TOWARDS ADAPTIVE FAÇADE RETROFITTING FOR ENERGY NEURAL MIXED-USE BUILDINGS

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ABSTRACT

The purpose of this paper is to provide a set of guidelines for systemized façade retrofitting in mixed-use buildings to become nearly energy neutral. Heating, ventilating, and air-conditioning (HVAC) are parts of the major energy consumption in buildings. Nevertheless, until recent times, all efforts and attentions have mainly been focused on increasing and optimizing the thermal insulation of the envelope components. The development of dynamic building envelope technologies, which are capable of adapting to changing outdoor and indoor environments, is considered to contribute to achieving nearly energy neutral buildings. However, the potential benefits of this technological development are relevant since the building envelope plays a key role in controlling the energy and mass flows from outdoors to indoors (and vice versa) and, moreover, the facades offer a significant opportunity for solar energy exploitation. Therefore, this paper analyses the potential benefits of responsive façade retrofits. The advantages, limitations and challenges of the technologies have been highlighted and the needed future steps in these areas have also been suggested in a flow chart.

KEYWORDS: *Adaptive façade, retrofit, energy neutral, mixed- use, indoor comfort*

I. INTRODUCTION

The populations in Dutch cities have grown notably in recent years. Amsterdam has shown the fastest population growth rate of the major Dutch cities, which in turn have grown three times faster than the 1% average of the Netherlands as a whole since 2009. Within this timeframe, the city has grown with roughly 11,000 people each year. To accommodate the increase of inhabitants, extra dwellings and accompanying amenities need to be built [1]. The city of Amsterdam is planning to create 70,000 additional dwellings in the next 20 years, an enormous increase of 18% of its current stock [2]. In its policy for 2040, the city government explicates that in order to deal with this spatial challenge, Amsterdam needs to densify current urban forms and transform monotone industrial areas into mixed-use neighborhoods for both work and living [3]. This is because all these people do not only require space for living, but also need energy, heating, cooling, and food. On top of that, they produce waste. All of this leads to more required space and an increase in the total human footprint.

It must be clear that a new way in designing the living environment is needed. Transforming industrial or office buildings to dwellings is one of these strategies with commercial and residential functions. Mixed-use functions are a productive use of space, and they add vitality to urban areas. This development also fits the city's policy for mixed-use areas.

Refurbishment is a necessary step in reaching the ambitious energy and decarbonisation targets for 2020 and 2050 that require an eventual reduction of up to 90% in CO2 emissions [4]. Since the built environment represents one third of Dutch energy demands, retrofitting projects are becoming an important tool for reducing urban fossil fuel dependency and lowering greenhouse gas emissions (Ministry of Economic Affairs, 2014). In this context, the rate and depth of refurbishment need to grow. The number of buildings to be renovated every year should increase, while the energy savings in renovated buildings should reduce the current energy demand by more than 60%. To achieve this, the city of Amsterdam commissioned the report ‘Energiestrategie Amsterdam 2040’, which stated the mission to become the beating heart of a sustainable metropolis by 2040 [5]. Therefore, it is also necessary to enable the building industry to design and construct effective refurbishment strategies.

However, transformation and retrofitting of existing building stock in Amsterdam occurs through a number of projects. Amsterdam’s former Marineterrein is currently one of these projects that is transitioning from a restricted navel site into public space. The city is looking for ways to connect the Marineterrein to the urban fabric, drawn on its historical identity, and include a smart energy infrastructure. As much as 70% of the energy consumed in Amsterdam is used for heating and electricity in buildings. Making savings here and increasing their sustainability will be an especially large challenge for Amsterdam.

In this sense, the purpose of this research is to present a set of guidelines for façade retrofitting, applied to a demo case. Therefore, the former ‘Verbindingsschool’ (VBS), on the Marine is chosen. The building measures 58 x 18 x 17 meters, it is oriented north-south and was built in 1967. These kinds of large school buildings are representative for a big portion of the Dutch school buildings built between 1960 – 1970. For a reduction of the energy consumption, a transformation into a mixed-used building with residential and restaurant functions at the ground level has been chosen. In this context, former stacked school buildings are often thought to be more cost-effective targets for retrofitting, because of the consisted architecture and economies of scale on a large block. Moreover, they are considered to be retrofitted more easily because their exteriors are more uniform than single-family houses – which makes external insulation or replacement glazing easier to install [6].

This leads to the following research question: “How can the energy upgrade with a adaptive systemized façade refurbishment for a mixed- use building program be integrated in the early design phase, in order to support decision making?”

The research question is to find a feasible solution for a mixed-used building transformation being nearly energy neutral.

II. METHODOLOGY

This chapter describes the necessary steps to reduce the energy demands of the demo case for the building simulation to become a nearly zero energy building. First, the overarching approach in form of the *Trias Energetica* is described. The second part introduces the literature review, which gives an overview of the legislative preconditions in the Netherlands and displays applicable retrofittings. Thirdly, benefits of case studies are ranked in a catalogue of climate responsive building components. Fourth, the relevant methods are described with regards to the demo case study. This includes the introduction of the building simulation software that is used to simulate the demo case as well as the description of how individual responsive components can contribute to the demo case.

3. Trias Energetica

To limit the carbon emissions to the highest degree possible the *Trias Energetica* approach, which was developed by the Technical University Delft (E.H. Lysen, 1996) was applied for the demo case simulation. The answer to research question initially follows the first part by identifying those retrofitting measures which are the most suitable to reduce the energy demand of the building. After a successful reduction of the energy demand, the second part intends to find the most appropriate façade retrofit to cover the energy demand. The remaining energy demand is covered by an efficient application of fossil resources. The combination of the aforementioned parts answers the research question in the form of a flow chart as described in **Appendix 3.** The *Trias Energetica* approach heavily influences the selection of the measures by focussing on energy efficiency and energy supply and not on one part individually. This is the main advantage of the approach because it is not limited to one aspect of an energy analysis. The essential principles of the *Trias Energetica* are shown in Fig. 1.

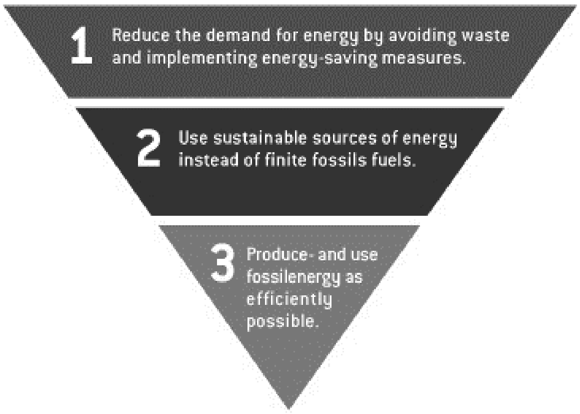

Figure 1. Trias Energetica framework (Rijksdienst voor Ondernemend Nederland, 2013)

IV. Results

4.1. Review of passive climate responsive building components

Conventional heating, ventilating, and air-conditioning (HVAC) systems are having an impact on carbon dioxide emissions, as well as on security of energy supply. A very promising strategy to overcome current technology limitations is represented by revisiting the conventional approach that considers the building as a static object and moves towards the vision where the building is a responsive and dynamic system [7]. In this framework, the building skin is that element of the construction which shows the largest potential, especially if its properties can be continuously tuned so that the best response to different dynamic indoor and outdoor boundary conditions can be achieved. Although it is not possible to state that the dynamic building envelope alone could represent the only solution to achieving a nearly zero energy building, expectations are placed on integrated façade systems. In particular, passive systems must be considered. Extensive research has shown the positive effects of passive design that responds to improve indoor thermal comfort and minimize the energy consumption. The most promising techniques are evaluated below and result in a catalogue of climate responsive building components **Appendix 2.**

4.1.1. Operations of passive solar air heating and ventilation systems

Passive solar heating and natural ventilation technologies share similar working mechanism. The driving force which controls the airflow rate is the buoyancy effect, whereby the airflow is due to the air temperature difference and so as the density difference at the inlet and outlet. Usually, the facades are designed in flexible functions basis whether to trap or store the heat; or create air movement that causes ventilation thus cooling effect [8]. **Appendix 1.** summarizes some of the selected literature reviews of passive solar facade and roof designs which includes the studies of collector performance and energy analysis, findings and recommendations.

4.1.2. Trombe wall

The classical Trombe wall is a sun-facing wall that separated from the outdoors by glazing and air channel in between (without dampers (A and B in Fig. 2). The massive wall absorbs and stores the solar energy through the glazing. Part of the energy is transferred into the indoor of the building (the room) through the wall by conduction. Meanwhile, the lower temperature air enters the channel from the room through the lower vent of the wall, heated up by the wall and flows upward due to buoyancy effect. The heated air then returns to the room through the upper vent of the wall. Some of the challenges with this classical Trombe wall design are as follows:

Low thermal resistance- Once the wall absorbs small amount of solar energy such as during night and overcast condition, extreme heat loss from the building can be occurred because some heat flux is released from the inside to outside of the building [9]. During the winter or cold climate condition at insufficient solar energy, inverse thermo-siphons case can be happened. Once the indoor temperature is higher than the wall temperature, reverse air circulation occurs from the upper vent to the lower vent, which results decreasing the building temperature [9], [10]. It is not possible to measure heat transfer exactly due to the air movement depending on solar energy. The solar radiation is not stable and periodical, which causes temperature fluctuations of the wall [10]. Size of the inlet and outlet openings is affected the convection process and thus impacts the overall heating temperature [10], [11]. Low aesthetic value [12].

Studies have been carried out to improve the classical Trombe wall design. The improvement can be classified into three aspects, i.e. inlet and outlet air openings control, thermal insulation designs, and air channel designs. By installing adjustable dampers at the glazing and adjustable vents of the wall, the classical Trombe wall can be beneficial for winter heating and summer cooling [13,14]. By referring to Fig. 2, in winter, damper B is closed while damper A, lower and upper vents are left open to circulate the heated air return to the room. Whereas during summer, damper A and upper vent are closed. The buoyancy forces generated by the solar heated air between the warm wall and glazing draws room air from the lower vent and the heated air is then flows out to the ambient through open damper B. Thus, during summer the Trombe wall facilitates room air movement for summer cooling. Alternatively, in the case of Trombe wall that without adjustable damper at the glazing, the upper and lower vents are closed when the outdoor temperature is lower than the indoor [15].

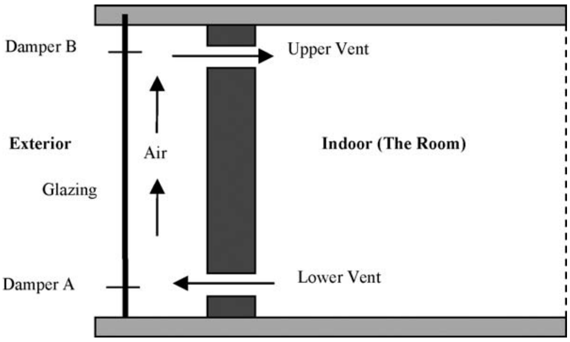

Figure 2. Schematic diagram of classical Trombe wall (without dampers)

Insulation levels of glazing and storage wall influence the surface temperatures and thereby the fluid flow rate. These two thermal insulation methods have their own strengths for different climate conditions. For winter heating, increasing the thermal resistance of glazing is generally more advantageous as this reduces the heat loss through glazing while making use of conductive heat transfer from the storage wall to the room. Richman and Pressnail [16] introduced a low-e coating on a spandrel glass to minimize the radioactive losses to the exterior. Gan [13] proposed that using double glazing could increase the flow rate by 11–17%. Jie et al. [14] introduced the PV-Trombe wall concept that not only improve the aesthetical aspect but also able to capture the heats and simultaneously reduce the PV cells temperature. On the other hand, insulating the interior surface of the storage wall for summer cooling can avoid excessive overheating due to south facing glazing [13]. Matuska and Sourek found that there was no effect on indoor comfort when sufficient insulation layers were applied on the storage wall [17].

In addition, composite Trombe–Michel wall has also been studied to overcome the heat loss from the inside to the outside of building [15]. The concept of composite Trombe–Michel wall is similar to the traditional Trombe wall except there is an insulating wall at the back of the massive wall (Fig. 3). The thermal energy can be transferred from outside to the interior air layer by conduction through the massive wall. Then it can be transferred by convection while using the thermo-circulation phenomenon of air between the massive wall and the insulating wall. During non-sunny days, winter or at nights, the vents in the insulating wall are closed. Hence, due to greater thermal resistance of this design, the thermal flux that going from indoor to outdoor is reduced.

Typically, Trombe wall is a sensible heat storage wall. Another innovative design of Trombe wall is filling phase change materials (PCM) into the masonry wall to store the latent heat. For a given amount of heat storage, the phase change units require less space and are lighter in weight compared to mass wall [9]. Therefore, it is convenient for building retrofitting. Studies indicated that concrete–PCM combination Trombe wall can be used to develop low energy house as it is an effective energy storage wall [10,12].

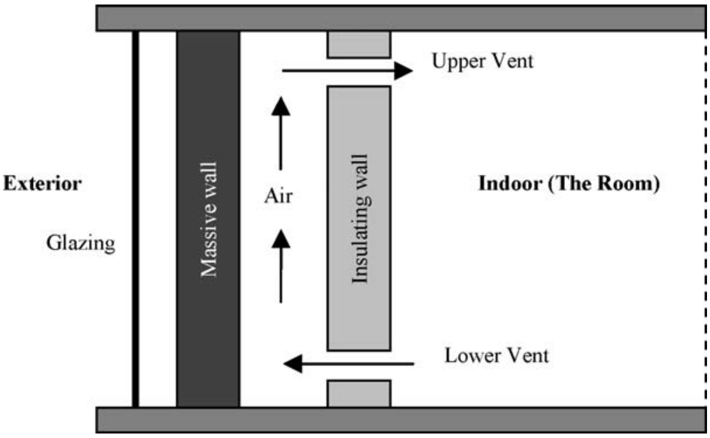

Figure 3. Schematic diagram composite Trombe-Michel wall

4.1.3. Solar chimney

The purpose of the solar chimney is to generate airflow through a building, converting thermal energy into kinetic energy of air movement. The driving force which controls the airflow rate through the solar chimney is the density difference of air at inlet and outlet of the chimney. It provides ventilation not only for cooling but also heating if fan is used to direct the heated air into the building. When solar chimney is attached to wall, the working mechanism is similar to Trombe wall. It operates as passive heating by supplying warm air that heated up by the solar collector into the room. For cold or moderate climate, when the outdoor temperature is lower than the indoor temperature, solar chimney is functioned as passive cooling where natural ventilation is applied. However, for hot climate, when the outdoor temperature is higher than the indoor, it operates as thermal insulation to reduce heat gain of the room. These three different modes are as illustrated in Fig. 4 [19].

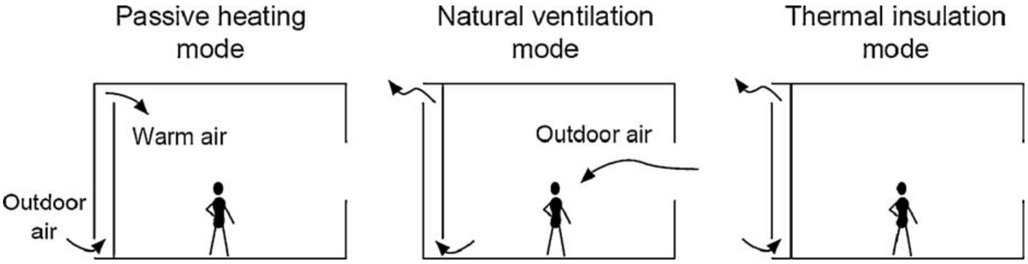

Figure 4. Solar chimney operation models

The simplest and most obvious layout is to have a vertical chimney. Nonetheless, this may not be architectural attractive in term of aesthetics aspect. So a cheaper and less visually obtrusive format is to lay the collector along the roof slope while for greater height, a combination of both types may be used [20,21]. Some of the selected studies of solar chimney performance were as shown in **Appendix 1**. They are such as typical solar chimney, vertical types that similar to Trombe wall and double facades which hybrid with PV panel. Studies showed that solar chimneys are able to warm the air or ventilate the room air to create cooling effect even during cloudy days. However, depend on the local climate conditions, when solely solar chimney cannot satisfy the thermal comfort, other active or passive heating and cooling systems might need to apply.

4.1.4. Solar roof

Methods of passive cooling by roof are such as water firm, roof pond, roof garden and thermal insulation. Solar roof ventilation may perform better than Trombe wall design in climates where the solar altitude is large. This is because roof collectors provide larger surface area to collect the solar energy and hence higher air exit temperature [22]. Nevertheless, Khedari et al. [23] observed that with only roof solar collector system, there is little potential to satisfy room thermal comfort. Additional device such as Trombe wall to be used together with roof solar collector would provide better cooling effect. Dimoudi et al. [24,25] studied the thermal performance of the ventilated roof during summer and winter. The ventilated roof component consisted of reinforced concrete slab and insulation layer as the typical component but with an air gap between the insulation and the upper prefabricated slab. Results showed that there was no clear improvement of the thermal performance during the winter period but its main advantage is during the summer period, whereby the building is protected from the solar gains due to its insulation properties. On the other hand, Zhai et al. [26] has reported that the efficiency of double pass of air gap can induce more air change rate and hence is generally 10% higher than that of single pass roof solar collector **Appendix 1.** Roof-integrated water solar collector that made of several layers of glass followed by water chamber and metallic sheet at the bottom was developed by Juanico [27] and could be used for domestic heating and cooling systems.

4.1.5 Passive solar cooling via evaporative effect

Passive solar cooling technologies which generate cold air could be found in the roof designs but it is not common for façade designs. Most of passive solar cooling technologies through facades are based on buoyancy mechanism that forces the air movement to ventilate the air in the room and thus creates cooling effect. This is as discussed in previous section as natural ventilation. In this section, the focus is to discuss on passive solar cooling via evaporative effect. Evaporative cooling is the oldest technique of cooling and may be applied in both active and passive systems. Conventional mechanical cooling systems that require high energy cost and harm the environmental have prompted the researchers to begin looking back at the evaporative technique and trying to improve its efficiency [28]. Hence it has been intensively used as evaporative cooler or heat exchanger in air-conditioning system. However, building integration of evaporative cooling is just a handful amount and yet to be developed.

Amer [29] has found that among some passive cooling systems, evaporative cooling gave the best cooling effect, followed by solar chimney, which reduced inside air temperature by 9.6 ºC and 8.5 ºC, respectively. Evaporative cooling process uses the evaporation of water to cool an air stream. Basically water absorbs heat from the air (surrounding) to evaporate into vapour. Thus, reduce the temperature of the air or surrounding. In Middle East wind towers were developed to scoop the cool wind into the building, which was made to pass over water cisterns to produce evaporative cooling and a feeling of freshness [19]. Evaporative cooling can be classified into direct and indirect evaporating cooling Fig. 5.

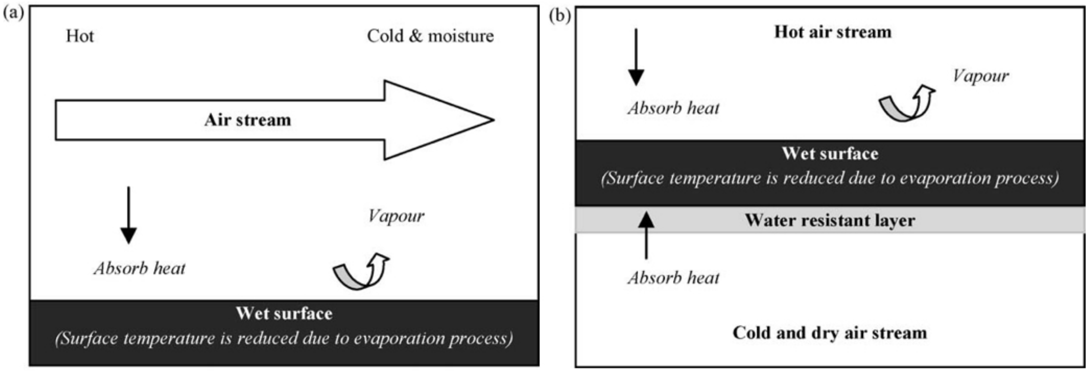

Figure 5. Evaporative process for (a) direct evaporative cooling and (b) indirect evaporative cooling

4.2. Building integration of evaporative cooling

One of the building integration applications of evaporative cooling is porous roof. During periods of precipitation, rainwater penetrates through the porous layer and is stored within the layer. The porous layer retains a significant amount of rainwater, which is released back into the atmosphere via evaporation during sunlight hours. When evaporation takes place, the surface temperature of the porous layer decreases due to the release of latent heat. Therefore, heat flux from the roof slab, which could raise the room temperature of the building, would also be reduced. When the air is at high humidity during night time or on cloudy days, the porous layer adsorbs moisture from the air and continues to cool the roof materials its high evaporation rate tends to cool down the surface temperature. A previous research study showed that siliceous shall comprise of a high number of mesopores are effectively keeping surface moisture from vapour adsorption, is found to have the greatest evaporation performance [30]. As a result, siliceous shale is able to reduce the roof surface temperature up to 8.63 ºC as compared to mortar concrete. Raman et al. [21] on the other hand developed solar air heaters for solar passive designs that cooperate with evaporation for summer cooling. The system consists of two solar air heaters with natural flow, one is on the roof another one is on the ground. The roof air heater acts as an exhaust fan, venting out the air from the room during sunshine whereas the air heater on the ground is functioned as air heater during winter and as an indirect evaporative cooler during summer. However, the system performed well during winter but not for summer cooling. As a result, modifications were made whereby the south wall collector and a roof duct were wetted on the top side by an evaporative cooled surface were constructed. The results showed that the modified system was able to give better thermal comfort for both seasons.

4.1.4. Passive solar; combined technologies

Proper design of orientation, structure, envelope, construction materials of a building is important to control the thermal loads from the solar heat gain, hence reduce the HVAC size, which in turn enhancing the feasibility of solar cooling technologies. Solar passive features can add 0–15% to design and construction costs [31].

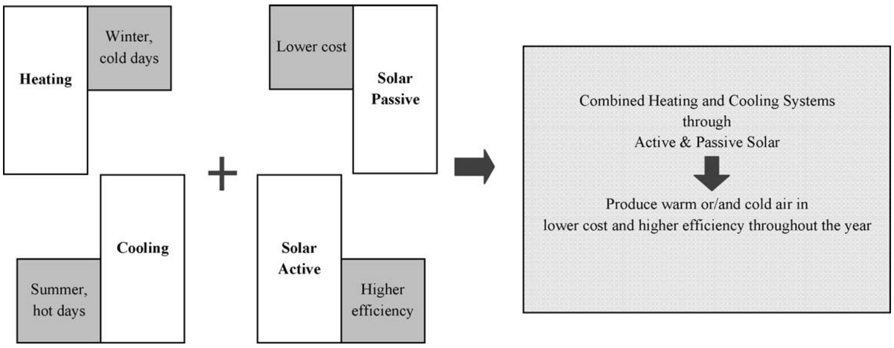

Fig. 7. Overcoming the limitations by combining heating and cooling systems, and the solar active and passive technologies.

However, paying this initial cost in return is long life energy saving. For instance, the solar H.P. Co-operative Bank building in India has demonstrated that solar passive designs, double glazing are able to reduce the total heat loss by about 35% [32]. Integrating the solar heating and cooling systems in building envelope is a necessity if the systems are to be economically feasible. Typically, it could be roof or facade integrations such as wall, balcony, awning or shade of the building. The integration is only possible if the design of the solar system is included in the design of the building itself. The major component of any solar system is the solar collector. They are usually black or dark in color to maximize the absorption and minimize the emittance of radiation that reaches the surface. Unfortunately, black surfaces are not always considered aesthetically acceptable in all cases, e.g. facade integration. Therefore, active solar collectors are often being considered as technical element [33,34]. They are installed separately from the building or confined to the roof top so that they are less visible to minimize the building aesthetic impact [17,35]. Consequently, the installation cost of an active solar heating or cooling system might consider as additional initial cost of the building. On the other hand, passive solar designs are building integrated whereby facades or roofs are part of the heating or cooling system components. This in turn reduces initial cost. Moreover, passive solar designs are the function flexibility. Designs such as Trombe wall and solar chimney are able to provide warm air or create cooling effect depend on the climate needs by damper controllers. As compared to the active solar thermal technologies, the solar collectors are only meant for collecting heat. The heated air or water is either directly used by building occupants or to be used as heat source for heating or cooling systems. The combined heating and cooling systems require an additional system that not as simple as shifting the damper controllers.

5. Case studies

A numerous of cases are documented based on their expression of climate-responsive design to discover most dominant aspects that this kind of design involves. The case studies together with the results of the literature reviews are ranked in a catalog for adaptive building components **Appendix 4**. From this, the right façade renovation can be chosen to improve the comfort of the indoor climate. Afterwards, different ways of articulation will be classified to show how we can express these design elements, which forms a decision-making flowchart for further adaptive façade improvements at the end **Appendix.**

6. Building simulation

The demo case simulation represents the building envelope of the building at the beginning of the master thesis in September 2017 **Appendix 5.** The modelling of optimal energy efficiency, as a base-line for further adaptive modifications, through passive measures is done through EnergyPlus together with the plugin OpenStudio (Fig. 6). EnergyPlus is able to simulate heating, cooling, lighting, ventilation, and other energy flows as retrofitting for the current demo case building as well as water use accurately Boyano et al. [36]. This is done by simulating heat and mass transfer flows and complemented by adequate weather data for The Netherlands [37]. The building is divided into different thermal zones with specific properties, as described before in the 3D model simulation. Moreover, exact properties like windows, shape of shading surfaces, and building schedules are applied to simulate the building close to reality. All simulations for the measures and packages build up directly on the demo case.

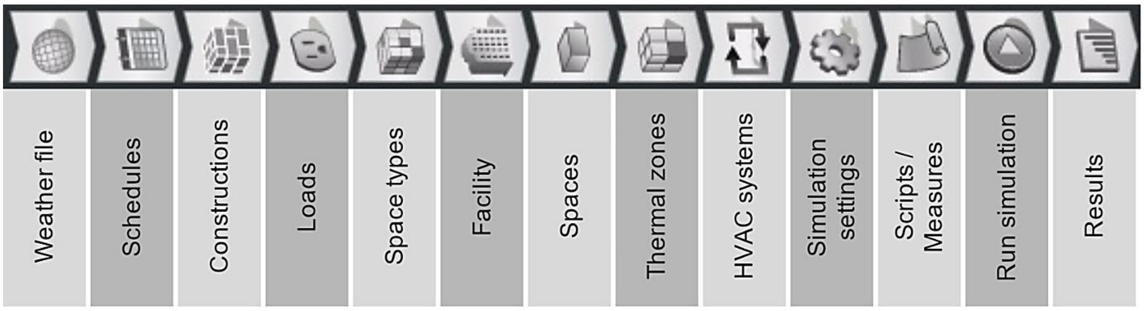

Figure 6. OpenStudio workflow based on the actual structure of the software (OpenStudio version 2.3.0)

The dynamic character of the simulation is far more advanced and accurate than a steady-state simulation thanks to the consideration of time-dependent changes Harrell [38]. A static simulation would neglect building schedules and weather where a dynamic simulation does not. It would only make a statement about a specific point in time and not a whole-time frame Saelens et al. [39]. The outcomes of these simulations shows a total usage of 278.6 kWh/m2/yr for the proposed mixed- use building transformation **Appendix 6.**

VII. Conclusion and Discussion

This research investigated the potential of energy and carbon emission reduction in combination with a building transformation for mixed-use. For this purpose, a former school building in Amsterdam was assessed as a demo-case. In this paper, an overview of the technological evolution of the building envelope that has taken place, ranging from traditional to adaptive components, has been given, focusing on one hand on the different approaches that have characterized this development and, on the other hand, providing some examples of innovative solutions and highlighting the main potential and criticism resulting from an intensive experimental activity on this field. Data used in this research obtained from literature and case studies for some passive solar technologies for façade retrofitting. The researches reviewed were grouped into the following four systems: building-integrated Trombe wall, unglazed transpired solar façade, solar roof, and solar chimney.

With this study, relevant passive solar designs for heating and cooling have been analyzed; they generally have their own limitations. Single passive solar designs might not sufficient to provide indoor thermal comfort, particularly regions that have extreme climates. For instance, although Trombe wall and solar chimney is a less advanced technology, some energy efficiency gains are expected. However, there is still significant potential for optimization. Responsive building components can play the key role of the building envelope towards highly energy efficient building by controlling the energy and mass flows from outdoors to indoors (and vice versa).

In order to achieve an energy demand analysis of the demo case and to assess the potential to reduce the primary energy demand and carbon emissions, OpenStudio together with EnergyPlus as a simulation program is used to model all the building characteristics. This information is complemented by adequate data for the Netherlands. After that, the current use was observed without any additional passive or active measures from natural sources through a simulation programme. The results have shown that the building uses 278.6 kWh/m2/yr, which is below the set norm of 300 kWh/m2/yr for the average energy-use of an apartment building with a restaurant function on the building's ground level. Most potential for becoming an energy neutral building can be gained in heat-losses through the side walls, by replacing these for relatively big glass surfaces with responsive building components. A flow chart has been developed for testing this, so that the right choice for the definitive design can be made during the development phase.

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Appendix 1: Summary selected reviewed passive solar design.

Facade/roof designs	Special features	Performance			Benefits / findings	Limitations / recommendations
		Given conditions	*Temperatures (instantaneous efficiency, %)*	*Flow rate*		
Solar chimney	Vertical, similar to Trombe wall.	I = 650 W/m$^{2;}$ air gap depth = 0.2 m.	Exhaust air = 39 ºC; indoor air = 30 ºC (41%).		• Temperature rise and air velocity increased with solar radiation. • Temperature rise decreased with air gap depth. • No reverse air flow circulation was observed even at large gap of 0.3 m.	N/A
Solar wall	Similar to Trombe wall, consists of glass cover, air gap, black metallic plate, insulator.	I = 406 W/m^2; T$_a$ = 30 ºC height = 1 m; air gap depth = 0.145 m.	Exhaust air = 42 ºC; indoor air = 28 ºC.	Mass flow rate = 0.016kg/s.	• Temperatures increased with increased wall height and decreased gap.	• In very hot season, providing residents' comfort is insufficient by natural ventilation but it is able to reduce the heat gain which in turn reduces the cooling load.
Double facades	(i) Outer skin: glaze; inner skin: glaze/ (ii) Outer skin: PV panel; inner skin: glaze.	Cavity width = 0.8 m; inlet area = outlet area.	N/A	(i) Airflow rate = 0.27m$^{3/}$/ms. (ii) Airflow rate = 0.36m^3/ms.	• PV facade increased the efficiency of PV cells when oudoor air temparature is higher than the indoor.	• The outer skin temperature of PV panel increased depending on the degree of transparancy.
Single-sided heated solar chimney	(i) Outer skin: glaze; inner skin: glaze/ (ii) Outer skin: PV panel; inner skin: glaze.	Length = 1 m; breath/ height = 0.1; inlet temperature = 20 ºC	Exhaust air = 33 8C.	Airflow rate = 0.5kg/s.	• The airflow rate reaches maximum when breath/ height = 0.1	• The optimised heght can be determined according to the optimised section ratio of breath to height and available practical field conditions.
Solar chimney	Under hot and humid climate conditions, studies inculuded during clear sky, partly cloudy and cloudy days.	(i) Clear sky: T$_a$= 35 ºC I = 800 W/m^2; wind velocity = 2.6 m/2. (ii) Partly cloudy: T$_a$= 34 ºC; I = 594 W/m^2; wind velocity = 2.5 m/s. (iii) Cloudy day: T$_a$ = 32 ºC; I = 509 W/m^2; wind velocity = 1.8 m/s.	(i) Exhaust air = 38 ºC; indoor air = 33 ºC. (ii) Exhaust air = 36 ºC; indoor air = 32 ºC. (iii) Exhaust air = 33 ºC; indoor air = 32 ºC.	N/A	• Solar chimney can reduce indoor temparatur by 1.0 - 3,5 *C compared to the ambient temperature of 32- 40 *C.	• Indoor temperature can be further reduced by 2.0 - 6.2 ºC with combination of spraying of water on the roof.
Roof solar collector	Air gap and openings of roof solar collector.	N/A	N/A	10 - 100 m^3/h.	• Lager air gap larger and equal size of openings induced higher rate of airflow rate.	• Insufficient natural ventilation to satisfy redidents' comfort. • Another device such as Trombe wall might be needed to improve comfort performance.
Rood-integrated water solar collector	Roofintegrated, combining the conventional roof and flat plat solar collector by replacing water-coil and internal insulation with water pond and metallic sheet.	N/A	N/A	N/A	• Able to control heat delivery adapt with the environmental conditions. • Able to create heating or cooling effects. • Provide hot domestic hot water during winter.	Large area of roof is needed.
Roof solar collector	Single and double pass designs.	I = 500 W/m^2; T$_a$ = 0 ºC; mass flow rate 2000 kg/h	(i) Single pass: supply air = 12 ºC; indoor air = 8 ºC (27%). (ii) Double pass: supply air = 18 ºC; indoor air = 13 ºC (39%).	N/A	• Instantaneous efficiency of double pass was 10% higher than single pass collector whether spacing heating or natural ventilation.	• Two or more shorter collectors in parallel are recommended instead of one longer collector.

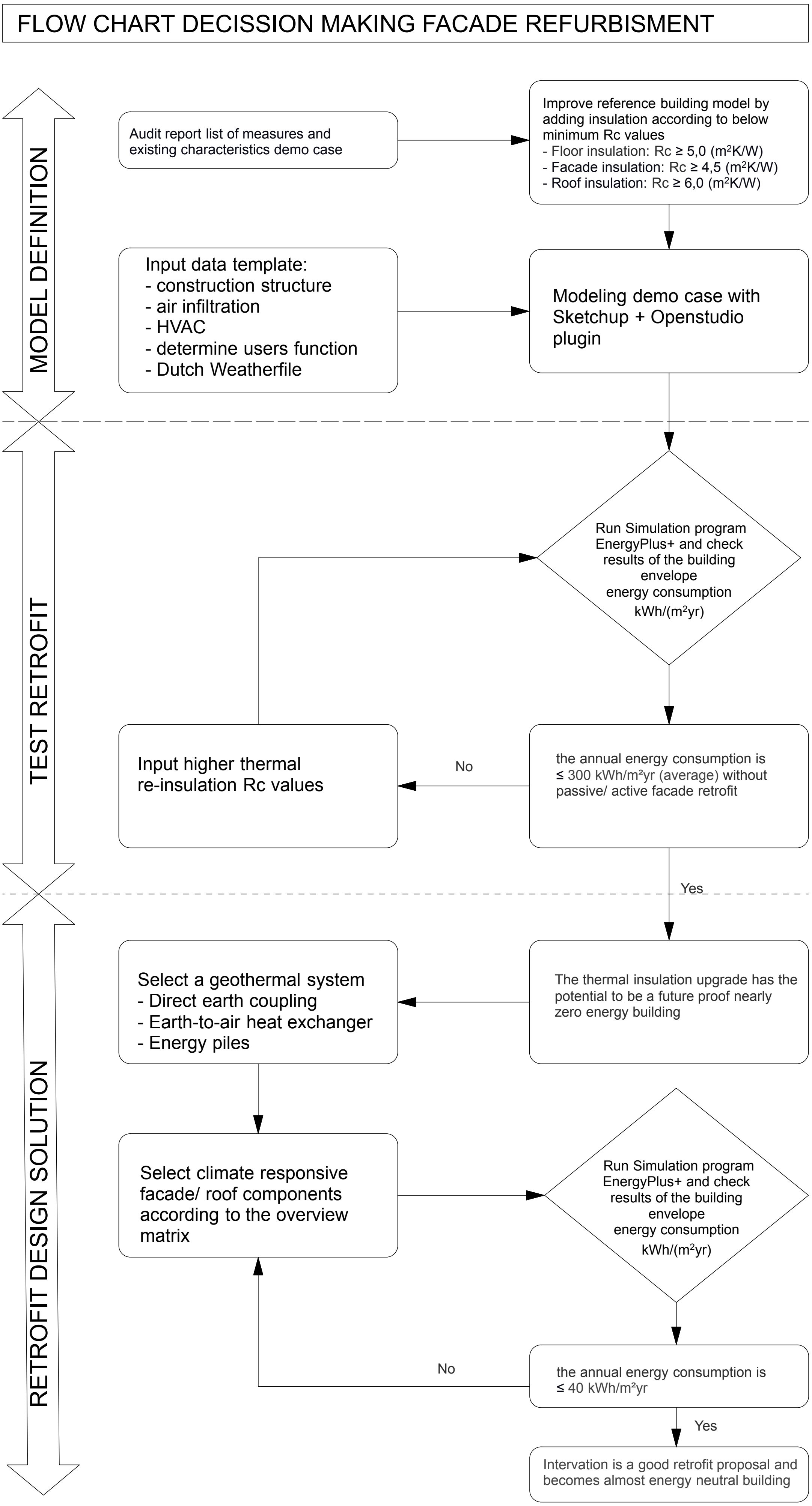
Table. 1. Summary passive solar design

Appendix 2: Catalogue building components

Catalogue of climate responsive building components

	Natural source					Energy flow threatment						Building element integration							Comfort		
	Earth	Sun	Wind	Waste	Water	Exchange	Prevent	Promote	Redirect	Long-term storage	Short-term storage	Façade / External wall	Foundation	Internal floor	Internal wall	Roof	Space	Window / Opering	Cooling	Heating	Ventilation
Daylight system																					
Advanced passive glazing		✓					✓											✓	✓	✓	
Light shelves		✓					✓		✓									✓			
Skylights		✓						✓								✓					✓
Insulation system																					
Dynamic insulation			✓	✓		✓						✓				✓				✓	✓
Translucent insulation		✓					✓	✓				✓				✓				✓	
Thermal shutters				✓			✓											✓		✓	
Geothermal system																					
Direct earth coupling	✓					✓							✓						✓		
Earth-to-air heat exhanger	✓		✓			✓							✓						✓	✓	✓
Energy piles	✓					✓				✓			✓						✓	✓	
Roof systems																					
Green roof		✓			✓		✓				✓					✓			✓	✓	
Roof pond		✓	✓		✓			✓								✓			✓	✓	
Thermal storage system																					
Thermo-activation				✓							✓		✓	✓					✓	✓	
Phase change materials		✓		✓							✓	✓			✓	✓			✓	✓	
Passive thermal mass		✓		✓							✓	✓	✓	✓	✓				✓	✓	
Trombe wall		✓		✓							✓	✓								✓	✓
Ventilation system																					
Hollow core				✓							✓			✓					✓	✓	✓
Solar chimney		✓						✓				✓								✓	✓

Appendix 3: Flow chart decission making



4# Case Studies

For this research I gathered a list of buildings, both international and in The Netherlands, which implemented high performance building adaptive facade systems. All of them are given in detailled brief case studies. The information contained in the brief case study examples are collected from published articles, books, and websites, so some performance claims may be unsubstantiated. Note, many of the cases integrate two or more types of facade systems.

CASE STUDY 1#

Blue Ridge Parkway Destination Center

Project summery

Location
Asheville, NC, USA

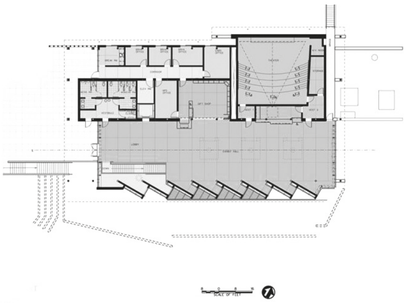
Architect
F Lord, Aeck & Sargent

Buildingtype
Visitor Center

Client
National Park Service

Completed
2007

Sustainable features
Green roof
Hydronic radiant heated flooring
High-efficiency HVAC system with an energy recovery whee
Low-tech passive solar Trombe walls



Site plan

About the project

The Blue Ridge Parkway Destination Center in Asheville, North Carolina features an award-winning film and exhibits which highlight the natural and cultural heritage, economic traditions, and recreational opportunities found in Western North Carolina and along the Blue Ridge Parkway. The visitor center houses a 70-seat theater, information and orientation services, and a retailshop. Nestled into a hillside, the LEED Gold certified building evokes a "tree-house" atmosphere and is projected to use 75 % less energy than a comparable conventionally designed facility. The project achieve more (11) than the maximum 10 points allowable in the USGBC's optimized energy performance category. That's because, in addition to numerous energy conservation integrated design strategies such as hydronic radiant heated flooring and a high-efficiency HVAC system with an energy recovery wheel, our most innovative strategy was the use of high-tech computational fluid dynamics (CFD) modeling to analyze our use of low-tech passive solar Trombe wall.

Trombe walls use the sun to heat a small air space between a glass wall and a heavy-mass wall such as concrete. The trapped heat is then transferred into the building, either indirectly through the concrete or, as is the case with the Destination Center, directly through vents. To study the walls, Lord, Aeck & Sargent partnered with Pennsylvania State University's Applied Research Laboratory (ARL) to construct the CFD computer model to study the movement of fluid flow - air in this case - and heat transfer. The Destination Center's south façade features a row of 13 passive solar Trombe walls in a saw-tooth formation; the walls help to heat the building in the winter and cool it in the summer.

CASE STUDY 2#

Project summery

Location
Amsterdam, The Netherlands

Architect
bureau SLA

Buildingtype
Learning Centre

Client
City of Amsterdam

Completed
2015

Sustainable features
PV Solar cells
Trombe walls

Nature & Environment Learning Centre

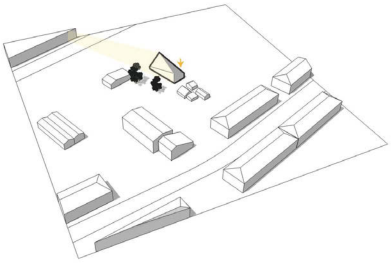
About the project

The Nature and Environment Learning Centre (NME) is a energy neutral building. This in itself is uninteresting. What makes the energy management of the new school building interesting is that sustainability is visible, tangible and perceptible. The particular shape of the building allows, for example, an optimal orientation of the roof towards the sun. Another example are the large concrete slabs in front the building. They heat up fresh air before it enters the classrooms.

The layout of the plan is almost symmetrical. On the left and right are classrooms, on the first floor two identical rooms serve as office space and a canteen. In the middle is nothing: through the glass entrance doors one can look straight at the school gardens on the other side of the building. The long facades consist from top to bottom of window frames of about a meter wide. Operable window parts are cladded with white lacquered wooden panels, so that the pattern of long vertical window frames is not interrupted. On the south side eight dark concrete slabs are mounted to the wall. In front of the slabs is a large glass pane and at the top is one can see a long narrow wooden hung window.
These are the so-called Trombe-walls. The dark concrete slab warms up by sunlight and accumulates - by its mass - the heat. In the cavety between the glass pane and the hot concrete slab ventilation air is guided by means of natural draft. The hung window leads the fresh, pre-heated ventilation air into the classroom. In the warm months of the year, the hung window may close and other parts of the façade can be opened.

The Trombe-wall has never secured a foothold in the design of sustainable buildings, a handful of self-construction projects of some fanatical ecological builders after. That is unfortunate. The Nature and Environment Learning Centre shows that Trombe-walls not only work very well, but that they can also create an architecturally interesting setting. In order to increase the surface area of the concrete walls a pattern of recessed half-shells is fitted. The pattern can be read, with some effort, as an anthology of Dutch nature poetry.

Site plan



Optimal sun diagram

CONTINUED CASE 2#

Project summery

Location
Amsterdam, The Netherlands

Architect
bureau SLA

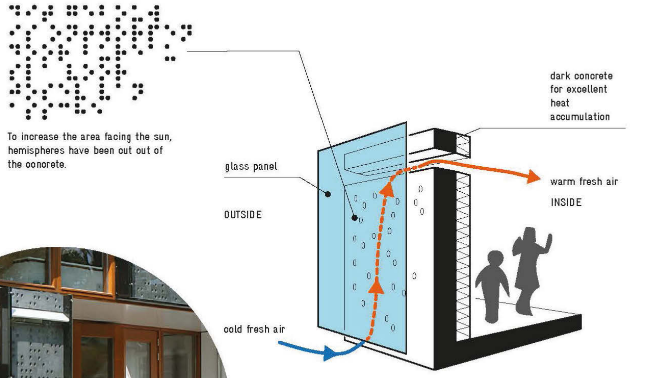
Buildingtype
Learning Centre

Client
City of Amsterdam

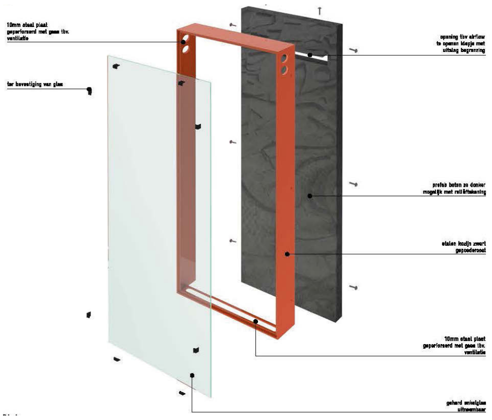
Completed
2015

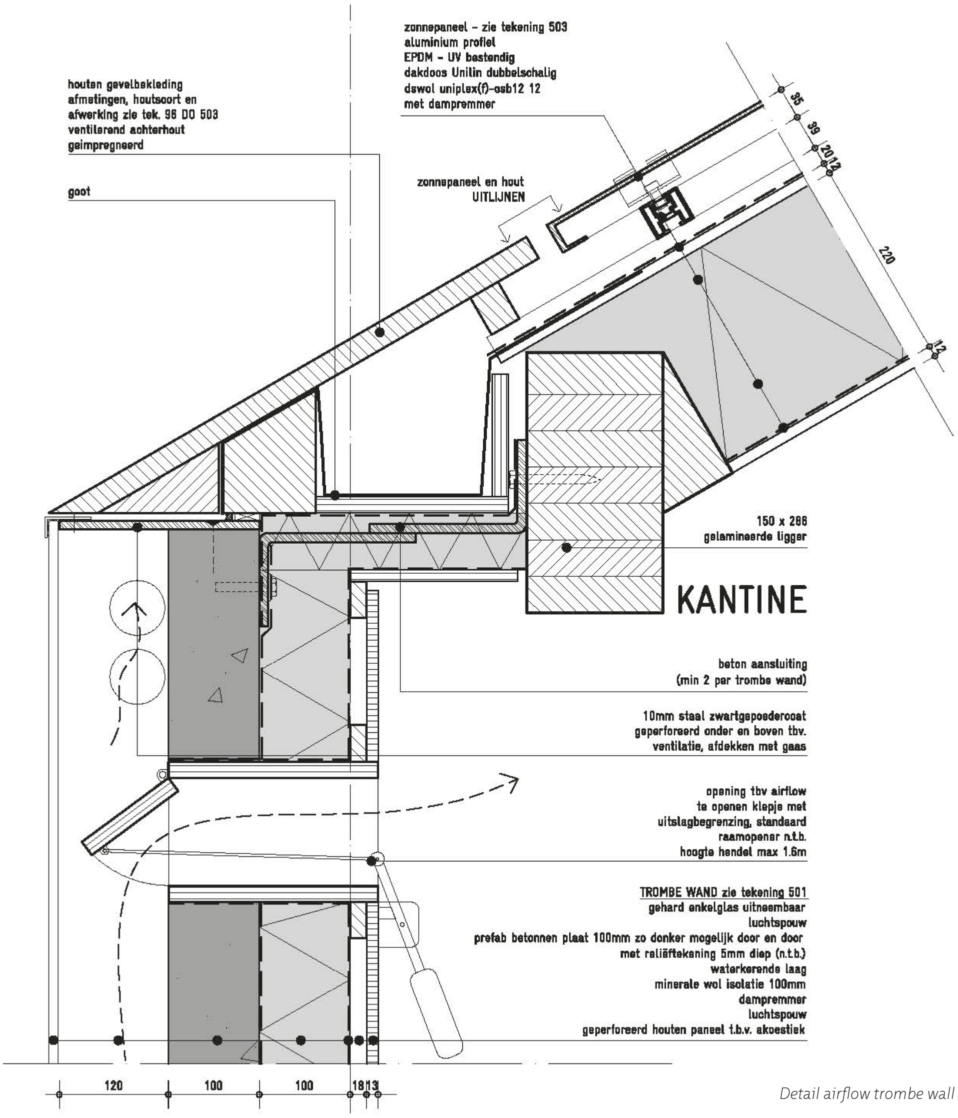
Sustainable features
PV Solar cells
Trombe walls

Nature & Environment Learning Centre



Working principles trombe wall





Detail airflow trombe wall

CASE STUDY 3#

Sony City Osaki

Project summery

Location
Tokyo, Japan

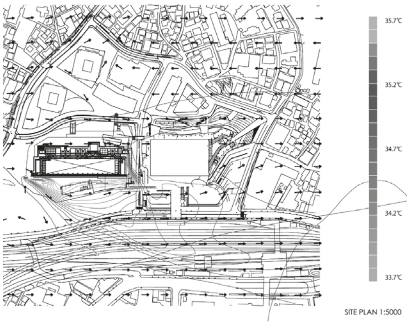
Architect
Nikken Sekkei

Buildingtype
Office

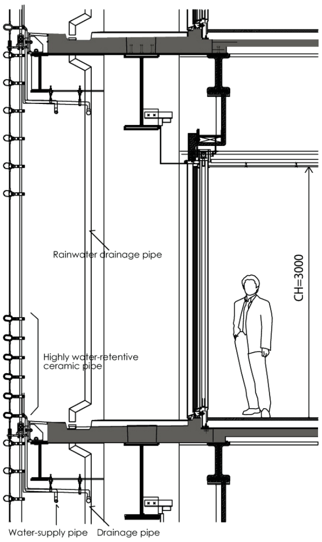
Client
Sony Corporation

Completed
2011

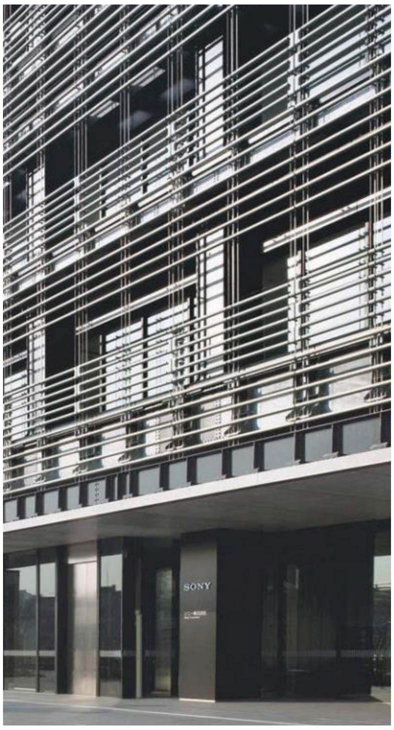
Sustainable features
Evaporative cooling



Site plan



Facade section ceramic cores

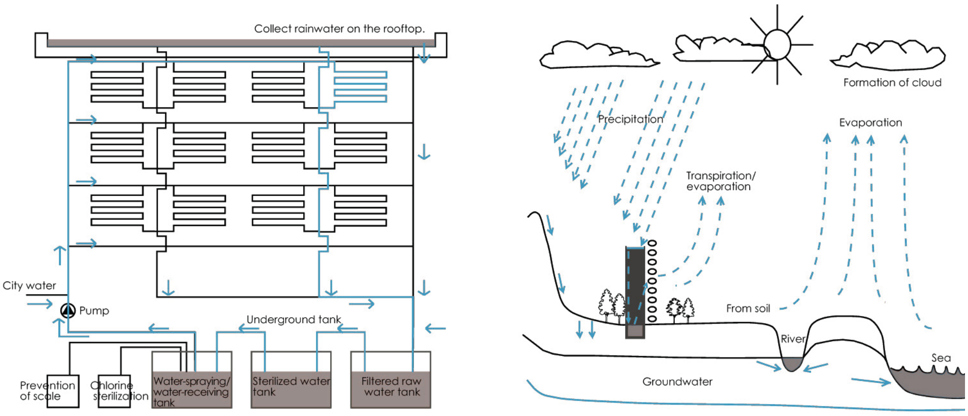


About the project

Developed by Japanese architecture firm Nikken Sekkei, the Sony City Osaki Building in Tokyo is the first building in the world to use a natural 'BioSkin' cooling concept, which draws heat away from the building as water evaporates around it, thus causing the surrounding air to cool. The BioSkin concept was inspired by traditional Japanese techniques to cool the air such as bamboo shading screens, called Sudare, and a water spraying technique called Uchimizu.

The system comprises specialized ceramic louvres which funnel rainwater through the system. In effect, the system acts as an enormous sprinkler for cooling the building environment. The BioSkin tubes are made from extruded aluminium cores, with a highly water-retentive terracotta shell attached to the core via an elastic adhesive. When rainwater collects on the rooftop, it drains to a subsurface storage tank where the water is filtered and sterilized. The water is then pumped up and circulated through the pipes, which are incorporated into balcony railing and horizontal screens.

The rainwater penetrates outward through the ceramic cores, evaporating from the pipe's surface and cooling the air. Excess water is drained down to the ground surrounding the building, helping to recharge the ground water cycle and reduce the load on drainage systems. Based on tests and experiments, it has been shown that as the water evaporates, the temperature of the ceramic pipes and the surrounding air drops by an estimated 2 degrees Celcius.



Cutting edge practice of biomimicry integration

CASE STUDY 4#

Project summery

Location
Singapore, Malaysia

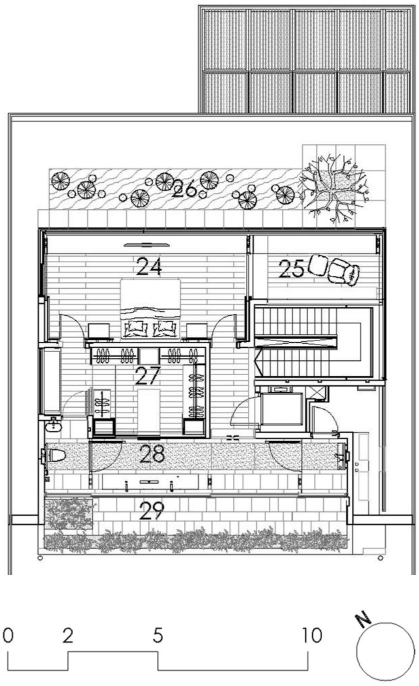
Architect
Maria Warner Wong

Buildingtype
Residential

Client
Private

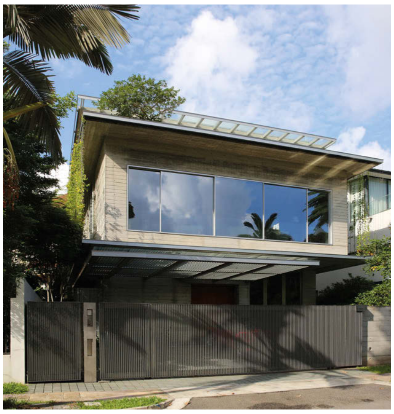
Completed
2013

Sustainable features
Evaporative cooling



Site plan

Private house

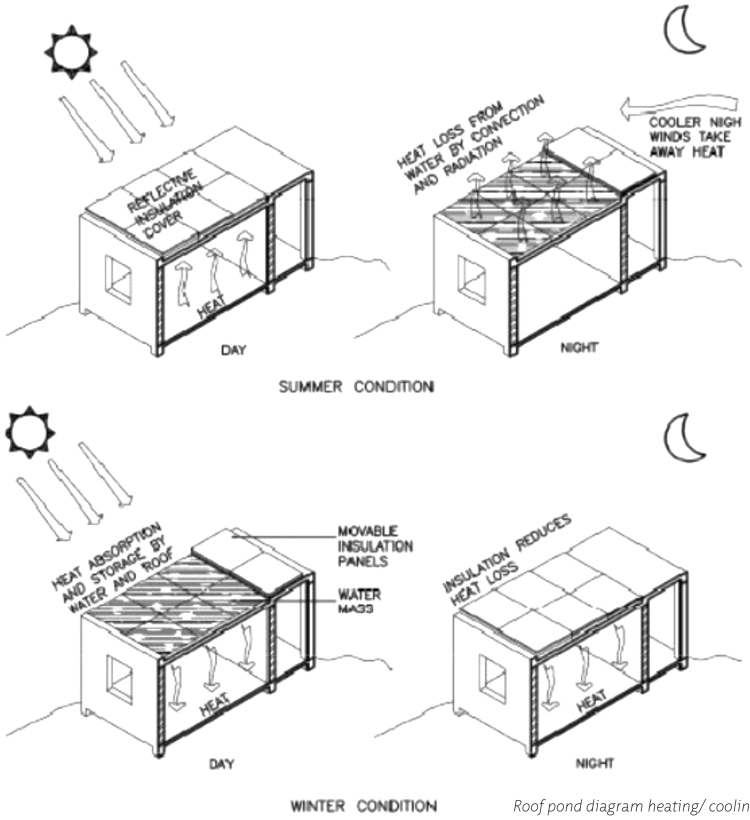


About the project

The spaces in this family home on Chiltern Drive in central Singapore were crafted like a garment, woven around the needs and desires of its inhabitants. The home aspired to be deeply rooted, connected to the surrounding environment, the history of its development, as well as the family's lifestyle.

The house was constructed as a single monolithic concrete structure. What makes the building ideal for the so-called passive isolation technique with a roof pound invented by Robert R. Hay (1967).

A roofpond uses water as thermal mass that is located on the roof of a building. This strategy utilizes the higher heat capacity of water to mediate the temperature of the interior space beneath. It mimics the ways in which Mother Nature tempers and controls the global climate. Therefore, roofponds can be defined as a passive solar strategy in which both heating and cooling occur through the use of natural environmental forces (Marlatt et al., 1984). This passive solar strategy is the only one that has the ability to both heat and cool without additional system components (Hay & Yellott, 1968). From a thermal standpoint, roofponds are strong performers, providing high solar savings fractions, interior temperature stability, enhanced thermal comfort and very low operational power requirements (Hoffstatter, 1985). Moreover, due to convective heat transfer within the water bags, heat gains or losses are quickly distributed throughout the roofpond to create a very homogeneous distribution of heat throughout the floor area covered by the system (Haggard et al., 1975).



Roof pond diagram heating/ cooling

CASE STUDY 5#

Project summery

Location
Viborg, Denmark

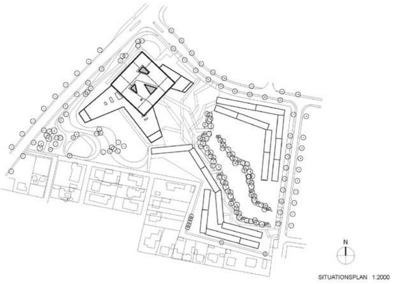
Architect
Henning Larsen Architects

Buildingtype
Town Hall

Client
Sony Corporation

Completed
2011

Sustainable features
Cooling
Heating
Rainwater buffer
Purifies the air
Reduces the ambient temperature
Increase solar panel efficiency
Reduces ambient noise



Site plan

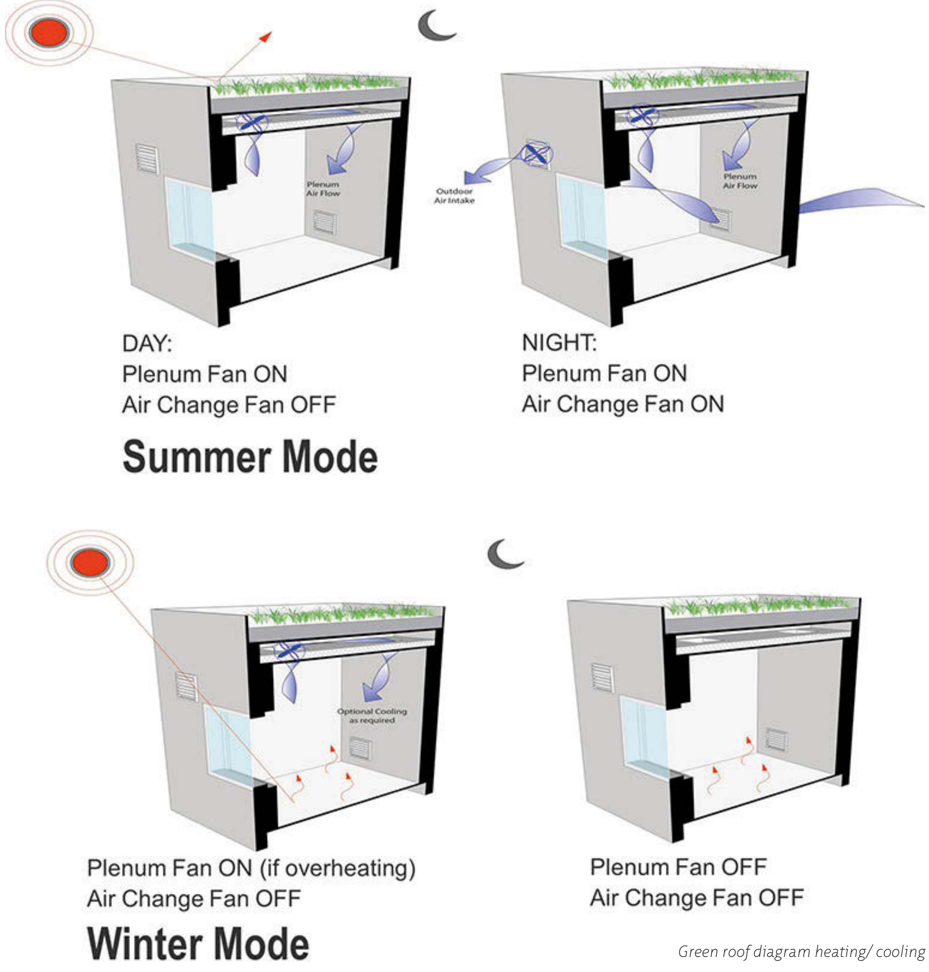
Viborg Town Hall

About the project

The new town hall building in Viborg, Denmark is a marvel of sustainable and striking design, thanks to Henning Larson Architects. Features of the complex stay true to the clean, sharp artistry of the region, as well as comply with impressive environmental standards to monitor the building's footprint. Built on the outskirts of the city, the town hall has space to sprawl and shares a distinct balance with the greenery in its surroundings.

The green roof running from the building base beautifully interacts with the landscape and the green parking roofs surrounding the front square. Green Roofs have become a very important component of sustainable urban development within the last 30 years. Growing environmental awareness and the striking economical and ecological advantages are the driving forces for this great success. At present, Green Roofs, sky gardens and rooftop gardens can be found in nearly all big cities around the world, benefiting the urban environment and their inhabitants.

Green roofs and cool roofs can help protect water resources adversely impacted by climate change by reducing electricity usage, improving air quality, and shrinking our carbon footprint. Green roofs can also greatly reduce the volume of stormwater runoff from rainfall events.



Green roof diagram heating/ cooling

CASE STUDY 6#

Project summery

Location
Frankfurt, Germany

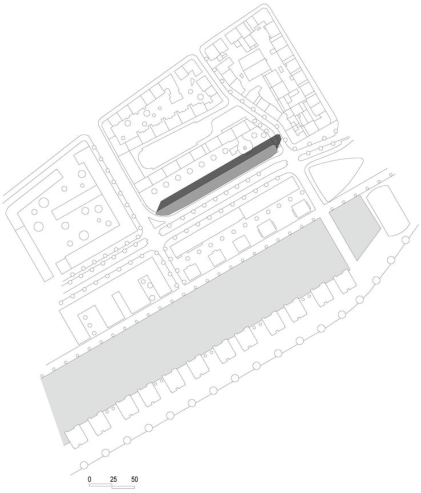
Architect
HHS architects

Buildingtype
Residential

Client
ABG Frankfurt holding Wohnungsbau- und Beteiligungsgesellschaft mbH

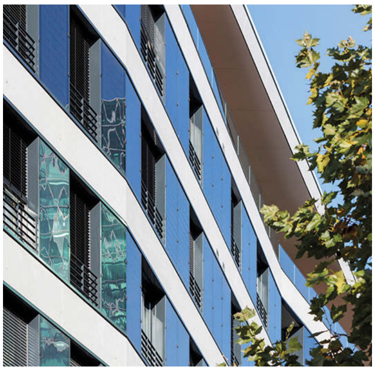
Completed
2015

Sustainable features
Integrated solar cells



Site plan

Townhouse Frankfurt



About the project

The »Active Townhouse« (Aktiv-Stadthaus) just south of Frankfurt's main train station is the first multi-story residential building in Germany to comply with the Efficiency Plus Standard, which the Federal Ministry of Building introduced in 2012. On an annual basis, the new-build is expected to achieve a net positive energy balance (including household electricity) both in terms of primary energy and final energy.

The building presents both the BMVBS and ABG Holding with a research and presentation object, which provides an example of sustainable building in the context of climate change and Germany's energy transition. This project aims to test the applicability of the existing PlusEnergy design concept, which has already been used in single-dwelling units, for the first time to a large-scale apartment building in the centre of a major city.

The planned building, which is approximately 150 metres long and only 10 metres wide, has 74 rental units ranging from two to four-room apartments.

The building's energy source is its large mono-pitch roof. To generate sufficient electrical energy using the installed solar power modules, it protrudes over the body of the building on all sides. The south façade is also fitted with solar power modules.

A nearby sewer, from which heat is extracted using heat exchangers, provides a heat source for the building. The apartments are supplied with drinking and process water via heat pumps and large buffer tanks. To alleviate the burden on the electricity network, battery storage increases the internal consumption of the self-generated electrical energy. The electric cars on the ground floor, which can be used on a car-sharing basis, support this system.

The tenants can avail of this innovative energy and supply system through a flat-rate rental payment. A touch panel installed in the apartments enables them to track their individual power consumption at all times.

CASE STUDY 7#

Project summery

Location
Anton Chico, United States

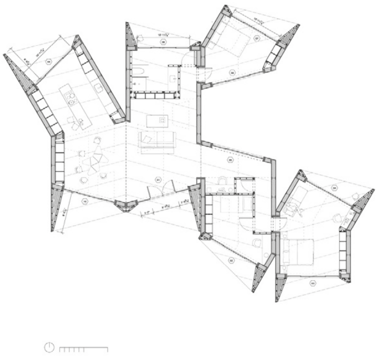
Architect
MOS architects

Buildingtype
Museum

Client
Museum of Outdoor Arts

Completed
2015

Sustainable features
Solar chimney
Passive solar heating/ cooling
Ventilation



Site plan

Museum of Outdoor Arts Element House

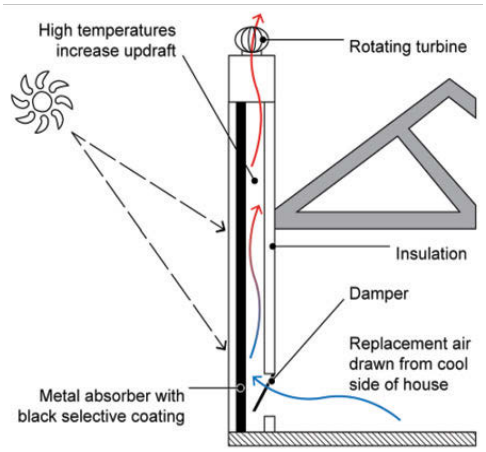
About the project

The Museum of Outdoor Arts Element House is a structural insulated panel (SIPS) modular building designed to operate independently of public utilities by integrating passive systems and on-site energy-generation. The house functions as a guest house and visitor center for Star Axis, a nearby land art project by the artist Charles Ross in New Mexico.

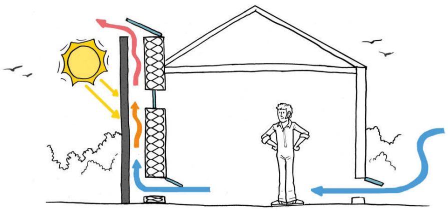
Using simple sustainable building practices to increase environmental performance, everything is stripped down to basic components. The organization of the house is based on an expansive geometric system of growth, radiating and aggregating outward, one module after another. A decentralized field of solar chimney volumes replaces the traditional solid mass of the domestic hearth. The house controls heat and light through two primary aspects: window placement and the solar chimney.

A solar chimney (also known as a solar tower) is a solar thermal power plant wherein heated air rises in a tall chimney. The inflowing air is heated in a greenhouse with an open rim surrounding the base of the chimney and a turbine at the base of the chimney turns a generator to produce electrical power.

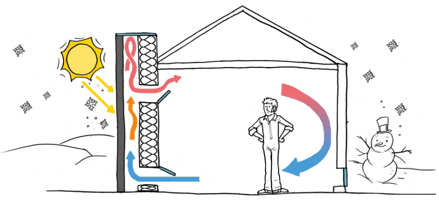
The following diagrams illustrates the basic elements of a solar chimney:



COOLING



HEATING



Trombe wall diagram heating/ cooling

CASE STUDY 8#

National Renewable Energy Laboratory

Project summery

Location
Golden , CO, United States

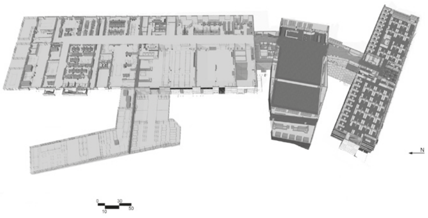
Architect
SmithGroupJJR

Buildingtype
Laboratory

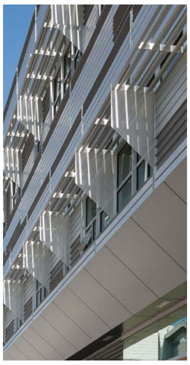
Client
Energy Systems Integration Facility (ESIF)

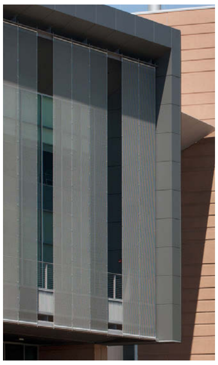
Completed
2013

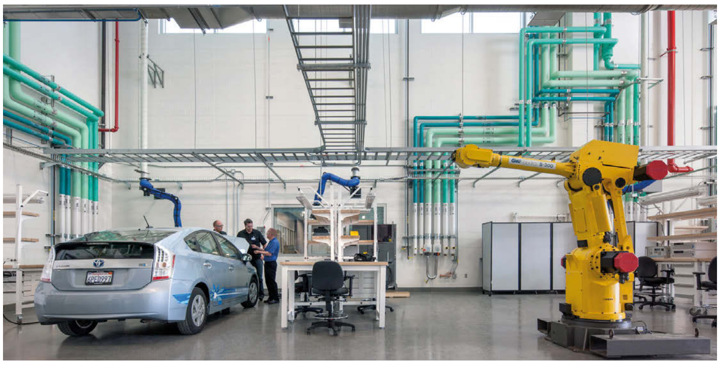
Sustainable features
Solar chimney ventilation
Geothermal heating/ cooling
operable windows
solar optical tubes
vampire switch
evaporative Shower Towers
photovoltaic-covered canopy



Site plan



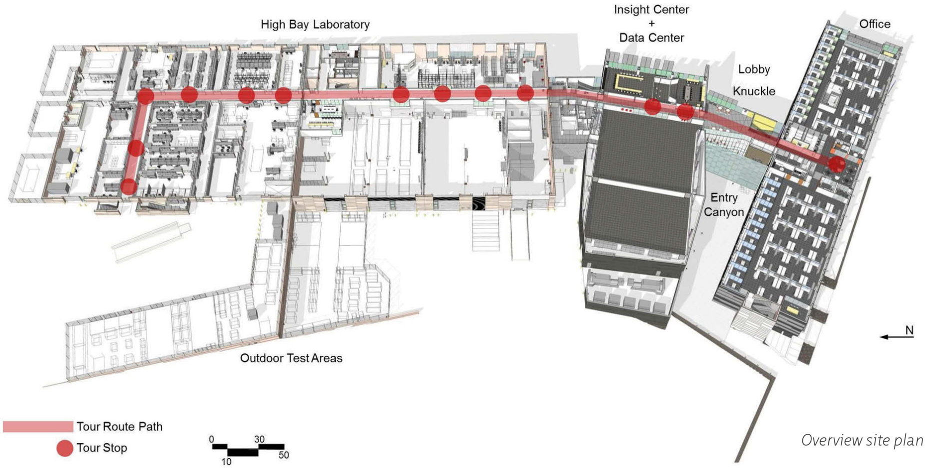




About the project

The Energy Systems Integration Facility (ESIF) at the Department of Energy's National Renewable Energy Laboratory (NREL) campus in Golden, Colorado is a model in sustainable design and energy efficient performance. The ESIF creates a new home for scientists and engineers to collaborate on the development and delivery of renewable energy technologies and houses the most powerful and energy efficient data center in the world dedicated solely to renewable energy and energy efficiency research, this advanced research complex will transform the nation's energy infrastructure. SmithGroupJJR, a recognized leader in architecture, engineering, and planning, served as designer of the three-story, 182,500-square-foot research complex. JE Dunn Construction performed as general contractor for the design-build venture.

Located southeast of the existing SmithGroupJJR-designed the Science & Technology Facility. The ESIF is the nation's only facility that can conduct integrated megawatt-scale testing of the components and strategies needed to safely move clean energy technologies onto the electrical grid "in-flight" at the speed and scale required to meet federal policy. A showcase of sustainable design, the ESIF incorporates the best in energy efficiency, environmental performance, and advanced controls using a "whole building" integrated design approach that complies with Energy Star standards. SmithGroupJJR and JE Dunn worked together to support the Department of Energy's goal to develop an energy efficient building that imparts minimal impact on the environment. The ESIF was designed to earn a LEED Platinum rating from the U.S. Green Building Council.



Overview site plan

CONTINUED CASE 8#

Project summery

National Renewable Energy Laboratory

Location
Golden , CO, United States

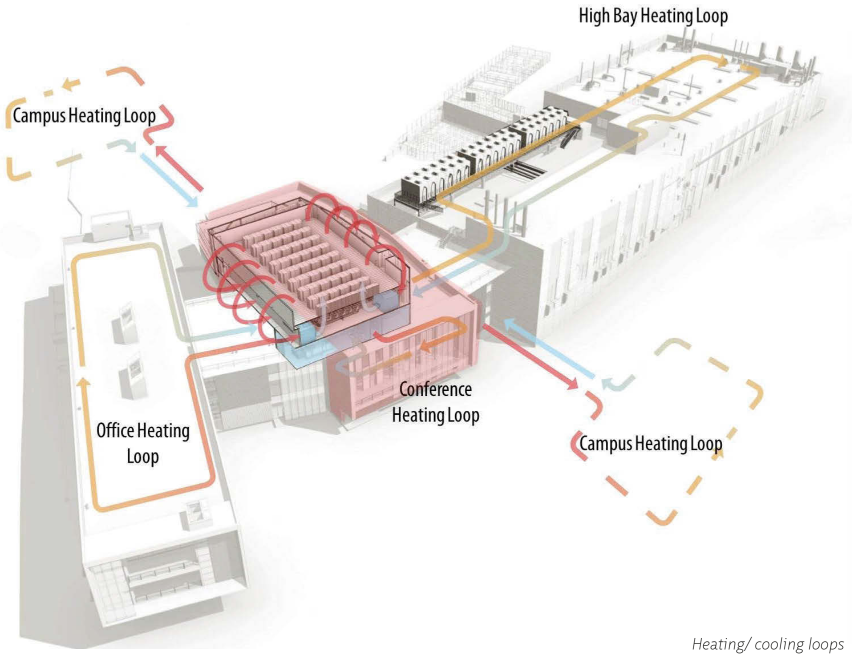
Architect
SmithGroupJJR

Buildingtype
Laboratory

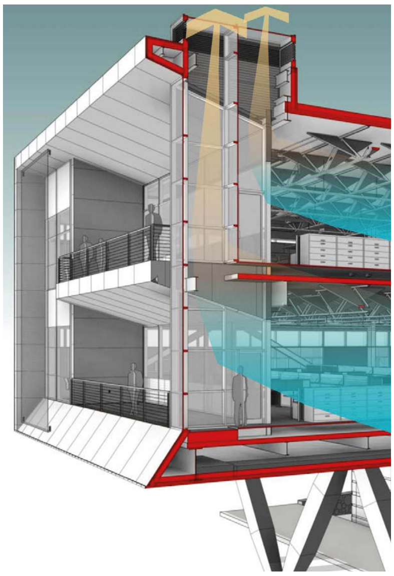
Client
Energy Systems Integration Facility (ESIF)

Completed
2013

Sustainable features
Solar chimney ventilation
Geothermal heating/ cooling
operable windows
solar optical tubes
vampire switch
evaporative Shower Towers
photovoltaic-covered canopy

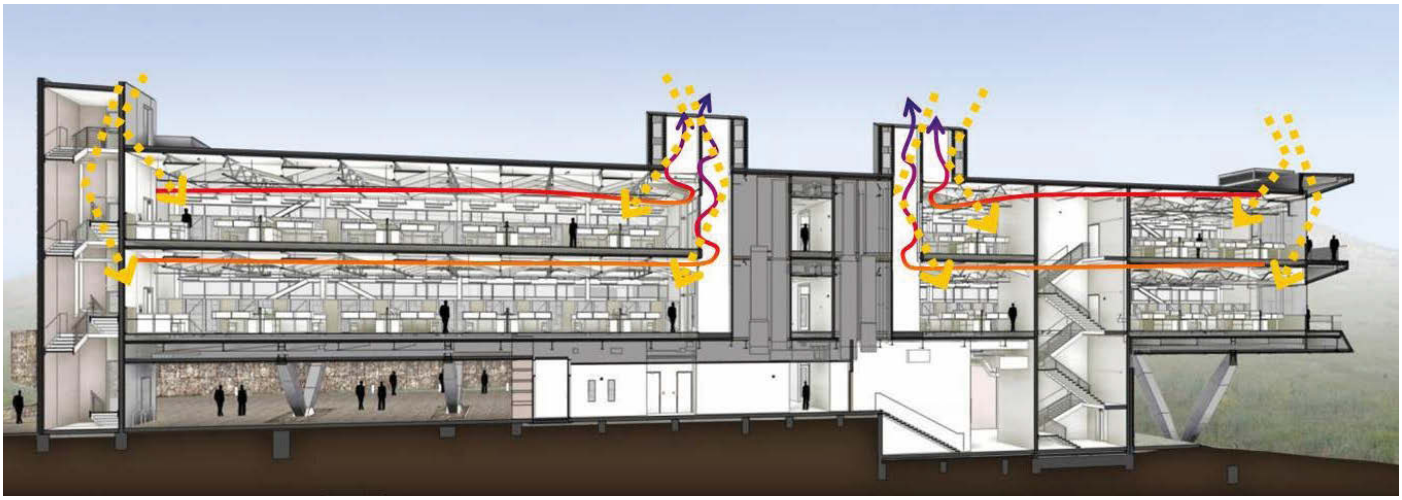


Heating/ cooling loops



Solar chimney ventilation

Southwest facade

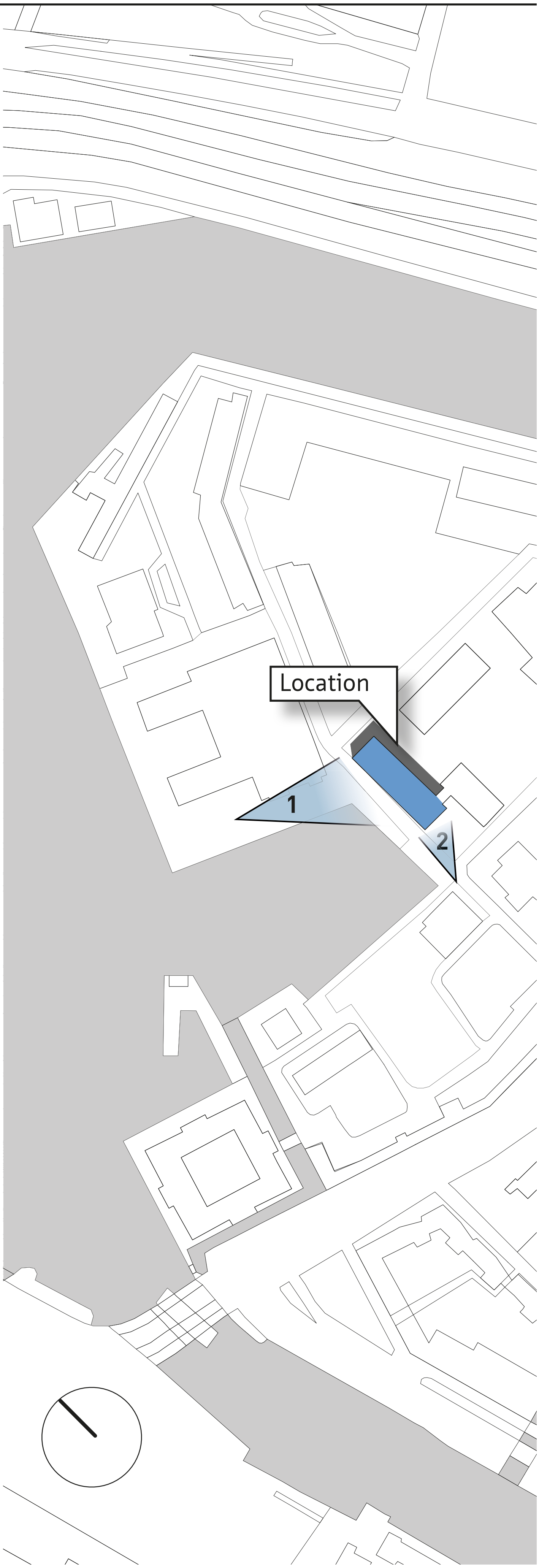


Longitudinal section airloops ventilation

Appendix 5: Location Demo Case

Photo 1. Front view of Former Verbindingsschool. Source: J.J.M. Aling (2017)

Photo 1. Side view of Former Verbindingsschool. Source: J.J.M. Aling (2017)



Project data

Location: *Marineterrein Amsterdam, The Netherlands*
Demo case: *former Verbindingsschool*
Characteristics: *regtangular building volume of 4 floors*
Floor space: *10.000m2*
Built: *1962-1966*
Architect: *ir. F.C. de Weger, Rotterdam*

Appendix 6: OpenStudio Simulation Results Demo Case

Overview workflow:

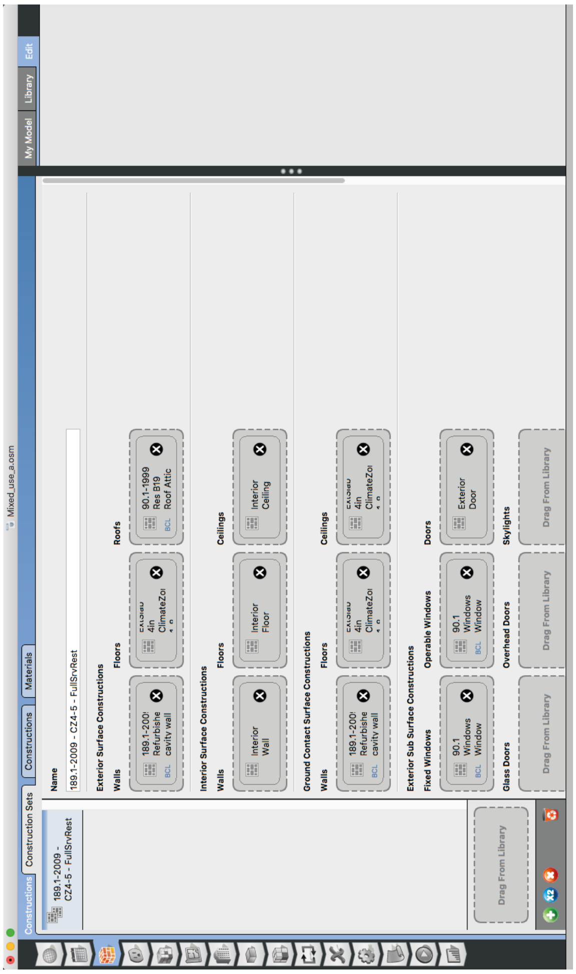


Fig. 1. Constructionsets

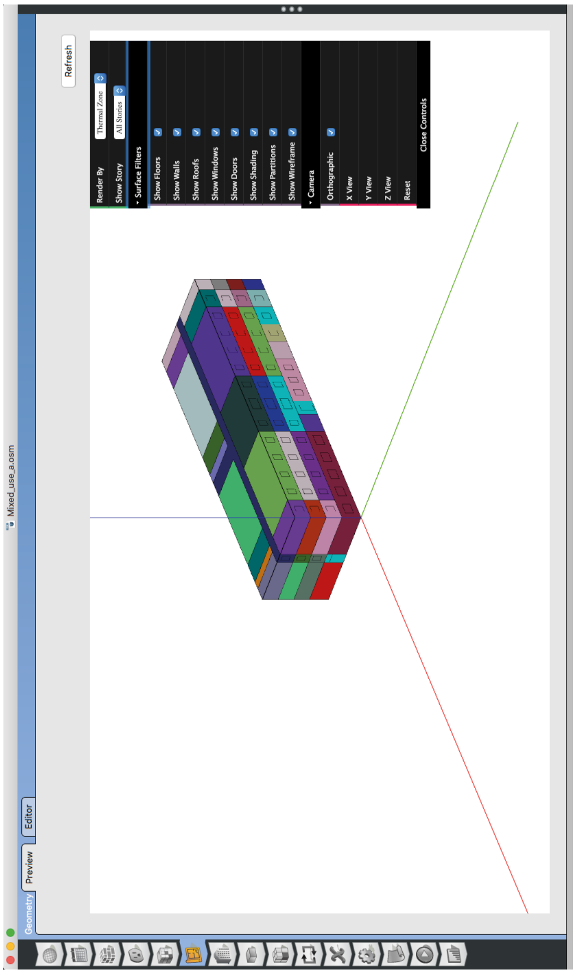


Fig. 1. Thermal zones of the mixed-use building

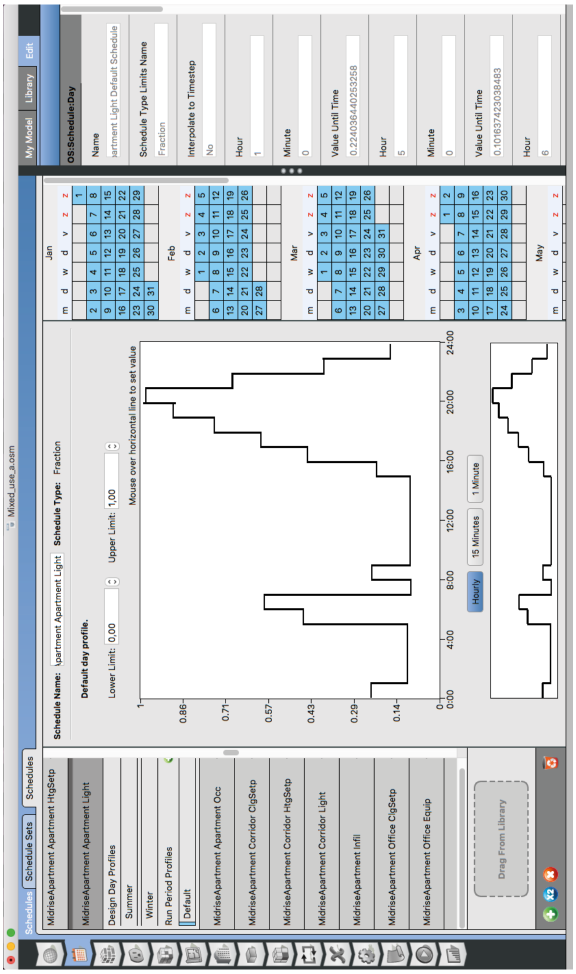


Fig. 3. Example light schedule - Apartment

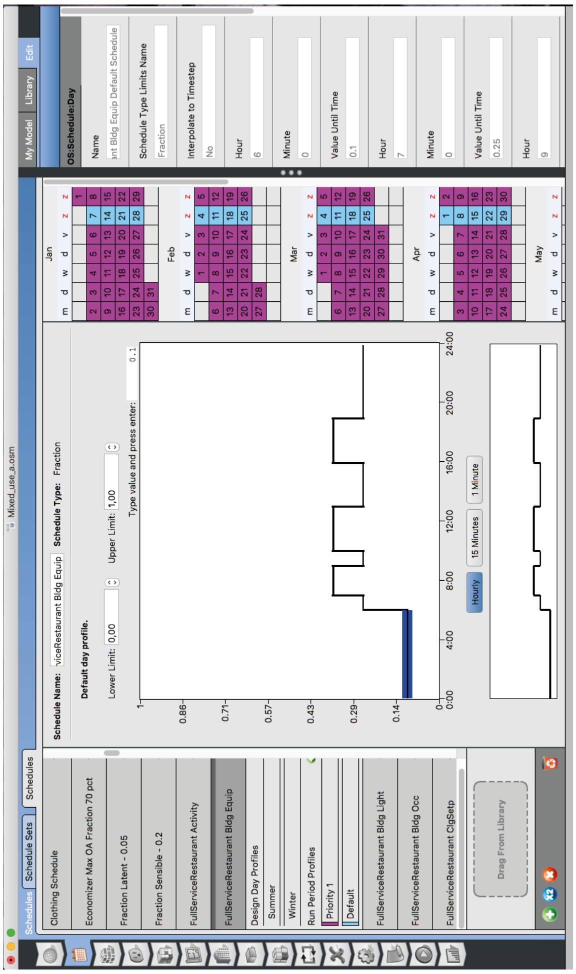


Fig. 4. Example schedule restaurant equipment

OpenStudio Results

Model Summary

Building Summary

Information	Value	Units
Building Name	Mixed use building (Rest, App, Meeting, Gum)	building_name
Net Site Energy	3,736	GJ
Total Building Area	4,014	m^2
EUI (Based on Net Site Energy and Total Building Area)	0.93	GJ/m^2
OpenStudio Standards Building Type	Mixed use building	

Weather Summary

	Value
Weather File	AMSTERDAM - NLD IWEC Data WMO#=062400
Latitude	52.30
Longitude	4.77
Elevation	-7 (ft)
Time Zone	1.00
North Axis Angle	180.00
ASHRAE Climate Zone	

Sizing Period Design Days

	Maximum Dry Bulb (C)	Daily Temperature Range (K)	Humidity Value	Humidity Type	Wind Speed (m/s)	Wind Direction
AMSTERDAM ANN CLG .4% CONDNS DB=>MWB	27.8	8.0	-6.83	Wetbulb [C]	4.2	50.0
AMSTERDAM ANN CLG .4% CONDNS DP=>MDB	22.6	8.0	-7.22	Dewpoint [C]	4.2	50.0
AMSTERDAM ANN CLG .4% CONDNS ENTH=>MDB	26.1	8.0	138164400.0	Enthalpy [J/kg]	4.2	50.0
AMSTERDAM ANN CLG .4% CONDNS WB=>MDB	25.8	8.0	-6.28	Wetbulb [C]	4.2	50.0
AMSTERDAM ANN HTG 99.6% CONDNS DB	-7.3	0.0	-21.83	Wetbulb [C]	4.6	80.0
AMSTERDAM ANN HTG WIND 99.6% CONDNS WS=>MCDB	9.5	0.0	-12.5	Wetbulb [C]	17.6	80.0
AMSTERDAM ANN HUM_N 99.6% CONDNS DP=>MCDB	-6.2	0.0	-23.94	Dewpoint [C]	4.6	80.0

Unmet Hours Summary

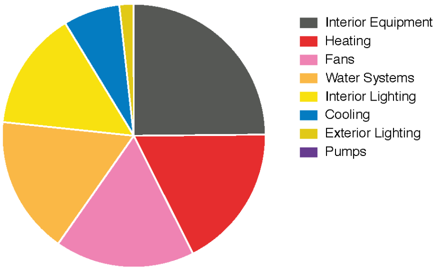
Time Setpoint Not Met	Time (hr)
During Heating	3729.25
During Cooling	1246.0
During Occupied Heating	2489.0
During Occupied Cooling	1229.5

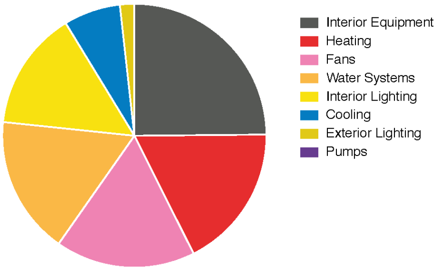
Unmet Hours Tolerance

Tolerance for Time Setpoint Not Met	Temperature (C)
Heating	0.11
Cooling	0.11

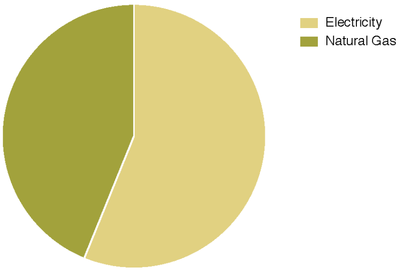
Annual Overview

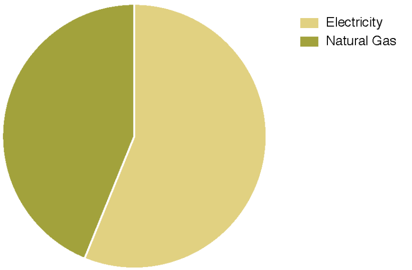
End Use - view table



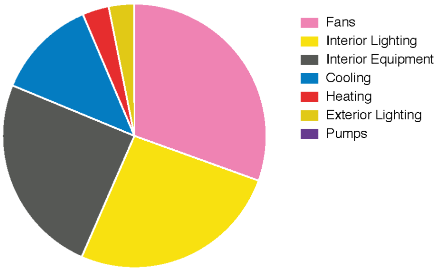


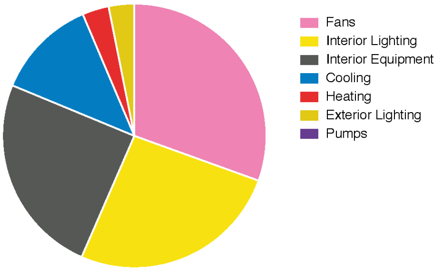
Energy Use - view table



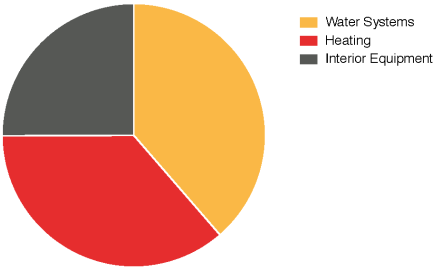


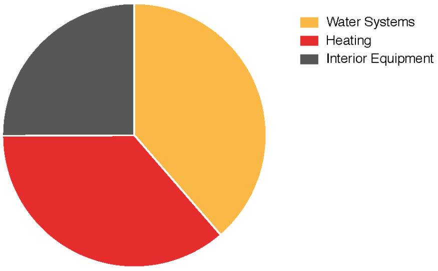
EUI - Electricity - view table





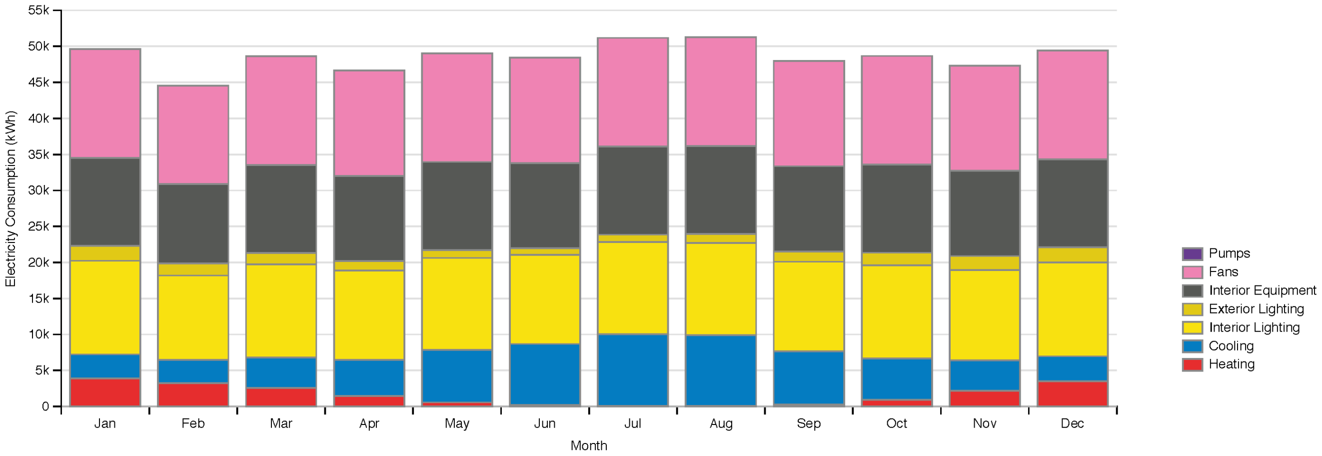
EUI - Gas - view table

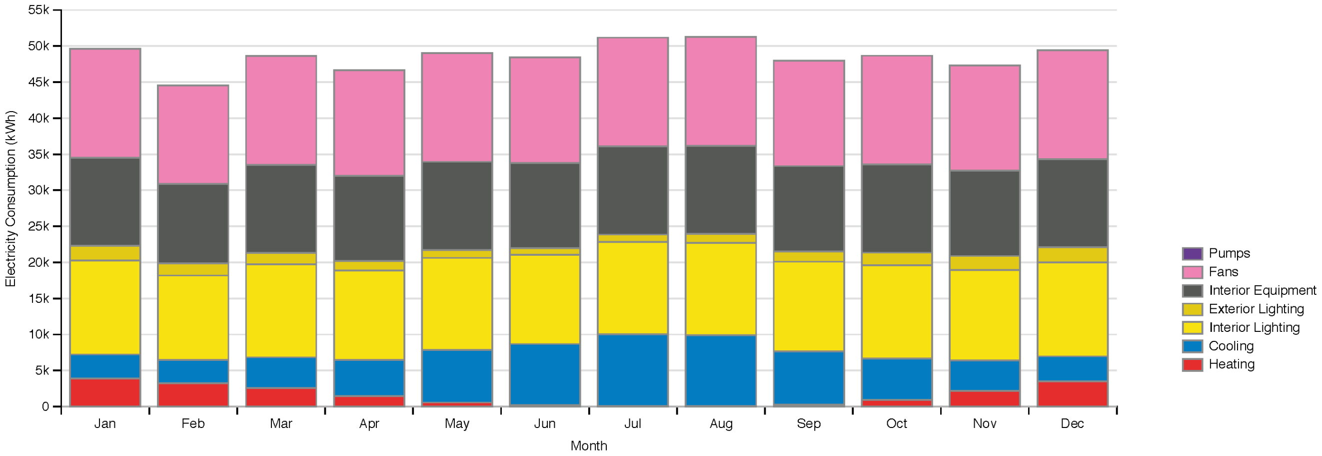




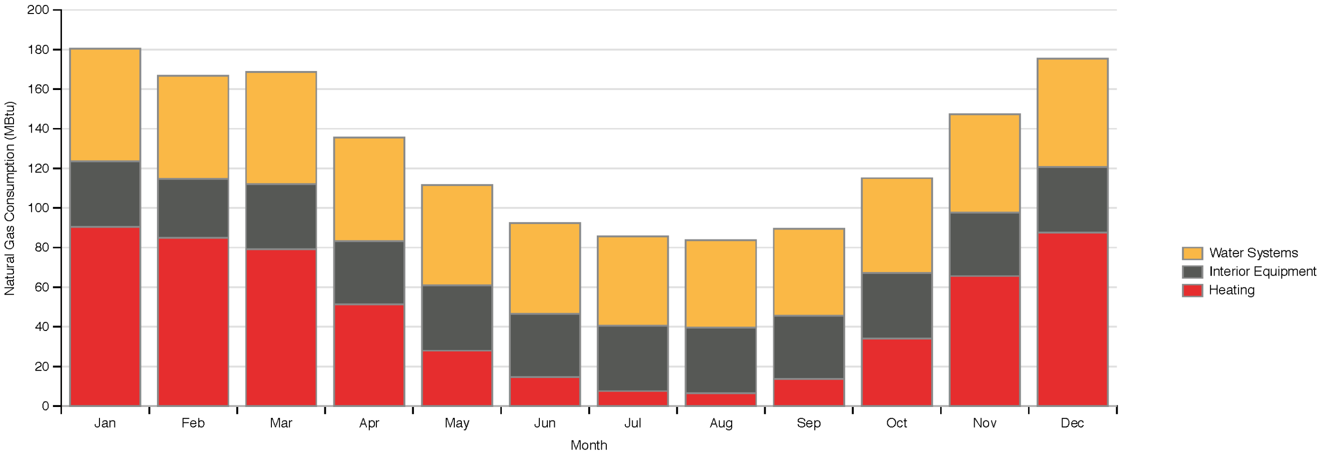
Monthly Overview

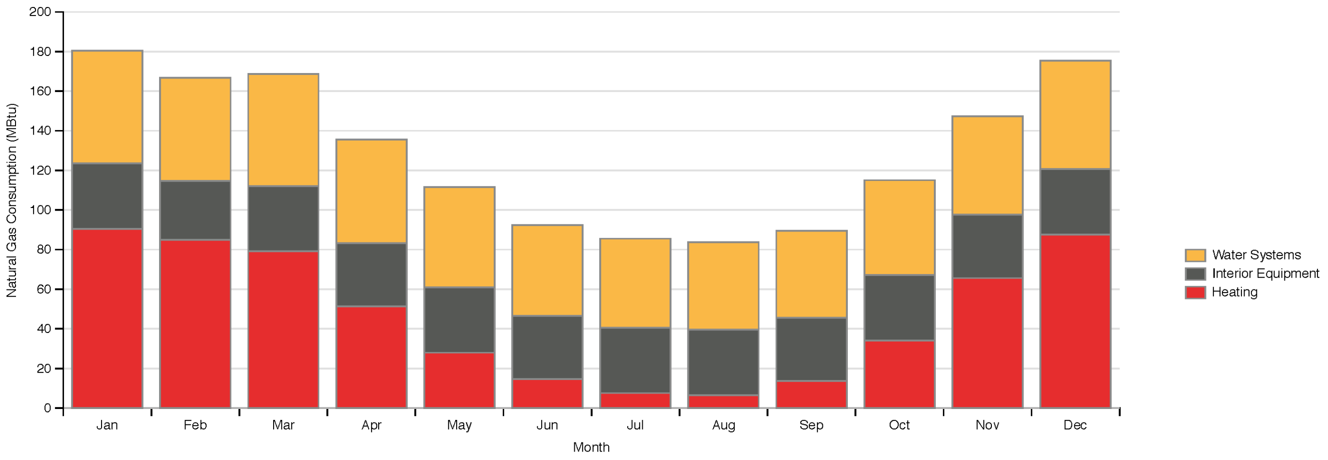
Electricity Consumption (kWh) - view table



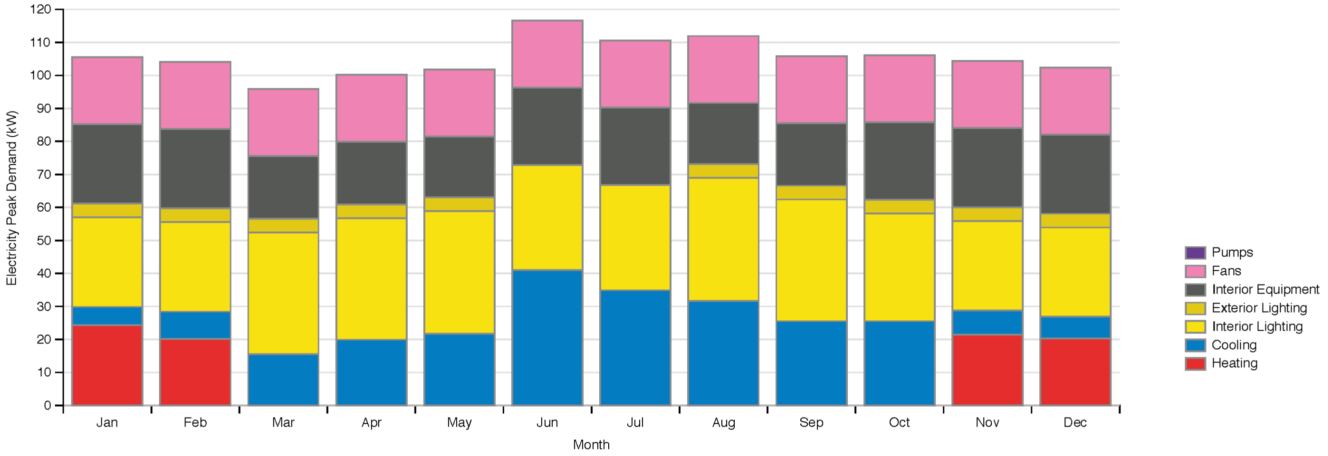


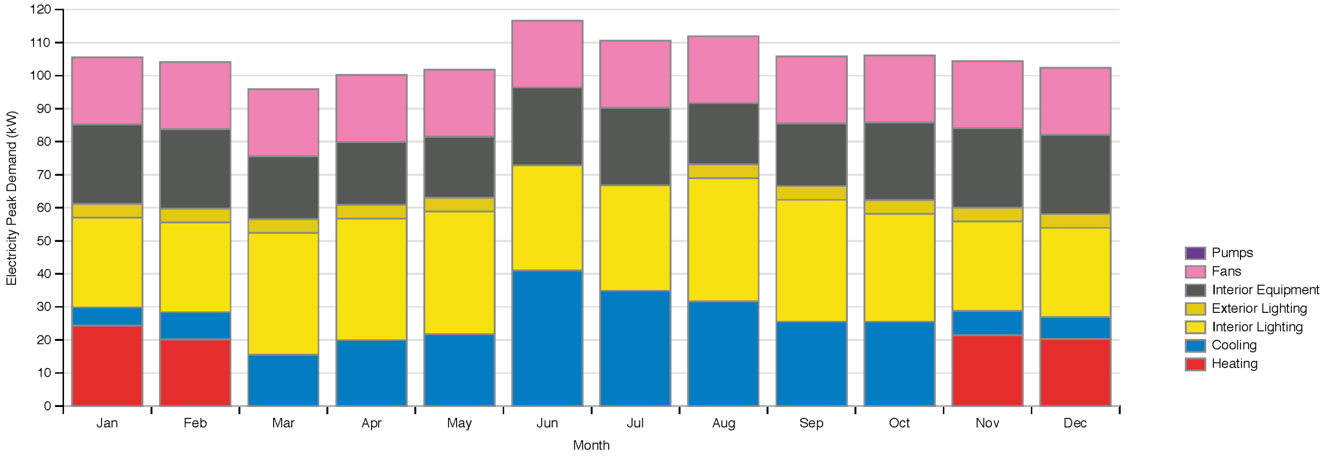
Natural Gas Consumption (MBtu) - view table



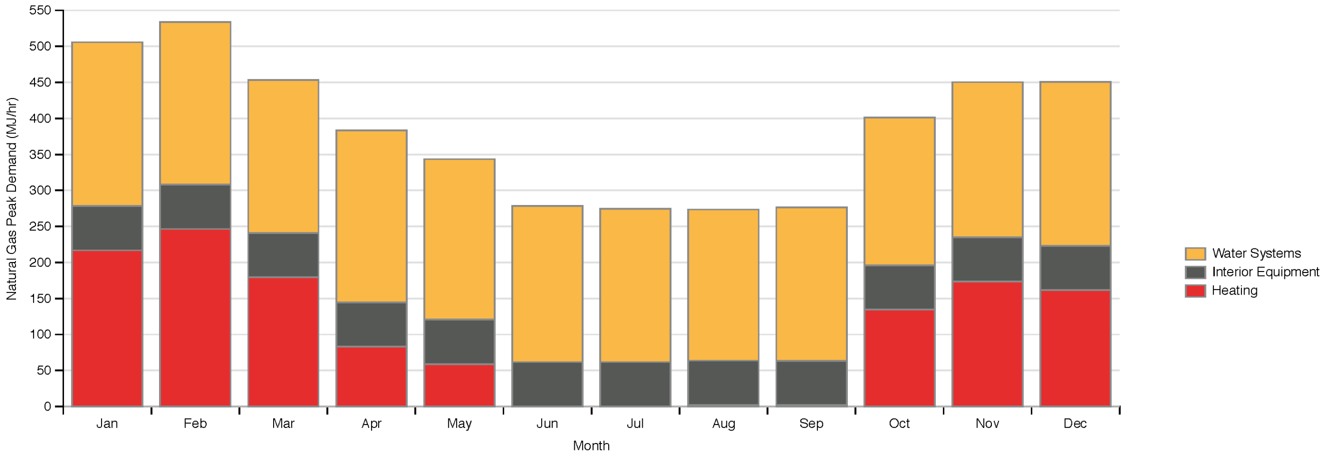


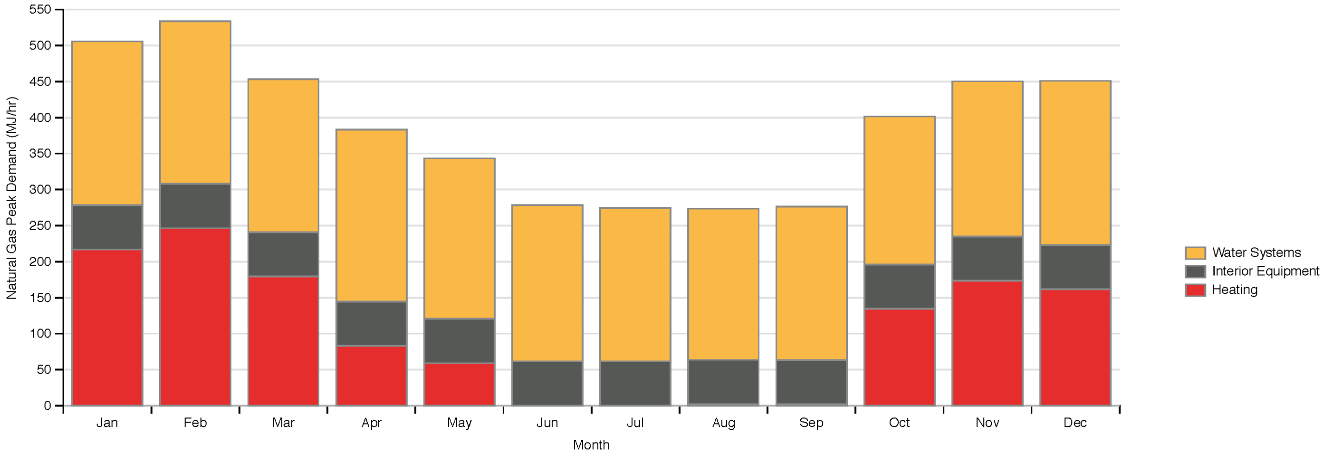
Electricity Peak Demand (kW) - view table





Natural Gas Peak Demand (MJ/hr) - view table





Utility Bills/Rates

No Data to Show for Utility Bills/Rates

Envelope

Base Surface Constructions

Construction	Net Area (m^2)	Surface Count	R Value (m^2*K/W)
189.1-2009 Refurbished cavity wall insulation	140	92	4.61
90.1-1999 Res B19 Roof Attic and Other	93	16	6.30

Sub Surface Constructions

Construction	Area (m^2)	Surface Count	U-Factor (W/m^2*K)
90.1 Windows Window Fixed 3671 Vnl-Clr-Ins-V79-Ins-Clr	17	103	

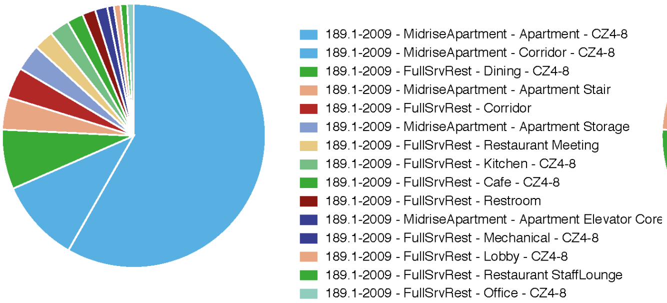
Base Surface Constructions

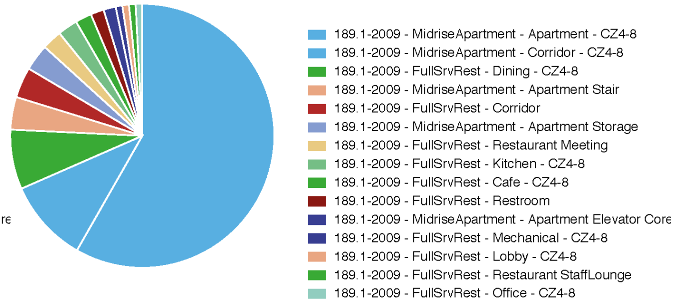
Construction	Net Area (m^2)	Surface Count	R Value (m^2*K/W)
189.1-2009 Refurbished cavity wall insulation	140	92	4.61
90.1-1999 Res B19 Roof Attic and Other	93	16	6.30

Description	Total (%)	North (%)	East (%)	South (%)	West (%)
Gross Window-Wall Ratio	10.87	15.24	3.95	11.39	3.13
Gross Window-Wall Ratio (Conditioned)	12.01	15.95	3.95	12.11	5.68
Skylight-Roof Ratio	0.0				

Space Type Breakdown

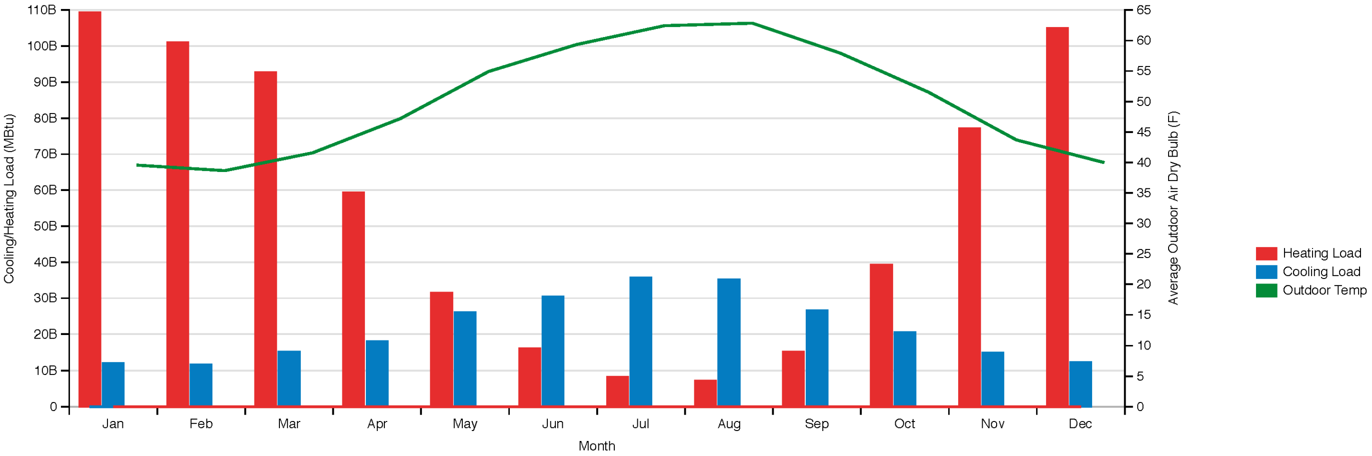
Space Type Breakdown - view table

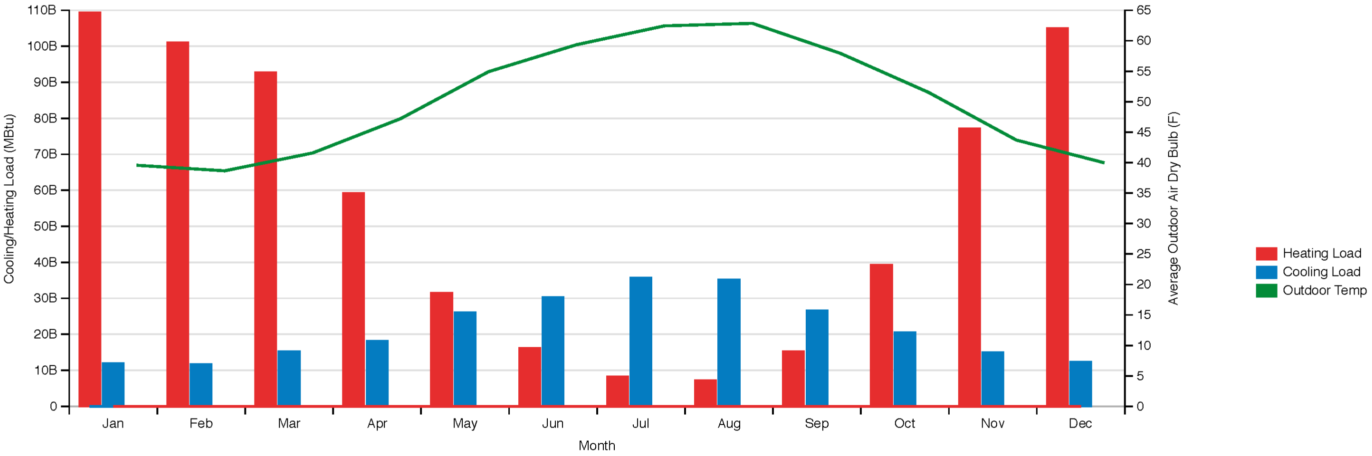




HVAC Load Profiles

Monthly Load Profiles - view table





Air Loops Detail

ExerciseCenterFlr1 ZN - EmployeeLoungeFlr1 ZN - RestroomFlr1 ZN SAC

Object	Sizing	Sizing Units	Description	Value	Value Units	Count
(supply)						
OS:AirLoopHVAC:OutdoorAirSystem	Autosized	m^3/s	Minimum Outdoor Air Flow Rate	Autosized	m^3/s	
OS:Coil:Cooling:DX:SingleSpeed	Autosized	W	Rated COP	3.65	COP	
OS:Coil:Heating:Gas	Autosized	W	Gas Burner Efficiency	0.80		
OS:Coil:Heating:Gas	Autosized	W	Gas Burner Efficiency	0.80		
OS:Fan:ConstantVolume	Autosized	m^3/s	Pressure Rise	622.72	Pa	
OS:SetpointManager:SingleZone:Reheat			Control Zone	ExerciseCenterFlr1 ZN		
(demand)						
Thermal Zones			Total Floor Area	9	m^2	3
Thermal Zones			thermostat ranges for cooling	-4.5 to -4.5	C	
Thermal Zones			thermostat ranges for heating	-6.0 to -6.0	C	
Terminal Types Used			OS:AirTerminal:SingleDuct:Uncontrolled			3
(controls)						
HVAC Operation Schedule				SmallHotel Split-AC Operation		
Night Cycle Setting				CycleOnAny	Choice	
Economizer Setting				NoEconomizer	Choice	
Demand Controlled Ventilation Status				false	Bool	

FrontLoungeFlr1 ZN SAC

Object	Sizing	Sizing Units	Description	Value	Value Units	Count
(supply)						
OS:AirLoopHVAC:OutdoorAirSystem	Autosized	m^3/s	Minimum Outdoor Air Flow Rate	Autosized	m^3/s	
OS:Coil:Cooling:DX:SingleSpeed	Autosized	W	Rated COP	3.65	COP	
OS:Coil:Heating:Gas	Autosized	W	Gas Burner Efficiency	0.80		
OS:Coil:Heating:Gas	Autosized	W	Gas Burner Efficiency	0.80		
OS:Fan:ConstantVolume	Autosized	m^3/s	Pressure Rise	622.72	Pa	
OS:SetpointManager:SingleZone:Reheat			Control Zone	FrontLoungeFlr1 ZN		
(demand)						
Thermal Zones			Total Floor Area	15	m^2	1
Thermal Zones			thermostat ranges for cooling	-4.5 to -4.5	C	
Thermal Zones			thermostat ranges for heating	-6.0 to -6.0	C	
Terminal Types Used			OS:AirTerminal:SingleDuct:Uncontrolled			1
(controls)						
HVAC Operation Schedule				SmallHotel Split-AC Operation		
Night Cycle Setting				CycleOnAny	Choice	
Economizer Setting				DifferentialDryBulb	Choice	
Demand Controlled Ventilation Status				false	Bool	

FrontOfficeFlr1 ZN SAC

Object	Sizing	Sizing Units	Description	Value	Value Units	Count
(supply)						
OS:AirLoopHVAC:OutdoorAirSystem	Autosized	m^3/s	Minimum Outdoor Air Flow Rate	Autosized	m^3/s	
OS:Coil:Cooling:DX:SingleSpeed	Autosized	W	Rated COP	3.65	COP	
OS:Coil:Heating:Gas	Autosized	W	Gas Burner Efficiency	0.80		
OS:Coil:Heating:Gas	Autosized	W	Gas Burner Efficiency	0.80		
OS:Fan:ConstantVolume	Autosized	m^3/s	Pressure Rise	622.72	Pa	
OS:SetpointManager:SingleZone:Reheat			Control Zone	FrontOfficeFlr1 ZN		
(demand)						
Thermal Zones			Total Floor Area	12	m^2	1
Thermal Zones			thermostat ranges for cooling	-4.5 to -4.5	C	
Thermal Zones			thermostat ranges for heating	-6.0 to -6.0	C	
Terminal Types Used			OS:AirTerminal:SingleDuct:Uncontrolled			1
(controls)						
HVAC Operation Schedule				Always On Discrete		
Night Cycle Setting				StayOff	Choice	
Economizer Setting				NoEconomizer	Choice	
Demand Controlled Ventilation Status				false	Bool	

MeetingRoomFlr1 ZN SAC

Object	Sizing	Sizing Units	Description	Value	Value Units	Count
(supply)						
OS:AirLoopHVAC:OutdoorAirSystem	Autosized	m^3/s	Minimum Outdoor Air Flow Rate	Autosized	m^3/s	
OS:Coil:Cooling:DX:SingleSpeed	Autosized	W	Rated COP	3.65	COP	
OS:Coil:Heating:Gas	Autosized	W	Gas Burner Efficiency	0.80		
OS:Coil:Heating:Gas	Autosized	W	Gas Burner Efficiency	0.80		
OS:Fan:ConstantVolume	Autosized	m^3/s	Pressure Rise	622.72	Pa	
OS:SetpointManager:SingleZone:Reheat			Control Zone	MeetingRoomFlr1 ZN		
(demand)						
Thermal Zones			Total Floor Area	7	m^2	1
Thermal Zones			thermostat ranges for cooling	-4.5 to -4.5	C	
Thermal Zones			thermostat ranges for heating	-6.0 to -6.0	C	
Terminal Types Used			OS:AirTerminal:SingleDuct:Uncontrolled			1
(controls)						
HVAC Operation Schedule				Always On Discrete		
Night Cycle Setting				StayOff	Choice	
Economizer Setting				NoEconomizer	Choice	
Demand Controlled Ventilation Status				false	Bool	

Plant Loops Detail

Laundry Service Water Loop

Object	Sizing	Sizing Units	Description	Value	Value Units	Count
(supply)						
OS:Pump:ConstantSpeed	Autosized	m^3/s	Rated Power Consumption	Autosized	W	
OS:WaterHeater:Mixed	1	m^3	Heater Thermal Efficiency	0.81	fraction	
OS:SetpointManager:Scheduled			Control Variable - Temperature	60.0 to 60.0	C	
(demand)						
OS:WaterUse:Connections			Water Use Connections 36			
(controls)						
Loop Flow Rate Range	Autosized	m^3/s	Minimum Loop Flow Rate	0.0	m^3/s	
Loop Temperature Range				10.0 to 60.0	C	
Design Loop Exit Temperature				60.00	C	
Loop Design Temperature Difference				5.00	K	

Main Service Water Loop

Object	Sizing	Sizing Units	Description	Value	Value Units	Count
(supply)						
OS:Pump:ConstantSpeed	Autosized	m^3/s	Rated Power Consumption	Autosized	W	
OS:WaterHeater:Mixed	1	m^3	Heater Thermal Efficiency	0.81	fraction	
OS:SetpointManager:Scheduled			Control Variable - Temperature	60.0 to 60.0	C	
(demand)						
OS:WaterUse:Connections			Water Use Connections 1			
OS:WaterUse:Connections			Water Use Connections 2			
OS:WaterUse:Connections			Water Use Connections 3			
OS:WaterUse:Connections			Water Use Connections 4			
OS:WaterUse:Connections			Water Use Connections 5			
OS:WaterUse:Connections			Water Use Connections 6			
OS:WaterUse:Connections			Water Use Connections 7			
OS:WaterUse:Connections			Water Use Connections 8			
OS:WaterUse:Connections			Water Use Connections 9			
OS:WaterUse:Connections			Water Use Connections 10			
OS:WaterUse:Connections			Water Use Connections 11			
OS:WaterUse:Connections			Water Use Connections 12			
OS:WaterUse:Connections			Water Use Connections 13			
OS:WaterUse:Connections			Water Use Connections 14			
OS:WaterUse:Connections			Water Use Connections 15			
OS:WaterUse:Connections			Water Use Connections 16			
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OS:WaterUse:Connections			Water Use Connections 19			
OS:WaterUse:Connections			Water Use Connections 20			
OS:WaterUse:Connections			Water Use Connections 21			
OS:WaterUse:Connections			Water Use Connections 22			
OS:WaterUse:Connections			Water Use Connections 23			
OS:WaterUse:Connections			Water Use Connections 24			
OS:WaterUse:Connections			Water Use Connections 25			

OS:WaterUse:Connections			Water Use Connections 26			
OS:WaterUse:Connections			Water Use Connections 27			
OS:WaterUse:Connections			Water Use Connections 28			
OS:WaterUse:Connections			Water Use Connections 29			
OS:WaterUse:Connections			Water Use Connections 30			
OS:WaterUse:Connections			Water Use Connections 31			
OS:WaterUse:Connections			Water Use Connections 32			
OS:WaterUse:Connections			Water Use Connections 33			
OS:WaterUse:Connections			Water Use Connections 34			
OS:WaterUse:Connections			Water Use Connections 35			
(controls)						
Loop Flow Rate Range	Autosized	m^3/s	Minimum Loop Flow Rate	0.0	m^3/s	
Loop Temperature Range				10.0 to 60.0	C	
Design Loop Exit Temperature				60.00	C	
Loop Design Temperature Difference				5.00	K	

Site and Source Summary

Site and Source Energy

	Total Energy (kWh)	**Energy Per Total Building Area (kWh/m^2)**	**Energy Per Conditioned Building Area (kWh/m^2)**
Total Site Energy	1037733.4	258.6	278.6
Net Site Energy	1037733.4	258.6	278.6
Total Source Energy	2338900.0	582.7	627.9
Net Source Energy	2338900.0	582.7	627.9

Site to Source Energy Conversion Factors

	Site=>Source Conversion Factor
Electricity	3.167
Natural Gas	1.084
District Cooling	1.056
District Heating	3.613