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SUSTAINABLE HEATING, COOLING AND VENTILATION OF AN ENERGYPLUS HOUSE

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Introduction

In 2011 Technical University of Denmark (DTU) was accredited to participate in worldwide competition Solar Decathlon Europe 2012. The origins of this competition start in USA, in 2002 and later in 2010 European version was created.
The idea of the competition is described as:
"The Solar Decathlon is an international competition organized by the U.S. Department of Energy in which universities from all over the world meet to design, build and operate an energetically self-sufficient house, grid-connected, using solar energy as the only energy source and equipped with all of the technologies that permit maximum energy efficiency" (Solar Decathlon, 2012).
There is a European version of the competition which is explained by the organization as:
"The Solar Decathlon Europe (SDE) was created through an agreement signed between the Ministry of Housing of the Government of Spain and the United States Government, in October 2007, who committed to organize a sustainable solar houses competition in Europe. The document specified that the European competitions were to be held in alternate years from those in America" (Solar Decathlon, 2012).

The main goals of the competition can be described as follows:

- To raise awareness of the students participating in the competition on the benefits and opportunities offered by the use of renewable energies and sustainable construction, challenging them to think creatively and develop innovative solutions that contribute to energy savings and how it affects our everyday lives.

- To encourage the construction professionals to select materials and systems that reduces the environmental impact of a building over its entire lifetime, optimizing its economic viability and providing comfort and safety of occupants.

- To educate the general public about responsible energy use, renewable energy, energy efficiency, and the technologies available to help them reduce their energy consumption.

- To emphasize the correct order of intervention: first reducing the building energy consumption and increasing its energy efficiency; and afterwards integrating solar active systems and/or other renewable technologies. Moreover the building systems must be selected and dimensioned using environmental and cost-effective criteria.

- To encourage the use of solar technologies and other renewable energy sources.

- To promote architecturally attractive solar system integration, working on using the solar technologies to replace conventional construction materials in the building envelope such as the roof, skylights or facades.

- To clearly demonstrate that high performance solar homes can be comfortable, attractive and affordable. (Solar Decathlon, 2012)

There are 10 categories that teams compete in. Each category is awarded by the number of points. These categories can be seen in the list:

- 1: Architecture (120 p)
- 2: Engineering and construction (80 p)
- 3: Energy efficiency(100 p)
- 4: Electrical energy balance (120 p)
- 5: Comfort conditions (120 p)
- 6: House functioning (120 p)

- 7: Communication and social awareness (80 p)
- 8: Industrialization and market viability (80 p)
- 9: Innovation (80 p)
- 10: Sustainability (100 p)

The main goal is to score as close as possible to 1000 points. However, categories are awarded with points by making objective measurements, and subjective, by jury, evaluations. One important aspect to observe is that there is a strong link between all of the components of the house, influencing scored points.

The FOLD – House description

The architectural concept of the house is a design which embraces, tunes and shares. The description of the architectural narrative gives broader explanation of the concept as:

"EMBRACE - Climatic conditions change according to your geographical whereabouts. But one thing is common: The sun is the greatest energy source of all. It defines the natural resources of the plot. These resources differ depending on the geographical context, and when creating a shelter the designer embraces solar, biological, economical, ecological and cultural resources of the plot. The shelter is created by folding the plot with all its implemented resources as a protective membrane around the family.

TUNE - FOLD can take on countless configurations. The size, inclination and orientation of the different surfaces are adjusted to the site specific resources. All surfaces are optimized to function optimally for the specific context. In Madrid the optimal surface functions are photovoltaic's on the roof for renewable energy production, a green wall for the urban microclimate and a light wall to increase the security of the urban space.

SHARE - Sustainable living is a collective mindset that engages everybody. It demands responsibility and awareness. The society is a delicate organism, and everybody is a crucial part of the sustainable project. This project is all about how we manage the resources. And the only sensible thing is to allocate surplus resources to places of less resource. Establishing a solar democracy like this addresses all three aspects of the general sustainably concept: Economy, society and environment" (Team DTU, 2012).

The design of the house intends to minimize heat gain to the house from the environment, also to provide the optimal positioning for PV/T panels, which are placed on the roof. The house's largest glazing façade is oriented to the North side, with a 19˚ turn towards West.

The house is constructed from light weight wooden elements/slabs. Walls, roof and floor structures are formed by placing prefabricated elements in a sequential order and sealing the joints. South and North glazing walls are inserted later, sealing the joints between glazing frame and house structure. The house is supported on 20 cm to 30 cm concrete blocks.

Pre-fabricated house elements are made from layers of Kerto board (laminated veneer lumber), which in combination with I beams in between forms structural part, and mineral wool insulation. The house is insulated with two types of insulation: 20 cm of conventional mineral wool (manufactured by Rockwool) and 8 cm of compressed mineral wool "Aerowolle" (manufactured by Rockwool).

Entire house envelope, except glazing parts, are made from the same materials and prefabricated elements. It includes not only the structural part but various installations as well, such as embedded pipe loops, photovoltaic/thermal panels etc. Three dimensional visualization of the house is shown in the figures below:

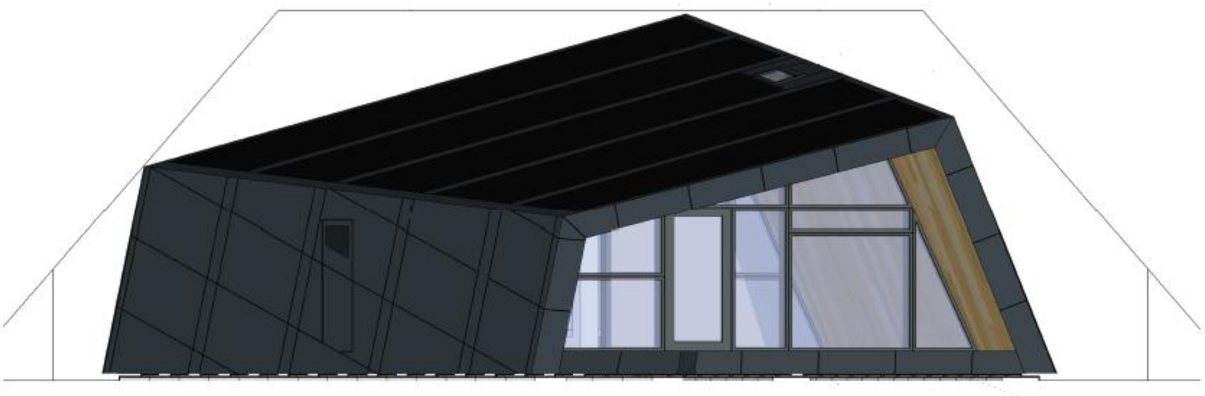

Figure 1: South-West side (House visualization – Team DTU)

Figure 2: North-East side (House visualization – Team DTU)

The area of the surfaces of the house and the thermal transmittance of the different components of the envelope are presented in the table below:

Table 1: House construction details (O. B. Kazanci, M. Skrupskelis, 2012)

External walls	**South**	**North**	**East**	**West**	**Floor**	**Roof**
Area [m^2]	-	-	19,3	37,2	66,2	53
U-value [W/m^2K]	-	-	0,09	0,09	0,09	0,09
Windows	**South**	**North**	**East**	**West**	**Floor**	**Roof**
Area [m^2]	21,8	36,7	-	-	-	0,74
U-value [W/m^2K]	1,04	1,04	-	-	-	1,04
Solar transmission	0,3	0,3	-	-	-	0,3

The huge glazing surfaces in South and North side of the house are covered by the overhangs, which eliminates direct solar radiation to the house during the summer season. For the winter season direct solar radiation enters the house, creating favorable effect for the heating mode. No active shading systems were designed and installed in the house except for the skylight window.

Inside the house there is one big space combining kitchen, living room and bedroom areas. Shower and toilet areas are partly separated by partitions. Technical room is completely isolated from the main indoor space, having a separate entrance. Wall between technical room and indoor space is insulated with the same level of insulation as the outside walls. The reason of technical room being separated is to limit the heat load entering the main indoor space released by the machinery and equipment installed there. Technical room is partly exposed to the outdoor air temperature, by implemented natural ventilation concept.

The effect of the natural ventilation in this area is created by the opening in the floor and the opening (with installed grills) on the door. The cold air below the house will rise through the floor, heat up and get out of the room via the opening in the door.

Design Methodology of the HVAC System

With the given constraints on the system, an entire HVAC system for the house had to be designed following the ambitions given in the introduction.

The initial design conditions required for the house to be fully functioning in two different climates: Denmark (Copenhagen) and Spain (Madrid). Indoor climate requirements were set by regulations of "Solar Decathlon Europe 2012" competition, as explained:

- Temperature limits inside the house: 23,0°C -25,0°C
- Relative humidity in the house: 40% - 55%
- Maximum CO_2 concentration in the house: 800 ppm

Even though the design was mainly aimed at keeping the conditions during the competition period, it had to be assured that the house performs as intended all year round. This was implemented with different set-points in the simulations as explained in the respective chapter.

To design a heating/cooling and ventilation system, load calculations were performed. Construction of the house is defined by the architectural design team. This design was taken as the basis for load calculations. Design heating and cooling needs are determined by three mechanisms: transmission load, internal heat load and radiation gain.

The heating and cooling needs are: ultimate cooling load is 52,0 W/m^2, average cooling load is 35,^{2} W/m^2, ultimate heating load is 45,6 W/m^2 and average heating load is 26,6 W/m^2, given that the indoor floor area is 66,2 m^2.

The ideal design of the house should enable autonomous performance, in terms of energy consumption and production. Maximum amount of energy should be produced and least amount of energy should be consumed to run the house and the appliances installed. The only electrical energy source to the house is solar energy, utilized via Photo-Voltaic panels placed on the entire roof area. The electrical system is designed to be grid-connected. Coupled with the PV panels is the solar thermal system, which absorbs the heat produced by PV panels and utilizes it in the Domestic Hot Water tank, herein DHW, making combined Photo-Voltaic/Thermal system (herein PV/T).

Cooling and heating system of the house is water based, with a low temperature heating and high temperature cooling concept. Heat source/sink is the ground, utilized via a borehole heat exchanger. "Free cooling" is obtained during the cooling season without any extra energy consumption other than the circulation pump and ground coupled heat pump is used to achieve the necessary supply temperature to the embedded pipes during the heating season.

As an addition to the space heating and cooling, ground heat exchanger could also be utilized for the PV/T cooling. Yet, initial evaluations showed that this concept was too expensive to be realized, since it requires extra capacity of the ground heat exchanger.

The house being high-tech, it stores great amount of machinery and electronic equipment which operate the house. All of these components release heat to the environment. As it is a need to limit heat production in the house, a solution is to isolate all equipment which is not used by the occupants on a day to day basis. The equipment is placed in the technical room, which has no direct thermal connection to the inside area.

In order to regulate the air quality in the house, mechanical and natural ventilation systems are installed. The mechanical ventilation consists of 2 supply diffusers to the space and 4 exhausts (kitchen hood, bathroom, toilet and the clothes dryer). Since the natural ventilation doesn't consume almost any energy it should be prioritized over the mechanical ventilation whenever outside conditions are "feasible" (outside temperature close to room temperature).

HVAC System and Control Concept

The individual operation of the components of the HVAC system and operation of the system as a whole had to be controlled in order to assure optimal performance of each component and optimal performance of the system as a whole. This was mainly done on a seasonal basis (heating/cooling) and with more detailed conditions within each season. Most significant parameters of each component of the HVAC system are presented below.

The ground heat exchanger was designed to be a borehole with a depth of 120 meters, single U-tube configuration and with a diameter of 0.12 m. The inner and outer radii of the heat exchanger pipes were 0.013 m and 0.016 m, respectively. Obtained borehole resistance was 0.1 m-K/W and total resistance to the undisturbed ground (8.3°C and 14.3°C for Copenhagen and Madrid, respectively) was 0.37 m-K/W.

The space heating and space cooling in the house is provided by the pipes that are embedded in the floor and the ceiling. It is a dry radiant system, having piping grid installed under the wooden layer, with an aluminum layer for thermal conductance. Space heating is only obtained by the embedded pipes in the floor and space cooling is obtained by embedded pipes in the ceiling and, if necessary, in the floor. The supply and return flows will be coming from/going into the ground, to the installed ground heat exchanger. To control water flow and temperature (dew-point temperature) a mixing station is installed.

The designed embedded pipe system is given as the following:

- For the ceiling, Uponor foam board system, with aluminum heat conductive device, PEX pipe 12x1,7 mm. In total 6 circuits are designed for the ceiling system, with maximum flow rate in one circuit of 0,07 m3/h.
- For the floor, Uponor chipboard system, with aluminum heat conducting device, PEX pipe 17x2,0 mm. In total 4 circuits are designed for the floor system, with maximum flow rate in one circuit of 0,07 m^3/h for the cooling case, and 0,15 m^3/h for heating case.

The chosen air handling unit, herein AHU, to be installed in the house is a part of Nilan Compact-P unit. Maximum air flow rate provided by the unit is 320 m3/h, which is 1,5 ach, at 100 Pa. The flow rate fully covers the need for the design flow rate. The pressure drop in duct network for supply is 26,1 Pa, and for extract network is 27,2 Pa.

AHU has two heat recovery systems: passive (cross flow heat exchanger) and active (reversible heat pump coupled with the DHW tank). Active heat recovery/heat removal is obtained via a heat pump cycle that changes the evaporator/condenser in the supply air duct to the interior. This is achieved via a 4-way valve in the heat pump cycle. Passive heat recovery system has an efficiency of 88% (sensible heat). Thermal energy of the exhaust air is transported to the supply air. By pass mode is possible.

Mechanical ventilation gives more control over the parameters like temperature, relative humidity and CO_2 levels however due to the use of mechanical fans it consumes a certain amount of energy (40 Wh/m^3). This amount of energy can be eliminated when the outside conditions are “feasible” for natural ventilation. Natural ventilation option is possible via two windows in South and North façades and the operable skylight window.

Another part of the system that directly interacts with the ground is PV/T. PV/T part is intended to produce electricity (nominal electrical efficiency is 15.73%), Photo-Voltaic, and produce heat for the Domestic Hot Water and domestic appliances (dishwasher, clothes washer and clothes dryer). Production of heat, also serves the purpose of PV/T cooling which helps keeping the electrical efficiency close to the optimum.

PV/T area (67.8 m^2) is divided into Part A (45.4 m^2) and Part B (22.4 m^2), for different control purposes. Part A is solely intended to charge DHW tank. If there is any flow in Part A this is when there is DHW need and the flow can only be directed to the DHW tank.

On the other hand, Part B serves for both purposes; charging the DHW tank and PV/T cooling. The mode depends on the control logic that has been chosen. When there is a DHW need, Part B also contributes to the charging of the DHW tank. Initial simulations and calculations showed that the ground (one borehole) is not capable of providing necessary supply temperature to the embedded pipes when house cooling and PV/T cooling are active simultaneously. Therefore PV/T cooling option is only applicable when house doesn’t need cooling. There is also a drain-back tank between the PV/T loops and the DHW tank which makes it possible to drain all the water from the PV/T loop, when necessary, in order to avoid boiling or freezing of the water in the circuits.

The DHW tank of 180 liters is equipped with two spiral heat exchangers and an electric heater. One of the spiral heat exchangers is connected to the PV/T loops via the drain-back tank and the other one to the active heat recovery system of the ventilation. The top part of the tank (54 liters) is heated by the electric heater (1.5 kW).

House performance

In order to evaluate the house on an all year round basis simulations have been carried out and the results of the simulations are presented in the following table:

Table 2: Energy consumption by building needs (TRNSYS) (O. B. Kazanci, M. Skrupskelis, 2012)

	Copenhagen	Madrid
Heating [kWh/m^2]	31,6	20,7
Cooling [kWh/m^2]	0,5	1,0

Ventilation [kWh/m^2]	0,7	5,2
DHW [kWh/m^2]	7,3	3,8
Rest of the electricity [kWh/m^2]	5,6	4,4
Total electricity consumption [kWh/m^2]	45,6	35,1
Total primary energy consumption [kWh/m^2]	114,1	105,2
Total energy balance (electricity) [kWh/m^2]	66,7	137,0

The performance of the house considering air temperature, relative humidity and air quality, during the competition period (September 17th – September 28th 2012), is presented in the figures below:

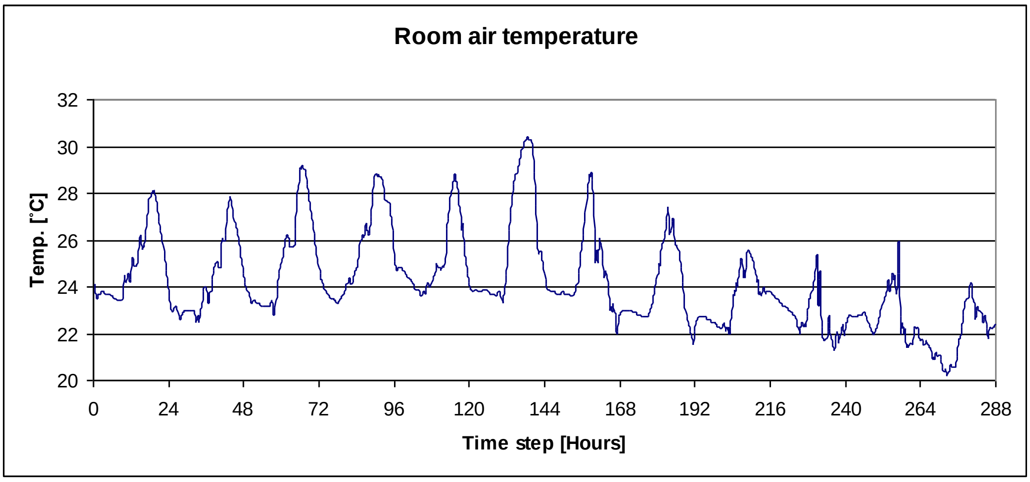

Figure 3: Room Temperature – FOLD. Team DTU (Solar Decathlon, 2012)

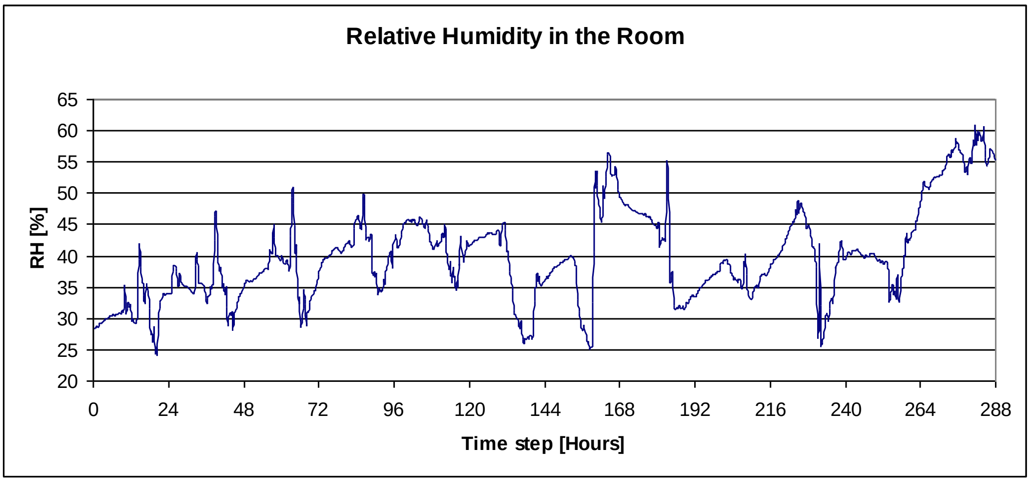

Figure 4: Relative Humidity in Room – FOLD. Team DTU (Solar Decathlon, 2012)

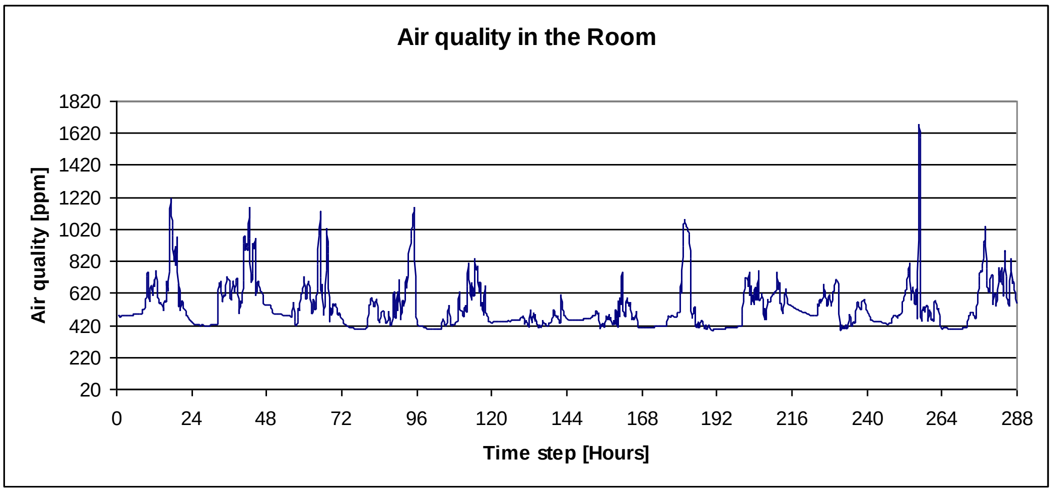

Figure 5: Air quality in Room – FOLD. Team DTU (Solar Decathlon, 2012)

Measurements were carried out 24 hours per day, with a time step of 15 min, yet the scoring was only done from hour 21:00 to 06:00 and from 10:00 to 16:00. For the rest of the hours, house was open to public therefore measurements didn't influence the final scoring.

The electrical energy performance of the house is presented in the figure below:

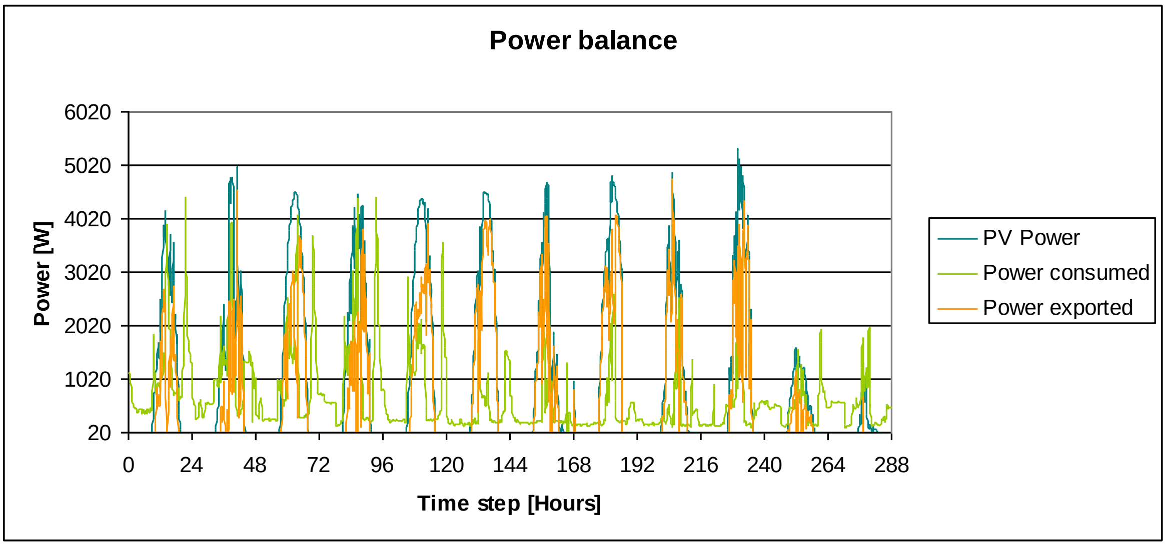

Figure 6: Power balance. Team DTU (Solar Decathlon, 2012)

Discussion

The evaluations using simulations show that the house performs as a "plus-energy house" on an annual basis however it should be kept in mind that the results are aggregated values within a year and the time of energy production and consumption doesn't necessarily correspond to each other.

For both of the locations, the highest contribution to the energy consumption is from the heating demand. This is mainly due to the North and South glass façades. This effect somewhat offsets the positive effect of the low U-value of the walls.

Embedded pipes in the floor and ceiling are advantageous in achieving the goal of energy efficient heating cooling, mainly due to the high temperature cooling and low temperature heating concept enabling the natural resources to be coupled/integrated into the HVAC system, in this case being ground heat exchanger.

"Free cooling" is possible to observe for both of the locations, taking Madrid as an example, the same amount of cooling would have been delivered with 848 kWh of electricity compared to 65 kWh of electricity, if it were to be done with the chosen chiller. For the heating case, long-term effects should be considered and kept in mind while realizing this design.

PV/T panels enable the house to be self sufficient and even produce energy than it consumes on the electrical side and PV/T panels also contribute significantly to the heat demand for the domestic hot water consumption.

Even though the mechanical ventilation provides better control over the important comfort parameters, natural ventilation possibilities should be exploited until the limits in order to save energy.

The design phase was an iterative process with continuous internal and external feedback. Every component was designed in such a way, with given physical and practical constraints, that the optimum performance and output would be obtained. However it was observed that it is not enough only for one component of the system to perform optimally but what really matters is the interaction of these components within the entire system. This necessitated a holistic approach to the project and to the design procedure.

At the end of the competition evaluated performance of the designed HVAC system based on the scoring. From the comfort conditions competition, for the tasks related to HVAC, the obtained scores were 63,18 out of 70, 8,37 out of 10 and 4,91 out of 5 points for temperature, relative humidity and CO_2 level, respectively (Solar Decathlon Europe, 2012). This indicated that the designed system performed successfully and scored close to maximum in all of the three tasks.

References

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