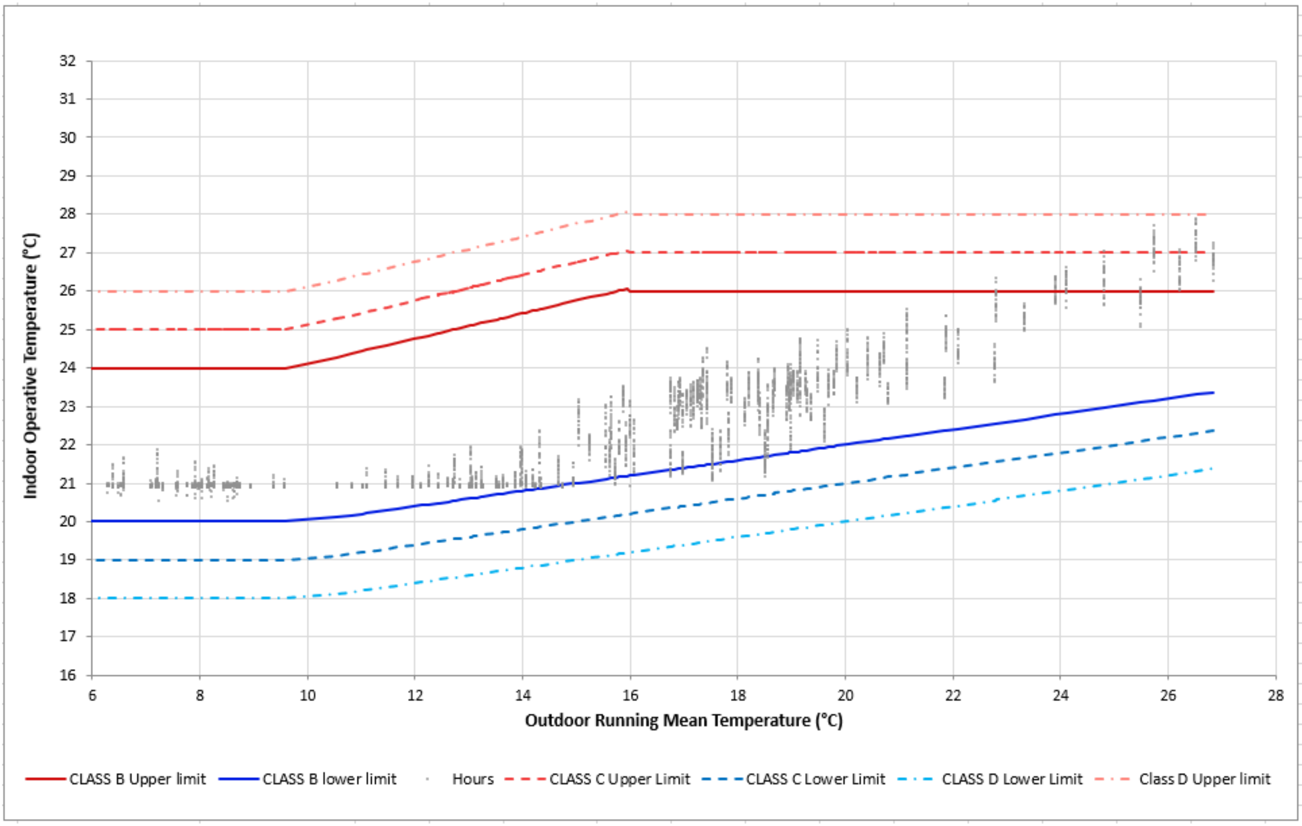
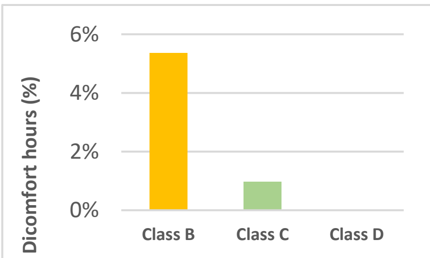


Figure 85: ATG graph for EWF & Facade renovation variation case.

Room	Living
Room type	Alpha
Temperature type	Operative
Analysis period	Jan- Sept
Thermal performance	Good
Class	B

Comfort category	No. of discomfort hours	% of discomfort time
Class B	228	5.37%
Class C	41	0.97
Class D	0	0



8.3 Conclusions

The simulation for energy performance and thermal comfort have been carried out for six different cases using the Design Builder software. On comparing all the six cases together, it is derived that the space heating energy consumption and the total energy consumption for the case 6 is the lowest with a total reduction of 79% thus transforming the existing building into a highly energy-efficient building. This tremendous reduction is due to the major refurbishment of the apartment building where in addition to the installation of EWF system, the existing heating system is replaced and the façade is renovated. To conclude about the potential of EWF system alone, approximately 14% of the total energy consumption is reduced as compared to the existing building without renovating the façade. The system thus has a great potential to reduce the energy consumption for the refurbishment of the apartment buildings. The thermal comfort for case 6 is also the best performing with the least number of discomfort hours especially during summer months. Since case 6 has the best performance among all the different cases in terms of both energy efficiency and thermal comfort, it is chosen for incorporation in the final design. The design shall thus have 'EWF ventilation system annually with natural ventilation during summers, renovated façade by adding exterior insulation and double-glazing windows, ATES heating system with radiator, and ATES system for DHW'. For further improvement in the performance, PVT panels can be added to the building which is elaborated in the next chapter. The BENG criteria assessment for nearly energy-neutral design is performed in the next chapter.

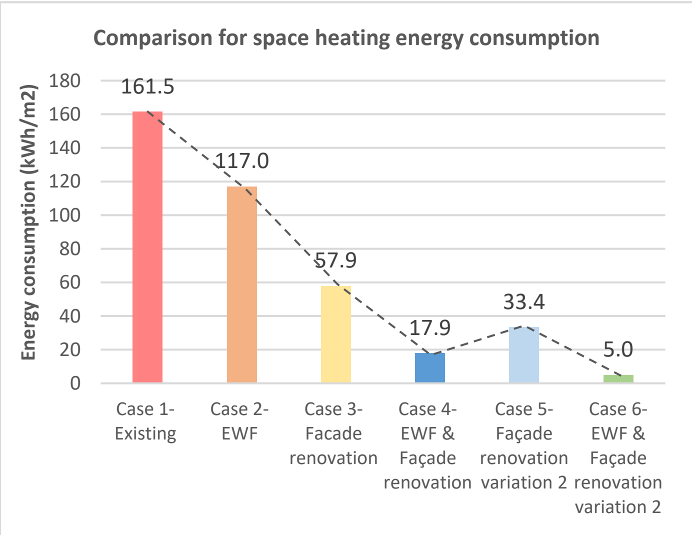


Figure 87: Comparison graph for space heating energy consumption.

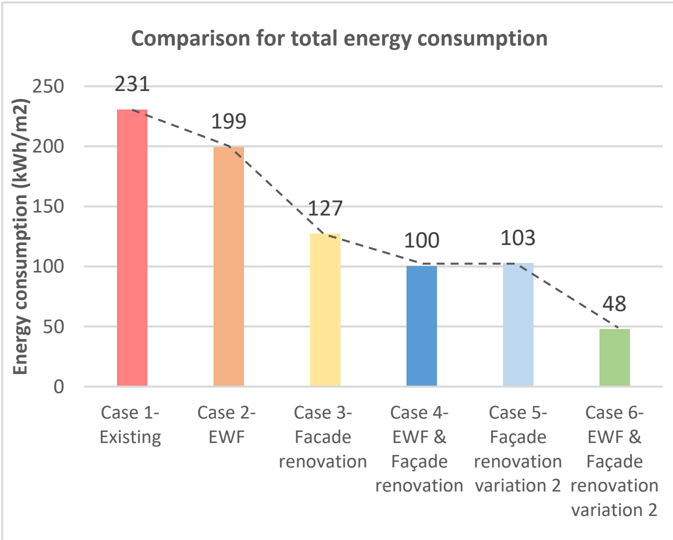


Figure 86: Comparison graph for Total energy consumption.

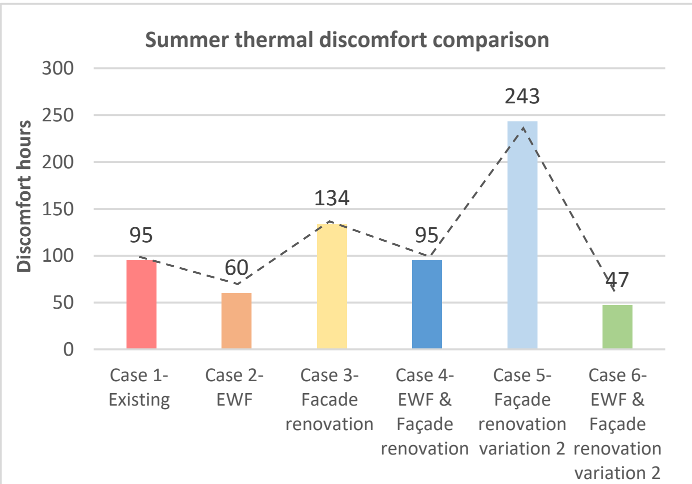


Figure 88: Comparison graph for summer thermal discomfort.

8. Final Design

Based on the energy and comfort assessment, final refurbishment strategy for the Arthur Van Schendelplein building is selected to achieve the goal of a nearly energy neutral design. This chapter describes the final design solution for the total refurbishment of the building, integration of the EWF system in the building and the results of the BENG assessment for the design.

Figure 89: Entrance view of the building.

8.1 EWF design scheme

Principle

The pioneering Earth, Wind & Fire system acts as a central air-conditioning green technology for the Arthur Van Schendelplein housing. The elements Climate Cascade and Solar Chimney are placed centrally at the core of the building uniting both the blocks and exhibiting the energy-efficiency of the building through its exposed chimney and cascade. The air enters at the top of the climate cascade and passes through water nozzles placed at a lower level in the cascade. The water nozzles in the cascade pre-warms or pre-cools the air temperature thereby also humidifying it. The air is then passed through a twin coil unit to further heat up the air temperature to 18 °C in the winters and finally supplied to the apartments through supply ducts placed at each level of the building. When the pressure generated at the base of the Climate Cascade is lesser than the pressure loss, auxiliary fans are activated to generate the necessary pressure. For the exhaust, the exhaust ducts from the apartments bring the air to the shunt channel which is then pulled up in the Solar chimney due to the effect of thermal draft. The auxiliary fans are activated when the thermal draft is insufficient to pull the air to the top. The Solar Chimney has a heat recovery system at the top to restore the heat from the exhaust air before finally exhausting the air from the top of the chimney. The Cascade and the Chimney are both connected at the top together leaving the possibility to incorporate a Ventec roof in the future. The Cascade and the Chimney are both connected to an ATES system for restoring the heat from the Chimney during summers and for cooling/heating the water to 13 degrees before pumping it to the nozzles in the Cascade.

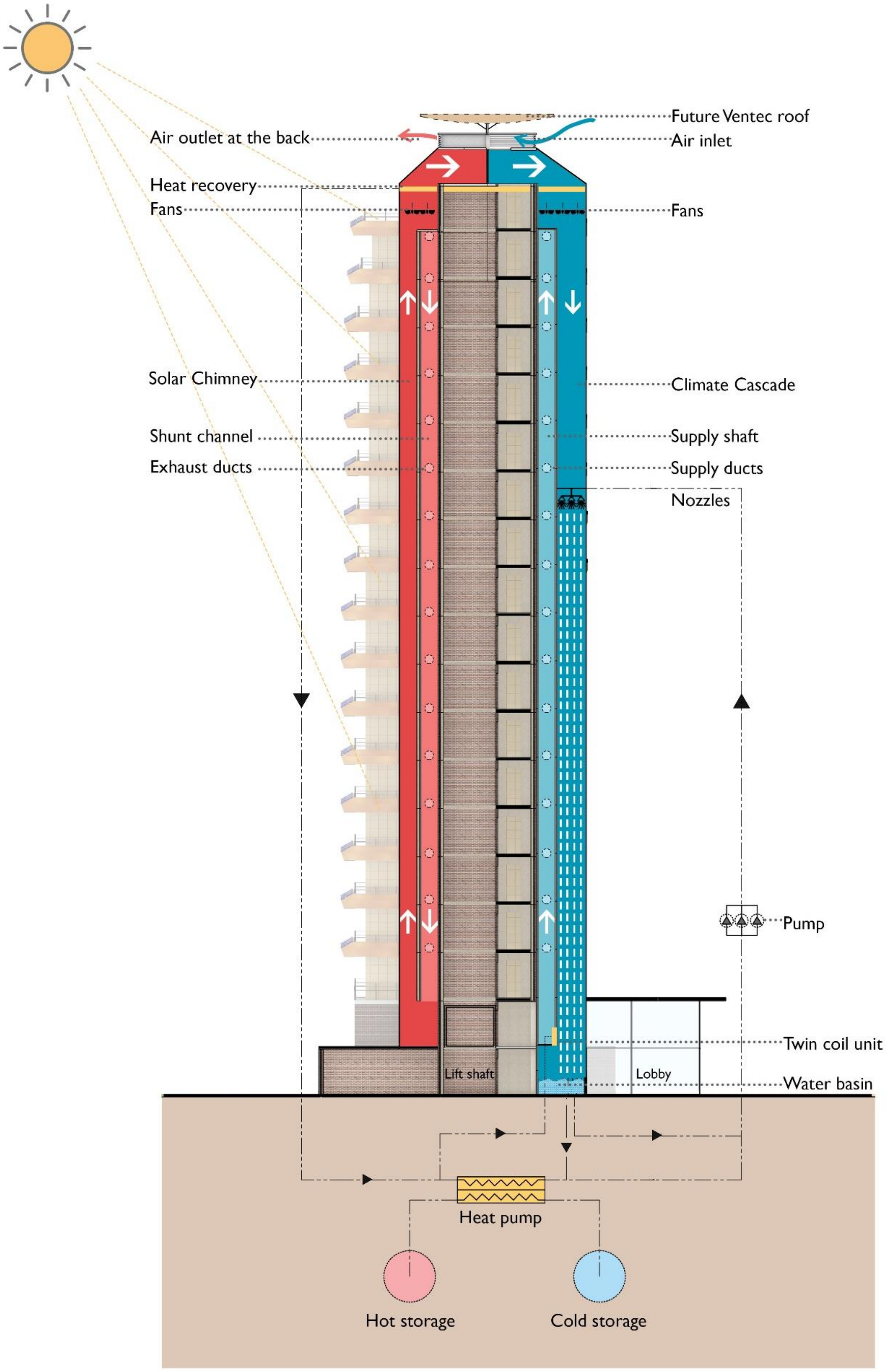


Figure 90: EWF scheme for the building.

Climate Cascade

The Climate Cascade being the heart of the EWF system is strategically placed at the heart of the building and designed as an eye-catching feature. The glazed cascade penetrates through the entrance lobby such that the cascade is the first thing that catches the attention of the people as they enter the building. Moreover, exposing the cascade with its glazed covering and exposed mechanism enlightens the people about the eco-technology of the building. To optimize the performance of the cascade, following components are installed:

- Opening flaps in all the four directions to ensure that fresh air is always drawn at the windward side.
- A heat exchanger at the top of the cascade that is connected through the solar chimney's restored heat. This heat exchanger pre-heats the air slightly before passing it through the water nozzles. It has a bypass for the air to pass during summers in order to avoid any additional pressure losses.
- The support fans ensure that sufficient air flows into the apartments when the pressure generated is lesser than the pressure losses of the supply system.
- The water nozzles are installed at lower level to save pump energy.
- The twin coil unit at the bottom of the cascade is connected to a heat pump.
- Pressure dampers, that are activated when the pressure generated is extremely high than required.
- A water filtering tank which filters the water collected in the water basin before pumping it again till the nozzles. Since the building doesn't have a basement, the equipment room for water filtration is located in the parking space at the ground floor itself.

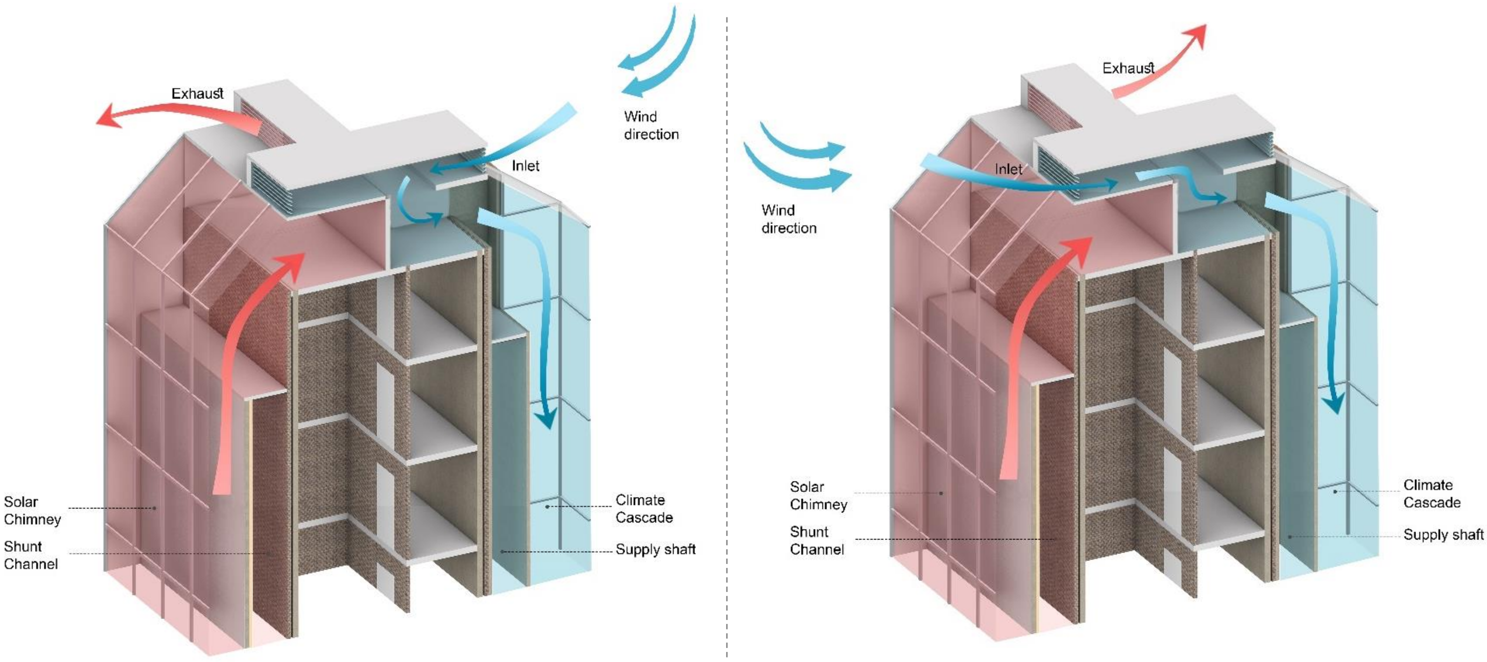
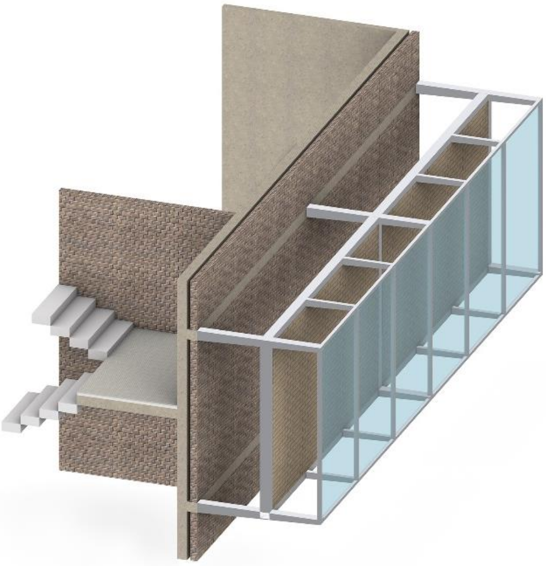


Figure 91: Inlet and extract detail for Climate Cascade and Solar Chimney.

Solar Chimney

The Solar chimney is located on the backside of the core facing the South-east direction. For optimising the performance of the chimney, the back wall is built with a high thermal wall to absorb the heat during the day and support the extraction during night-time when there is absence of the solar radiation for generating thermal draft in the chimney. The front wall is installed with an argon filled 4-16-4 double glazing with a high solar transmittance. The construction of the chimney follows a stick system.

Figure 92: Back view of the building showing solar chimney.



1. Existing concrete wall
2. Existing brick wall
3. Horizontal steel section
4. Steel frame to support shunt wall
5. Insulation 70mm
6. Brick wall 110mm
7. Horizontal steel section to support chimney glazing
8. Transrom and mullion
9. Glazing

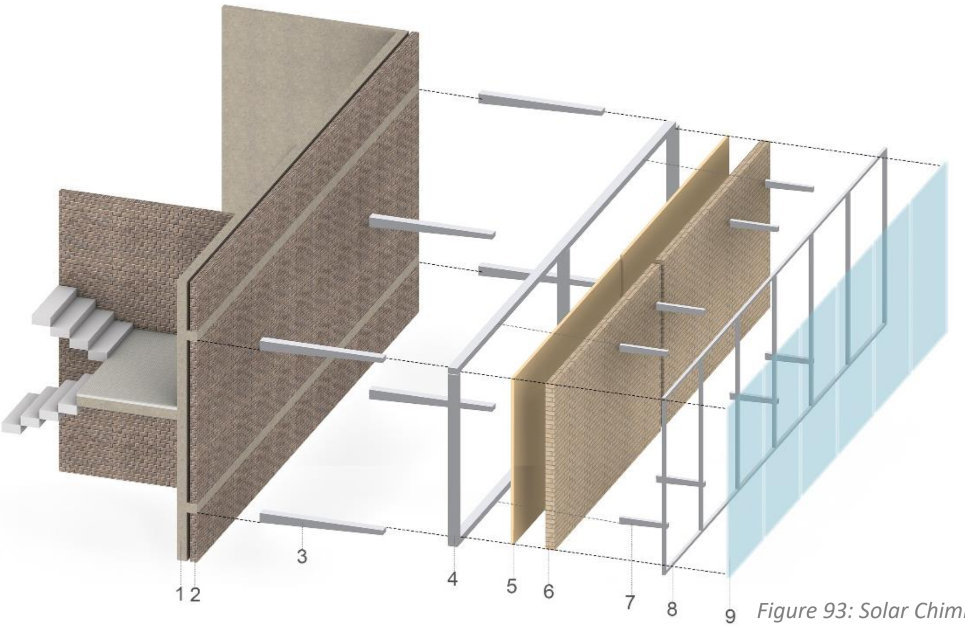


Figure 93: Solar Chimney construction diagram.

8.2 Duct integration

The horizontal supply and exhaust ducts at every floor from the Climate Cascade and Solar Chimney are integrated outside the galleries at opposite sides. The secondary supply ducts to each apartment are provided to living room and bedrooms whereas the secondary exhaust ducts are provided to kitchen, toilet and bathroom. Since the floor height of the apartment is only 2.8m, the ducts are planned adjacent to the existing walls so that the room height stays unaffected.

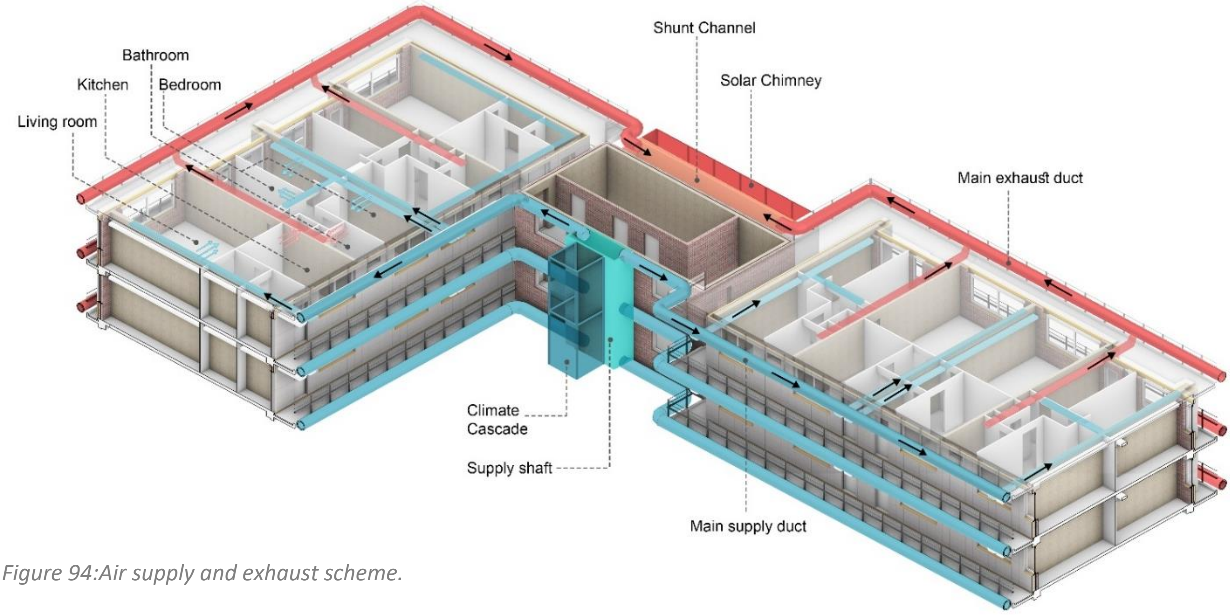


Figure 94:Air supply and exhaust scheme.

The integration of ducts outside galleries is conceptualised as a prefabricated product with a solar panel attached to it which can be integrated in similar apartment refurbishment project using EWF. Based on the duct integration concept, three design possibilities were tested to optimize the product for its feasibility and performance shown in figure 95. The designs were derived followed by the calculation of the duct sizes based on the shape. Since the floor-to-floor height of the apartments is only 2.8m, the ducts should occupy lesser space. The air volume needed and the duct size is calculated in table 25. The duct shape and its placement on the gallery defines the design and the area available for the PV panel. The performance of the PV panel is one of the important criteria for the design of the prefabricated module. The PV module with lesser area and higher energy output is preferred. Another criterion is the view angle from the gallery since the modules will restrict the view to a certain extent. The comparison of the three design options is listed in table 26.

Table 25: Duct size calculation

	Block	**Taller**	**Shorter**
	No. of apartments per floor	9	6
Main duct	Air volume per floor (m3/h)	1800	1200
	Air velocity (m/s)	2.5	2.5
	Duct area (m2)	0.2	0.13
	Duct size – circular (m)	0.5 dia.	0.4 dia.
	Duct size – rectangular (m)	0.25 x 0.8	0.16 x 0.8
Secondary duct	Air volume per apartment (m3/h)	200	
	Air volume per duct (m3/h)	100	
	Air velocity (m/s)	1.5	
	Duct area (m2)	0.018	
	Duct size- rectangular (m)	0.08 x 0.23	

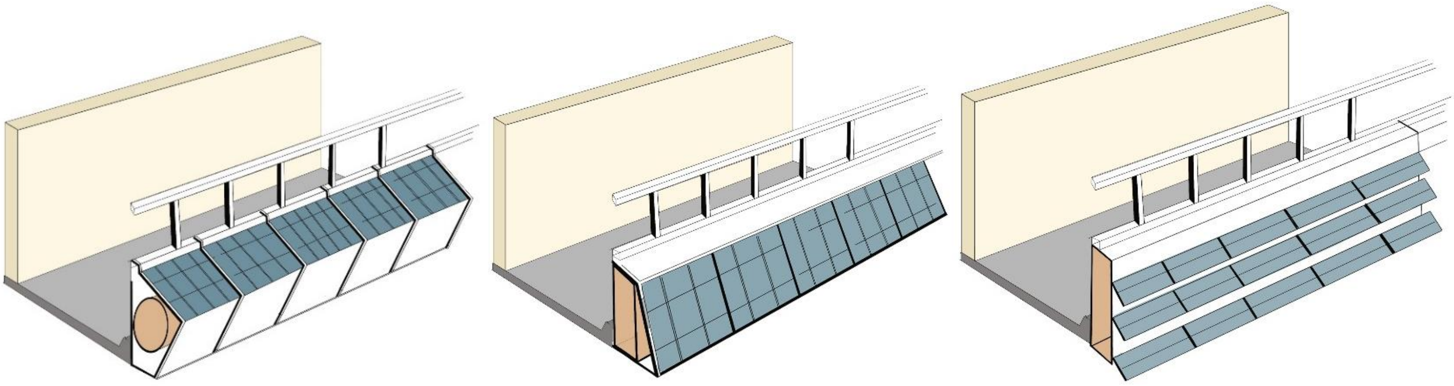


Figure 95: Design options for integrating ducts in the galleries.

Criteria		Option 01	Option 02	Option 03
PV performance	PV angle from horizontal	30 deg.- PV panel	80 deg.- PV panel	30 deg.- PV strips
	PV area (m2)	1542	1690	1480
	Annual energy (MWh)	207.4	153.8	198.2
	Rating	⍟⍟⍟	⍟	⍟⍟
Aesthetics	Rating	⍟⍟⍟	⍟⍟	⍟⍟⍟
View from the gallery	Description	Bulky (760mm width)	Slightly bulky (530mm width)	Sleek (395mm width)
	Rating	⍟⍟	⍟⍟	⍟⍟⍟

Table 26: Comparative table for the three design options.

Based on the above comparison, design options 01 and 03 have a better overall performance. However, option 03 needs careful attention such that the PV modules don't overshadow each other. On the contrary, option 01 with a larger PV panel has the possibility to attach water tubes beneath for improving the PV efficiency as well as meeting some demand for the DHW. The PV yield is highest for option 01 thus contributing more towards renewable energy share. Option 01 is thus chosen for the final design which is detailed further.

The module was first tested through a physical model to establish the different components needed. Each module has a length of 1.2 m since the modules are designed to be attached on the railing post and the distance between the post is 1.2m.

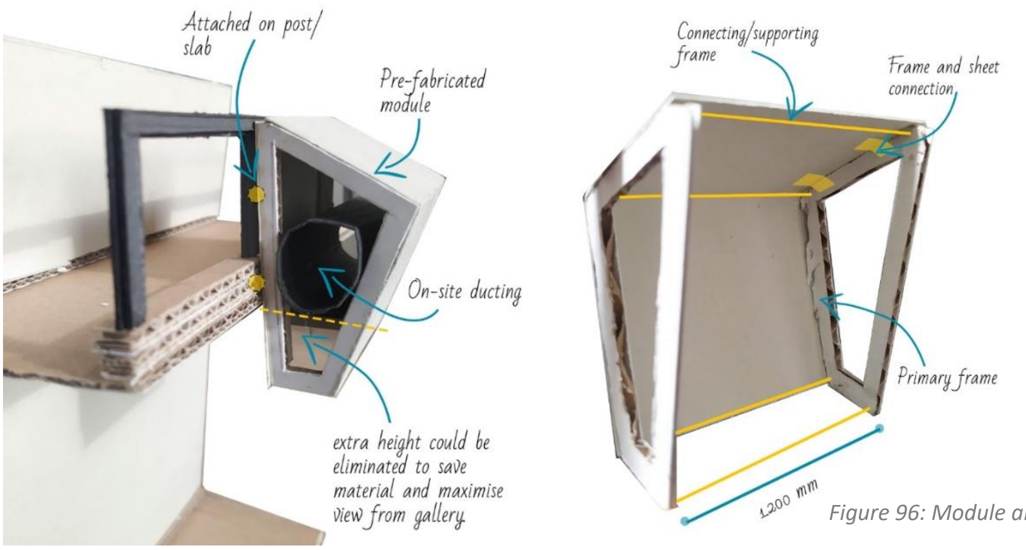


Figure 96: Module analysis through physical modelling.

The assembly process for the integration of the module is described below and shown in the figure 97.

Step 01: First the ductwork is connected to the existing slab through the use of steel section anchored in the slab. The primary duct is well-insulated in order to avoid any heat loss through the ducts.

Step 02: Once the duct is fixed in place, the inner cover plate is attached from the gallery side which is fixed to the railing post from the top and the bottom. Followed by this, the pre-fabricated module is attached from the outside for covering the duct. This pre-fabricated module has steel connecters installed at the top for connecting the PVT panels.

Step 03: As a final step, the PVT panel is attached at the top of the pre-fabricated module.

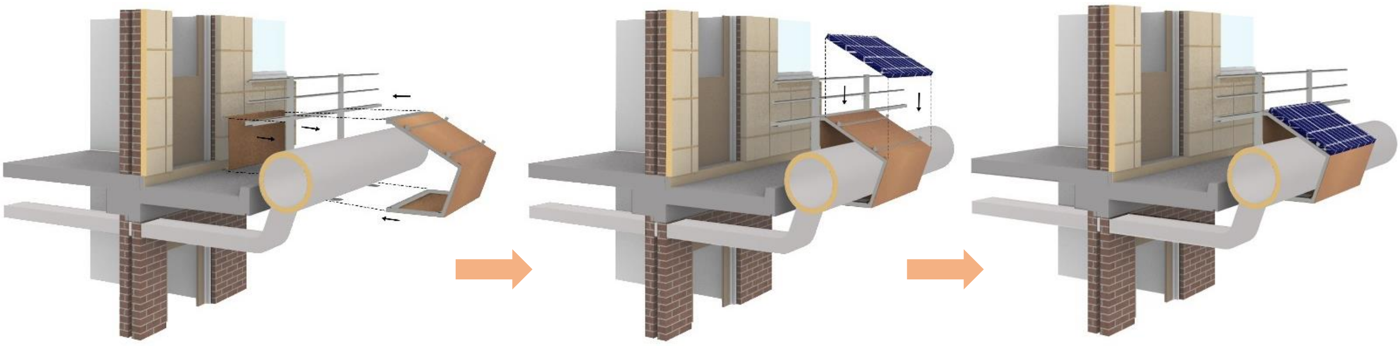


Figure 97: Assembly process for module integration.

8.3 Refurbishment details

In addition to connecting the module with the railing, another important aspect is the refurbishment of the existing façade. An exterior insulation layer is added to the existing brick wall to improve the energy performance of the building. The existing single glazing windows are replaced by the double-glazed windows to improve the glazing performance and the air-tightness of the wall. The order of refurbishment is described below and shown in the figure 98.

Step 01: The first step is to attach the primary duct to the existing post as described in section 8.2. For connecting the secondary ductwork, a hole is made in the existing brick to make space for duct to enter the apartment.

Step 02: After finishing the ductwork in the apartment, the hole made in the existing wall is then packed with insulation material to avoid any heat loss through the façade and an external insulation layer is added to the existing brick wall using anchor fixing. A reinforcement mesh is added from outside to hold the insulation layer.

Step 03: Next, the existing single glazed window is removed from the façade and a double-glazed window is added to the façade.

Step 04: The façade refurbishment is completed by adding an exterior finish layer.

Step 05: For the final step, the pre-fabricated module is attached to the railing post and slab as described in the section 8.2. The pre-fabricated module consists of a primary steel frame, alucobond cover sheeting and connectors for the PVT panel at the top.

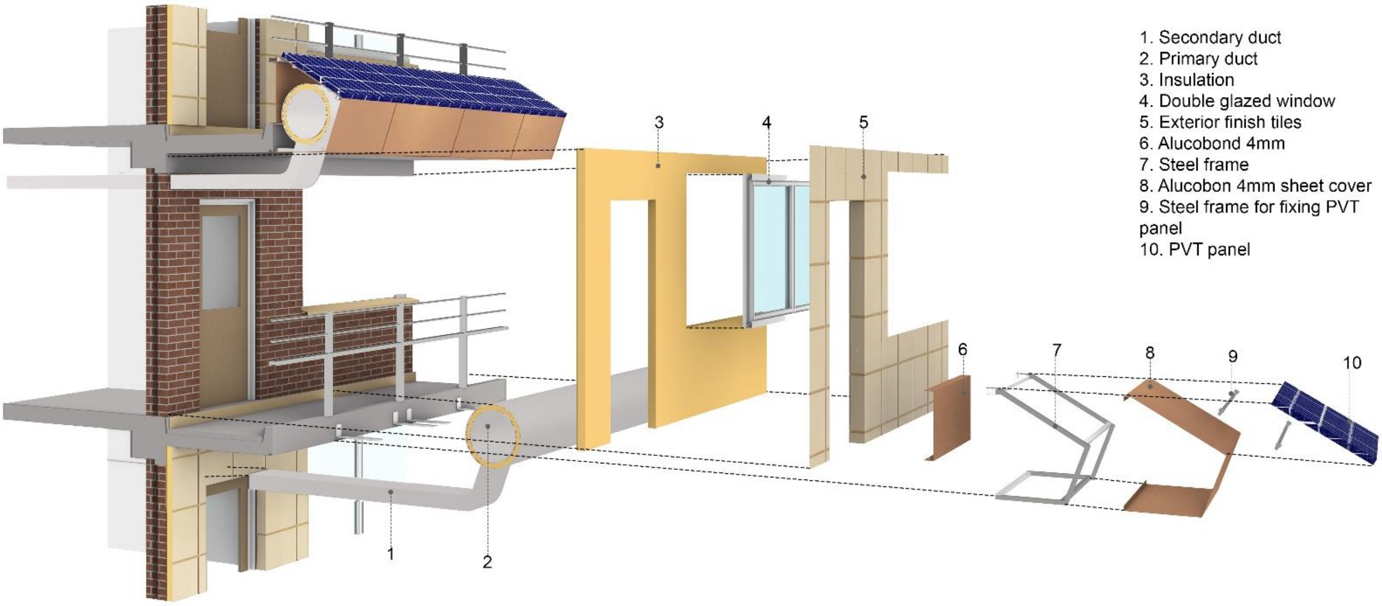


Figure 99: Diagram showing the order of the refurbishment.

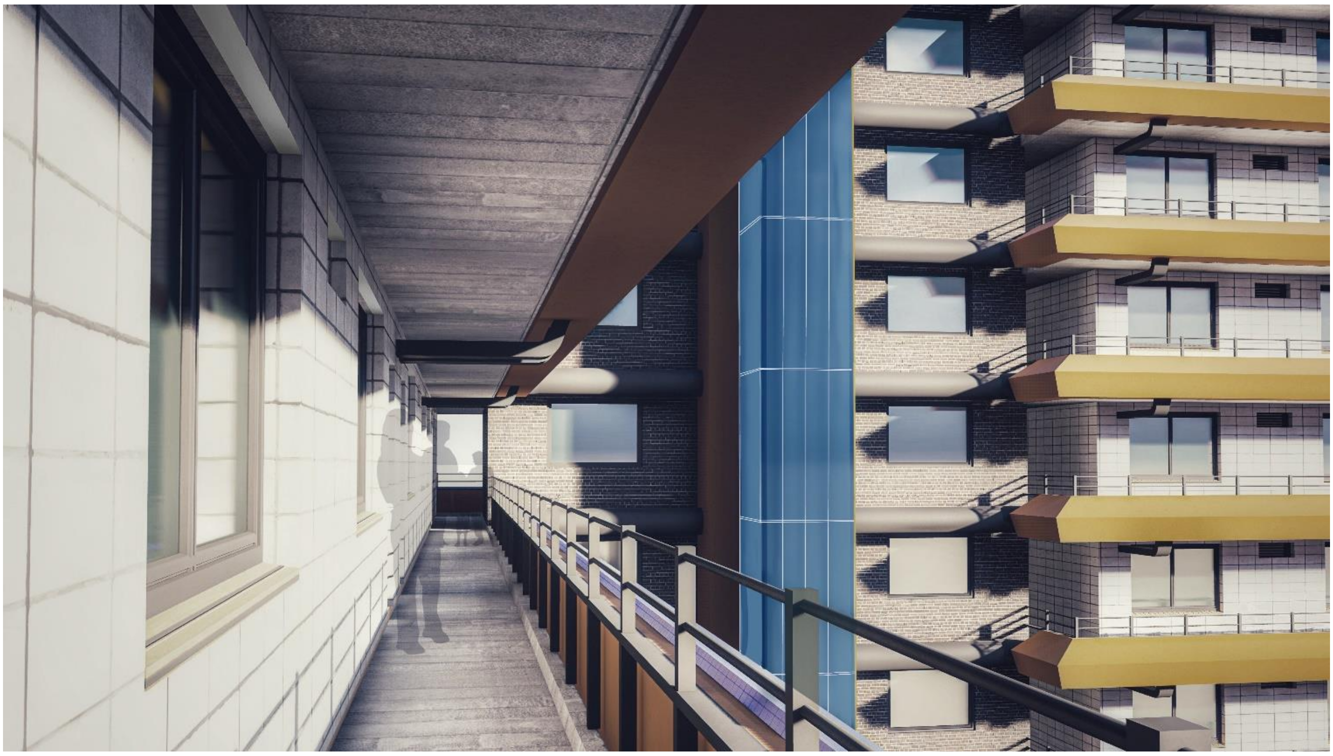
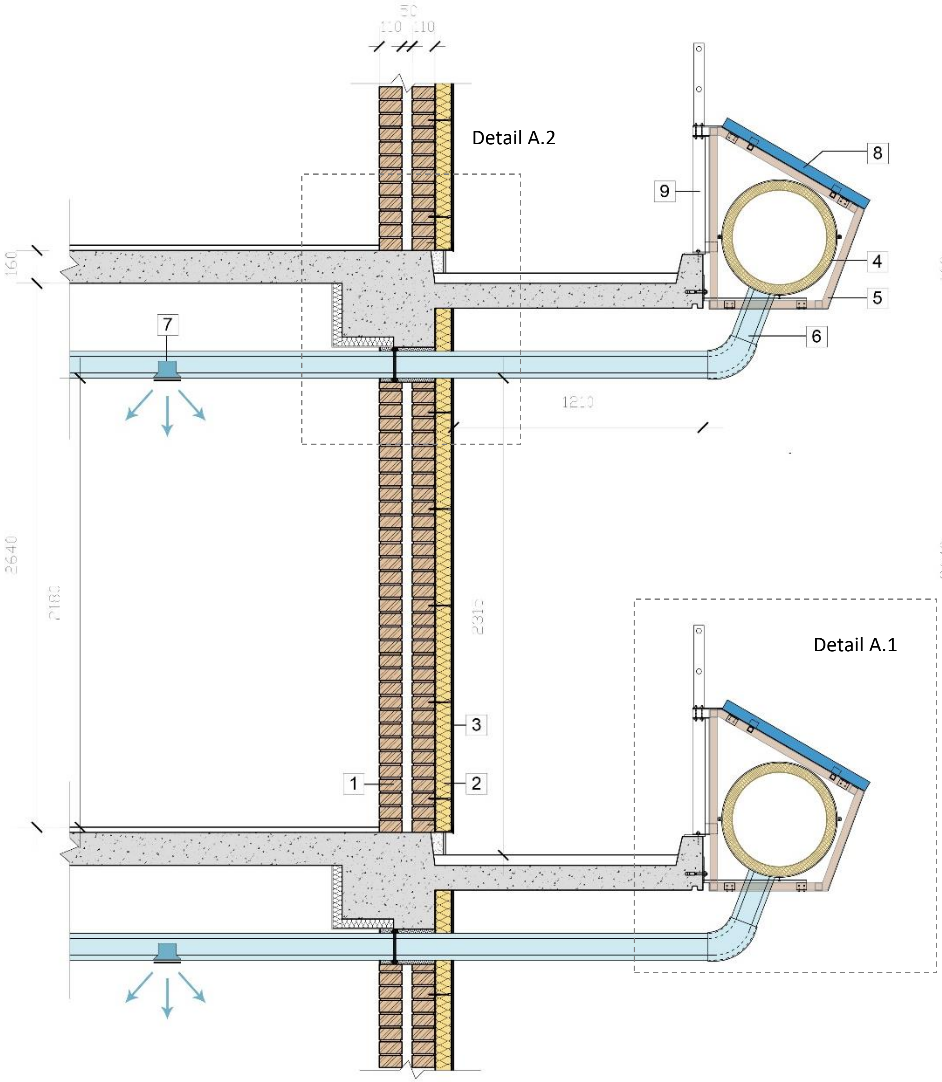


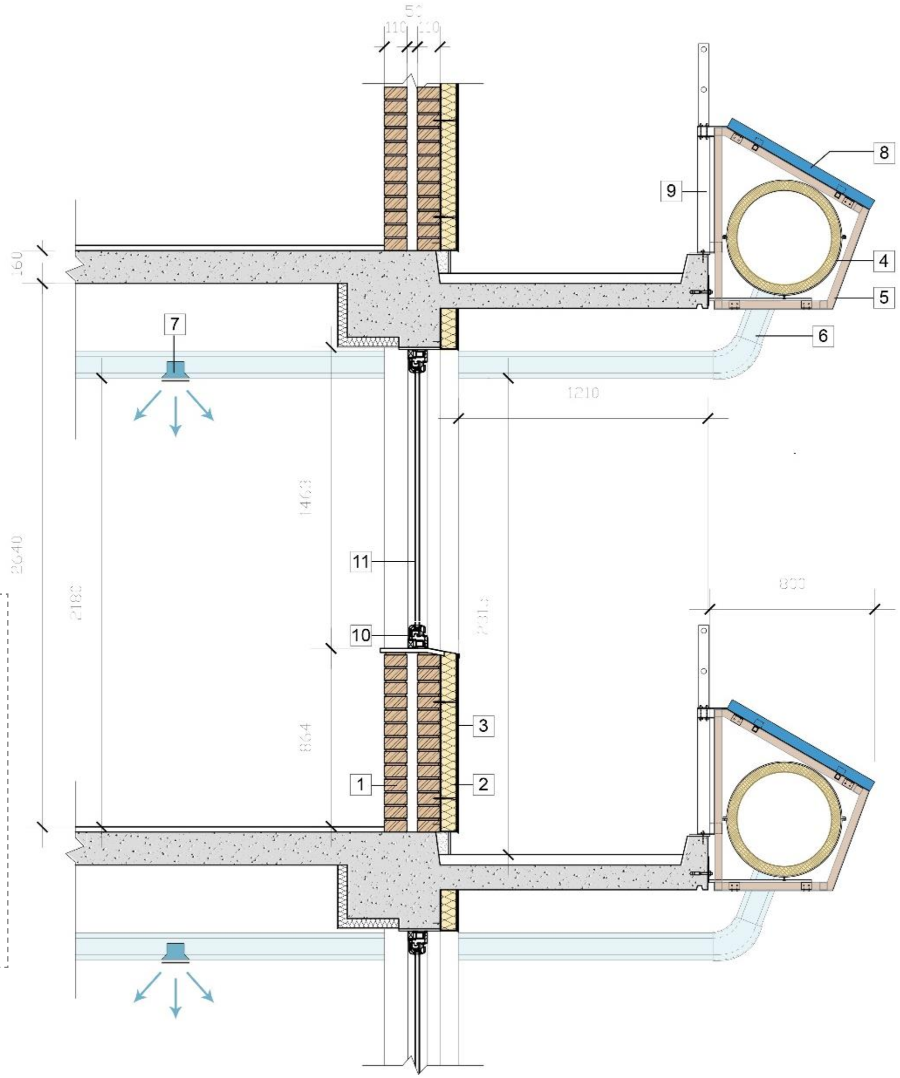
Figure 98: View from the gallery.

The detailed drawings for the refurbishment are provided below:



Section A

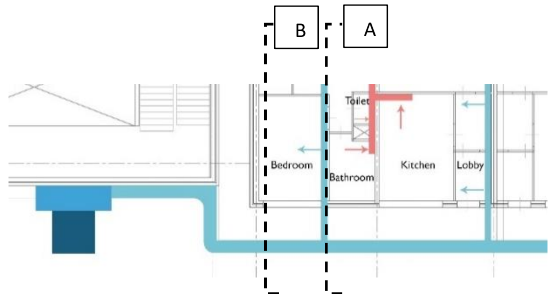
Figure 100: Sectional detail through the duct connection.



Section B

Figure 101: Sectional detail through the glazed part of the facade.

1. Cavity brick wall
2. 75mm Rockwool insulation
3. Exterior finish
4. 500mm dia. supply ductwork
5. Pre-fabricated module
6. 230 x 80mm secondary ductwork
7. Diffuser
8. PVT panel
9. Existing railing post
10. Aluminium window frame
11. 6-13-6 mm low-e double glazing with argon gas filling



`1. Railing- horizontal post 80x40mm

2. Railing- vertical post- 60x40mm

3. RCC slab

4. Anti-reflective glazing

5. PV layer

6. Water tubes

7. Insulation

8. Primary hollow steel frame 35x35mm

9. Alucobond 4mm

10. Primary duct 530mm dia.

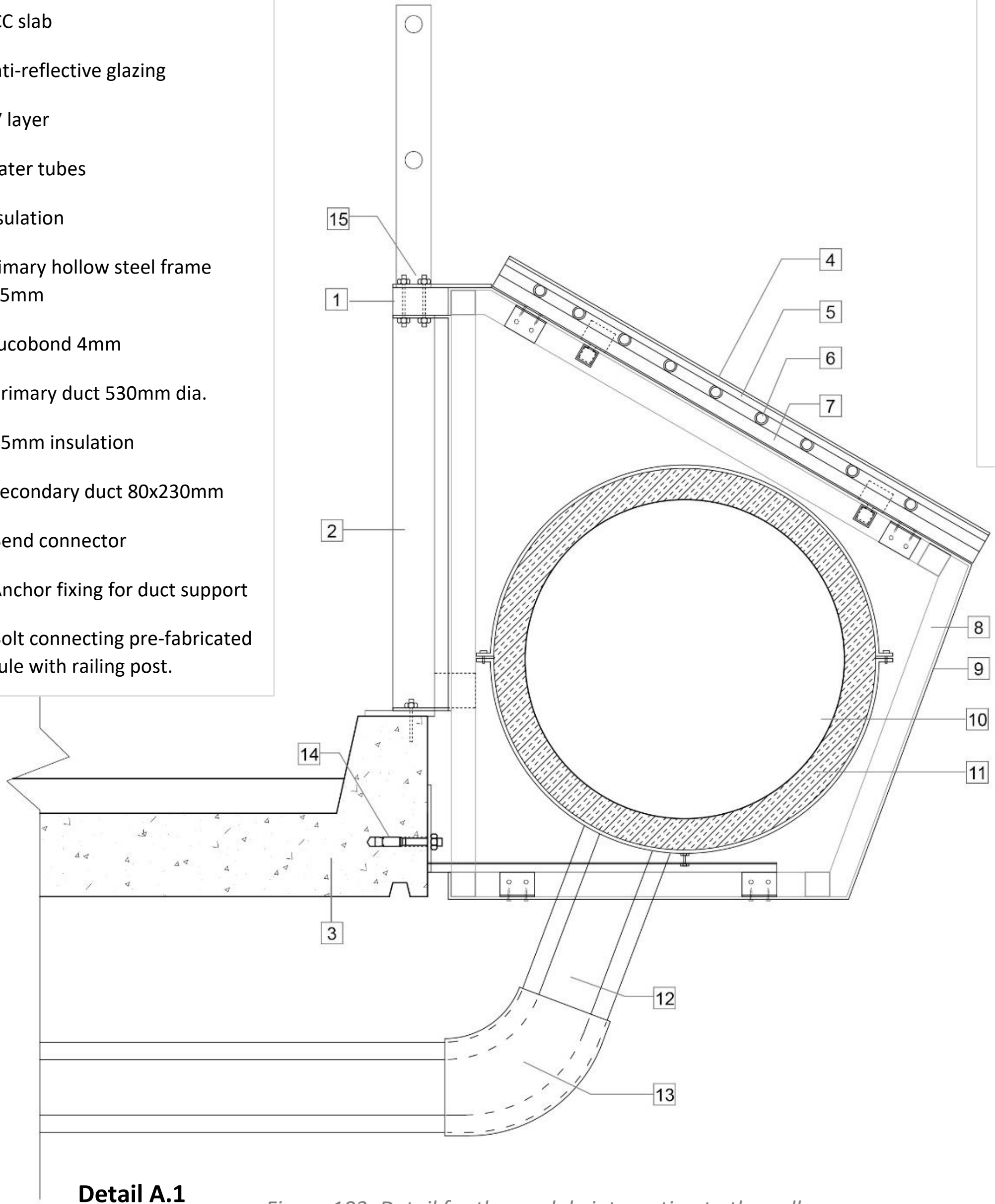
11. 45mm insulation

12. Secondary duct 80x230mm

13. Bend connector

14. Anchor fixing for duct support

15. Bolt connecting pre-fabricated module with railing post.



Detail A.1

Figure 103: Detail for the module integration to the gallery.

1. Cavity brick wall

2. Adhesive layer

3. Rockwool insulation 75mm

4. Reinforcement Mesh

5. Render Primer

6. Fixing anchor

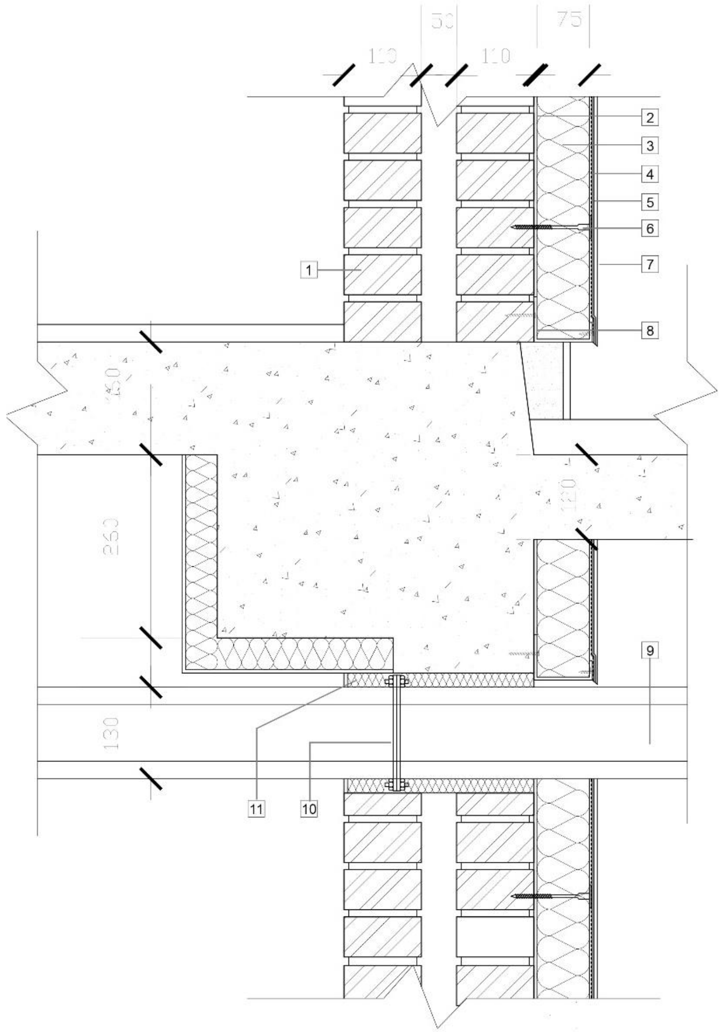
7. External finish sheet 5mm

8. Steel C- profile

9. Secondary duct 80x230mm

10. Steel plate connecting ducts

11. Insulation packing



Detail A.2

Figure 102: Detail for the duct fixing through the external wall.

8.4 Building Installation

Based on the results obtained from the energy & comfort assessment of the building, the final design has the following installations for achieving a nearly energy neutral design:

- EWF system for the ventilation of the building,
- Low temperature water radiator for space heating connected to the ATES system, and
- DHW system connected to the ATES system and the heat pump

The working principle of the entire building system for the summer and the winter scenario is explained below:

Winter Scenario

During the winter months, the ATES system acts a heat source by transferring the heat from the aquifer to the building to meet the heating energy demand. Secondly, the heat recovered from the Solar Chimney is used for pre-heating the incoming air in Climate Cascade. When the outside temperature is 2°C, the air at the top of the chimney is 20-25 °C. After passing through a heat recovery system with an efficiency of 70%, 15-20 °C heat is recovered which is then passed to the Climate Cascade through the use of a water medium. The air-to-water heat exchanger installed at the top of the Cascade pre-warms the incoming air till 10-11 °C which is then passed through the water sprinklers. The water from the Cascade is passed through a ground source heat exchanger to maintain the water temperature of 13 °C. The air at the bottom of the Cascade is further heated till 18 °C through the use of a twin-coil unit which is connected to the heat pump. The 18 °C is then supplied to the apartments through the use of supply ducts. For the space heating, the heat pump connected to the ATES system heats the water temperature will 50°C which is then supplied to the radiators in the apartments. For the domestic hot water, the heated water from the main heat pump is firstly passed through a booster

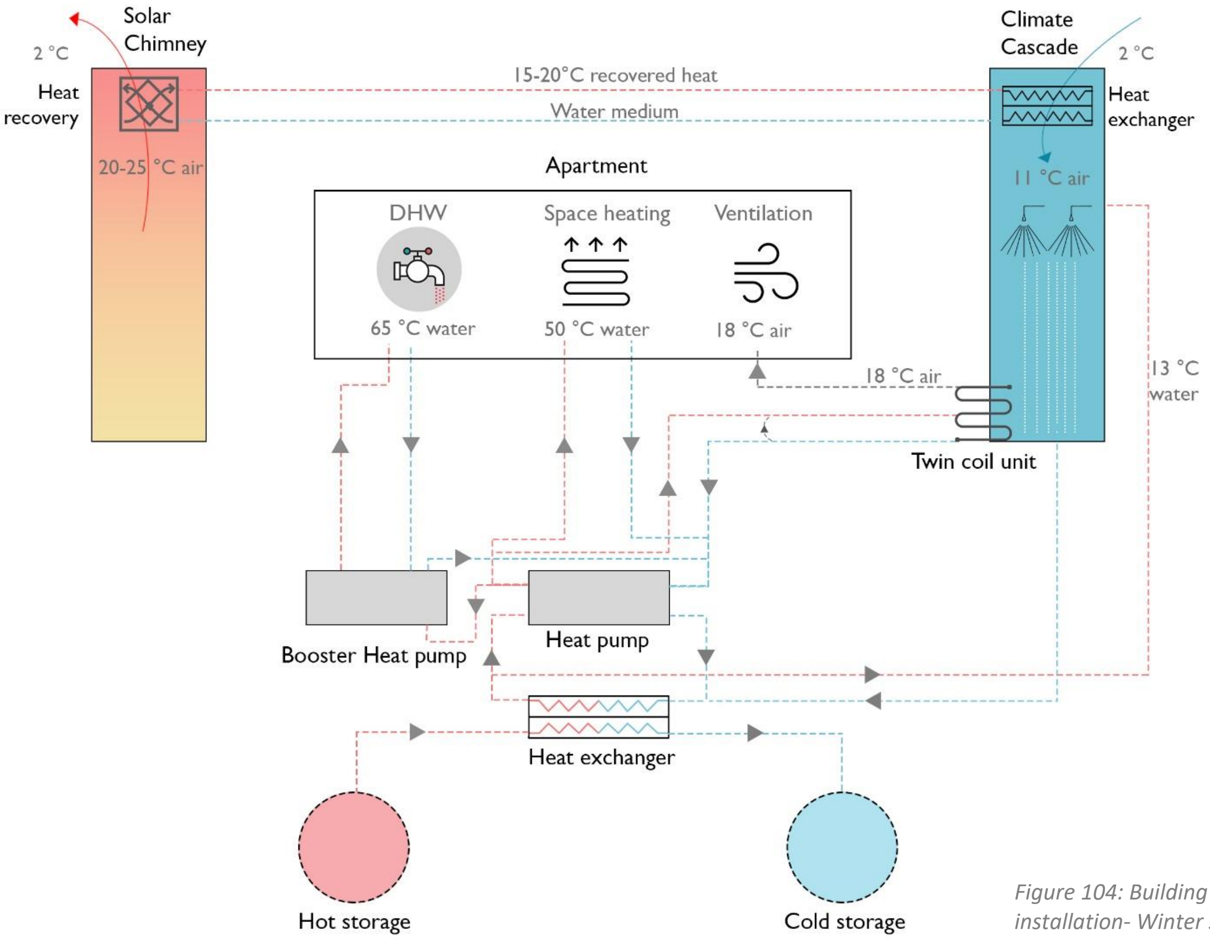


Figure 104: Building installation- Winter scenario

heat pump to further increase the water temperature till 65- 70 °C. This hot water is then supplied to the apartments in the bathroom and the kitchen.

Summer Scenario

During the summer months, the ATES system is only used for cooling the water temperature till 13 °C since the building doesn't have an active cooling system. Since the DHW system is connected to the heat pump, there is also a need to use the heat from the ATES during the summer months to heat the water. However, in this case the recovered heat from the Solar Chimney is used for DHW in order to reduce the energy consumption to a certain extent. Hence this would reduce the dependence on the ATES system for DHW. When the outside temperature is 28 °C, the air temperature at the top of the chimney is 30-35 °C which is passed through a heat recovery system. 25-30 °C heat is recovered from the Solar Chimney which is then passed to a booster heat pump for further increasing the water temperature till 65 °C.

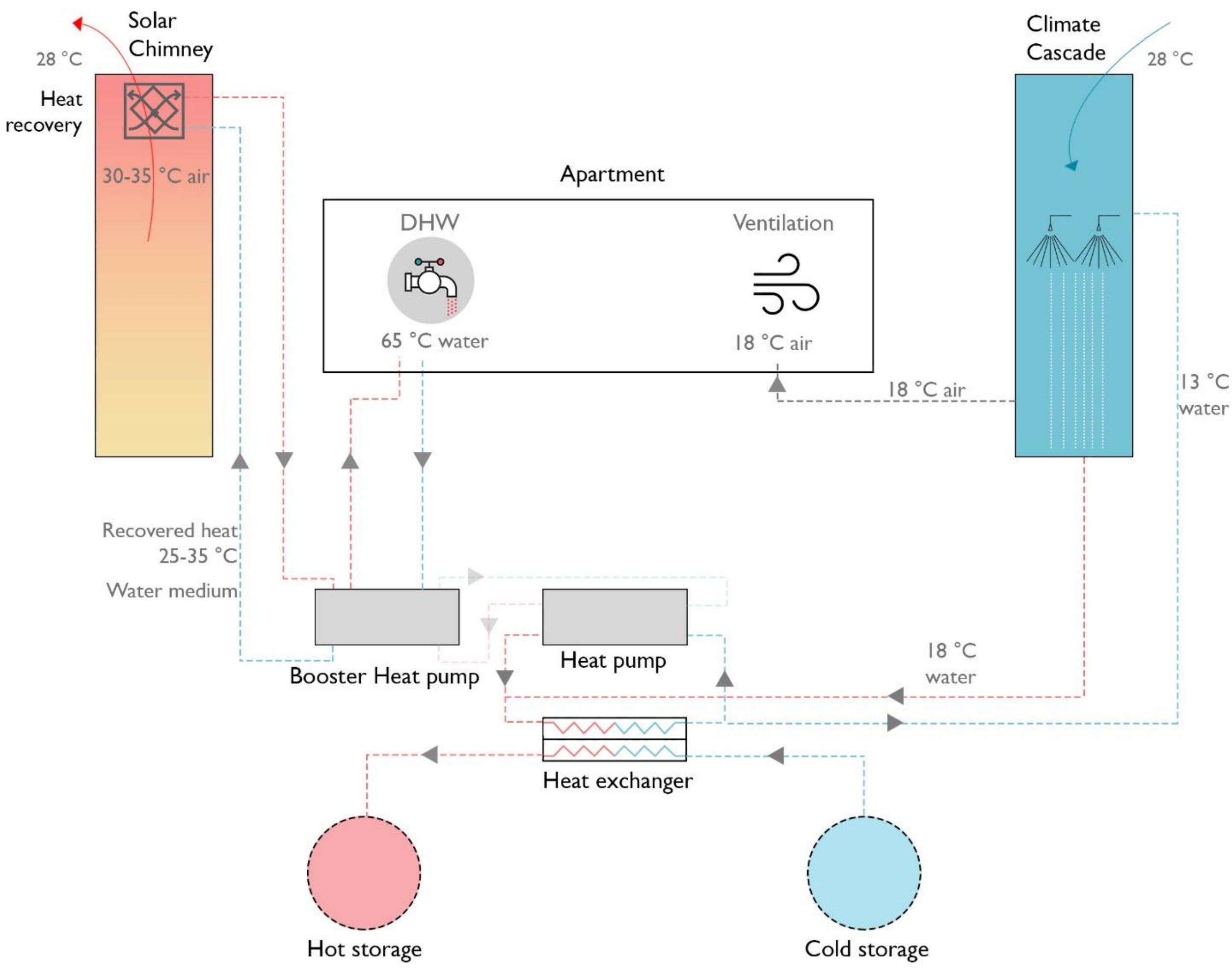


Figure 105: Building installation: Summer scenario.

8.5 BENG criteria evaluation

The final refurbished design is evaluated for BENG criteria to derive whether the building achieves the goal of a nearly energy neutral design. BENG 1 sets a maximum energy requirement for heating and cooling, BENG 2 sets the maximum allowed primary fossil energy use and BENG 3 sets the minimum percentage of renewable energy share for the building. The final energy consumption values obtained from the Design Builder software is used for the BENG assessment. However, those values are obtained for secondary energy which needs a conversion into primary energy for BENG assessment. The Primary energy conversion factor (PEF) is taken as 1.45. Secondly, the ATES system has some part of renewable energy and some part of electrical energy for which a COP of 4 is used for heating and a COP of 3 is used for DHW. The Heating energy consumption also includes auxiliary energy that is the additional heating consumed in the Climate Cascade to heat the supply air till 18 °C. The total primary energy consumption for the building is calculated in the table below.

Annual Energy Use								
	Energy from DB calculations	**COP**	**Secondary energy (kWh)**	**PEF**	**Primary Energy (kWh)**	**Auxiliary secondary energy (kWh)**	**Auxiliary primary energy (kWh)**	**Total Energy (primary + auxiliary) (kWh)**
Heating	89,100	4	22,275	1.45	322,98.7	237,347	344,153.15	376,451.9
Fans & Pumps		-	23,830	1.45	345,53.5			34,553.5
DHW	1,058,706	3		1.45		352,902	511,707.9	511,707.9
Lighting	1,48,797	-	148,797	1.45	215,755.6			215,755.6
								1,138,468.95

Table 27: Annual Primary energy use.

The total renewable energy use of the building consists of the energy generated by the PV panels installed outside the galleries and the renewable energy share from the ATES system for heating and DHW. The PV panels are currently only installed at the prefabricated duct module. For further increasing the renewable energy share, the PV panels can also be installed at the roof of the building.

Annual Primary Energy consumption	
Total Energy (primary + auxiliary) (kWh)	1,138,468.95
Energy generated by PV (kWh)	207,360
Annual primary Energy consumption (kWh) (E_total)	931,108.95

Renewable Energy	
Heating	66,825
DHW	705,804
PV	207,360
Total (E_ren)	979,989

The final design satisfies all the three BENG criteria thus it can be derived that the refurbishment of the Arthur Van Schendelplein building transforms the building into nearly energy neutral housing.

BENG Assessment				
Usable Floor area (UFA)(m2)	17820			
BENG category	**Criteria**	**Formula**	**Results**	
BENG 1	<65	Heating	57.9	Satisfied
BENG 2	<50	(E_total-Lighting)/UFA	40.14	Satisfied
BENG 3	>40	E_ren/ (E_total + E_ren)	51.28%	Satisfied

Table 28: BENG criteria evaluation for the building.

9. EWF in housing refurbishment guidelines

Based on the different design strategies explored earlier, design guidelines have been formulated which serve as a starting point for implementing EWF system in housing refurbishment projects with similar typology. This chapter provides a brief introduction to the guidelines for integrating Solar Chimney and Climate Cascade. The guidelines have two broader categories- Architectural integration and technical design.

Architectural integration-

The EWF system with its stunning elements Climate Cascade and Solar Chimney provides an opportunity to emphasize the architectural quality of the existing building. This category includes the integration strategies based on four aspects:

- Placement of CC and SC elements with defining the decision parameters for the selection of one placement strategy.
- Duct integration possibilities for the design scheme.
- The construction systems for both the elements.

Technical design-

This category provides the main technical design strategies for both the elements to maximise the performance of the system. The Climate Cascade with many technical parameters is difficult to design without in-depth knowledge of its working mechanism. The technical design category shall help in bridging this knowledge gap.

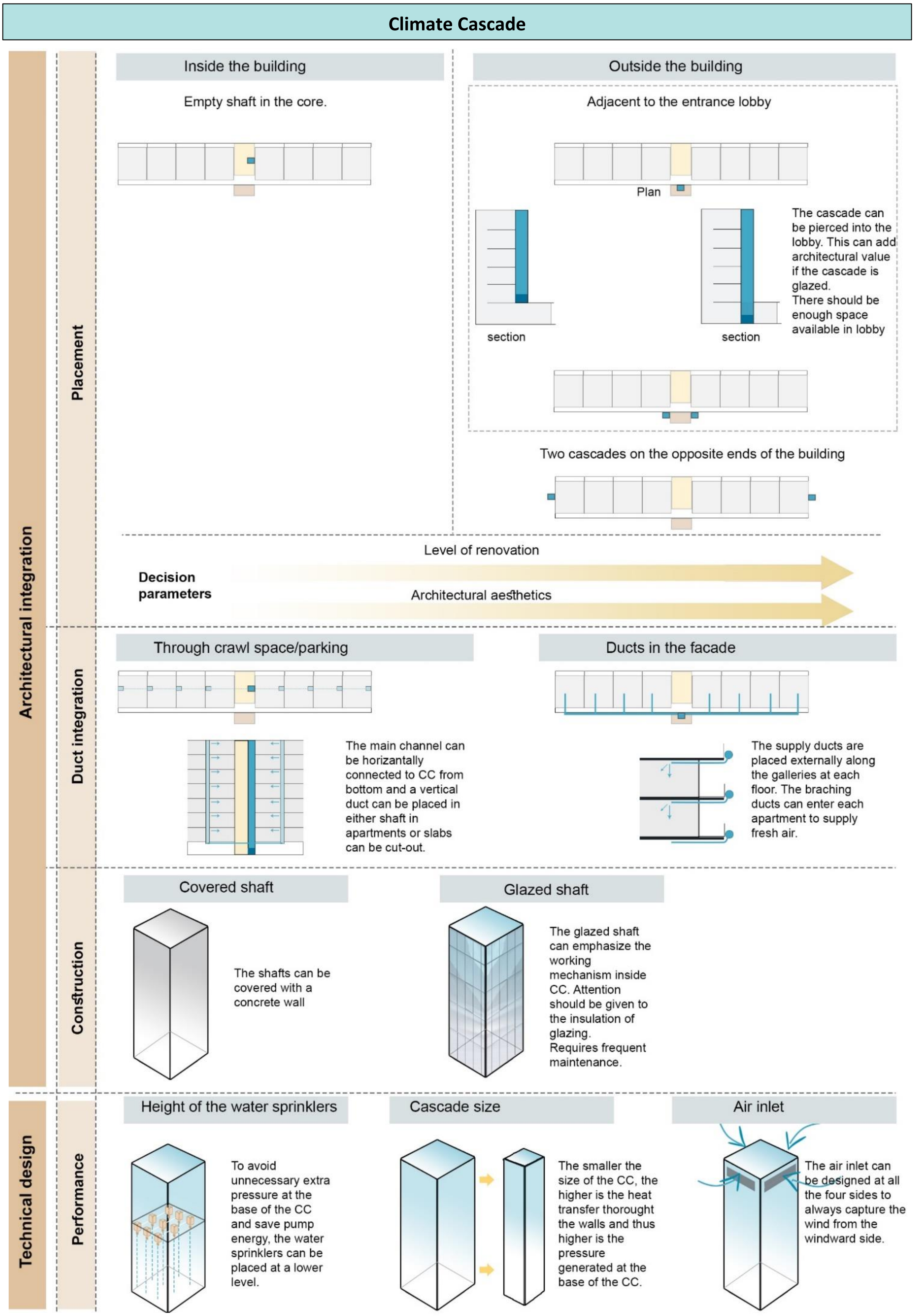


Figure 106: Climate Cascade design guidelines.

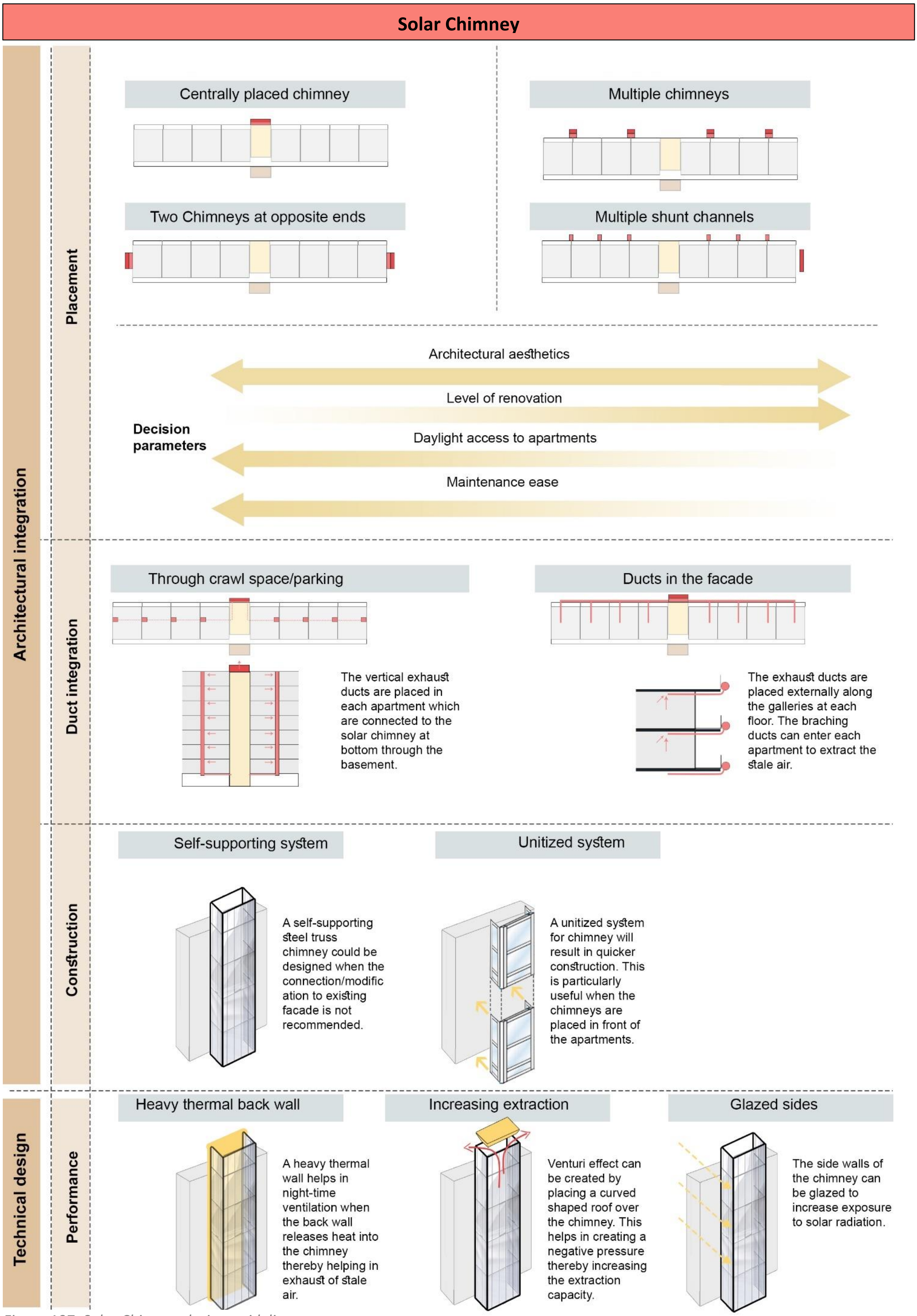


Figure 107: Solar Chimney design guidelines.

10. Discussion

The research explored different strategies for integrating EWF into the housing buildings as well as additional refurbishment measures essential to improve the energy efficiency and comfort. A step-by-step methodology has been followed to accomplish the research in the available time frame. However, throughout the extent of the process, certain limitations were faced and a few assumptions were taken up wherever necessary. This chapter elaborates on these limitations, assumptions and a few directions on future research.

The design options were derived on the basis of placement and the number of Solar chimney and Climate Cascade; however, the effect of the shape of SC and CC were not explored. For the Climate Cascade, the heat transfer through the walls of the Cascade has a considerable impact on the pressure generated at the base and thus the shape of the Climate Cascade can impact the energy performance of the system. For all the design options explored in this research, the Climate Cascade is designed with a square shape. For the Solar Chimney, during the literature study it was found out that a multi-directional chimney with a trapezoid shape has higher thermal draft thus reducing the fan energy consumption. However, since the excel calculation model for the Solar Chimney is prepared for the rectangular shape, further research on the shape has not been performed. In addition to all the other parameters that were explored, the shape effect can be included for a comprehensive design strategy.

One of the assumptions was the pressure loss value for the supply system that was taken up as 150 Pa based on the discussion with Dr. Ben Bronsema. The total pressure loss calculation for the supply system includes the pressure losses due to grills, vents, heat exchangers, duct bends and length, etc. which is technically further calculated more precisely by the mechanical engineer and hence the detailed calculation has not been performed for this research.

The effect of the wind speed factor has not been considered while calculating the pressure generated values in the Climate Cascade. The wind flaps for the air inlet are provided in all the four directions that are controlled by a Building Management System with the assumption that the wind will enter the Climate Cascade due to high wind speed at 54 metres height. The pressure generated at the base of the Climate Cascade also includes the wind factor in addition to the hydraulic and thermal pressure, thus further improving the performance of the Climate Cascade. The excel calculation model can be further upgraded to include this aspect.

The Climate Cascade is designed as a glazed shaft rather than a typical concrete shaft with the assumption that a well-insulated glazing shall result in negligible heat loss to the outside. The decision to design a glazed shaft was based on enhancing the architectural character of the building by exposing the efficiency of the system to the residents and enhancing their knowledge about this ecotechnology. Since the research did not focus on the effect of materiality in detail, validation of the glazed shaft has not been taken into account. However, this materiality aspect can be dived deeper for assessing the performance of the Climate Cascade and this would add an architectural feature to the building rather than hiding the system in a covered concrete shaft.

The calculations performed for the Solar Chimney show that there is lesser thermal draft during the summer months due to less difference in the outside and inside temperature. This results in some amount of fan energy consumption. In order to overcome this issue, some amount of exhaust air can be extracted from the windows with the use of natural ventilation. However, since the design builder software does not incorporate the physical modelling of the Solar Chimney, the calculations does not include this aspect.

One of the major limitations was modelling and simulating the EWF system in the Design Builder software. Since the EWF system is not included in the Design Builder templates, the system was imitated such that an air supply of 18°C is provided into the spaces by adding a Variable air volume template from the Design Builder HVAC template. The calculations were thus performed by studying the effect of the 18 °C air supply into the spaces on the total energy consumption of the building. The humidification/dehumidification effect of Climate Cascade and the extraction capability of Solar Chimney is thus not included in the simulation. Thus, the final results obtained from the simulations might have some percentage of deviation from the actual energy consumption of the building.

The existing apartment buildings have negligible ventilation energy consumption as compared to the EWF system. The current prevailing strategy for apartment refurbishment includes the installation of MVHR systems. A comparison between ventilation energy consumption for MVHR and EWF could also add another decision-making parameter for a holistic comparison.

For evaluating the thermal comfort of the design, the ATG method has been followed which categorises the building in alpha or beta type. The EWF system ideally falls somewhere in between both the categories since it has a cooling effect but there is an absence of active space cooling in the building. The design thus falls under a hybrid category. However, the ATG method does not have an evaluation criterion for hybrid design and thus this research has chosen beta type category for the EWF system. Moreover, the thermal comfort conditions for the residential buildings are not as strict as the office buildings. Hence more research is needed for a detailed conclusion regarding the evaluation of thermal comfort for residential buildings.

For the energy performance assessment, the amount of ventilation is kept same for all the cases for a fair comparison. The existing state of the building is simulated with the provision of natural ventilation throughout the day. However, in reality the operation of the window openings is performed by the user and thus the amount of natural ventilation might differ. This effect is however not included in the Design Builder software.

The BENG calculation is performed with the NTA8800 software. However, the present research includes the verification of the BENG assessment using the results obtained from the Design Builder software. Hence the BENG assessment for the final design is a first impression of the energy performance results.

Future recommendations:

At present, the research focussed on the investigation and design of the system integration based on the energy and comfort performance. A valuable addition to this research could be the evaluation of the economical aspect associated with installation of the EWF system.

In addition to thermal comfort, the air quality assessment could be carried out to paint an overall picture for the health benefits of the residents of the apartment. With unprecedented circumstances such as corona, where the residents are obliged to stay and work from home, air quality is the need of the hour.

Another recommendation which would be beneficial for the assessment of the EWF system's performance is developing a dynamic simulation calculation tool to get more accurate results rather than imitating the supply air temperature of the EWF system in a software. Although this would require immense amount of time since there are multiple parameters involved in the excel calculation model and translating those into a dynamic simulation tool would be certainly challenging.

11. Conclusions

This section discusses the conclusion of the study by answering the research question: *How can the Earth, Wind & Fire system be integrated in the Housing refurbishment in the Netherlands to achieve a nearly energy neutral design and improve the indoor comfort of the building?"*

The primary objective of the research was to investigate the potential of the EWF system as an energy-retrofitting method for the Housing buildings in the Netherlands with indoor comfort and energy neutrality as performance indicators. For the purpose of carrying out the said investigation, several design strategies for implementing the EWF system were applied and evaluated for Arthur Van Schendelplein apartment building located in Delft, Netherlands.

With its spectacular components, Climate Cascade, Solar Chimney and Ventec roof, the system bridges the gap between architecture and technology and serves as a symbol of energy-efficiency for the building. The different design strategies were tested for their energy performance by varying several parameters involved in their technical design. Varying the number and the size of the Climate Cascade has an impact on the energy consumed by the Climate Cascade consisting of fan, pump and additional heating energy. Increasing the number of Climate Cascade reduces the energy consumption due to more heat transfer through the walls of the Cascade. On the contrary, the variation in the number of the Solar Chimneys does not have a considerable difference in its performance if the input parameters are same for a single chimney and multiple chimneys. In regards to the placement of the Climate Cascade and the Solar Chimney elements, it is important to consider the effect on the daylight availability into the apartments. The placement and the number of the chimneys define the size of the Solar Chimney which in turn impacts the amount of daylight entering into the apartments. Since the effect of these variables can play a significant role in impacting the energy performance of the EWF system, a design guideline is developed for integrating the EWF system in the refurbishment of the apartment buildings. These design guidelines can be useful for the engineers and the architects to design the integration of the EWF system with an understanding of the design strategies and the criteria to achieve maximum energy performance. Apart from the technical parameters, one of the major variations in the design options and also a vital driver in decision-making is the architectural aesthetics. The refurbishment of the apartments with EWF system would result in a major transformation in the aesthetic appeal of the building thus serving as an added benefit in addition to reducing the energy consumption of the building. The social housing associations could perceive this as an opportunity to showcase the energy-efficiency of their building renovation by exposing the Climate Cascade and the Solar Chimney components.

The results of the simulations show that the annual energy consumption of the case study building reduces by 14% after installing the EWF system and keeping the other installations and the façade intact. However, when the existing façade is refurbished in addition to installing the EWF system, the annual energy consumption reduces by 57% as compared to the existing situation. The gallery apartment buildings constructed before 1990s usually have poor energy performance and comfort and the biggest contributor to this inferior energy and comfort performance is the poorly-insulated facades of the apartments. It is thus important to acknowledge that in addition to installing the EWF system, the refurbishment strategy should also focus on improving or replacing the existing façade to reduce the energy demand for space heating. The existing apartment buildings relying solely on natural ventilation often have a bad thermal comfort especially during peak summer days due to the absence of active space cooling. The EWF system being an energy-efficient ventilation system plays a vital role to provide a good air quality and thermal comfort in the apartment buildings throughout the year. Particularly during the summer months, the EWF system improves the comfort of the apartments due to the cooling effect of the air supplied through the Climate Cascade.

The simulation for the final design showed that the annual energy consumption of the case study building reduces by 79% after the total refurbishment of the building where in addition to installing the EWF system, the existing heating and DHW system is replaced by Aquifer Thermal Energy Storage system and the existing façade is refurbished by adding an exterior insulation and double-glazed windows. The refurbishment of the case study building also satisfies the BENG criteria and thus can be termed as a 'nearly energy neutral' apartment building. The EWF system has an effective contribution in reaching this goal.

As a result of this research, it can be concluded that the integration of the Earth, Wind & Fire system has a great potential to reduce the energy consumption of the old apartment buildings in the Netherlands thereby also improving the indoor comfort. Moreover, it is also derived that the transformation of the old housing stock into a nearly energy neutral building requires a deep refurbishment strategy which is dependent on the existing state of the building.

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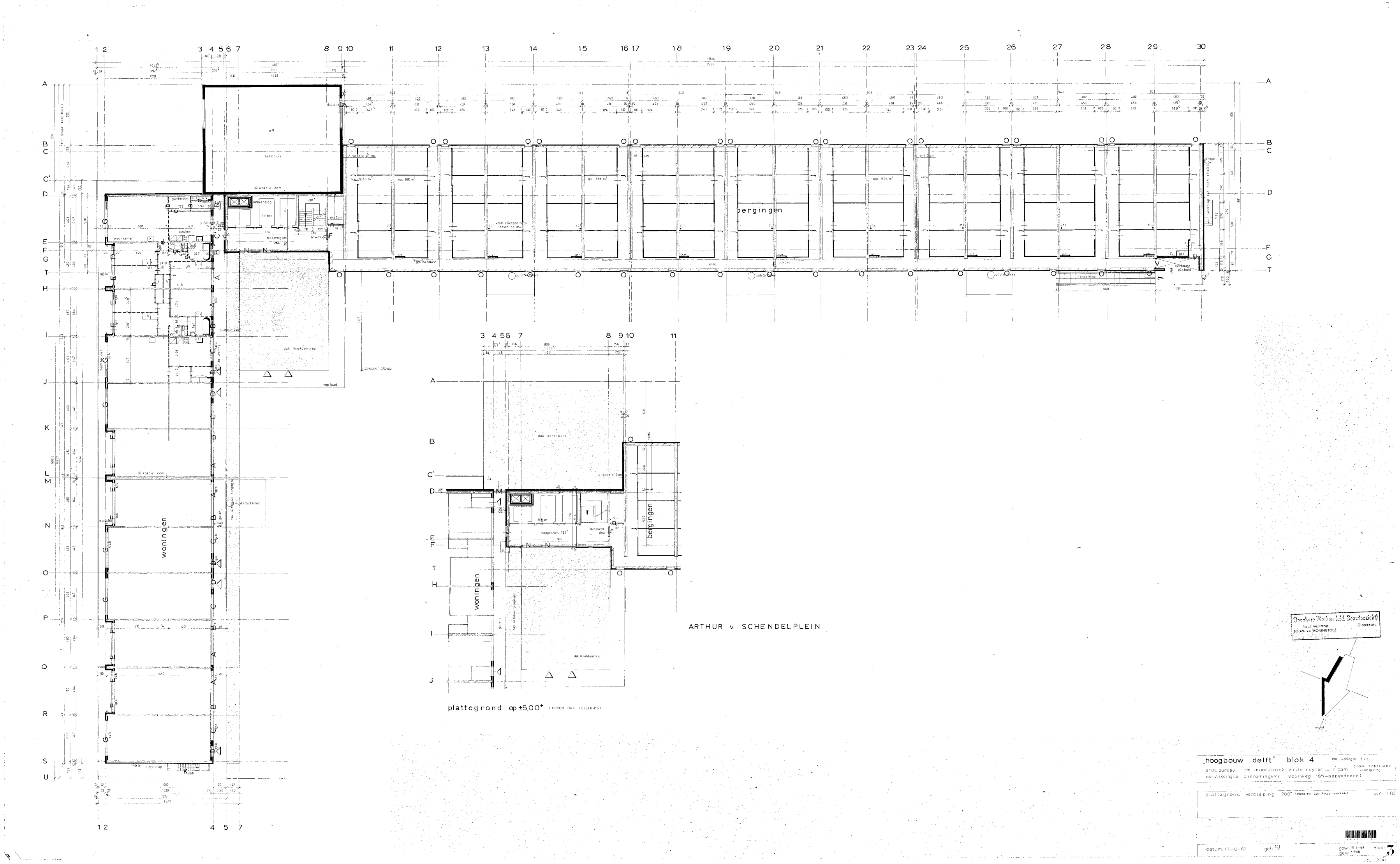
Appendix A: Existing building drawings



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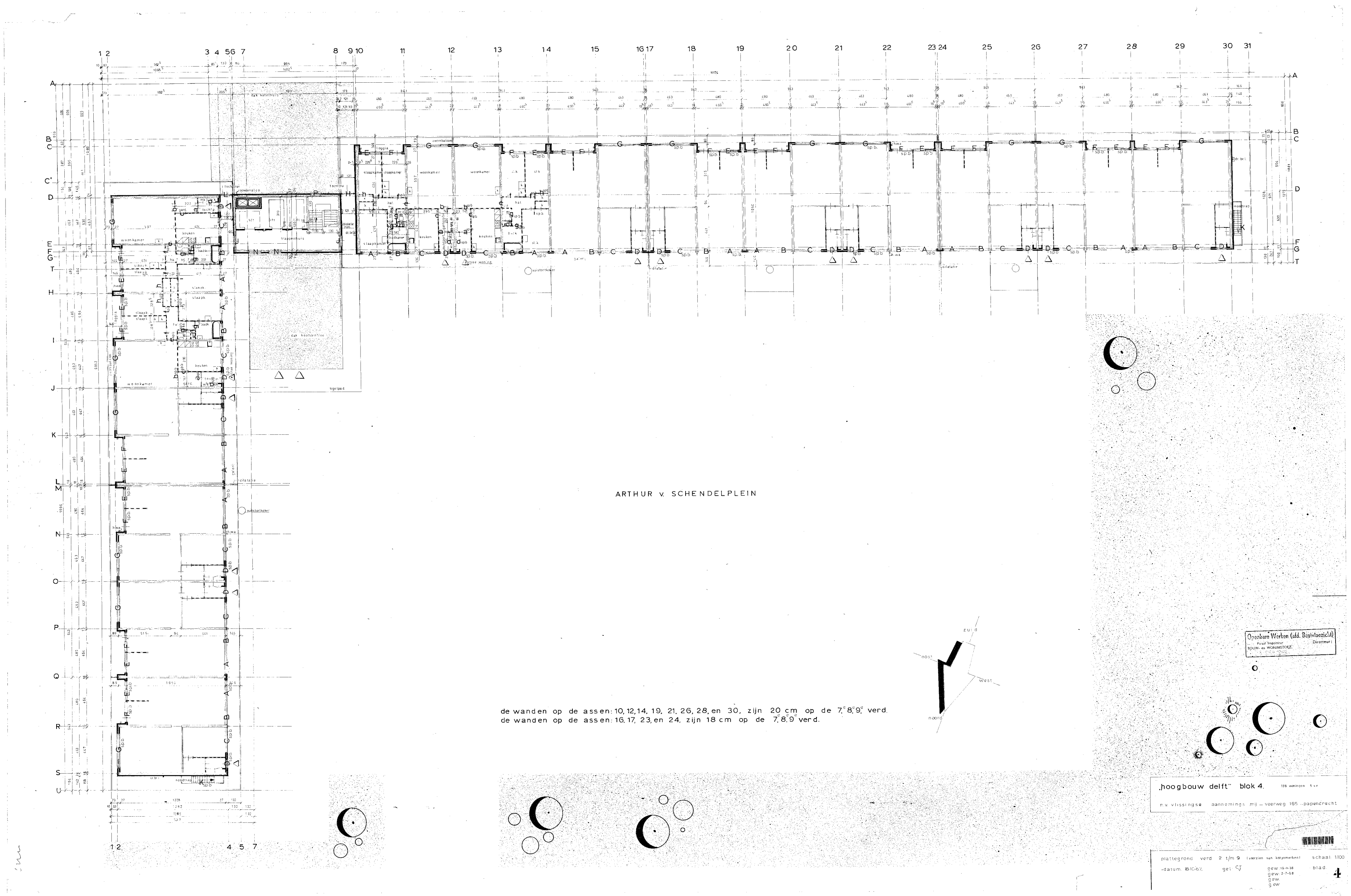
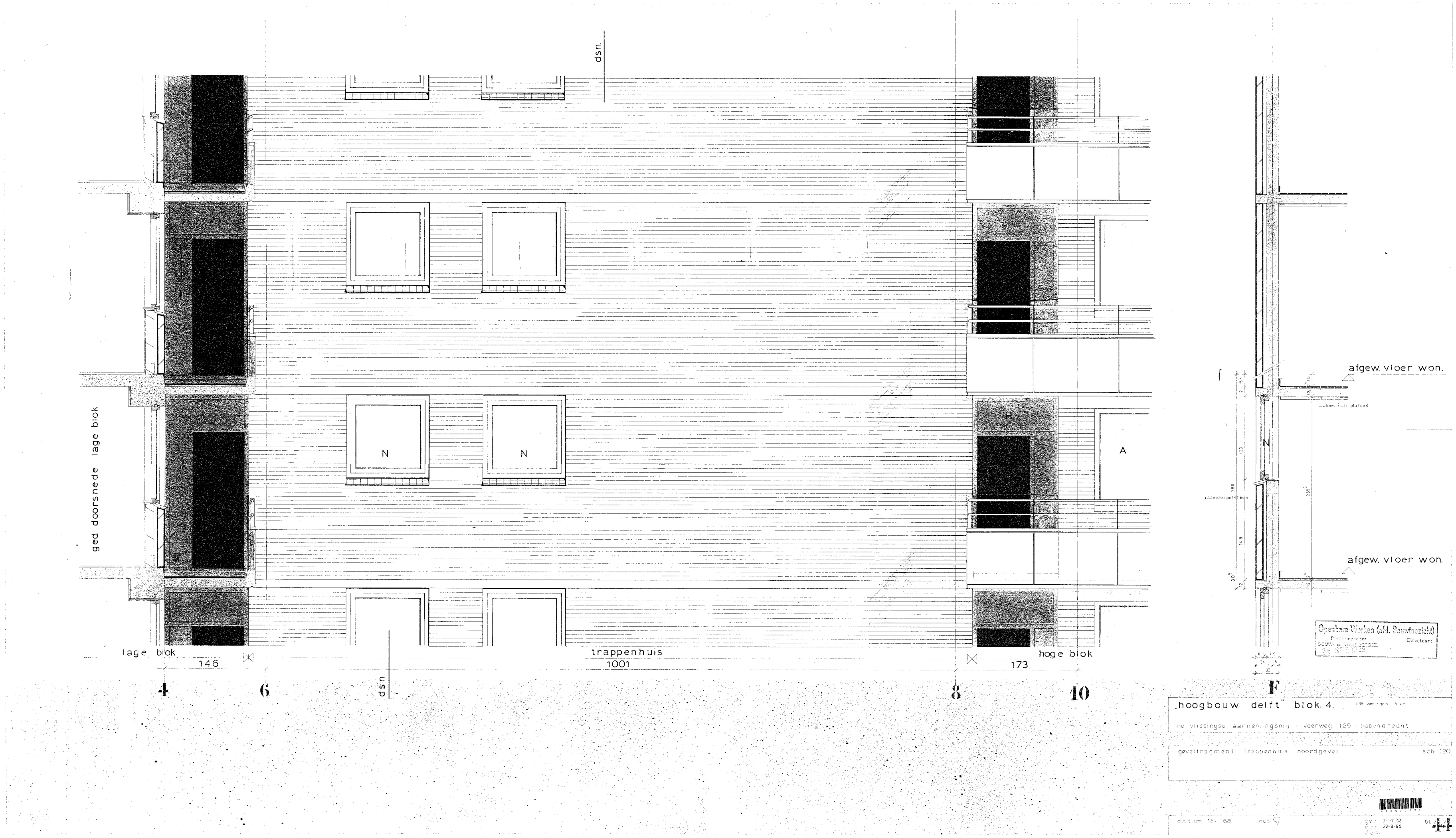

ARTHUR v. SCHENDELPLEIN
de wanden op de assen: 10, 12, 14, 19, 21, 26, 28, en 30, zijn 20 cm op de 7, 8, 9, verd.
de wanden op de assen: 16, 17, 23, en 24, zijn 18 cm op de 7, 8, 9 verd.
„hoogbouw delft" blok 4.
n.v. vlissingse aannemings mij – veerweg 165 – papendrecht



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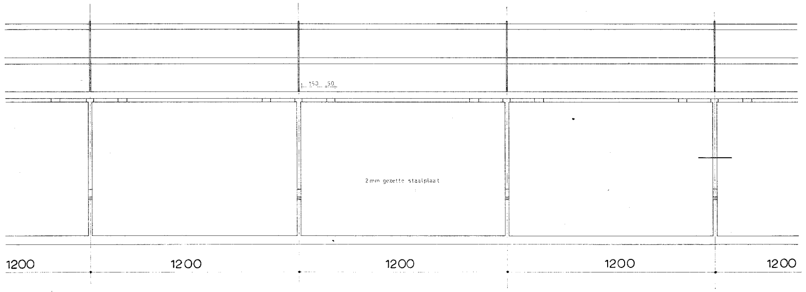
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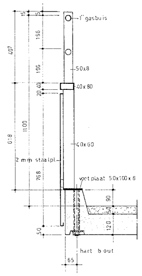

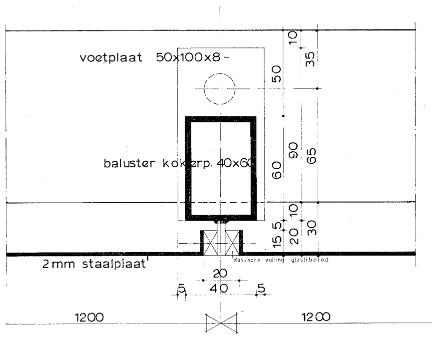
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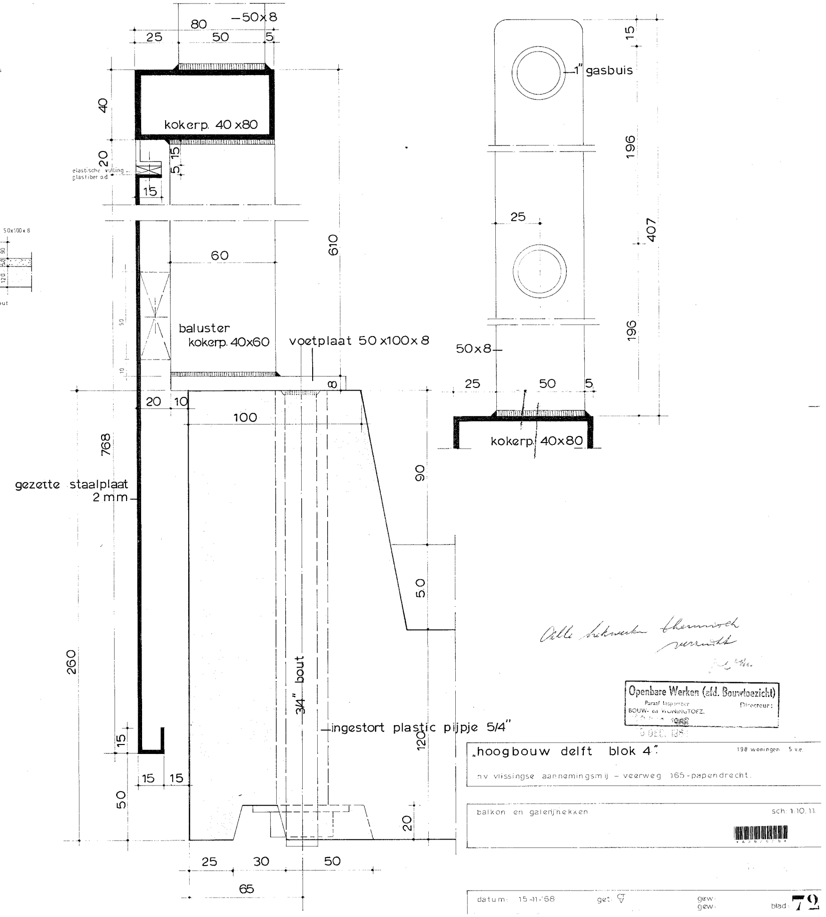
1200
1200


50x8
kokerp. 40x80
1" gasbuis
baluster kokerp. 40x60
voetplaat 50x100x8
50x8
kokerp. 40x80
gezette staalplaat 2 mm
3/4" bout
ingestort plastic pijpje 5/4"
Openbare Werken (afd. Bouwtoezicht)
hoogbouw delft blok 4
balkon en galerijhekken
datum 15-11-'66
72

Appendix B: Excel model inputs

Solar Chimney

alpha_rad (radiation)	5.5
alpha_c (convection)	2.3
a glas1 (absorption coefficient)	0.1
a glas2 (absorption coefficient)	0.9
alpha_e (heat transfer coefficient from surface to outside)	25
alpha_i (heat transfer coefficient from surface to inside)	7.8
rho c (air density x air velocity)	1200
Tin	22
tau (Transmission coefficient)	0.8
A facade	553.96
A cavity	11
Uglass1	1.2
alpha_e *	1.418182
Needed ventilation	39600
Velocity	1
height	50

Climate Cascade

KLIMAATCASCADE		
n_verdieping	17	
height	54	m
width	1.77	m
length	1.77	m
Area	3.1	m2
dh	0.135	m
HYDRAULISCH DRUKVERSCHIL		
dp	84.8	Pa
THERMISCH DRUKVERSCHIL		
t_Kc_gem	19.2	C
dp	-18.8	Pa
TOTAAL DRUKVERSCHIL		
dp	103.5	Pa

	AIR		
	NVO/verd	41000	m2
27	q-_vent	5	m3/hm2
	m_air_in	39600	m3/h
	m_air_in	13.2	kg/s
	t_air_in	28	degr C
	x_sat_air_in	0.00162	kg/kg
	rho_air	1.2	kg/m3
	c_air	1012	J/kgK
	v_air	3.5	m/s
	t_air_out	17.41	C
	RH_air_out	99	%
	t_air_supply	18	degr C

VAPOUR		
x_air_in	0.0115	kg/kg
x_air_in	11.5	g/kg
RH_air_in	0.55	
p_vapour	1920.01	Pa
p_totaal	101325	Pa
p_vapour_sat	3490.93	Pa
rho_v_in	0.0138	kg/m3
c_vap	2020	J/kg/K
L_wat	2.26E+06	J/kg
x_air_out	0.01227	kg/kg
x_air_out	12.27	g/kg

WATER		
r_water/air	0.530303	kg/kg
m_wat_in	7.00	kg/s
t_wat_in	13	degr C
spectrum	10	
d_wat	0.88	mm
d_vmd	1.2	mm
d_smd	1.54	mm
rho_a_wat_in	0.4287851	kg/m3
c_wat	4184	J/kgK
v_wat	5.19438	m/s
t_wat_out	17.28	C
aantal spr.	10	
kg/s per spr.	0.7	

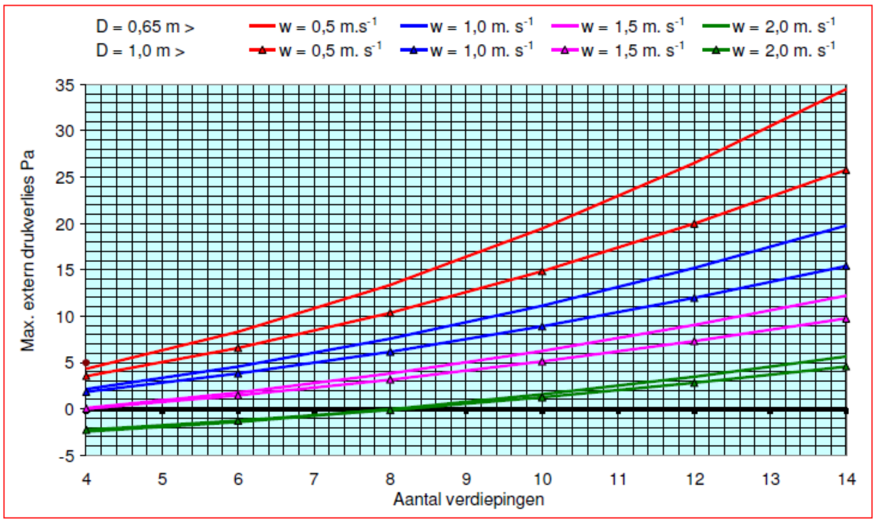
Solar Chimney Formula

1. Pressure loss calculation

Pressure loss is the summation of dynamic pressure, external pressure loss, Pressure loss due to resistance in Solar Chimney, Pressure loss due to resistance in Shunt Channel, Pressure loss due to bend and Heat exchanger pressure loss. All the formulas have been derived from Bronsema (2013).

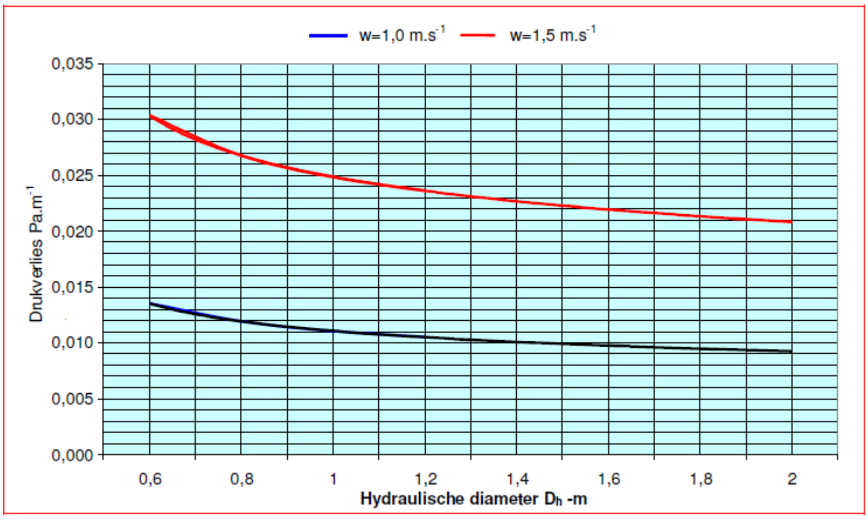
Dynamic pressure= $0.5 * density\ of\ air\ \left(\frac{kg}{m3}\right) * air\ speed\ (\frac{m}{s})$

External pressure loss is derived from the graph below:



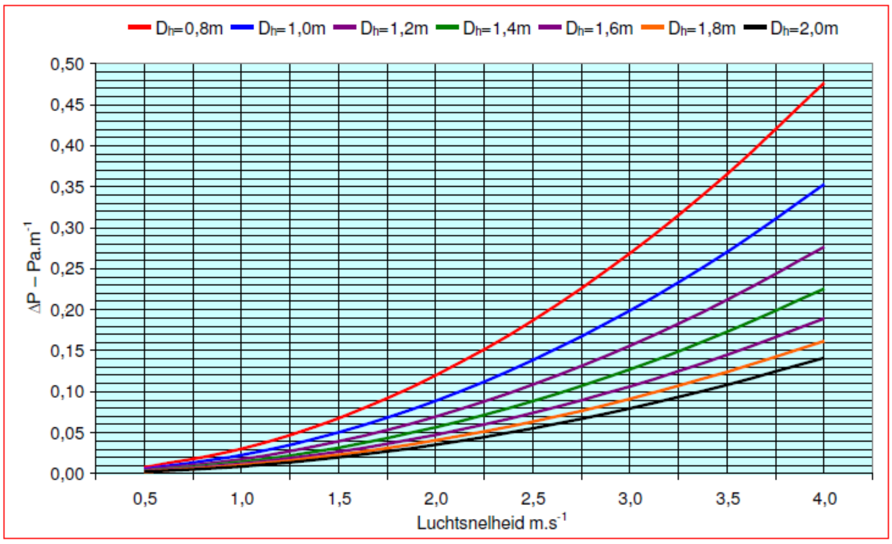
Shunt Channel loss= $Shunt\ pressure\ loss\ (Pa) * Chimney\ height(m)$

Shunt pressure loss is derived from the graph below:



Solar Chimney loss= $Chimney\ pressure\ loss\ (Pa) * Chimney\ height\ (m)$

Chimney pressure loss is derived from the graph below:



Pressure loss due to bends= $(Drag\ coefficient * air\ speed\ (\frac{m}{s}) * air\ density\ (\frac{kg}{m3}))/2$

2. Thermal draft calculation

Thermal draft (Pa) = $Air\ density\ \left(\frac{kg}{m3}\right)\left(\left(\frac{T0}{T1}\right) - \left(\frac{T0}{T2}\right)\right) * gravitational\ constant\left(\frac{m}{s2}\right) * chimney\ height(m)$

Where,

To is the air temperature at 0°C
T1 is the air temperature outside (°C)
T2 is the air temperature in chimney (°C)

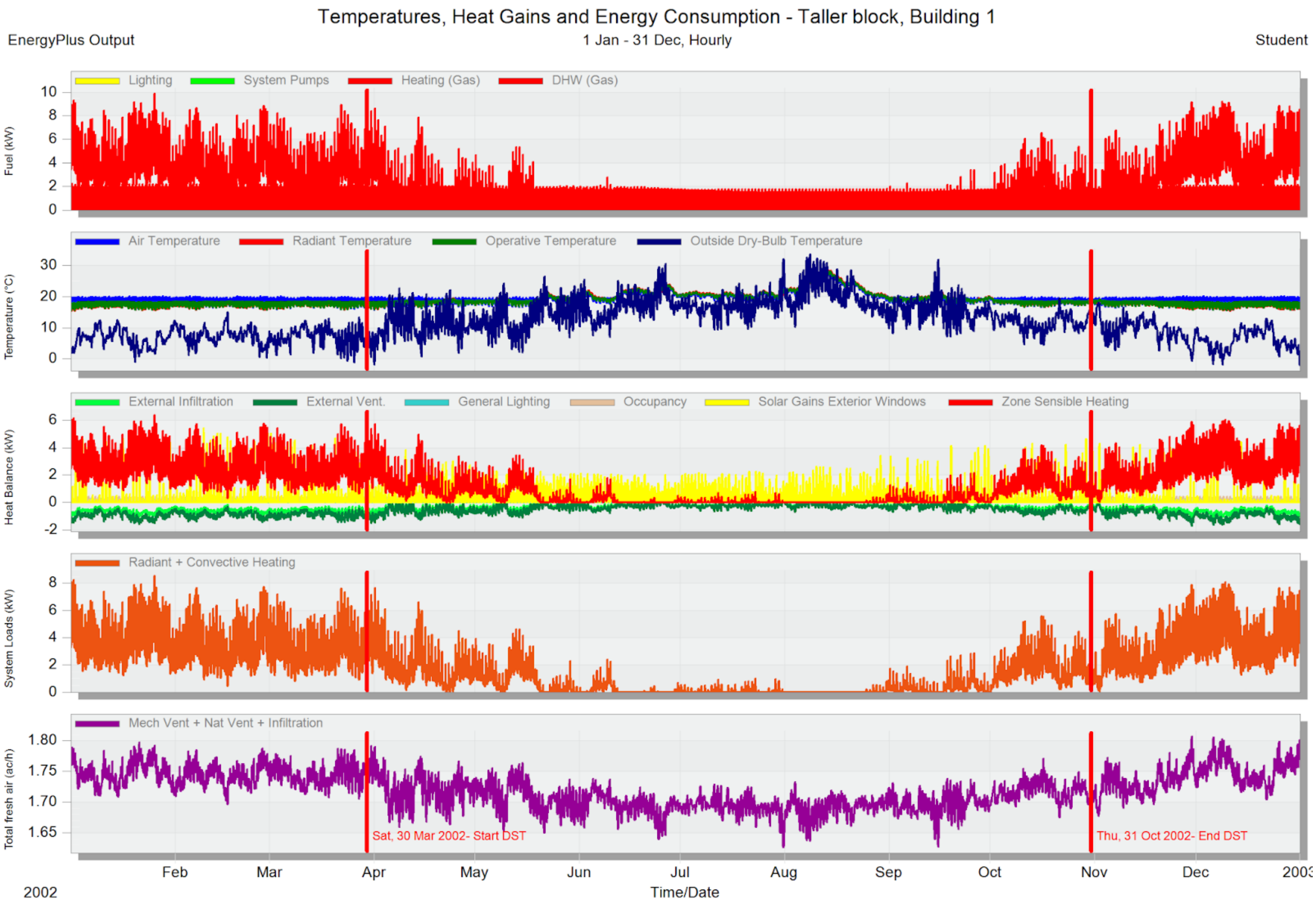
Appendix C: Design Builder Simulation results

Case 1: Existing building

Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1

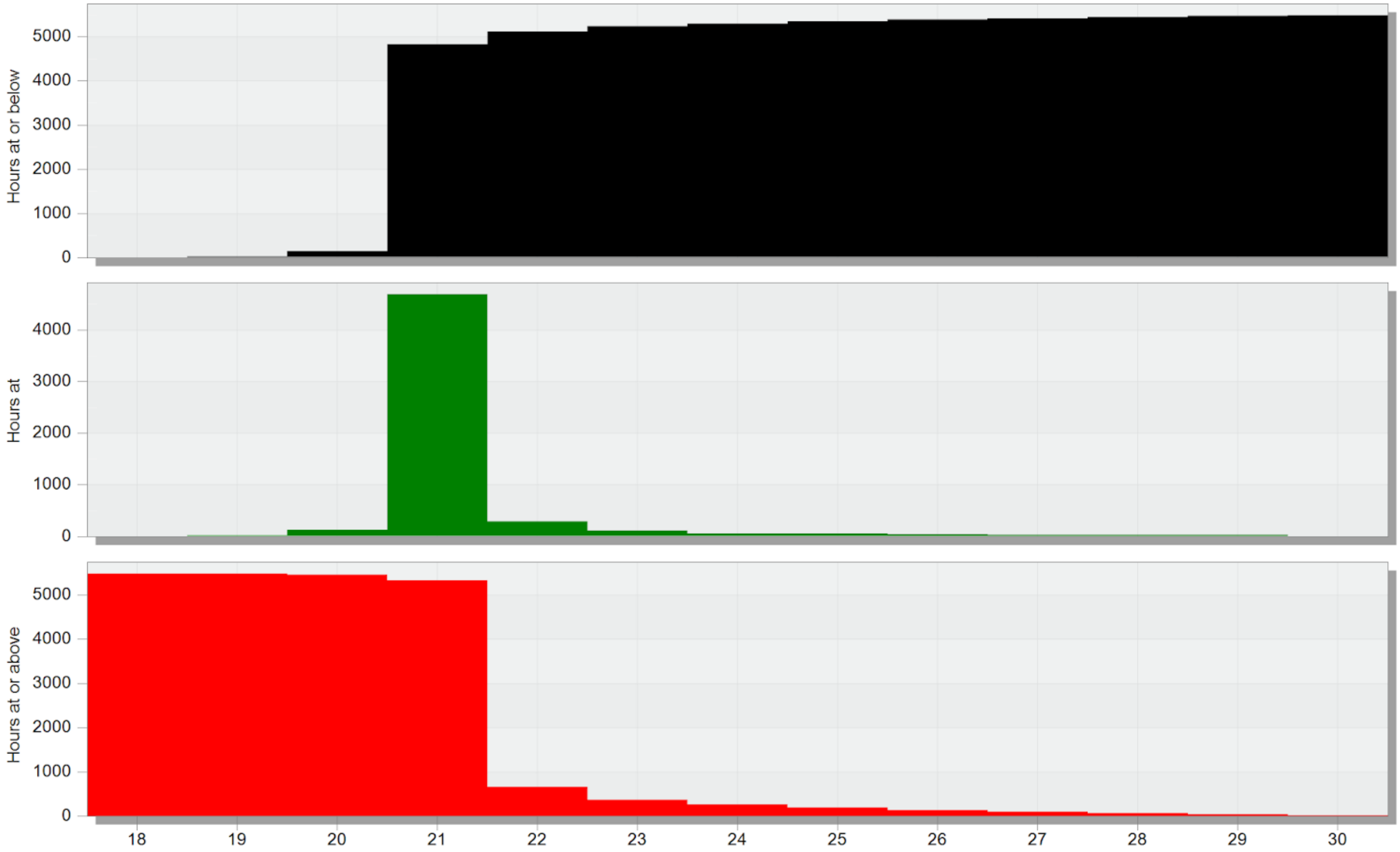
EnergyPlus Output | 1 Jan - 31 Dec, Annual | Student

	Year
Lighting (kWh)	751.54
System Pumps (kWh)	7.97
Heating (Gas) (kWh)	14536.31
DHW (Gas) (kWh)	5344.27
Air Temperature (°C)	18.99
Radiant Temperature (°C)	18.64
Operative Temperature (°C)	18.81
Outside Dry-Bulb Temperature (°C)	11.95
External Infiltration (kWh)	-3216.73
External Vent. (kWh)	-4877.93
General Lighting (kWh)	751.54
Occupancy (kWh)	1580.06
Solar Gains Exterior Windows (kWh)	4333.27
Zone Sensible Heating (kWh)	10429.77
Radiant + Convective Heating (kWh)	13993.98
Mech Vent + Nat Vent + Infiltration (ac/h)	1.72


Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Lighting
System Pumps
Heating (Gas)
DHW (Gas)
Fuel (kW)
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Heat Balance (kW)
Radiant + Convective Heating
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
Sat, 30 Mar 2002- Start DST
Thu, 31 Oct 2002- End DST
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2002
Time/Date

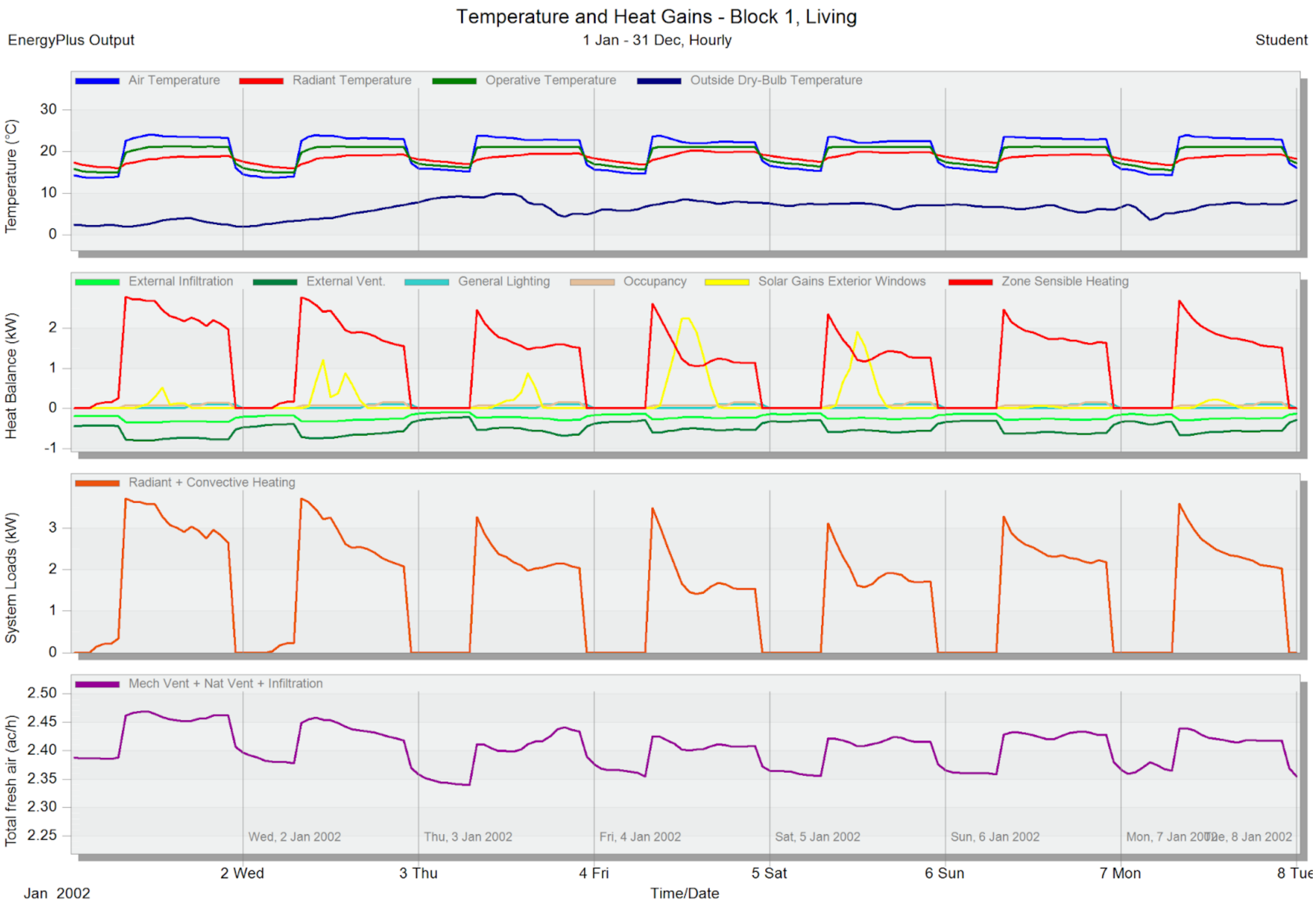
Temperature Distribution for Taller block, Building 1, Block 1, Living

1 Jan - 31 Dec - Zone conditions reported for occupied periods, defined by schedule: Dwell_DomLounge_Occ_new

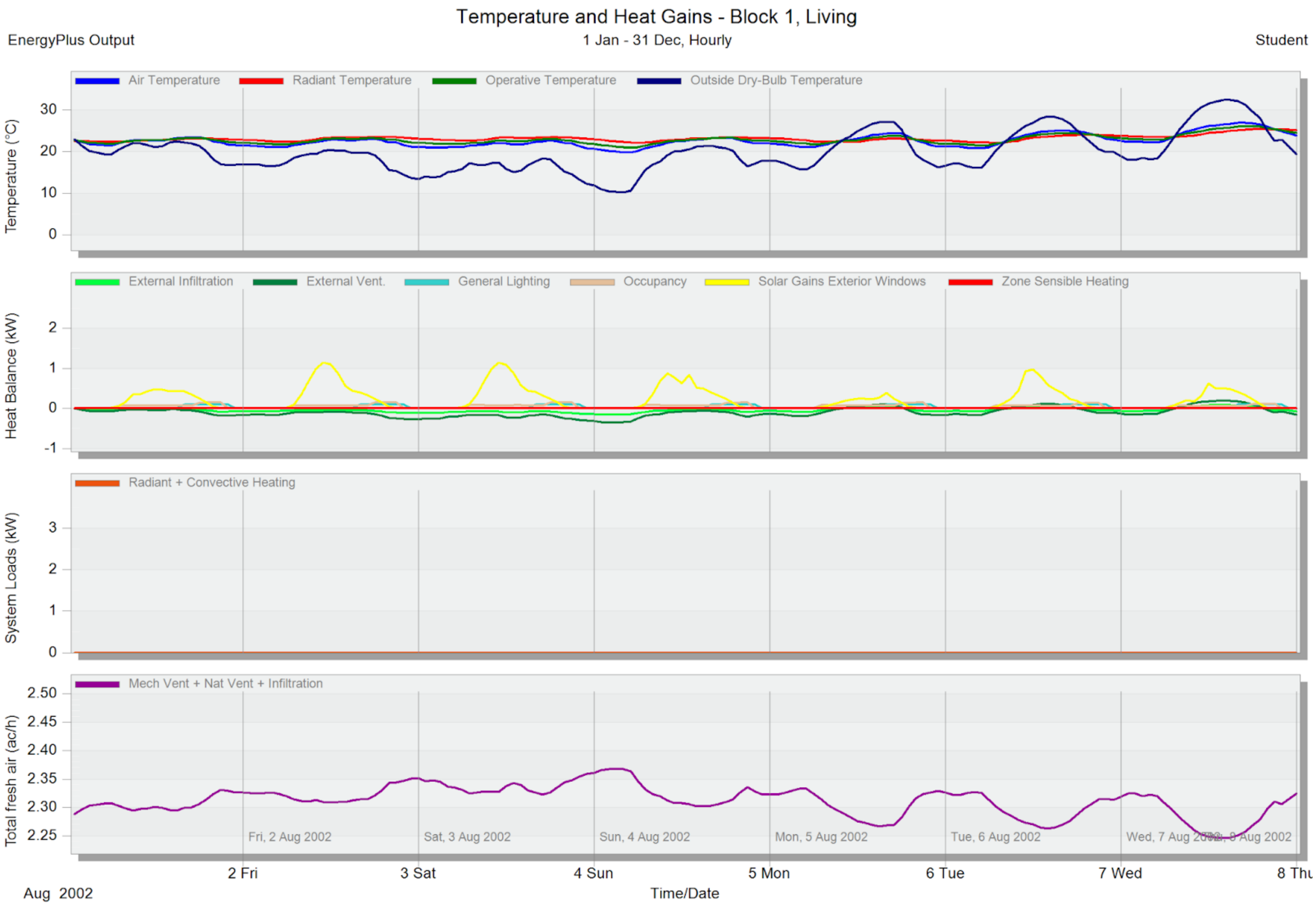


	18	19	20	21	22	23	24	25	26	27	28	29	30
Hours at or below	0.3	15.0	139.3	4827.0	5116.8	5228.0	5285.3	5338.0	5379.5	5414.0	5443.8	5470.8	5475.0
Hours at	0.3	14.8	124.3	4687.8	289.8	111.3	57.3	52.8	41.5	34.5	29.8	27.0	4.3
Hours at or above	5475.0	5474.8	5460.0	5335.8	648.0	358.3	247.0	189.8	137.0	95.5	61.0	31.3	4.3

Temperature bins (°C)



Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
30
20
10
0
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Heat Balance (kW)
2
1
0
-1
Radiant + Convective Heating
System Loads (kW)
3
2
1
0
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
2.50
2.45
2.40
2.35
2.30
2.25
Wed, 2 Jan 2002
Thu, 3 Jan 2002
Fri, 4 Jan 2002
Sat, 5 Jan 2002
Sun, 6 Jan 2002
Mon, 7 Jan 2002
Tue, 8 Jan 2002
2 Wed
3 Thu
4 Fri
5 Sat
6 Sun
7 Mon
8 Tue
Jan 2002
Time/Date

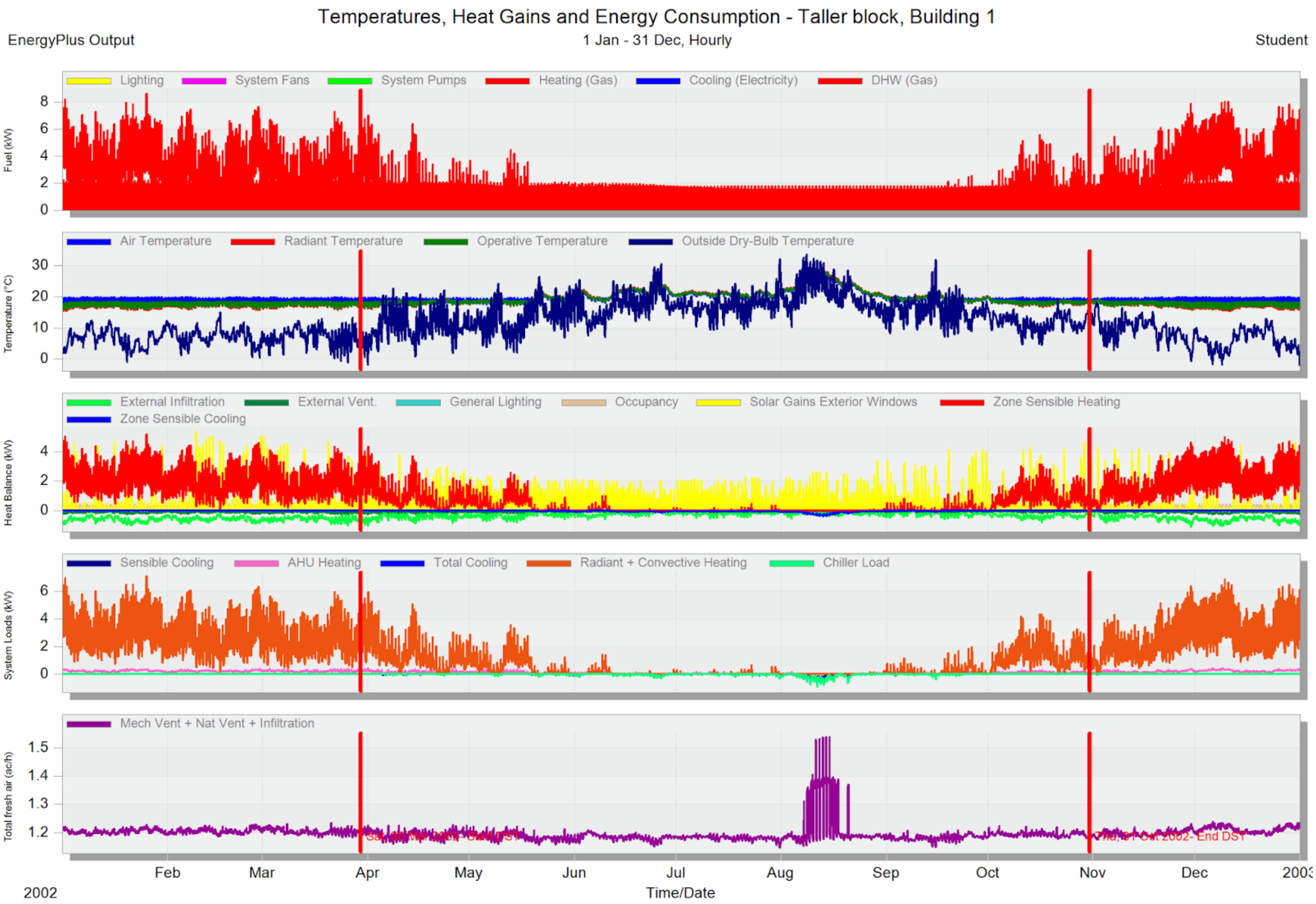

Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Heat Balance (kW)
Radiant + Convective Heating
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
Fri, 2 Aug 2002
Sat, 3 Aug 2002
Sun, 4 Aug 2002
Mon, 5 Aug 2002
Tue, 6 Aug 2002
Wed, 7 Aug 2002
2 Fri
3 Sat
4 Sun
5 Mon
6 Tue
7 Wed
8 Thu
Aug 2002
Time/Date

Case 2: EWF

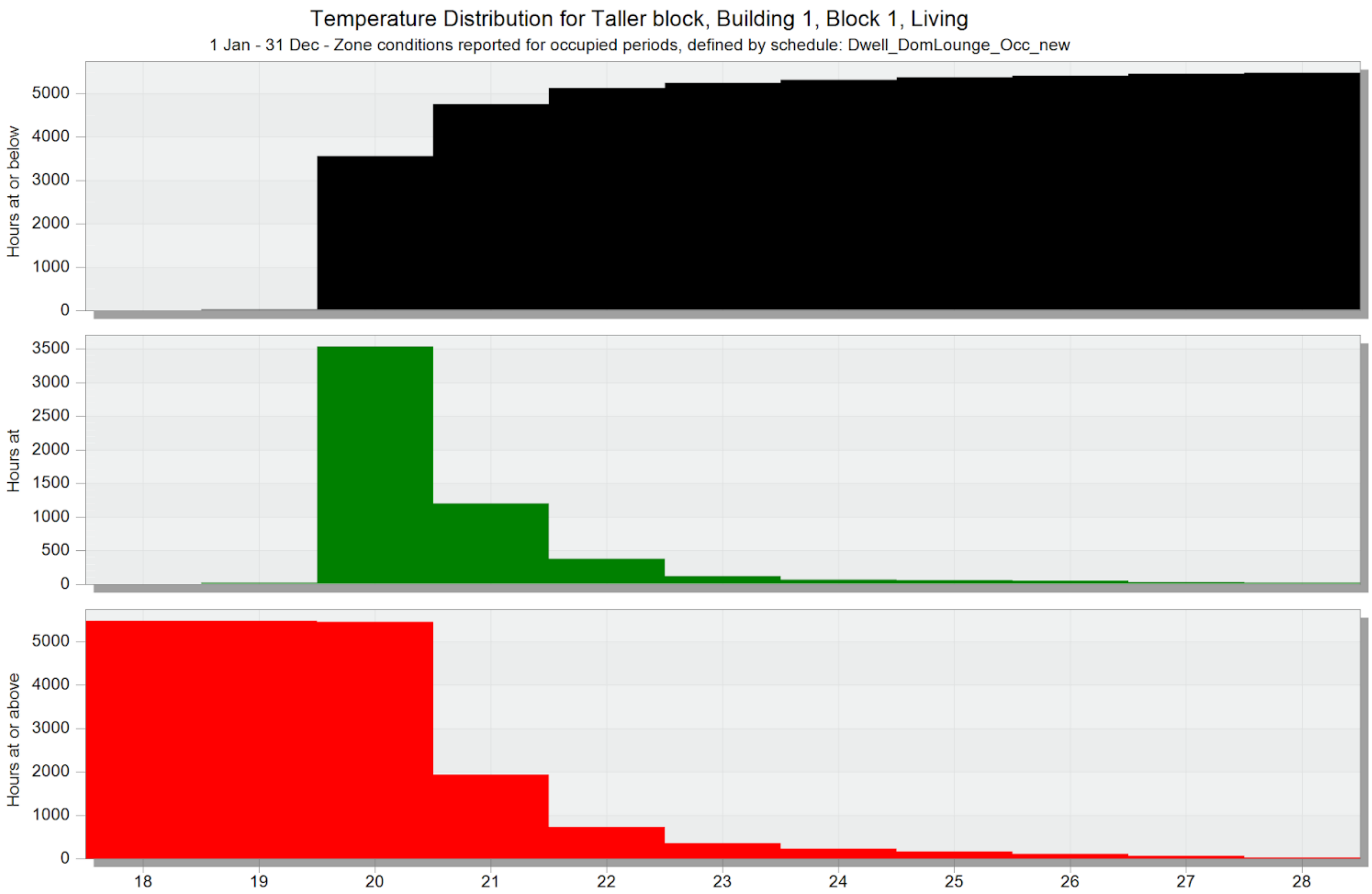
Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1

EnergyPlus Output | 1 Jan - 31 Dec, Annual | Student

	Year
Lighting (kWh)	751.54
System Fans (kWh)	437.70
System Pumps (kWh)	5.74
Heating (Electricity) (kWh)	1091.28
Heating (Gas) (kWh)	10530.76
Cooling (Electricity) (kWh)	325.73
DHW (Gas) (kWh)	5344.63
Air Temperature (°C)	19.22
Radiant Temperature (°C)	18.72
Operative Temperature (°C)	18.97
Outside Dry-Bulb Temperature (°C)	11.95
External Infiltration (kWh)	-3322.76
General Lighting (kWh)	751.54
Occupancy (kWh)	1580.96
Solar Gains Exterior Windows (kWh)	4333.27
Zone Sensible Heating (kWh)	7137.00
Zone Sensible Cooling (kWh)	-237.13
Sensible Cooling (kWh)	-169.45
AHU Heating (kWh)	1091.28
Total Cooling (kWh)	-202.90
Radiant + Convective Heating (kWh)	10102.75
Chiller Load (kWh)	-204.69
Mech Vent + Nat Vent + Infiltration (ac/h)	1.03

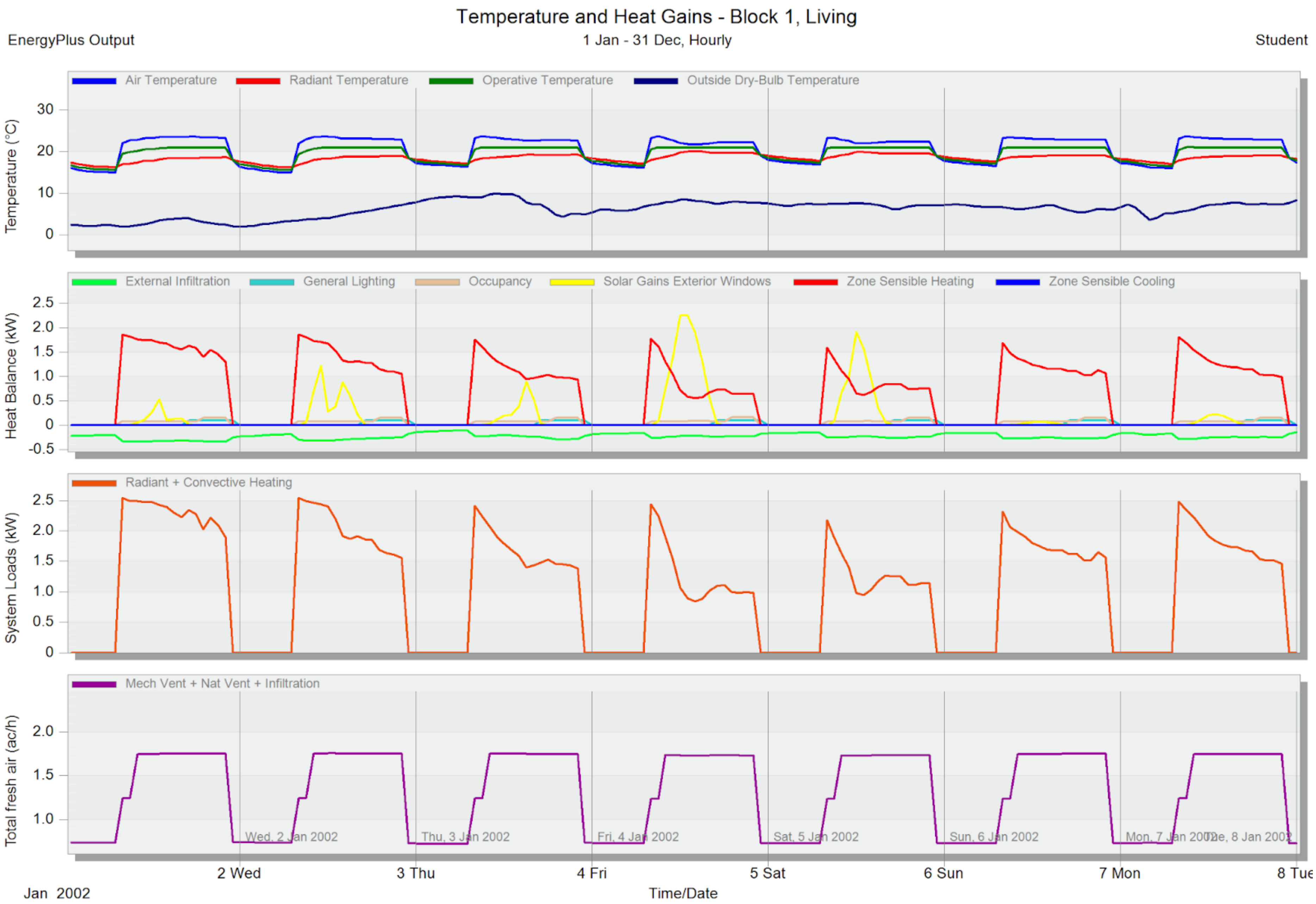


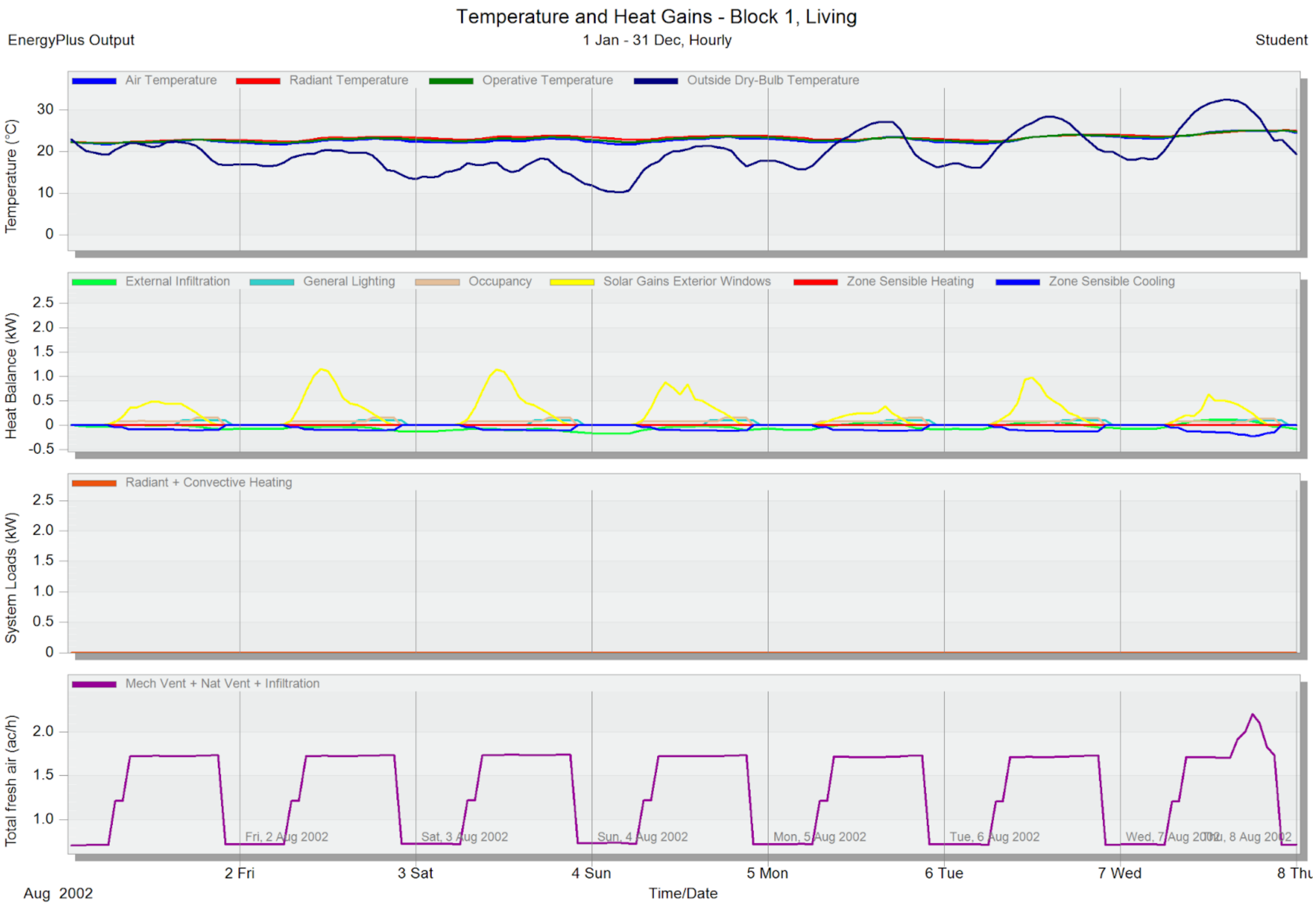
Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Lighting
System Fans
System Pumps
Heating (Gas)
Cooling (Electricity)
DHW (Gas)
Fuel (kW)
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Zone Sensible Cooling
Heat Balance (kW)
Sensible Cooling
AHU Heating
Total Cooling
Radiant + Convective Heating
Chiller Load
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2003
2002
Time/Date



	18	19	20	21	22	23	24	25	26	27	28
Hours at or below	0.5	22.8	3554.3	4754.5	5127.8	5246.8	5313.0	5368.3	5414.8	5449.0	5475.0
Hours at	0.5	22.3	3531.5	1200.3	373.3	119.0	66.3	55.3	46.5	34.3	26.0
Hours at or above	5475.0	5474.5	5452.3	1920.8	720.5	347.3	228.3	162.0	106.8	60.3	26.0

Temperature bins (°C)


Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Zone Sensible Cooling
Heat Balance (kW)
Radiant + Convective Heating
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
Wed, 2 Jan 2002
Thu, 3 Jan 2002
Fri, 4 Jan 2002
Sat, 5 Jan 2002
Sun, 6 Jan 2002
Mon, 7 Jan 2002
Tue, 8 Jan 2002
2 Wed
3 Thu
4 Fri
5 Sat
6 Sun
7 Mon
8 Tue
Jan 2002
Time/Date

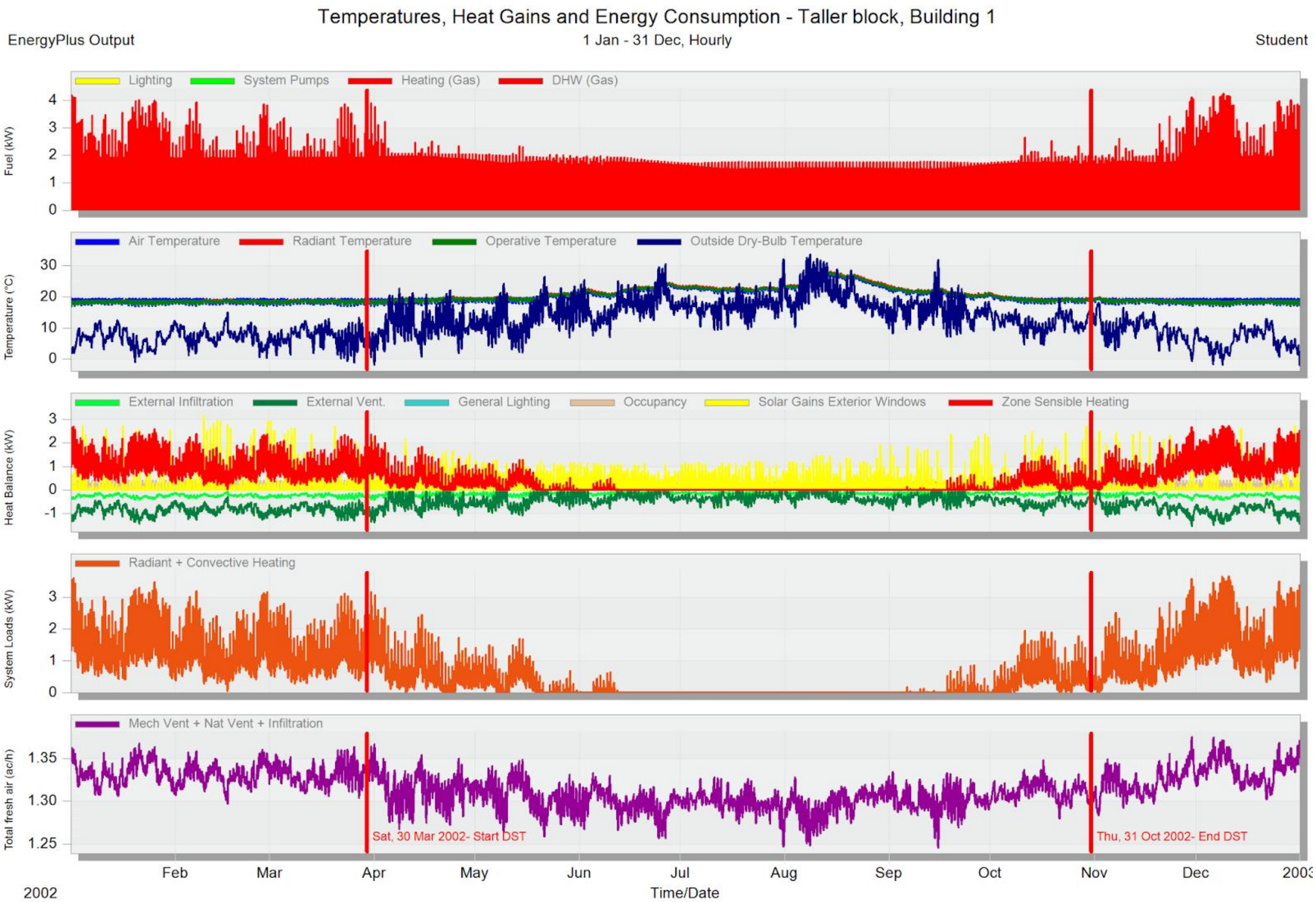

Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
30
20
10
0
External Infiltration
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Zone Sensible Cooling
Heat Balance (kW)
2.5
2.0
1.5
1.0
0.5
0
-0.5
Radiant + Convective Heating
System Loads (kW)
2.5
2.0
1.5
1.0
0.5
0
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
2.0
1.5
1.0
Fri, 2 Aug 2002
Sat, 3 Aug 2002
Sun, 4 Aug 2002
Mon, 5 Aug 2002
Tue, 6 Aug 2002
Wed, 7 Aug 2002
Thu, 8 Aug 2002
2 Fri
3 Sat
4 Sun
5 Mon
6 Tue
7 Wed
8 Thu
Aug 2002
Time/Date

Case 3: Façade renovation

Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1

EnergyPlus Output | 1 Jan - 31 Dec, Annual | Student

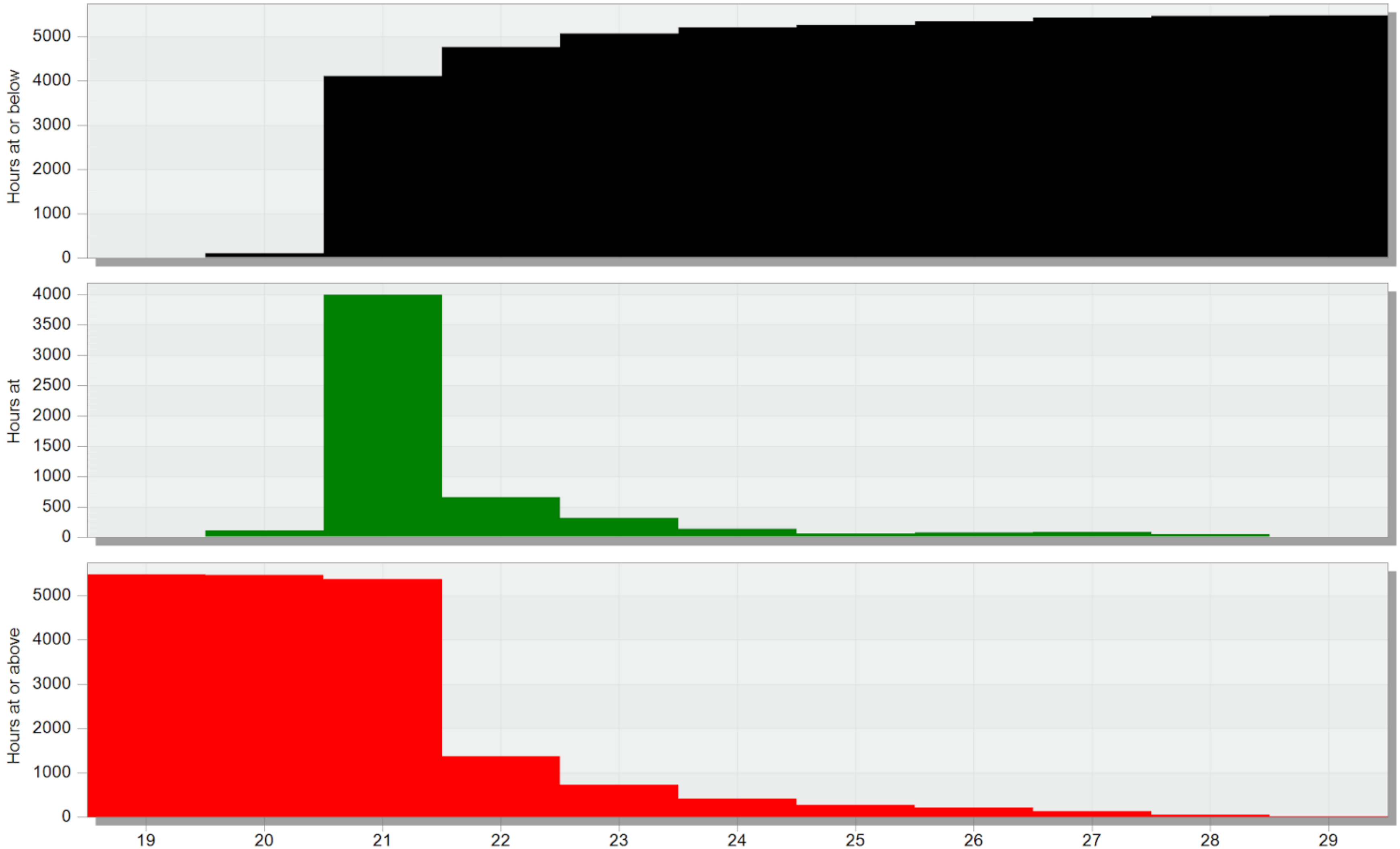
	Year
Lighting (kWh)	727.81
System Pumps (kWh)	3.44
Heating (Gas) (kWh)	5191.48
DHW (Gas) (kWh)	5191.51
Air Temperature (°C)	19.92
Radiant Temperature (°C)	20.19
Operative Temperature (°C)	20.05
Outside Dry-Bulb Temperature (°C)	11.95
External Infiltration (kWh)	-1498.54
External Vent. (kWh)	-4936.96
General Lighting (kWh)	727.81
Occupancy (kWh)	1505.12
Solar Gains Exterior Windows (kWh)	2409.07
Zone Sensible Heating (kWh)	3733.24
Radiant + Convective Heating (kWh)	5022.13
Mech Vent + Nat Vent + Infiltration (ac/h)	1.31



Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Lighting
System Pumps
Heating (Gas)
DHW (Gas)
Fuel (kW)
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Heat Balance (kW)
Radiant + Convective Heating
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
Sat, 30 Mar 2002- Start DST
Thu, 31 Oct 2002- End DST
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2002
Time/Date

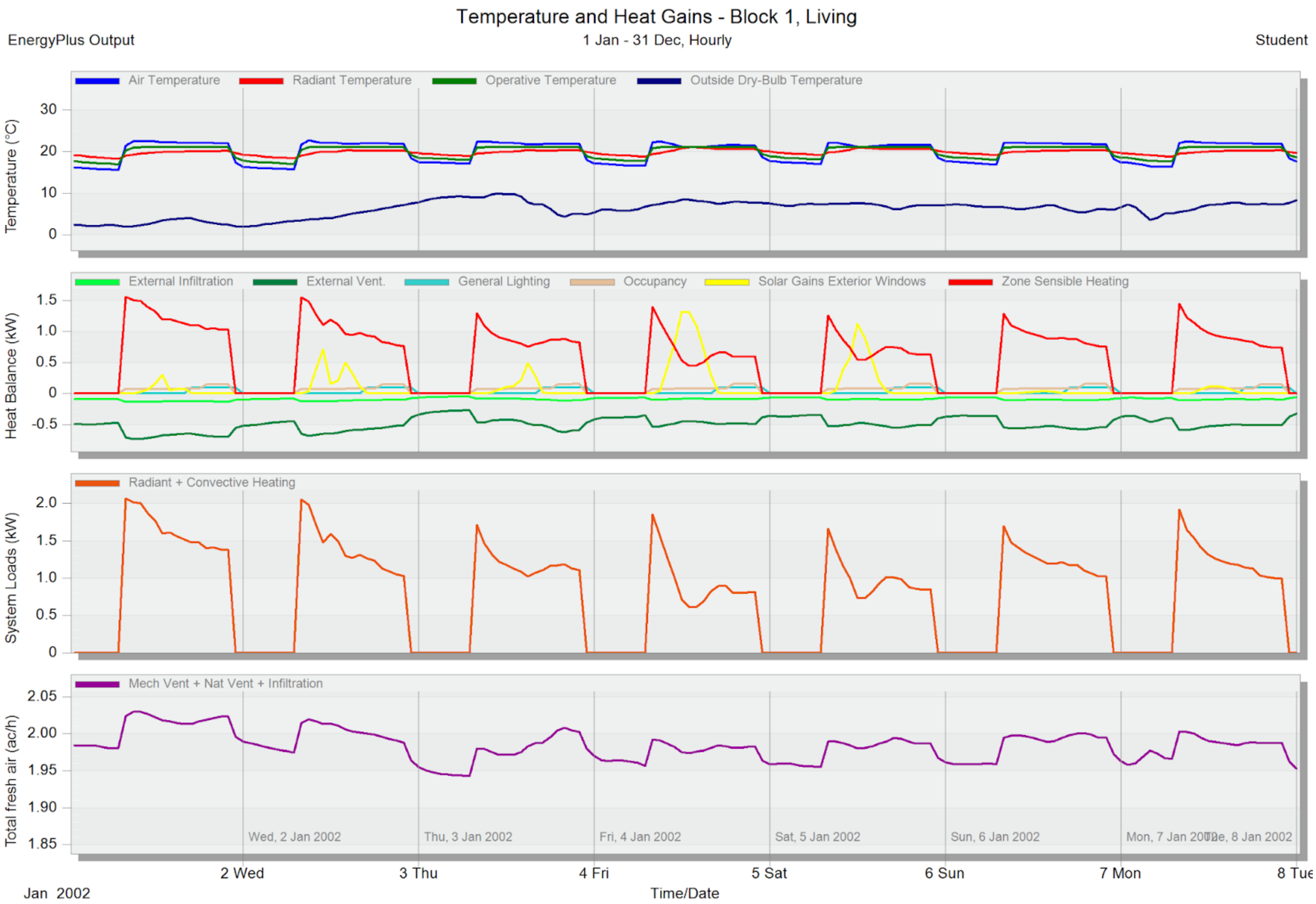
Temperature Distribution for Taller block, Building 1, Block 1, Living

1 Jan - 31 Dec - Zone conditions reported for occupied periods, defined by schedule: Dwell_DomLounge_Occ_new

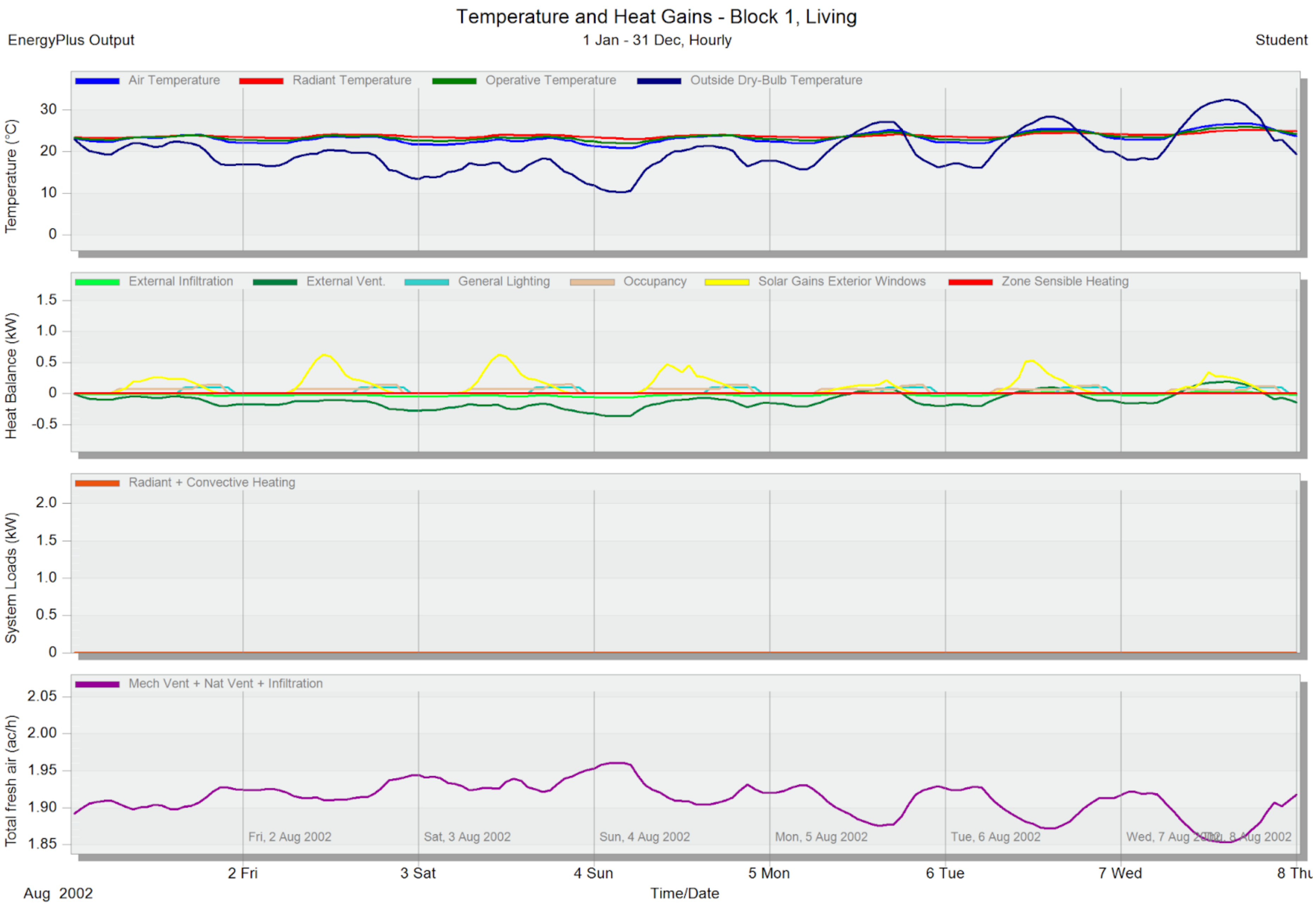


	19	20	21	22	23	24	25	26	27	28	29
Hours at or below	5.0	107.3	4104.5	4760.8	5071.5	5205.0	5263.3	5340.3	5425.8	5472.5	5475.0
Hours at	5.0	102.3	3997.3	656.3	310.8	133.5	58.3	77.0	85.5	46.8	2.5
Hours at or above	5475.0	5470.0	5367.8	1370.5	714.3	403.5	270.0	211.8	134.8	49.3	2.5

Temperature bins (°C)



Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
30
20
10
0
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Heat Balance (kW)
1.5
1.0
0.5
0
-0.5
Radiant + Convective Heating
System Loads (kW)
2.0
1.5
1.0
0.5
0
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
2.05
2.00
1.95
1.90
1.85
Wed, 2 Jan 2002
Thu, 3 Jan 2002
Fri, 4 Jan 2002
Sat, 5 Jan 2002
Sun, 6 Jan 2002
Mon, 7 Jan 2002
Tue, 8 Jan 2002
2 Wed
3 Thu
4 Fri
5 Sat
6 Sun
7 Mon
8 Tue
Jan 2002
Time/Date



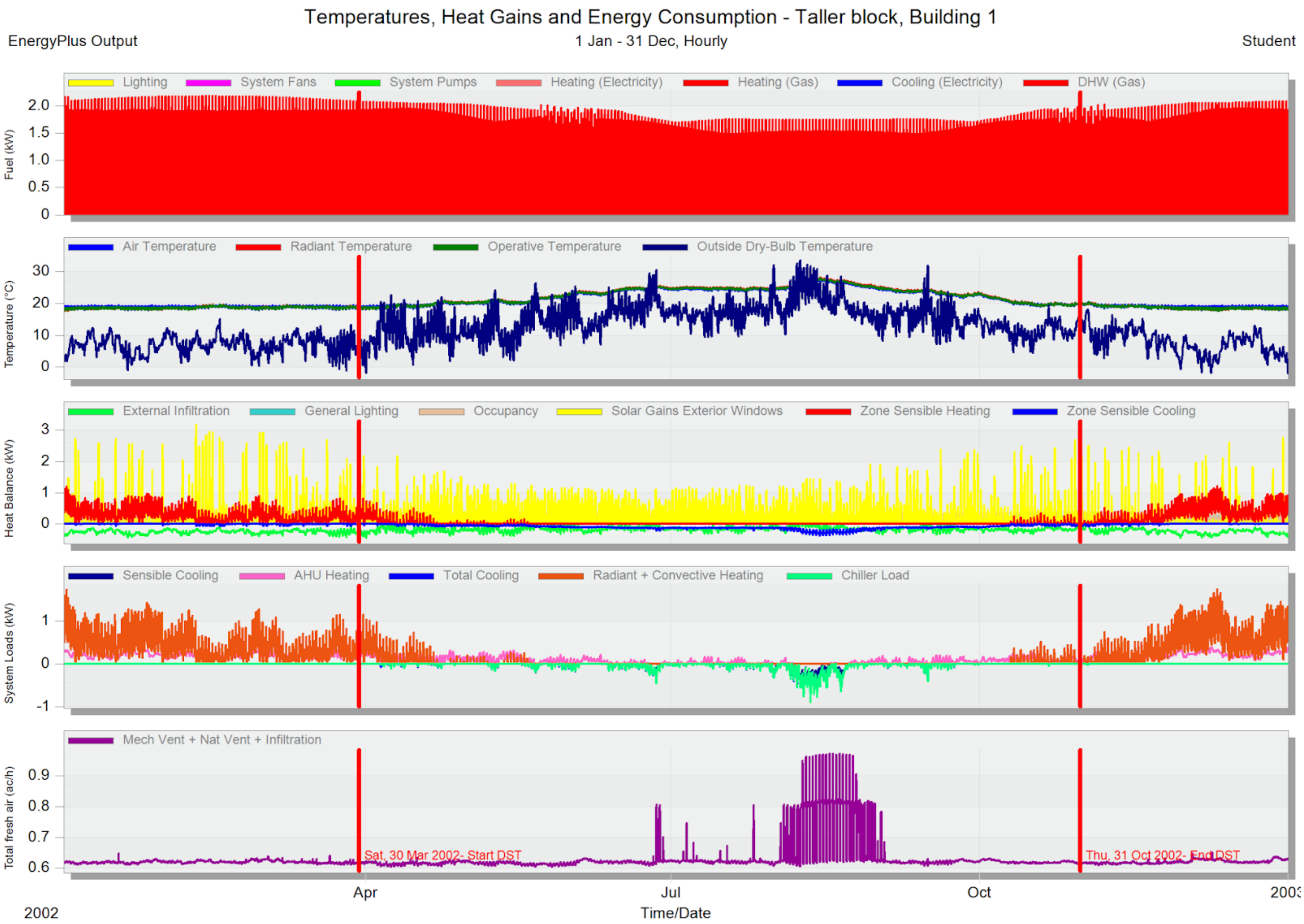
Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Heat Balance (kW)
Radiant + Convective Heating
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
Fri, 2 Aug 2002
Sat, 3 Aug 2002
Sun, 4 Aug 2002
Mon, 5 Aug 2002
Tue, 6 Aug 2002
Wed, 7 Aug 2002
2 Fri
3 Sat
4 Sun
5 Mon
6 Tue
7 Wed
8 Thu
Aug 2002
Time/Date

Case 4: EWF & Façade renovation

Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1

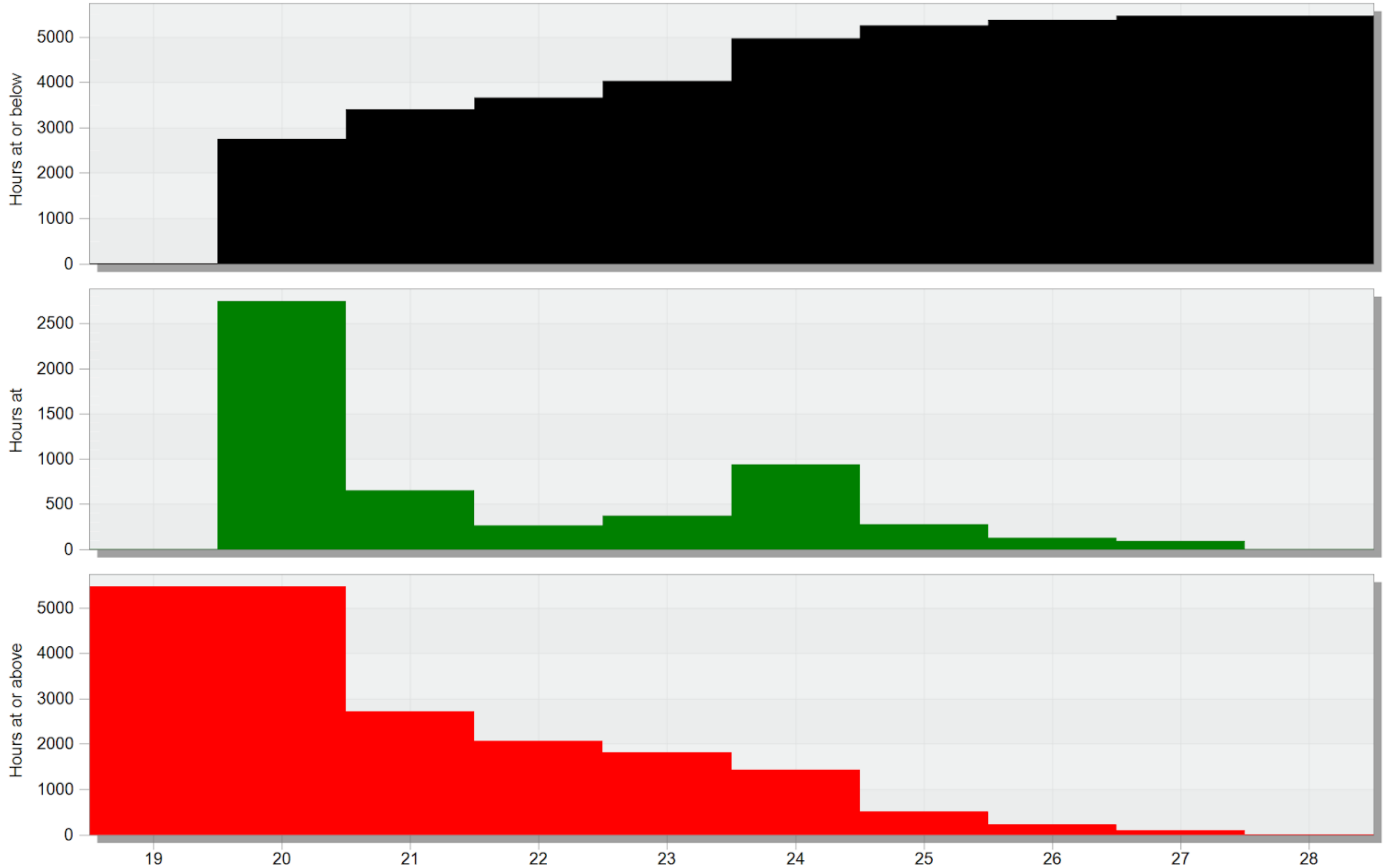
EnergyPlus Output | 1 Jan - 31 Dec, Annual | Student

	Year
Lighting (kWh)	727.81
System Fans (kWh)	424.45
System Pumps (kWh)	1.52
Heating (Electricity) (kWh)	1056.67
Heating (Gas) (kWh)	1613.34
Cooling (Electricity) (kWh)	316.12
DHW (Gas) (kWh)	5188.66
Air Temperature (°C)	20.97
Radiant Temperature (°C)	21.05
Operative Temperature (°C)	21.01
Outside Dry-Bulb Temperature (°C)	11.95
External Infiltration (kWh)	-1690.12
General Lighting (kWh)	727.81
Occupancy (kWh)	1459.62
Solar Gains Exterior Windows (kWh)	2409.07
Zone Sensible Heating (kWh)	980.70
Zone Sensible Cooling (kWh)	-553.26
Sensible Cooling (kWh)	-172.51
AHU Heating (kWh)	1056.67
Total Cooling (kWh)	-206.21
Radiant + Convective Heating (kWh)	1556.27
Chiller Load (kWh)	-207.95
Mech Vent + Nat Vent + Infiltration (ac/h)	0.63


Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Lighting
System Fans
System Pumps
Heating (Electricity)
Heating (Gas)
Cooling (Electricity)
DHW (Gas)
Fuel (kW)
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Zone Sensible Cooling
Heat Balance (kW)
Sensible Cooling
AHU Heating
Total Cooling
Radiant + Convective Heating
Chiller Load
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
Sat, 30 Mar 2002- Start DST
Thu, 31 Oct 2002- End DST
Apr
Jul
Oct
2002
Time/Date

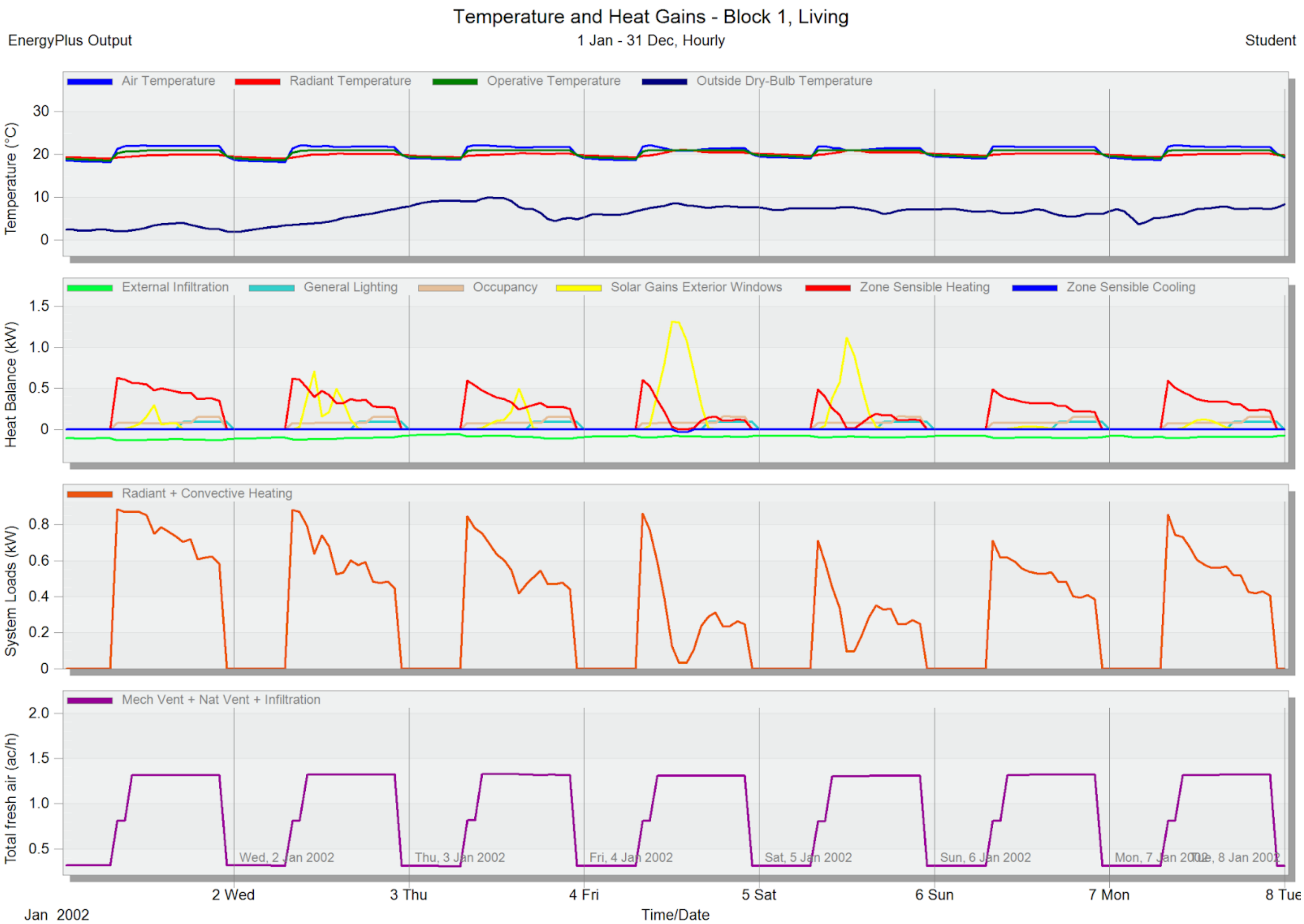
Temperature Distribution for Taller block, Building 1, Block 1, Living

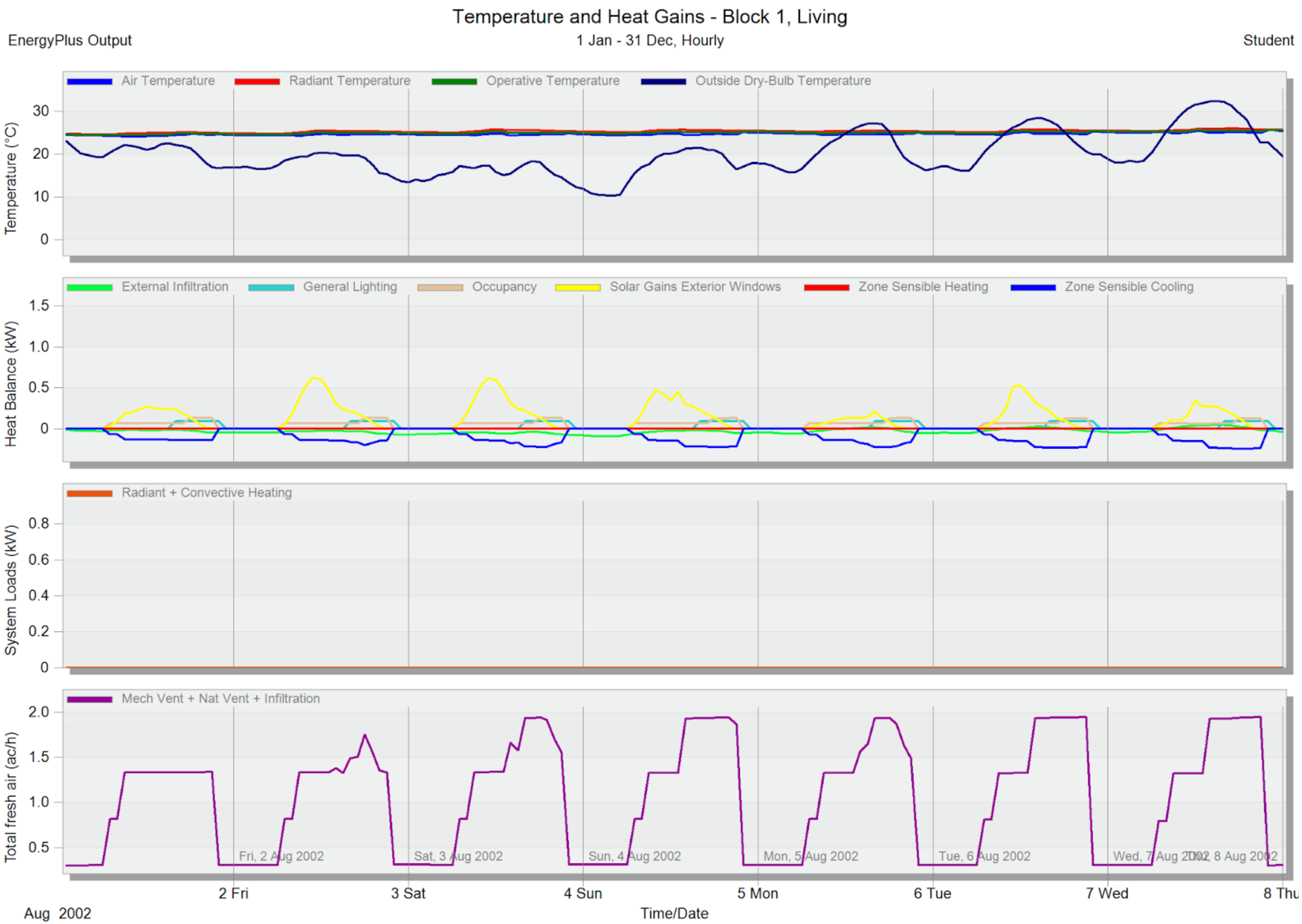
1 Jan - 31 Dec - Zone conditions reported for occupied periods, defined by schedule: Dwell_DomLounge_Occ_new



	19	20	21	22	23	24	25	26	27	28
Hours at or below	0.8	2751.8	3401.3	3661.0	4034.5	4972.0	5250.5	5379.8	5472.3	5475.0
Hours at	0.8	2751.0	649.5	259.8	373.5	937.5	278.5	129.3	92.5	2.8
Hours at or above	5475.0	5474.3	2723.3	2073.8	1814.0	1440.5	503.0	224.5	95.3	2.8

Temperature bins (°C)


Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Zone Sensible Cooling
Heat Balance (kW)
Radiant + Convective Heating
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
2 Wed
3 Thu
4 Fri
5 Sat
6 Sun
7 Mon
8 Tue
Jan 2002
Time/Date



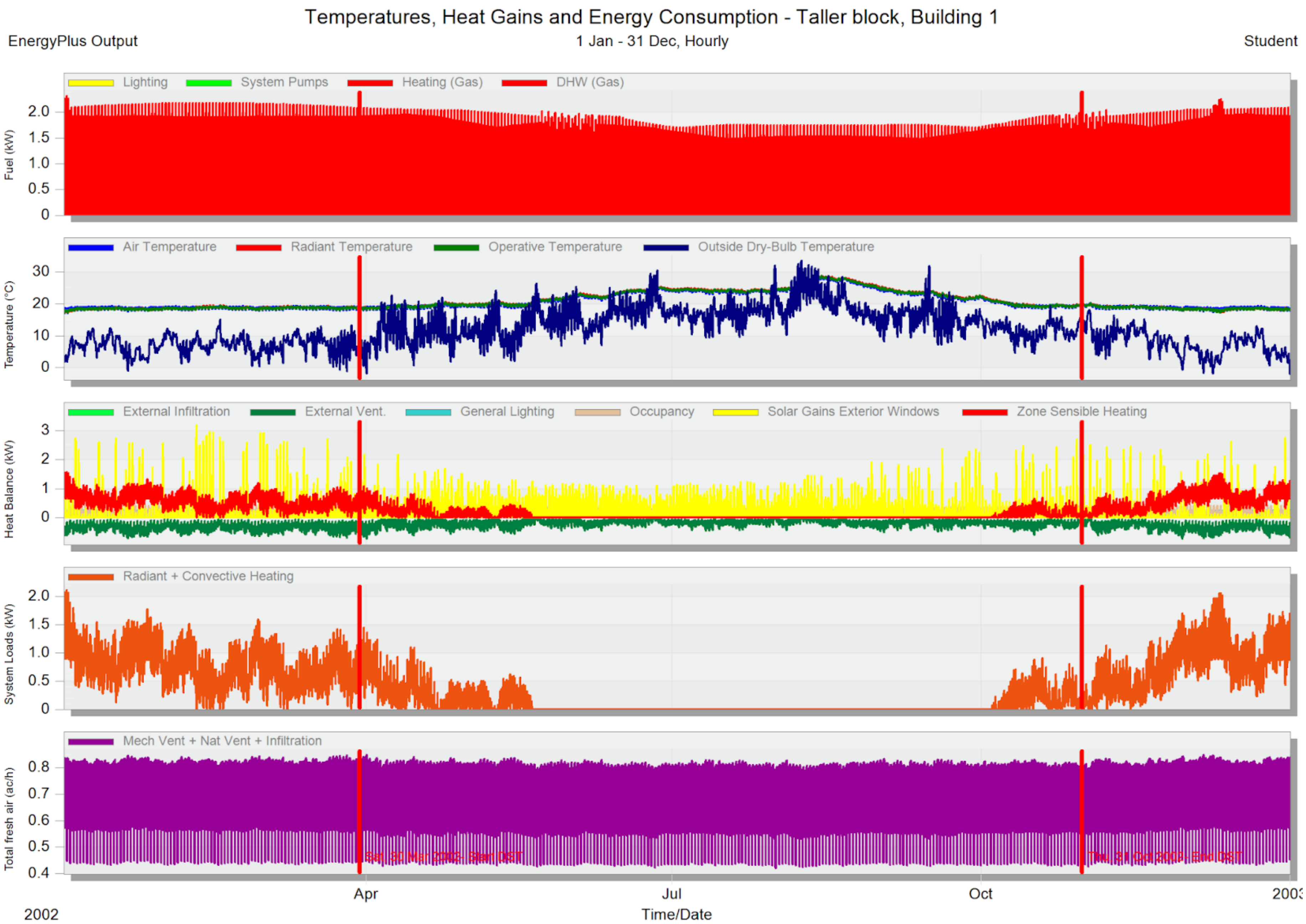
Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Zone Sensible Cooling
Heat Balance (kW)
Radiant + Convective Heating
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
Fri, 2 Aug 2002
Sat, 3 Aug 2002
Sun, 4 Aug 2002
Mon, 5 Aug 2002
Tue, 6 Aug 2002
Wed, 7 Aug 2002
Thu, 8 Aug 2002
2 Fri
3 Sat
4 Sun
5 Mon
6 Tue
7 Wed
8 Thu
Aug 2002
Time/Date

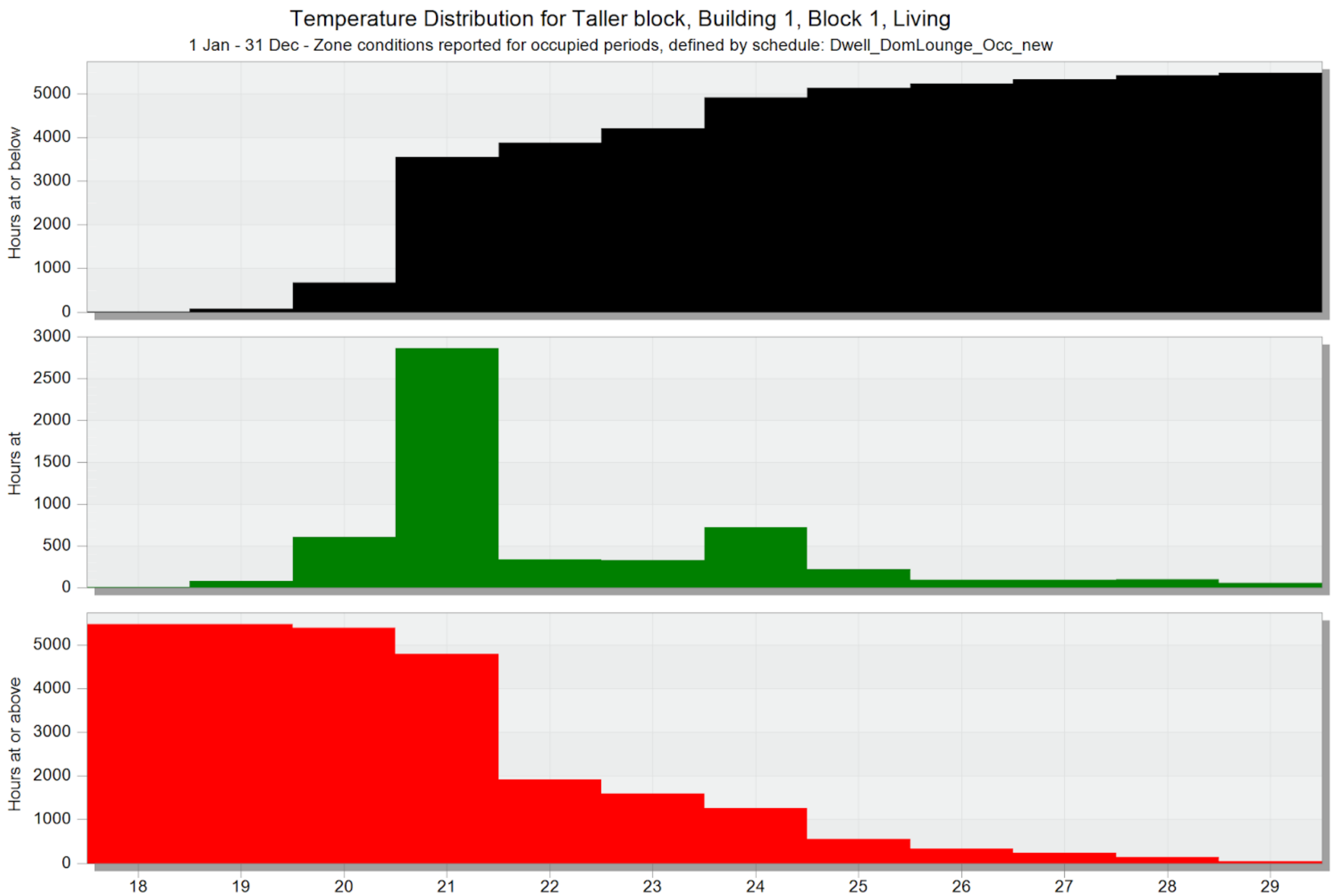
Case 5: Façade renovation variation

Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1

EnergyPlus Output — 1 Jan - 31 Dec, Annual — Student

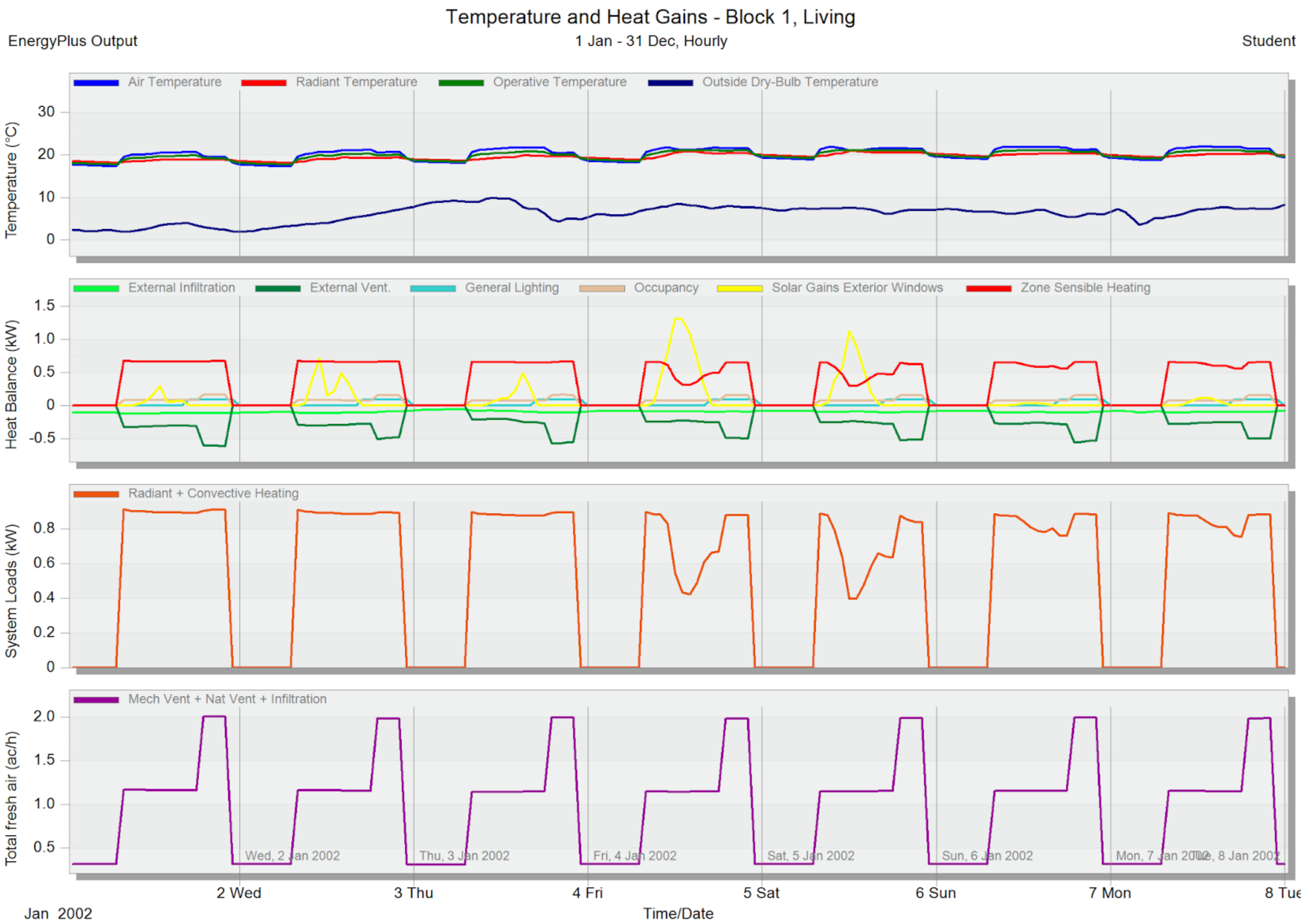
	Year
Lighting (kWh)	727.81
System Pumps (kWh)	2.75
Heating (Gas) (kWh)	3005.09
DHW (Gas) (kWh)	5188.15
Air Temperature (°C)	20.72
Radiant Temperature (°C)	20.86
Operative Temperature (°C)	20.79
Outside Dry-Bulb Temperature (°C)	11.95
External Infiltration (kWh)	-1645.51
External Vent. (kWh)	-2236.72
General Lighting (kWh)	727.81
Occupancy (kWh)	1475.41
Solar Gains Exterior Windows (kWh)	2409.07
Zone Sensible Heating (kWh)	2149.97
Radiant + Convective Heating (kWh)	2899.87
Mech Vent + Nat Vent + Infiltration (ac/h)	0.69


Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Lighting
System Pumps
Heating (Gas)
DHW (Gas)
Fuel (kW)
2.0
1.5
1.0
0.5
0
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
30
20
10
0
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Heat Balance (kW)
3
2
1
0
Radiant + Convective Heating
System Loads (kW)
2.0
1.5
1.0
0.5
0
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
0.8
0.7
0.6
0.5
0.4
Apr
Jul
Oct
2002
Time/Date

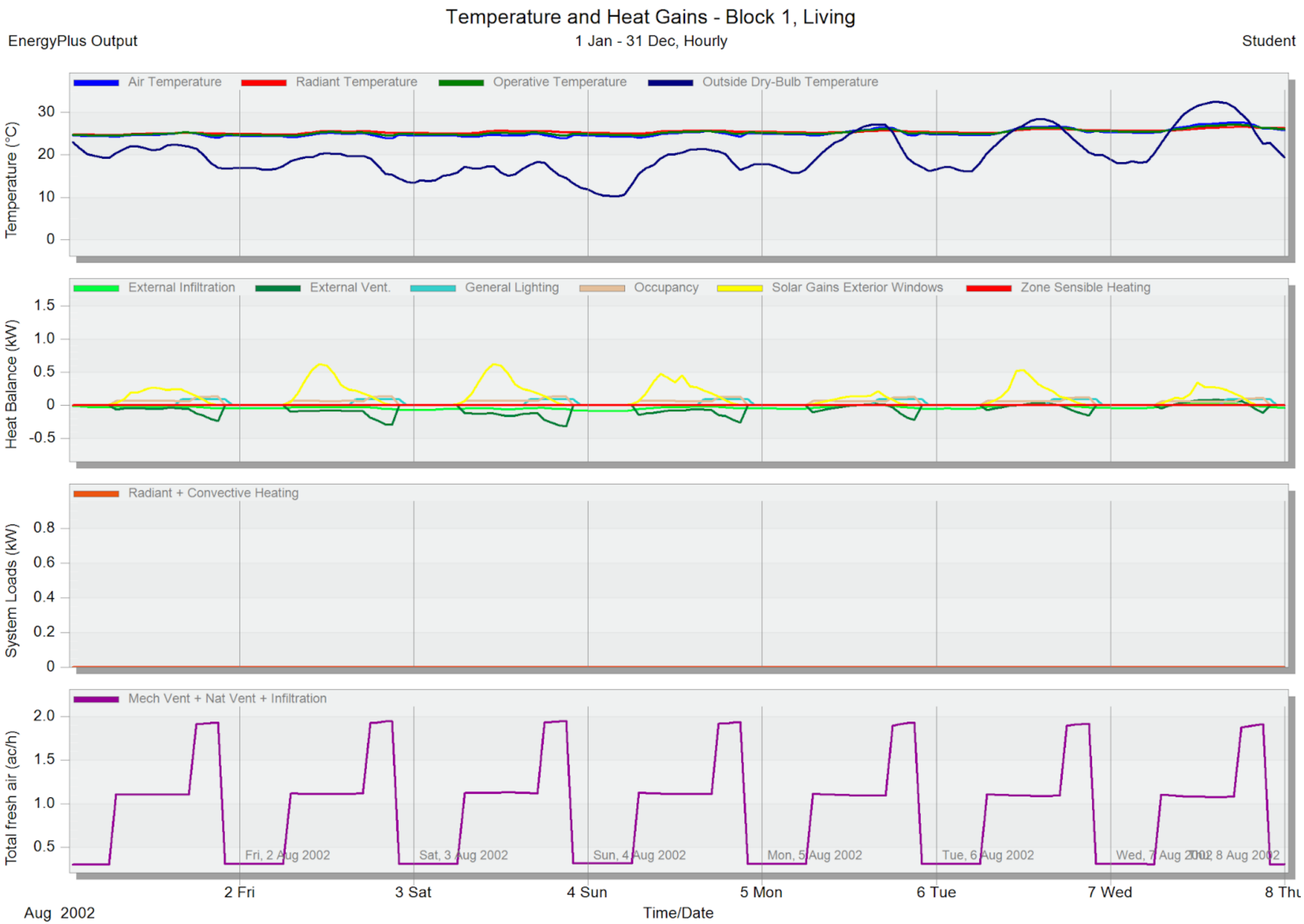


	18	19	20	21	22	23	24	25	26	27	28	29
Hours at or below	1.3	76.0	683.8	3546.8	3877.0	4203.3	4923.8	5140.3	5232.0	5325.0	5421.3	5475.0
Hours at	1.3	74.8	607.8	2863.0	330.3	326.3	720.5	216.5	91.8	93.0	96.3	53.8
Hours at or above	5475.0	5473.8	5399.0	4791.3	1928.3	1598.0	1271.8	551.3	334.8	243.0	150.0	53.8

Temperature bins (°C)



Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Heat Balance (kW)
Radiant + Convective Heating
System Loads (kW)
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
Wed, 2 Jan 2002
Thu, 3 Jan 2002
Fri, 4 Jan 2002
Sat, 5 Jan 2002
Sun, 6 Jan 2002
Mon, 7 Jan 2002
Tue, 8 Jan 2002
2 Wed
3 Thu
4 Fri
5 Sat
6 Sun
7 Mon
8 Tue
Jan 2002
Time/Date



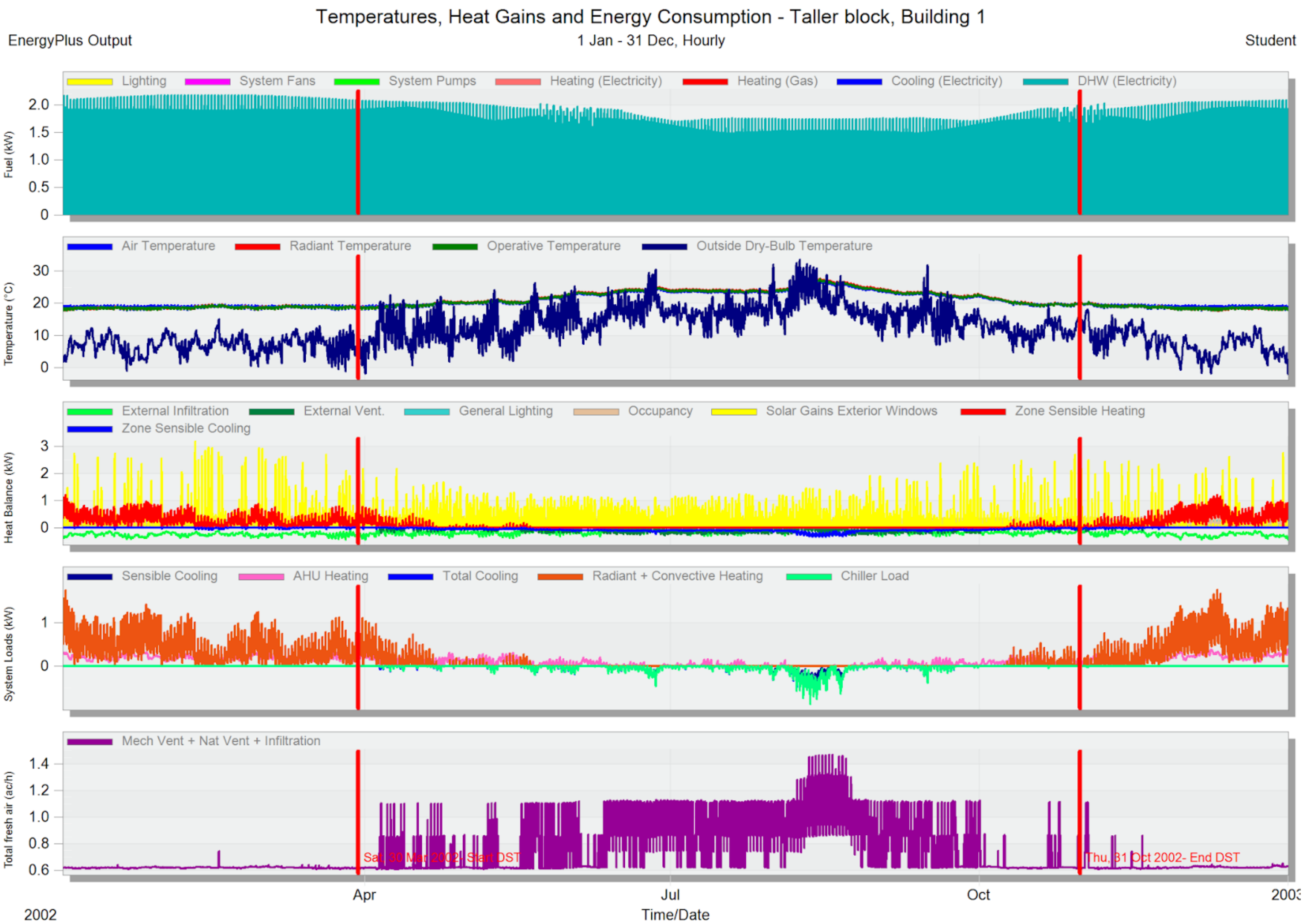
Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
30
20
10
0
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Heat Balance (kW)
1.5
1.0
0.5
0
-0.5
Radiant + Convective Heating
System Loads (kW)
0.8
0.6
0.4
0.2
0
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
2.0
1.5
1.0
0.5
Fri, 2 Aug 2002
Sat, 3 Aug 2002
Sun, 4 Aug 2002
Mon, 5 Aug 2002
Tue, 6 Aug 2002
Wed, 7 Aug 2002
Thu, 8 Aug 2002
2 Fri
3 Sat
4 Sun
5 Mon
6 Tue
7 Wed
8 Thu
Aug 2002
Time/Date

Case 6: EWF & Façade renovation variation

Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1

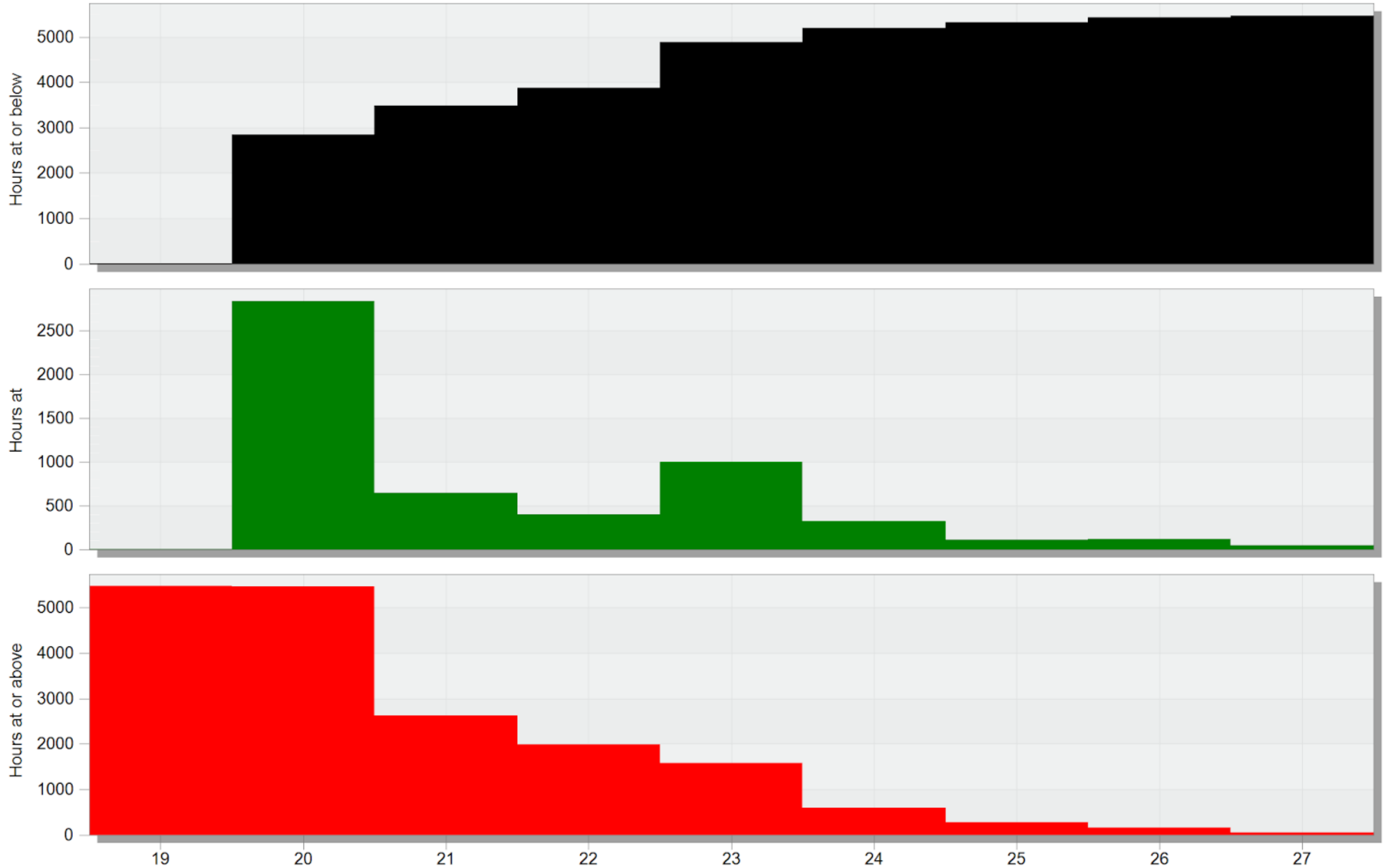
EnergyPlus Output | 1 Jan - 31 Dec, Annual | Student

	Year
Lighting (kWh)	727.81
System Fans (kWh)	423.59
System Pumps (kWh)	33.75
Heating (Electricity) (kWh)	444.17
Heating (Gas) (kWh)	1265.92
Cooling (Electricity) (kWh)	362.12
DHW (Electricity) (kWh)	5189.23
Air Temperature (°C)	20.61
Radiant Temperature (°C)	20.71
Operative Temperature (°C)	20.66
Outside Dry-Bulb Temperature (°C)	11.95
External Infiltration (kWh)	-1623.21
External Vent. (kWh)	-497.25
General Lighting (kWh)	727.81
Occupancy (kWh)	1493.45
Solar Gains Exterior Windows (kWh)	2409.07
Zone Sensible Heating (kWh)	1048.31
Zone Sensible Cooling (kWh)	-424.72
Sensible Cooling (kWh)	-167.59
AHU Heating (kWh)	1055.42
Total Cooling (kWh)	-200.15
Radiant + Convective Heating (kWh)	1672.44
Chiller Load (kWh)	-201.18
Mech Vent + Nat Vent + Infiltration (ac/h)	0.79


Temperatures, Heat Gains and Energy Consumption - Taller block, Building 1
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Lighting
System Fans
System Pumps
Heating (Electricity)
Heating (Gas)
Cooling (Electricity)
DHW (Electricity)
Fuel (kW)
2.0
1.5
1.0
0.5
0
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
30
20
10
0
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Zone Sensible Cooling
Heat Balance (kW)
3
2
1
0
Sensible Cooling
AHU Heating
Total Cooling
Radiant + Convective Heating
Chiller Load
System Loads (kW)
1
0
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
1.4
1.2
1.0
0.8
0.6
Sat, 30 Mar 2002- Start DST
Thu, 31 Oct 2002- End DST
Apr
Jul
Oct
2002
Time/Date

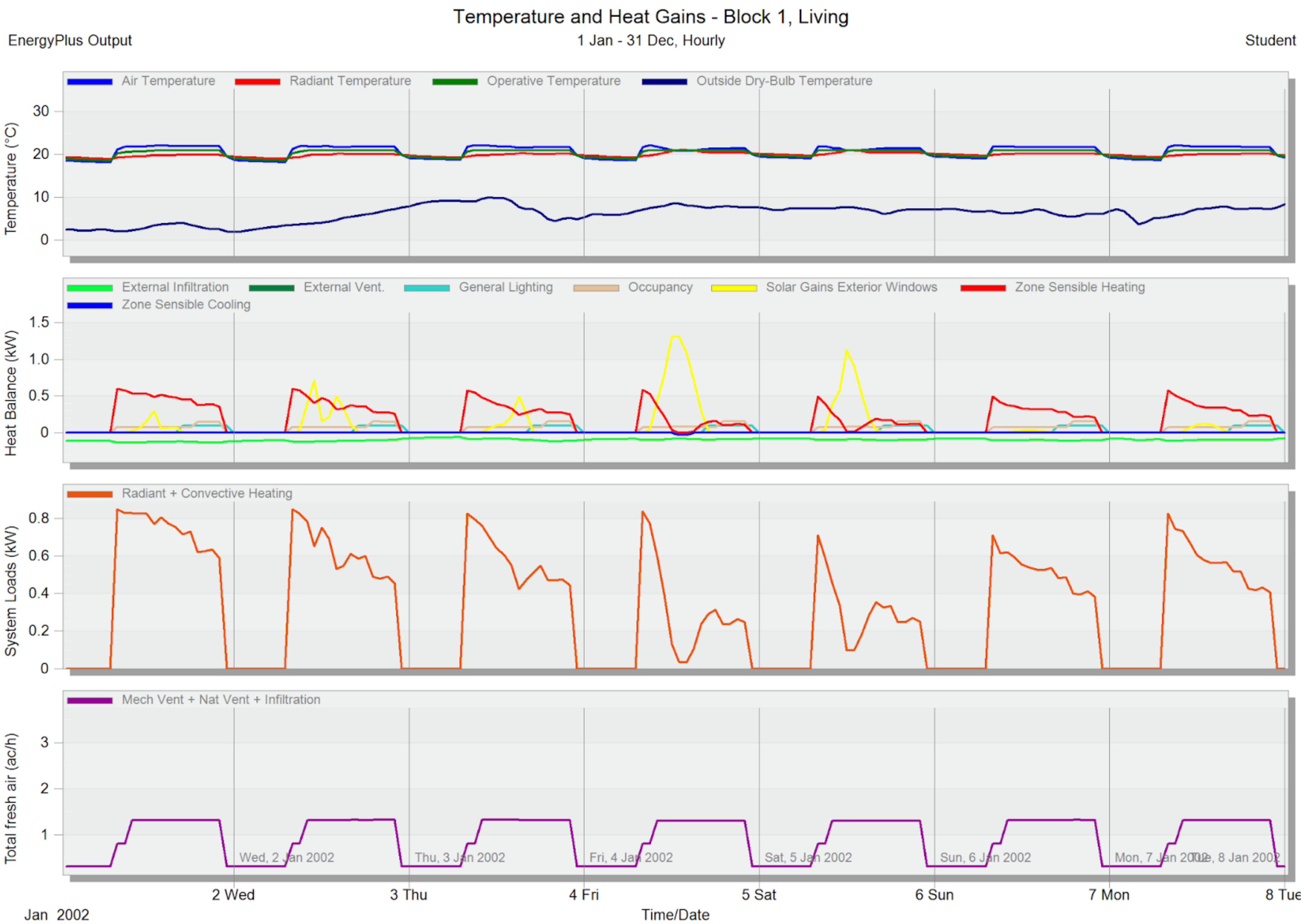
Temperature Distribution for Taller block, Building 1, Block 1, Living

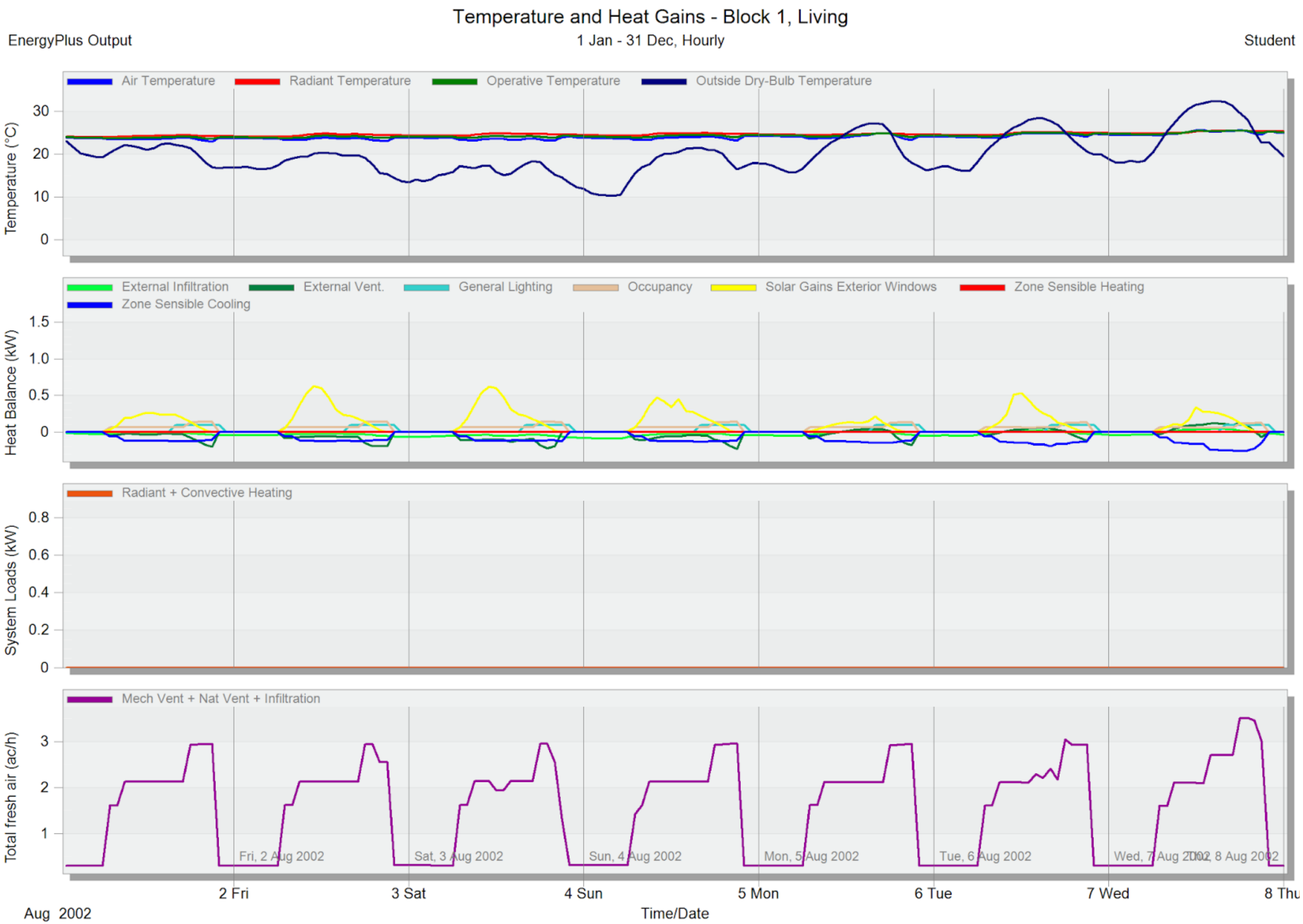
1 Jan - 31 Dec - Zone conditions reported for occupied periods, defined by schedule: Dwell_DomLounge_Occ_new



	19	20	21	22	23	24	25	26	27
Hours at or below	1.3	2841.8	3486.5	3886.8	4881.0	5201.8	5314.0	5427.5	5475.0
Hours at	1.3	2840.5	644.8	400.3	994.3	320.8	112.3	113.5	47.5
Hours at or above	5475.0	5473.8	2633.3	1988.5	1588.3	594.0	273.3	161.0	47.5

Temperature bins (°C)


Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
30
20
10
0
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Zone Sensible Cooling
Heat Balance (kW)
1.5
1.0
0.5
0
Radiant + Convective Heating
System Loads (kW)
0.8
0.6
0.4
0.2
0
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
3
2
1
Wed, 2 Jan 2002
Thu, 3 Jan 2002
Fri, 4 Jan 2002
Sat, 5 Jan 2002
Sun, 6 Jan 2002
Mon, 7 Jan 2002
Tue, 8 Jan 2002
2 Wed
3 Thu
4 Fri
5 Sat
6 Sun
7 Mon
8 Tue
Jan 2002
Time/Date


Temperature and Heat Gains - Block 1, Living
EnergyPlus Output
1 Jan - 31 Dec, Hourly
Student
Air Temperature
Radiant Temperature
Operative Temperature
Outside Dry-Bulb Temperature
Temperature (°C)
30
20
10
0
External Infiltration
External Vent.
General Lighting
Occupancy
Solar Gains Exterior Windows
Zone Sensible Heating
Zone Sensible Cooling
Heat Balance (kW)
1.5
1.0
0.5
0
Radiant + Convective Heating
System Loads (kW)
0.8
0.6
0.4
0.2
0
Mech Vent + Nat Vent + Infiltration
Total fresh air (ac/h)
3
2
1
Fri, 2 Aug 2002
Sat, 3 Aug 2002
Sun, 4 Aug 2002
Mon, 5 Aug 2002
Tue, 6 Aug 2002
Wed, 7 Aug 2002
Thu, 8 Aug 2002
2 Fri
3 Sat
4 Sun
5 Mon
6 Tue
7 Wed
8 Thu
Aug 2002
Time/Date