Technical University of Denmark

Analysis of a plus-energy house for improved building and HVAC system design

Andersen, M.E. ; Schøtt, J.; Kazanci, Ongun Berk; Olesen, Bjarne W.

Published in:
Proceedings of ROOMVENT 2014, 13th SCANVAC International Conference on Air Distribution in Rooms

Publication date:
2014

ANALYSIS OF A PLUS-ENERGY HOUSE FOR IMPROVED BUILDING AND HVAC SYSTEM DESIGN

M. E. Andersen, J. Schøtt, O. B. Kazanci, B. W. Olesen
International Centre for Indoor Environment and Energy, Dept. of Civil Engineering, Technical University of Denmark, Nils Koppels Allé, Building 402, Kgs. Lyngby, Denmark

Abstract

The purpose of this study is to evaluate the energy consumption and indoor environment of a plus-energy house located in Denmark. The house is a detached, single-family house built for the Solar Decathlon Europe competition in 2012 by the Technical University of Denmark. The house is currently being used as a full-scale experimental facility. The measurement period considered in this study is from September 26, 2013 to April 3, 2014.

Measurements from the house are compared to the results obtained from a simulation model of the house in the commercially available building simulation software, IDA ICE. Different parameters are investigated in order to improve the energy performance and the indoor environment of the house. Some of the investigated parameters are the orientation of the house, positioning and areas of the windows, thermal bridges, and infiltration. Various improvement suggestions are presented based on the parametric studies and the comparison of the results.

It was found that there is an average standard error of 2.7 % when comparing the simulation results with the obtained experimental data regarding the operative temperature. The simulated energy consumption of the heat pump is 13.7 % lower than the measurements. The ventilation system is determined to have 23 % lower energy consumption in the simulated model when compared to the measurements.

The improved model has a 25 % reduced window area, and an improved building envelope. The study concludes that the improved model reduces the total energy consumption by 68 %. The time in thermal indoor environment category I, according to EN 15251, is improved from 71 % to 97 %.

Keywords: Energy consumption, indoor environment, IDA ICE, full-scale measurements, plus-energy house.

1 Introduction

Energy consumption in buildings will continue to be a vital part of achieving the goal of reducing the greenhouse gas emissions. As the buildings evolve to be more energy efficient, some undesired effects are also appearing. A result of this evolution is an increase of thermal discomfort for the occupants due to factors such as overheating and poor indoor air quality.

There has been a growing international focus on reducing the energy consumption to reduce the impacts of global warming. The energy used in buildings represents 41 % of the total energy demand in Europe, Olsen (2014), which encourages the development of zero energy houses and plus energy houses, Greenmatch (2014). The low energy houses have, as a result of the low infiltration, low U-values and often due to large glazing façades, a tendency to overheat resulting in discomfort for the occupants, Larsen (2011).

This study is focusing on a plus-energy house, Fold, which was constructed for the international student competition Solar Decathlon Europe 2012 by the Technical University of Denmark. Fold is a plus-energy house because it produces more energy than it consumes on a yearly basis, Kazanci et al. (2013), Kazanci et al. (2014). The house was located in Denmark and since September 2013, it has been used as a full-scale experimental facility where different heating, cooling and ventilation strategies had been tested. Various physical parameters were measured, as well as the energy production and consumption. Even though the house is classified as a plus-energy house due to the electricity production by the photovoltaic/thermal panels placed on the roof, there is potential for improvement regarding the energy consumption and indoor environment.

The main goal of this study is to provide improvement suggestions (i.e. lowered energy consumption and improved indoor environment) based on the parametric analyses, carried out with computer simulations which are validated with measurements. One of the main focuses has been on the window area and the respective heating demand, as indicated by previous studies on the house, Kazanci et al. (2012), Kazanci et al. (2014).

The effects of different parameters which affect the energy performance and indoor environment of the house were studied via the commercially available building simulation software IDA ICE, EQUA (2014). Operative temperatures obtained from the simulation model and from the house were compared in order to validate the simulation model. The energy consumption of different components of the HVAC system was also compared.

2 House details

The house considered in this study is a single family, detached, one-storey house with a floor area of 66 m^2 and a conditioned volume of 213 m^3. The house had two large glazing façades oriented to North and South. The largest glazing façade was oriented towards the North with a 19° turn towards the West. The house and its two glass façades may be seen in Figure 1:

Figure 1 *–The South façade (left) and the North façade (right)*

The U-values of the different construction parts are shown in Table 1:

Table 1 – *U-values for different types of constructions*

Glazing façades	1.04 W/m^{2}K
Roof	0.090 W/m^{2}K
Walls	0.089 W/m^{2}K
Floor	0.088 W/m^{2}K

The HVAC system of the house consisted of a reversible air-to-brine heat pump, water-based radiant heating and cooling system and an air handling unit that is coupled with the domestic hot water tank via a reversible air-to-water (or water-to-air, depending on the operation mode) heat pump.

There was a flat plate heat exchanger placed in between the hydronic loops of the house and the heat pump in order to avoid frost damage during the winter months.

The main sensible heating and cooling strategy of the house relied on the low temperature heating and high temperature cooling principle via the hydronic radiant system. There were pipes embedded in the floor and in the ceiling structure. The embedded pipes in the ceiling were designed to be used for cooling purposes only while the embedded pipes in the floor could be used for heating as well as cooling during the peak loads. Four loops were located in the floor and six loops in the ceiling. A mixing station was installed in the system, in order to control the flow to the individual loops, the flow rate, and the supply temperature to the embedded pipes.

The indoor air quality (ventilation) was regulated by an air handling unit. Passive and active heat recovery options were available. The passive heat recovery was obtained via a cross-flow heat exchanger while the active heat recovery was obtained via a reversible air-to-water heat pump cycle that was coupled to the domestic hot water tank. The air handling unit could supply fresh air at a flow rate of 320 m^3/h at 100 Pa. The design ventilation rate was determined to be 0.5 ach. Humidification of the supply air was not possible due to the limitations of the air handling unit.

The infiltration was determined to a value of 5.3 l/s pr. m^2 at an induced pressure of 50 Pa. The test was conducted according to the methods described in EN 13829 (2001).

3 Physical measurements and the simulation model of the house

During the measurement period, the air and globe temperatures were measured at different heights (from 0.1 m to 3.7 m). The measurements of the globe temperatures at a height of 1.1 m (operative temperature) were used for the comparison of the measurements with the simulation results. The measurement location and equipment may be seen in Figure 2:

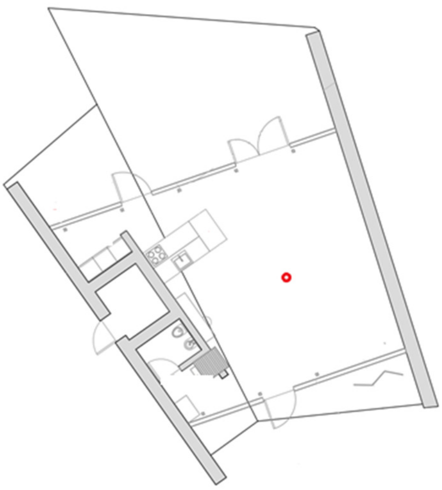

Figure 2 *– The location of the measurements(left) and the measurement equipment (right)*

The geometry of Fold was modeled in Google SketchUp to construct the advanced shapes of the house. The geometry was then imported into IDA ICE where windows, constructions and other parameters were specified. The Early Stage Building Optimization (ESBO) tool in IDA ICE was used as a base for the implementation of the HVAC system. The ESBO HVAC system was then modified in order to represent the real system. The HVAC system in the simulation model was constructed as close as possible to the real system, however an exact copy was not possible to obtain because some of the components from the real system were not available in IDA ICE.

A weather file was constructed with experimental weather data located 25 km away in a straight line from the house to eliminate as many sources of errors as possible. The weather file consisted of six parameters: dry-bulb temperature, relative humidity, wind direction, wind speed, direct normal radiation and diffuse radiation on a horizontal surface. The first four parameters were obtained directly from the datasheets of the weather station. The solar radiation parameters were calculated from the global solar radiation in the datasheet according to the method described in Kragh et al. (2002).

4 Results

The results from the measurements, simulations, comparisons and the results of the improvement suggestions are presented.

4.1 Temperature

Figure 3 shows the operative temperature from the measurements and from the simulation results.

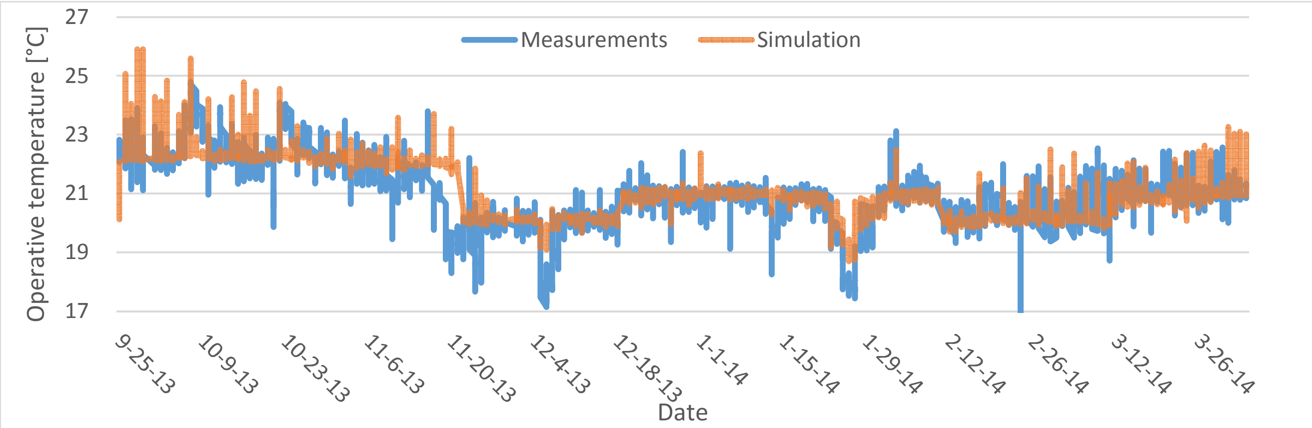

Figure 3 - *Comparison of operative temperature at 1.1 m*

It may be seen in Figure 3 that the temperature predicted by the simulations has a tendency to be higher than the measurement in the house. The relative difference between measurements and simulation results was determined to be 2.7 % during the measurement period. It was observed that the difference was higher when there was direct sunlight present. When this contribution was higher than 100 W/m^2 the relative difference between the two temperatures increased to a value of 4.6 %.

4.2 Energy consumption

A comparison of energy consumption for the reversible heat pump and the ventilation system was conducted for the simulation and measurements. In order to obtain the energy consumption from the simulations, the power in the given time step was multiplied with the length of the time step. Furthermore, the power output from the ventilation system had to be re-calculated using Coefficient of Performance (COP) values given by the manufacturer.

The result of these calculations showed that the energy consumption in the simulations was 13.7 % lower for the heat pump and 23 % lower for the ventilation system compared to the actual energy consumption.

4.3 Improvements

Based on the measurements in the house and the simulation model, several improvement options were investigated. In order to compare the different scenarios, the thermal indoor environment is evaluated according to the operative temperature intervals given in EN 15251 (2007). The energy consumption is also taken into account when comparing the different improvements.

Previous studies have shown that a major concern regarding Fold is the high heating demand, Kazanci et al. (2014), and since the current study uses the data obtained from the heating season, the focus of the improvements had been to minimize the heating demand. Nevertheless, improvements regarding the cooling season were also investigated.

The improvements with the biggest impact regarding both thermal indoor environment and energy consumption were reducing the window area, reducing the infiltration and minimizing the thermal bridges. The results of the investigations on these three improvements are presented in Table 2, Table 3 and Table 5.

In the tables below the reference case refers to the current state of the house. The values for the reference case are obtained from the IDA ICE model.

***Table 2** – Results of reduced window area*

Window area reduction		Reference	5%	10%	15%	20%	25%	38%	58%
Indoor environment category	I	71%	74%	76%	79%	81%	84%	89%	94%
	II	27%	24%	22%	20%	17%	16%	11%	5%
	III	2%	2%	2%	1%	1%	1%	1%	0%
	IV	0%	0%	0%	0%	0%	0%	0%	0%
Energy consumption	kWh/ year	6371	6151	5943	5729	5519	5311	4742	4125

In Table 3 the values for the infiltration are given at an induced pressure of 50 Pa.

***Table 3** - Results of reduced infiltration*

Infiltration (l/s pr. m^2)		Reference (5.3)	1.5	1.0	0.5
Indoor environment category	I	71%	80%	81%	81%
	II	27%	19%	18%	18%
	III	2%	1%	1%	1%
	IV	0%	0%	0%	1%
Energy consumption	kWh/ year	6371	5552	5438	5323

In IDA ICE it is possible to define how much a building part is exposed to thermal bridges, an example is shown in Table 4. For the simulation of the effect of thermal bridges, every building part was changed corresponding to the investigated class.

***Table 4** – Example of thermal bridges in IDA ICE for external windows parameter*

Very Poor	Poor	Typical	Good	None
0,40	0,06 W/m^{2}K	0,03 W/m^{2}K	0,02 W/m^{2}K	0,00 W/m^{2}K

***Table 5** - Results of thermal bridges*

Thermal bridges		Very Poor	Poor	Typical	Good	None
Indoor environment category	I	42%	68%	79%	80%	83%
	II	29%	29%	19%	18%	16%
	III	21%	3%	1%	1%	0%
	IV	8%	1%	0%	0%	1%
Energy consumption	kWh/ year	9993	6626	5520	5359	4982

When the window areas were reduced, the amount of daylight in the house was also investigated in order to assure that the daylight levels inside the house abide the regulations of 200 lux from the Danish Building Regulations, Energistyrelsen (2014). The investigation showed that the reference case abide the regulations 93 % of the time. The case with a smallest window area abide the regulations 82 % of the time.

In Table 6 the results for different orientations of the house are shown.

Table 6 - *Results of different orientations*

Orientation		Reference	North West	West	South West	South	South East	East	North East
Indoor environment category	I	71%	69%	64%	66%	69%	69%	67%	69%
	II	27%	25%	26%	23%	22%	21%	24%	28%
	III	2%	5%	6%	6%	5%	5%	7%	3%
	IV	0%	2%	4%	4%	5%	5%	1%	0%
Energy consumption	kWh/ year	6371	7184	7870	7579	7123	7290	7203	6626

Different alternatives have also been investigated as an addition to the previously mentioned parameters:

- Automatically controlled exterior solar shading was implemented. In the current state there is no solar shading except the overhangs.
- Natural ventilation was simulated. Natural ventilation was provided from 10 % of the window area in the glazing façades that could open and it was controlled based on the temperature set-points in the house.
- Thermal mass was simulated by adding 0.1 m concrete in the walls.
- An increased embedded pipe system (EPS) area was simulated with EPS installed in the walls

The respective results of these variations are presented in Table 7.

Table 7 - *Results of other improvements*

Other parameters		Reference	Exterior solar shading	Natural ventilation	Thermal mass	Increased EPS area
Indoor environment category	I	71%	74%	74%	72%	88%
	II	27%	23%	23%	26%	11%
	III	2%	3%	3%	3%	1%
	IV	0%	0%	0%	0%	0%
Energy consumption	kWh/ year	6371	6104	6053	6192	6467

Regarding the orientation, the current orientation is the best solution both regarding thermal indoor environment and overall energy consumption. Regarding the thermal indoor environment the increased EPS area, the exterior solar shading and the natural ventilation had the biggest impact. The last two primarily made an impact in the cooling season by counteracting the cooling loads due to solar radiation.

4.4 Optimized Fold

An optimized version of the house is proposed to make it more energy efficient and improve the indoor environment. In the optimized house, the area of the glazing façades were reduced by 25 % and the U-value for the glass was lowered to $0.5\frac{W}{m^2 \cdot K}$. The infiltration was set according to the requirements for Danish houses in 2020, Energistyrelsen (2014), and the thermal bridges were reduced to make it more appropriate for a modern house. In the optimized house, there was natural ventilation when the outdoor temperature was lower than the indoor temperature to provide cooling during hot periods in the summer.

The results for thermal indoor environment and total energy consumption for the reference case and the optimized case are shown in Table 8.

Table 8 – *Results of the optimized house*

		Reference	Optimized
Indoor environment category	I	71%	97%
	II	27%	3%
	III	2%	0%
	IV	0%	0%
Energy consumption	kWh/ year	6371	2023

The optimized model significantly improved the thermal indoor environment and there was no duration when the operative temperatures were worse than the specification given in category II of EN 15251. Furthermore, the temperature never exceeded 26°C indicating that there was no overheating. The energy consumption was reduced by 68 % when the improvements were implemented.

5 Discussion

Despite being designed and constructed as a competition house, the house could still be improved in different ways. This study investigated some of the parameters that could be improved.

Various factors could have caused the discrepancies between the measurements and the simulation results. The house had been transported and it had been assembled (three times) and disassembled (two times). Hence it is likely that the infiltration and thermal bridges changed from the original values. In addition, the house had been stored in containers for several months, which could have lowered the performance of the building envelope.

By building a new house, the infiltration and the thermal bridges will be reduced. The cost of these improvements is estimated to be minimal. Most of the proposed improvements in this study are changes that would have to be made in the design-stage of the house. For example it would be troublesome to change the overall design of the glazing façades after the construction has been completed hence the practicality of the different improvements should be considered. It would however be possible to change some of the windows with insulated wall segments.

The differences between the actual HVAC system and the modelled HVAC system could also be a source of discrepancy in the results.

6 Conclusion

This study used measurements to validate simulation results. It was found that the average relative difference in operative temperature between simulations and measurements were 3 %, and the relative difference in energy consumption for the heat pump was 14 % and 23 % for the ventilation system. The simulations were used to investigate the effects of several parameters such as window area reduction, infiltration, thermal bridges, orientation, exterior solar shading, natural ventilation, thermal mass and increased embedded pipe system area on energy consumption and thermal indoor environment.

The simulations showed that the most important improvement was to reduce the heating demand of the building therefore the most effective improvements were reduction of window area, infiltration and thermal bridges. An improved house design based on the simulations is obtained. The improved house performed better in both thermal indoor environment and energy consumption than the reference case. The duration in indoor environment category I of EN 15251 was increased from 71 % to 97 % and the yearly energy consumption was reduced by 68 % compared to the reference building.

7 Acknowledgements

This study was supported by Elforsk, project number 344-060, titled “Sustainable plus-energy houses”.

8 References

Energistyrelsen. *Bygningsreglementet 01.01.2014.*, 2014.

EN 15251. *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.* European Committee for Standardization, 2007.

EN 13872. *Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method.* European Committee for Standardization, 2001.

EQUA Simulation AB. *EQUA*. 2014. http://www.equa-solutions.co.uk/ (seen 21. 05 2014).

Greenmatch. *Lavenergihus, nul-energi hus, passivhus eller plusenergihus?* Greenmatch. 26. Marts 2014. http://www.greenmatch.dk/blog/2014/03/lavenergihus,-nul-energi-hus,-passivhus-eller-plusenergihus/ (seen 29th May 2014).

Kragh, Jesper, Nielsen, Toke R, Svendsen, Svend. *Grønlandske vejrdata.* BYG DTU, 2002.

Kazanci, Ongun B., Skrupskelis, Martynas, Olesen, Bjarne W. and Pavlov, Georgi K. *Solar Sustainable Heating, Cooling and Ventilation of a Net Zero Energy House.* CLIMA 2013 - 11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings. Prague: Society of Environmental Engineering (STP), 2013. 5513-5522.

Kazanci, Ongun B., Skrupskelis, Martynas, Sevela, Pavel, Pavlov, Georgi K., and Olesen, Bjarne W. *Sustainable Heating, Cooling and Ventilation of a Plus-Energy House via Photovoltaic/Thermal Panels.* Energy and Buildings, 2014. doi:http://dx.doi.org/10.1016/j.enbuild.2013.12.064

Larsen, Tine Steen. *Overheating and insufficient heating problems in low energy houses up to now call for improvements in future.* Rehva Journal, May 2011: 36-40.

Olsen, Arne Damsgaard. *State of Green.* www.stateofgreen.com. stateofgreen.com/files/download/237 (seen 21st February 2014).

Skrupskelis, Martynas and Kazanci, Ongun B.. *Solar sustainable heating, cooling and ventilation of a net zero energy house*. Kgs. Lyngby: Technical University of Denmark, 2012