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A Zero Energy House for and by Frank Gehry

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A Zero Energy House for and by Frank Gehry

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Abstract. This paper presents an energy concept of set of two residential buildings: a main house and a guest house in Santa Monica, California of total floor area of 836 m^2. The aim of this concept was to create a built environment with high comfort for users and the lowest possible impact on the environment. The architect and owner of the project Frank Gehry (88), see this as his statement in the discussion on sustainability. A site potential analysis has been performed, which then led to the proposal of optimal systems. For the energy supply a PV, highly efficient reversible heat pump/chiller with heat source/ surplus heat sink by closed loop geothermal system as well as evacuated tube thermal collectors have been proposed. To increase internal comfort, movable ventilated internal shades, a wind driven solar chimney supported cross ventilation and an air quality controlled natural ventilation, or a radiant floor conditioning with high cooling and low heating temperatures are used. The concept also includes an individual zone adjustment possibility by gravity wall systems. To optimize the whole system, a set of simulations and mock-up tests has been carried out. The results are then compared in this paper with the measurement results from the occupied building operation and further optimization possibilities are presented.

1. Introduction

This paper presents an energy concept for a set of zero-energy residential buildings in coastal Mediterranean climate without a conventional air-conditioning. The process of concept development and the supporting simulations and design assumptions are described. The assumptions of the studies have then been confronted with the measured data from the operation which is in some points different from the original assumptions. These changes have led to limiting the efficiency of the whole system. Measurements also show the potential to provide comfortable internal environment without an AC unit. In order to fulfil the goal of comfortable high-end residential building with low energy and resource consumption the control system must be tuned to allow users to implement their preferences (for example to easily switch between manual and automatic window opening).

2. Site and building analysis

The building site is located at the south-eastern edge of the Rustic Canyon in Santa Monica, California. It is bordered by neighbouring residential lots in the NE-SW axis to ca 42 m and by two streets in NW-SE axis to ca 72 m. The surrounding buildings are 2-3 storeys high and in combination with the slope of the canyon, the site offers an unshaded view to the West on the Pacific Ocean. The situation is shown in figure 1 (left).

Buildings themselves consist of a main house dividable into the core and four wings, which is located in the north-western part of the site and the guest house which is occupying the south-eastern boundary of the site. The space between them is filled by a swimming pool. The main building has a rather complex geometry, characteristic to the author and owner, Frank Gehry. Most of the west facing facades with the ocean view and also roofs of living and dining room in the main house are glazed. The main building is shown in figure 1 (right).

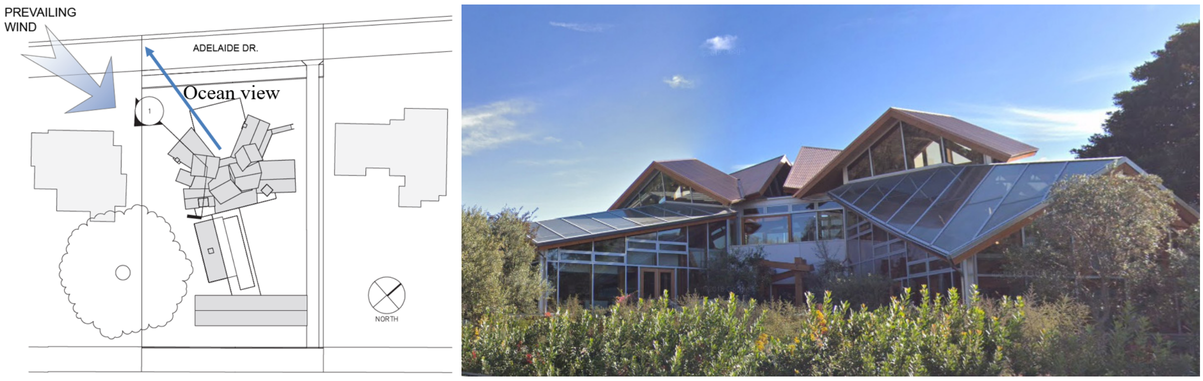

Figure 1. Situation (left) and the main building (right)

In order to identify the buildings potentials and possible shortcomings in terms of internal comfort a thermal analysis has been carried out. This included the statistical weather data analysis [1]. Most of these were carried out on the South-Western wing of the building (see figure 1 left). This has the most solar exposure and was designed as full glazed. This process gave us following outputs essential for further simulations and development:

- Solar energy potential (global solar insolation)
- Annual temperature profile visualized in figure 2has shown a few hot peaks, but the typical temperatures were below 21 °C. It has also identified a hot September week with the dry bulb temperature of 35 °C. The annual mean temperature is 16.7 °C
- The maximal dew point temperature of 15.6 °C during the night and low values during the day have documented a dry climate. Further statistical analysis has underlined the dry climate and the application of cold surfaces in combination with natural ventilation.
- Wind rose of LA and the Santa Monica Pier has confirmed the WSW wind preferences. The statistical analysis of the wind data has also shown a good wind capacity
- Psychometric chart has shown only a few hours with temperature above 26.6 °C (80 °F) and humidity levels above 60 %.

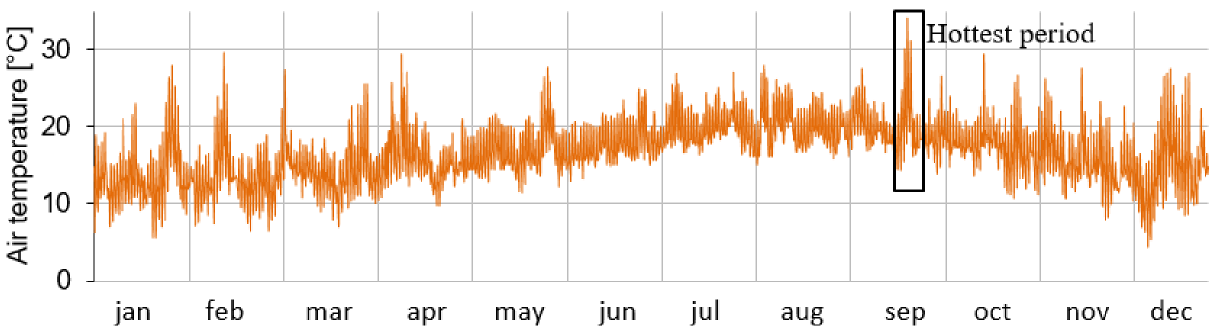

Figure 2. Annual temperature profile identifying the hottest period used for simulations [1]

3. Concept development

The above described analysis has led to general findings about the building and the site's climate. The sunny location has a very good solar potential (above 1 800 kWh/m² solar gains on a horizontal surface and above 2 000 kWh/m²a for a 30° South tilted roof). This on the other hand demands adequate solar protection for large glazed surfaces. Furthermore, high summer sun implies a careful glass roof design.

From the temperature point of view, the site is offering several advantages. Except for the obvious low heating demand which can be expected from the mean annual temperature at 16.7°C this temperature also defines the ground temperature below 10 m. The ground can therefore work as a free cooling source and works as a great heat source for a heat pump. The day-night temperature swings in summer of 12 °C or more, night temperatures almost always below 20 °C and limited high temperatures (ca 20 hours a year above 29 °C) create a good potential for night cooling. Because daytime peaks happen in seasons with colder nights, these can be buffered by optimized thermal mass. Outside temperature in summer can be used as a source for cross ventilation. This can be supported by the clear dominant wind direction from WSW. For this purpose, an optimal roof shaping and façade openings is needed.

Small problem can pose the humidity (maximal absolute humidity level at 15 g/kg) at outside temperatures. With space conditioning a limited dehumidification potential is required

The basic premise of the sustainable concept development was "high comfort (thermal and visual) – low impact (emissions-resources, energy)". The strategy was therefore divided into three steps: Load reduction, supply systems optimization and usage of renewable energy sources.

4. Simulations and concept optimization

4.1. CFD

CFD Simulations were considered for different scales using [2]. Landscape scale CFD simulation helped to understand the micro-climate and the influence of the terrain. It has shown that the winds come from the ocean into the valley instead of being deviated and climbing up to the hill. Winds at the building site come then directly from the sea. Neighbourhood scale simulation defined the influence of the surrounding buildings. The building was to be built in already existing neighbourhood with a landscape profile, buildings and vegetation. Therefore, the wind shading effects of the neighbourhood had to be considered. This simulation has shown that the 11.5 m tall neighbouring building and the gigantic vegetation cause strong wind shadow effects especially for the critical ocean breeze. Detailed building CFD simulation analysed the pressure distribution around the building and helped to optimize the natural wind ventilation. Based on the results of previous simulations, this one has confirmed, that at original roof level of 9.3 m defined by the local building regulations, the effect of the neighbour is quite strong. As a result, an increase of the total height of the building to 11.5 m (same height as the neighbouring building) has been proposed. This proposal has been supported by another CFD simulation, which has shown that the wind exposure creates a suction effect pulling the warm air out of the house. The cool ocean breeze trickles in at the façade to cool the space and the solar shade. As this was the base for the zero-energy building this simulation proved argumentation was used towards the advisory board of the permit authorities and convinced them to allow for a liberation and a final roof height of 2.2 m above the rules.

4.2. Solar radiation and thermal study

Considering that the solar gains and loads are the most important external impact on a highly glazed building an analysis of the solar exposure and radiation was crucial in the design process. A 3D model including all relevant neighbourhood and trees was used to determine the sun radiation direction as well as the total solar exposure of the surfaces [3][4]. This study allowed to determine, which surfaces need additional shading but also the primary areas to consider PV and solar thermal panels. Comparison of different shading strategies allowed to identify the option with the minimal hours of façade shading especially for the West facades, which would reduce the view to the ocean.

In total three options were considered. All the options used internal shade with 10% transmission due to critical wind exposure for the site. Option O1 used the glass with the solar heat gain coefficient of SHGC = 0.6 and the shades have been only radiation controlled. The setpoint for closing the shades was 180 W/m^2. Option O2 used the same glass, but the shading elements were closed at the internal temperature of T_{room} > 26 °C and opened again at T_{room} < 21 °C. It also used increased ventilation if T_{room} > 24 °C. Option O3 was the most complex one. It used a glass with sghc = 0.38 on both façade and roof, while the roof glazing has also been treated with 30% frit on position 2. This option also considered increased ventilation if T_{room} > 24 °C. Façade shading closed if if T_{room} > 26 °C and vertical radiation on the façade was higher than 250 W/m^2. Roof shading was only radiation controlled and closed if the radiation was higher than 180 W/m^2. The hours with closed shading systems (internal with transmission of 20 %) on individual surfaces are summarized in table 1.

Table 1. Comparison of the shading strategies. Setpoints represent $T_{set,shade}$ – shading closed if T_{room} > 26 °C and opens again if T_{room} < 21 °C; $I_{set,1}$ – Shading closes if solar irradiation is higher than 180 W/m^2; $I_{set,1}$ – Shading closes if solar irradiation is higher than 250 W/m^2; $T_{set,ventilation}$ – ventilation rate increases if if T_{room} > 24 °C and gets back to normal if T_{room} < 21 °C;

	O1	O2	O3
Glass façade shgc	0.6	0.6	0.38
Glass façade 30 % frit on pos. 2	no	no	no
Glass roof shgc	0.6	0.6	0.38
Glass roof 30 % frit on pos. 2	no	no	yes
Temperature setpoint – shading façade	no	$T_{set,shade}$	$T_{set,shade}$
Radiation setpoint – shading façade	$I_{set,1}$	no	$I_{set,1}$
Temperature setpoint – shading roof	no	$T_{set,shade}$	no
Radiation setpoint – shading roof	$I_{set,2}$	no	$I_{set,1}$
Temperature setpoint – increased ventilation	no	$T_{set,ventilation}$	$T_{set,ventilation}$
Southern façade – shading hours	2 408	460	266
Western façade – shading hours	1 652	460	263
Eastern façade – shading hours	1 613	460	28
Northern façade – shading hours	280	0	0
Glass roof	3 243	1 427	3 243

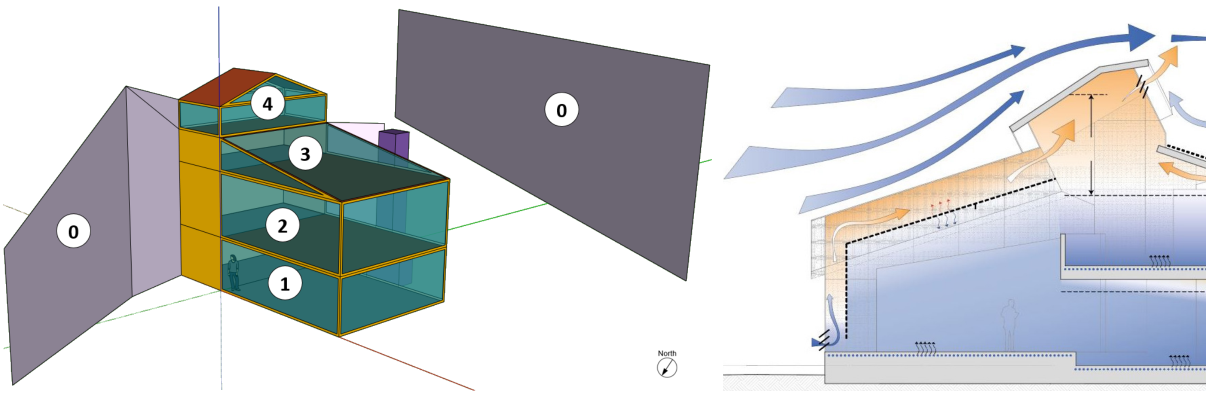

Figure 3. Simulated wing stratification (left) and heat gains flushing by ventilation (right) in the internal fully open building; 0 – shading buildings, 1 – zone bottom, 2 – zone middle, 3 – zone roof, 4 – zone air hat

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Parallel to the solar radiation study and shading optimization, thermal simulations took place [5]. For this purpose, the simulated zone was divided into four thermal zones as shown in figure 3 (left). As mentioned before, the hottest period of the year which occurs in September was selected as the boundary condition for the simulations. In the base variant the glazing characterized by U = 1.1 W/m^{2}K and shgc of 60 % has been considered

Five case scenarios have been investigated:

- V1 – natural ventilation, two-layer heat protection glazing VLT 70 %, SHGC 60 %, no shading
- V2 – internal low emission (0.3) shading on the roof
- V3 – internal low emission (0.3) shading on the roof + activated floor cooling
- V4 – mixed shading: internal low emission (0.3) shading on the roof + external shading for walls
- V5 – mixed shading + activated floor cooling

The comparison of the perceived temperature in the zone during the hottest period of the year can be seen in figure 4. Based on the results of the simulations, the variant V5 has been chosen as the best strategy.

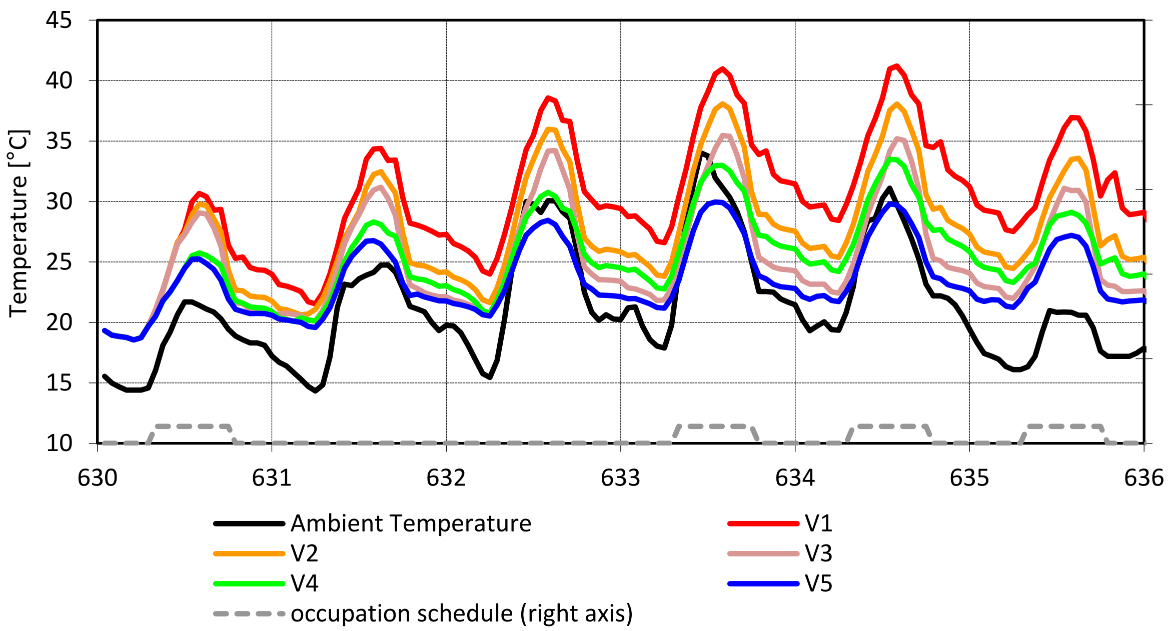

Figure 4. Perceived room temperature for simulated variants – hottest period

4.3. *Final concept*

Based on the simulations and optimizations of the southwestern wing, the concept for the whole project has been proposed and the systems scaled. Figure 5 shows the main features on the section of the main house. To reduce the heat losses, a well-insulated envelope was necessary (U_{walls} = 0.29 Wm^{-2}K^{-1}; U_{roof} = 0.19 Wm^{-2}K^{-1}; U_{floor} = 0.63 Wm^{-2}K^{-1}; Infiltration 0.2 h^{-1}; $U_{window\ frame}$ = 1.90 Wm^{-2}K^{-1}; highly selective glazing Viracon VE1-2M [6]).

Ventilation is achieved naturally through motorized façade flaps controlled by two CO_2 sensors in the house. The ventilation control works in steps to avoid surplus ventilation with heat or humidity loads. Based on the external and internal hat loads ventilation flaps at the lower facades and on the rooftop were sized to allow for a sufficient cross ventilation using the ocean breeze. The pressure resistance of insect screens had to be considered for all façade openings due to poison spiders in the region. System is controlled by room and outdoor temperature as well as humidity. For protection wind velocity and direction plus rain sensors also give an input to the system.

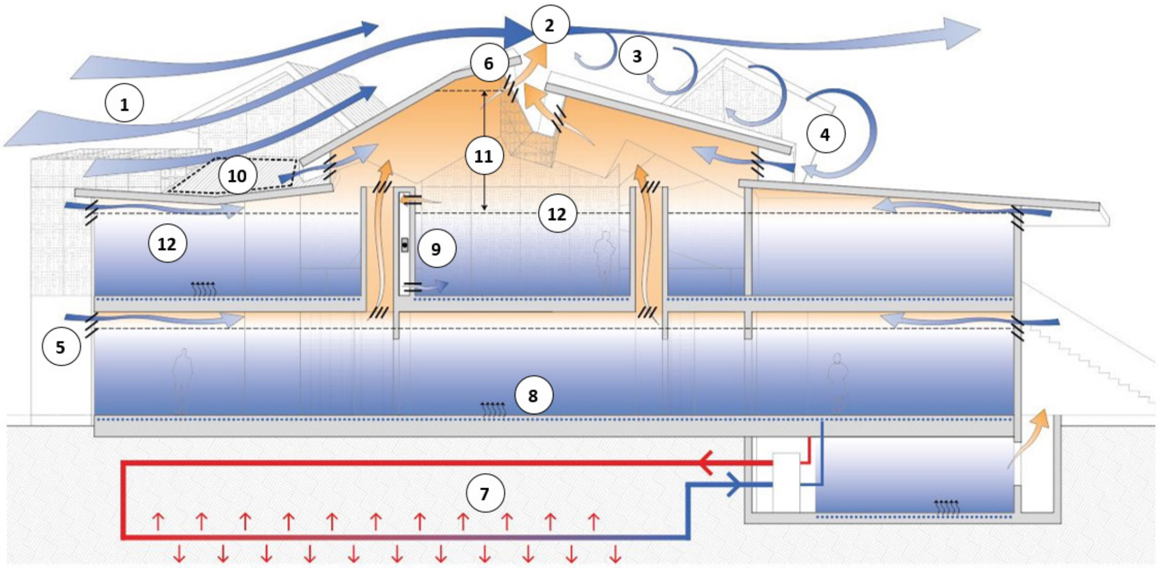

Figure 5. Concept for the main house: 1- WSW prevailing wind; 2- low pressure zone; 3- high pressure zone; 4- recirculating airflow; 5- natural wind ventilation (17 m^2); 6- wind scoop – solar chimney (8 m^2); 7- geothermal system (9 geothermal boreholes 100 m deep); 8- radiant floor; 9- gravity wall; 10- PV and solar thermal; 11- heat reservoir; 12- warm buffer – cold air zone boundary;

To limit solar heat gains a first measure is to install a neutral high selective glass with only 33% solar but 70% daylight transmission. All solar exposed glass surfaces have in addition either a 30 to 50% fritting on position 2 or an internal reflective shading device with maximal 10% rest transmission. To minimize the impact on the thermal comfort below the shading, the 70% reflective shading material – like Soltis – 92E [7] – has only 4% rest transmission and comes with a low emissivity coating towards the space, which reduces the thermal heat radiation by 70%. The heat accumulated around the shading material is ventilated out by a thermal chimney or the wind driven exhaust flow in the one space building with the all open section. Shading control is due to related room temperature, radiation for the different orientations, ventilation status and cooling capacity status, with a priority especially for the façade shading to cross ventilation to maximize the outdoor connection. Only if the room temperatures can't be hold around the set point with all other measures the façade shading is pulled down.

Basic conditioning is provided by radiant floors with high cooling temperatures (18 °C) and low heating temperatures (27 °C). Areas with carpet or wood topping are only activated for heating purpose and blocked in cooling mode to avoid condensation problems. Individual zone adjustment is achievable through a gravity wall system, a system well matching with a natural ventilation system and without any fan noise in the free mode. Gravity wall systems use the natural buoyancy effect of air to run a soundless return air cooling/heating system, allowing for a room by room temperature and maximal humidity control, due to its condensation performance. The activation of the gravity walls is controlled by room thermo-/hygrostates, which will activate the lower set point of the cold-water buffer if dehumidification is demanded. By personal access occupants can activate a 5-step fan support for a boosting of the cooling. In heating mode, the fan is automatically active, to supply the warm air at the bottom of the wall.

The energy for heating and cooling as well as domestic hot water and pool heater is produced by a 20-ton reversible water to water heat pump/chiller. This uses finally 9 closed loop geothermal boreholes – after the local thermal respond tests 1 borehole could be saved due to high conductivity values of the soil –, each 100 m deep as a heat source/sink. This is taking advantage of the climatic expected ground temperatures around 15.5 °C and lower. For direct free cooling a bypass around the reversible heat pump/chiller is necessary, allowing in addition to separate the floor supply from the gravity walls, while they may demand mechanical cooling, while the floor systems can still run on free cooling. The hot water boiler is connected to a solar collector system for preheating or full coverage of the domestic hot water load, which has a backup from the warm side of the heat pump and/or desuperheater outlet. To minimize visual impact and maximize the system output evacuated tube collectors are chosen (11.5 m^2), which allow a horizontal installation with a rotation tilt of each individual tube to the absorber slop.

To cover as much overall electricity demand of the project as possible, 220 m² photovoltaic panels panels are installed on the roof of the South house. Surplus electricity is stored in the public grid and reimported at nighttime or during overcast periods.

5. Operation measurements and discussion

To illustrate the system performance, a measurement of temperatures and some of the system characteristics for the Master bedroom (located in the core of the main house on the 1st floor) on the 5th of June 2018 is presented. It must be mentioned, that due to the users' requests, some of the automatic system features have been disabled. One of these features is automatic opening of the windows, when users have claimed, the noise of opening and closing was disruptive during nights or social events. Figure 6 shows the ambient temperature, temperature of the radiant floor slab as well as the room air and operative temperatures. It also shows whether the radiant floor slab and gravity walls are in operation at the time.

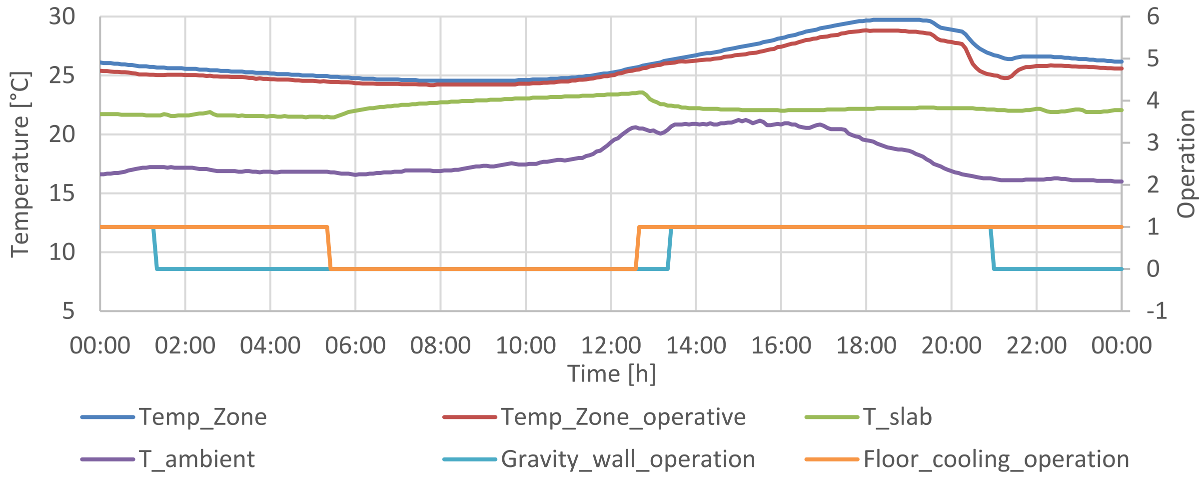

Figure 6. Measured temperatures and cooling systems operation on the 5th of June 2018 in Master bedroom on the second floor

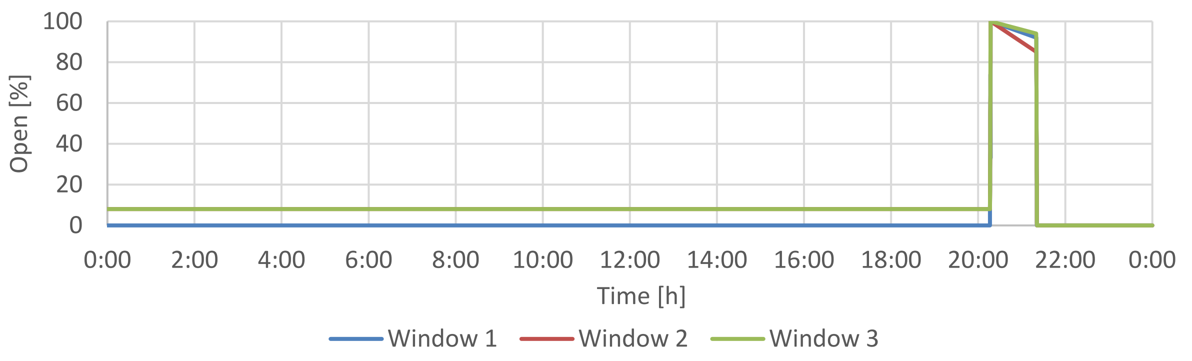

Figure 7. Windows' position log (100 % means fully open) on the 5th of June 2018 in Master bedroom

Figure 7 than shows to what extent have the windows in the room been opened. It can be seen that the windows have only been fully opened for approximately one hour. Provided that the measurement takes place on a Tuesday, it can be assumed, that the room was not occupied during the day.

From the figures 6 and 7 an increase of the space temperature especially in the afternoon is visible due to the collection of the warm air in the upper part of the building. This triggers the operation of the radiant floor slab. Since this has not been enough to stop the increase of the internal temperatures, the gravity wall has been turned on, supporting the airflow with a fan running on 3rd of its 5 speed steps. Neither of these steps have been capable to stop the increase of the internal air temperature, which has reached approximately 30 °C. Due to the blocked automatic ventilation control the free cooling potential of the outdoor temperature with maximal 22°C could not be used. Manual opening the windows in the evening took advantage of the ocean breeze and a rapid cooling of the room was started. Reflecting the function of a master bedroom the higher temperatures in the afternoon are not critical. This shows that the originally proposed concept and system has the potential to provide comfortable internal environment without an AC unit, when operated automatically. The systems control has to be tuned to fulfil its original purpose while meeting the user preferences.

Project findings based on measurements and a 1 year operation show that an online project performance documentation can help to understand system problems in early stages and check occupants' remarks. First discomfort comments by Mr and Mrs Gehry during last summer were aimed on low room temperatures when the system tried to reach the internal air temperature of 72°F (22°C). With an increased set point to 77°F (25°C) they felt more comfortable.

Wrong pump sizing and ignored intelligent pump specifications ended with whistling valves contradicting the low noise conditioning system goal. Errors in the piping installation short cut the buffer tanks on the cold and hot side of the heat pump and initiated frequent activations of the heat pumps. A recent repiping to the intended hydraulics could aims to solve this issue and its effect will be reviewed. This shows that even a careful developed and evaluated concept needs a strict supervision in the installation by the design team. A big advantage is the fully flexible building management system, which allows even a control adjustment from Stuttgart as well as reconfiguration of parameters and interconnections.

6. Conclusions

This paper has presented an energy concept for a set of zero- energy residential buildings in coastal Mediterranean climate without a conventional air-conditioning. The focus was aimed on sustainability. The process of concept development has been described including the supporting simulations and design assumptions. Simulations as CFD, solar studies and thermal simulations and calculations have played a crucial part in the design process and the paper shows the importance of informed design decisions. The conducted CFD studies have shown, that in order to use the natural ventilation potential of the site, the rooftop must be elevated above the regulations limit. These results have then served as an argument in the negotiations with the authorities and helped to get the approval to build a taller building. The assumptions of the studies have then been confronted with the measured data from the operation which is in some points different from the original assumptions. The disruptive noise produced by automatic opening and closing of the ventilation openings has led to the switch towards manual operation. This as documented in this paper has led to limiting the effectivity of the system as a whole. Measurements also show, the potential to provide comfortable internal environment without an AC unit. In order to fulfil the goal of comfortable high-end residential building with low energy and resource consumption the control system has to be tuned to allow users to implement their preferences (for example to easily switch between manual and automatic window opening).

The review of the system and concept shows that considering the local potentials in Santa Monica, a fully natural ventilated house with a renewable energy based supply system can work. The close collaboration of the energy-concept team and the architect can lead to a functional internal environment system with no impact on the architectural quality of the house. Even more, a reasonable renewable concept can serve as a very strong argument for the authorities to grant exceptions from general rules in order to ensure its functionality.

This project should be considered a statement of a world known architect – known less for his green buildings than for his sculptural buildings – towards green building with a very high architectural standard. This project shows that these terms do not contradict each other, but can possibly constitute a strong symbiosis.

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