Naturally
Tokyo

Found in Translation?

A case study of Dutch *Earth, Wind, and Fire* system integration & optimization in an office building in Tokyo

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Abstract

Earth, Wind, and Fire (EWF) is a natural ventilation system developed by Dr Ben Bronsema for office buildings in the Western European climate. Powered by nature: ground temperature & gravity for cooling, wind for energy generation & ventilation, and sun for the heat and natural draft, this system claims not only to use little energy but also naturally purifies while humidify/dehumidify the air. No study has been done to see the performance of the system in a warmer climate, such as Tokyo. This thesis intends to answer that question.

The dynamic duo of EWF: air supply system called Climate Cascade (CC) and air exhaust system called Solar Chimney (SC) are sized and calculated using 2 separate Excel models, from which the key parameters are identified, and design choices can be made. It was clear that as Tokyo's temperature is warmer than Amsterdam's, the focus needs to be given to cooling rather than heating. The challenge: space is limited in Tokyo hence the proposal of making SC a plug & play unitized system.

Armed with a case study integrating EWF into a relatively new 10-story medium-sized office building in Tokyo, the study explored and compared 4 different systems: the existing energy-conscious VRF system, conventional VAV system, EWF with a chilled ceiling, and EWF through chilled beams.

In conclusion, EWF can contribute to energy reduction (40%) without compromising thermal comfort in comparison to the conventional VAV. Regarding VRF, further research needs to be done to properly simulate EWF with HR in the dynamic simulation software used. Moreover, EWF contributed to ventilation energy reduction in all cases evaluated, as well as improving thermal comfort.

Keywords: Earth Wind and Fire, natural ventilation system, air conditioning system, HVAC system, energy retrofitting, energy neutrality, office buildings, Tokyo, thermal comfort.

Preface

I am fortunate to be able to call 2 of the largest built-up urban area in the world: Jakarta and Tokyo, as my home. The first is my hometown of birth, while the second is home for my higher education, work experience, and first actual city exploration and immersion without private cars. In the first, air-conditioning is, by default, a daily-necessity, and in the second, air-conditioning in heating mode during winter and cooling mode during summer is still indispensable. I has never lived, or experienced a world without conventional air-conditioning, until I came to study in the Netherlands.

Then one day, I had the chance to attend Dr Ben Bronsema's presentation about his Earth, Wind, and Fire concept, and how it was designed and developed in the hope to replace the conventional HVAC system in office buildings in the Netherlands. He called it natural air-conditioning.

Both fascinated and challenged, it was one of those "the calling" moment when I was determined to see how I could apply this system back home. Which home? Considering Tokyo has both need for heating and cooling, and in that way, more similar to the intended climate of EWF in the Netherlands, I chose Tokyo.

"I want you to act as if the house is on fire, because it is." Greta Thunberg

The clock is ticking, our mother earth is dying, and the future of life in this planet as we know it desperately need real action from us today. *What are we waiting for?*

Acknowledgment

This thesis is not only the result of my own sweat and tears but also the fruit of immense support from my family in Indonesia, my partner Alejandro González Tineo in Japan (special thanks for the data processing & Excel master class!), and my thesis circle here in the Netherlands: my respected mentors Regina Bokel, Alejandro Prieto, and the source of inspiration for this thesis Ben Bronsema. Equally important, the other 2 'EWF girls': Yamini Patidar and Shriya Balakrishnan, with whom I have shared critical discussion and bottomless encouragement and help throughout this thesis.

I would also like to personally thank: Ado Kamagata, for his selfless help in providing crucial information for this thesis; Ron van der Plas for sharing his expertise in mechanical and EWF integration; Lorenzo Lignarolo for the tutorial in using Ben's Excel Calculation model.

Furthermore, *doumo arigatou gozaimasu* to my-former-manager-now-director of OC Global, Wong Kuok Hung for believing in me and allowing me to take a longer-than-normal sabbatical leave from the company for this Master study; and to my former Team Leader Kazuhiro Miyatake, for the kind communication and advice along the way, and for being my Guarantor for the Permanent Residency of Japan that has allowed me to leave the country and pursue this study in the Netherlands without ruining my chance to go back to Japan as it is officially a second home now.

Last but not least, my deep appreciation and gratitude to my *sensei* in Japan: Teruo Yomo sensei and Tsutomu Shigemura sensei for their wisdom, patience, and support up until the very last moment of providing recommendation letters for me – years after my graduation. This master would not be possible without both of your effort for me.

THANK YOU!

Earth, Wind, & Fire *girls*

1. Introduction

1.1 PROBLEM STATEMENT

Japan, despite being the third richest country in the world (Silver, 2020), is only ranked 34 out of 35 OECD (Organization for Economic Co-operation and Development) countries in 2017 for Primary Energy Self Sufficiency Ratio, with merely 9.6%. Still largely dependent on fossil fuels such as oil, coal and LNG (liquefied natural gas), Japan's dependence was 87.4% in 2017, rose as a result of increased utilization of thermal power generation to make up for the shortage of electricity caused by the shutdown of nuclear power plants after the Great East Japan Earthquake in 2011. Thus, Japan's dependency of imports from overseas for fossil fuel is painstakingly high: 99.7%, 97.5%, and 99.3% for crude oil, LNG, and coal, respectively (Agency for Natural Resources and Energy, 2019).

On the other hand, the Greater Tokyo Area is not only the most populous metropolitan in the world, with more than 37.468 million residents as of 2018 (United Nations, Department of Economic and Social Affairs, 2018), but also the largest built-up urban area in the world. With 8,230 km^2 built-up land area, Greater Tokyo Area is the third-largest single metropolitan area, behind New York City and Boston-Providence (Demographia World Urban Areas, 2020).

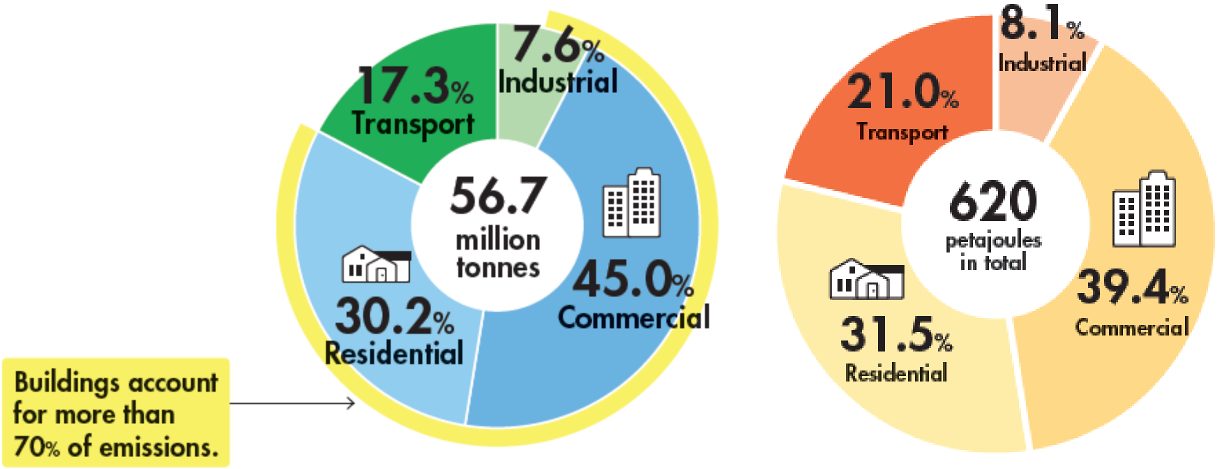

Figure 1 Sectoral Breakdown of energy-related CO2 emission (left) and energy consumption (right) in Tokyo in 2016 (Tokyo Metropolitan Government, 2019)

Furthermore, buildings account for more than 70% of CO_2 emissions in Tokyo, with 30.2% from the residential sector and 45% from the commercial sector (Tokyo Metropolitan Government, 2019).

These characteristics might have been the reasons for Japan to commit to reducing greenhouse gas emissions by 26% in 2030 in comparison to the 2013 level (Agency for Natural Resources and Energy, 2019). Consequently, Tokyo Metropolitan Government has set equally ambitious goals by 2030: 30% and 38% reduction for greenhouse gas emission and energy consumption respectively, in comparison to the year 2000 (Tokyo Metropolitan Government, 2019). Moreover, on 26 October 2020, Japan PM Yoshihide Suga, pledged to "reduce greenhouse gas emissions in Japan to net-zero by 2050, that is, carbon-neutral by 2050, and aim to achieve a decarbonized society" (Ohno, 2020).

In order to achieve these goals, an innovative solution is needed, especially for energy consumption in commercial buildings, as it is the highest. Therefore, a sustainable alternative to the conventional air-conditioning system in buildings could be the most effective solution.

Conversely, vacant office buildings in Tokyo are on the rise, and the COVID-19 pandemic has prompted many companies to postpone their plans to relocate or move to a bigger office, consolidating workplaces or cancelling rent contracts as a result of increasing work-from-home practices (Jiji, 2020). On the bright side, vacant buildings make for a better 'deep renovation' condition, i.e., energy retrofitting to Zero Energy Buildings (ZEB) that is sure to contribute in achieving the previously mentioned goals.

This research aims to provide a sustainable alternative to a conventional air-conditioning system in office buildings in Tokyo through the following objectives:

- To explore the potential of Earth, Wind, and Fire system (hereinafter referred to as "EWF") by Dr Ben Bronsema for the climate of Tokyo
- To develop a case study of integrating EWF into an existing office building in Tokyo
- To evaluate the impact of EWF system in comfort level and in achieving energy-neutrality in an office building in Tokyo
- When relevant, to optimize the EWF system following the evaluation found in the previous objective, to be better suited for the climate of Tokyo

This leads to the following research question:

"Is the Dutch **Earth, Wind and Fire system** (EWF), in place of the existing **air-conditioning system**, an efficient **energy-retrofitting method** to achieve **energy-neutrality** in an **office building in Tokyo** without compromising **thermal comfort** of users?"

To answer the main research question, the following sub-questions have been proposed. For a better understanding, they have been grouped into 3 categories:

Site context

- How does the climate of Tokyo impose challenges in achieving thermal comfort throughout the year?

Office buildings in Tokyo

- What are the typologies of office buildings in Tokyo and their air-conditioning systems?
- What is the energy consumption of office buildings in Tokyo and what are the applicable regulations related to it?

EWF system & its integration

- What are the elements of EWF and how are they a sustainable alternative to the existing air-conditioning system?
- What are the criteria for EWF integration into an existing building?
- How effective is the proposed EWF design in comparison to the existing air-conditioning system in terms of energy consumption and thermal comfort?

1.2 THESIS STRUCTURE

The thesis has the following structure.

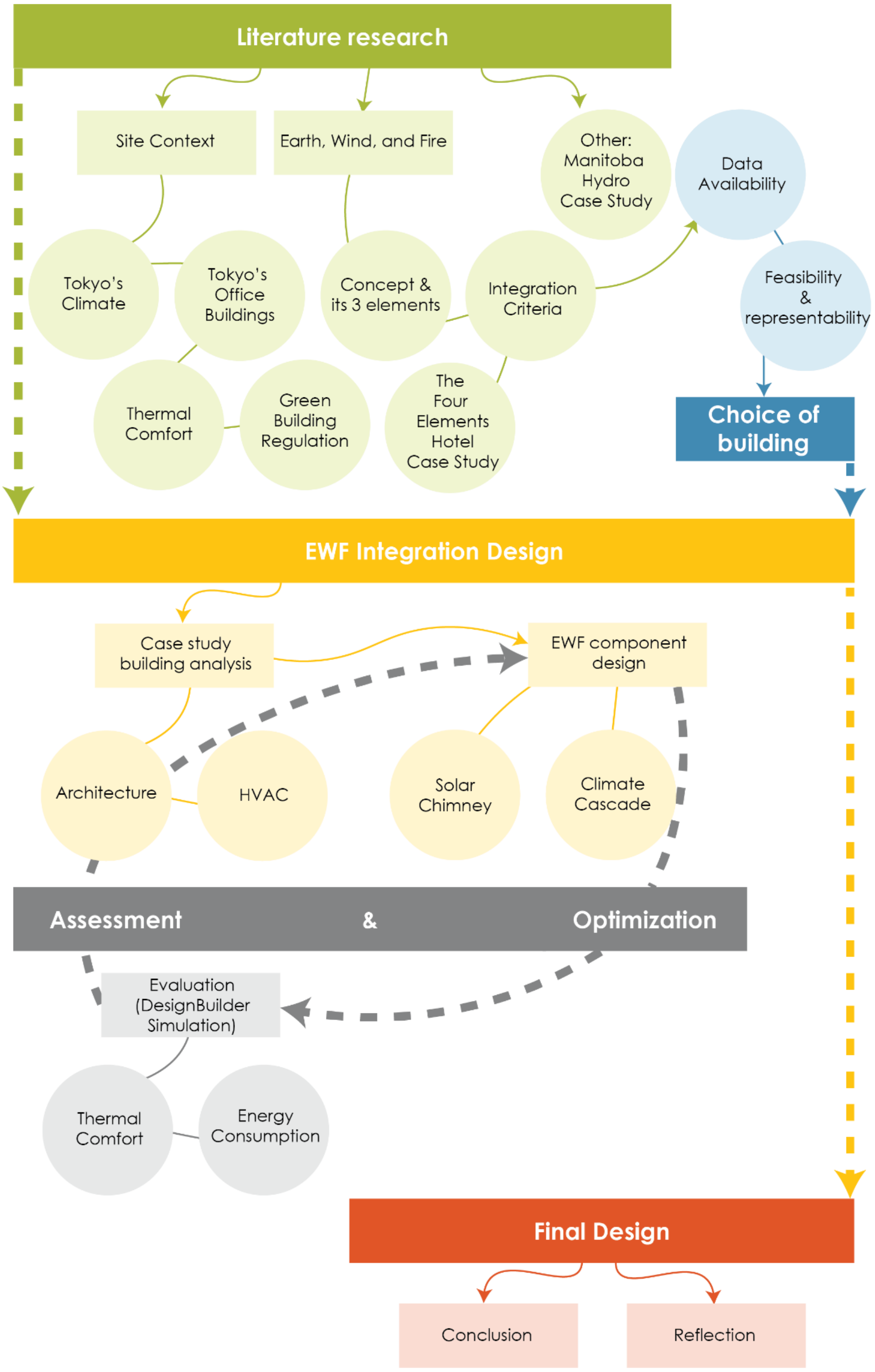

Figure 2 Thesis Structure

2. Site Context

2.1 TOKYO: CLIMATE

The climate in Tokyo is warm and temperate, with a great deal of rainfall, even in the driest month. According to Köppen and Geiger, this climate is classified as Cfa, identified as humid subtropical climate. characterized by hot and humid summers, and cold to mild winters (Wikipedia, 2020a). For comparison to the climate of The Netherlands (Amsterdam), please refer to Appendix 1.

2.1.1 Temperature

The temperature in Tokyo mostly stay above freezing point, with January as the coldest month with the monthly mean daily minimum temperature at 3.7°C, and August as the hottest one with 34.1°C in 2020. The annual average temperature is 16.5°C *(Japan Meteorological Agency, 2020)*.

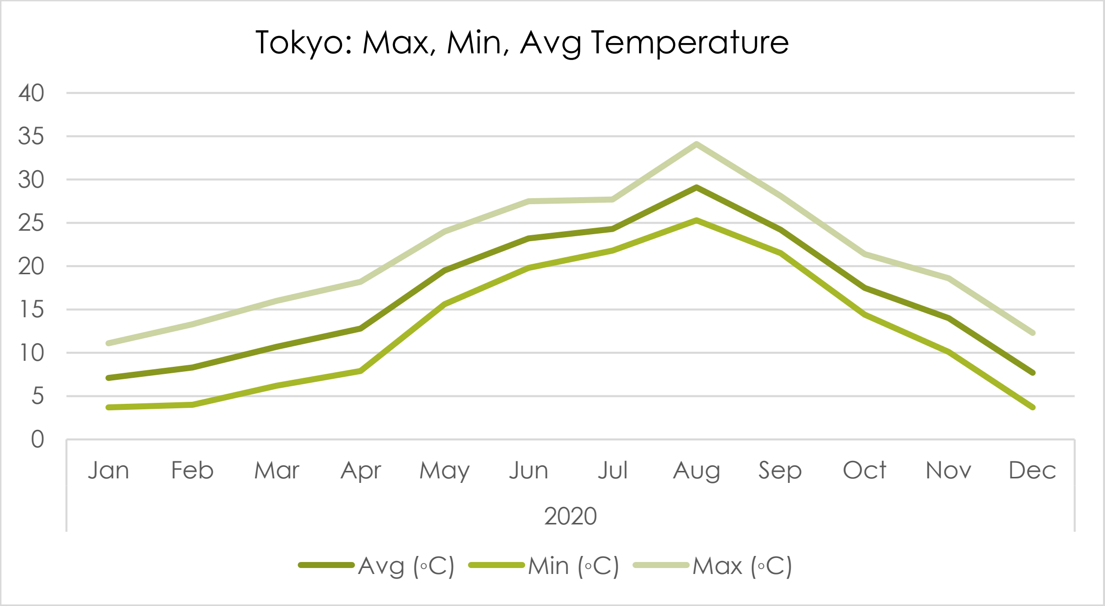

Figure 3 Max, Min, and Average Temperature in Tokyo in 2020

2.1.2 Precipitation

In 2020, April was the wettest month whereas December was the driest, while July has the rainiest days, usually called *Tsuyu (梅雨)* or the rainy season that starts from June. The annual average for rainfall is 1590 mm *(Japan Meteorological Agency, 2020)* in 223 rainy days in 2020 (World Weather Online, 2020).

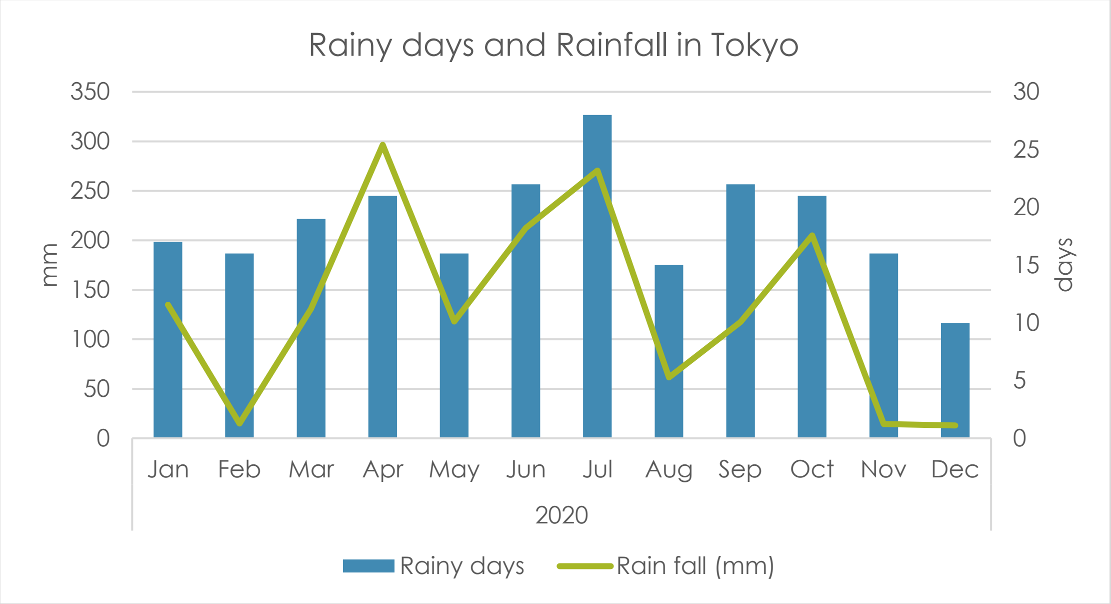

Figure 4 Rainy days and Average Rainfall in Tokyo in 2020

2.1.3 Relative Humidity (RH) & Cloud Amount

The monthly mean RH in Tokyo in 2020 stays above 50%, with February having the lowest RH (55%), and July with the highest (89%). This trends almost entirely in-line with the amount of clouds, with July the most cloudy (97%), although the least amount of clouds is in December with 50%, followed closely by February with 52% *(Japan Meteorological Agency, 2020)*.

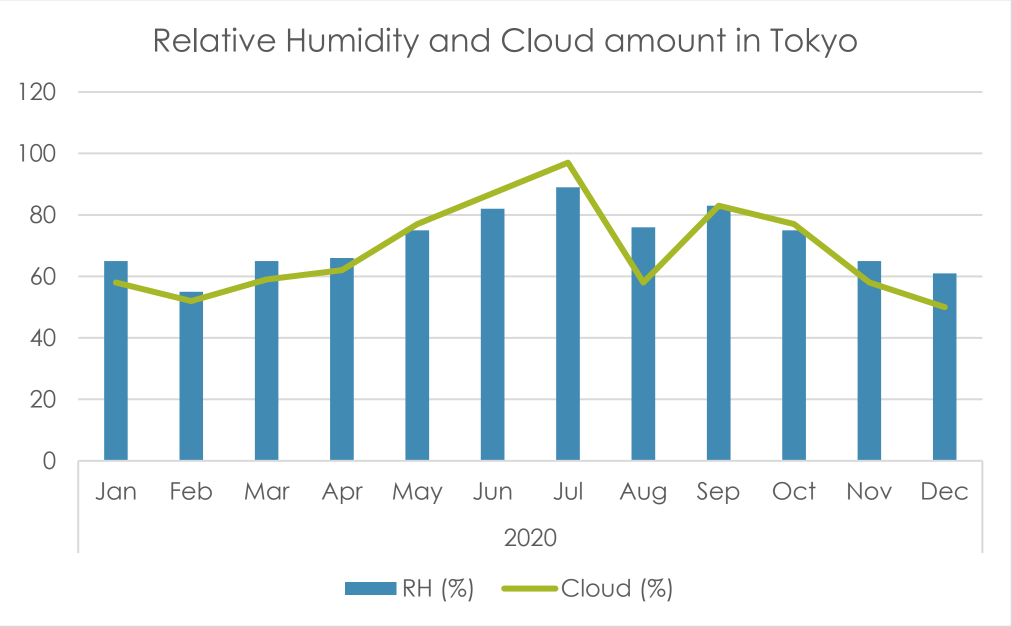

Figure 5 RH and Cloud amount in Tokyo in 2020

2.1.4 Wind speed and Wind Rose

Throughout the year, the monthly mean wind speed in Tokyo is rather uniform and mild, ranging from 2.1 – 3.2 m/s *(Japan Meteorological Agency, 2020)*, with most wind originating from the north-north-west direction (Meteoblue, 2020).

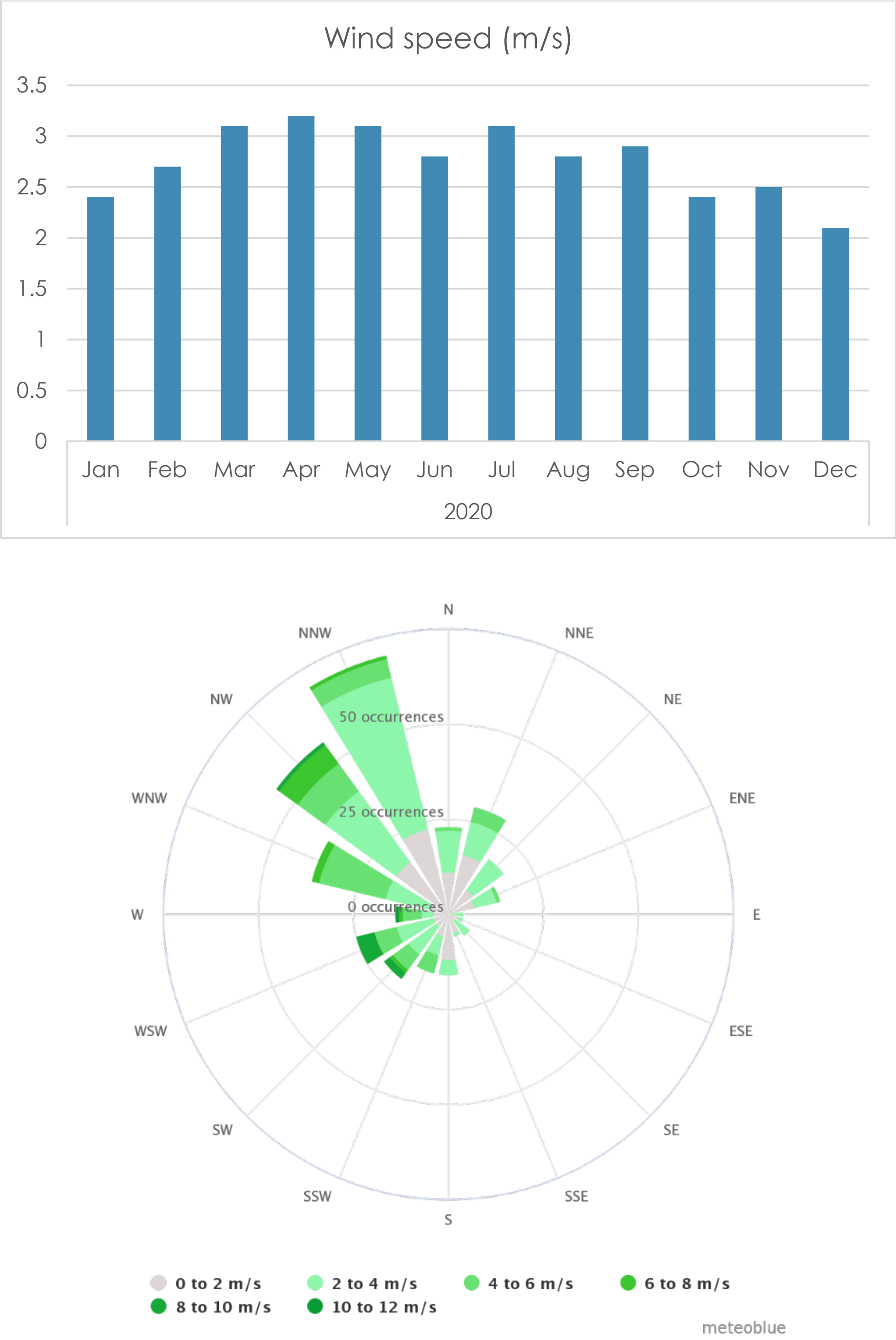

Figure 6 Wind Speed and Wind Rose in Tokyo in 2020

2.1.5 Sun path and Sun Angle

With a dummy building model, the sun path, sun angle, and the casted shadows can be analyzed for 4 different seasons in Tokyo. Data is taken from andrewmarsh.com.

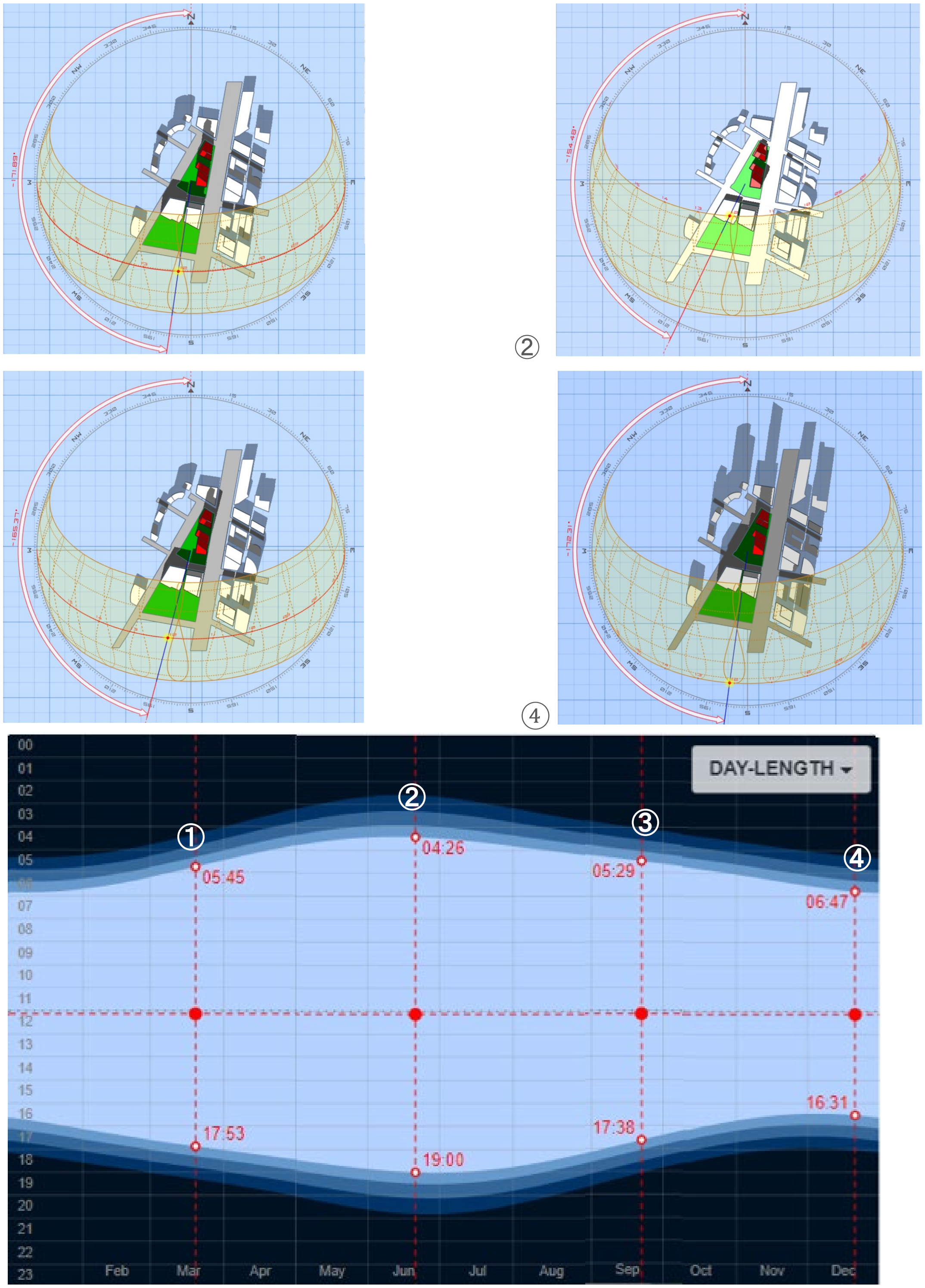
①
②
③
④

Figure 7 ① Spring equinox (20 Mar), ② Summer solstice (21 Jun), ③ Autumn equinox (22 Sep), ④Winter solstice (21 Dec)

2.1.6 Global Solar Radiation and Sun Hour

The peak for both monthly mean global solar radiation and sun hours in Tokyo in 2020 was in August, whereas the lowest points vary: January for solar radiation and July for sun hours (Japan Meteorological Agency, 2020).

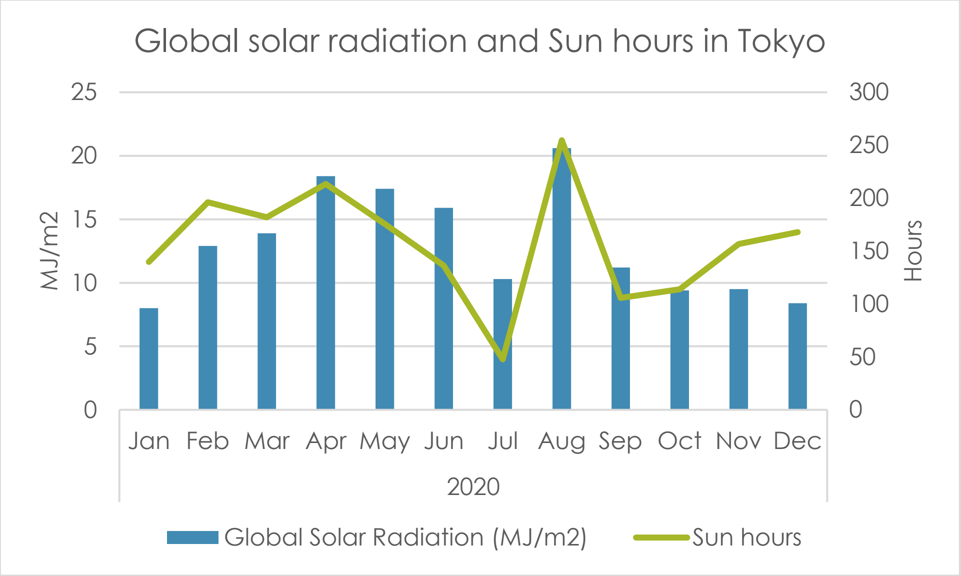

Figure 8 Global solar radiation and Sun hours in Tokyo in 2020

2.2 TOKYO: OFFICE BUILDING

Office buildings in Japan are not classified under *Tokusyukenchikubutsu（特殊建築物）*, or 'Special Building' under Japan's Building Standards Law article 2 paragraph 2, unlike hotels, apartments, schools, etc., thus one can assume that there is more freedom in designing offices as the applicable laws are less. However, as space is relatively limited in Tokyo and in general profitability is highly valued, securing the maximum (rentable) floor area is the priority. Consequently, the shape of the building is largely determined by the site condition (Wikipedia, 2020b).

In principle, office buildings in Tokyo can be classified by size: Large buildings (Gross floor area 5,000 tsubo[1] or more) and Small & Medium buildings (Gross floor area 300-5,000 tsubo).

As shown in Figure 9, small and medium office buildings are the majority in Tokyo, representing more than 90%, with most of the buildings are 20 years old or more. On the other hand, for large office buildings, the ratio for the building age is less significant, with less than 20-year-old buildings represents 45%.

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[1] Tsubo (坪) is Japanese unit of measurement for an area of 3.3 m^2, or about 2 tatami-size

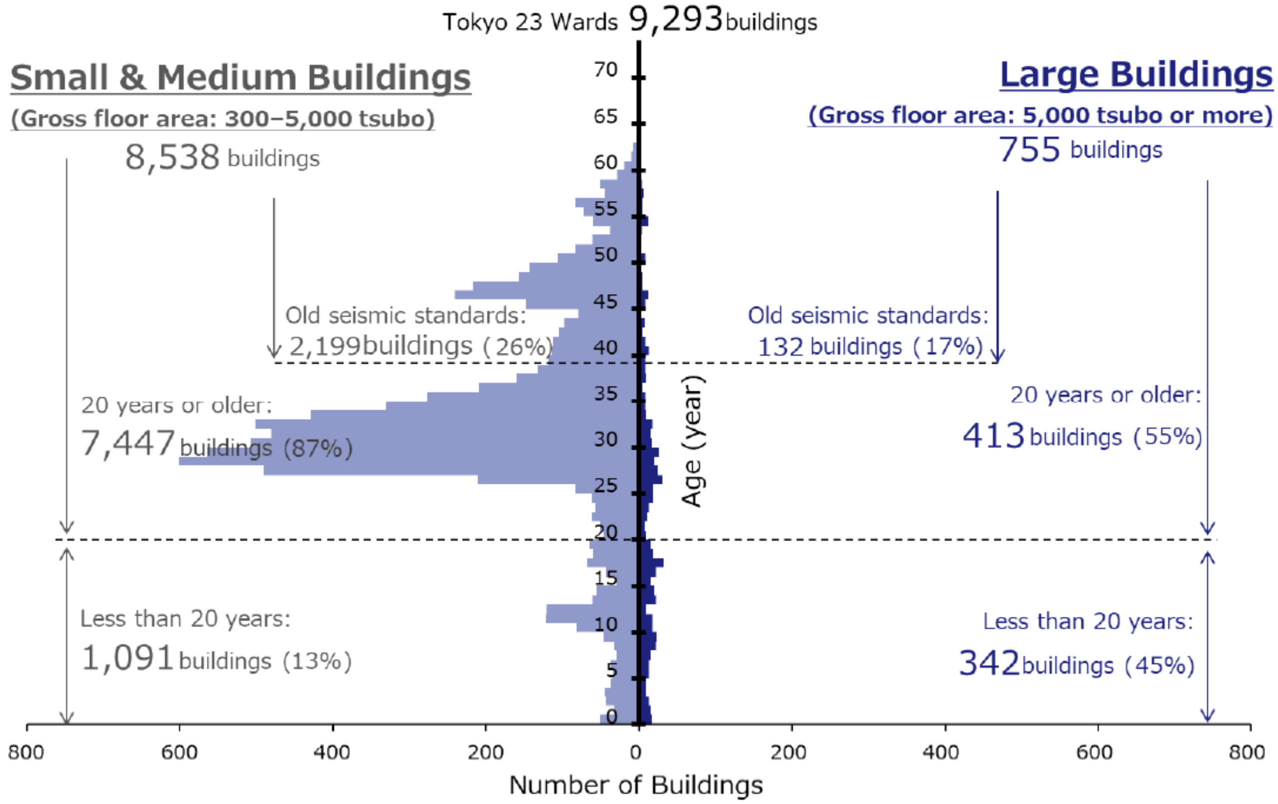


Figure 9 Tokyo's Office Pyramid 2020: Number of Buildings (Xymax Real Estate Institute, 2020b)

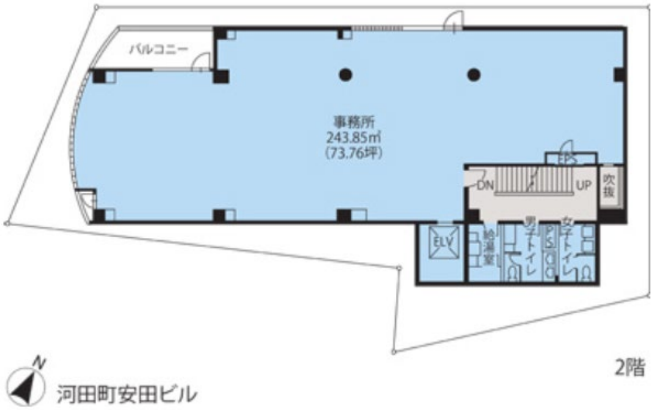
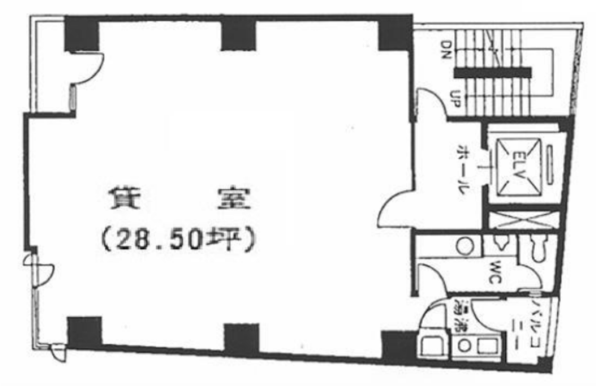
2.2.1 Typology

Following the previously-mentioned classification by size, the office typologies in Tokyo will be explored the same by giving examples chosen by the writer. To narrow down the samples, the examples will be taken from Shinjuku area: a good mix of entertainment and business area in downtown Tokyo.

1. *Small & Medium Buildings*

   This group would be the ideal type for EWF integration (to be further explained in 2.2.3. Integration criteria), although different from the Netherlands, spaces in Tokyo are much more limited, and most of the buildings are built fully within the site. Unless otherwise stated, the sources of the followings are taken from https://www.offisite.jp/.

Table 1 Small & Medium Office Buildings in Tokyo-1

<table>
<tr><th>Kawadacho Yasuda Building</th><th>Nishishinjuku Koide Building</th></tr>
<tr><td></td><td></td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>▪ Built in 1988
▪ Office
▪ 3 floors above ground, 1 basement
▪ Typical floor area: 243.85m^2
▪ Individual air conditioner</td><td>▪ Built in 1990
▪ Office
▪ 11 floors above ground, 1 basement
▪ Typical floor area: 94.05m^2</td></tr>
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(source: office.tatemono.com)

Table 2 Small & Medium Office Buildings in Tokyo-2

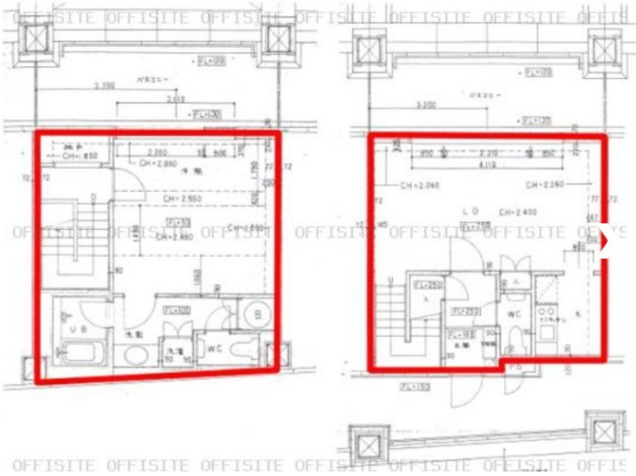
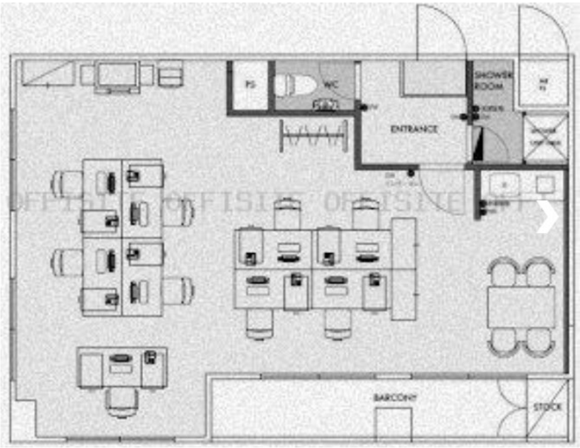
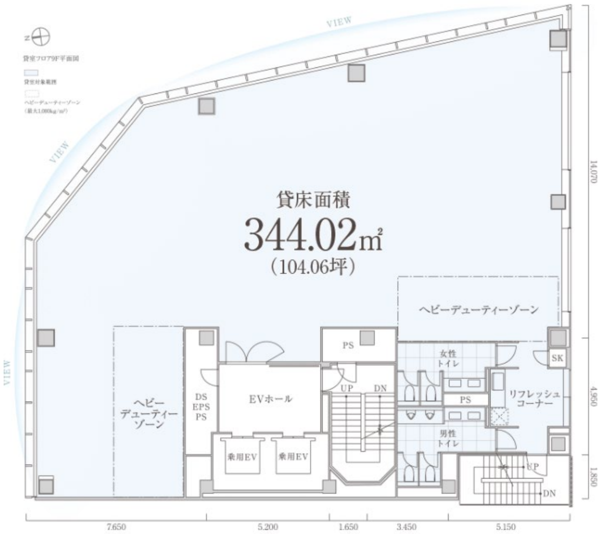
Nishishinjuku KF Building	**DUO Nishishinjuku**
	
	
▪ Built in 1993 ▪ Office ▪ 8 floors above ground, 1 basement ▪ Typical floor area: 82.14m^2 ▪ Individual air conditioner	▪ Built in 1994 ▪ Office ▪ 10 floors above ground, 2 basements ▪ Typical floor area: 65.42m^2 ▪ Individual air conditioner

Table 3 Small & Medium Office Buildings in Tokyo-3

Nishishinjuku TK Building	**PMO Shinjuku Gyoenmae**
	
	
▪ Built in 2003 ▪ Mixed use: Office, restaurant ▪ 9 floors above ground, 1 basement ▪ Typical floor area: 80.29m^2	▪ Built in 2019 ▪ Office ▪ 9 floors above ground ▪ Typical floor area: 344.02m^2 ▪ Individual air conditioner (source: www.pmo-web.com)

2. Large Buildings

Some of the iconic office buildings in Tokyo are in this group, many with shops and restaurants on the lower parts, or even hotels on the higher part. Good connection to the train station is also key. Below are some of the examples (Officetar, 2015).

Table 4 Large Office Buildings in Tokyo-1

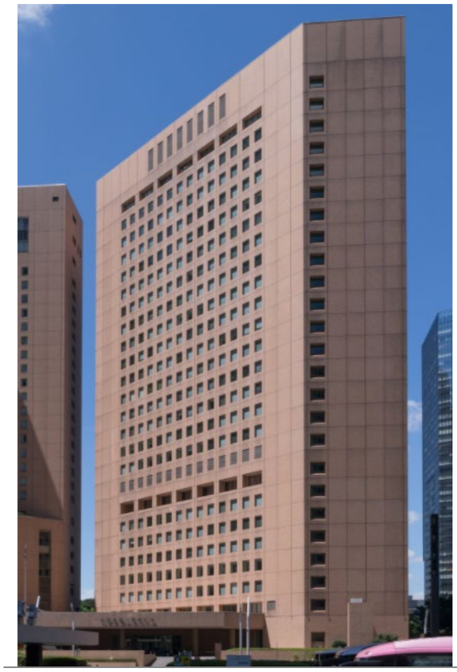
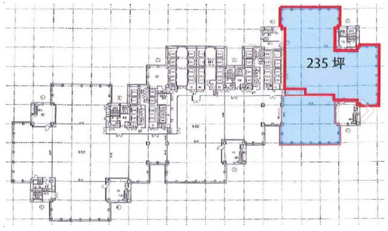
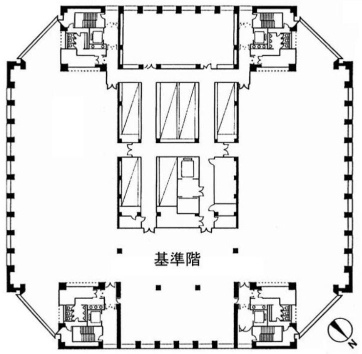
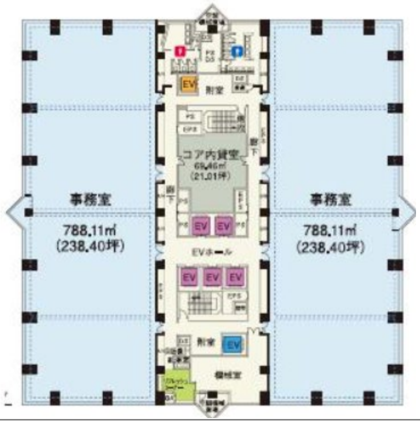
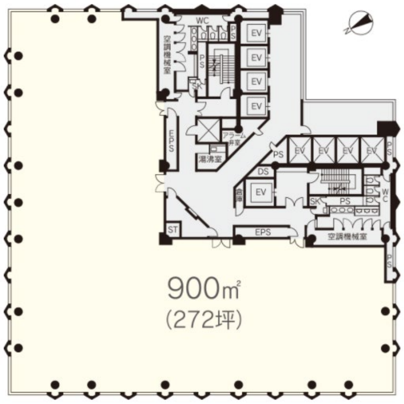
Odakyu Daiichi Seimei Building	**Shinjuku Park Tower**	**Tokyo Opera City**
		
		
▪ Built in 1980 ▪ Mixed use: office, hotel, restaurants ▪ 26 floors above ground, 4 basements ▪ Typical floor area: 1909m^2 ▪ Individual air conditioner, connected to district heating/cooling	▪ Built in 1994 ▪ Mixed use: office, hotel, restaurants ▪ 52 floors above ground, 5 basements ▪ Typical floor area: 3468m^2 ▪ Central (VAV) and Individual air conditioner	▪ Built in 1996 ▪ Mixed use: office, theater, museum, restaurants ▪ 54 floors above ground, 4 basements ▪ Typical floor area: 2159m^2 ▪ Individual air conditioner

Table 5 Large Office Buildings in Tokyo-2

Nishi Shinjuku Mitsui Building	**Nittochi Nishi-Shinjuku Building**	**CONCIERIA Nishishinjuku Tower's West**
		
		
▪ Built in 1999 ▪ Office ▪ 27 floors above ground, 2 basements ▪ Typical floor area: 1576m^2 ▪ Individual air conditioner	▪ Built in 2002 ▪ Office ▪ 23 floors above ground, 2 basements ▪ Typical floor area: 900m^2 ▪ Central and Individual air conditioner	▪ Built in 2008 ▪ Mixed use: Condominium, Office ▪ 44 floors above ground, 4 basements ▪ Typical floor area: 936m^2 ▪ Individual air conditioner

2.2.2 Air-Conditioning

In general, there are 2 types of air-conditioning system in offices in Tokyo: centralized, individual, or both, as has been explored in the previous section.

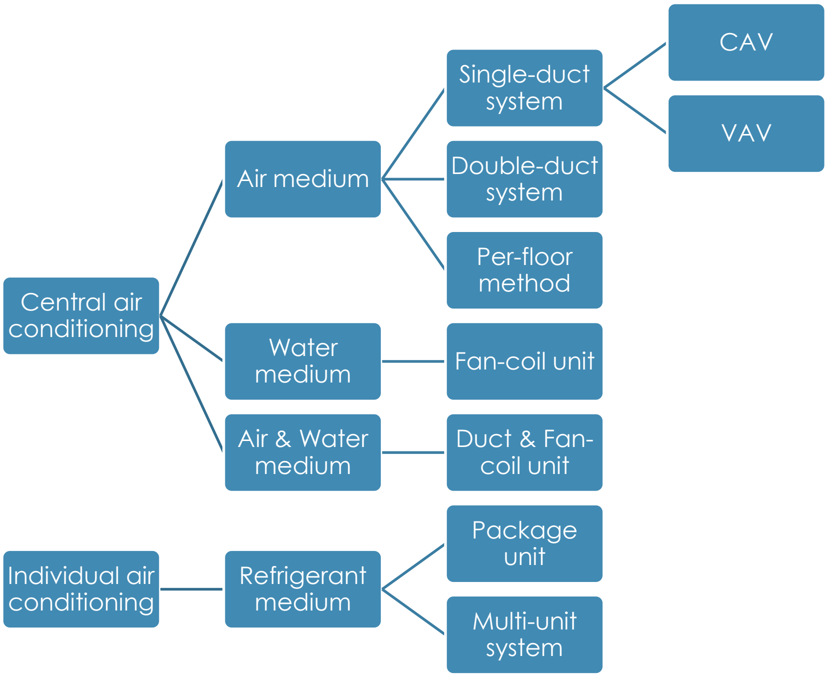


Figure 10 Classification of air-conditioning system (Kikuchi, 2000)

Individual air conditioning is the type that allows control to turn on / off, switch between air conditioning and heating, and adjust the temperature for each floor or room. Heat sources are distributed and installed on each floor or zone. Most medium and small office buildings use this individual air conditioning system.

On the other hand, central air conditioning, as the name suggests, is the type that is centrally controlled in the central control room. The heat source is placed in one place (such as the machine room in the basement or rooftop). Most large office buildings with more than 300 tsubo per floor are equipped with central air conditioning.

Although rare, there are large office buildings with individual air conditioning. In some cases, central air conditioning and individual air conditioning are used together, usually by installing individual air conditioning later in a building where only central air conditioning was originally installed (Officee, 2018).

2.2.3 Energy Consumption and Energy Price

A comprehensive study has been conducted by Xymax Real Estate Institute about energy consumption and energy cost of around 100 office buildings in the Greater Tokyo area since 2010. In the following graph from the same study, energy consumption and energy cost are converted into indices, with figures as of December 2010 set at 100.

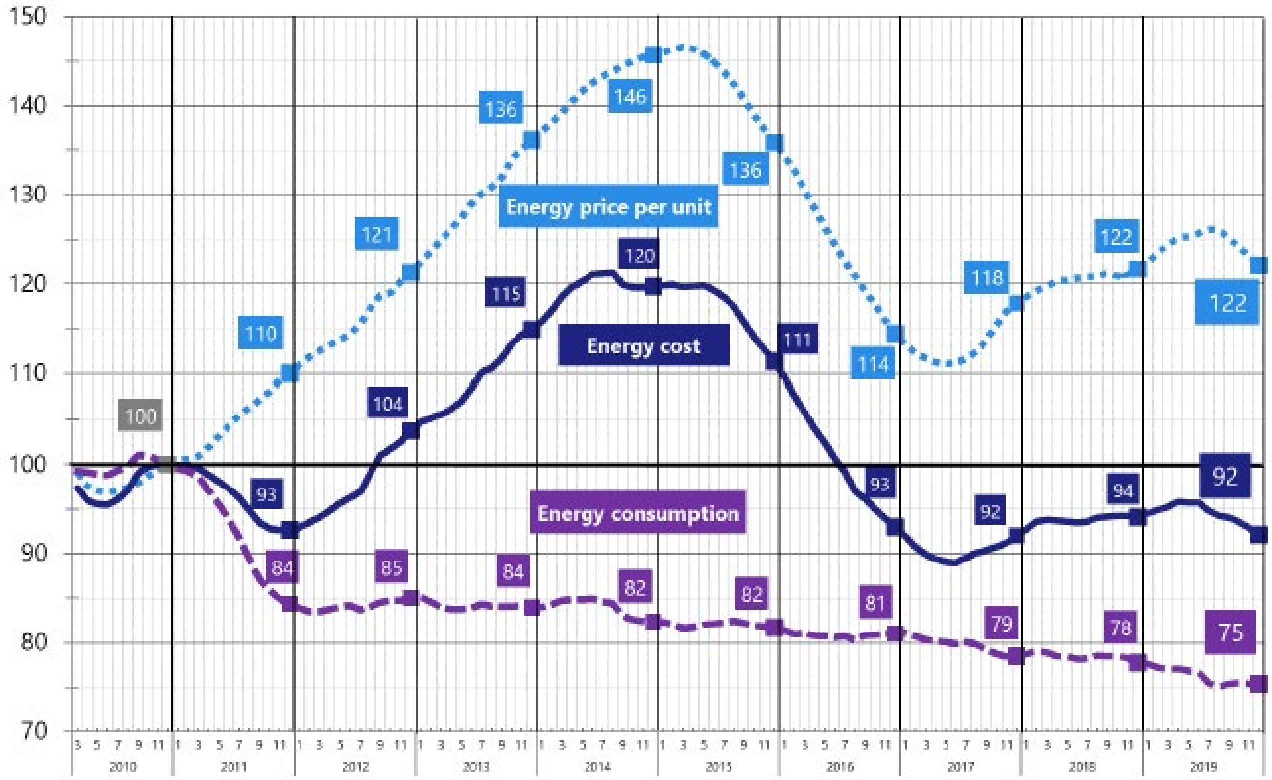


Figure 11 Tokyo's Office Building Energy Consumption & Cost (12-month average) (Xymax Real Estate Institute, 2020a)

The energy consumption in 2019 has decreased by 25 points in comparison to 2000, whereas the price per unit has increased by 22 points. As of the number, the average energy consumption in 2019 was 125.0 MJ/sqm/month (1,500 MJ/sqm/year)[2], whereas the average unit price in 2019 rose 0.01yen year on year to 2.05 yen/MJ.

2.2.4 Thermal Comfort

With the aim to use as little energy as possible to achieve thermal comfort, the adaptive comfort model shall be used. Since Japan does not have adaptive comfort standards and the ASHRAE standard-55 does not include applicable data for Japan, the writer resorts to journal paper to gain insights about the comfortable temperature in office buildings in Tokyo.

An adaptive model for thermal comfort in offices in Tokyo & Yokohama (Greater Tokyo) has been studied, where a total of 4660 samples were collected from about 1350 people: they were found to be highly satisfied with the thermal environment in their offices. Even though the Japanese government recommends the indoor temperature setting of 28°C for cooling and 20°C for heating as an attempt to save energy, the comfort globe temperature was

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[2] The energy consumption calculated is the primary energy based on the following coefficients: Electricity: 9.76 MJ/kWh, City gas: 45 MJ/m^3, Cold/hot water, steam: 1.36 MJ/MJ

found to be 2.6°C lower in cooling mode (25.4°C) and 4.3°C higher in heating mode (24.3°C), in line with actual indoor temperatures. When neither heating nor cooling was used, the comfort temperature was 25°C (Rijal et al., 2017).

Another paper that specifically studies thermal comfort from 435 occupants and 2402 questionnaires in the summer of Tokyo has concluded that the occupants' comfort temperature was found to be 27.2°C (Indraganti et al., 2013). Another interesting point made in this study was: *"The indoor airspeeds were low, indicating a need for ceiling fans. In 50% of the environments, the indoor temperature was more than the 28°C limit. As the buildings were designed for air-conditioning mode, running them in natural ventilation mode posed challenges"*. This raises the fact that many office buildings in Tokyo were not designed for natural ventilation in mind.

2.2.5 Indoor Air Quality

In recent years, in order to improve the efficiency of heating and cooling that leads to energy saving, ventilation tends to be insufficient due to tighter number of airtightness. Moreover, new building materials that contain chemical substances e.g. printed plywood have been used, causing indoor air pollution since the 1990s (Wikipedia, 2020c).

For "Specific Building", or in Japanese called *Tokuteikenchikubutsu（特定建築物）*, which is defined by the total floor area and building's function, Air Environment Measurement is mandated under the Building Hygiene Management Law. For office buildings, it is a Specific Building if the total floor area is 3,000 m^2 or more (Ito, n.d.). Below are the standards.

Table 6 Standards for air environment when air conditioning equipment is installed (MHLW, n.d.)

Dust	0.15 mg / m3 or less
CO	10 ppm or less (* if the outside air is already 10 ppm or more, 20 ppm or less)
CO_2	1,000 ppm or less
Temperature	17°C - 28°C When the temperature in the living room is lower than the temperature of the outside air, the difference should not be significant.
RH	40% - 70%
Wind speed	0.5 m/s or less
Formaldehyde	0.08 ppm or less (for new buildings & large-scale renovations, conduct measurement at least once between June & September)

2.2.6 Green Building Regulation

Tokyo has implemented 3 programs that support sustainable building policy within the city. For existing buildings, the programs are divided into 2 depending on the scale: Tokyo Cap-and-Trade Program and Carbon Reduction Reporting Program, whereas for new buildings, Green Building Program is applicable, as shown in the figure below.

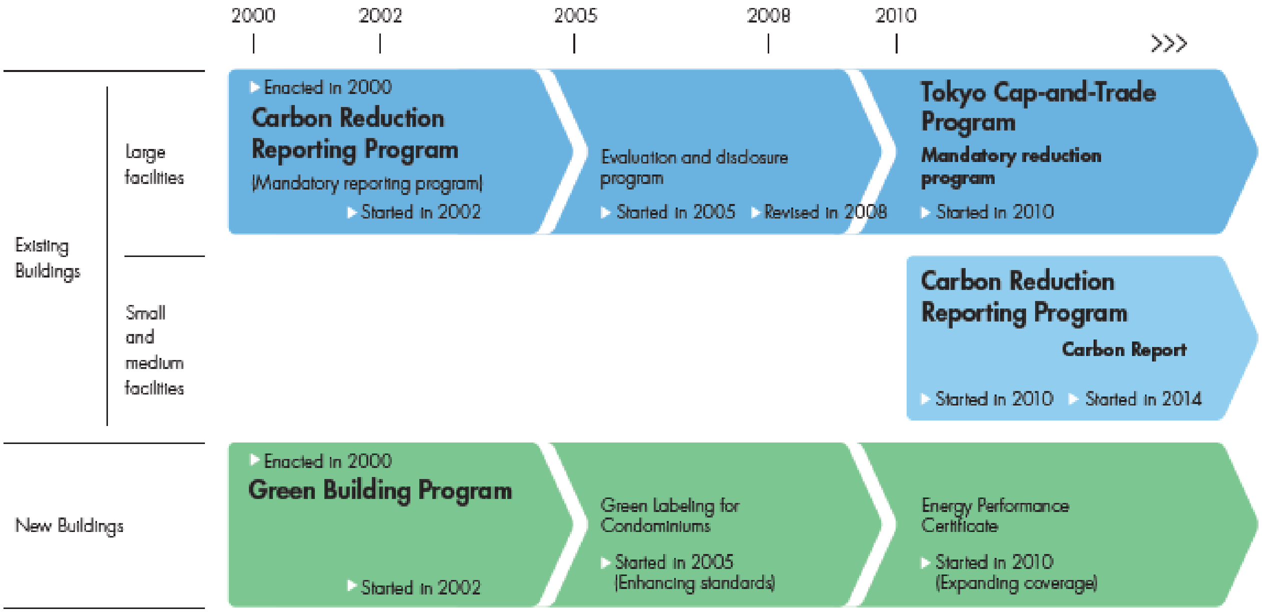


Figure 12 Three programs supporting sustainable building policy in Tokyo (Tokyo Metropolitan Government, 2019)

1. *Tokyo Cap-and-Trade Program*

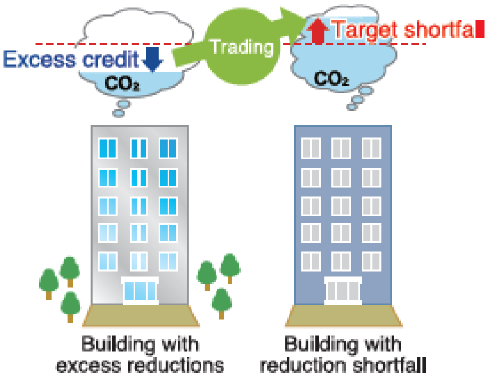


Figure 13 Illustration of Cap-and-Trade Program (Tokyo Metropolitan Government, 2019)

Applicable to existing large[3] facilities, this program is a mandatory reduction program designed to reduce total CO_2 emission levels in Tokyo, targeting factories and commercial facilities, including office buildings. These facilities are required to reduce their emissions by themselves or through emissions trading. For facilities demonstrating outstanding performance in emissions reduction as well as in the introduction, use, and management of energy-efficient equipment are certified as top-level facilities that receive lower compliance factors according to their rate of progress.
There are only 4 buildings for "Top Level" and 2 buildings for "Near-Top-Level" of Category I for office buildings in FY[4] 2019 (Tokyo Metropolitan Government, 2020).

---

[3] Facilities which annual energy consumption is greater than 1,500 kL crude oil equivalent
[4] Fiscal Year (FY) in Japan starts from 1 April until 31 March the next year.

Program design

Covered facilities	Approx. 1,200 large CO_2-emitting facilities that consume 1,500 kiloliters or more (crude oil equivalent) of energy annually
Covered gas	Energy-related CO_2
Compliance periods	Five-year period 1st period: FY 2010-FY 2014 2nd period: FY 2015-FY 2019 3rd period: FY 2020 – FY 2024
Compliance factors	1st period: 8% for offices etc. or 6% for factories, etc. 2nd period: 17% or 15% respectively 3rd period: 27% or 25% respectively
Emission trading	Excess reductions and offset credits are tradable
Penalties	Fines, charges (1.3 times the shortfall) Publish the fact of violation

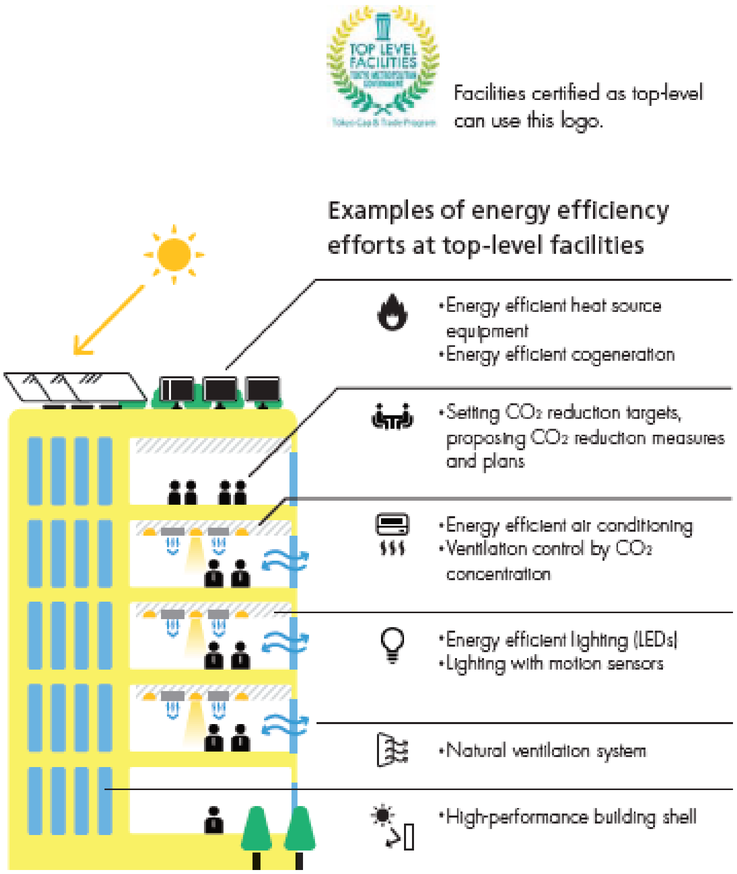


Figure 14 Tokyo Cap-and-Trade Program design (left) and Top Level Facility certification example in an office building (right) (Tokyo Metropolitan Government, 2019)

2. Carbon Reduction Reporting Program

This program applies to the 160,000 buildings of existing small and medium facilities that are not covered by Cap-and-Trade program, which account for approximately 60% of the total of the combined industrial and commercial sectors in Tokyo, underlining the importance of reducing emissions from this group.

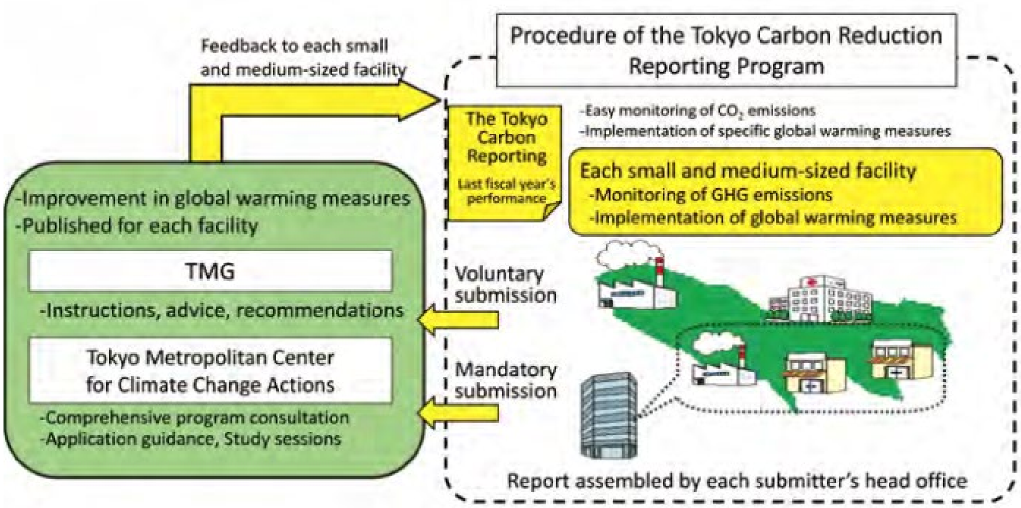
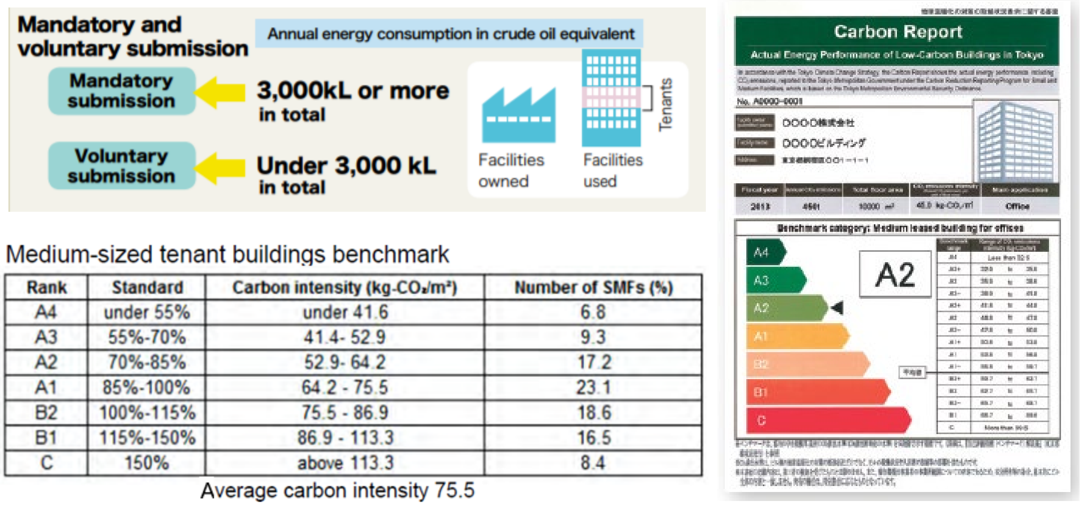


Figure 15 Illustration of Carbon Reduction Reporting Program(Tokyo Metropolitan Government Technology Council, 2017)

First introduced in 2010 to encourage owners of small and medium facilities to identify their CO_2 emissions and implement energy efficiency measures, in FY 2020, TMG will evaluate and publicize businesses with excellent reduction performance or with great efforts to introduce renewable energy, in the hope to motivate other businesses to take action. Using the data from the submitted the reports, TMG provides Low Carbon Benchmarks to see their performance; self-rating of emission levels compared to the same business type and a Carbon Report that depicts energy efficiency levels in an easy-to-understand format.



Medium-sized tenant buildings benchmark

Rank	Standard	Carbon intensity (kg-CO_2/m²)	Number of SMFs (%)
A4	under 55%	under 41.6	6.8
A3	55%-70%	41.4- 52.9	9.3
A2	70%-85%	52.9- 64.2	17.2
A1	85%-100%	64.2 - 75.5	23.1
B2	100%-115%	75.5 - 86.9	18.6
B1	115%-150%	86.9 - 113.3	16.5
C	150%	above 113.3	8.4

Average carbon intensity 75.5

Carbon Report

Actual Energy Performance of Low-Carbon Buildings in Tokyo

No. A0000-0001

○○○○株式会社

○○○○ビルディング

Fiscal year		Total floor area	CO_2 emissions intensity	Main application
2013	4561	10000 m²	45.0 kg-CO_2/m²	Office

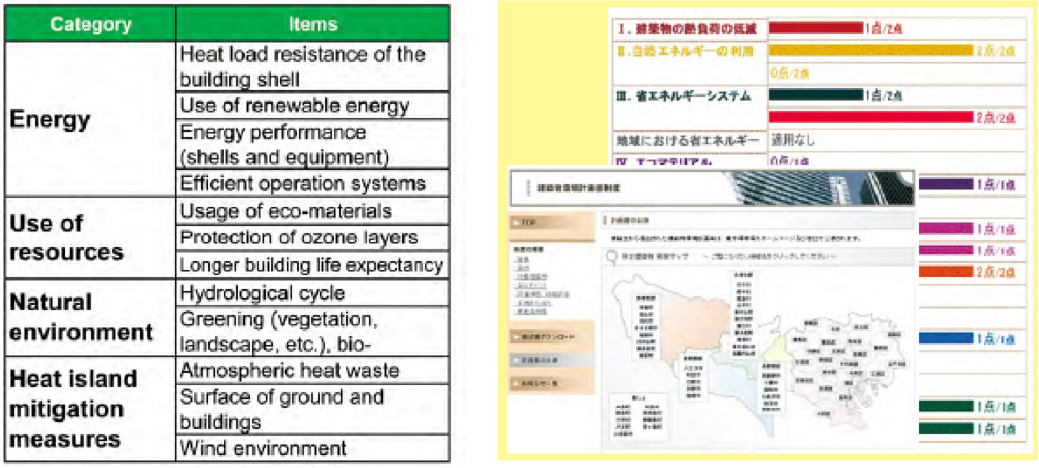
Benchmark category: Medium leased building for offices

Figure 16 Low Carbon Benchmark example (left)and Carbon Report example (right) (Tokyo Metropolitan Government Technology Council, 2017)

3. *Green Building Program*

Applicable to newly constructed/expanded buildings with a total floor area of 2,000 m² or more (mandatory if the total floor area exceeds 5,000 m²)), this program aims to improve the environmental performance of new buildings and to create a real estate market where greener buildings are valued more.

From FY 2020, TMG has expanded the program coverage and introduce ZEB (Net Zero Energy Building) Evaluation as a higher rank than the current highest one to assess the energy efficiency of building equipment.



Category	Items
Energy	Heat load resistance of the building shell
	Use of renewable energy
	Energy performance (shells and equipment)
	Efficient operation systems
Use of resources	Usage of eco-materials
	Protection of ozone layers
	Longer building life expectancy
Natural environment	Hydrological cycle
	Greening (vegetation, landscape, etc.), bio-
Heat island mitigation measures	Atmospheric heat waste
	Surface of ground and buildings
	Wind environment

Figure 17 Green Building Program's item assessed (left) and how it looks on TMG's website (right) (Tokyo Metropolitan Government Technology Council, 2017)

3. Earth, Wind, and Fire

This chapter is co-written by 2 other colleagues: Shriya Balakrishnan and Yamini Patidar. The writer's name is written next to the title of the sections.

3.1 CONCEPT

3.1.1 Introduction (S. Balakrishnan)

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 (B. 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 (initially called Ventec roof) (Ben Bronsema et al., 2018). It has been designed for office buildings in the western European climate. The application of the 3 RBE's will be explained in the following sections.

3.1.2 Utilization of Environmental Energy (Y. Patidar)

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 (B. Bronsema, 2013).

<u>Earth</u>

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.

<u>Wind</u>

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 Ventec roof

3.1.3 Application of EWF (S. Balakrishnan)

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 (Ben 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 approximate 7-8°C in the winters (Ben 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 (Ben 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.

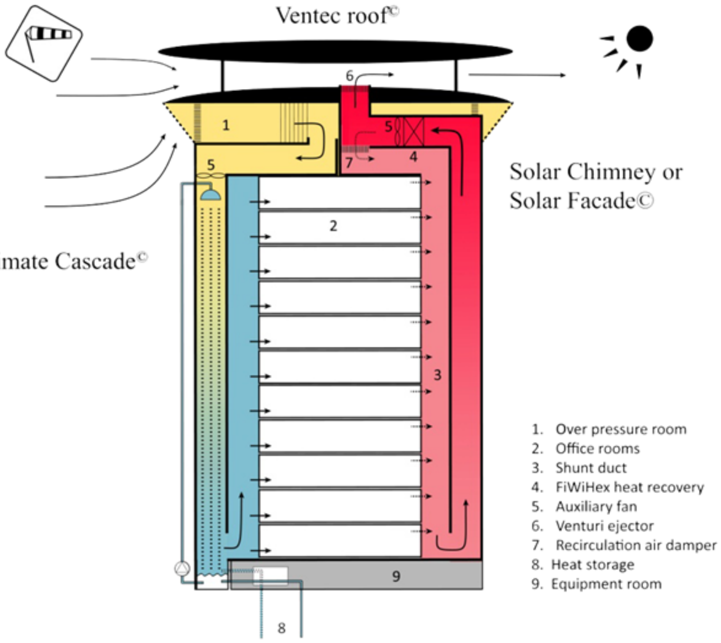
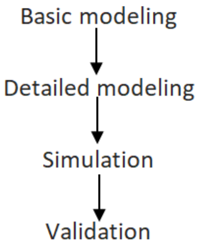


Figure 18 Earth, Wind and Fire Natural Air Conditioning system (B. Bronsema, 2013)

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) (Ben 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 (Ben Bronsema et al., 2018).

3.1.4 Calculation and Simulation Method (S. Balakrishnan)

The research and practical implementation of the solar chimney, climate cascade and ventec roof were developed according to modelling, simulation and method validation methodology (B. Bronsema, 2013). The research followed the following procedure:



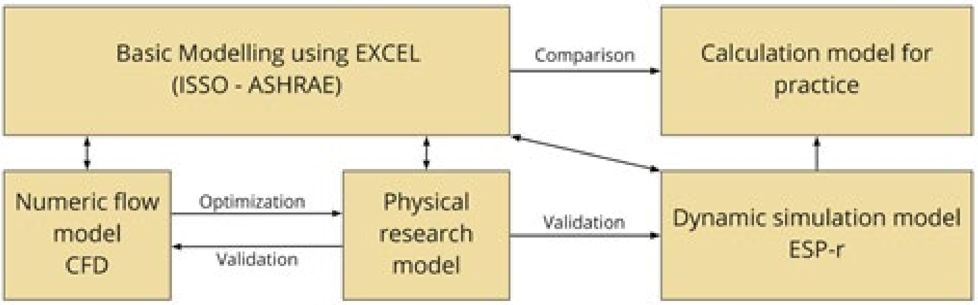


Figure 19 Calculation and Simulation process (B. Bronsema, 2013)

Basic modelling

The basic modelling process included simple detailed calculation models which helped in developing the first impressions of the feasibility and potential of the applied concept (B. Bronsema, 2013). The scientific and technical data required to perform these calculations were derived from Installation Technology Manual (ISSO 2002), the Taschenbuch für Heizung + Klimatechnik, ASHRAE Handbooks Fundamentals (ASHRAE 2001) and HVAC Systems and Equipment (ASHRAE 2000) (B. Bronsema, 2013). The mathematical formulas derived from the manuals were converted into MS Excel calculation model to make the process more dynamic and user friendly. The basic modelling provided insight into the underlying phenomena of heat transfer and flow and how they work together. This stage revealed many uncertainties showing the need for advanced calculation tools and methods (B. Bronsema, 2013).

Numerical flow modelling with CFD

The numerical values in the excel calculation model were derived from the CFD simulation model. In this stage, flow models were developed into virtual prototypes which provided details of heat transfer and flow patterns at a micro-level. The CFD model helped in analyzing the physical effects of heat transfer and wind flow without building a physical prototype of the responsive building elements (B. Bronsema, 2013).

Dynamic simulation with ESP-r

The excel calculations and CFD simulations were used for calculating and designing the solar chimney and climate cascade under stationary conditions. In order to study the dynamic behaviour and annual estimates of the energy performance of the RBE's, dynamic simulation model ESP-r was used (B. Bronsema, 2013). ESP-r is an integrated energy modelling tool for the simulation of the thermal, visual and acoustic performance of buildings and the energy use and gaseous emissions associated with environmental control systems (B. Bronsema, 2013). The climate cascade and the solar chimney were modelled in the ESP-r model using thermal and flow networks which simulated the heat and mass flow of the two networks together.

Validation by measurements in a physical examination model

Based on the results revealed from the excel calculation and CFD simulation models, a physical prototype of the solar chimney, climate cascade and ventec roof was developed. This physical model was a scale model which helped in dealing with real-time issues and could be monitored reliably. Based on the input data from the calculations, the physical models were tested and the results from the physical model were used as an input to calibrate and validate the excel calculation, CFD and ESP-r models.

3.2 ELEMENTS

3.2.1 Climate cascade (Y. Patidar)

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 (B. 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, 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.

Climate cascade thus plays an important role in achieving the goal of energy-neutral building.

Providing a good indoor climate is an important design criterion for Climate Cascade which can be divided into thermal comfort and productivity (for office buildings).

1. Climate cascade for diabatic 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 (B. 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 (B. 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.

2. Basic modelling

The basic modelling of the climate cascade is done using the excel model developed during Ben's PhD. Before modelling and doing calculations, it is important to understand a few parameters as briefly described below. The mathematical equations used for the calculations are elaborated in the Appendix.

Climate cascade as a heat exchanger

The heat transfer is represented by the equation:

$$\Phi = h.A.(\theta_m - \theta_\infty)$$

Where,

Φ = Heat transfer from air to water which is equal to the required enthalpy change of air.

A= Active surface of the climate cascade determined by the cumulative area of the water droplets, product of the number of droplets formed per unit of time and its duration of stay.

h = Heat transfer coefficient

θm- θ∞ = Temperature difference between water (θm) and air (θ∞)

<u>Pressure build-up in the climate cascade</u>

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 (B. 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 a smaller drop. A choice should therefore be made in order to realize the greatest possible heat transfer for the finest possible spray spectrum (B. Bronsema, 2013).

3.2.2 Solar chimney

Two things are harvested in the solar chimney: the natural flow of exhaust for ventilation and the collected heat.

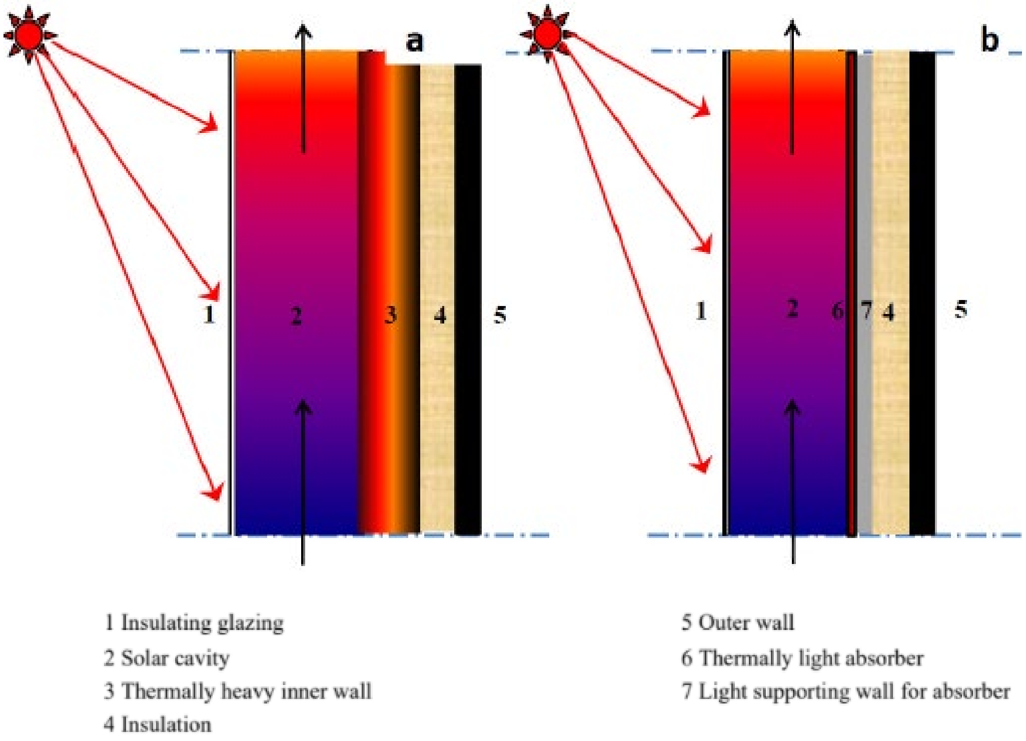


Figure 20 Principle of Solar Chimney (B. Bronsema, 2013)

Referring to the above figure, a is a solar chimney with Trombe wall and b is a solar chimney with a light inner wall. As the energy performance of the latter is better, b is the chosen type for further modelling.

1. *Glass wall*

   The glass wall of the solar chimney has been chosen such that 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.

2. *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 a and the emission factor ε respectively; at equal wavelength λ these are equal to each other; in formula:

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

In which

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

It is impossible to combine high absorption within the same wavelength range low emissions. This is possible for a spectrally selective surface. Using Planck's law to calculate the emittance of a black body $M_{\lambda b}$ at wavelength λ:

$$M_{\lambda b} = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{\mathrm{e}^{hc/\lambda kT} - 1}$$

In which

$M_{\lambda b}$	emittance at wavelength λ	[W.m $^{-2}$]
h	Planck's constant = 6.62 x10^{-34}	[Js]
c	speed of light	[m.s $^{-1}$]
k	Boltzmann constant = 1.38 x10^{-23}	[JK $^{-1}$]
λ	wavelength of the radiation	[μm]

With the temperature of the sun and solar chimney at 6000 K and 320 K respectively, the relative emittance of the sun and the solar chimney have been calculated as follows.

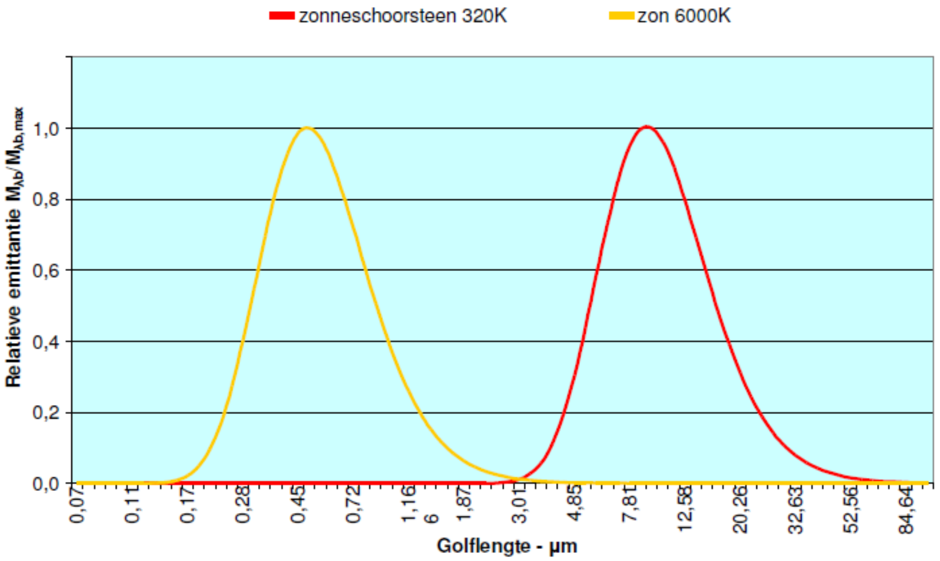


Figure 21 Relative emittance of the sun and the solar chimney (B. Bronsema, 2013)

A solar chimney should ideally be provided with a spectrally selective one 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. Materials that meet this requirement have been developed for solar thermal collectors and are commercially available.

3. *Insulation*

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

4. *Optimal orientation*

In order to optimize the energy performance of the solar chimney, it is important to choose the orientation with the most solar radiation. In the Netherlands, south orientation is optimal, also partly due to the fact that winter solar radiation has a higher economic value than that in the summer.

5. *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 has been analyzed.

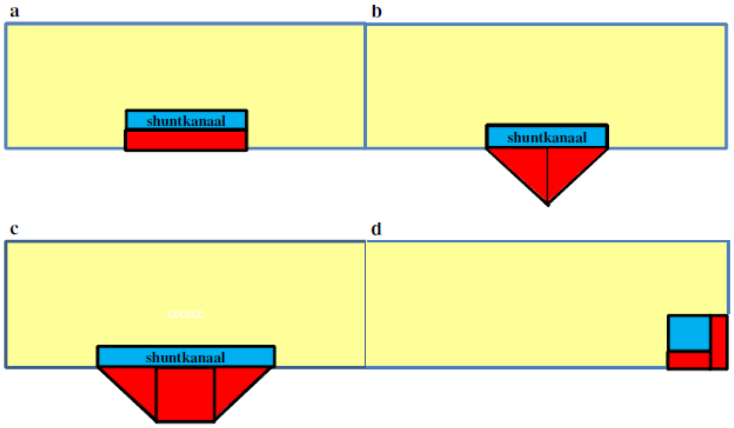


Figure 22 Four types of solar chimney (B. Bronsema, 2013)

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 one 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.

6. *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.

7. *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.

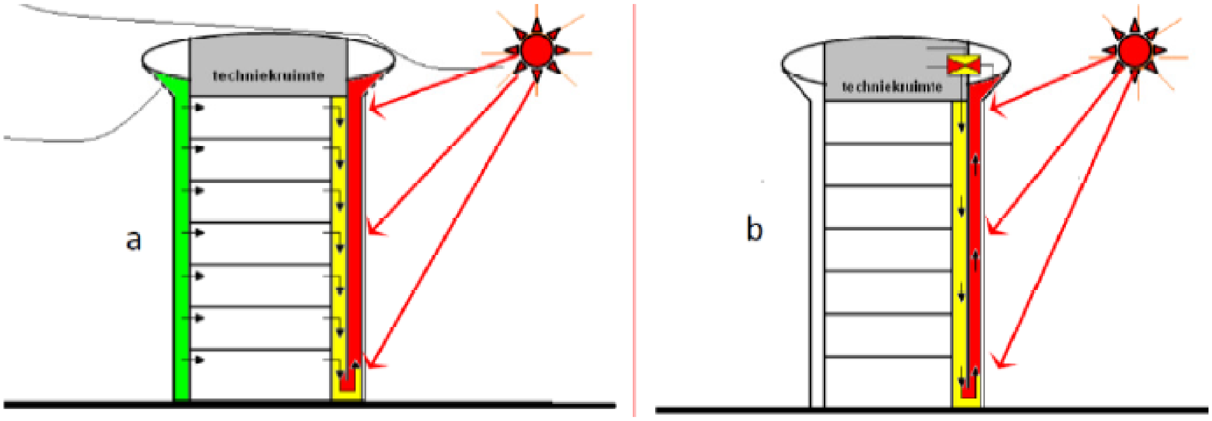


Figure 23 Principle of air extraction and recirculation via shunt channel (B. Bronsema, 2013)

3.2.3 Ventec roof (Y. Patidar)

The Ventec roof utilizes positive wind pressures for the supply of ventilation air to the building via an overpressure chamber and the Climate Cascade. Negative wind pressures are used to extract used ventilation air from the building through the Solar Chimney and a Venturi ejector. Overpressure chamber and venturi ejector are important components for the supply and 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 ms^{-1}, overpressures are to be expected at 12 - 32 Pa.

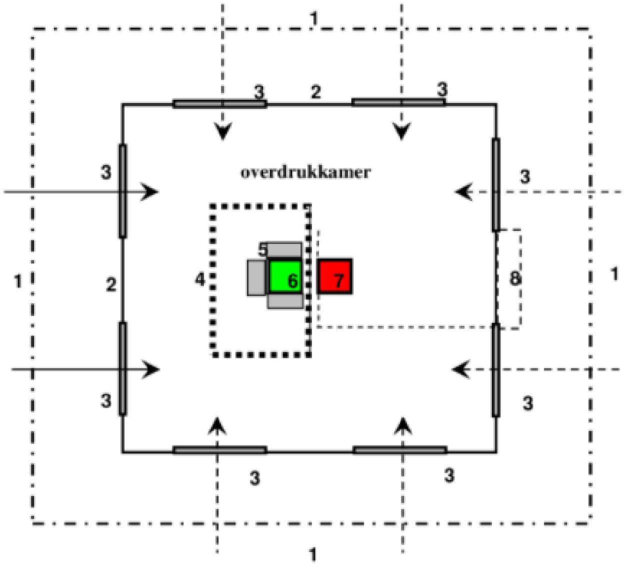


Figure 24 Schematic plan of the overpressure chamber (B. Bronsema, 2013)

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 heat recovery system. The pressure loss of the extraction system must be compensated by the thermal draft of the Solar Chimney.

A Venturi is a system for speeding the flow of the fluid, by constricting it in a cone-shaped tube. In the restriction, the fluid must increase its velocity reducing its pressure and producing a partial vacuum. The Earth, Wind & Fire concept makes use of this principle through the to guide wind through a constriction and to make use of the under-pressure generated. Because the venturi gets here used in an open system, it is hereinafter referred to as pseudo venturi.

3.3 INTEGRATION CRITERIA

EWF Design Manual has been developed by Peter Swier in 2015, who is also an alumnus. His graduation thesis is studied especially for the integration criteria that will be the base for choosing the case study building in Tokyo for this paper. The integration criteria, for the 3 elements of EWF, will be briefly elaborated in 2 categories: Compulsory and Additional.

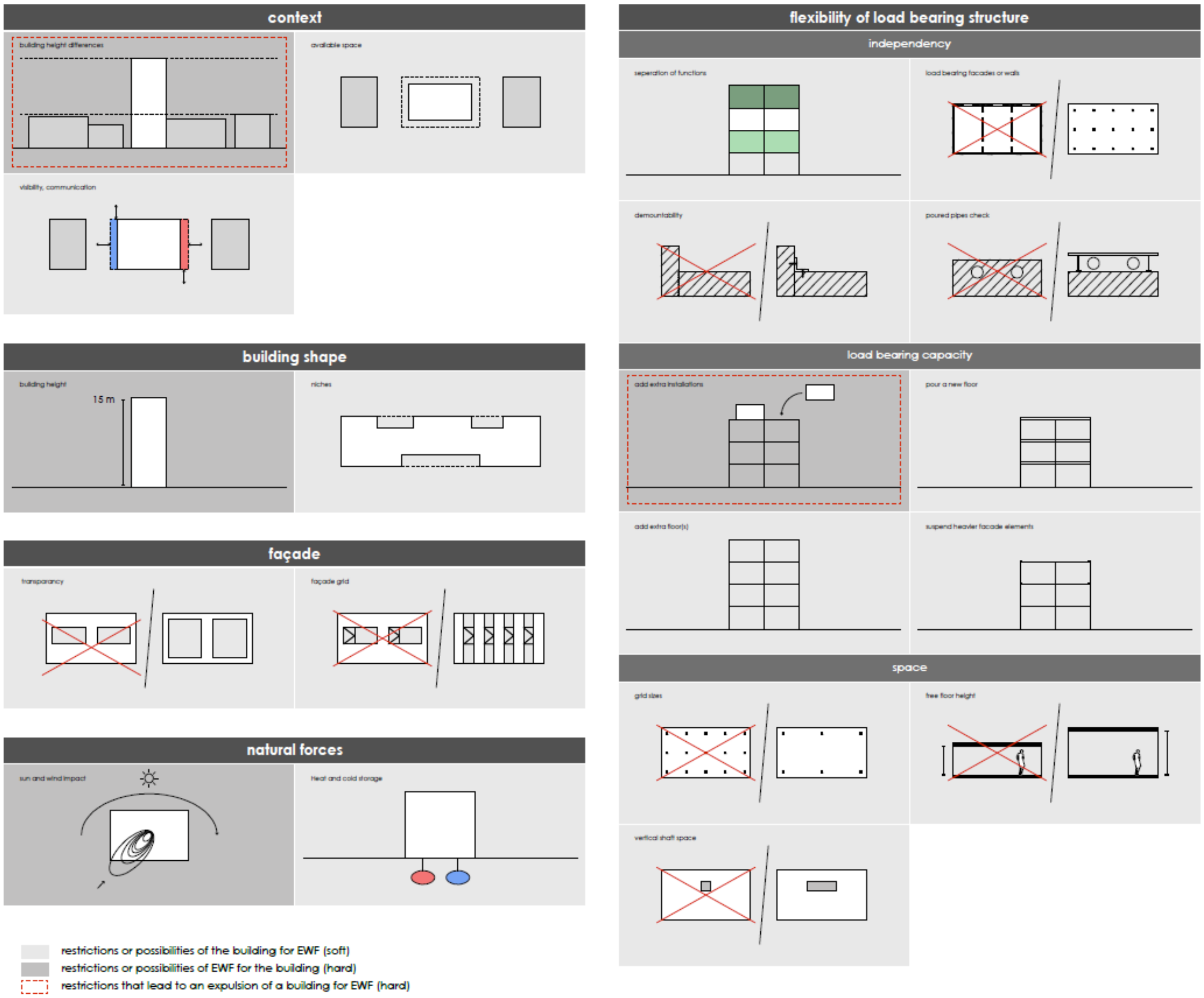


Figure 25 Illustrations of EWF Integration Criteria(Swier, 2015)

3.3.1 Compulsory

Boundary conditions that lead to an expulsion of a building for EWF integrated are described as compulsory, as follows:

- The building has to be preferably higher than its surroundings in order to make the Power Roof 3.0 work properly
- No load-bearing façades or walls
- Has sufficient load-bearing capacity for any additional installations i.e., Power Roof 3.0 (Solar chimney can have a separate load-bearing structure)

3.3.2 Additional

Boundary conditions that might need optimization when EWF is implemented is described as additional, as follows:

- Space availability and the most potential position of the EWF elements
- The building height should preferably be over 15m in order to gain sufficient pressure differences for the Climate Cascade and the Solar Chimney

- Possibility to add floors on top of the building, when the 15m building height is not achieved
- Enough space in free floor height. If the free floor height is too low, façade ducts should be considered to optimise the airflow.
- Enough available vertical shaft space. This influences the location of the climate cascade and air distribution ducts
- Sun and wind study should be conducted and the possibility of cold and heat storage should be researched

3.4 EWF CASE STUDY: THE FOUR ELEMENTS HOTEL

Initially named Breeze Hotel, this 11-story building with 198 'zero-energy rooms', 6 suites, and a total floor area of 9.343 m^2, 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 (OZ Architect, 2019).

Figure 26 Left to right: View from IJmeer Lake, 2 Solar Chimneys on the south façade, a huge balcony of the sky-bar on the north facade (OZ Architect, 2019)

The EWF here works as follows:

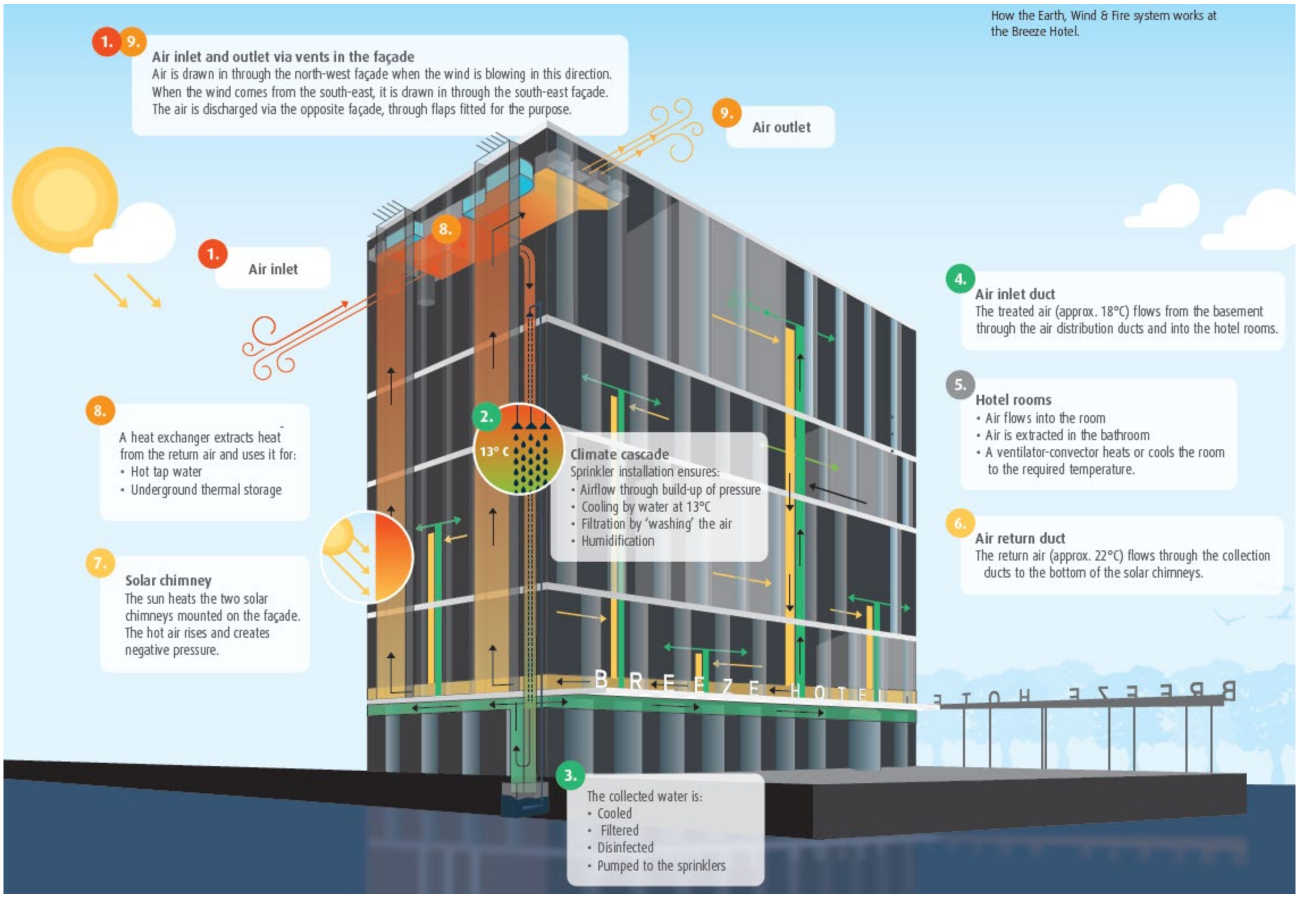


Figure 27 EWF Concept in the Four Elements Hotel (Heirbaut, 2019)

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 28 The 9 water spray heads of the Climate Cascade at The Four Elements hotel (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 extract 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 fresh air to move to the rooms. In winter a heater battery installed at the base of the cascade helps raises the temperature before being supplied to the rooms (Pearson, 2019).

This way, the supply and exhaust of ventilation air are 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 an energy-saving condition when guests leave their room (Pearson, 2019).

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

Table 7 EWF concept in perspective (Ben 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	2,5 m²	2,5 m²
Air velocity	≈ 6 m.s-1	≈ 3 m.s-1
Energy consumption	50 MWh.a-1	10 MWh.a-1
EU 1253/2014-SPFint-limit	0,8 kW.(m³.s-1)-1	
Maintenance	Very extensive	Little extensive
KISS factor - simplicity	low	high
Average life span	15…20 years Mechanical facilities	40 years Architectural facilities
Construction costs Excluding solar chimney	Neutral	

The writer talked to Bronsema who mentioned that the Ventec roof could not be realized due to unfeasible cost and was 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 in the bottom-left corner room on the south side of 8F 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.

3.5 OTHER CASE STUDY: MANITOBA HYDRO PLACE

Although not named as EWF, the natural ventilation concept of Manitoba Hydro Place in Winnipeg, Canada, is undoubtedly alike, hence worth looking into.

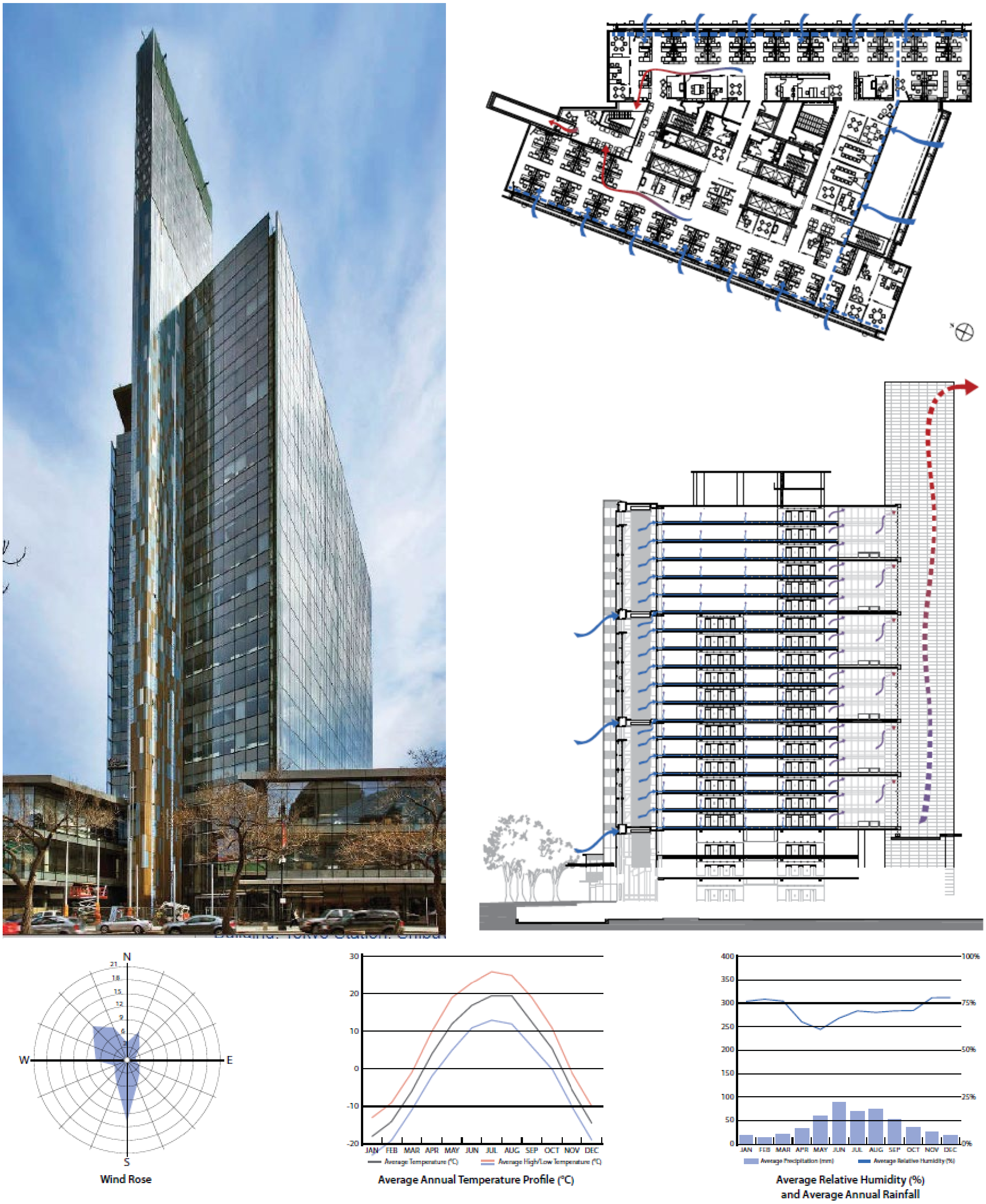


Figure 29 Manitoba Hydro Place's façade, natural ventilation flow, and climate data (Wood & Salib, 2008)

Consists of 2 converging 18-story office wings separated by a service core, the mass of Manitoba Hydro Place rest on a 3-story podium. The 2 office blocks face west and east-northeast respectively, with north and south-facing atria fusing the two blocks together as shown in Figure 30 below.

Figure 30 Left to right: Manitoba Hydro Place's South Façade, water feature, the top of the solar chimney (Wood & Salib, 2008)

Table 8 Manitoba Hydro Place's Data Summary (Wood & Salib, 2008)

Project data	
Location	Winnipeg, Canada
Year of completion	2008
Function	Office
Building Scale	22 stories, 115 m
Gross floor area (tower)	64,567 m^2
Project team	
Design architect	Kuwabara Payne McKenna Blumberg Architects
MEP engineer	AECOM
Climate engineer	Transsolar
Climatic data	
Climate	Cold
Average wind speed	4.7 m/s
Mean annual temp.	3°C
Mean annual precipitation	514 mm
Average RH	69% (hottest months) 77% (coldest months)

The 3-stacked south-facing atria collect heat from the sun and incoming fresh air from southerly prevailing winds. This incoming air is humidified by a water feature that flows from the ceiling to the floor, 6-story high, a somewhat similar feature to EWF's Climate Cascade. Fresh air then flows across the office spaces drawn by cross-ventilation and stale air is exhausted in the north atria solar chimney, as shown in Figure 29.

In contrast to most North American office buildings, where approximately 80% of supplied air is re-circulated and only 20 % is fresh, Manitoba Hydro Place supplies 100 % fresh air. This is available throughout the year, regardless of outside temperatures, due to the highly efficient heat-recovery system. Achievement: 73% annual energy saving for heating/cooling when compared to a fully air-conditioned Manitoba office (Wood & Salib, 2008).

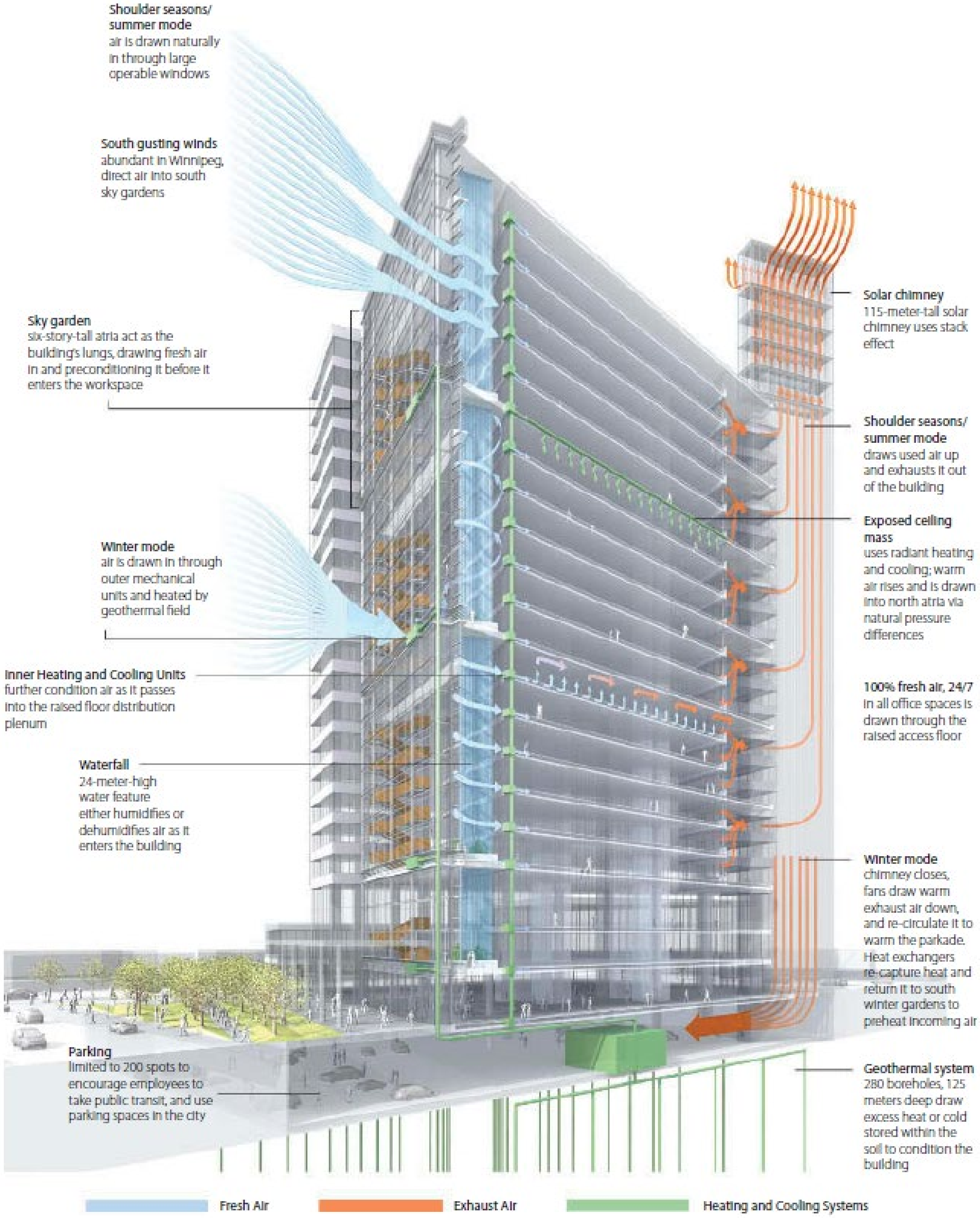


Figure 31 Manitoba Hydro Place's environmental strategy in a glance (Wood & Salib, 2008)

4. Building Selection for Case Study

Through desktop research and contact with the Japanese network that the writer has, the following 3 candidates have been chosen, following the criteria mentioned in 2.2.3.

4.1 BUILDING STOCK REPRESENTABILITY

In addition to what has been explained in 2.2 Office Typology, the majority of office buildings in Tokyo is Small & Medium size, visibly with not much space available around the building.

The focus will be given to Medium size office buildings, which is defined as having a total floor area of more than 3,000 m^2 and less than 20,000 m^2, in consideration of construction feasibility and similarity to the Four-Elements Hotel building.

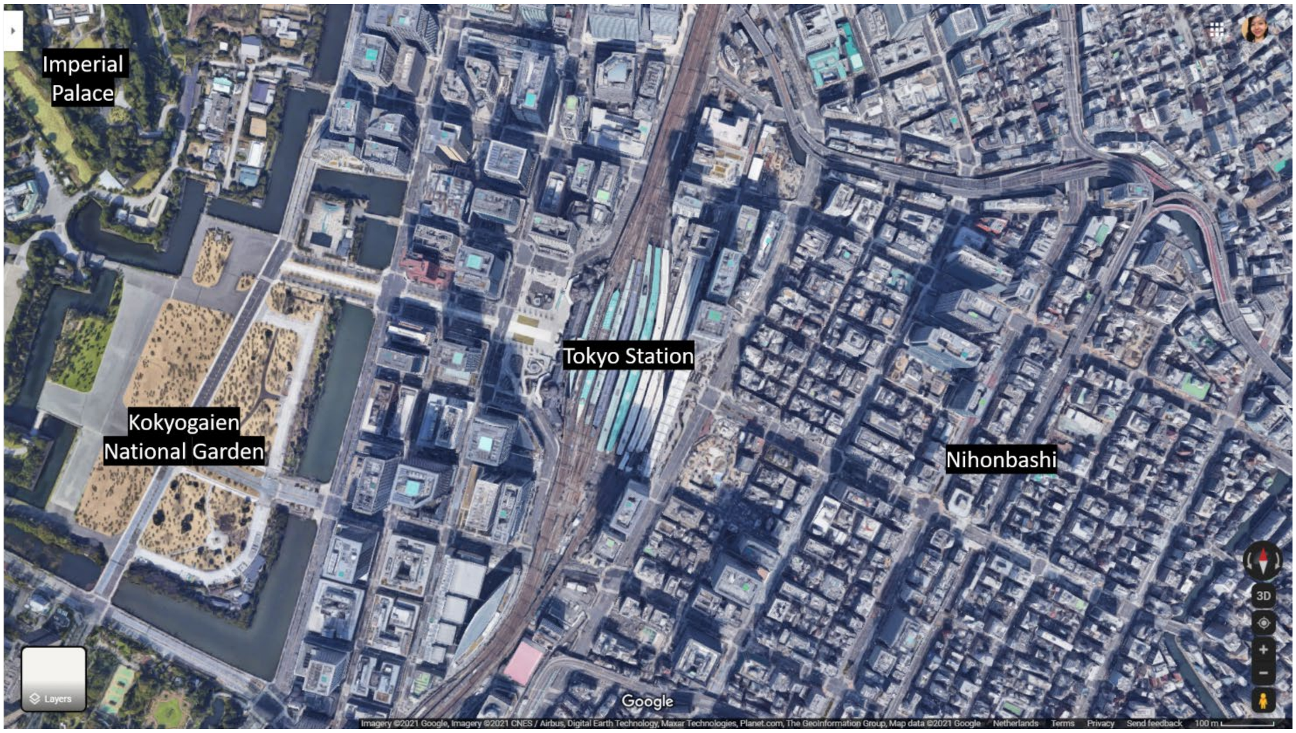


Figure 32 Google Map Satellite View of Tokyo

Moreover, although it is ideal to look for building with space in its surrounding for the possibility to add the EWF elements outside their building footprint, the writer had difficulties in finding one, as Tokyo is notorious for its space limitation, which is well-visible from Google Map, shown above. Thus, the focus will be given to buildings with not much space, as it is believed to be more representative of Tokyo's office building stock.

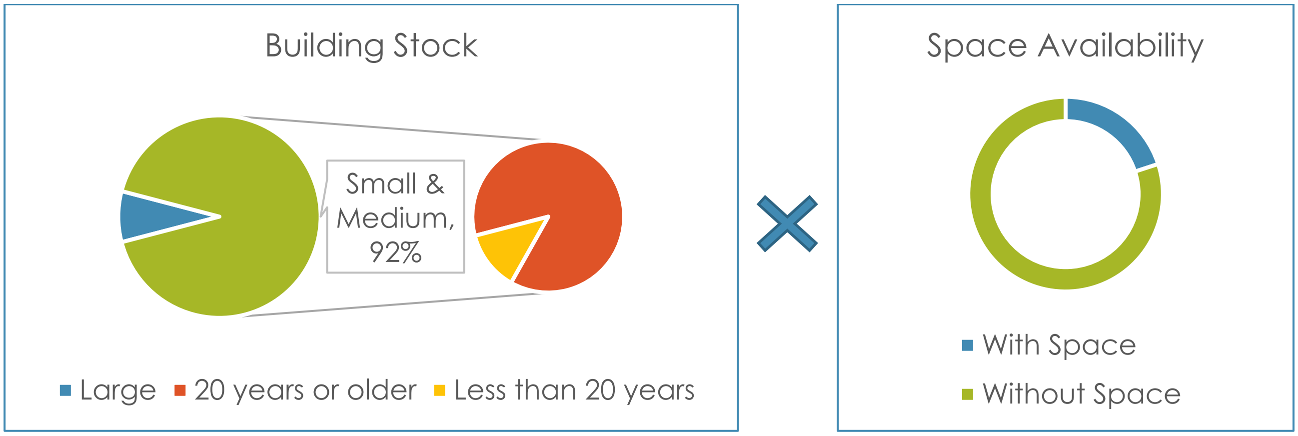


Figure 33 Building Stock Representability

4.2 BUILDING CANDIDATES

4.2.1 NK Building

This building has been designed with energy-saving in mind, hence the use of LED lighting and PV panels on the roof during the design stage, although the PV panels were cancelled at the end. Despite the limited space, the architect still strives to put soothing bamboos and other green elements within the building, giving the user's comfort a priority.

With limited room to play around the site for the addition of EWF elements, this building seems to be a good representation of a modern medium-size office in the heart of Tokyo's business area.

Table 10 NK Building data

Location	*1-16-3 Nihonbashi, Chuo-ku, Tokyo*
Date of completion	2016
Total floor area	5,116.39 ㎡
Typical floor area	391.30 ㎡ / 118.37 tsubo
Structure	Steel structure, with vibration damping
Building scale	1 basement floor, 10 floors above ground
Air-conditioning	Individual air-conditioning
Design	Flying Pumpkins & Team FP

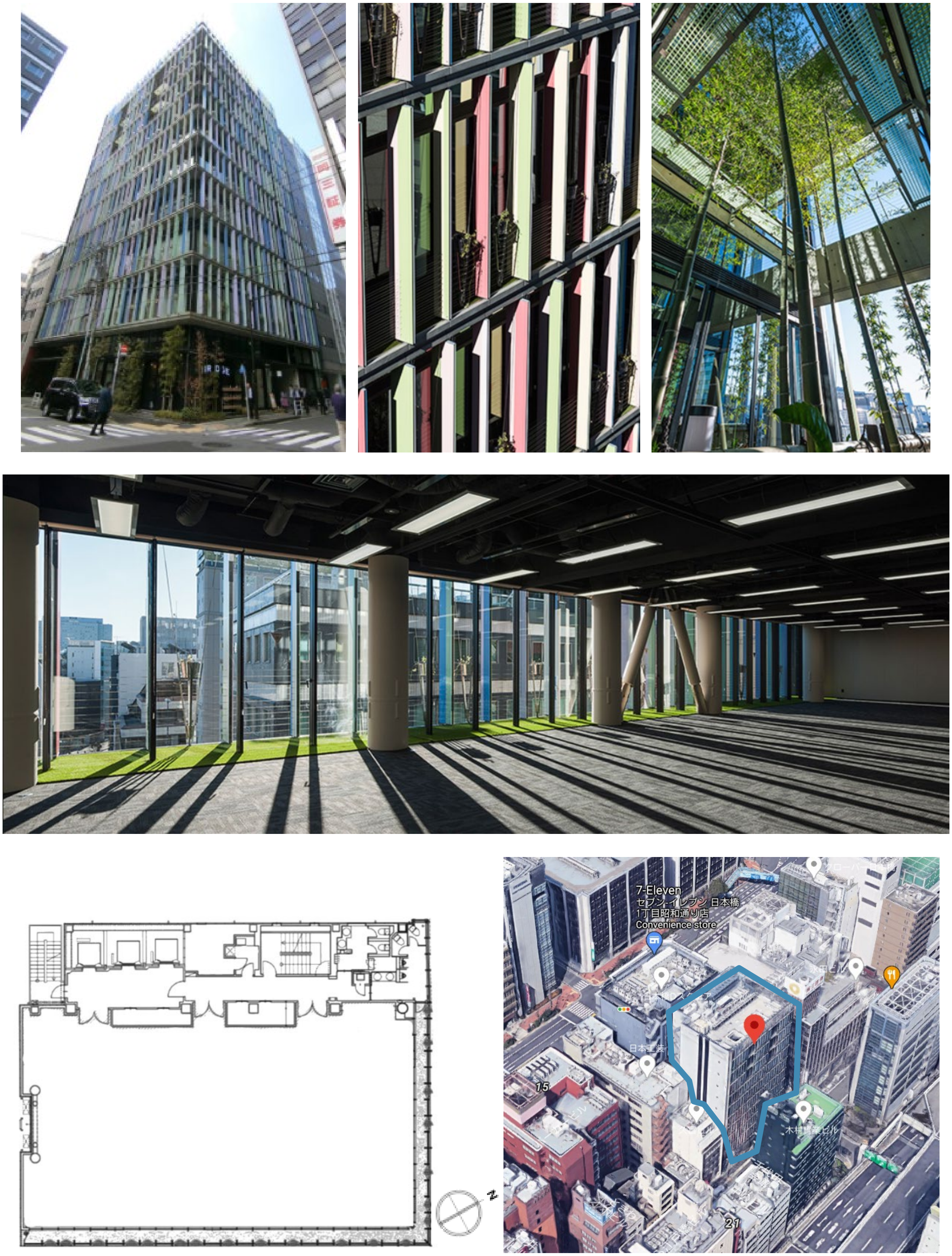


Figure 34 NK Building: Façade, interior views, Google bird-eye view, and floor plan (Flying Pumpkins & Team FP, 2013)

4.2.2 Acropolis Tokyo

As it might not always be feasible to build the EWF elements within the existing building footprint, it would be nice to have an example of a building that has space around its perimeter.

Table 11 Acropolis Tokyo building data

Location	*6-29, Shinogawamachi, Shinjuku-ku, Tokyo*
Date of completion	1994
Total floor area	20,311.98 ㎡/ 6,144.37 tsubo
Typical floor area	1344.93 ㎡ / 405.62 tsubo
Structure	Steel + RC structure
Building scale	3 basement floor, 10 floors above ground
Air-conditioning	Individual air-conditioning
Design	Kajima Corporation

Figure 35 Acropolis Tokyo Building: Outside view, Typical Floor plan, and Google bird-eye view

4.3 CONCLUSION

From the 2 building candidates, NK Building and Acropolis Tokyo, NK building has been chosen as the case study because of the simplicity of the design, similarity in scale to the Four Elements Hotel, ideal for easy comparison, and due to its representability of Tokyo offices' building stock and basic data availability.

4.3.1 Case study building: Architecture

Built in one corner in the Nihonbashi area, NK Building has only 2 open facades facing a busy road: southeast and northeast, adorned by traditional kimono's-coloured vertical lamellae that also act as sun-shading, channelling the fact that the street had many kimonos shop in the Edo period. The northwest side is entirely blocked by a neighbouring building, which is where the service core is, whereas the southwestern facade has a neighbouring building about half the height, as can be seen in Figure 34. The focus of the study will be given to the office floors, which are from 3F-10F. There are 2 types of floor plans (20.5x26m) for the office.

The Executive Office from 8-10F has 2 cut-outs rectangular bamboo garden.

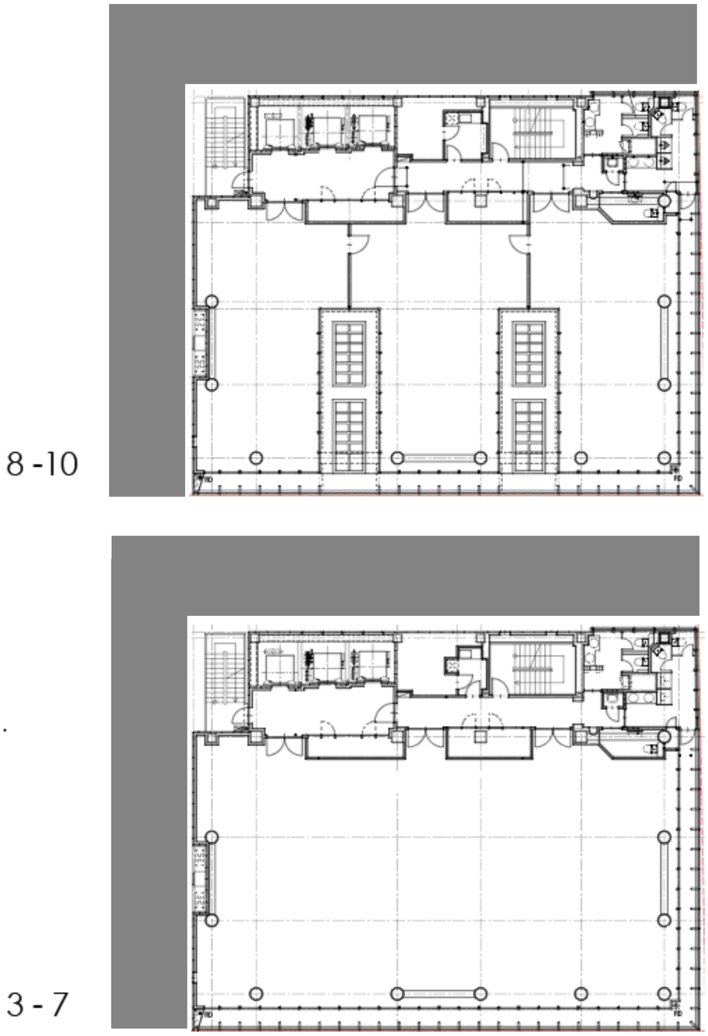


Figure 36 Two types of Office floor plan: Typical Office 3-7F & Executive Office 8-10F

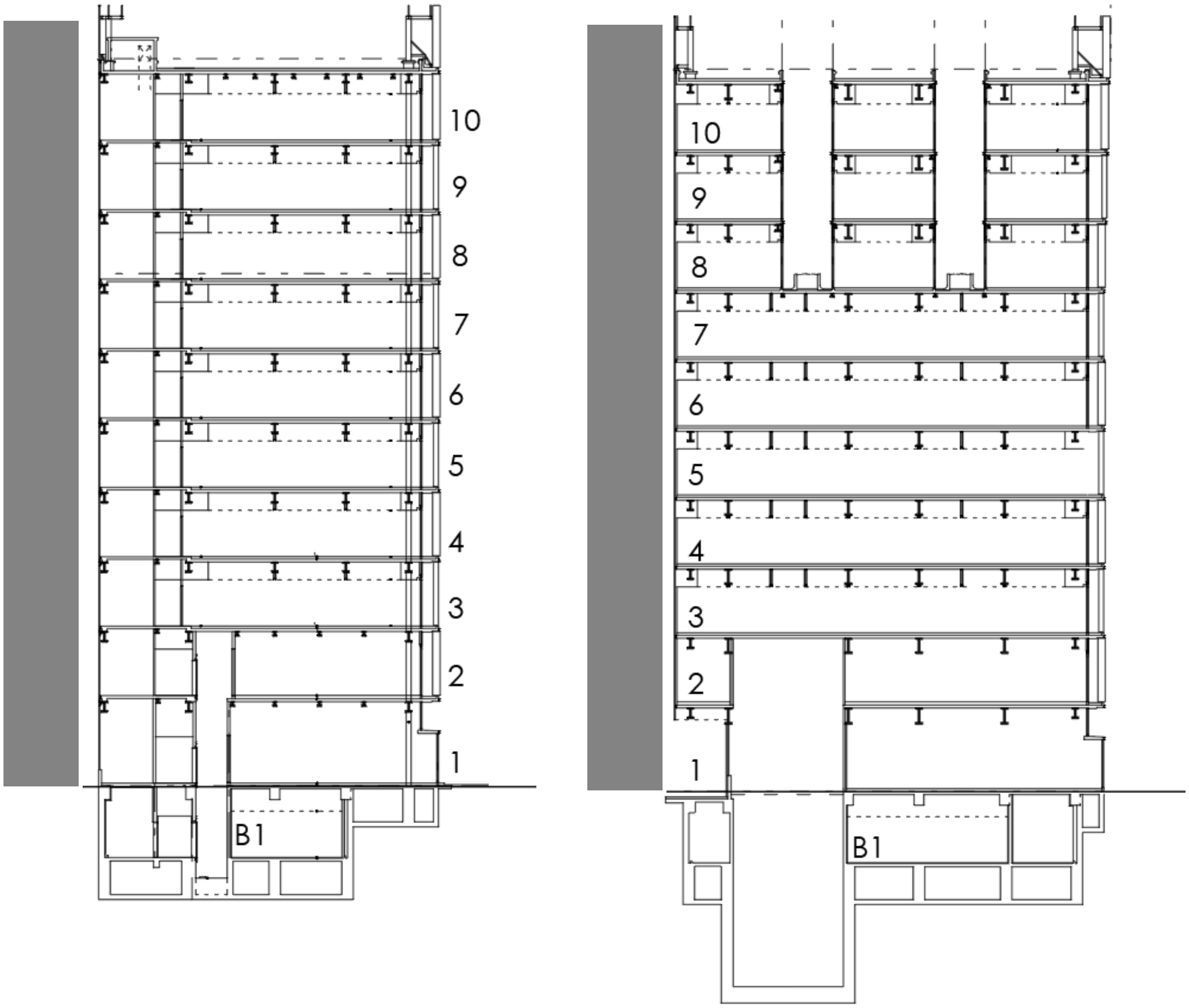


Figure 37 Building sections: northwest-southeast (left) and southwest-northeast (right)

There is an offset of 1.15 m deep from the curtain wall of the southeast and northeast façade until the end of the slab, where the lamellae are placed.

4.3.2 Case study building: HVAC system

The space heating, cooling, and ventilation system are handled by the same Variable Refrigerant Flow (VRF) with Heat Recovery and Dedicated Outdoor Air System (DOAS). VRF system is a relatively new and energy-efficient system (Wikipedia, 2021).

Table 12 Existing HVAC Design Condition

	Summer			Winter		
	Dry-bulb temperature (°C)	Relative humidity (%)	Absolute moisture (kg/kg)	Dry-bulb temperature (°C)	Relative humidity (%)	Absolute moisture (kg/kg)
Outdoor condition	34.3	56.4	0.0194	2	28.9	0.0013
Indoor comfort	26	50	-	22	40	-

5. Methodology

In addition to the fundamental literature research, a case study building has been chosen. Step-by-step design work is conducted for the integration of EWF. This case-study-specific design of the Solar Chimney and the Climate Cascade will be explored. This will be done using Excel static calculation model, to be elaborated in 5.1.2 and 5.1.3 respectively. The PV yield of the Power Roof will be briefly included in 5.2.

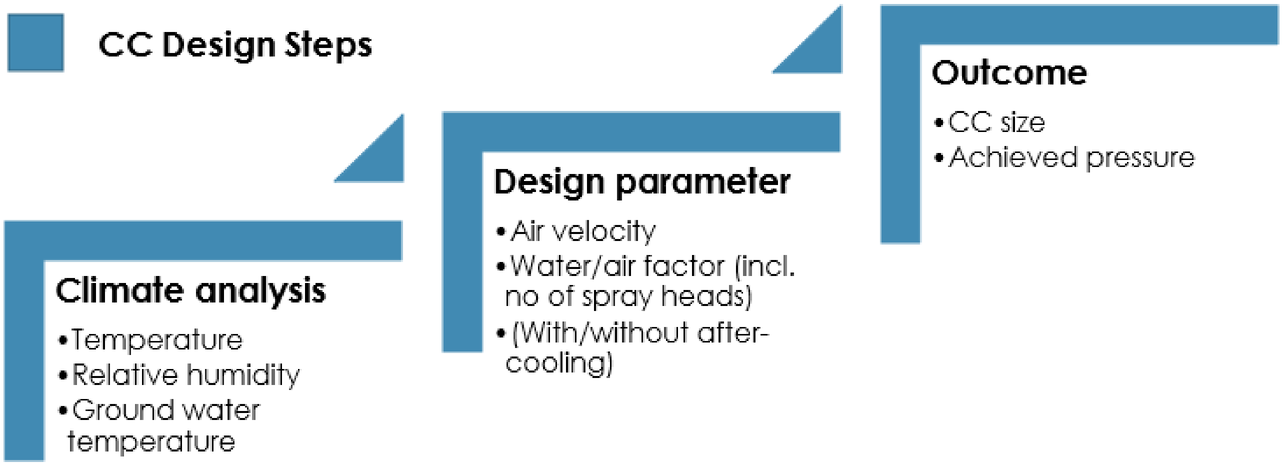
Going hand-in-hand with the previous integration design, assessment in energy consumption and thermal comfort will be conducted after a complete integration design has been finished. This will be done using DesignBuilder dynamic simulation model, which method will be explained in 5.3.

5.1 EXCEL CALCULATION

The following is a step-by-step guide of using CC Excel & SC Excel, with the intention for the reader to also try along. Therefore, the input and output of Excel are discussed at the same time.

5.1.1 Steps

The duo of Climate Cascade (CC) and Solar Chimney (SC) will act as the lungs of a building, with the first supplies fresh air and the latter exhausting stale air. As a designer, it is important to know the size of CC and SC and how these two can be integrated into an existing building in a renovation project.



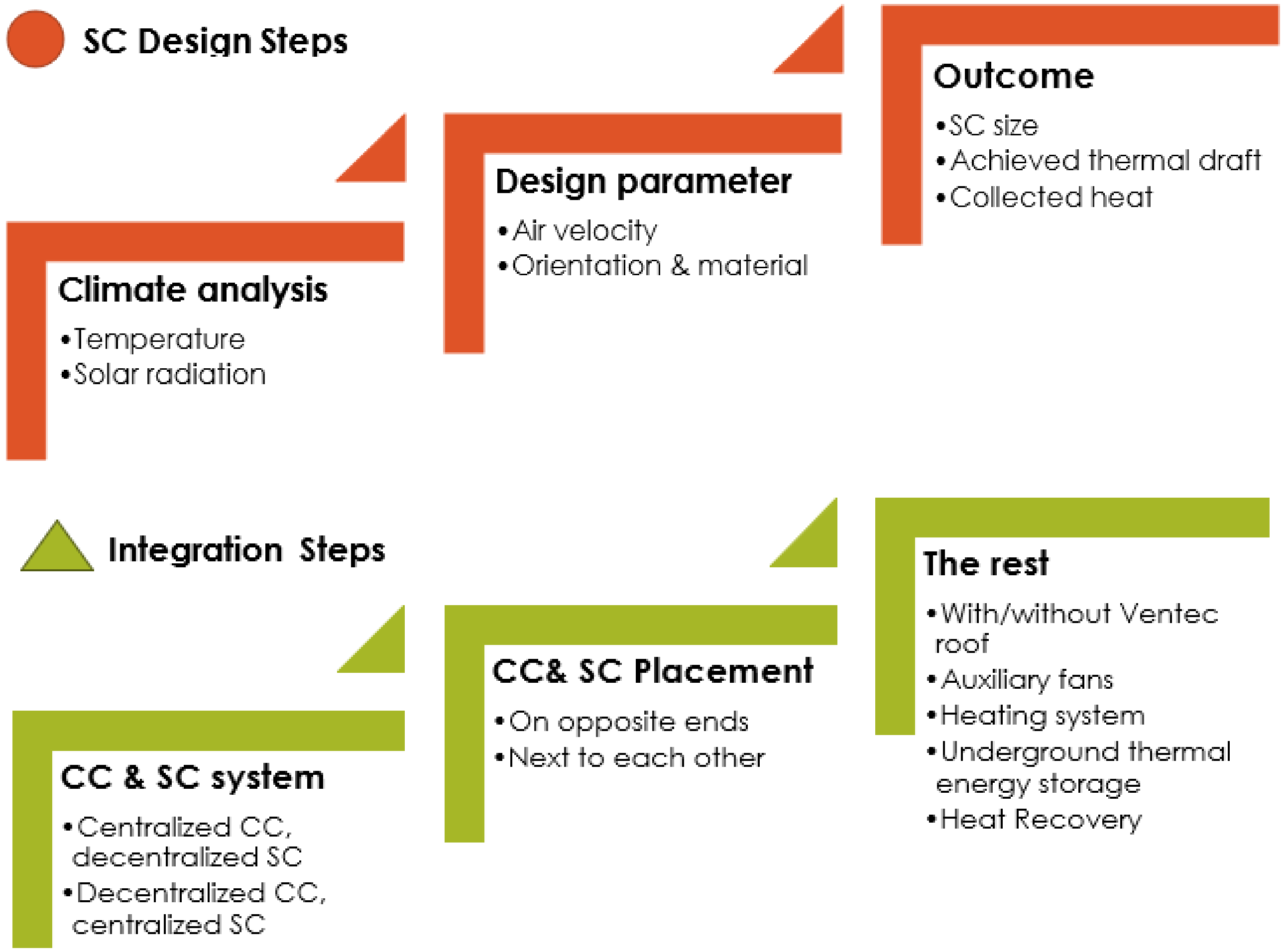


Figure 38 EWF Design Steps in a glance

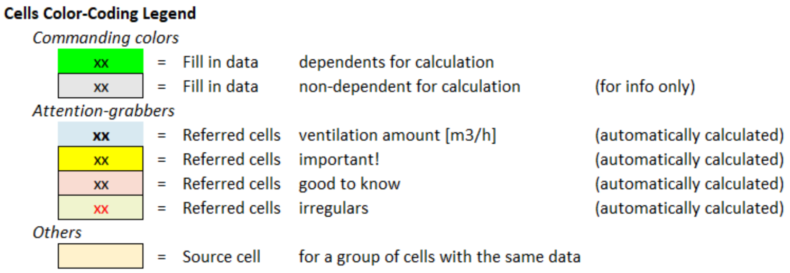
As this chapter focuses on the methodology, the Outcome part of CC Design Steps and SC Design Steps, as well as the Integration Steps will be summarized in the next chapter: Chapter 6 EWF Applied to NK Building.

5.1.2 CC Excel

The importance of clean fresh air supply in buildings has become undisputable after the coronavirus pandemic. In EWF, this is the responsibility of Climate Cascade (CC). The calculation and analysis for CC is conducted using the provided Excel Model from Dr Ben Bronsema. Some modification (too many to be mentioned one by one) has been made by the writer to enrich the study and user-friendliness to the Excel Model (hereinafter referred to as "CC Excel"). Interested parties are advised to contact the writer or Dr Ben Bronsema.

1. *Climate Analysis*

The general climate analysis of Tokyo and its comparison with that of Amsterdam have been discussed in 2.1. For a more accurate analysis, hourly weather data was used. The process of using the Excel Model will be briefly explained below, step by step. The cells are colour-coded in the following manner.



Cells Color-Coding Legend

Commanding colors

🟩 xx	=	Fill in data	dependents for calculation	
xx	=	Fill in data	non-dependent for calculation	(for info only)

Attention-grabbers

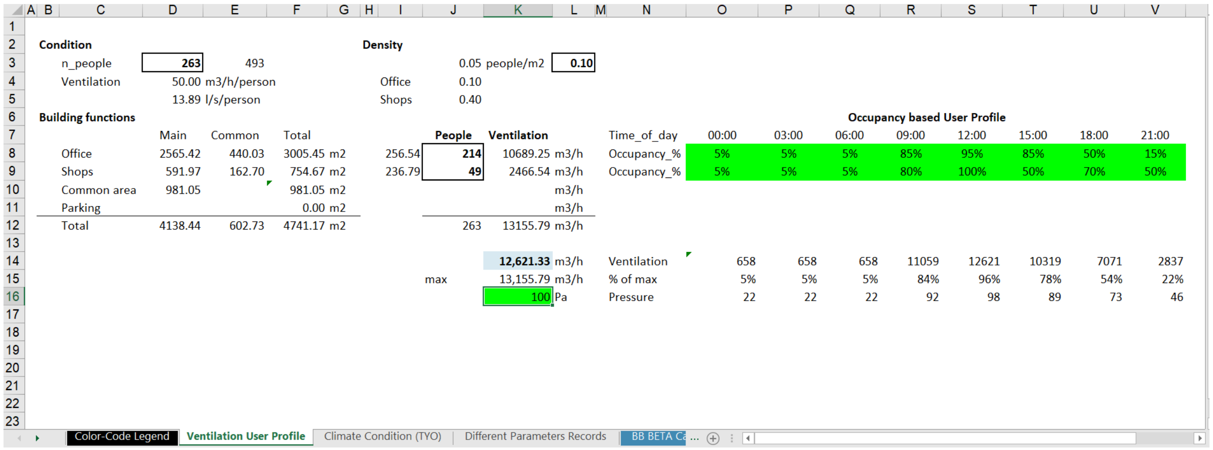
xx	=	Referred cells	ventilation amount [m3/h]	(automatically calculated)
🟨 xx	=	Referred cells	important!	(automatically calculated)
xx	=	Referred cells	good to know	(automatically calculated)
xx	=	Referred cells	irregulars	(automatically calculated)

Others

	=	Source cell	for a group of cells with the same data

a. Ventilation User Profile tab

This tab was added to define the amount of ventilation necessary following the number of people and/or ventilated space of the building. A 3-hour ventilation profile following occupancy rate in a day, starting from 00:00, 03:00, 06:00 and so on until 21:00, is included to better visualize the ventilation amount, as a building is rarely occupied 100% in 24-hour.



	B	C	D	E	F	G	I	J	K	L	N	O	P	Q	R	S	T	U	V
1																			
2	**Condition**						**Density**												
3		n_people	**263**	493				0.05	people/m2	**0.10**									
4		Ventilation	50.00	m3/h/person			Office	0.10											
5			13.89	l/s/person			Shops	0.40											
6	**Building functions**														**Occupancy based User Profile**				
7			Main	Common	Total			**People**	**Ventilation**		Time_of_day	00:00	03:00	06:00	09:00	12:00	15:00	18:00	21:00
8		Office	2565.42	440.03	3005.45	m2	256.54	**214**	10689.25	m3/h	Occupancy_%	5%	5%	5%	85%	95%	85%	50%	15%
9		Shops	591.97	162.70	754.67	m2	236.79	**49**	2466.54	m3/h	Occupancy_%	5%	5%	5%	80%	100%	50%	70%	50%
10		Common area	981.05		981.05	m2				m3/h									
11		Parking			0.00	m2				m3/h									
12		Total	4138.44	602.73	4741.17	m2		263	13155.79	m3/h									
13																			
14									**12,621.33**	m3/h	Ventilation	658	658	658	11059	12621	10319	7071	2837
15								max	13,155.79	m3/h	% of max	5%	5%	5%	84%	96%	78%	54%	22%
16									100	Pa	Pressure	22	22	22	92	98	89	73	46
17																			
18																			
19																			
20																			
21																			
22																			
23																			

Figure 39 CC Excel: Ventilation User Profile tab

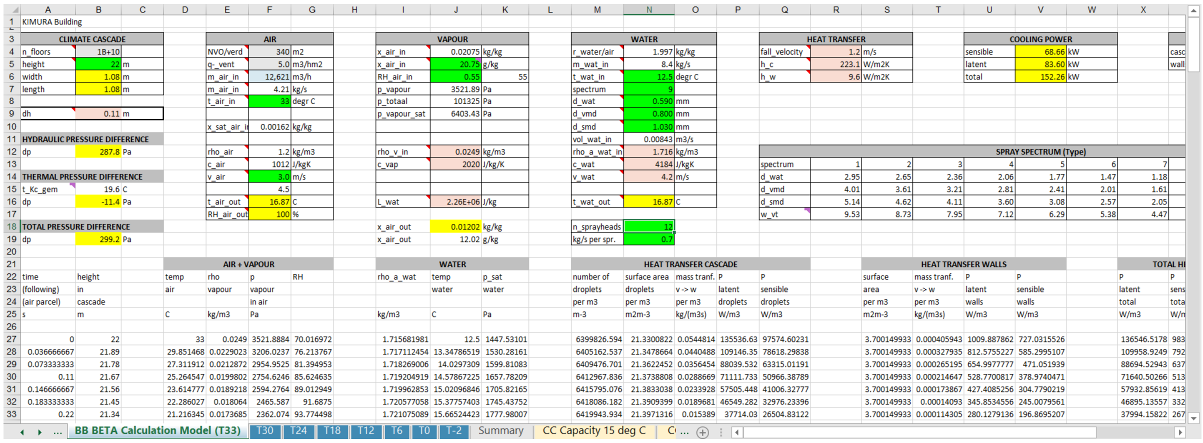
After inputting the data under *Condition* and *Building Functions*, decide on the *Occupancy based User Profile* highlighted in green. Finally, make an educated assumption of the required pressure loss for the CC, in the selected cell in Figure 39 also highlighted in green. In this paper, as the number of occupants of the study case building is unknown, the writer assumed 1 person/12 m^2 for both Office and Shops, which cells are framed and bolded, a moderate condition considering the aftermath of a pandemic. The normal condition setting can also be seen here, just for reference and not used for further calculation in this paper.

b. Climate Condition tab

This tab was added to include hourly dry-bulb temperature for the whole year of the analyzed city. Following this, in the same tab, hourly data of various necessary data such as required pressures, gained pressure from EWF, fan energy, pump energy, etc. are calculated automatically. The light-blue-highlighted cells are referred to *Occupancy based User Profile* set in the previous tab. The general energy calculation i.e. fan energy, pump energy, heating and cooling energy (to condition the ventilation air in CC and NOT space heating/cooling) are also in this tab.

c. BB Beta Calculation Model tab

This is the work of Dr Ben Bronsema, where the writer made copies of the tabs for each representative outdoor temperature – for Tokyo: T33, T30, T24, T18, T12, T6, T0, T-2, whereas for Amsterdam: T28, T24, T18, T12, T6, T0, T-2, T-10. The majority of the setting can be made in the hottest temperature tab, e.g. T33 for Tokyo, as can be seen below.


KIMURA Building

CLIMATE CASCADE		
n_floors	1B+10	
height	22	m
width	1.08	m
length	1.08	m
dh	0.11	m
HYDRAULIC PRESSURE DIFFERENCE		
dp	287.8	Pa
THERMAL PRESSURE DIFFERENCE		
t_Kc_gem	19.6	C
dp	-11.4	Pa
TOTAL PRESSURE DIFFERENCE		
dp	299.2	Pa

AIR		
NVO/verd	340	m2
q-_vent	5.0	m3/hm2
m_air_in	12,621	m3/h
m_air_in	4.21	kg/s
t_air_in	33	degr C
x_sat_air_in	0.00162	kg/kg
rho_air	1.2	kg/m3
c_air	1012	J/kgK
v_air	3.0	m/s
	4.5	
t_air_out	16.87	C
RH_air_out	100	%

VAPOUR		
x_air_in	0.02075	kg/kg
x_air_in	20.75	g/kg
RH_air_in	0.55	55
p_vapour	3521.89	Pa
p_totaal	101325	Pa
p_vapour_sat	6403.43	Pa
rho_v_in	0.0249	kg/m3
c_vap	2020	J/kg/K
L_wat	2.26E+06	J/kg
x_air_out	0.01202	kg/kg
x_air_out	12.02	g/kg

WATER		
r_water/air	1.997	kg/kg
m_wat_in	8.4	kg/s
t_wat_in	12.5	degr C
spectrum	9	
d_wat	0.590	mm
d_vmd	0.800	mm
d_smd	1.030	mm
vol_wat_in	0.00843	m3/s
rho_a_wat_in	1.716	kg/m3
c_wat	4184	J/kgK
v_wat	4.2	m/s
t_wat_out	16.87	C
n_sprayheads	12	
kg/s per spr.	0.7	

HEAT TRANSFER		
fall_velocity	1.2	m/s
h_c	223.1	W/m2K
h_w	9.6	W/m2K

COOLING POWER		
sensible	68.66	kW
latent	83.60	kW
total	152.26	kW

casc
wall

SPRAY SPECTRUM (Type)							
spectrum	1	2	3	4	5	6	7
d_wat	2.95	2.65	2.36	2.06	1.77	1.47	1.18
d_vmd	4.01	3.61	3.21	2.81	2.41	2.01	1.61
d_smd	5.14	4.62	4.11	3.60	3.08	2.57	2.05
w_vt	9.53	8.73	7.95	7.12	6.29	5.38	4.47

		AIR + VAPOUR				WATER		
time (following) (air parcel) s	height in cascade m	temp air C	rho vapour kg/m3	p vapour in air Pa	RH	rho_a_wat kg/m3	temp water C	p_sat water Pa
0	22	33	0.0249	3521.8884	70.016972	1.715681981	12.5	1447.53101
0.036666667	21.89	29.851468	0.0229023	3206.0237	76.213767	1.717112454	13.34786519	1530.28161
0.073333333	21.78	27.311912	0.0212872	2954.9525	81.394953	1.718269006	14.0297309	1599.81083
0.11	21.67	25.264547	0.0199802	2754.6246	85.624635	1.719204919	14.57867225	1657.78209
0.146666667	21.56	23.614777	0.0189218	2594.2764	89.012949	1.719962853	15.02096846	1705.82165
0.183333333	21.45	22.286027	0.018064	2465.587	91.6875	1.720577058	15.37757403	1745.43752
0.22	21.34	21.216345	0.0173685	2362.074	93.774498	1.721075089	15.66524423	1777.98007

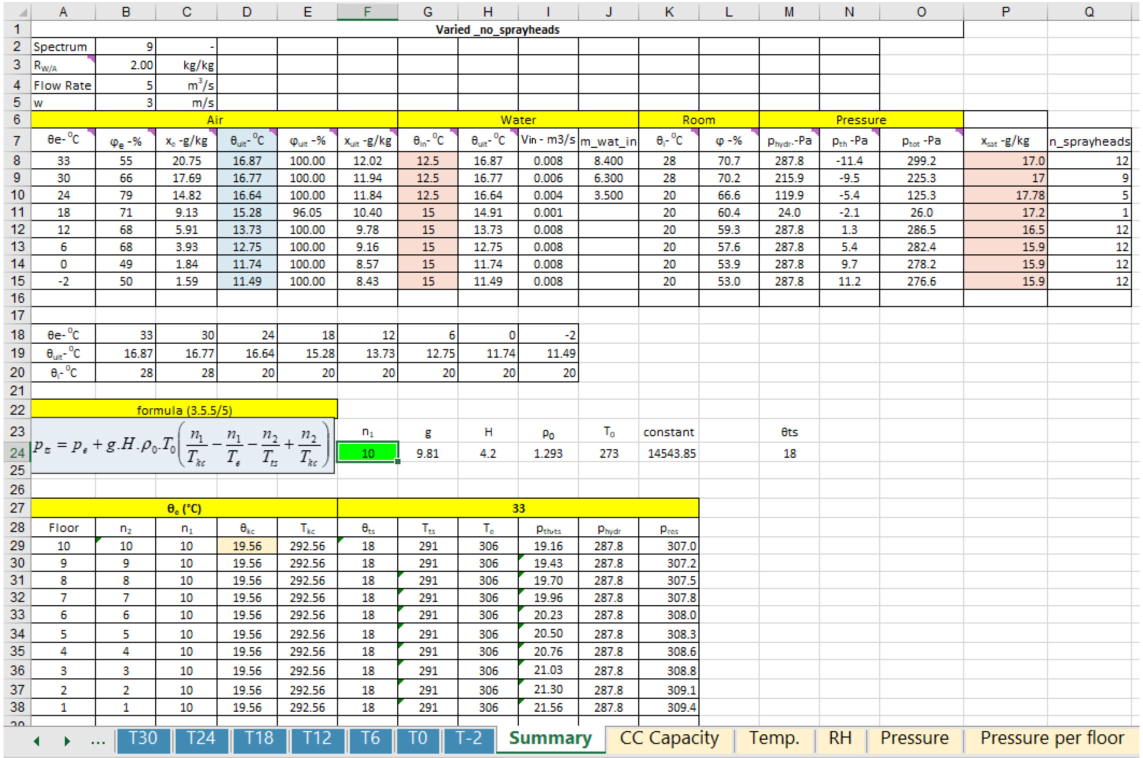
	HEAT TRANSFER CASCADE					HEAT TRANSFER WALLS				TOTAL HI	
time (following) (air parcel) s	number of droplets per m3 m-3	surface area droplets per m3 m2m-3	mass tranf. v -> w per m3 kg/(m3s)	P latent droplets W/m3	P sensible droplets W/m3	surface area per m3 m2m-3	mass tranf. v -> w per m3 kg/(m3s)	P latent walls W/m3	P sensible walls W/m3	P latent total W/m3	P sens tota W/m
0	6399826.594	21.3300822	0.0544814	135536.63	97574.60231	3.700149933	0.000405943	1009.887862	727.0315526	136546.5178	983
0.036666667	6405162.537	21.3478664	0.0440488	109146.35	78618.29838	3.700149933	0.000327935	812.5755227	585.2995107	109958.9249	792
0.073333333	6409476.701	21.3622452	0.0356454	88039.532	63315.01191	3.700149933	0.000265195	654.9977777	471.051939	88694.52943	637
0.11	6412967.836	21.3738808	0.0288669	71111.733	50966.38789	3.700149933	0.000214647	528.7700817	378.9740471	71640.50266	513
0.146666667	6415795.076	21.3833038	0.0233928	57505.448	41006.32777	3.700149933	0.000173867	427.4085256	304.7790219	57932.85619	413
0.183333333	6418086.182	21.3909399	0.0189681	46549.282	32976.23396	3.700149933	0.00014093	345.8534556	245.0079561	46895.13557	332
0.22	6419943.934	21.3971316	0.015389	37714.03	26504.83122	3.700149933	0.000114305	280.1279136	196.8695207	37994.15822	267

Figure 40 BB Beta Calculation Model tab

33°C has been chosen following the Tokyo design condition of ASHRAE 2017.

d. Summary tab

All the different temperature tabs are summarized here. Good to know that the regression equation used to calculate Gained Pressure, Outgoing Air Temperature, and Water Amount used in the Climate Condition tab are calculated in this tab.


Varied _no_sprayheads

Spectrum	9	-
$R_{W/A}$	2.00	kg/kg
Flow Rate	5	m^3/s
w	3	m/s

Air						Water				Room		Pressure				
θe-°C	φ_e -%	x_e -g/kg	θ_{uit}-°C	φ_{uit} -%	x_{uit} -g/kg	θ_{in}-°C	θ_{uit}-°C	Vin - m3/s	m_wat_in	θ_i-°C	φ -%	P_{hydr}-Pa	P_{th} -Pa	P_{tot} -Pa	x_{sat} -g/kg	n_sprayheads
33	55	20.75	16.87	100.00	12.02	12.5	16.87	0.008	8.400	28	70.7	287.8	-11.4	299.2	17.0	12
30	66	17.69	16.77	100.00	11.94	12.5	16.77	0.006	6.300	28	70.2	215.9	-9.5	225.3	17	9
24	79	14.82	16.64	100.00	11.84	12.5	16.64	0.004	3.500	20	66.6	119.9	-5.4	125.3	17.78	5
18	71	9.13	15.28	96.05	10.40	15	14.91	0.001		20	60.4	24.0	-2.1	26.0	17.2	1
12	68	5.91	13.73	100.00	9.78	15	13.73	0.008		20	59.3	287.8	1.3	286.5	16.5	12
6	68	3.93	12.75	100.00	9.16	15	12.75	0.008		20	57.6	287.8	5.4	282.4	15.9	12
0	49	1.84	11.74	100.00	8.57	15	11.74	0.008		20	53.9	287.8	9.7	278.2	15.9	12
-2	50	1.59	11.49	100.00	8.43	15	11.49	0.008		20	53.0	287.8	11.2	276.6	15.9	12

θe-°C	33	30	24	18	12	6	0	-2
θ_{uit}-°C	16.87	16.77	16.64	15.28	13.73	12.75	11.74	11.49
θ_i-°C	28	28	20	20	20	20	20	20

formula (3.5.5/5)

$$p_{ts} = p_e + g.H.\rho_0.T_0\left(\frac{n_1}{T_{kc}} - \frac{n_1}{T_e} - \frac{n_2}{T_{ts}} + \frac{n_2}{T_{kc}}\right)$$

n_1	g	H	ρ_0	T_0	constant	θts
10	9.81	4.2	1.293	273	14543.85	18

θ_e (°C)					33					
Floor	n_2	n_1	θ_{kc}	T_{kc}	θ_{ts}	T_{ts}	T_e	p_{thvts}	p_{hydr}	p_{res}
10	10	10	19.56	292.56	18	291	306	19.16	287.8	307.0
9	9	10	19.56	292.56	18	291	306	19.43	287.8	307.2
8	8	10	19.56	292.56	18	291	306	19.70	287.8	307.5
7	7	10	19.56	292.56	18	291	306	19.96	287.8	307.8
6	6	10	19.56	292.56	18	291	306	20.23	287.8	308.0
5	5	10	19.56	292.56	18	291	306	20.50	287.8	308.3
4	4	10	19.56	292.56	18	291	306	20.76	287.8	308.6
3	3	10	19.56	292.56	18	291	306	21.03	287.8	308.8
2	2	10	19.56	292.56	18	291	306	21.30	287.8	309.1
1	1	10	19.56	292.56	18	291	306	21.56	287.8	309.4

e. Graphs tabs in orange

These tabs show the result of the calculation in graphs, which can be seen in Figure 67 and Figure 68 in Chapter 8.

f. Other important things

The purified air coming out of the CC has 100% RH most of the time. Thus, it is important to make sure that the air will not be too wet - to keep moisture level within the recommended value of 12g/kg. For this reason, the incoming air of CC In Tokyo is set at 16.5°C.

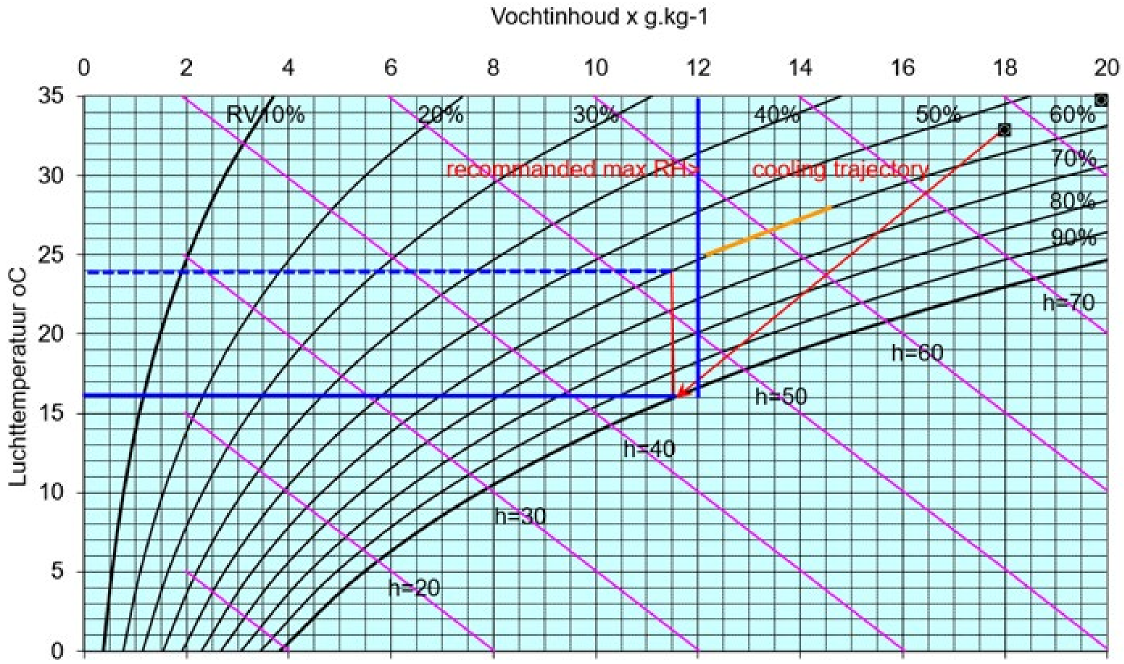
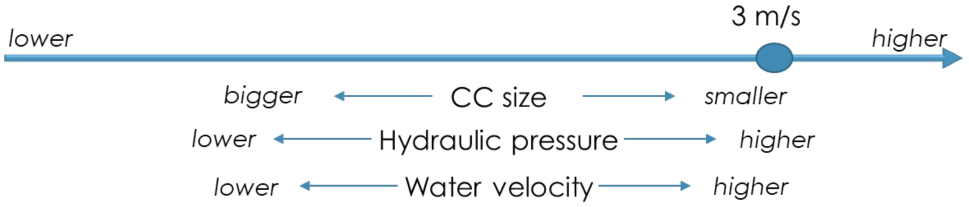


Figure 41 Mollier diagram: 16.5°C as the highest possible comfortable temperature for 100% RH

2. Design Parameter

From CC Excel, it has become clear that the height of (the spray-heads of) CC (in most cases are the height of the building), the amount of ventilation, and outdoor temperature are the 'fixed' design parameter, considering it is a renovation project. However, the height of spray-heads can be lowered if there is more than enough pressure, as pump energy can be saved in this way. As a designer, 2 parameters need to be decided, as follows.

a. Air velocity



As space is limited, the CC in the case study building needs to be as small as possible while still providing enough pressure.

b. Water/air factor

Defining the amount of water per air (kg/kg), the strategy is to use the lowest amount of water to achieve enough cooling on the hottest days. This is translated into the number of spray-heads in CC, as well as the Drop Size Distribution of the water droplets represented by the type of spray-heads.

5.1.3 SC Excel

The same way it takes two to tango, CC needs a partner to exhaust the stale air inside the building – Solar Chimney (SC) is here for that exact reason, plus a bonus performance of collecting heat at its top. The calculation and analysis for SC are conducted using the simple Excel Model from Dr Regina Bokel that is used to simulate ventilated cavity without sun-shading. Modification has been made to the Excel Model (hereinafter referred to as "SC Excel") by the writer to compare between 2 different climates more easily.

1. *Climate Analysis*

Hourly weather data of outside temperature and solar radiation are used in the SC Excel. Since the exhaust system will be centralized for the case study, duct work can be minimized and thus the necessary pressure is assumed as 25 Pa, where the yellow line is, below.

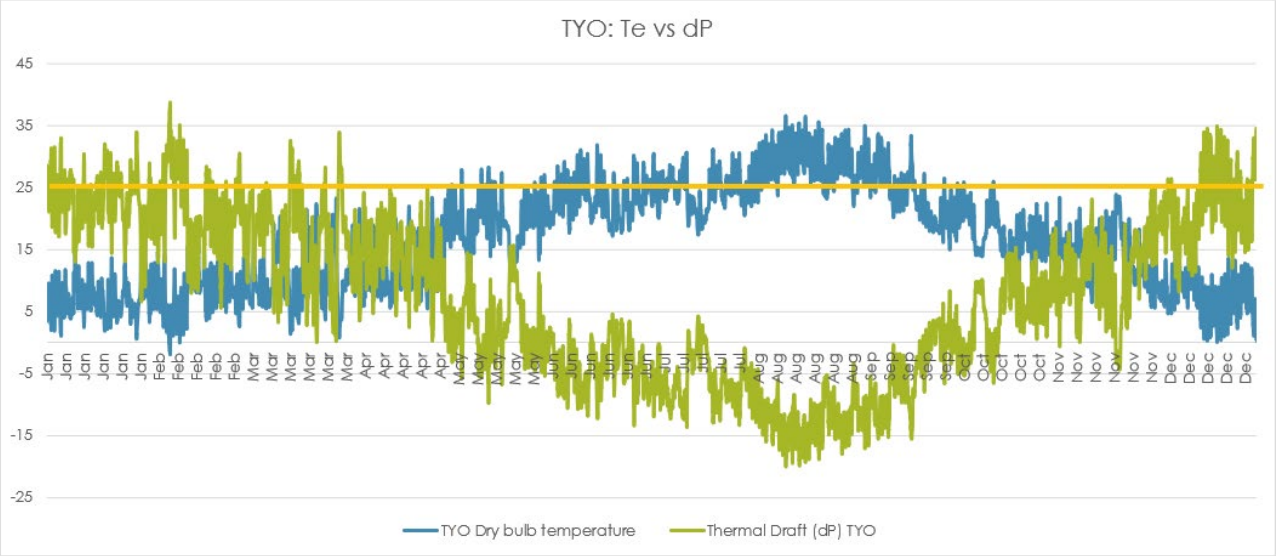


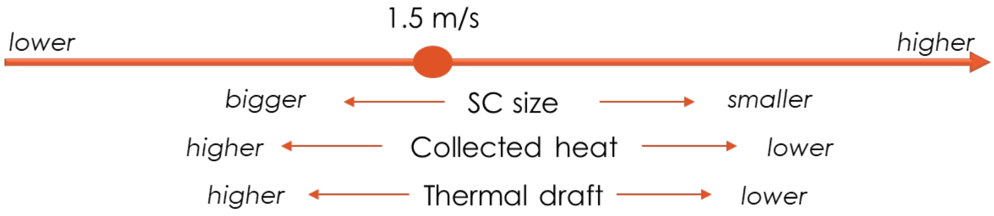
Figure 42 Thermal Draft of SC in Tokyo in 2020

From the graph above, it is clear that an auxiliary fan will be needed throughout the year for the SC to achieve enough pressure in Tokyo.

2. *Design Parameter*

From SC Excel, it is apparent that the height of SC (in most cases are the height of the building), the amount of ventilation, outdoor temperature, and solar radiation are the 'fixed' design parameter, considering it is a renovation project. The designer's toolbox in SC is as follows.

1. *Air velocity*



Although space is limited, the performance of SC is better (higher thermal draft and more collected heat) when the air velocity is lower.

2. *Orientation & material*

By instinct, the most optimum orientation of SC is towards the sun – as Tokyo is in the northern hemisphere: South. However, according to the performance study of the Four Elements Hotel's SC, the thermal draft is much more dependent on the outside temperature than on the solar radiation. Thus, while South orientation is optimal, other orientations will work as well because the majority of total radiation is diffused from the sky.

Regarding material, the criteria for the glass and the absorber has been explained in 3.2.2.

5.2 POWER ROOF

Achieving energy neutrality would not be possible without energy production. Power roof here is defined as Building-Added PV panels (BAPV) on the case study roof for electricity production.

A quick and dirty simulation of the PV yield on the roof of the case study building was done using PVWatts$^{®}$ Calculator – the annual yield is 67,115 kWh/year. This is a very optimistic assumption, considering all the rooftop space of 390 m^2 is used to place Premium Crystalline Silicone with anti-reflective coating and has 19% efficiency.

Another simulation was done using Grasshopper script with the building simply modelled as an extruded block in Rhinoceros. This time, the existing roof plan is incorporated, carefully placing the PV panels where possible – a more realistic approach than the previous one.

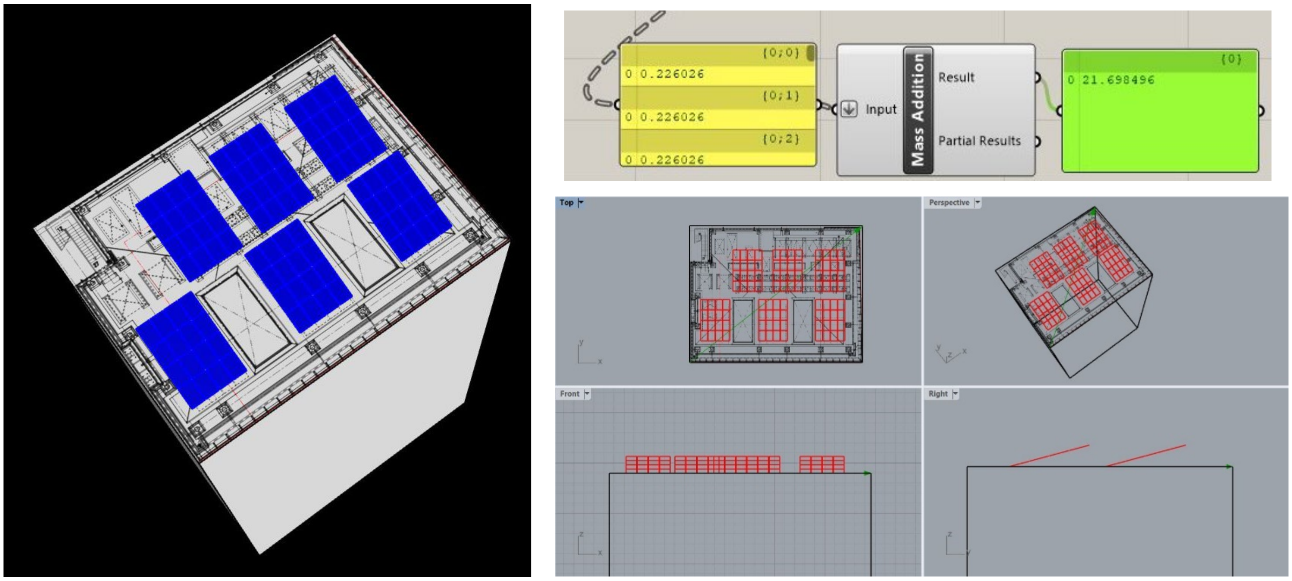


Figure 43 PV Yield of NK Building simulated in Grasshopper

DC system size is calculated as 22kW and 161m^2 of PV area, with the array tilted at 15°. The calculated annual yield is 22,465 kWh/year.

5.3 DESIGNBUILDER SIMULATION

In addition to the calculation done in Excel, the energy consumption and thermal comfort of both the existing and with EWF will be simulated in DesignBuilder version 5.5.2.007 (hereinafter referred to as "DB").

5.3.1 Construction

For simplicity, the simulation is conducted for 1 office floor with both roof and floor in adiabatic condition.

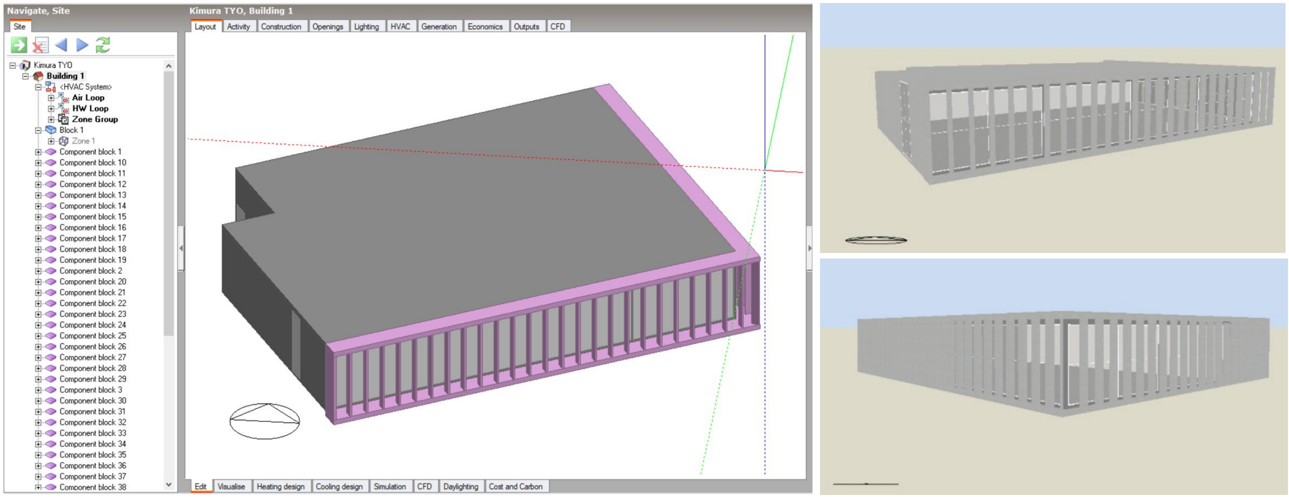


Figure 44 An Office Floor of NK Building Simulated in DesignBuilder

The floor is divided into 2 zone: Common Area and Open Office, separated by a partition wall. Only the Open Office is climatized in this model, thus the thermal and energy analysis is also only in this zone.

There are 2 types of wall used in the model: Extruded Cement Panel (ECP) t:60mm, R-value: 0.14 m^2K/W used as an exterior wall for the West and North façade to imitate the actual wall, and 'Lightweight curtain wall insulated to 2000 regs' template in DB for the South and East façade, to assume the actual curtain wall which thermal data is unknown.

No change in construction or façade refurbishment is planned as the building is relatively new, so only the HVAC system is changed in this simulation between Existing and EWF Design.

5.3.2 Occupancy & Schedule

Occupancy density is set as 0.2 people/m^2 and a Schedule similar to that shown in Figure 39, with no occupancy during weekends and holidays.

5.3.3 HVAC system

To simulate the existing system, a Detailed HVAC template of 'VRF with HR and DOAS' is used. On the other hand, simulating EWF in DB was proved to be tricky. In consultation with my 1st mentor and 2 other colleagues, EWF simulation in DB is simplified in this way: with Detailed HVAC, a new mechanical ventilation VAV with no reheat that supplies constant supply air of 16.5°C throughout the year, mimicking CC For the space heating and cooling, chilled ceiling with heated floor is added, assuming this to be the most energy-efficient way.

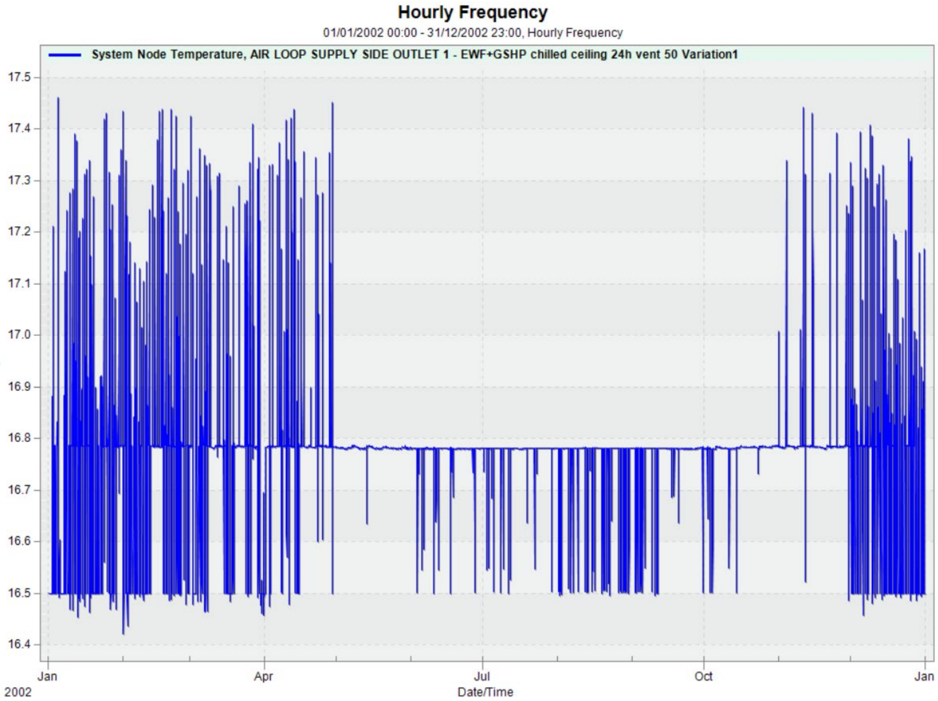


Figure 45 DB-EWF: hourly temperature of Supply Air Outlet

Even after several attempts, the temperature supplied to the room, simulating CC is not always 16.5°C, as shown above. Consider this when factoring the accuracy of the simulation.

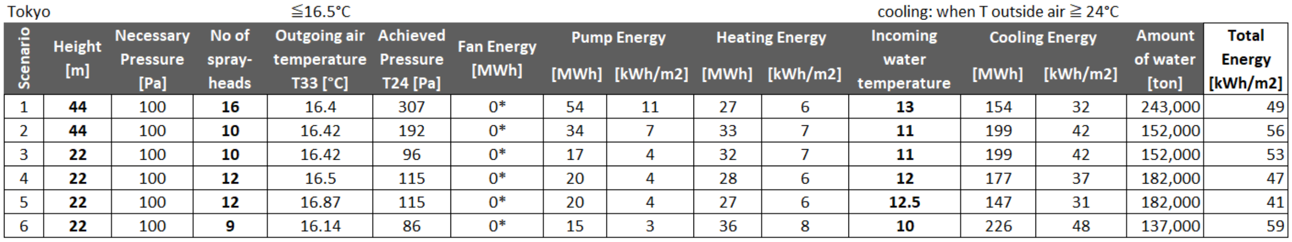
6. EWF Applied to NK Building

6.1 CALCULATION OUTCOME

6.1.1 CC Excel

With air velocity of 3 m/s, the CC size is 1.08 x 1.08 m, as known from the BB Beta Calculation Model tab. For the case study, 6 scenarios have been analysed, summarized below.

Table 13 Summary of 6 Scenarios Calculated in CC Excel



Tokyo ≦16.5°C cooling: when T outside air ≧ 24°C

Scenario	Height [m]	Necessary Pressure [Pa]	No of spray-heads	Outgoing air temperature T33 [°C]	Achieved Pressure T24 [Pa]	Fan Energy [MWh]	Pump Energy		Heating Energy		Incoming water temperature	Cooling Energy		Amount of water [ton]	Total Energy [kWh/m2]
							[MWh]	[kWh/m2]	[MWh]	[kWh/m2]		[MWh]	[kWh/m2]		
1	**44**	100	**16**	16.4	307	0*	54	11	27	6	**13**	154	32	243,000	49
2	**44**	100	**10**	16.42	192	0*	34	7	33	7	**11**	199	42	152,000	56
3	**22**	100	**10**	16.42	96	0*	17	4	32	7	**11**	199	42	152,000	53
4	**22**	100	**12**	16.5	115	0*	20	4	28	6	**12**	177	37	182,000	47
5	**22**	100	**12**	16.87	115	0*	20	4	27	6	**12.5**	147	31	182,000	41
6	**22**	100	**9**	16.14	86	0*	15	3	36	8	**10**	226	48	137,000	59

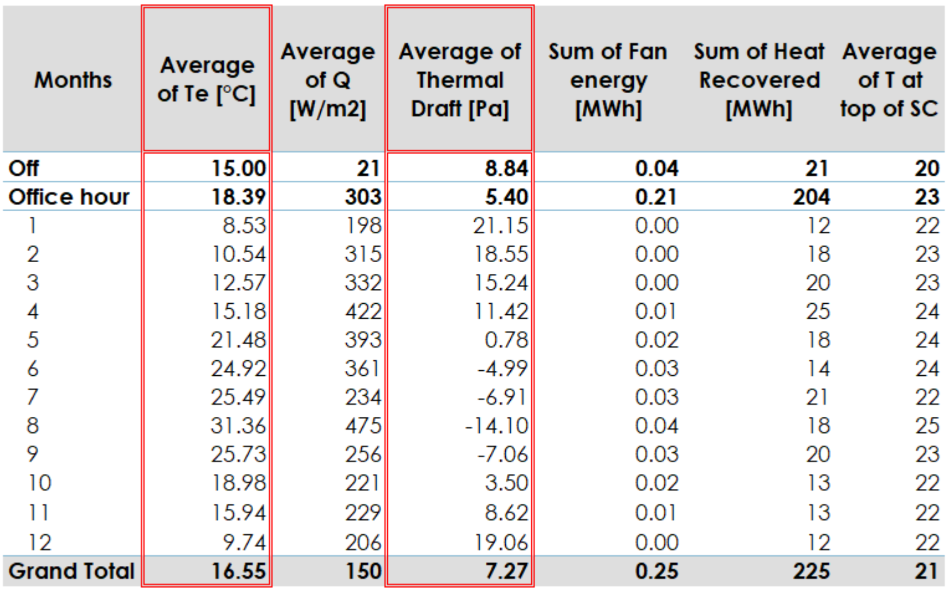
Scenario 5, with a total of 12 spray-heads, is chosen as comfort is achieved with the least energy for heating, cooling, and pump. Although the outgoing air temperature is slightly higher than 16.5°C in the chosen scenario, low energy used is prioritized over comfort, as mentioned in 5.1.1.

For maintenance and better performance of the CC (cooling capacity is better when the CC walls stay wet, 3 spray-heads will be located at the top (44 m) and the remaining 9 at half the height (22 m).

6.1.2 SC Excel

With an air velocity of 1.5 m/s, the SC size is 4 m x 0.65 m. Office hour in the following table is set as 8 am to 6 pm. On average, the designed SC in Tokyo only produce 7 Pa of thermal draft and 225 MWh of heat recovery during office hours, and 0.2 MWh of fan energy will be required during the same period.

Table 14 SC Excel Outcome



Months	Average of Te [°C]	Average of Q [W/m2]	Average of Thermal Draft [Pa]	Sum of Fan energy [MWh]	Sum of Heat Recovered [MWh]	Average of T at top of SC
Off	**15.00**	**21**	**8.84**	**0.04**	**21**	**20**
Office hour	**18.39**	**303**	**5.40**	**0.21**	**204**	**23**
1	8.53	198	21.15	0.00	12	22
2	10.54	315	18.55	0.00	18	23
3	12.57	332	15.24	0.00	20	23
4	15.18	422	11.42	0.01	25	24
5	21.48	393	0.78	0.02	18	24
6	24.92	361	-4.99	0.03	14	24
7	25.49	234	-6.91	0.03	21	22
8	31.36	475	-14.10	0.04	18	25
9	25.73	256	-7.06	0.03	20	23
10	18.98	221	3.50	0.02	13	22
11	15.94	229	8.62	0.01	13	22
12	9.74	206	19.06	0.00	12	22
Grand Total	**16.55**	**150**	**7.27**	**0.25**	**225**	**21**

6.2 DESIGN PRINCIPLE

6.2.1 Energy Vs Thermal Comfort

Referring to 2.2.4, the comfortable temperature in office buildings in Tokyo is concluded to be 26°C in summer (with cooling) and 24°C in winter (with heating). As the writer thinks that thermal comfort would be a luxury in the future if we fail to convert to renewable resources for our energy consumption in the built environment, energy consumption for a tolerance of 2°C higher in summer (28°C) and 4°C lower in winter (20°C), following the Government of Japan's recommendation, will be evaluated and compared. When prompted, energy will be prioritized over thermal comfort.

6.2.2 Shouchikubai (松竹梅) Pine-Bamboo-Plum Philosophy

In Japan, Pine-Bamboo-Plum philosophy, or *shouchikubai* in Japanese, is commonly used in design, with Plum referring to the most basic, followed by Bamboo with some upgrades, and finally Pine as the most advanced design. However in this paper, the 3-level of design is not meant to give superiority to one over the other, but more to show the process of EWF integration from the most basic one (Plum), to a more complicated but also advanced design proposal (Pine).

6.3 3 DESIGN PROPOSALS

6.3.1 EWF Design: Plum

Intended as the most 'play-by-the-rules', basic integration of EWF into the case-study building, the SC is placed at the most southern corner, while the CC is placed on the opposite ends. Be reminded that the southwest and northwest of this building is adjacent to another building.

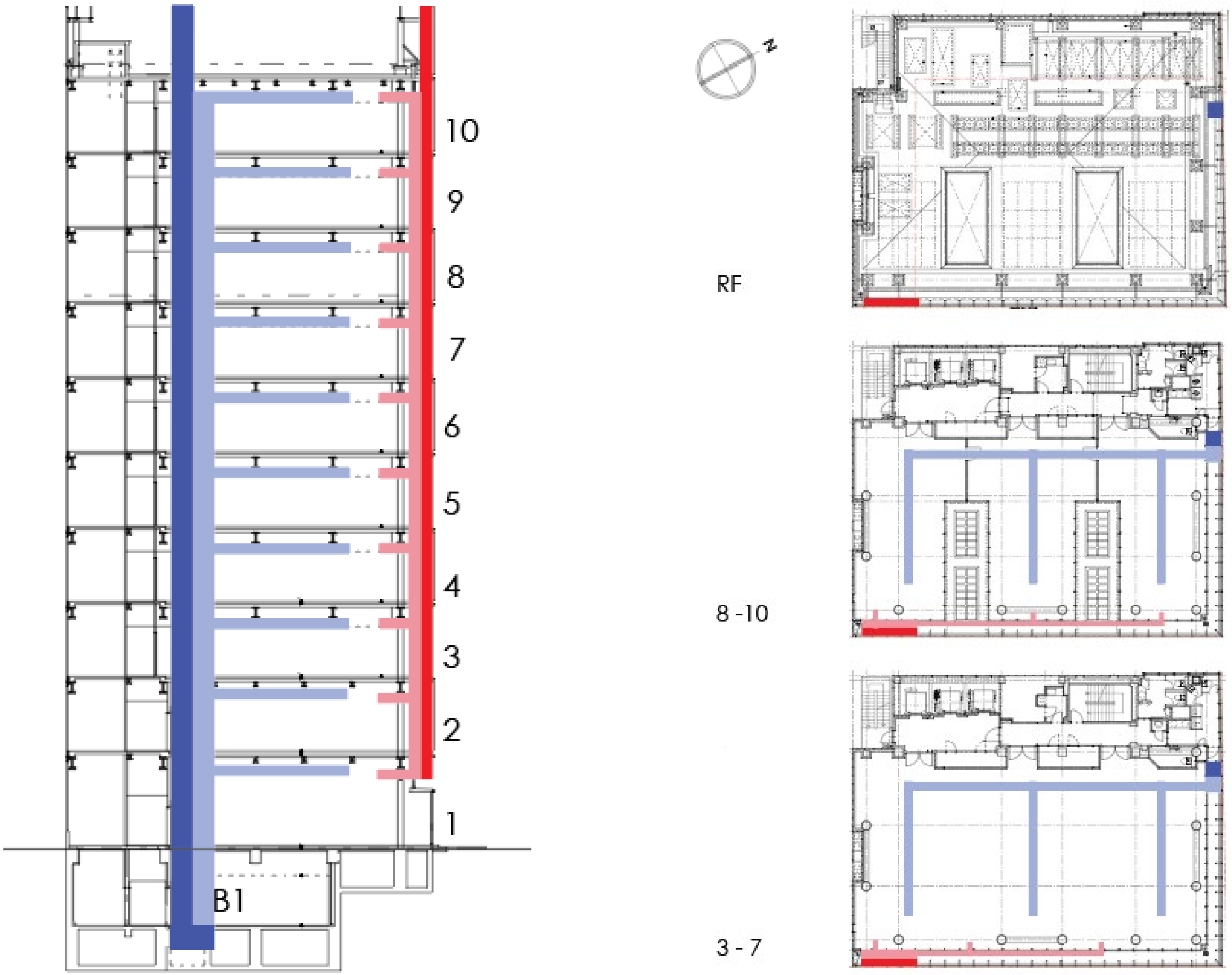


Figure 46 Plum Design Proposal

6.3.2 EWF Design: Bamboo

Adding the perspective of an architect that would like to infuse better aesthetic, space planning, and perhaps visual comfort as well, the following Bamboo designed is presented: the SC is separated into 2 smaller ones that are placed on the south-east façade in symmetry, harmonious with the existing architectural language. Moreover, the CC is still located on the opposite ends, this time occupying the existing duct space, thus the view from the office space will not be obscured.

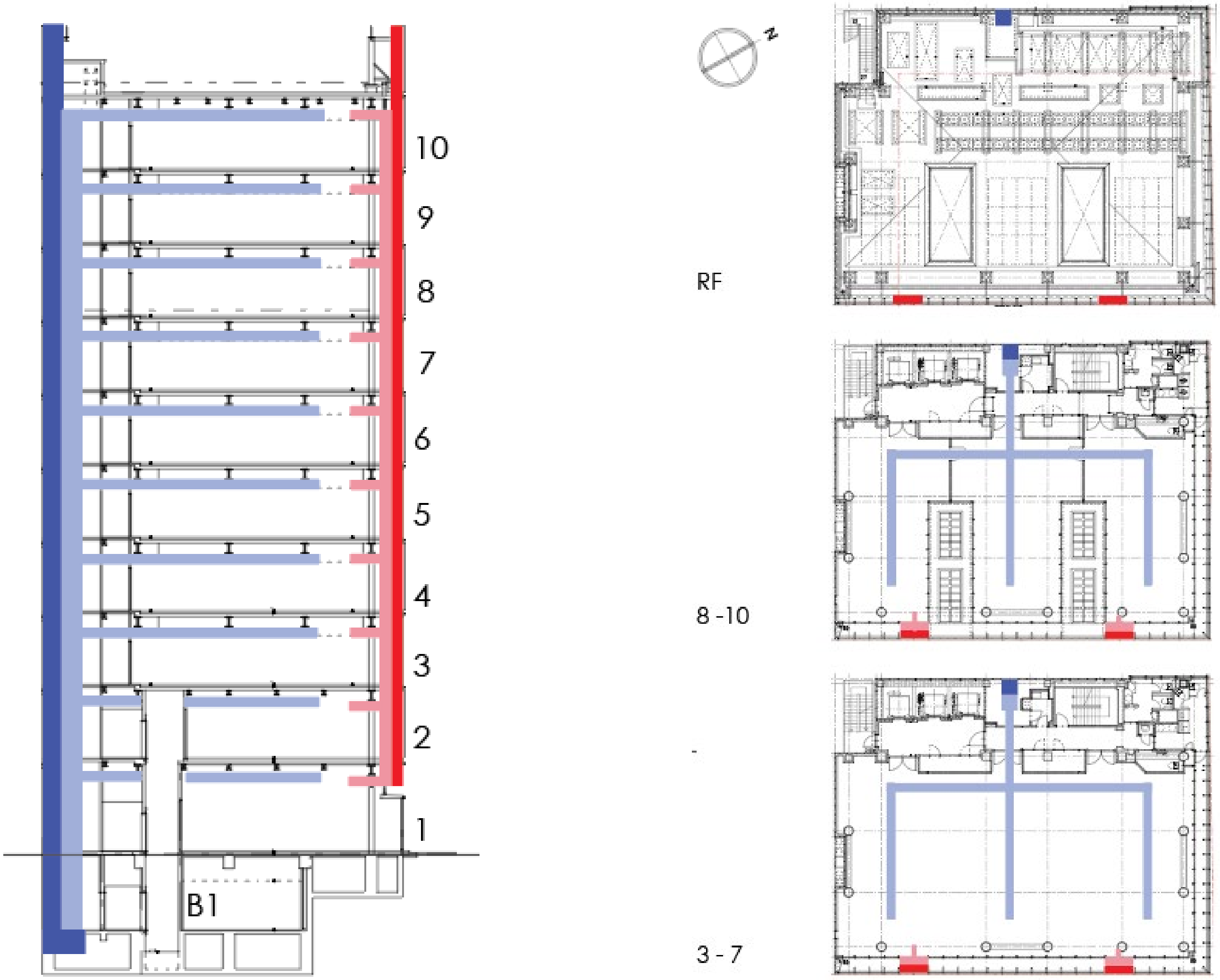


Figure 47 Bamboo Design Proposal

6.3.3 EWF Design: Pine

Finally, challenging the concept of having SC and CC next to each other to possibly incorporate a comparatively smaller Ventec Roof on the top is how the Pine design was initiated. For this, the most logical placement is on the centre of the southeast façade, as shown below.

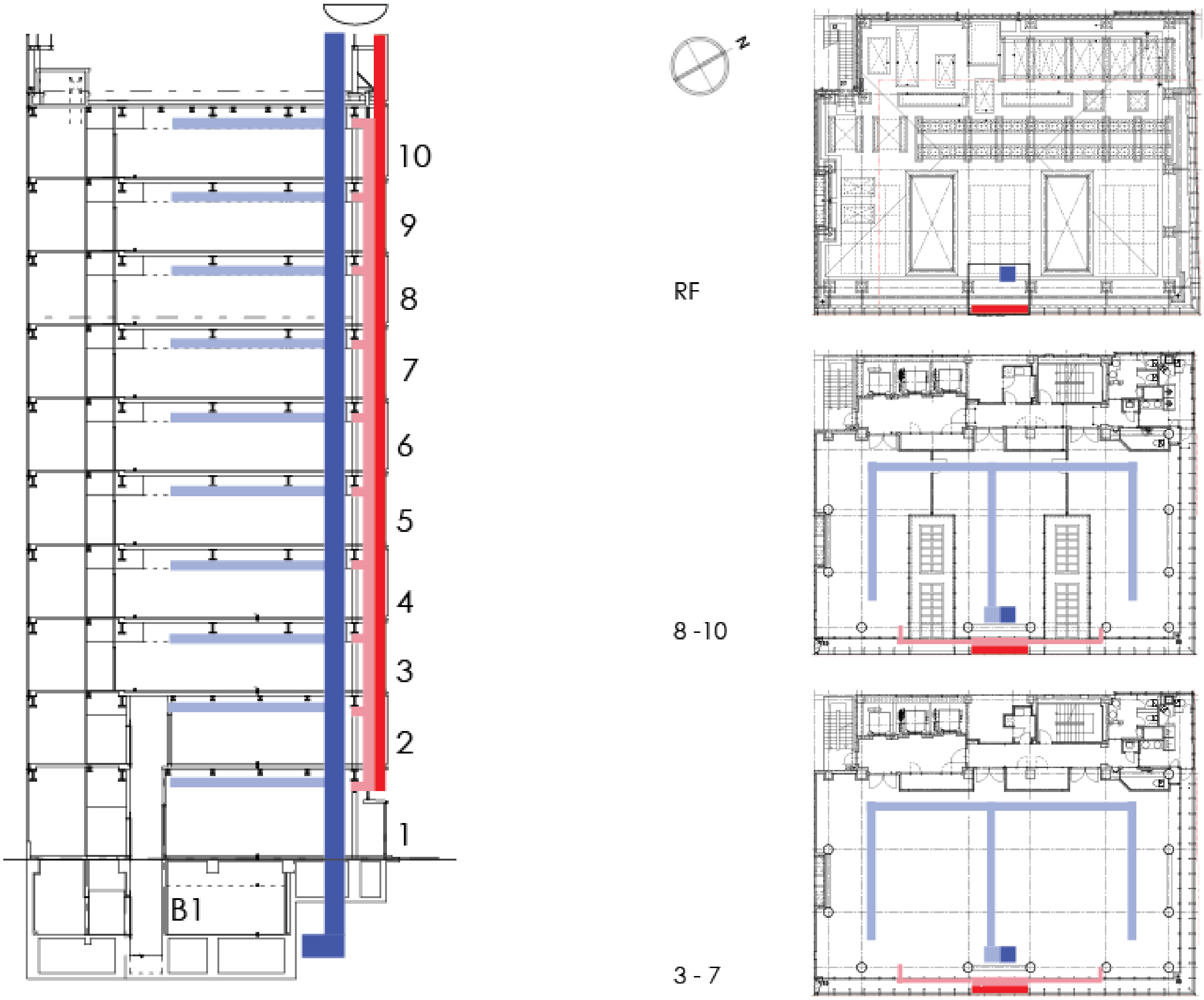


Figure 48 Pine Design Proposal

6.3.4 Chosen Design Proposal

The 3 design proposals are then qualitatively analyzed, based on the following 6 categories. The evaluation adopted the commonly used 3 symbols in Japan: ○ means good, ✖ means bad, and finally △ means in-between, not exactly good or bad.

1. *Performance (Heat Recovery)*

All 3 design proposal performs the same way as the design parameters are the same. Regarding the performance of HR, it was initially thought the closer the distance between SC and CC, the better it would be. However, upon consultation with Dr Ben Bronsema, it was concluded that when the ducts are well insulated, this difference in distance is negligible – hence all 3 designs are rated equally good.

2. *Material (quantity)*

The material used for ducts and its insulation is assumed here, with fewer equals to better evaluation. However, as there is no major difference in duct length among the 3 designs, all are rated equally good.

3. *Visual comfort*

Nothing is more frustrating when your hard-earned view from your working desk is blocked, even a little. With both SC and CC placed in the middle of the office, Pine is rated *bad*, whereas the other 2 options are rated *not exactly good*, as the view cannot be as good as when nothing is added.

4. *Maintenance*

Maintenance is simpler when the SC and CC are close to each other, as the equipment room can be placed in the same room. For this reason, Pine is rated *good*, while the other 2 as *not entirely bad*.

5. *Space use*

When space is limited, the value becomes high. Bamboo is rated *good* because the CC is placed on the existing duct space, Pine is rated *bad* as precious office space has to be used for CC, whereas Plum is rated as *so-so*.

6. *Aesthetic*

Channelling the role of an architect, Bamboo is rated *good* as the SC can be integrated well into the symmetrical southeast façade.

Table 15 Qualitative Evaluation of the 3 Design Proposals

No.	Category	Plum	Bamboo	Pine
1	Performance (HR)	○	○	○
2	Material (quantity)	○	○	○
3	Visual comfort	△	△	✕
4	Maintenance	△	△	○
5	Space use	△	○	✕
6	Aesthetic	△	○	△

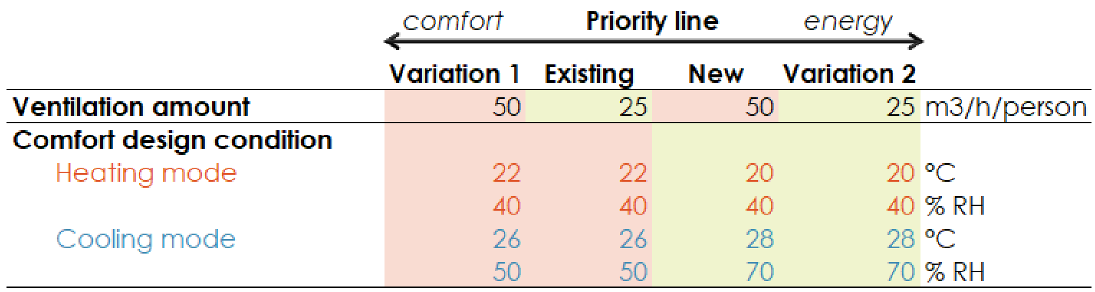
Bamboo is the chosen design as it has the best evaluation overall.

7. Assessment

7.1 PARAMETERS AND VARIATIONS

The simulations are conducted following these 2 parameters: ventilation amount and comfort design setting, creating 4 different variations, as shown in the following table. This is done due to the simplicity (inaccuracy)of the created DB model, in order to have a better picture of how the parameters are affecting thermal comfort and energy consumption in the building.

Table 16 DB Simulation: 4 Variations



	comfort	**Priority line**		*energy*	
	Variation 1	**Existing**	**New**	**Variation 2**	
Ventilation amount	50	25	50	25	m3/h/person
Comfort design condition					
Heating mode	22	22	20	20	°C
	40	40	40	40	% RH
Cooling mode	26	26	28	28	°C
	50	50	70	70	% RH

7.2 EXISTING

The existing building uses individual air conditioning with EHP (Electric Heat Pump) + Humidity Control: multi-unit system with 1 outdoor unit per floor. The ventilation amount is 25 m^3/h/person. The comfort setting of the existing is as follows: in cooling mode dry-bulb temperature of 26°C and RH 50%, and in heating mode 22°C and 40%, as described in 4.3.2.

7.2.1 HVAC setting

For simulating the existing HVAC condition, the setting in DB is set as ‘VRF with HR and DOAS’, as follows.

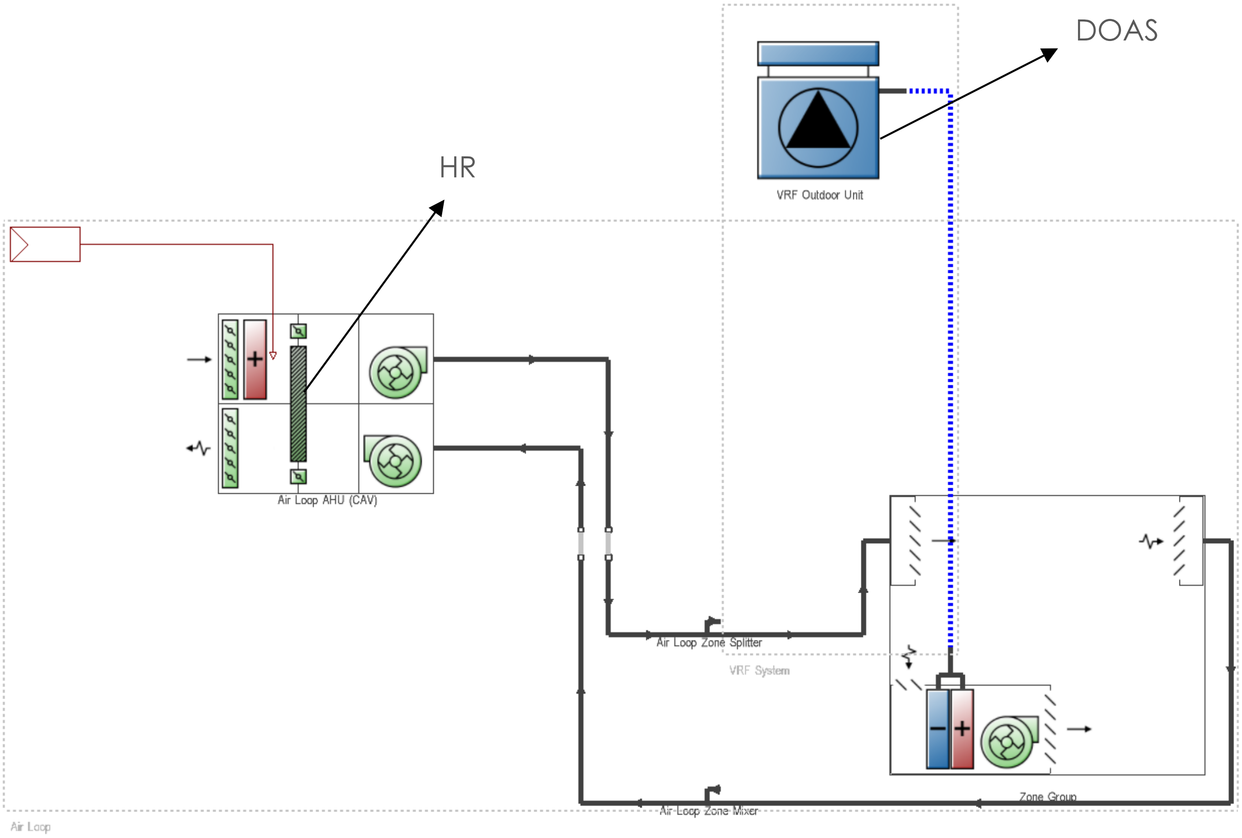


Figure 49 DB-existing: VRF with HR and DOAS schematic

7.2.2 Energy

From the 4 different variations, the writer expects Variation 2 to use the least energy, and Variation 1 to use the highest energy, and the result came as expected. Heating energy is lower than cooling energy in all cases. The total energy consumption of the existing building, as simulated in DB are as follows.

Table 17 DB-existing: Energy Consumption

Existing system	**Variation 1**	**Existing**	**New**	**Variation 2**	
Heating	3	2	3	2	kWh/m2
Cooling	29	27	22	21	kWh/m2
Ventilation*	50	29	48	27	kWh/m2
Total	82	58	73	50	kWh/m2

* includes system fans only

7.2.3 Comfort

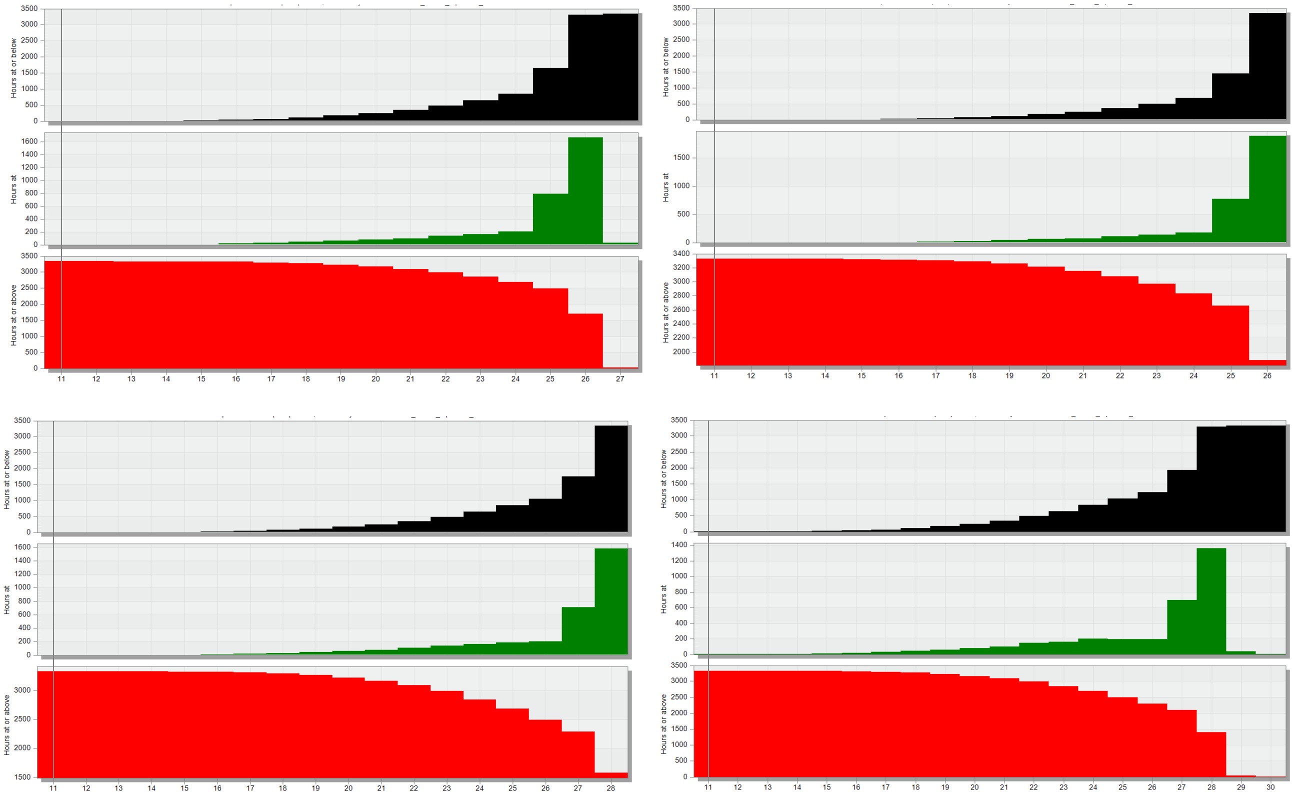
The majority has 100% comfort hours, which is good. In New Variation and Variation 2, the comfort for 26°C is only 76% and 74% respectively, as these two variations are the energy-conscious setting with summer cooling set to 28°C.

Table 18 DB-existing: Comfort Percentage for Comfort Setting of 26°C and 28°C in a Year

Existing system	**Variation 1**	**Existing**	**New**	**Variation 2**	
Hours at and above 27°C	26	0	2102	2288	hours
Discomfort % in a year	0	0	24	26	%
Comfort % in a year	**100**	**100**	**76**	**74**	%
Hours at and above 29°C	0	0	41	0	hours
Discomfort % in a year	0	0	0	0	%
Comfort % in a year	**100**	**100**	**100**	**100**	%

When we see the temperature distribution, the system seems to cool and heat the air rather fast, achieving the target comfort temperature most of the year.

Table 19 DB-existing: Temperature distribution



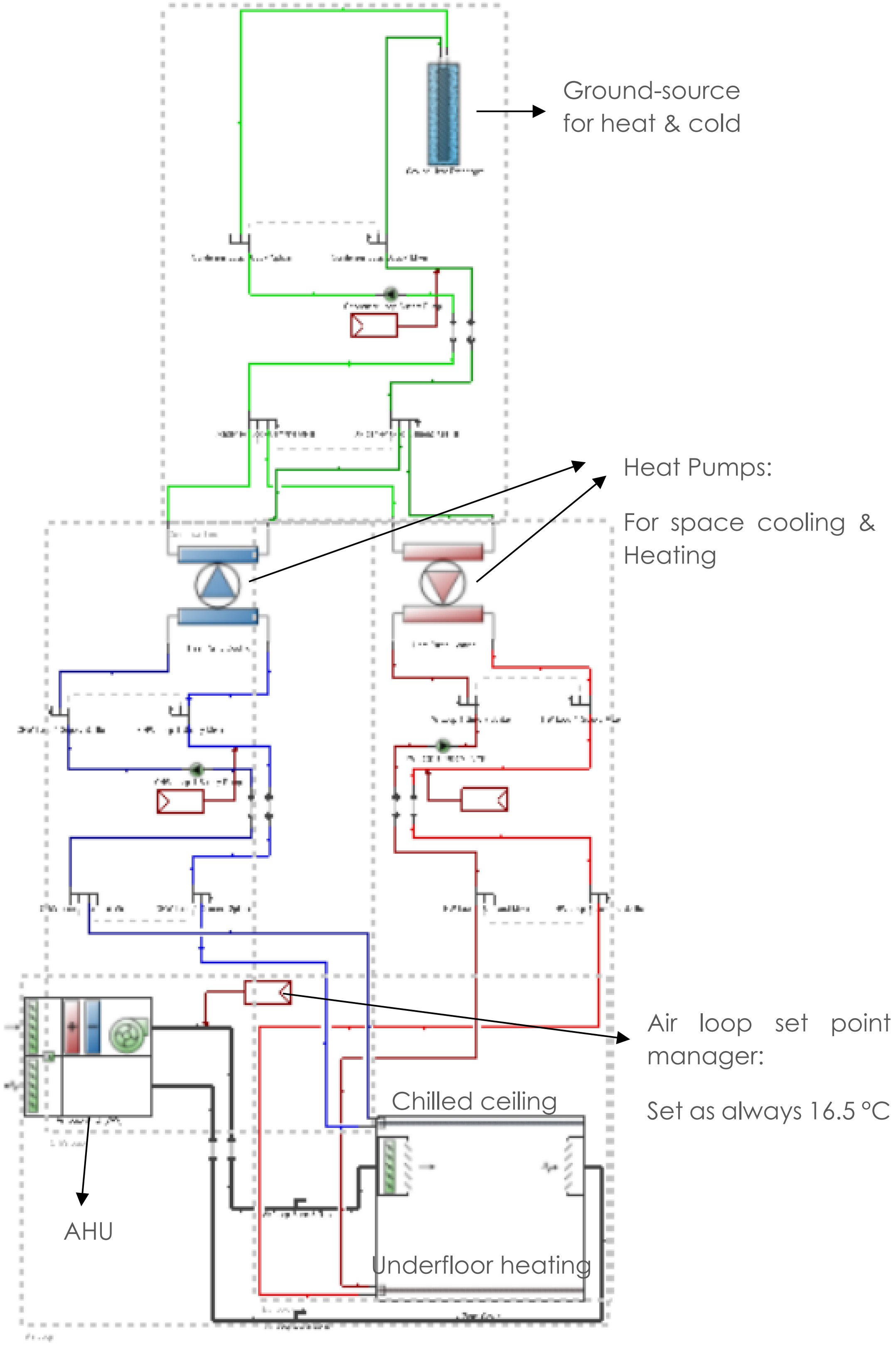
From top-left clockwise: Variation 1, Existing, New, and Variation 2.

7.3 EWF DESIGN

Different from the existing, the new design proposal will have the chosen EWF system as elaborated in the previous chapter that will handle the ventilation system, and climate ceiling with EHP is proposed for the space heating and cooling. The ventilation amount is 50 m^3/h/ person. The comfort setting is as follows: in cooling mode dry-bulb temperature of 28°C and RH 70%, and in heating mode 20°C and 30%.

7.3.1 HVAC setting

The EWF design is simulated in DB as 'VAV no reheat + GSHP', as follows.



Ground-source for heat & cold

Heat Pumps:

For space cooling & Heating

Air loop set point manager:

Set as always 16.5 °C

Figure 50 DB-EWF: VAV no reheat with GSHP, underfloor heating, & chilled ceiling schematic

7.3.2 Energy

Again, as expected, Variation 2 consumes the least energy and Variation 1, the highest.

Table 20 DB-EWF: Energy Consumption

EWF with climate ceiling	**Variation 1**	**Existing**	**New**	**Variation 2**	
Heating	15	14	10	10	kWh/m2
Cooling	77	72	67	63	kWh/m2
Ventilation (*from Excel*)*	31	29	25	23	kWh/m2
Total	123	114	101	96	kWh/m2

* includes system fans, system pumps, water cooling energy, and air heating energy

7.3.3 Comfort

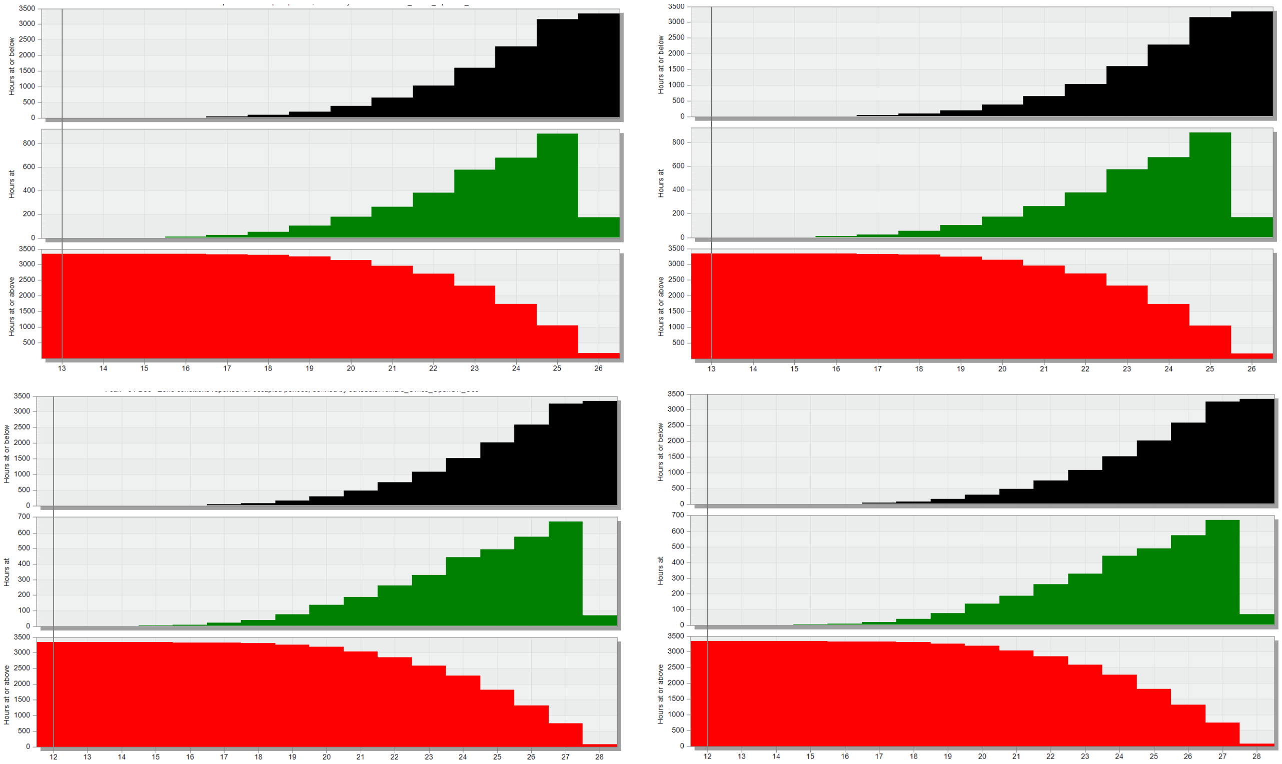
All variations have 92% or above comfort hours for both 26°C & 28°C settings, which is good.

Table 21 DB-EWF: Comfort Percentage for Comfort Setting of 26°C and 28°C in a Year

EWF with climate ceiling	**Variation 1**	**Existing**	**New**	**Variation 2**	
Hours at and above 27°C	0	0	741	741	hours
Discomfort % in a year	0	0	8	8	%
Comfort % in a year	**100**	**100**	**92**	**92**	%
Hours at and above 29°C	0	0	0	0	hours
Discomfort % in a year	0	0	0	0	%
Comfort % in a year	**100**	**100**	**100**	**100**	%

Seeing the temperature distribution, the system seems to cool and heat the air rather slowly while achieving the target comfort temperature most of the year. This results in less temperature difference between indoor and outdoor temperature, causing no temperature shock compared to the existing and is potentially more energy-friendly.

Table 22 DB-EWF: Temperature distribution



From top-left clockwise: Variation 1, Existing, New, and Variation 2.

7.4 ENERGY NEUTRALITY & BENCHMARKING

Regrettably, the new EWF design fails to achieve energy neutrality, with energy production by BAPV on Power Roof only roughly achieve 20-70% of the energy consumption per m^2.

Table 23 Energy-neutrality assessment

Annual energy consumption per m^2	Existing	New	
Heating	2	10	kWh/m2
Cooling	27	67	kWh/m2
Ventilation	29	25	kWh/m2
Lighting	81	81	kWh/m2
Computers etc.	56	56	kWh/m2
Total energy consumption per m^2	196	239	kWh/m2
Annual energy production per m^2			
BAPV on Power Roof *(optimistic)*	0	172	kWh/m2
% to energy consumption	0	72	%
BAPV on Power Roof *(pessimistic)*	0	56	kWh/m2
% to energy consumption	0	24	%

Moreover, compared to the average energy consumption of office buildings in Tokyo as elaborated in 2.2.3 to be 1,500 MJ/m2/year of primary energy, neither the Existing nor the New design falls above the average, although the latter performs 4% better than the first.

Table 24 Annual energy consumption per m2 (primary energy) assessment

Annual energy consumption per m^2 (primary energy)	Existing	New	%	
Heating	4	10	**155**	MJ/m2
Cooling	67	33	**-51**	MJ/m2
Ventilation	283	244	**-14**	MJ/m2
Lighting	794	794	**0**	MJ/m2
Computers etc.	551	551	**0**	MJ/m2
Total energy consumption per m^2 (primary energy)	1699	1631	**-4**	MJ/m2

Note:

Primary energy coefficients: Electricity: 9.76 MJ/kWh, City gas: 45 MJ/m3

COP used are as follows:

Existing heating (VRF) 4, existing cooling (VRF) 4

New heating (GSHP) 9, new cooling (direct groundsource) 20

7.5 DISCUSSIONS OF RESULTS

7.5.1 Existing

In terms of energy, the existing system is assumed to have heating, cooling, and ventilation energy consumption of 2, 27, and 29 kWh/m^2 respectively, whereas in terms of comfort, the comfort hour is 100% for both 26°C & 28°C settings. Considering the total primary energy is around 1700 MJ/m^2, it is 12% above the average in Tokyo, which is unexpected since the building is relatively new and designed with sustainability in mind.

7.5.2 EWF Design

In terms of energy, the new EWF design is assumed to have heating, cooling, and ventilation energy consumption of 10, 67 and 25 kWh/m^2 respectively, whereas in terms of comfort, the comfort hours are 92% and 100% for 26°C & 28°C settings respectively. Considering the total primary energy is around 1600 MJ/m^2, it is 6% above the average in Tokyo.

7.5.3 Comparison of Existing system with EWF design

When comparing the Existing building in its Existing variation, to the EWF Design in its New variation as elaborated in the previous sub-chapters, the new design of EWF, unfortunately, increases almost 5 times the heating energy and about 1.5 times of the ventilation energy but decreases the ventilation energy by almost 15%, thus still uses about ¾ more energy than the existing system, as summarized in 'Old & New difference' below.

When comparing the two within the same variation to have a fair comparison, the difference of EWF Design compared to the existing one is summarized below. The average of the difference from all the different variations is summarized in 'Average difference': EWF design uses ¼ less ventilation energy, although more heating and cooling energy compared to the existing system.

Table 25 Existing & EWF Design Comparison: Energy

	Variation 1			**Existing**			**New**			**Variation 2**			
Comparison	Existing	EWF	**%**	Existing	EWF	**%**	Existing	EWF	**%**	Existing	EWF	**%**	
Heating	3	15	**371**	2	14	**720**	3	10	**197**	2	10	**495**	kWh/m2
Cooling	29	77	**164**	27	72	**161**	22	67	**205**	21	63	**201**	kWh/m2
Ventilation	50	31	**-38**	29	29	**0**	48	25	**-47**	27	23	**-15**	kWh/m2
Total	82	123	**50**	58	114	**96**	73	101	**39**	50	96	**94**	kWh/m2

Average difference %	
Heating	**446**
Cooling	**183**
Ventilation	**-25**
Total	**70**

Old & New difference %	
Heating	**475**
Cooling	**143**
Ventilation	**-14**
Total	**74**

7.6 CONCLUSION

It is indisputable that EWF, as a natural ventilation system, contributed to a reduction in ventilation energy compared to the existing system in the case study, without compromising thermal comfort. On the other hand, heating and cooling energy increase in the EWF Design with underfloor heating as space heating and climate ceiling as space cooling. This seems due to the non-conventional (already energy-efficient) existing system that uses VRF on one hand, and could be due to the hot and humid temperature of Tokyo where only radiative cooling through climate ceiling might not be effective in quickly reducing the temperature while dehumidifying the air on the other end, hence the higher energy.

Another important note is that the existing system already has Heat Recovery (HR) also included in the simulation in DB, whereas the EWF design does not (to be included as improvement in Chapter 9). This is believed to have caused major differences in energy consumption between the 2 systems and is considered as the limitation of properly simulating EWF with HR in DB.

In terms of comfort, EWF performs better than the existing system, with more than 92% of comfort hours in all scenarios.

In terms of primary energy consumption, EWF performs slightly better, owing to the thermal energy storage as the source of cold. However, with the current condition, achieving energy neutrality is physically impossible without first reducing the energy demand. The first step would be to improve the thermal performance of the building envelope. Energy production is a challenge with the space limitation in Tokyo. A smart solution would be to tackle this issue in an urban setting rather than in individual building, As many office building in Tokyo has restaurants, it would be ideal if the organic waste could be used as biomass to aid energy production sustainably.

8. Final Design

8.1 SECTIONS

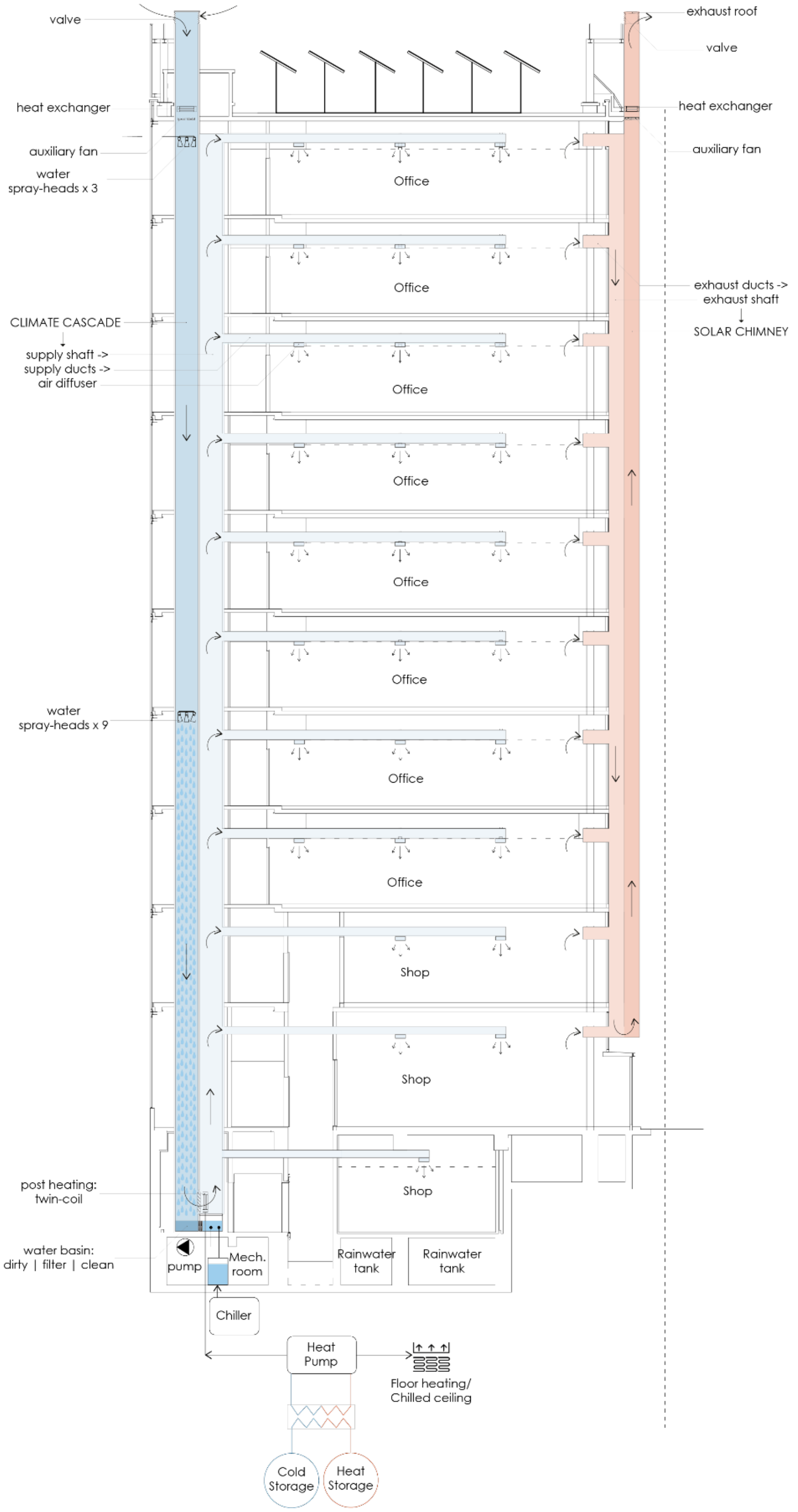


Figure 51 CC and SC in Section

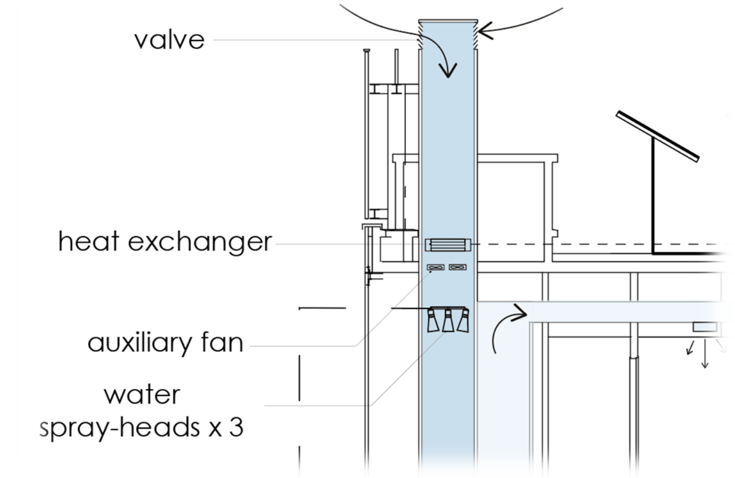


Figure 52 Top of CC

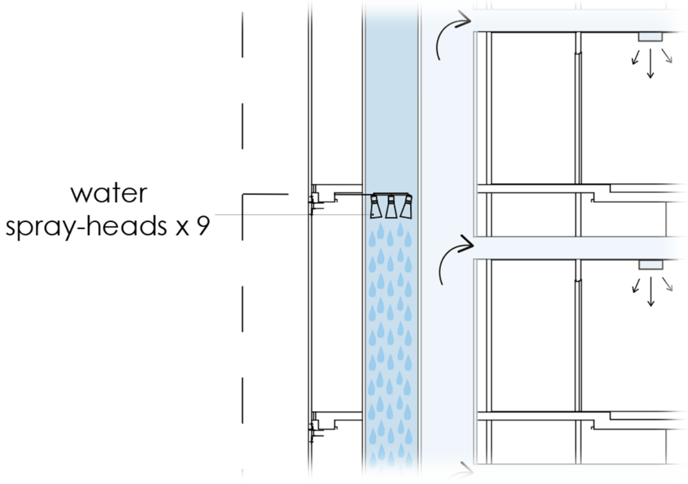


Figure 53 Middle of CC

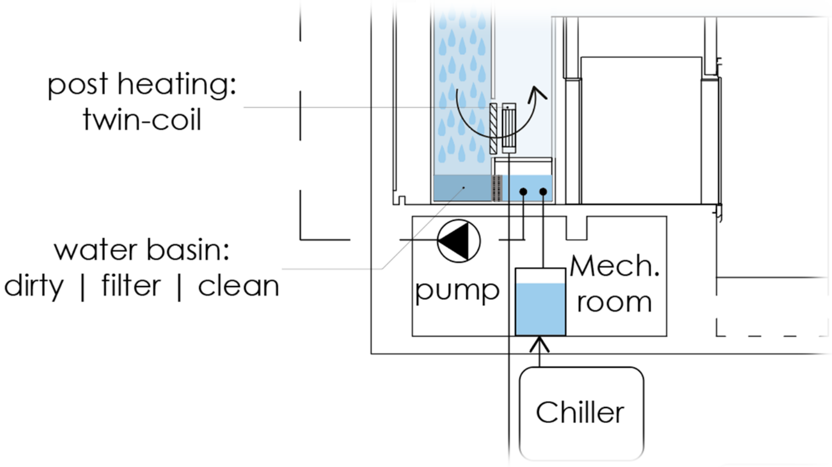


Figure 54 Bottom of CC

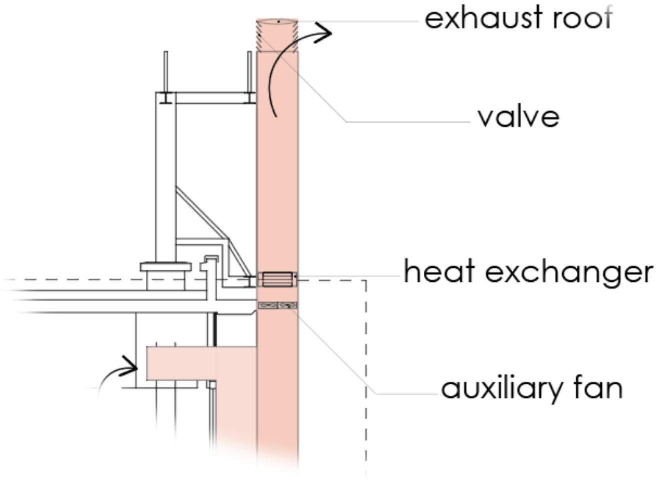


Figure 55 Top of SC

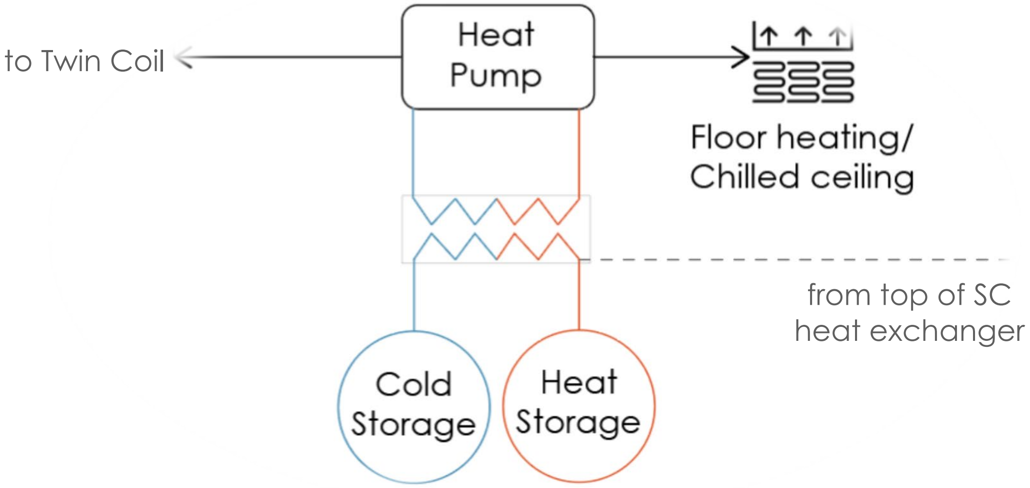


Figure 56 Schematic Diagram of ATES Connection

8.2 IMPRESSIONS

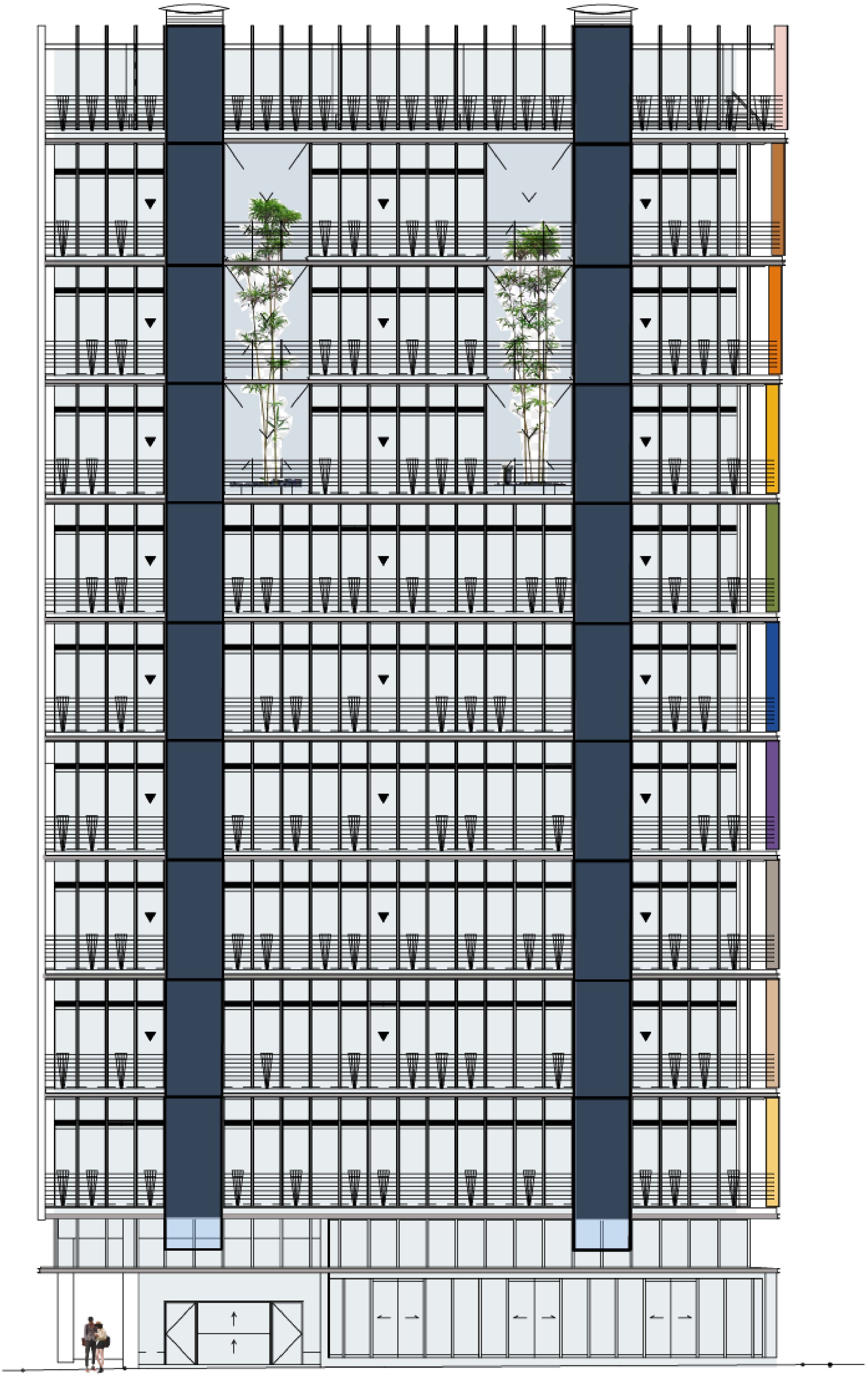


Figure 57 South Elevation impressions with SC

8.3 UNITIZED SC

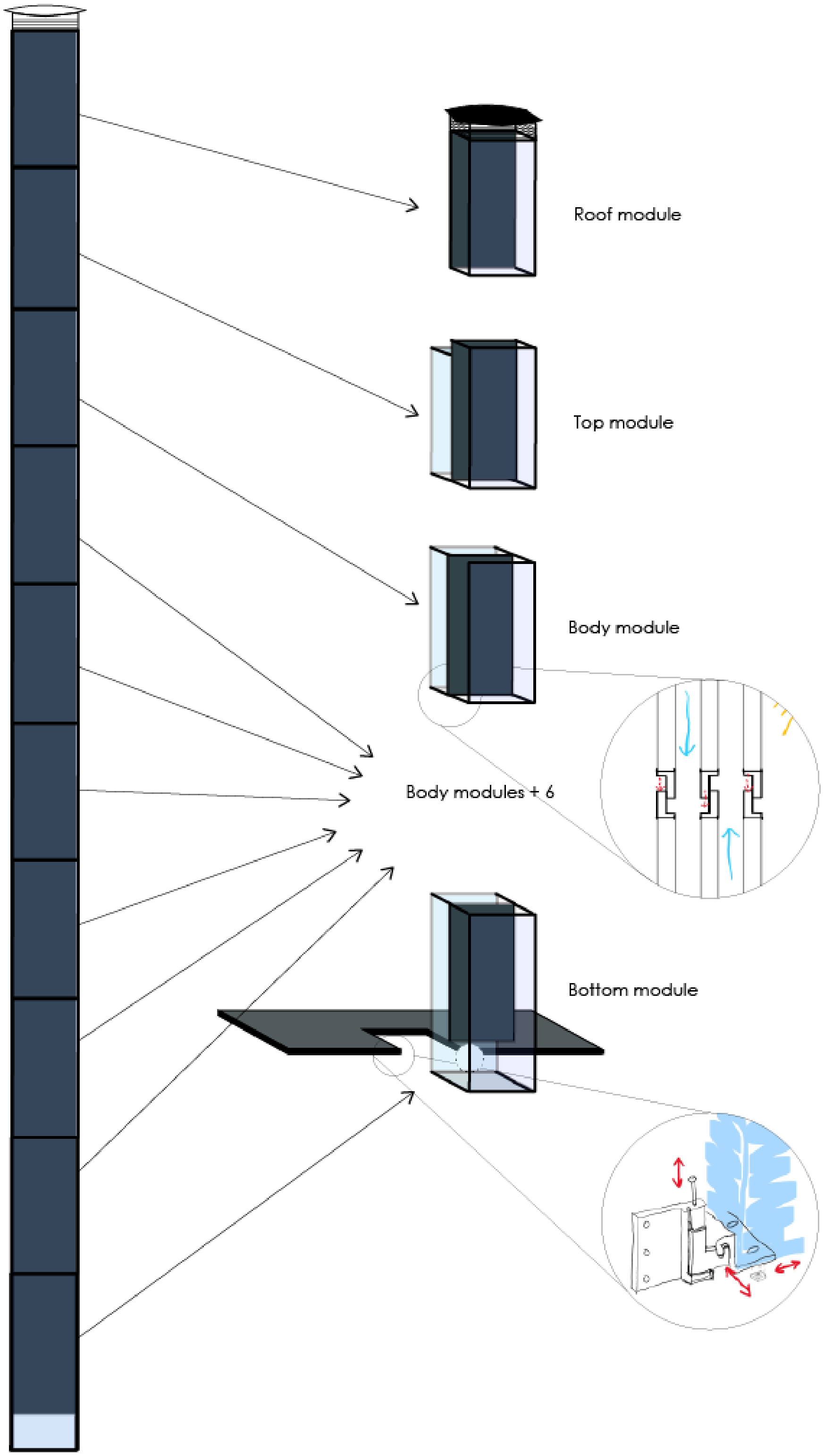


Figure 58 SC Prefab modules type

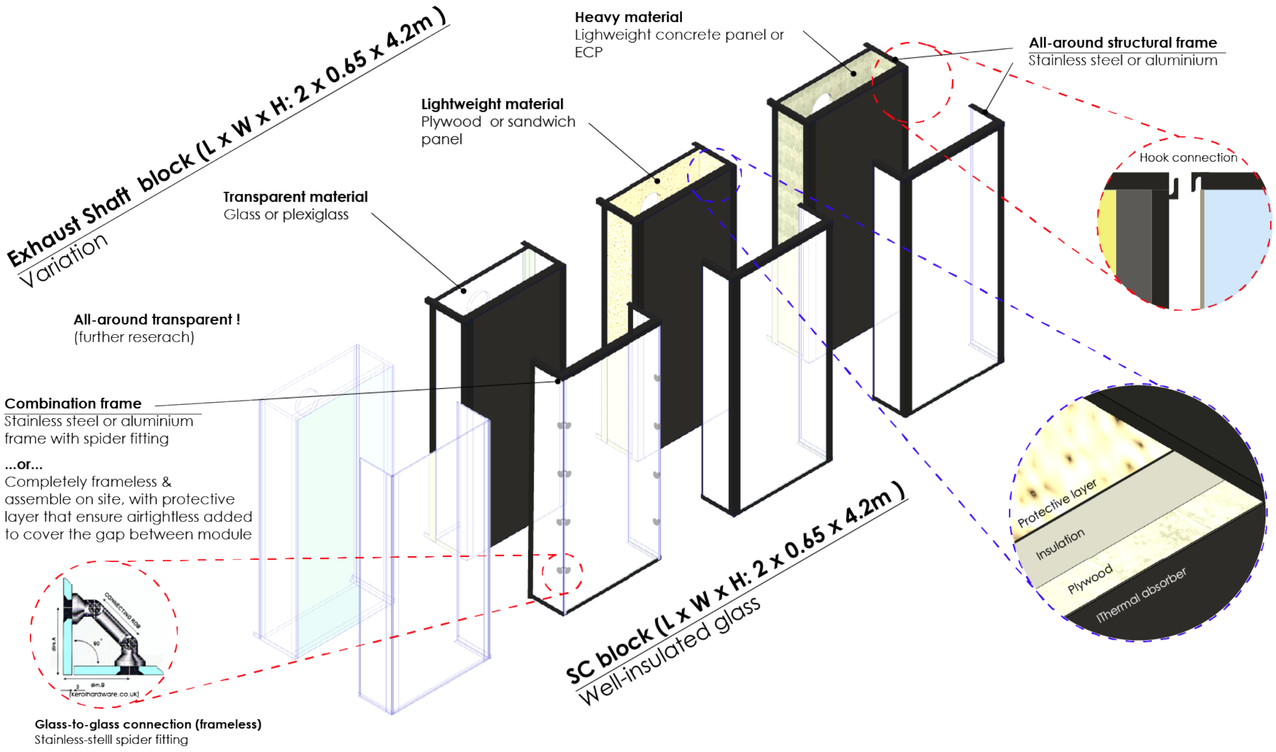


Figure 59 Material and Connection of Body Module

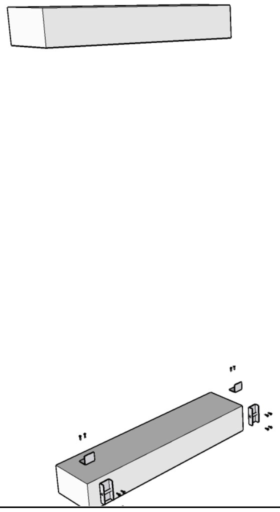
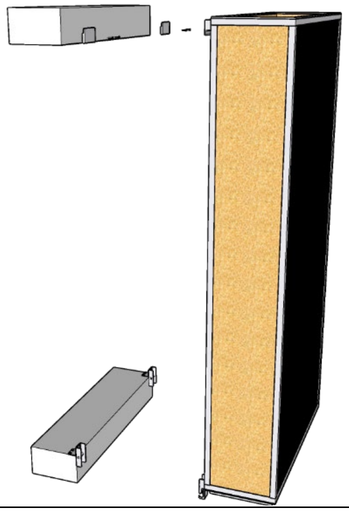
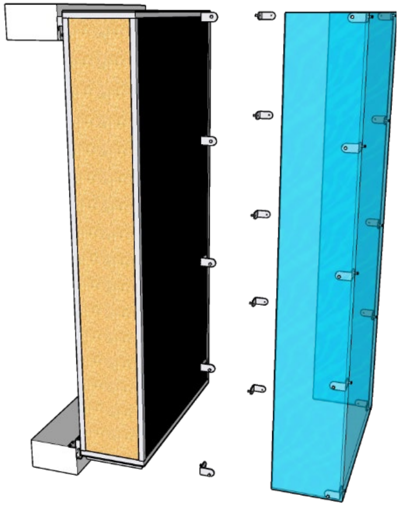
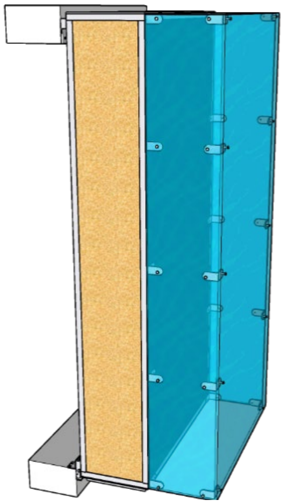
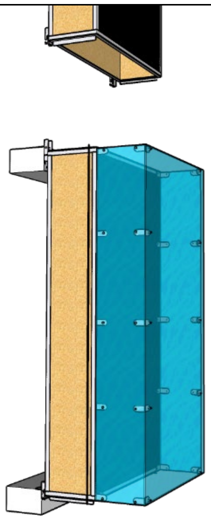
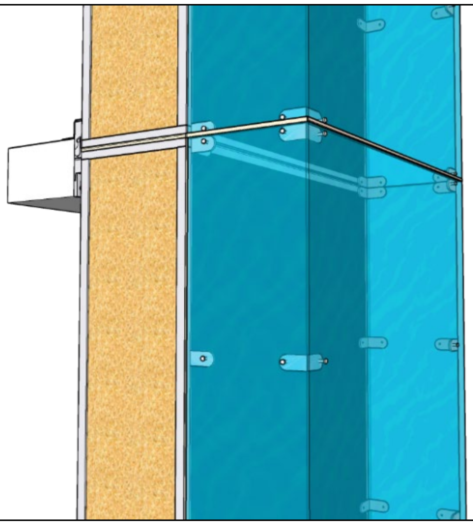
Initially, both the Exhaust Shaft block and the SC block would be designed as 1 unitized system. However, considering the distinct 2 different characteristics of the 2, one is opaque and the other transparent, as well as the many different possibilities of materials, separating them as 2 block modules, made more sense.

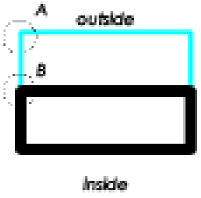
Next, the concept evolved to also allow for on-site construction, e.g. when using a glass-to-glass connection, inspired by the PV-Chimney project of MOR Team, TU Delft's Solar Decathlon Team Europe of 2019. This way, material for the structural frames could be saved, and the glass-to-glass connection provides more transparency.

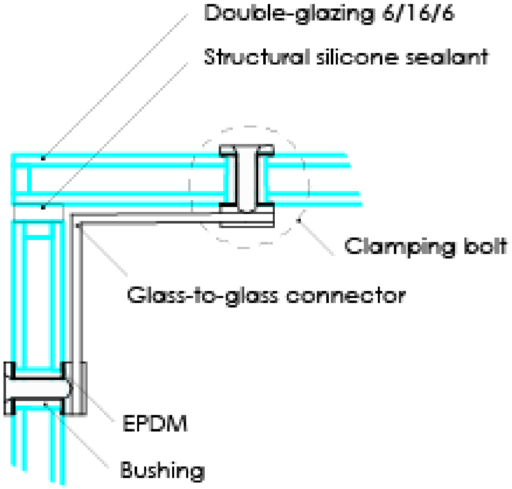
Finally, variations of material for the Exhaust Shaft block, in combination with options framed or non-framed SC Block can hopefully accommodate the various design needs.

The order of assembly of Exhaust shaft block: Sandwich panel (prefab) and SC Block: frameless with glass-to-glass connection (assembled on site) is visualized in Table 26. Note that improvement to the connections to the slab, as well as connection to the existing façade could be explored in a future study.

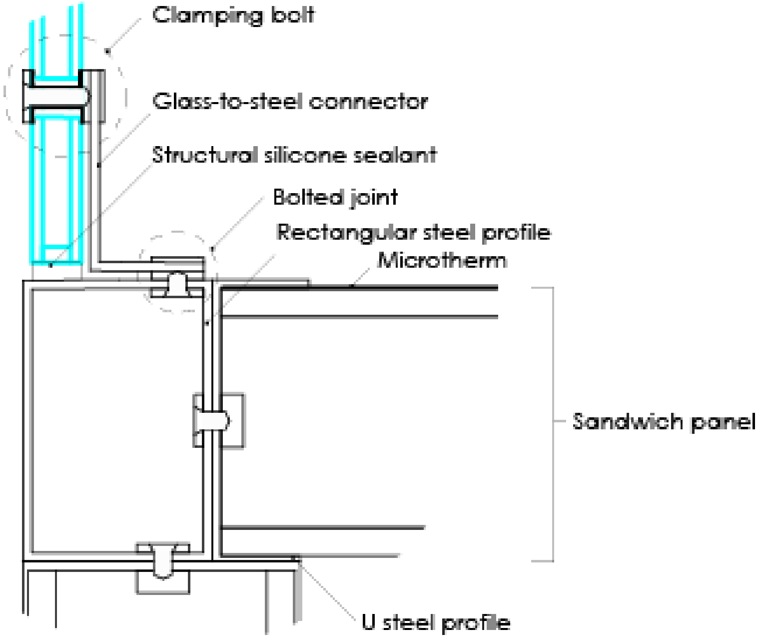
Table 26 SC Body Module: Order of Assembly

	
1: steel profiles to bottom slab	2: Hook Exhaust Shaft block to bottom slab, fix the module to steel profiles to top slab
	
3: assemble the frameless SC block	4: Connect frameless SC block to the Exhaust Shaft block
	
5: put the next block on top, repeat the process 2-4	6: add cover in-between blocks and modules to ensure airtightness


Top view



Detail A



Detail B

Figure 60 Body module Horizontal section details

9. Improvement & Recommendation

9.1 ENERGY NEUTRALITY

9.1.1 Reduce

1. *Better thermal resistance*

Although the building is relatively new, it is worth exploring the idea of improving the thermal resistance of the building envelope to possibly reduce energy consumption, as energy production from PV seems to be limited. This is beyond the scope of this thesis, thus will not be further detailed, but important to be mentioned here.

2. *Hybrid system*

There have been several studies that showed not only energy reduction but also better comfort when radiant cooling is combined with mixing ventilation (Hao et al., 2007; Kinoshita, 2016; Lipczynska et al., 2021). For this reason, the writer decided to see if combining EWF with chilled beam and underfloor heating can help reduce space heating & cooling energy consumption while maintaining thermal comfort, by doing the simulation with DB, the same way as described in 7.1.

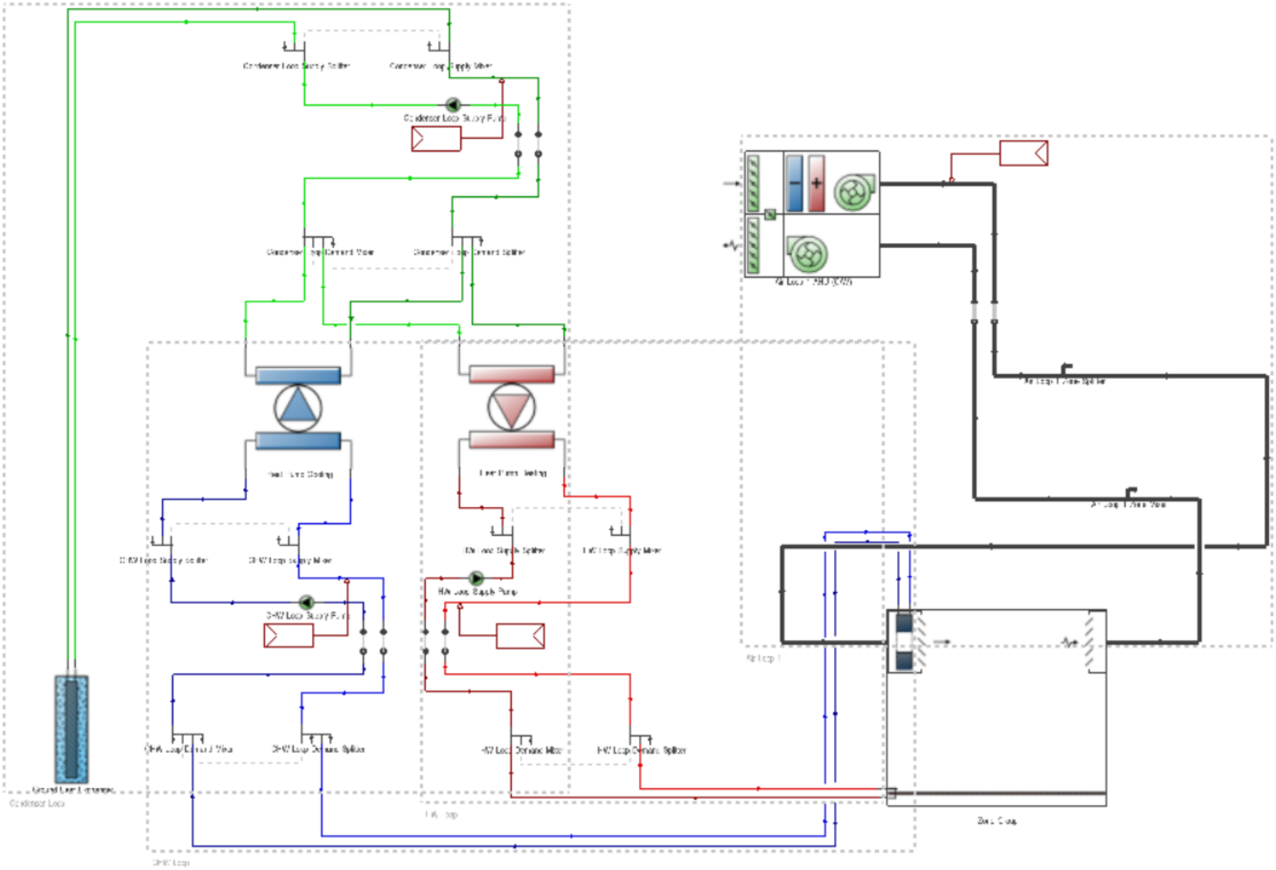


Figure 61 EWF + chilled beams, with underfloor heating schematic plan

Table 27 DB-EWF with chilled beams: Energy Consumption

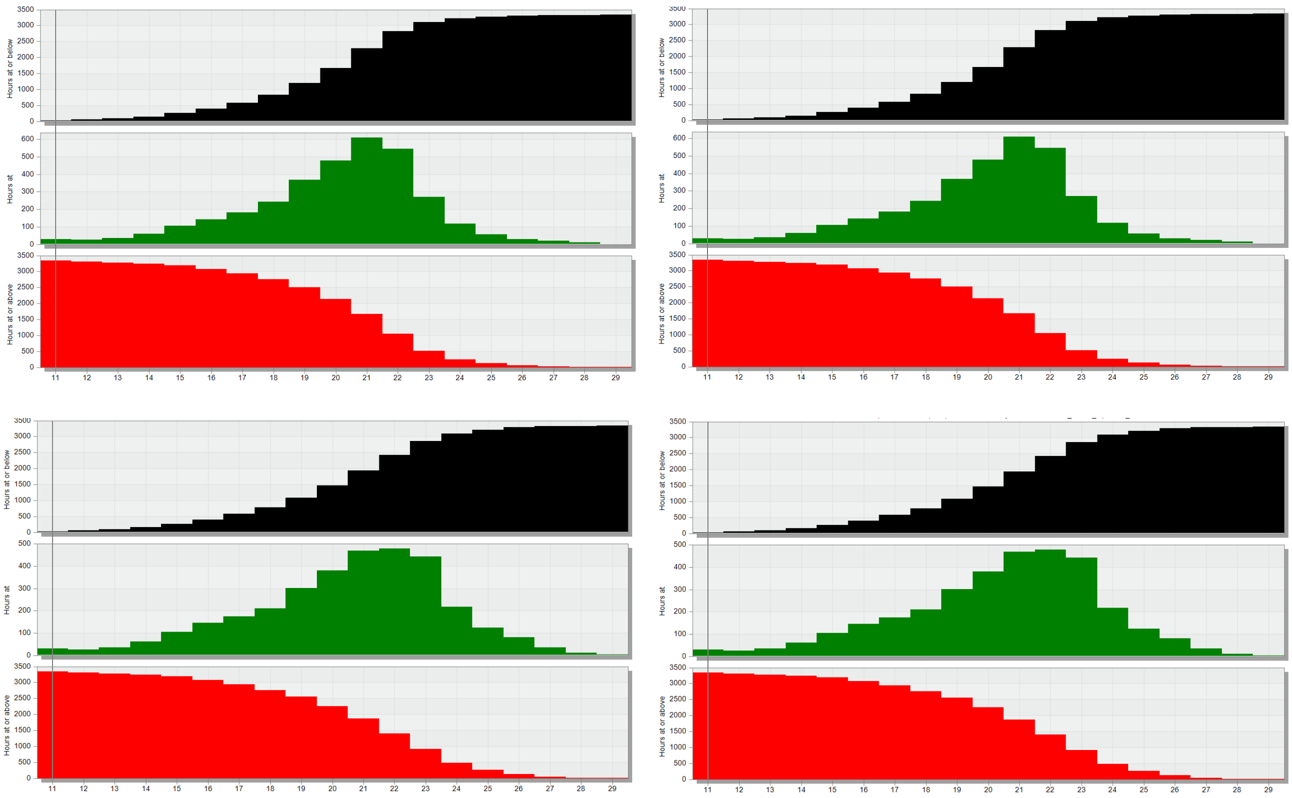
EWF with chilled beams	**Variation 1**	**Existing**	**New**	**Variation 2**	
Heating	4	4	4	4	kWh/m2
Cooling	81	81	73	73	kWh/m2
Ventilation (*from Excel*)*	31	29	25	23	kWh/m2
Total	116	114	102	100	kWh/m2

* includes system fans, system pumps, water cooling energy, and air heating energy

Table 28 DB-EWF with chilled beams: Comfort Percentage for Comfort Setting of 26°C & 28°C a Year

EWF with chilled beams	**Variation 1**	**Existing**	**New**	**Variation 2**	
Hours at and above 27°C	33	33	50	50	hours
Discomfort % in a year	0	0	1	1	%
Comfort % in a year	**100**	**100**	**99**	**99**	**%**
Hours at and above 29°C	0	3	3	3	hours
Discomfort % in a year	0	0	0	0	%
Comfort % in a year	**100**	**100**	**100**	**100**	**%**

Table 29 DB-EWF with chilled beams: Temperature distribution



From top-left clockwise: Variation 1, Existing, New, and Variation 2.

Table 30 EWF & EWF with Chilled Beams Comparison: Energy

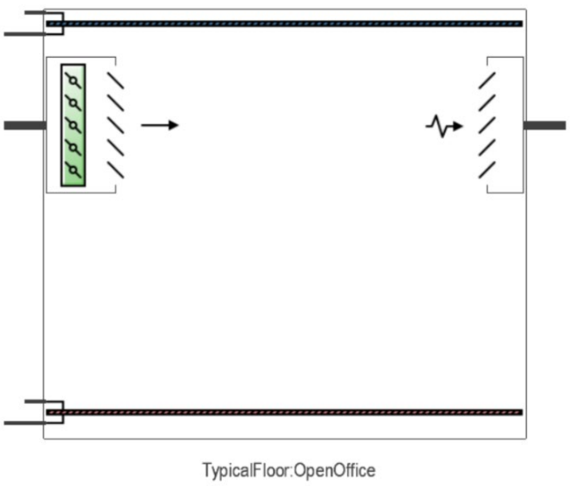
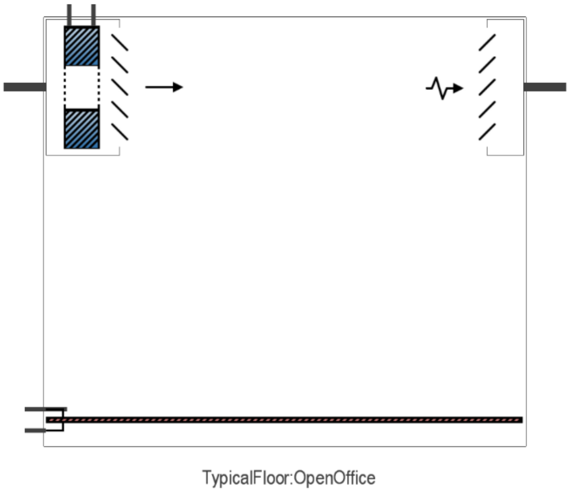
Average difference %	
Heating	**-69**
Cooling	**11**
Ventilation	**0**
Total	**-1**

It turns out that, in terms of energy consumption, the difference is marginal when comparing EWF with EWF & chilled beams. However, thermal comfort is improved both in comfort hours (all cases show 99% or more, instead of 92%) and temperature distribution (a pyramid-like distribution with most hours at 21-22°C, instead of concentrated close to the summer comfort temperature, 25 or 27°C).

From the well-balanced temperature distribution among ‘hours at and below’ in black, ‘hours at’ in green, and ‘hours at and above’ in red, as shown in Table 29, it can be derived that the temperature difference between indoor and outdoor is minimal and on the cool temperature of 22°C, a very-welcomed breeze especially during the hot and humid summers in Tokyo.

Different from the original EWF design with climate ceiling as shown below, the ventilation air that passes the chilled beams seems to help with a more effective space cooling.

Table 31 EWF & EWF with Chilled Beams Comparison: Air distribution schematic

EWF with the chilled ceiling and underfloor heating	EWF with chilled beams and underfloor heating
	

9.1.2 Reuse

This question that keeps coming back throughout this thesis: what to do with the recovered heat from the top of SC? In order to have an overview of the system and the related temperatures in summer and winter, it is important to decide whether to use air or water as the heat transport medium between CC and SC.

Air-medium

As shown by the exclamation mark Figure 62, using air-to-air heat recovery (hereinafter referred to as “A-HR”) in winter will require a smart system that can detect, and maybe filter, the recovered heat when it is more than needed, which in this case 18°C is more than the needed 16.5°C.

On the other hand in summer, the recovered ‘cold’ can be sent to CC to precool the incoming air from 31°C to 27°C as shown in Figure 63, a small win that still counts.

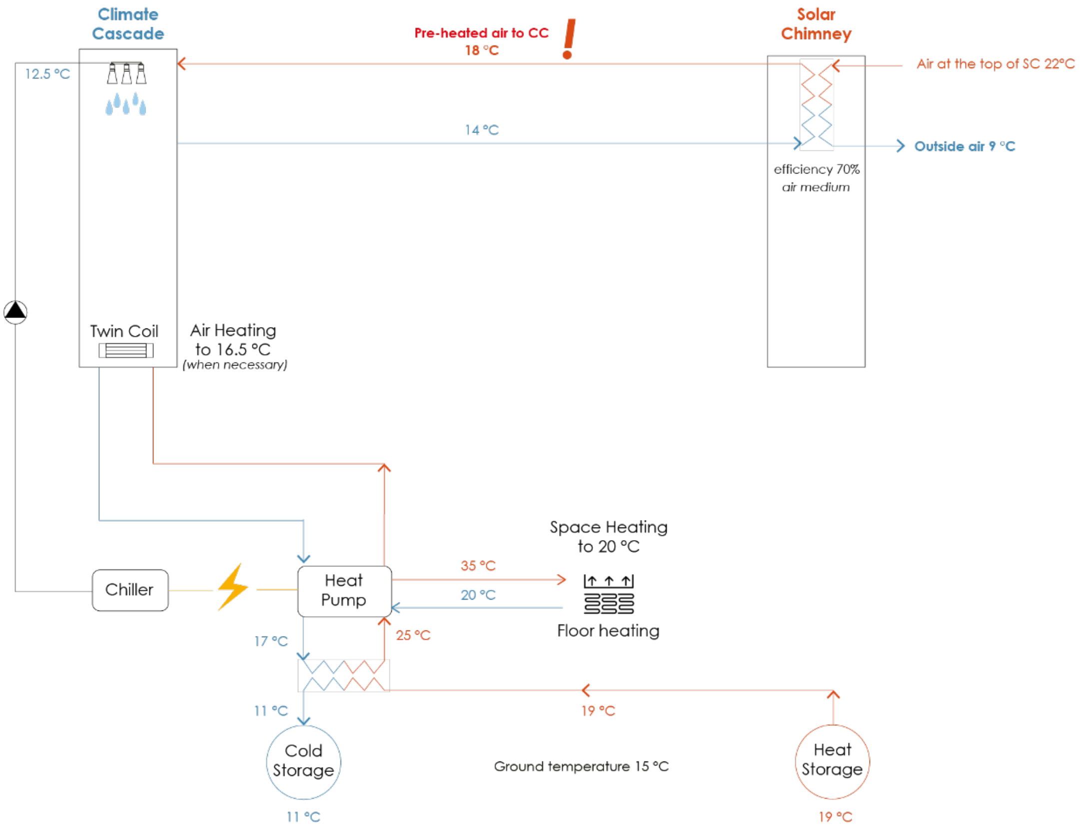


Figure 62 Winter system schematic: Air-medium heat recovery

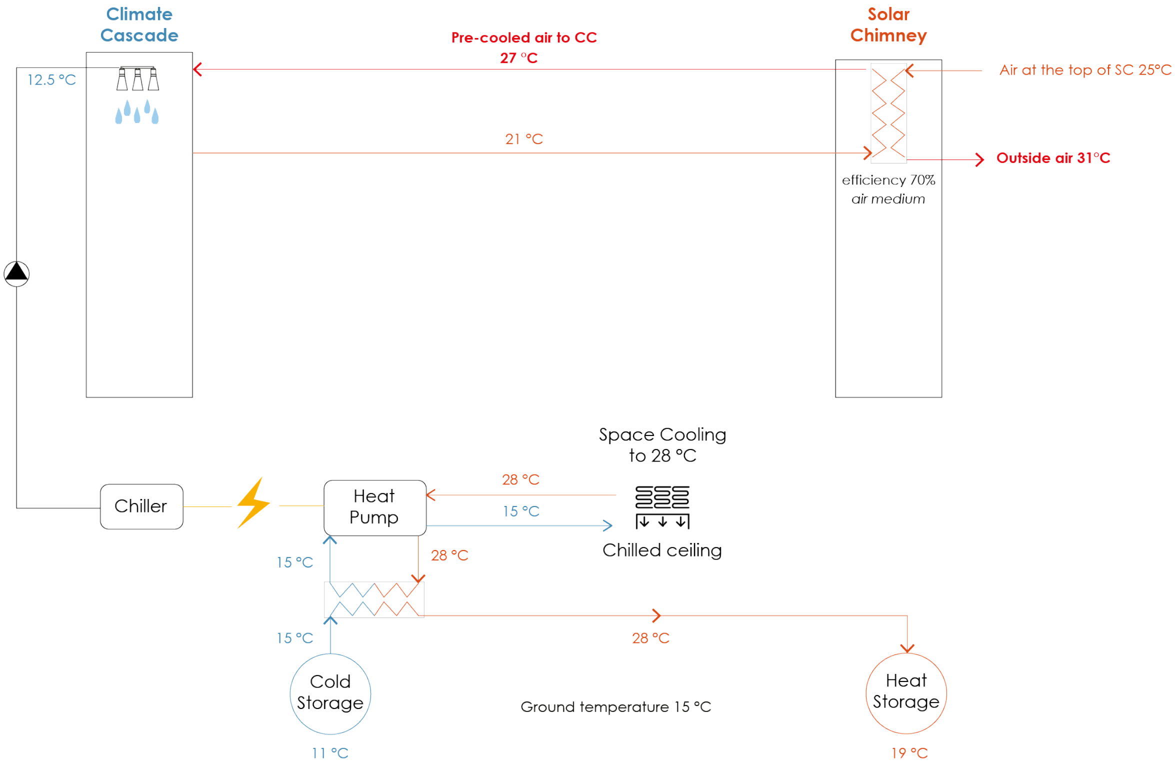


Figure 63 Summer system schematic: Air-medium heat recovery

Water-medium

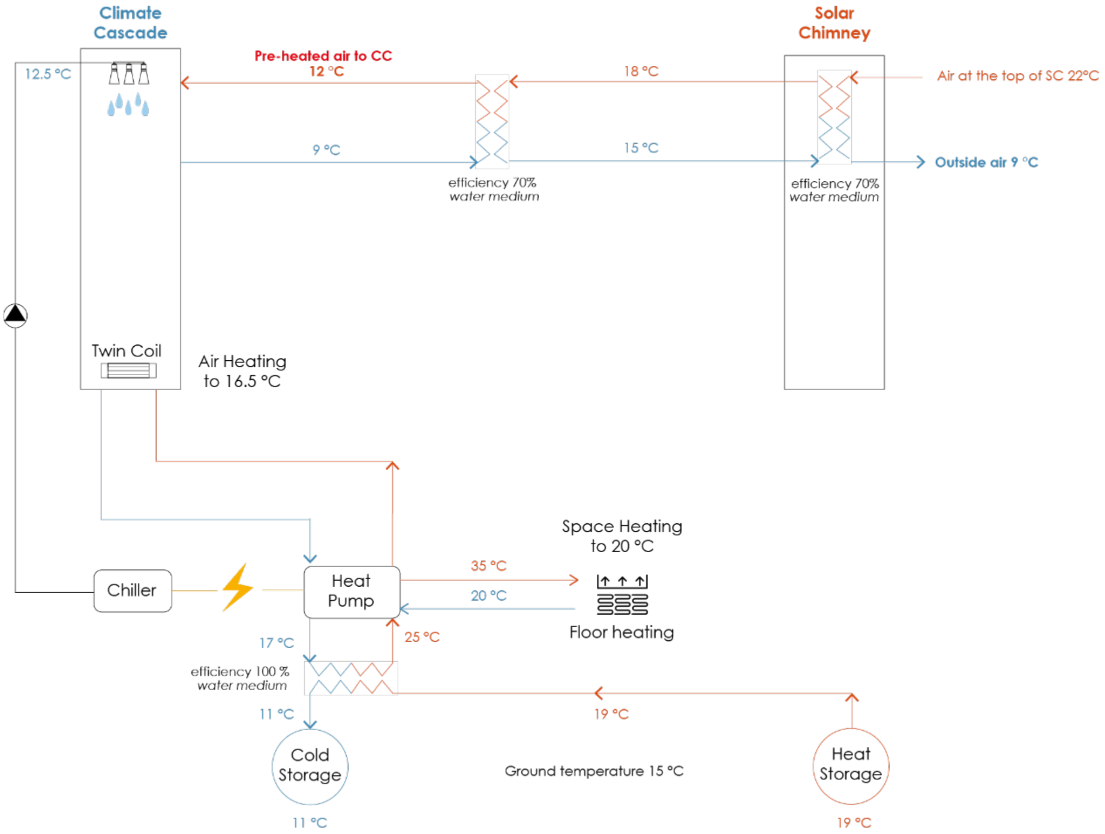


Figure 64 Winter system schematic: Water-medium heat recovery

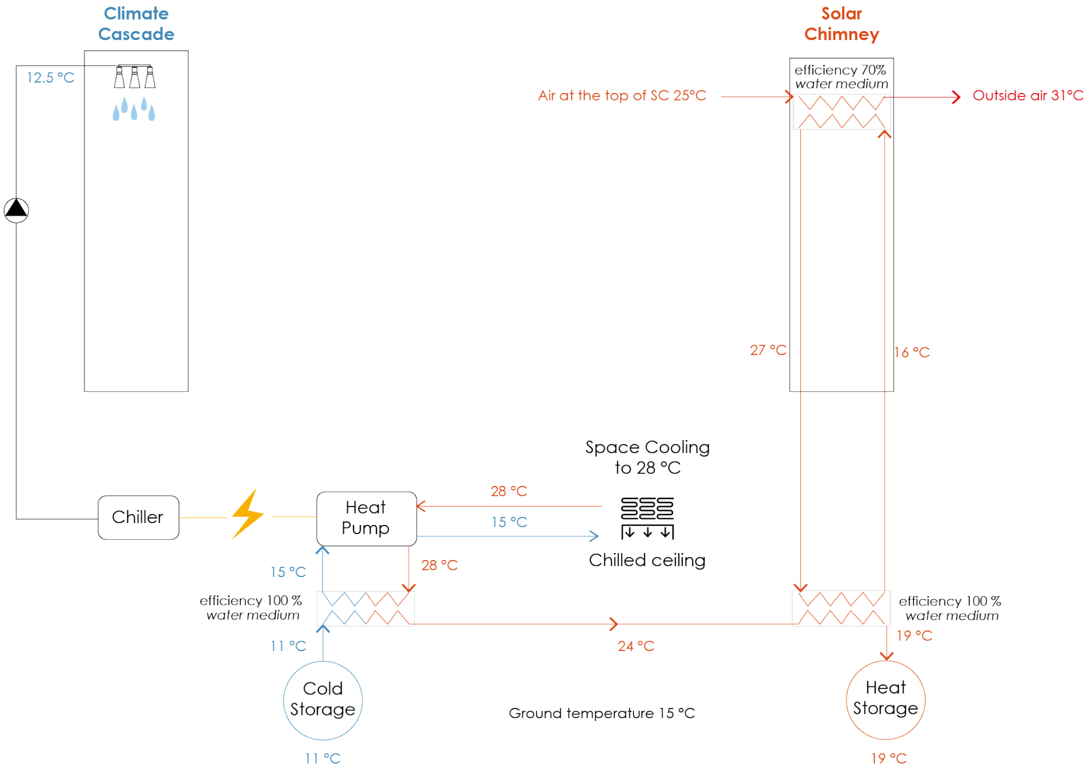


Figure 65 Summer system schematic: Water-medium heat recovery

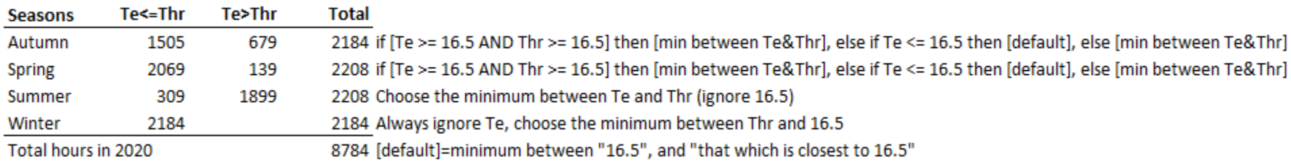
For water medium heat recovery (hereinafter referred to as "W-HR") in winter, unfortunately, 2 heat exchangers will be required. As shown in Figure 64, the incoming air to CC is pre-heated from 9°C to 12°C, which later needs to be heated by the twin-coil to reach 16.5°C.

In summer, there is no 'cold' recovered from the top of SC, thus it can be sent to the heat source of the ATES system, as shown in Figure 65.

Validation

In order to validate how much heating and cooling energy (of ventilation air in CC) can be saved by reusing the heat (or cold) from SC using air-medium heat recovery, an additional algorithm is added to the CC Excel, as follows.

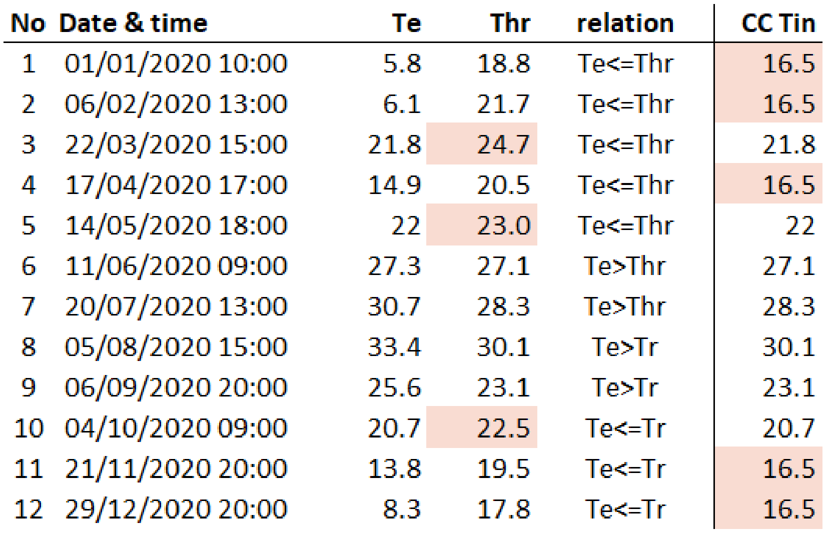
Table 32 Reuse (HR): Algorithm



Seasons	Te<=Thr	Te>Thr	Total	
Autumn	1505	679	2184	if [Te >= 16.5 AND Thr >= 16.5] then [min between Te&Thr], else if Te <= 16.5 then [default], else [min between Te&Thr]
Spring	2069	139	2208	if [Te >= 16.5 AND Thr >= 16.5] then [min between Te&Thr], else if Te <= 16.5 then [default], else [min between Te&Thr]
Summer	309	1899	2208	Choose the minimum between Te and Thr (ignore 16.5)
Winter	2184		2184	Always ignore Te, choose the minimum between Thr and 16.5
Total hours in 2020			8784	[default]=minimum between "16.5", and "that which is closest to 16.5"

T_e refers to outdoor temperature and T_{hr} refers to recovered temperature from the top of SC.

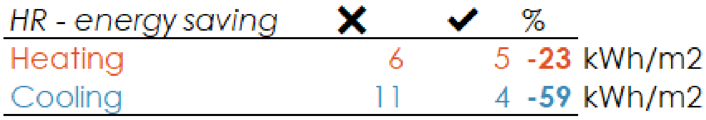
Table 33 Reuse (HR): Examples of results



No	Date & time	Te	Thr	relation	CC Tin
1	01/01/2020 10:00	5.8	18.8	Te<=Thr	16.5
2	06/02/2020 13:00	6.1	21.7	Te<=Thr	16.5
3	22/03/2020 15:00	21.8	24.7	Te<=Thr	21.8
4	17/04/2020 17:00	14.9	20.5	Te<=Thr	16.5
5	14/05/2020 18:00	22	23.0	Te<=Thr	22
6	11/06/2020 09:00	27.3	27.1	Te>Thr	27.1
7	20/07/2020 13:00	30.7	28.3	Te>Thr	28.3
8	05/08/2020 15:00	33.4	30.1	Te>Tr	30.1
9	06/09/2020 20:00	25.6	23.1	Te>Tr	23.1
10	04/10/2020 09:00	20.7	22.5	Te<=Tr	20.7
11	21/11/2020 20:00	13.8	19.5	Te<=Tr	16.5
12	29/12/2020 20:00	8.3	17.8	Te<=Tr	16.5

In some cases, there are still some waste heat, as shown in red, above. Would be nice if there could be a way to store this somehow, maybe in water, to be used for other things, e.g. domestic hot water.

Table 34 Reuse (HR): Heating & Cooling (of ventilation air) energy saving



HR - energy saving	✗	✓	%	
Heating	6	5	**-23**	kWh/m2
Cooling	11	4	**-59**	kWh/m2

If such a smart system as elaborated by the algorithm exist, an immense 60% of cooling energy and 20% of heating energy (of ventilation air) can be saved! Application of heat recovery should be made mandatory, as it is a big win after all.

Other consideration

Although A-HR is indeed more efficient owing to the fact that only 1 device is required, there are some disadvantages: in order to limit the pressure loss, A-HR works with low air velocities and therefore are bulky devices. Moreover, it is also more difficult to control (adjust) the flow in comparison with W-HR. On the other hand, W-HR, while requiring 2 devices, it requires less space, is easier to control, can be easily connected to the ATES system, and there have been more devices with better efficiency (around 90%) and very low-pressure loss, e.g. microchannel.

For application in Tokyo with limited space, it is worth exploring the application of W-HR, preferably the one with the highest efficiency, something that Japan is good at inventing.

9.1.3 Produce

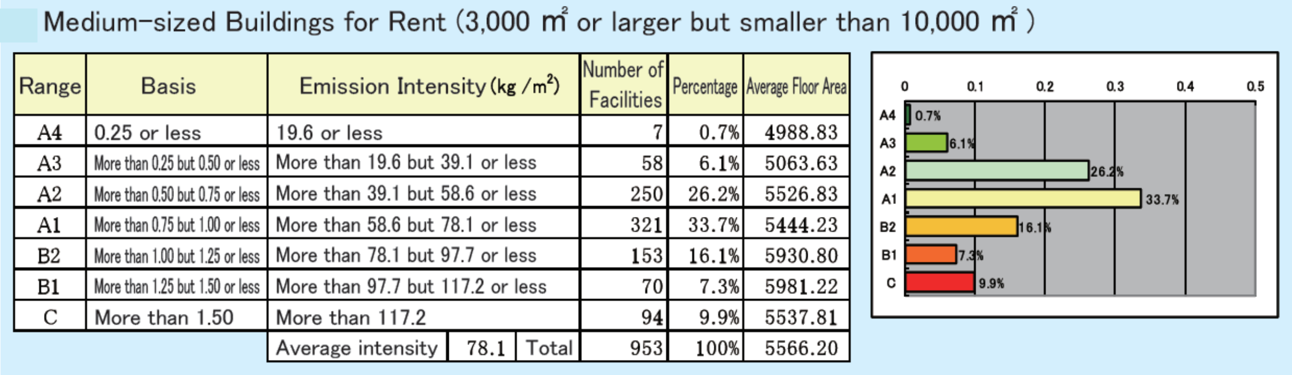
Due to the roof's space limitation, it is imperative to explore the feasibility of integrating BIPV on the façade. Especially important to also simulate the effect of shadings from the surrounding buildings.

9.2 RELEVANCE

9.2.1 Carbon Reduction Reporting Program

As discussed in 2.2.6, NK Building falls under the category of medium-size buildings that are mandated to submit Carbon Report if the annual energy consumption in crude-oil-equivalent is 3,000kL or more, which is the case for NK building. The carbon emission of the existing building is calculated as 95.4 kg-CO2/m^2, following the same conversion rate of 0.489 kg-CO2/kWh as the newest published benchmark from 2012 shown below, which means it falls under the B2 range, below the average of A1.

Table 35 Carbon Emission (kg-CO2/m^2) Benchmark for Medium-sized Office Buildings (TMG, 2012)



Medium-sized Buildings for Rent (3,000 m^2 or larger but smaller than 10,000 m^2)

Range	Basis	Emission Intensity (kg /m^2)	Number of Facilities	Percentage	Average Floor Area
A4	0.25 or less	19.6 or less	7	0.7%	4988.83
A3	More than 0.25 but 0.50 or less	More than 19.6 but 39.1 or less	58	6.1%	5063.63
A2	More than 0.50 but 0.75 or less	More than 39.1 but 58.6 or less	250	26.2%	5526.83
A1	More than 0.75 but 1.00 or less	More than 58.6 but 78.1 or less	321	33.7%	5444.23
B2	More than 1.00 but 1.25 or less	More than 78.1 but 97.7 or less	153	16.1%	5930.80
B1	More than 1.25 but 1.50 or less	More than 97.7 but 117.2 or less	70	7.3%	5981.22
C	More than 1.50	More than 117.2	94	9.9%	5537.81
		Average intensity 78.1 Total	953	100%	5566.20

The production of energy from renewable sources can soon contribute to the reduction of carbon emission reported here, as there is a new guideline published recently in 2021 that defines the calculation rule. This newly revised program is aimed to launch in the next fiscal year alongside the publishing of the newer version of the benchmark.

This has steered the focus to not only reduce carbon emission but also to integrate renewable energy production. Although the new EWF design consumes more energy than the existing, smart renewable energy production planning can help NK building to rise above the average.

9.2.2 Applicability

Transferability is key to the growth of this EWF system in Tokyo. The pros and cons will be briefly discussed based on the opinion of the writer in comparison to the case study. The discussion is based on the premise that these buildings are EWF-applicable, as explained in 3.3.

To smaller office buildings

It will be very challenging to take away some space for the ducts and vertical shafts of EWF in smaller buildings, although the taller ones with more facades open to the sun could benefit as much (if not more) than the case study, thus worth exploring.

To Acropolis Tokyo

With more space available in the surrounding and open facades as can be seen in 4.2.2, the designer will have more freedom to explore the placement and the design of EWF, maybe with more than one CC or SC. Refer to the thesis of my 2 EWF colleagues for more ideas.

To bigger office buildings

EWF is applicable to bigger office buildings. Taller buildings might need to vertically separate the CC and SC due to the higher pressure, but the scale of EWF applied to the NK building can be used as a reference.

9.2.3 Marketability

Prefabrication of CC & SC

Targeting existing office buildings to use EWF to reduce their carbon consumption, it is pivotal to convince the client that EWF is simple and easy to integrate the system, with all costs known from the beginning. By making the CC and SC a prefabricated system can contribute to this while ensuring a shorter construction period. As explored a little bit in 8.3, it would boost the marketability if the SC can be marketed as a product with a plug & play approach.

Fully transparent SC

It is unfortunate to see that the little open facades available in the NK building has to be covered by the non-transparent SC shafts. Several studies explore transparent insulating material (Dowson et al., 2011; Kaushika & Sumathy, 2003) as well as transparent thermal absorbing material (Fokaides et al., 2015). Without compromising the performance, it is of interest to explore the use of transparent insulation and absorbent material to have a fully transparent SC – all the more appealing – which means better marketability.

10. Comparison between EWF in Tokyo and Amsterdam

As EWF was designed for the Western European climate, it would provide clarity and a different perspective of the performance of the system in a warmer and more humid climate i.e. in Tokyo when a direct comparison of the two is made. In this chapter, all left graphic represents Tokyo's and right graphic represents Amsterdam's unless otherwise stated.

3 types of comparison will be made: performance comparison will be conducted using CC Excel and SC Excel, followed by urban & social context will be made following observations by the writer. Finally, a study comparing the energy consumption of conventional HVAC systems with EWF in a case study in Rotterdam will be presented and compared with the result of this paper.

10.1 PERFORMANCE

The performance of a natural ventilation system of EWF is consistently depending on the natural forces of the earth i.e. the climate of the site. Which climate data affecting what has been elaborated in 6.1.1 for CC and 6.1.2 for SC in their respective climate analysis. Only the result of the climate analysis will be shown below for a side-by-side comparison.

10.1.1 Climate Cascade

1. *Energy*

a. To condition the supply air in CC

Unfortunately for Tokyo, not only the air is warmer but also wetter, resulting in more than double the energy required for CC. The warmest temperature taken into account in Tokyo is 33°C whereas in Amsterdam 28°C, and the groundwater temperature in Tokyo is considered to be 15°C, whereas in Amsterdam 13°C. In order to achieve thermal comfort, the temperature of air coming out of CC needs to be 16.5°C in Tokyo and 18°C in Amsterdam. Therefore, the CC in Tokyo needs additional cooling more than the ground temperature of 15°C to better cool the air with less water to 16.5°C in CC, hence the more energy required.

Table 36 TYO/AMS comparison: Energy in CC

Tokyo ≦16.5°C cooling: when T outside air ≧ 24°C

Scenario	Height [m]	Necessary Pressure [Pa]	No of spray-heads	Outgoing air temperature T33 [°C]	Achieved Pressure T24 [Pa]	Fan Energy [MWh]	Pump Energy [MWh]	Pump Energy [kWh/m2]	Heating Energy [MWh]	Heating Energy [kWh/m2]	Incoming water temperature	Cooling Energy [MWh]	Cooling Energy [kWh/m2]	Amount of water [ton]	Total Energy [kWh/m2]
1	**44**	100	**16**	16.4	307	0*	54	11	27	6	**13**	154	32	243,000	49
2	**44**	100	**10**	16.42	192	0*	34	7	33	7	**11**	199	42	152,000	56
3	**22**	100	**10**	16.42	96	0*	17	4	32	7	**11**	199	42	152,000	53
4	**22**	100	**12**	16.5	115	0*	20	4	28	6	**12**	177	37	182,000	47
5	**22**	100	**12**	16.87	115	0*	20	4	27	6	**12.5**	147	31	182,000	41
6	**22**	100	**9**	16.14	86	0*	15	3	36	8	**10**	226	48	137,000	59

* Natural draft by EWF saved 1.68 MWh of Fan energy

Tokyo: 51 kWh/m² in average -> 51

Amsterdam ≦18°C cooling: when T outside air ≧ 24°C

Scenario	Height [m]	Necessary Pressure [Pa]	No of spray-heads	Outgoing air temperature T28 [°C]	Achieved Pressure T24 [Pa]	Fan Energy [MWh]	Pump Energy [MWh]	Pump Energy [kWh/m2]	Heating Energy [MWh]	Heating Energy [kWh/m2]	Incoming water temperature T24 [°C]	Cooling Energy [MWh]	Cooling Energy [kWh/m2]	Amount of water [ton]	Total Energy [kWh/m2]
1	**44**	100	**4**	16.8	150	0*	18	4	85	18	**13**	0	0	82,000	**22**

* Natural draft by EWF saved 1.62 MWh of Fan energy

Amsterdam: 22 kWh/m²

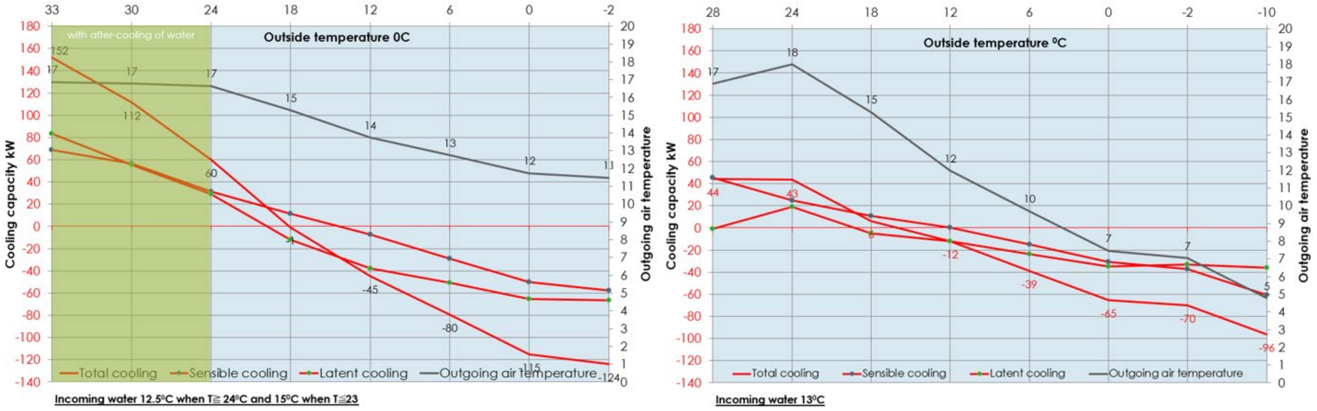


Figure 66 TYO/AMS comparison: Cooling capacity of CC

b. To achieve indoor comfort (space heating)

Fortunately for Tokyo, the energy required for additional space heating in the room is much lower, as can be seen below. The actual number is simulated in DB, but in simple comparison (by looking at the area under the red line and above the blue line), Tokyo need only about 1/3 of the space heating energy than in Amsterdam, as it is warmer thus have a warmer ground temperature. When the outside air is 18°C, the cooling of the water in CC will stop and use the ground temperature of 15°C to warm, whereas in Amsterdam the CC water temperature is 13°C to warm, thus less effective.

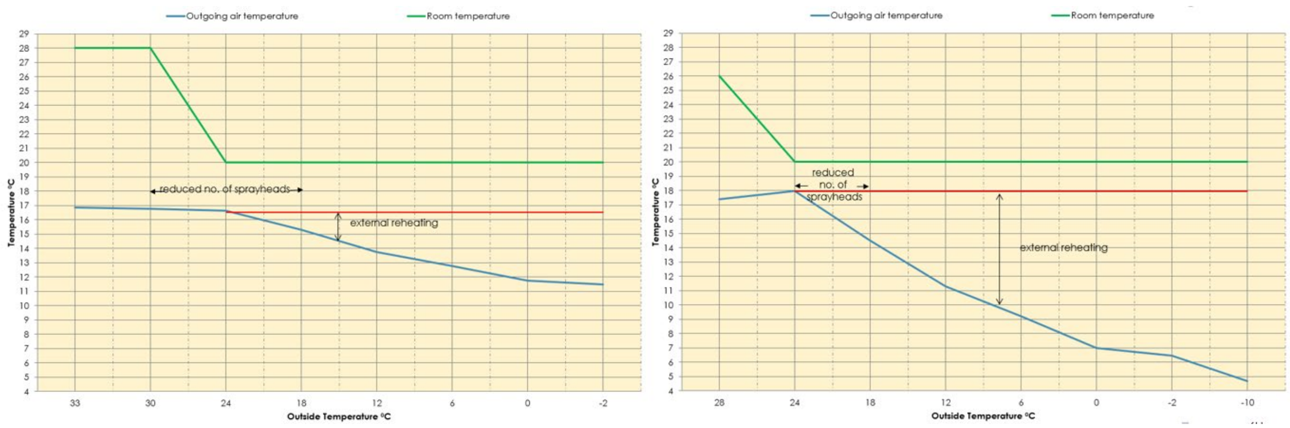


Figure 67 TYO/AMS comparison: Energy in Space Heating

2. Comfort

In addition to the comfort temperature setting as discussed in 6.2.1, moisture in the air especially during the summers in Tokyo can be unbearable. From the following comparisons of relative humidity (%) and absolute moisture (g/kg), CC managed to moderate humidity in the air in both Tokyo and Amsterdam to be within the comfortable range according to the respective country's standards.

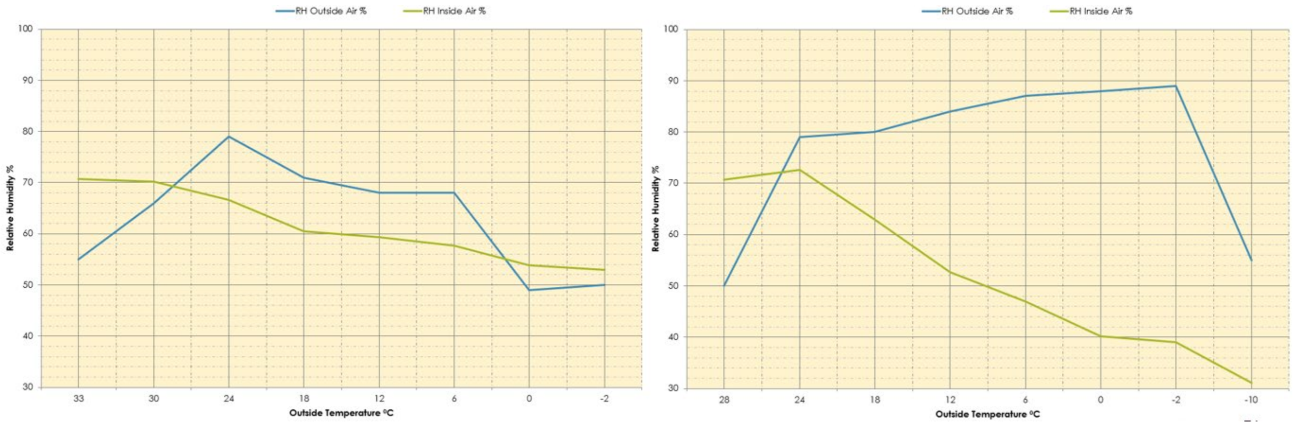


Figure 68 TYO/AMS comparison: Relative Humidity

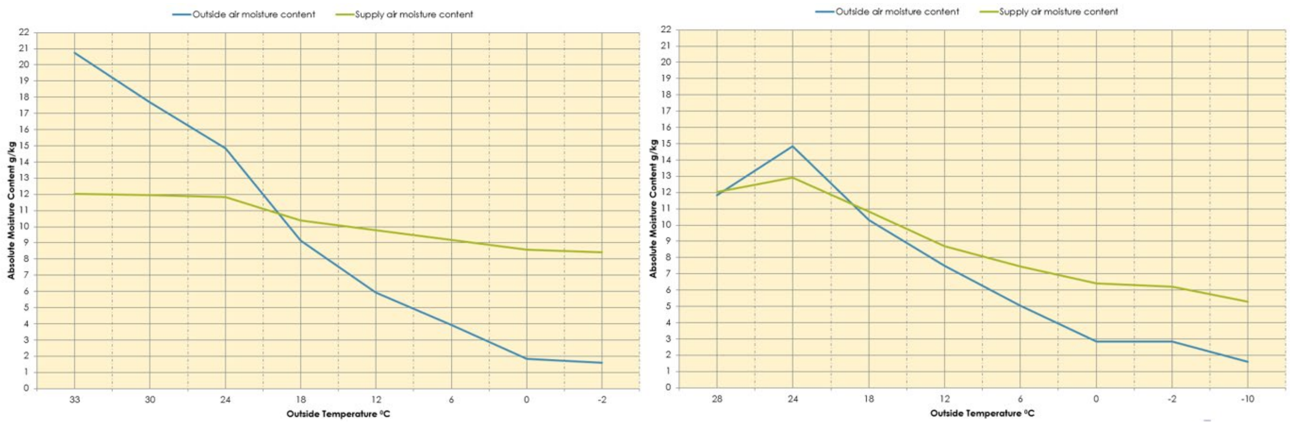


Figure 69 TYO/AMS comparison: Absolute Moisture

10.1.2 Solar Chimney

1. *Energy*

a. Electricity consumption

The energy used in SC comes from the auxiliary fan to aid the lack of thermal draft for the exhaust. Unfortunately for Tokyo, in order to compensate for the 25 Pa assumed pressure loss of the system, more fan energy (the area below the yellow line and above the green graph) than in Amsterdam. The blue graph is the outside air temperature. As can be seen in Table 37, Tokyo's fan energy is 0.1 kWh/m2, whereas Amsterdam's is negligible.

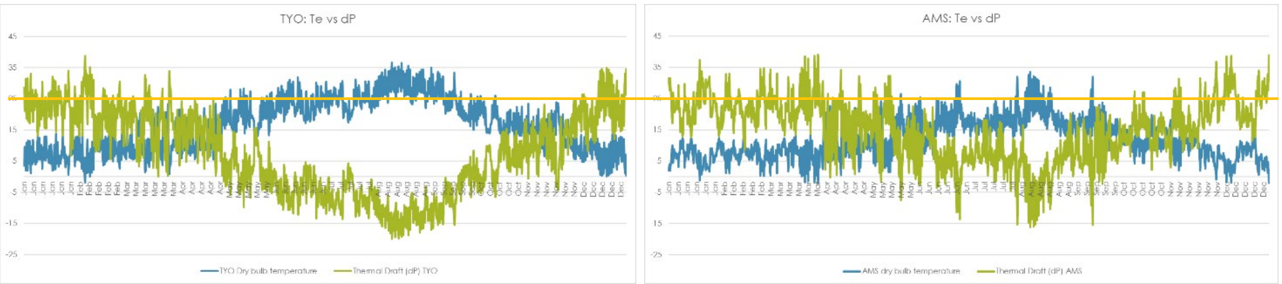


Figure 70 TYO/AMS comparison: Thermal draft of SC

b. Heat recovered

SC in Tokyo has 29% more heat recovered than SC in Amsterdam, with the annual amount of 225 MWh and 175 MWh respectively. This is because the temperature difference of air exhausted from the room (comfort temperature) and the air coming out at the top of the SC is bigger, thanks to the more solar radiation Tokyo has.

Table 37 TYO/AMS comparison: Energy of SC

Solar Chimney	TYO	AMS
Fan energy	0.1	0.0 kWh/m2
Heat recovered	48	37 kWh/m2

However, the shading factor from neighbouring buildings has not been considered in the calculation, thus the actual number in Tokyo might be lower.

It is also relevant to see the temperature at the top of SC in both cities, shown in grey below.

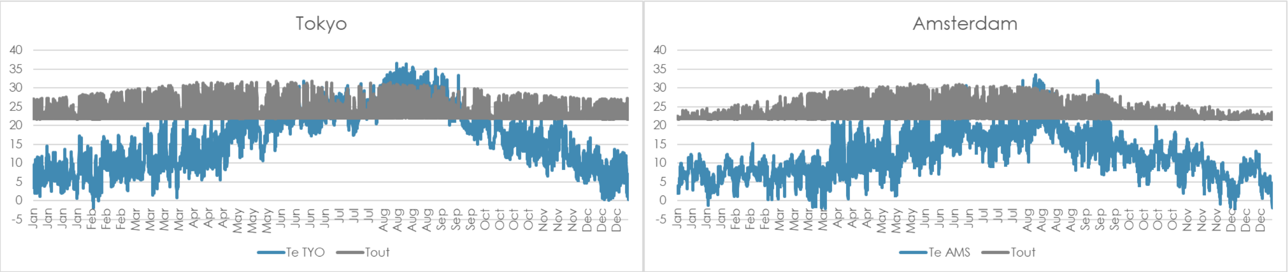


Figure 71 TYO/AMS comparison: Temperature at the top of SC

10.2 URBAN & SOCIAL

Tokyo, different from Amsterdam, has very limited space. The urban area is also densely built, meaning that more façade areas will be shaded by neighbouring buildings. For this reason, the success of EWF integration in office buildings in Tokyo would depend on the space efficiency of the system and the simplicity of the construction.

10.3 EWF & CONVENTIONAL HVAC ENERGY COMPARISON

10.3.1 Rotterdam

Sake Teeling has conducted a comparison study between the annual energy consumption of EWF and conventional HVAC system in a case-study building in Rotterdam (MFO-2 Building). The schematic diagram of each system is shown below.

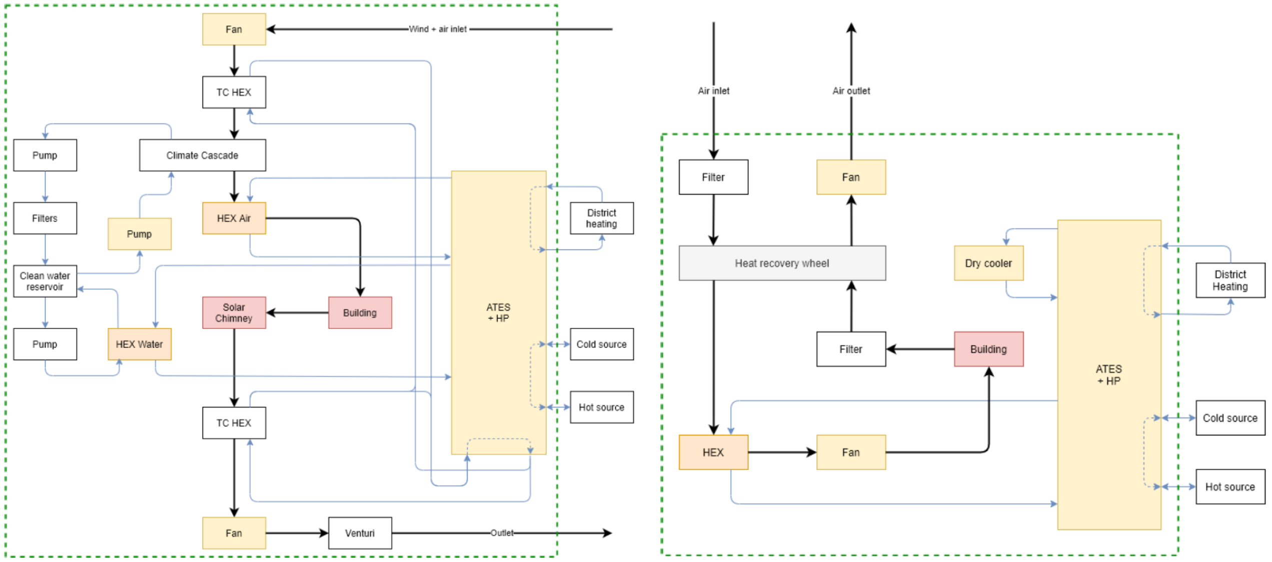


Figure 72 System schematic: EWF (left) and conventional HVAC (right) (Teeling, 2020)

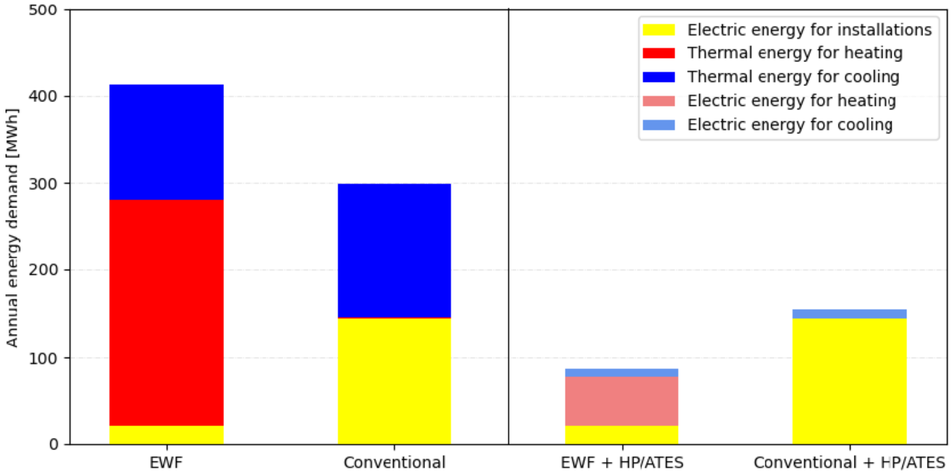


Figure 73 Annual Energy Demand of EWF and Conventional HVAC in Rotterdam (Teeling, 2020)

The study concluded that the EWF system consumes 44% lower annual electric energy demand compared to the conventional system in Rotterdam (Teeling, 2020).

10.3.2 Tokyo

As the case study building is a rather new building with an energy-conscious design, it is relevant to see the energy consumption comparison of EWF to a conventional HVAC system. The simulation uses DB and the NK building construction, the only difference is the HVAC setting: 'VAV Reheat, DX Cooling with Dehumidification', as follows.

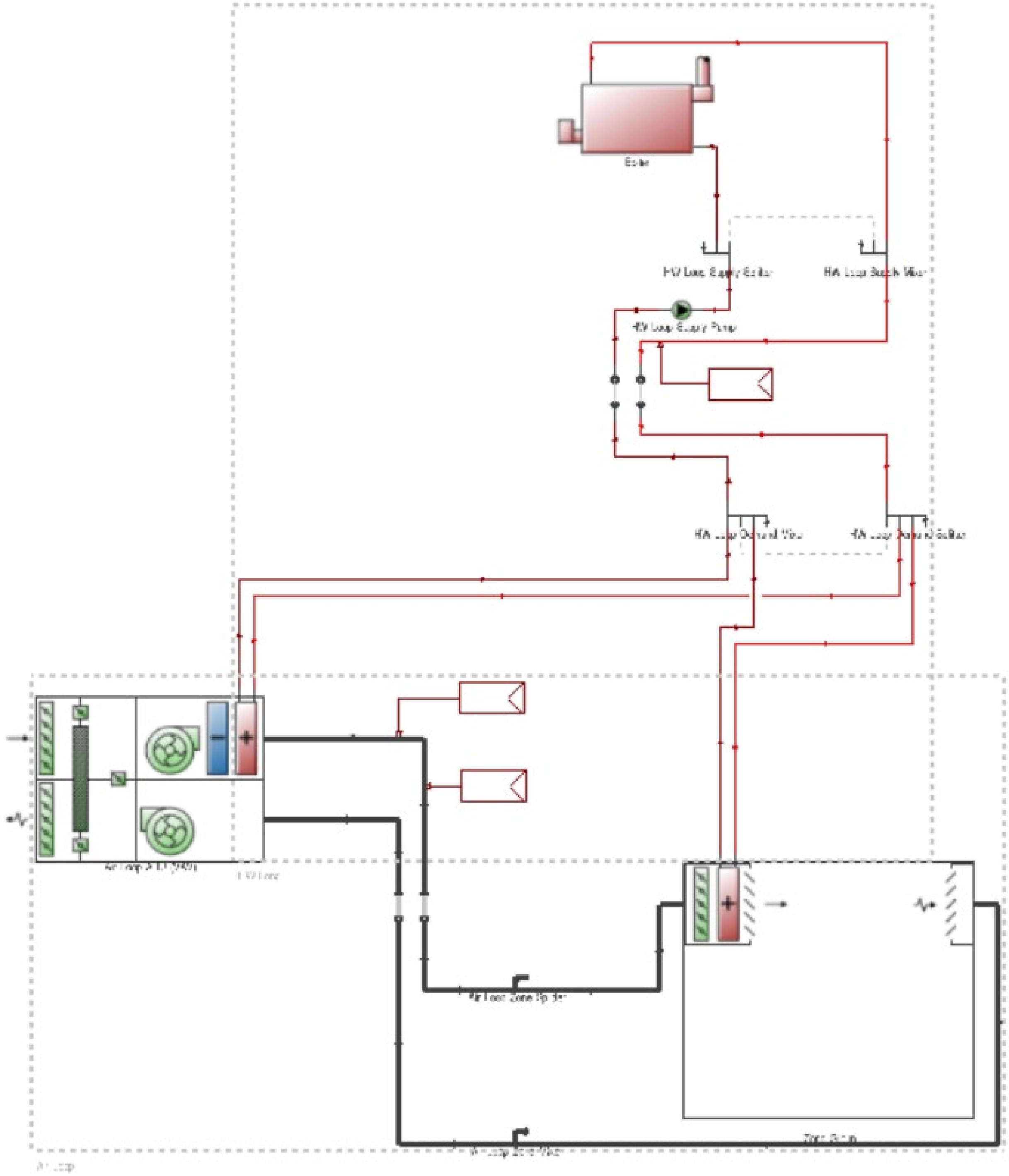


Figure 74 VAV Reheat with DX Cooling & Dehumidification HVAC setting in DB

Following the same simulation method as conducted in this study with 4 different variations as elaborated in 7.1, the result is summarized as follows.

Table 38 Existing-conventional & EWF Design Comparison: Energy

	Variation 1			**Existing**			**New**			**Variation 2**			
Comparison	Existing	EWF	**%**	Existing	EWF	**%**	Existing	EWF	**%**	Existing	EWF	**%**	
Heating	72	15	**-79**	64	14	**-79**	2	10	**414**	1	10	**626**	kWh/m2
Cooling	152	77	**-49**	135	72	**-47**	89	67	**-25**	86	63	**-27**	kWh/m2
Ventilation	44	31	**-29**	44	29	**-34**	35	25	**-28**	35	23	**-33**	kWh/m2
Total	268	123	**-54**	243	114	**-53**	126	101	**-19**	122	96	**-21**	kWh/m2

Average difference %	
Heating	**220**
Cooling	**-37**
Ventilation	**-31**
Total	**-37**

Old & New difference %	
Heating	**-85**
Cooling	**-50**
Ventilation	**-43**
Total	**-58**

The simulation result shows that on average, the EWF system contributed to 40% energy reduction, and with a more energy-conscious indoor comfort setting of the EWF system, about 60% energy reduction can be achieved.

11. Space for Sustainability: limited, yet limitless

This chapter is written as a prerequisite for the graduation annotation: Technology in Sustainable Development (TiSD), but more importantly, to showcase the limitless possibility of utilizing the limited space in office buildings in Tokyo for contributing to a carbon-neutral Tokyo and Japan by 2050, no matter how little.

Figure 75 Tokyo View from Tokyo Metropolitan Government Building

It takes little effort and imagination to notice how Tokyo is one of the most densely built cities in the world: the brightly lit and colourful neon lights illuminated the ever-busy arrays of thin and tall buildings – leaving almost no gaps in-between - packed with *salarymen*, as the Japanese likes to call it when referring to corporates' hard-working men and women. As far as scarcity value is concerned, limited space causes its value to rise, alongside its price: Tokyo is the 6th most expensive city in the world, leaving Amsterdam in 18th place, according to Globalpropertyguide.com.

While the writer thinks that prioritizing sustainability is indispensable for the survival of humanity, not profit, fortunately, studies have shown that connected the two: how organizing for sustainability can bring profit (Bonini & Swartz, 2014). Now, the question is: *How can we utilize office spaces in Tokyo differently to have a lower carbon emission in the end, taking the case study building (NK Building) as an example?*

Current condition

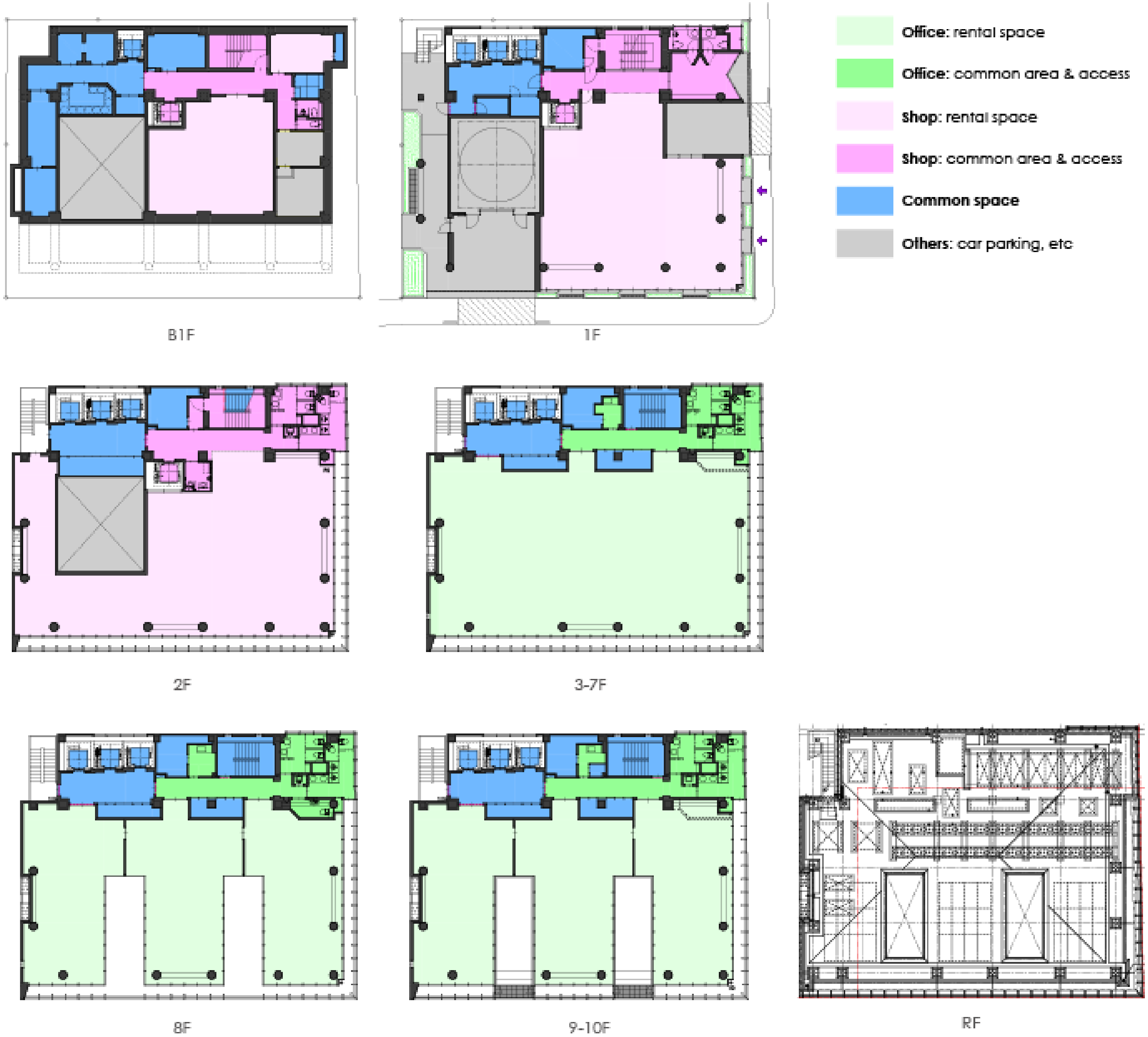


Figure 76 Case study building: space-use division (Flying Pumpkins & Team FP, 2013)

While the common area and access for both Office and Shop areas are largely dependent on the architectural layout, the MEP space, which is also included, is dependent on the adopted system for the building. In this case, the roof space has to be utilized for the outdoor units of these systems, as there is no space in the surrounding of the building.

Table 39 NK Building Space Allocation Percentage

Floor	**Office (%)**		**Shop (%)**		**Common space (%)**	**Others (%)**
	Rentable	non-rentable	Rentable	non-rentable		
B1	-	-	30	10	35	25
1	-	-	40	10	20	30
2	-	-	60	10	20	10
3	70	10	-	-	20	-
4	70	10	-	-	20	-
5	70	10	-	-	20	-
6	70	10	-	-	20	-
7	70	10	-	-	20	-
8	70	10	-	-	20	-
9	70	10	-	-	20	-
10	70	10	-	-	20	-
Total (%)	**50**	**10**	**10**	**5**	**20**	**5**

🟨 partial change 🟩 total change

Considering this as a renovation project where the architectural layout is not changed, we can see from the above table that parts of the non-rentable area of Office (10%) and Shop (5%), mostly referring to the MEP space when the new system requires less, and most of the Others (5%), referring to the car parking space. These happened to be closed spaces inside the building, which will be referred to as '*the-10%*', for simplicity in this chapter. What kind of things can be proposed in such spaces that can contribute to the reduction of carbon emission of the building? To answer the question, a desired future for the NK building needs to be envisioned first before backcasting on the things that should be done to achieve it.

Backcasting

Desired future of NK building in 2050: a smart and net-energy positive building that showcases sustainability, therefore its users also practice sustainable lifestyle e.g. commute by bike/ train/on foot/car-sharing, conscious-use of energy & resources (lighting, heating/cooling, water, etc), active participation in urban farming & composting within the facility.

The new space-use proposal for the-10% can be classified by 2 types of carbon reduction: direct and indirect impact.

Direct impact refers to the 3 types of energy correlated to the built-environment: Building Related Energy (BRE), User Related Energy (URE), and Material Related Energy (MRE), whereas indirect impact refers to anything beyond that, including for research & innovation, raising awareness, and education. The carbon reduction impact for the latter is rather long-term and therefore can be controversial when discussing carbon reduction. Using the space to research, teach, or showcase examples of sustainability means that consumption might actually be higher. Pasona Urban Farm by Kono Designs is an interesting example of how an office can integrate high-tech urban farming. Although it consumes more energy to facilitate farming, the building has an overarching value of showcasing urban farming and inspiring people to become farmers, a steadily declining profession in Japan (Andrews, 2013). All of the food is harvested, prepared, and served in the on-site cafeteria, a farm-to-table approach, resulting in zero food mile.

Figure 77 Pasona Urban Farm (Andrews, 2013)

New ideas

New space-use proposal for direct carbon reduction impact for the-10%:

- Gardening/ Tree-planting -> carbon sequestration, biodiversity
- Vertical farming -> reduced food-mile, food production
    - Shiitake mushrooms
    - Leafy vegetables (might increase energy use)
- Energy-production gym -> electricity production from kinetic
- Composting facility -> electricity production from biomass

New space-use proposal for indirect carbon reduction impact for the-10%:

- Bicycle parking -> to replace cars

- Sustainability exhibition space -> to educate & inspire people
- Weekly energy use billboard -> to encourage positive competition for energy reduction
- Pigs or chicken café -> to indirectly encourage veganism & animal love

The dilemmas

Although free solar energy is abundant in the country-of-the-rising-sun, the densely placed buildings almost make façade-integrated PV panels obsolete in low to mid-rise buildings, while roof-top space is also mostly occupied with mechanical equipment, leaving not much room for BAPV.

Moreover, the EWF system that harvest natural resources also uses comparatively bigger duct sizes and requires shaft spaces for the integration of SC and CC. While the total space requirement might be less than the conventional HVAC system, integrating it in Tokyo would require a smart and modular approach, exactly due to the limited space.

This highlights the fact that sustainability requires space. Favourably, sustainability is not a choice but for survival. The same way a person cannot live alone, a building as small as an NK building cannot 'survive' and become net-energy positive on its own. The scale needs to be seen at least on a district level where energy, heat, and cold, can be shared.

Opportunities

The COVID-19 pandemic has shown that people can work from home. Office space requirement is expected to reduce in the future, which means there will be more space in the existing building stock convertible to more meaningful purposes for carbon reduction.

Moreover, means to prevent buildings from demolition could be a double win for both sparing precious resources from building new construction and reusing the existing space, prolonging the lifetime. Improving adaptability and flexibility of space-use and modularity of building components can greatly contribute to this.

Conclusion

There are many ways to use office space in Tokyo differently to lower the carbon emission, some with direct impact while the others are more long-term and indirect. However, the impact is minuscule if only done by 1 building. Therefore, it is as important to raise awareness of the importance of sustainability in all parts of life so that this can be followed and done by more, if not everyone. Only then will the limited space become limitless.

12. Discussion

12.1 LIMITATIONS

Addressing the elephant in the room, accumulated stress due to the lack of social activity, freedom to travel, and normality in daily life caused by the COVID-19 pandemic might have affected the depth, accuracy, and/or richness of this thesis than initially intended.

Limitation in the simulation accuracy using DesignBuilder was observed. On one side, this is due to the novelty of the EWF concept along with its unique '*climate machine*' properties, and the limited time and expertise on working with DB as well as mechanical engineering knowledge. However, the presented result is believed to show sufficient trends of the intended purpose.

Time always seems to be the limitation (or blessing in disguise) for the writer. The deeper the research goes, the more unknown & possibilities were found, hence the long list of recommendations for further research.

12.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Research-oriented recommendations:

- Explore the possibilities of cooling (or cooling storage) from waste-heat, e.g. utilize sorption or desiccant cooling using the heat recovered from SC
- Explore EWF design without the use of ATES and use a chiller instead to cool the CC water in Tokyo or other cities with similar climates.
- Explore different variations of SC adapted to the need of the building: prioritizing electricity production or heat gain by adding and/or adjusting the placement of PV or PV/T or Thermal Collector.
- Explore different systems for space heating & cooling in combination with EWF, e.g. EWF with chilled beams, or any other hybrid system.
- Explore the IAQ of the air coming out of CC, especially concerning coronavirus.

Other recommendations:

- A standardized and user-friendly CC Excel and SC Excel (or other forms of calculation software) could be published for interesting parties to use, possibly with a user manual or video tutorial. A proper EWF dynamic simulation is of course very welcomed.

13. Conclusion

Referring to the research question:

"Is the Dutch **Earth, Wind and Fire system** (EWF), in place of the existing **air-conditioning system**, an efficient **energy-retrofitting method** to achieve **energy-neutrality** in an **office building in Tokyo** without compromising **thermal comfort** of users?"

If an efficient energy-retrofitting method is defined as an energy reduction of at least 50%, then the answer is:

No, it is not efficient for the case of NK Building, as it turned out that the existing air-conditioning system is already energy efficient. However, the limitation in properly simulating EWF with HR in DB is believed to have affected the energy consumption, thus further study is recommended.

Moreover, as the case study building's air-conditioning system also does the space heating and cooling altogether, replacing this with EWF means an additional space heating and cooling would have to be integrated. As a ventilation system, EWF contributed to 15% energy reduction proving the fact that the natural ventilation concept of EWF works.

Furthermore, the EWF system uses 40% less energy in comparison to a conventional HVAC system in Tokyo, showing similar trends with another study conducted in Rotterdam. Naturally Tokyo seemed to have been *found in translation*.

As an energy-retrofitting method in such an urbanized area like Tokyo, space efficiency in addition to ease of construction seems pivotal. For this reason, EWF elements, i.e. CC and SC needs to be developed as unitized yet adjustable modules. In addition, the existing system demands most of the space on the roof for its Outdoor units, leaving limited space e.g. PV panels, whereas the EWF system does not – this is believed to bring an added value to the use of space for sustainability in the building.

On the other hand, energy neutrality is difficult to achieve without reducing the energy consumption first, or else increase the energy production through renewable sources. Various ideas have been explored.

Finally, EWF integration has not compromised thermal comfort in any of the different variations explored – EWF has improved thermal comfort. It is worth noting that in Tokyo, different from in Amsterdam, the key is to combine with effective space cooling system, more than heating.

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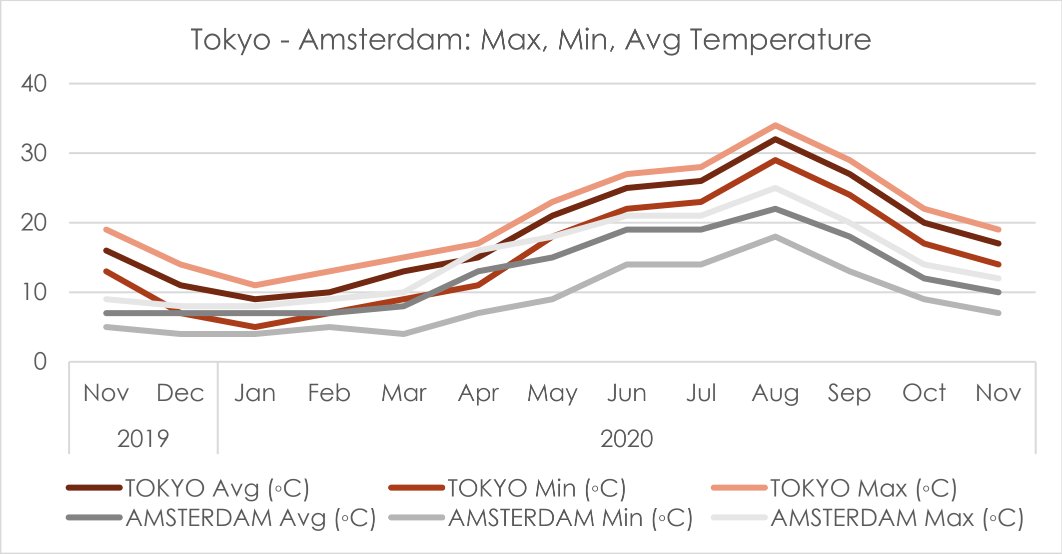
Appendix

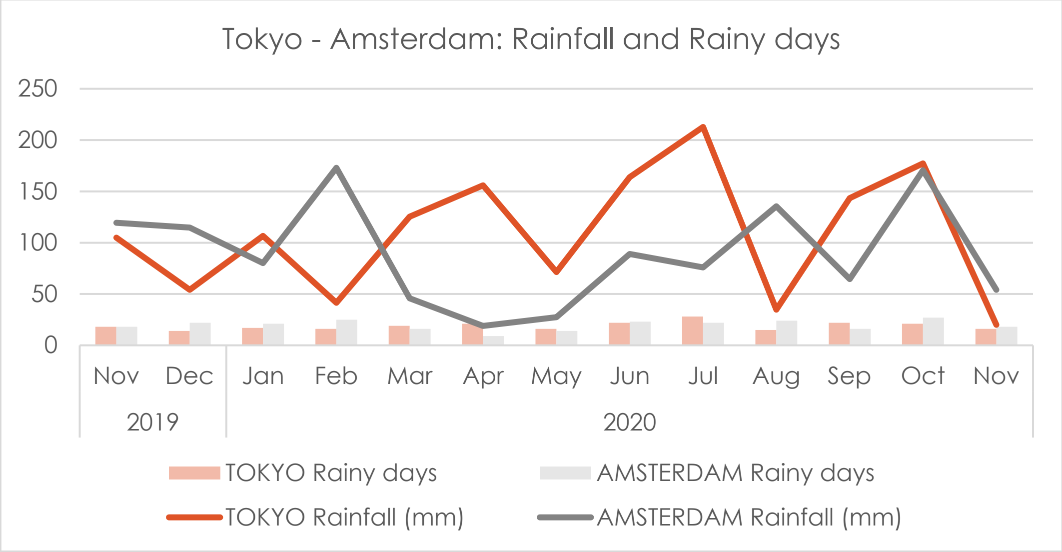
1. Climate comparison: Tokyo – Amsterdam

a. General comparison

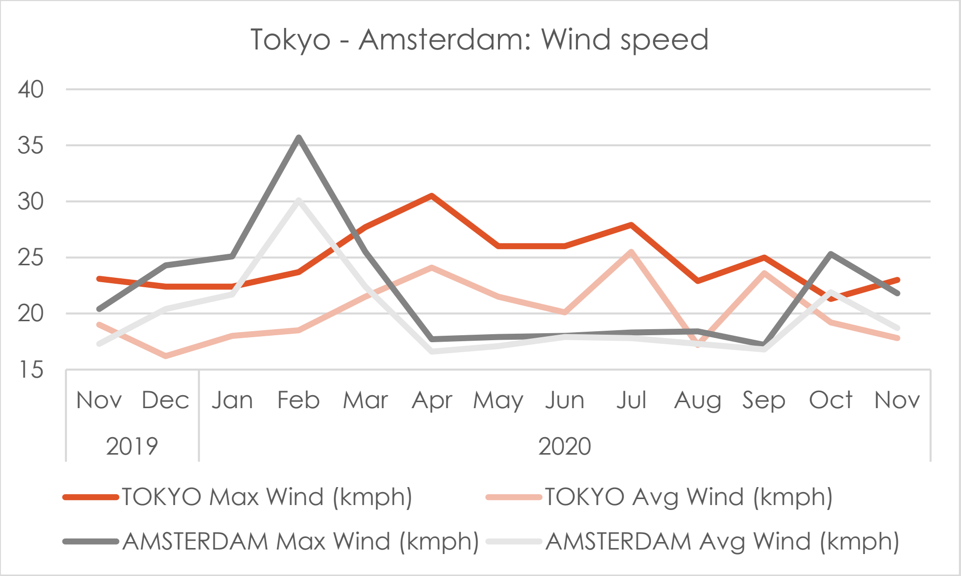
Tokyo is red, and Amsterdam is gray. Source: https://www.worldweatheronline.com/



In terms of temperature, Tokyo and Amsterdam have rather similar phenomenon, with Amsterdam on the colder side.

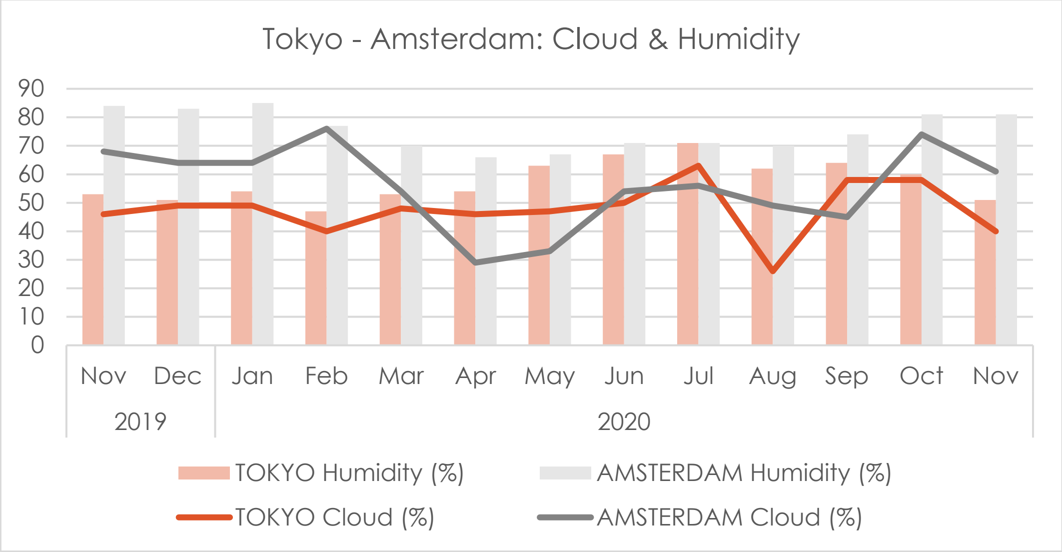


For rainfall, Amsterdam's rainfall is rather high in February and October, whereas Tokyo's is in July and October. Amsterdam seems to have slightly more rainy days overall.

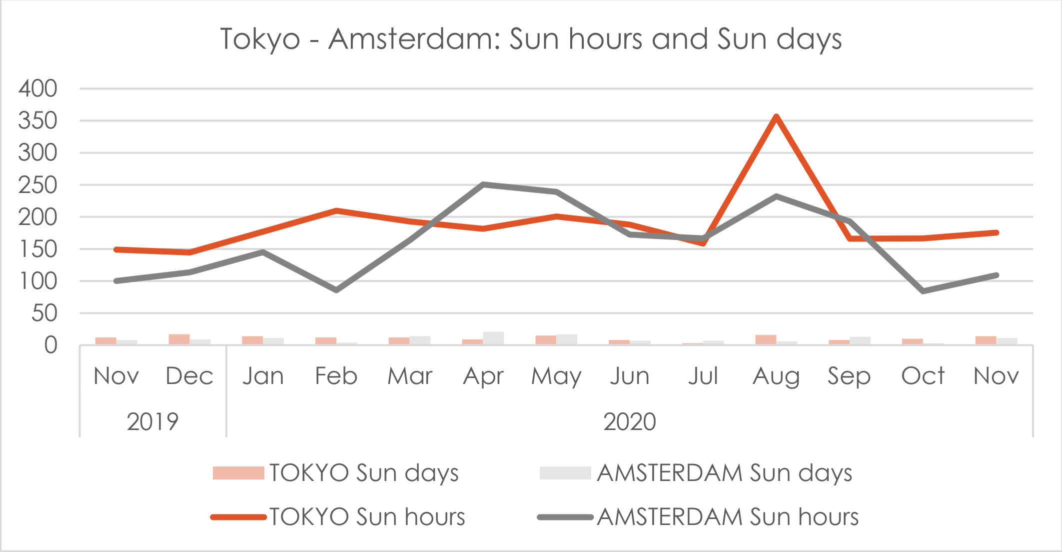


Amsterdam's wind speed is high in February and October, whereas Tokyo's more balanced throughout the year, with July having the highest average.

Amsterdam has deeper snowfall in February, but all in all the phenomenon is similar.

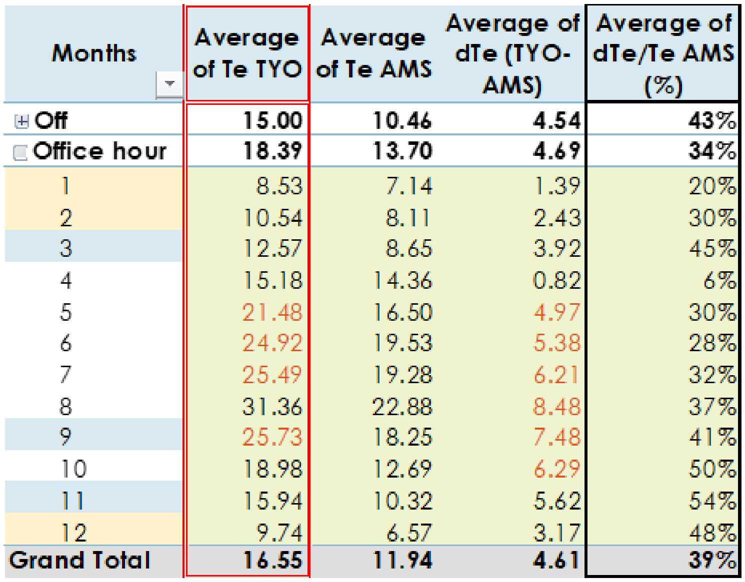


Surprisingly, Amsterdam has higher humidity during autumn and winter, possibly due to the higher percentage of clouds. Tokyo's humidity is at its peak in July.



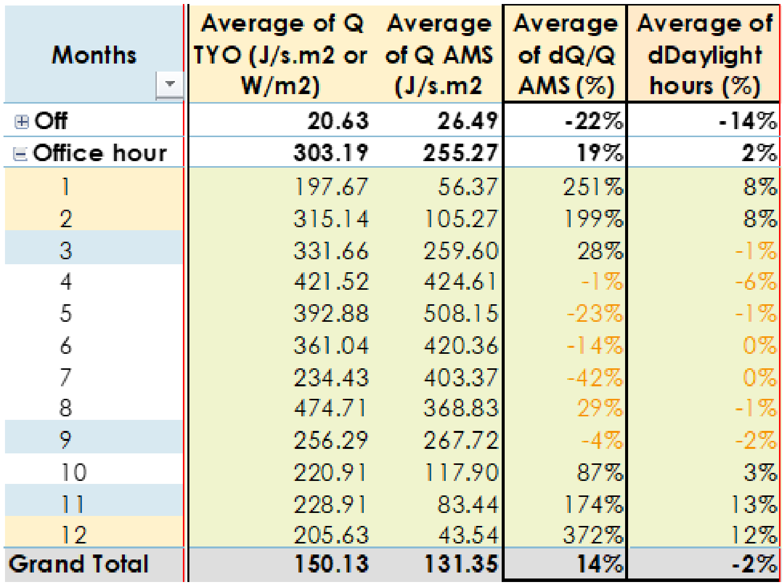
Tokyo's sun hours are at its peak in August, while Amsterdam's is in April. The overall trend seems to be similar.

b. Detailed comparison



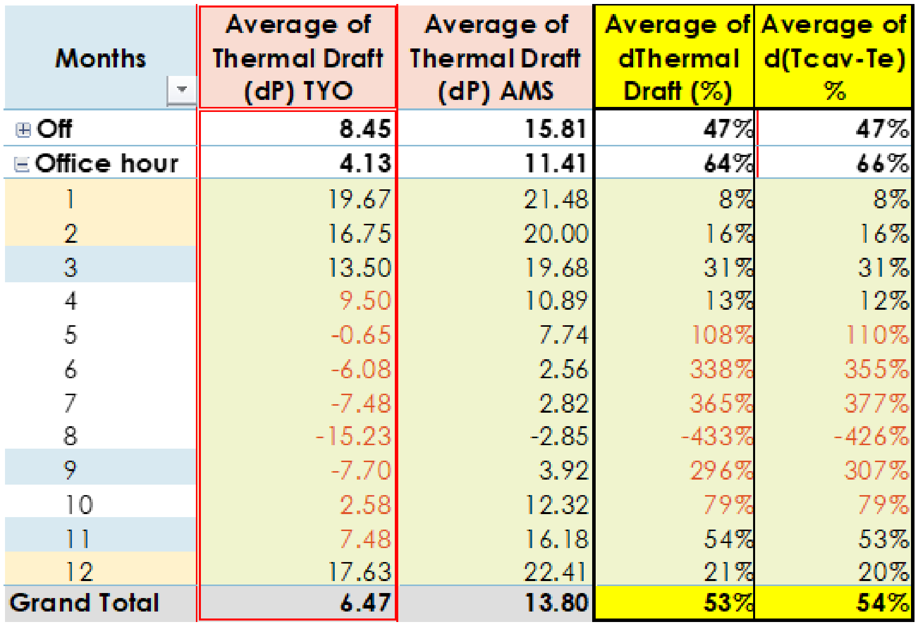
Months	Average of Te TYO	Average of Te AMS	Average of dTe (TYO-AMS)	Average of dTe/Te AMS (%)
⊞ Off	**15.00**	**10.46**	**4.54**	**43%**
⊟ Office hour	**18.39**	**13.70**	**4.69**	**34%**
1	8.53	7.14	1.39	20%
2	10.54	8.11	2.43	30%
3	12.57	8.65	3.92	45%
4	15.18	14.36	0.82	6%
5	21.48	16.50	4.97	30%
6	24.92	19.53	5.38	28%
7	25.49	19.28	6.21	32%
8	31.36	22.88	8.48	37%
9	25.73	18.25	7.48	41%
10	18.98	12.69	6.29	50%
11	15.94	10.32	5.62	54%
12	9.74	6.57	3.17	48%
Grand Total	**16.55**	**11.94**	**4.61**	**39%**

1. TYO is 39% warmer than AMS
   Especially in Mar, Sep, and Nov, TYO is 1.5 times warmer.



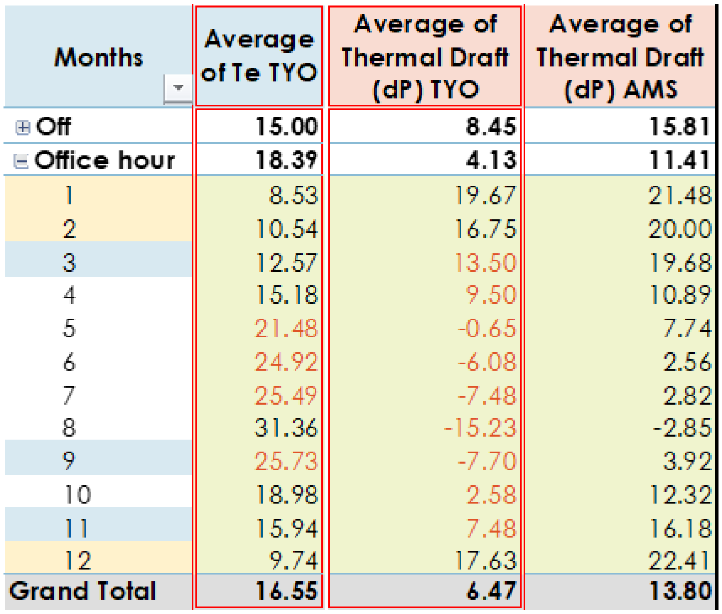
Months	Average of Q TYO (J/s.m2 or W/m2)	Average of Q AMS (J/s.m2	Average of dQ/Q AMS (%)	Average of dDaylight hours (%)
⊞ Off	**20.63**	**26.49**	**-22%**	**-14%**
⊟ Office hour	**303.19**	**255.27**	**19%**	**2%**
1	197.67	56.37	251%	8%
2	315.14	105.27	199%	8%
3	331.66	259.60	28%	-1%
4	421.52	424.61	-1%	-6%
5	392.88	508.15	-23%	-1%
6	361.04	420.36	-14%	0%
7	234.43	403.37	-42%	0%
8	474.71	368.83	29%	-1%
9	256.29	267.72	-4%	-2%
10	220.91	117.90	87%	3%
11	228.91	83.44	174%	13%
12	205.63	43.54	372%	12%
Grand Total	**150.13**	**131.35**	**14%**	**-2%**

2. TYO has 14% more solar radiation than AMS.
   Especially in winter (Dec, Jan, Feb), TYO has 3 times more sun radiation.
   However, from Apr to Sep, AMS actually has more sun radiation, peaking in July.
   This agrees with the fact that AMS also has more sunhours than TYO in Mar-Sep (Spring & Summer)



Months	Average of Thermal Draft (dP) TYO	Average of Thermal Draft (dP) AMS	Average of dThermal Draft (%)	Average of d(Tcav-Te) %
⊞ Off	8.45	15.81	47%	47%
⊟ Office hour	4.13	11.41	64%	66%
1	19.67	21.48	8%	8%
2	16.75	20.00	16%	16%
3	13.50	19.68	31%	31%
4	9.50	10.89	13%	12%
5	-0.65	7.74	108%	110%
6	-6.08	2.56	338%	355%
7	-7.48	2.82	365%	377%
8	-15.23	-2.85	-433%	-426%
9	-7.70	3.92	296%	307%
10	2.58	12.32	79%	79%
11	7.48	16.18	54%	53%
12	17.63	22.41	21%	20%
Grand Total	**6.47**	**13.80**	**53%**	**54%**

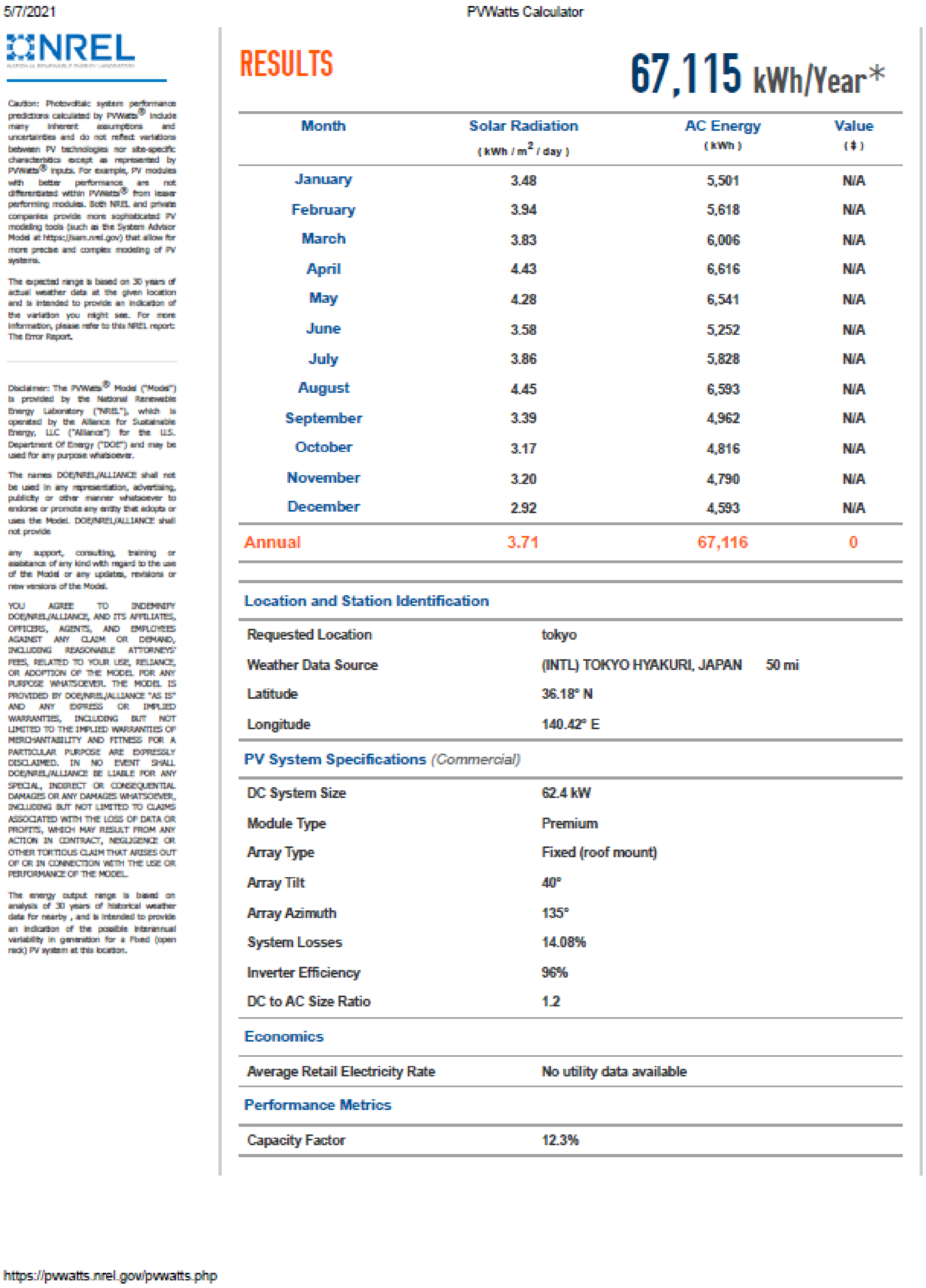
3. The designed SC in TYO only produces roughly half the Thermal Draft than in AMS.
Especially from May-Oct, the difference in Thermal Draft in AMS and TYO is huge.
This is mostly due to the fact that Tcav-Te in AMS is higher, mostly owing to the older climate.
This is in line with the difference of Tcav-Te between AMS and TYO.



Months	Average of Te TYO	Average of Thermal Draft (dP) TYO	Average of Thermal Draft (dP) AMS
⊞ Off	15.00	8.45	15.81
⊟ Office hour	18.39	4.13	11.41
1	8.53	19.67	21.48
2	10.54	16.75	20.00
3	12.57	13.50	19.68
4	15.18	9.50	10.89
5	21.48	-0.65	7.74
6	24.92	-6.08	2.56
7	25.49	-7.48	2.82
8	31.36	-15.23	-2.85
9	25.73	-7.70	3.92
10	18.98	2.58	12.32
11	15.94	7.48	16.18
12	9.74	17.63	22.41
Grand Total	**16.55**	**6.47**	**13.80**

4. Te TYO is favourable (20-26 deg C) during office hours (8AM-6PM) in May, Jun, Jul, & Sep.
If we consider the pressure of 15 Pa, Fan Energy would be necessary from Mar-Nov (9 out of 12 months!)

2. PV Yield



5/7/2021 PVWatts Calculator

Caution: Photovoltaic system performance predictions calculated by PVWatts® include many inherent assumptions and uncertainties and do not reflect variations between PV technologies nor site-specific characteristics except as represented by PVWatts® inputs. For example, PV modules with better performance are not differentiated within PVWatts® from lesser performing modules. Both NREL and private companies provide more sophisticated PV modeling tools (such as the System Advisor Model at https://sam.nrel.gov) that allow for more precise and complex modeling of PV systems.

The expected range is based on 30 years of actual weather data at the given location and is intended to provide an indication of the variation you might see. For more information, please refer to this NREL report: The Error Report.

Disclaimer: The PVWatts® Model ("Model") is provided by the National Renewable Energy Laboratory ("NREL"), which is operated by the Alliance for Sustainable Energy, LLC ("Alliance") for the U.S. Department Of Energy ("DOE") and may be used for any purpose whatsoever.

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The energy output range is based on analysis of 30 years of historical weather data for nearby , and is intended to provide an indication of the possible interannual variability in generation for a Fixed (open rack) PV system at this location.

RESULTS

67,115 kWh/Year*

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	3.48	5,501	N/A
February	3.94	5,618	N/A
March	3.83	6,006	N/A
April	4.43	6,616	N/A
May	4.28	6,541	N/A
June	3.58	5,252	N/A
July	3.86	5,828	N/A
August	4.45	6,593	N/A
September	3.39	4,962	N/A
October	3.17	4,816	N/A
November	3.20	4,790	N/A
December	2.92	4,593	N/A
Annual	3.71	67,116	0

Location and Station Identification

Requested Location	tokyo
Weather Data Source	(INTL) TOKYO HYAKURI, JAPAN 50 mi
Latitude	36.18° N
Longitude	140.42° E

PV System Specifications *(Commercial)*

DC System Size	62.4 kW
Module Type	Premium
Array Type	Fixed (roof mount)
Array Tilt	40°
Array Azimuth	135°
System Losses	14.08%
Inverter Efficiency	96%
DC to AC Size Ratio	1.2

Economics

Average Retail Electricity Rate	No utility data available

Performance Metrics

Capacity Factor	12.3%

https://pvwatts.nrel.gov/pvwatts.php

3. DB Simulation

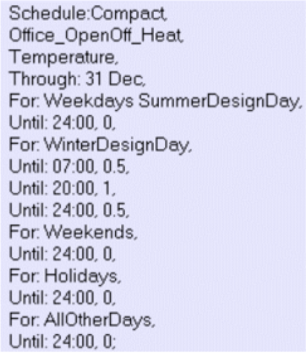
Parameters

comfort ↔ **Priority line** *energy*

	Variation 1	**Existing**	**New**	**Variation 2**	
Ventilation amount	50	25	50	25	m3/h/person
Comfort design condition					
Heating mode	22	22	20	20	°C
	40	40	40	40	% RH
Cooling mode	26	26	28	28	°C
	50	50	70	70	% RH

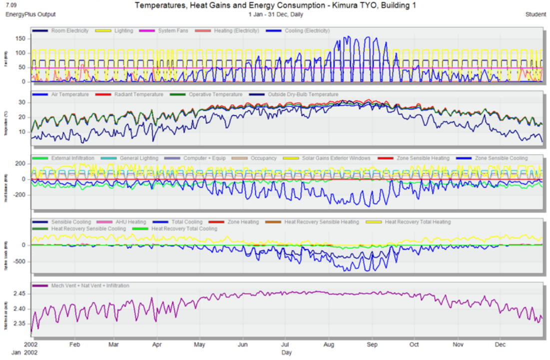
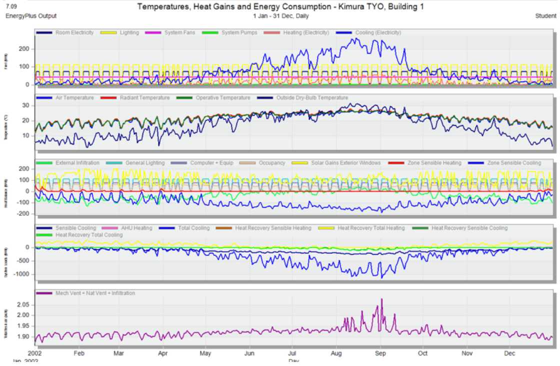
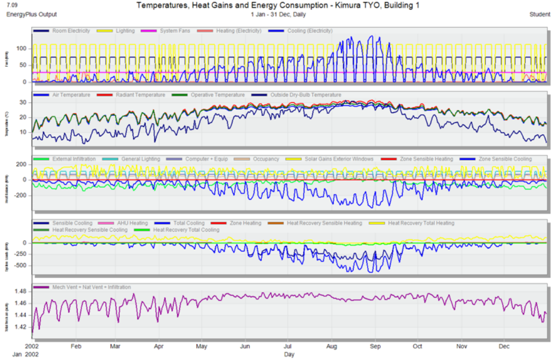
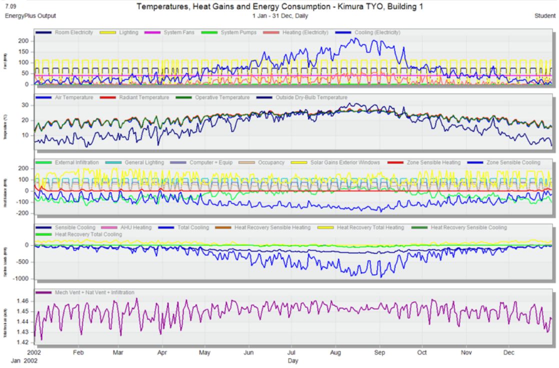
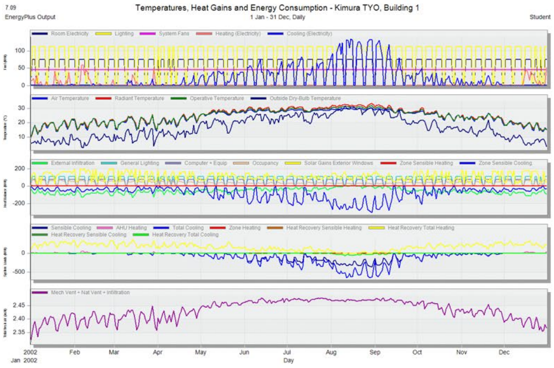
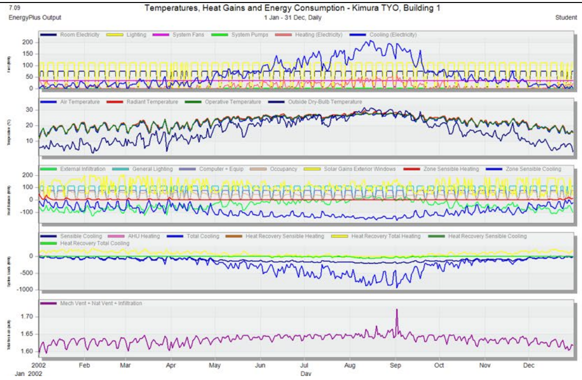
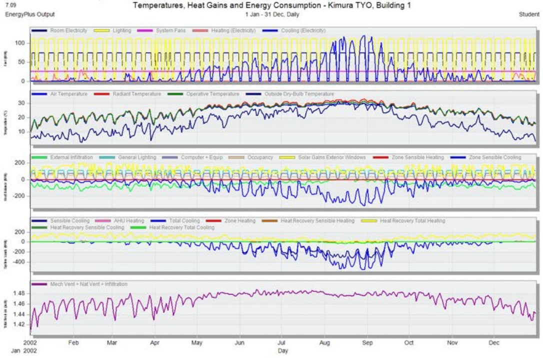
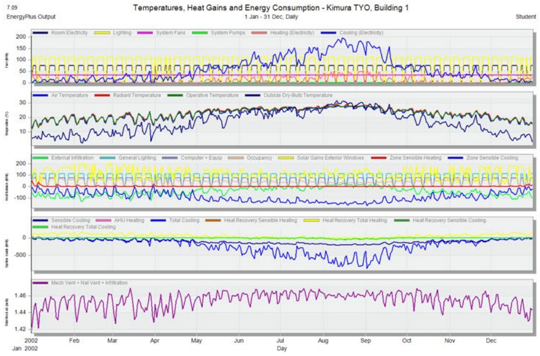
a. EWF – Existing (VRF) comparison

Ventilation 24/7 on, Heating & Cooling schedule as follows.

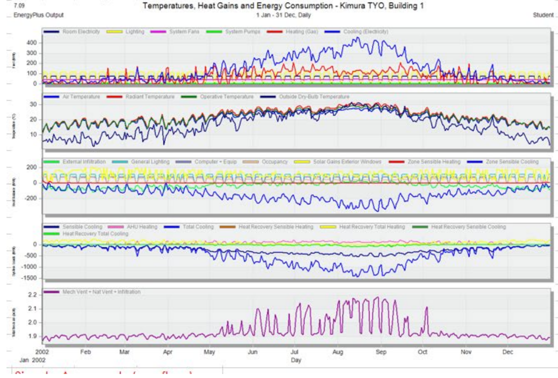
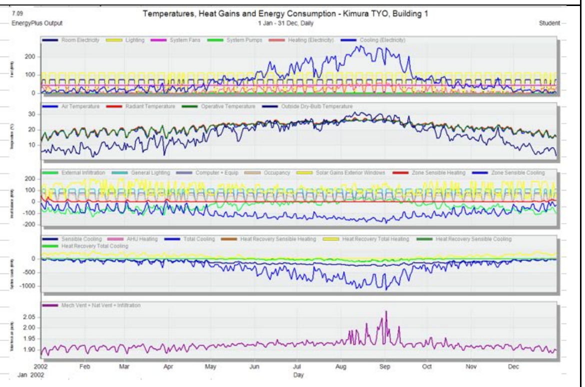
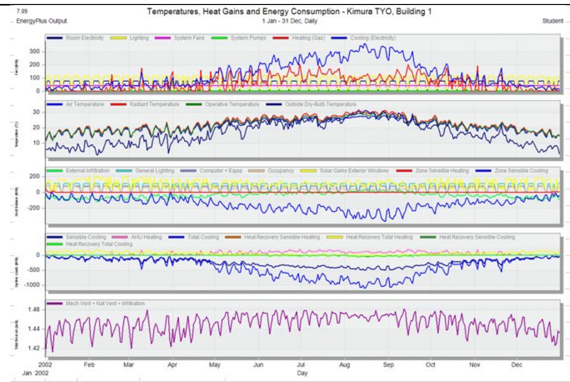
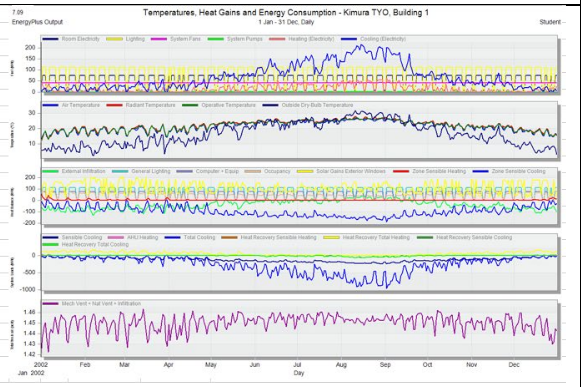
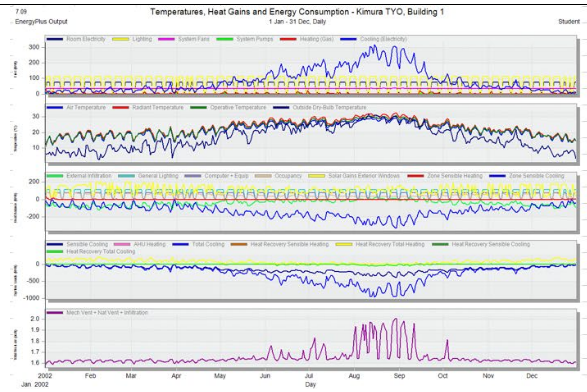
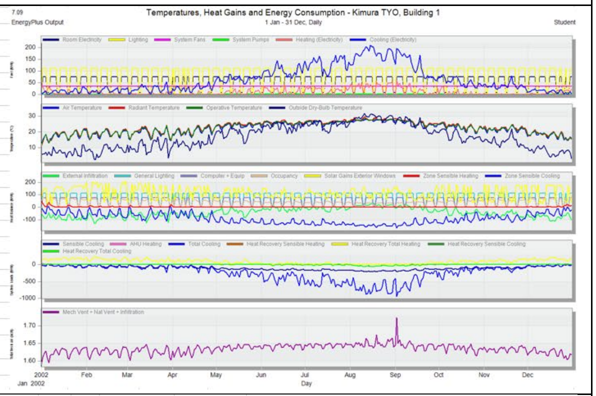
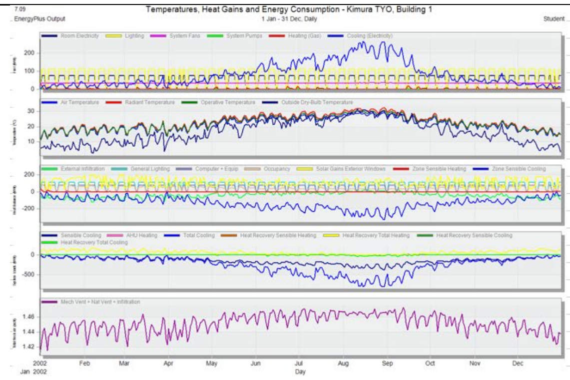
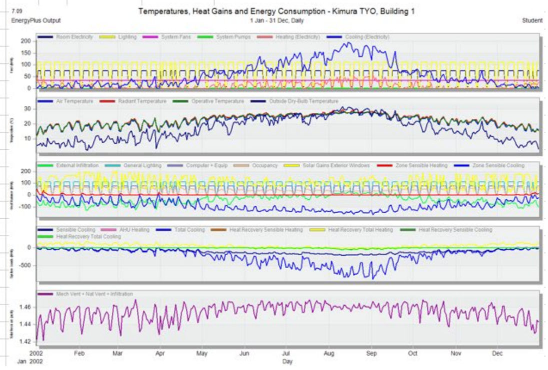


```
Schedule:Compact,
Office_OpenOff_Heat,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 24:00, 0,
For: WinterDesignDay,
Until: 07:00, 0.5,
Until: 20:00, 1,
Until: 24:00, 0.5,
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: AllOtherDays,
Until: 24:00, 0;
```

```
Schedule:Compact,
Office_OpenOff_Cool,
Temperature,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0.75,
Until: 20:00, 1,
Until: 24:00, 0.75,
For: Weekends,
Until: 24:00, 0.5,
For: Holidays,
Until: 24:00, 0.5,
For: WinterDesignDay AllOtherDays,
Until: 24:00, 0;
```

	EWF	Existing (VRF)
Variation 1		
Existing variation		
New variation		
Variation 2		

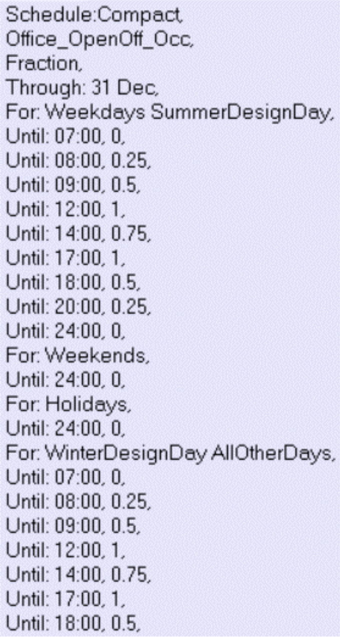
b. EWF – conventional (VAV) comparison

	EWF	Conventional (VAV)
Variation 1		
Existing variation		
New variation		
Variation 2		

c. Existing (VRF) comparison - EWF with chilled beams

Ventilation schedule for EWF with chilled beams=occupancy schedule

Heating & cooling schedule for EWF with chilled beams



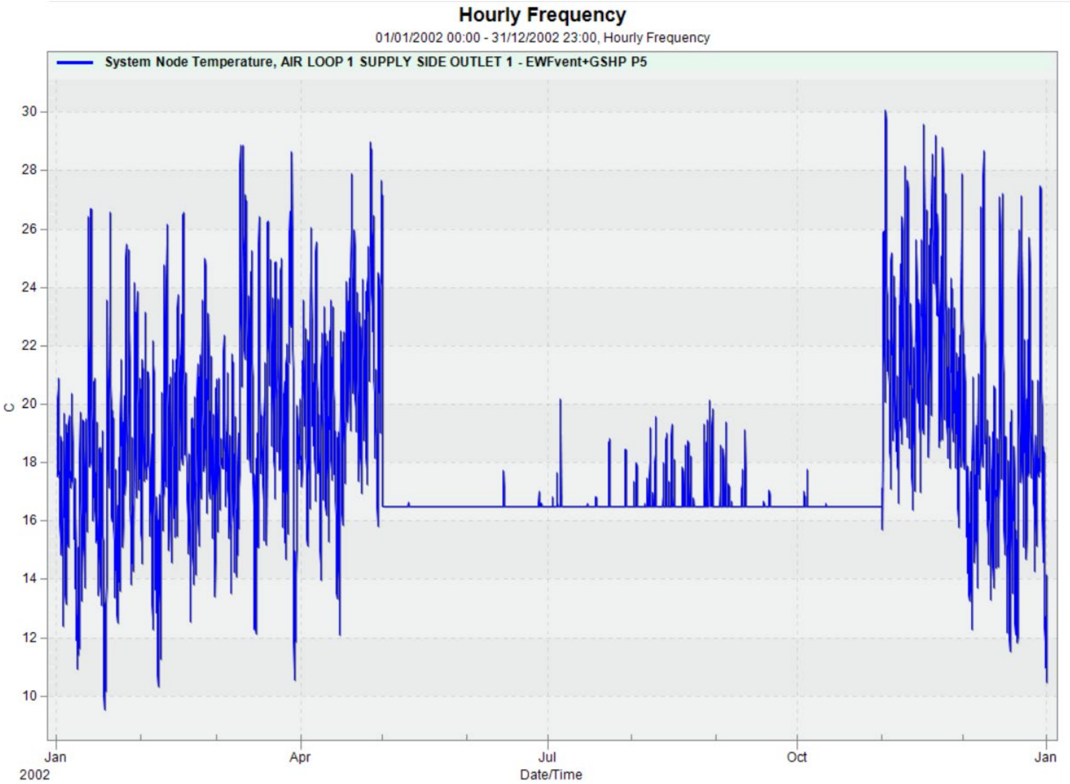
```
Schedule:Compact,
Office_OpenOff_Occ,
Fraction,
Through: 31 Dec,
For: Weekdays SummerDesignDay,
Until: 07:00, 0,
Until: 08:00, 0.25,
Until: 09:00, 0.5,
Until: 12:00, 1,
Until: 14:00, 0.75,
Until: 17:00, 1,
Until: 18:00, 0.5,
Until: 20:00, 0.25,
Until: 24:00, 0,
For: Weekends,
Until: 24:00, 0,
For: Holidays,
Until: 24:00, 0,
For: WinterDesignDay AllOtherDays,
Until: 07:00, 0,
Until: 08:00, 0.25,
Until: 09:00, 0.5,
Until: 12:00, 1,
Until: 14:00, 0.75,
Until: 17:00, 1,
Until: 18:00, 0.5,
```

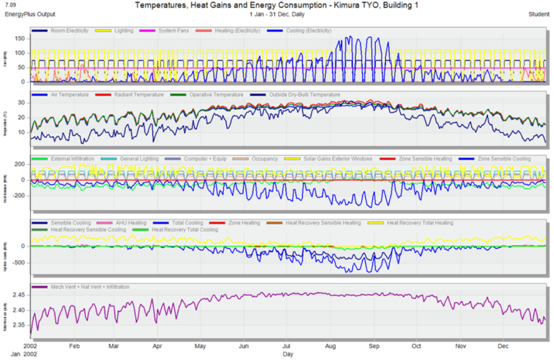
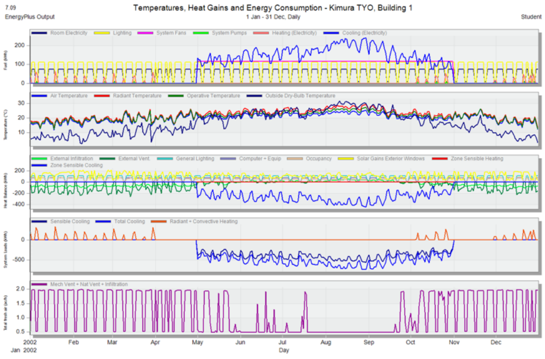
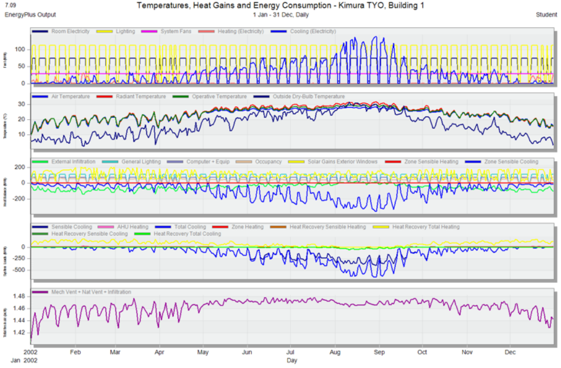
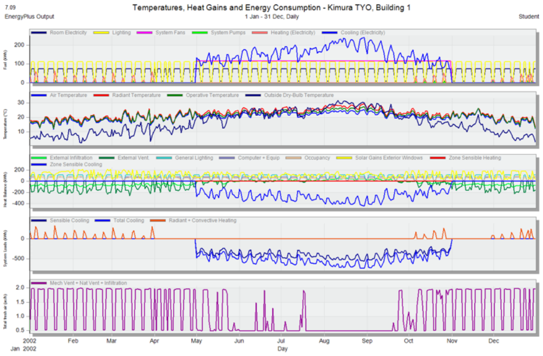
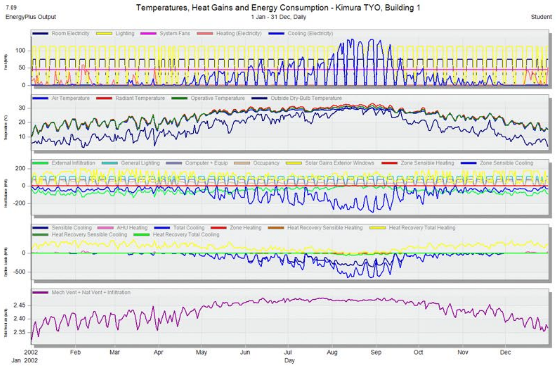
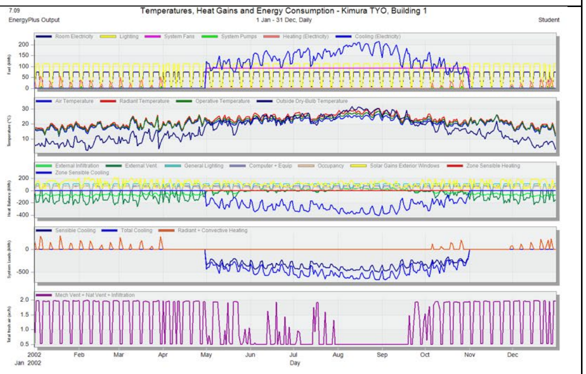
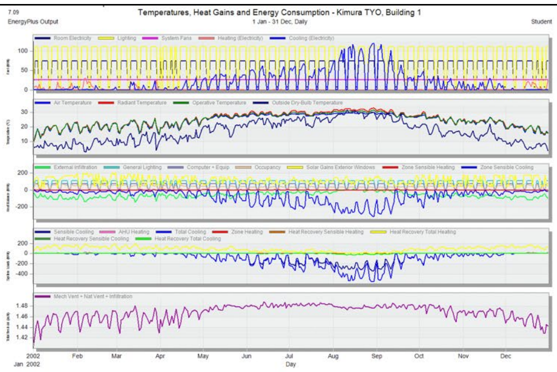
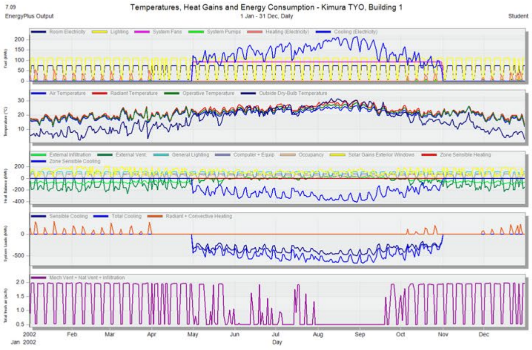
```
Schedule:Compact,
Office_OpenOff_Heat,
Temperature,
Through: 31 Mar,
For: Weekdays WinterDesignDay,
Until: 07:00, 0.5,
Until: 20:00, 1,
Until: 24:00, 0.5,
For: Weekends,
Until: 24:00, 0.5,
For: Holidays,
Until: 24:00, 0.5,
For: AllOtherDays,
Until: 24:00, 0,
Through: 30 Sep,
For: AllDays,
Until: 24:00, 0,
Through: 31 Dec,
For: Weekdays WinterDesignDay,
Until: 07:00, 0.5,
Until: 20:00, 1,
Until: 24:00, 0.5,
For: Weekends,
Until: 24:00, 0.5,
For: Holidays,
Until: 24:00, 0.5,
```

```
Schedule:Compact,
Office_OpenOff_Cool,
Temperature,
Through: 30 Apr,
For: AllDays,
Until: 24:00, 0,
Through: 31 Oct,
For: Weekdays SummerDesignDay,
Until: 05:00, 0.5,
Until: 20:00, 1,
Until: 24:00, 0.5,
For: Weekends,
Until: 24:00, 0.5,
For: Holidays,
Until: 24:00, 0.5,
For: AllOtherDays,
Until: 24:00, 0,
Through: 31 Dec,
For: AllDays,
Until: 24:00, 0;
```

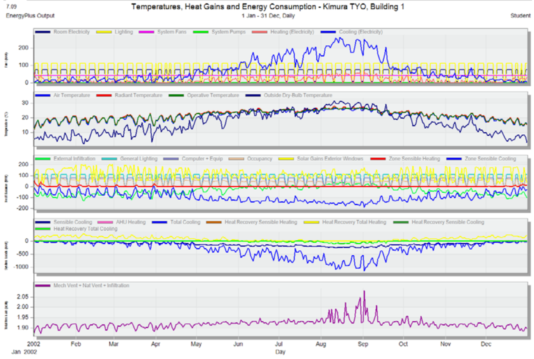
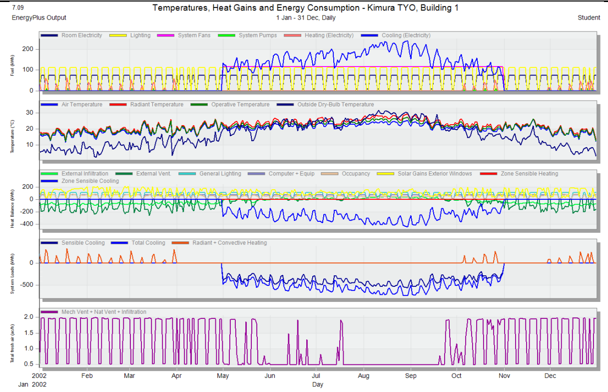
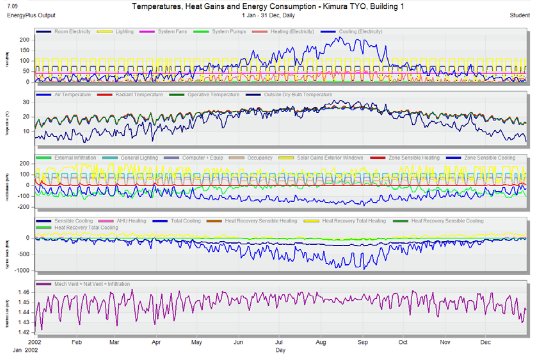
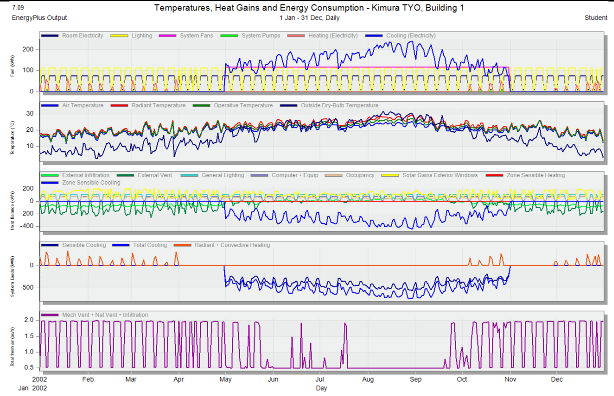
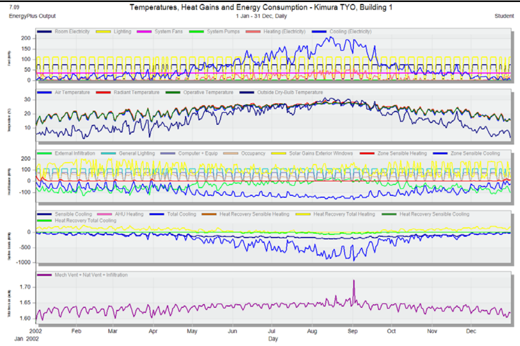
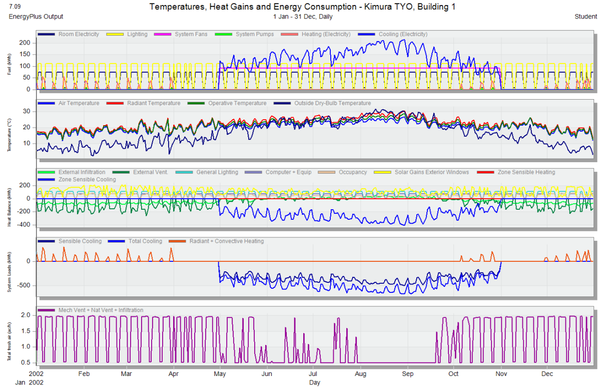
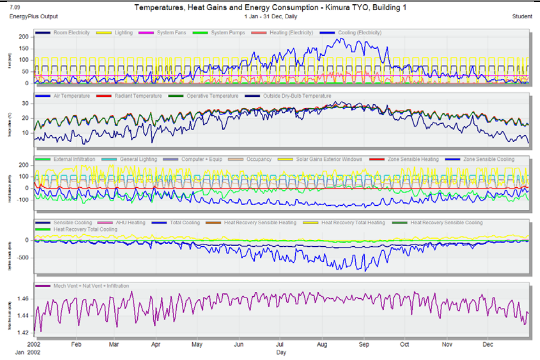
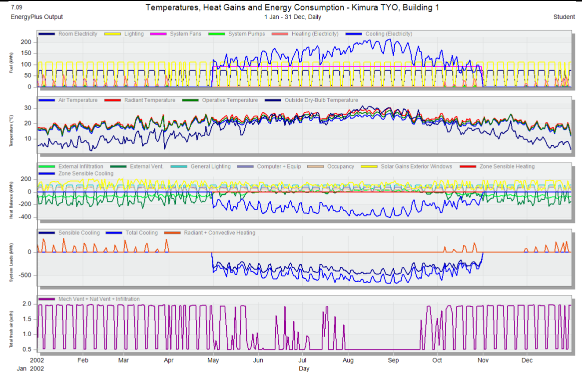
EWF with chilled beams:

supply air outlet temperature set to always 16.5, but not achieved in winter & spring.



	Existing (VRF)	EWF with chilled beams (new schedule)
Variation 1		
Existing variation		
New variation		
Variation 2		

d. EWF – EWF with chilled beams

	EWF	EWF with chilled beams (new schedule)
Variation 1		
Existing variation		
New variation		
Variation 2		

4. Formulas

Formulas for each of the elements of EWF, cited from Dr. Ben Bronsema's dissertation: *Earth, Wind & Fire Natuurlijke Airconditioning*.

a. Climate Cascade

The heat flow between air and water in a Climate Cascade is determined by the required thermal power, expressed in the formula:

$$\Phi = q_{v.l} . \rho_l . (h_{l.in} - h_{l.out})$$ (Bronsema, 2013)

Where,
Φ = Heat flow [W]
$q_{v.l}$ = volume flow air [dm^3 .s^{-1}]
ρ_l = density of air [g. dm^3]
$h_{l.in}$ = enthalpy of the air at entry [Jg^{-1}]
$h_{l.out}$ = enthalpy of the air at exit [Jg^{-1}]

The heat flow consists of a sensible component Φ_v and a latent component Φ_l, at which:

$$\Phi = \Phi_v + \Phi_l$$ (Bronsema, 2013)

The sensible heat transfer in a Climate Cascade can be described with the general formula:

$$\Phi_v = A_{dr} . h_{c.dr}(\theta_{dr} - \theta_\infty) + A_{wnd} . h_{c.wnd}(\theta_{wnd} - \theta_\infty)$$ (Bronsema, 2013)

Where,
Φ_v = sensible component heat flow [W]
A_{dr} = cumulative surface water droplets in the spraying zone [m^2]
$h_{c.dr}$ = convective heat transfer coefficient of air on droplets [Wm^{-2} K^{-1}]
θ_{dr} = temperature of water droplets [°C]
θ_∞ = temperature of air flow [°C]
A_{wnd} = total wall surface [m^2]
$h_{c.wnd}$ = convective heat transfer coefficient air and walls [Wm^{-2} K^{-1}]
θ_{wnd} = temperature of the wall [°C]

The latent heat transfer in a Climate Cascade can be described in an analogous way with the general formula:

$$\Phi_v = A_{dr}.K_{dr}.r(c_{d.opp} - c_{d.\infty}) + A_{wnd}.K_w.r\ (c_{d.wnd} - c_{d.\infty})$$ (Bronsema, 2013)

Where,
Φ_v = sensible component heat flow [W]
A_{dr} = cumulative surface water droplets in the spraying zone [m^2]
K_{dr} = mass transfer coefficient humidity on droplets [ms^{-1}]
r = evaporation heat of water at the condensing temperature [$J.g^{-1}$]
$c_{d.surface}$ = water vapour concentration at the surface of the droplets [gm^{-3}]
$c_{d.\infty}$ = water vapour concentration in the air [gm^{-3}]
A_{wnd} = total wall surface [m^2]
K_w = mass transfer coefficient air humidity on wall [ms^{-1}]
$c_{d.wnd}$ = water vapour concentration at the surface of the wall [gm^{-3}]

The spray spectrum

For designing the spray spectrum, it is essential to determine the properties of the drop, diameter, area and volume.

The average droplet diameter is expressed mathematically in the formula:

$$D[1,0] = \frac{\sum n.d}{n}$$ (Bronsema, 2013)

Where,
$D[1,0]$= average drop diameter. Often written as d_{10} [mm]
d = diameter of individual drops [mm]
n = number of drops

The relationship between the average drop diameter and its average volume is written as:

$$D[3,0] = \sqrt[3]{\frac{\sum n.d^3}{n}}$$ (Bronsema, 2013)

Where,
$D[1,0]$= average droplet diameter by volume or VMD, Volume Mean Diameter, often written as d_{30} [mm]

Similarly, the relationship between the mean droplet diameter and their mean area is written as:

$$D[2,0] = \sqrt[3]{\frac{\sum n.d^2}{n}}$$ (Bronsema, 2013)

Where,

$D[2,0]$= average droplet diameter on surface or SMD, Surface Mean Diameter, often written as d_{20} [mm]
The relationship between the mean droplet diameter and the mean surface area is usually expressed in the Sauter Mean Diameter SMD that is written as:

$$D[3,2] = \frac{\sum n.d^3}{\sum n.d^2} \qquad \text{(Bronsema, 2013)}$$

Where,
$D[3,2]$= Sauter Mean Diameter, often written as d_{32} [mm]

The active surface of a Climate Cascade is determined by the cumulative surface area of the water droplets that are simultaneously in the cascade. This cumulative area is a function of the number of drops and the SMD d_{32}. The number of drops depends on the water flow and the VMD d_{30}. The residence time of a drop in the Climate Cascade is a function of the height and of the fall speed, which in turn is directly related to the weight and thus to the VMD d_{30}. The falling velocity of a drop or a drop collection is determined by the initial speed, gravity and air resistance. During the fall, the speed increases with the gravitational acceleration g but due to the increasing speed also increases the air resistance. The air resistance is determined by the drag coefficient C_w, which depends on the nature of the flow, laminar, turbulent or intermediate, expressed in Reynolds' number Re according to the formula:

$$Re = \frac{d_{dr}.\rho_l\ (w_{dr}-w_l)}{\mu_l} \qquad \text{(Bronsema, 2013)}$$

Where,
Re = Reynolds number
d_{dr} = drop diameter [m]
ρ_l = density of the air [kg.m^{-3}]
w_{dr} = speed of the drop [ms^{-1}]
w_l = air speed [ms^{-1}]
μ_l = dynamic velocity air [Pa.s]
Laminar flow occurs at Re ≤ 1 and turbulent flow at Re ≥ 300
The drag coefficient C_w can be calculated by the formula of Wallis:

$$C_w = \left(\frac{24}{Re}\right).(1 + 0.1\, R_e^{0.687}) \qquad \text{(Bronsema, 2013)}$$

The minimum inlet pressure for most sprinklers is 0.5 bar with an initial speed in the spray spectrum is realized from ≈ 10 ms^{-1}. The final velocity is independent of the initial velocity. For the sprinkler system, this means that the initial speed can become low; gravity then does its job to reach the final velocity. The pressure at the nozzles can therefore be low, so that the pump energy can be limited. The final velocity w v, t of a water droplet, where the gravity mg is in equilibrium with the drag force F_w is given by the formula:

$$w_{dr.t} = w_l + \sqrt{\frac{2.m.g}{\rho.A_{dr}.C_w}}$$ (Bronsema, 2013)

Where,
$w_{dr.t}$ = final velocity of a drop [ms^{-1}]
w_l = air speed [ms^{-1}]
m = mass of drop [kg]
g = gravitational acceleration
A = projected area of drop [m^2]
C_w = drag coefficient

The heat transfer coefficient by convection $h_{c.dr}$ in the spray zone from air to water drops is a function of several variables such as temperature, speed of the media, viscosity, thermal conductivity, turbulent or laminar flow and geometry of the drops. The following relationship can be used for $h_{c.dr}$:

$$Nu = \frac{h_{c.dr}.d_{10}}{\lambda} = 2 + 0.6\, Pr^{\frac{2}{3}}.Re^{\frac{1}{2}}$$ (Bronsema, 2013)

Where,
Nu = Nusselt's number
$h_{c.dr}$ = convective heat transfer coefficient [$Wm^{-2}\,K^{-1}$]
λ = thermal conductivity coefficient [$Wm^{-1}\,K^{-1}$]
Pr = Prandl's number
Re = Reynolds number

For air in the temperature range of 20 ˚C - 40 ˚C, Pr ≈ 0.71 (Recknagel, 2010) applies.

$$Re = \frac{d_{10}\,.\,(w_{dr} - w_\infty)}{v}$$

Where,
w_{dr} = speed of the drop [ms^{-1}]
w_∞ = speed of air [ms^{-1}]
v = kinematic viscosity [$m^2.s^{-1}$]

The relative air velocity $(w_{dr} - w_{\infty})$ of a water droplet with respect to the air is in high degree depending on the droplet diameter d.

b. Solar Chimney

BASIC MODELLING

A solar chimney can be regarded as a heat exchanger with solar heat as the primary medium and air and a heat-exchanging surface: the glass wall and the inner walls as the secondary medium.

a. Hydraulic diameter

Hydraulic diameter D_h of the channel, defined by the formula:

$$\boxed{D_h = \frac{2.a.b}{a+b}}$$

Where a and b stand for the width and depth of the solar chimney.

b. Thermal draft

$$\boxed{\Delta p = \rho_0 \left[\frac{T_0}{T_1} - \frac{T_0}{T_2} \right] .g.h}$$

Δp	thermal draft	[Pa]
ρ_0	density of air at 0 $_0$ C [kg.m $_{-3}$]	
g	gravitational constant [ms $_{-2}$]	
T_0	air temperature at 0 $_0$ C [K]	
T_1	air temperature outside [K]	
T_2	air temperature in chimney [K]	
$H.$	height of the column	[m]

c. Pressure loss

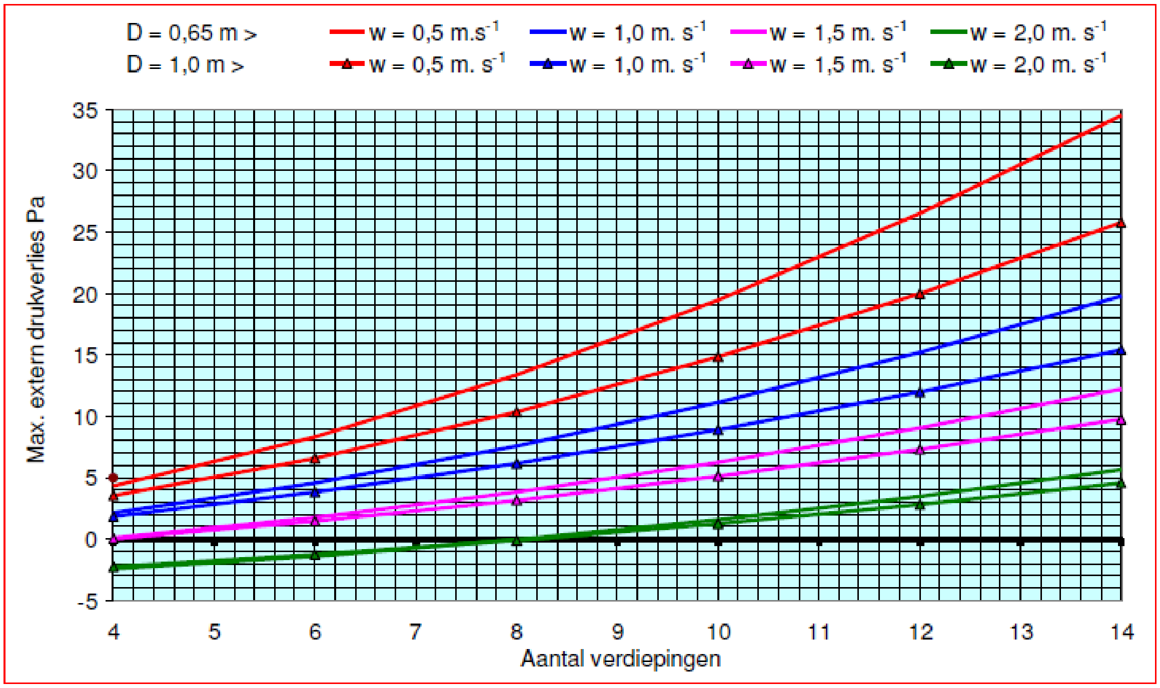
Dynamic pressure

$$\boxed{P_d = 0{,}5\rho w^2}$$

P_d	dynamic pressure [Pa]
ρ	density of air [kg.m $_{-3}$]
w	air speed [ms $_{-1}$]

External pressure loss

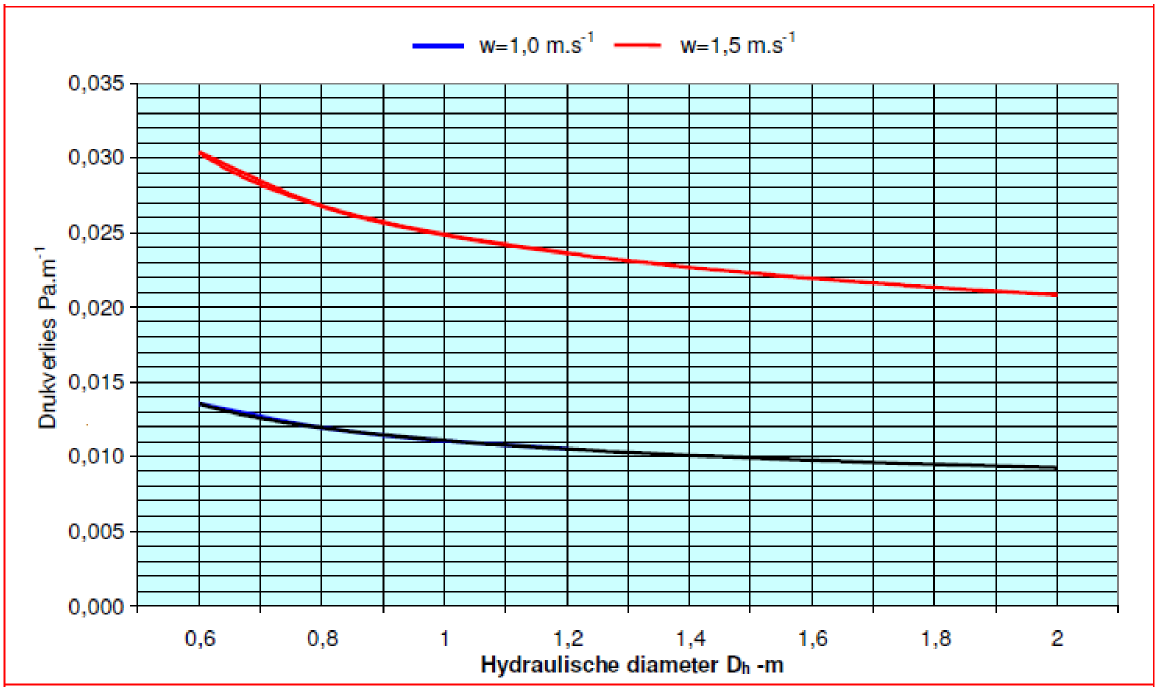
From the following graph



Figuur 4.2.8/3 – Maximum externe druk als functie van luchtsnelheid, aantal verdiepingen en diepte van de zonneschoorsteen –Referentiecondities

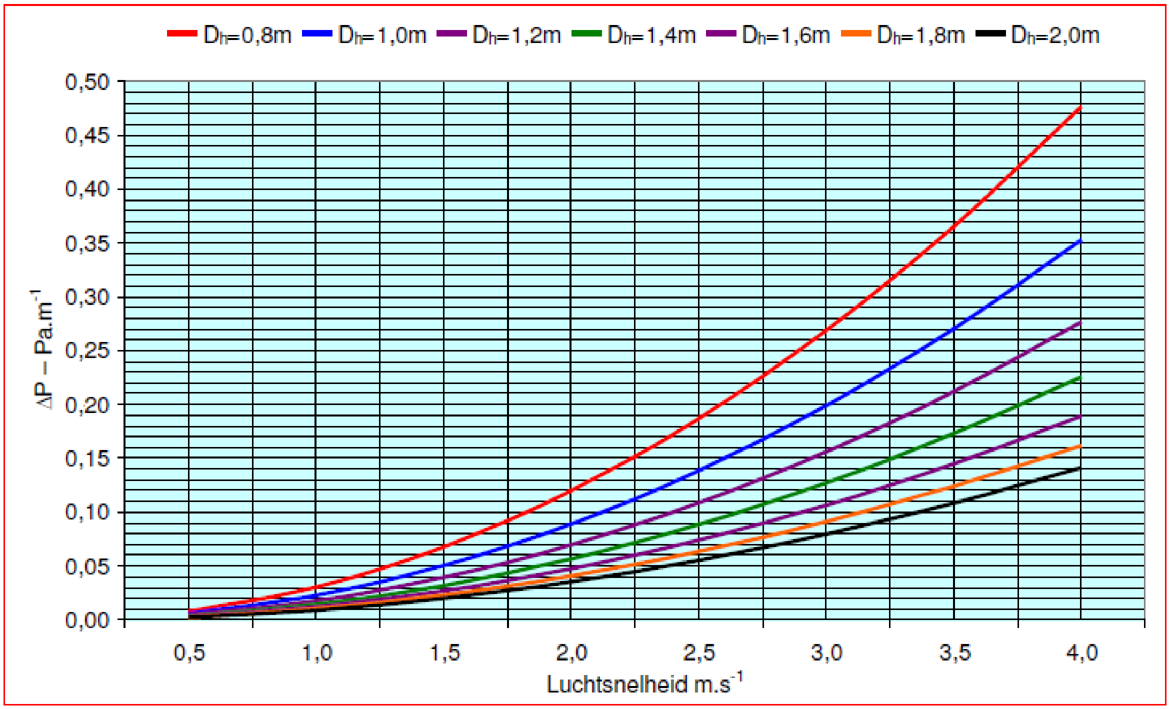
Shunt channel pressure loss

From the following graph



Figuur 4.2.7/2 – Drukverlies shuntkanaal: wrijving + plaatselijke weerstanden.

Solar chimney pressure loss (due to friction)



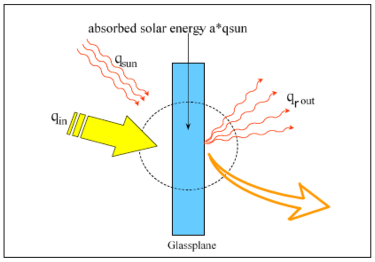
Figuur 4.2.7/1 – Drukverlies door wrijving als functie van de luchtsnelheid – ε =10mm - θ_∞ =25^0 - 40^{0}C

c. Heat Balance in a Ventilated Cavity

The followings are taken from ‘AR1B021_Building Physics_Lecture notes 02_2021_2022_Q1_v2’ by Regina Bokel, as used in SC Excel.

Heat balance of the exterior glass pane:

$$\text{Tglass1:}\ a_{glass1}\cdot q_{sun}+\alpha_e\left(T_e-T_{glass1}\right)=\alpha_c\left(T_{glass1}-T_{cavity}\right)+\alpha_{rad}\left(T_{glass1}-T_{glass2}\right)$$

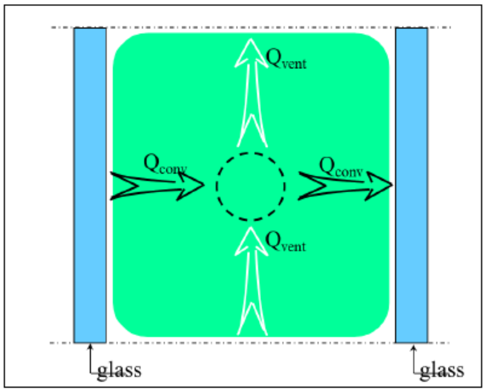


$$\text{Tout:}\ T_{cavity}=\frac{\left(T_{in}+T_{out}\right)}{2}$$

$$\text{Tcavity:}\ \alpha_c\left(T_{glass1}-T_{cavity}\right)\cdot A_{facade}+v_{air}\cdot A_{cavity}\cdot\left(\rho c\right)_{air}\cdot T_{in}=\alpha_c\left(T_{cavity}-T_{glass2}\right)\cdot A_{facade}+v_{air}\cdot A_{cavity}\cdot\left(\rho c\right)_{air}\cdot T_{out}$$

$$\text{Tglass 2:}\ a_{glass2}\cdot\tau\cdot q_{sun}+\alpha_c\left(T_{cavity}-T_{glass2}\right)+\alpha_{rad}\left(T_{glass1}-T_{glass2}\right)=\alpha_i\left(T_{glass2}-T_i\right)$$

Four equations with four unkowns:



$$T_{glass1}\cdot(\alpha_e+\alpha_c+\alpha_{rad})+T_{cavity}\cdot(-\alpha_c)+T_{glass2}\cdot(-\alpha_{rad})=\alpha_e T_e+a_{glass1}\cdot q_{sun}$$

$$T_{glass1}\cdot(-\alpha_c\cdot A_{facade})+T_{cavity}\cdot(2\alpha_c\cdot A_{facade})+T_{glass2}\cdot(-\alpha_c\cdot A_{facade})+T_{out}\left(v_{air}\cdot A_{cavity}\cdot(\rho c)_{air}\right)$$
$$=v_{air}\cdot A_{cavity}\cdot(\rho c)_{air}\cdot T_{in}$$

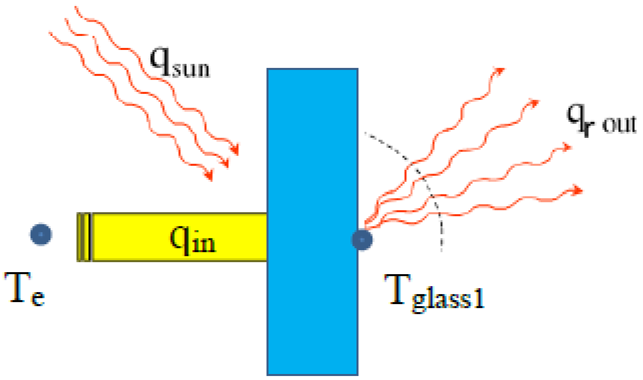
$$T_{glass1}\cdot(-\alpha_{rad})+T_{cavity}\cdot(-\alpha_c)+T_{glass2}\cdot(\alpha_i+\alpha_c+\alpha_{rad})=\alpha_i T_i+a_{glass2}\cdot\tau\cdot q_{sun}$$

$$T_{cavity}-T_{out}\cdot\tfrac{1}{2}=T_{in}\cdot\tfrac{1}{2}$$

Used as matrix in excel as follows.

$$\begin{pmatrix} T_{glass1}\\ T_{cavity}\\ T_{glass2}\\ T_{out}\end{pmatrix}=\begin{pmatrix}\alpha_e+\alpha_c+\alpha_{rad} & -\alpha_c & -\alpha_{rad} & 0\\ -\alpha_c A_{facade} & 2\alpha_c A_{facade} & -\alpha_c A_{facade} & v_{air}A_{cavity}(\rho c)_{air}\\ -\alpha_{rad} & -\alpha_c & \alpha_i+\alpha_c+\alpha_{rad} & 0\\ 0 & 1 & 0 & -\frac{1}{2}\end{pmatrix}^{-1}\cdot\begin{pmatrix}\alpha_e T_e+a_{glass1}q_{sun}\\ v_{air}A_{cavity}(\rho c)_{air}T_{in}\\ \alpha_i T_i+a_{glass2}\tau q_{sun}\\ T_{in}\frac{1}{2}\end{pmatrix}$$

However, considering the insulation of the outer glass plane (assume that all the insulation of the glass is between Tglass1 and Te) as follows



The following can be defined:

$$q_{in}^{*} = \left(T_e - T_{glass1}^{*}\right) \cdot \frac{1}{r_e + R_{glass1}} = \left(T_e - T_{glass1}^{*}\right) \cdot \alpha_e^{*}$$

With an adapted heat transfer coefficient

$$\alpha_e^{*} = \frac{1}{\frac{1}{U_{glass}} - \frac{1}{\alpha_i}}$$

thus the equation for Tglass1 is as follows:

$$a_{glass1} \cdot q_{sun} + \alpha_e^{*} \left(T_e - T_{glass1}^{*}\right) = \alpha_c \left(T_{glass1}^{*} - T_{cavity}\right) + \alpha_{rad} \left(T_{glass1}^{*} - T_{glass2}\right)$$