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Heiselberg, Per Kvols

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Influence of occupant behavior and operation on performance of a residential Zero Emission Building in Norway

Natasa Nord[1], Live H. Qvistgaard[2], Ivar S. Tryggestad[3]

Norwegian University of Science and Technology, Department of Energy and Process Engineering, NO-7491 Trondheim, Norway

[1]natasa.nord@ntnu.no

[3]ivarstryggestad@gmail.com

Norconsult AS
Trollbygget, Jåttåvågveien 18, NO-4020 Stavanger, Norway

[2]Live.Holmedal.Qvistgaard@norconsult.com

Abstract
Zero Energy/Emission Building (ZEB) has become a term for buildings that are self-energy supplied or may even export energy. These buildings are characterized by energy efficient components and energy supply from renewable energy sources. Design of energy storage systems and energy supply systems are some of the important parameters for proper operation of a ZEB. At the same time, operation parameters and occupant behavior may significantly change their performance. In this study a demo ZEB building located in Larvik, Norway, was analyzed with respect to the occupant behavior. This study examined an integrated solution of the building energy supply system consisting of flat plate solar thermal collectors (STC) in combination with a ground-source heat pump (GSHP) and an exhaust air heat pump (EAHP) for the heating and cooling, and production of domestic hot water (DHW). Photovoltaic were used to provide electricity for the house. The excess solar heat was utilized to recharge the borehole. The entire building and integrated energy supply solution were simulated in IDA-ICE. To analyze occupant behavior, DHW use, set point temperatures, and electric equipment use were analyzed. Standard values and different scenarios based on the literature were tested to examine different occupant behavior. The results showed that the demo ZEB performance was robust under changeable occupant behavior, because some of the influences compensated each other. Simultaneous effects of the occupant behavior resulted in the electricity mismatch factor varying from a 15% reduction in a wasteful case to a 16% increase in a conservative case.

Keywords - zero emission building; renewable energy; ground source heat pump; exhaust air heat pump; family house

1. Introduction

The annual energy demand in the building sector in Norway represents about 40% of the total national energy use, of which 22% goes to the residential sector and 18% to the non-residential sector [1]. In residential buildings, space heating and domestic hot water production represent approximately 70% of the total energy use [2]. The building sector presents a great potential for nationwide energy savings. Predictions indicate that the Norwegian energy use for residential purposes will be reduced by 75% in 40 years from now. In 2010, the European Union adopted a recast of the Energy Performance of Buildings Directive (EPBD). It states that all new buildings in the EU will have to be 'nearly zero energy' by 2020 and that the energy will be 'to a very large extent' from renewable sources [3].

Earlier studies define calculation methods for the energy use in a ZEB [4]. A building may be characterized as a ZEB when it is able to export excess energy, generated by photovoltaic (PV) modules for instance, to the grid and achieve an annual positive net balance between demand and supply. Different ambition levels within the ZEB category depend on the different emission items included in the calculation [5]. Residential passive buildings are characterized by energy-efficient building envelopes. Requirements for specific heating energy use and specific power in dwellings of Passive house standard is 15 kWh/m^2 and 10 W/m^2 [6]. However, achieving these requirements is difficult in Norway due to a colder climate compared to Germany, where the requirements were first introduced. In Norway, the requirements are stated in the standard describing requirements for passive houses and low energy buildings [7]. As a result of low space heating demand, the hot water demand represents an increasing share of the total heating demand, 40-85% in residential passive buildings [6], giving the domestic hot water (DHW) preparation a greater role in modern buildings than before.

Stricter regulations of the energy use of buildings mean that the buildings constructed today are expected to be significantly energy efficient. However, the measured performance of modern low-energy buildings is often below expectations. User behavior has been found accountable for variances in excess of 50% in use of electrical equipment between design and measurements, and even larger variances when it comes to DHW use. Ventilation and temperature set points are also found to vary greatly in actual use compared to the expected values [8-10]. Creating simulation models that are able to simulate user behavior accurately has been proven to be difficult, and standardized patterns for use and internal gains are often used [11]. Since actual energy use has been shown to deviate a lot from the requirements, it is important to analyze the impact of user behavior and operation on the ZEB residential house performance in Norway.

2. ZEB demo building

In this study, a single-family demo dwelling (SFD), called the "Multikomfort", located in Larvik in southern Norway was analyzed. The building was built according to the Norwegian Zero Emission Building definition with an ambition level of O&M (Operation and Material). The annual average temperature in Larvik is 6.3°C. The house is a two-story home with a floor area of 202 m^2, and it was designed to accommodate a family of four to five members. The building is shown in Fig. 1.

Fig. 1. Architecture of the SFD "Multikomfort" [12]

The heat supply system consisted of flat plate solar thermal collectors (STC) in combination with a ground-source heat pump (GSHP) and an exhaust air heat pump (EAHP) for the heating and cooling, and production of domestic hot water (DHW). The energy supply of the SFD was mainly covered by renewable energy sources on site. Excess solar heat was used to recharge the GSHP boreholes. DHW was preheated by the solar collectors, and further heated by the EAHP. Electrical heaters cover additional heating demand. Ventilation air is heated directly from the ground source heat exchanger, while floor heating was used for space heating. Photovoltaic panels (PV) were used for production of electricity, and were integrated into the roof along with the STCs. The PV system used the grid for storage, and was sized to produce the same amount of electricity as consumed by the building under the standard conditions. An overview of the heating and cooling system, excluding the PV panels, can be seen in Fig. 2.

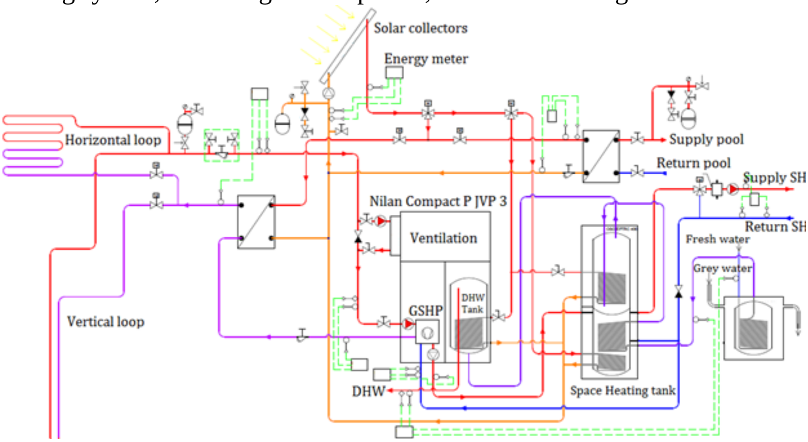

Fig. 2. Heating and cooling system with solar thermal system, GSHP and EAHP

3. Methods

Relevant information regarding the energy supply for the ZEB dwelling was collected from the project owners. Based on this, a model of the SFD and its energy supply system was created using the dynamic simulation tool IDA ICE 4.6 [13]. The performance of the reference configuration was adjusted using the standard values, in accordance with the NS 3700 [7]. Maximum specific heating demand was calculated, in accordance with the NS3700, to be 17.6 kWh/m^2.

Scenarios including variations in hot tap water use, indoor set point temperatures, and electricity equipment use were developed for analysis of the occupant behavior. Standard values for the different parameters were used as a reference, and variations around these were then made based on the data found in the literature [7, 14].

The implemented ventilation system was balanced mechanical CAV. Flow rates were set to 240 m^3/h. U-values for all the walls were set according to the standard values [7], while the U-value for the windows was 0.63 W/m^{2}K.

The solar, ground, and exhaust air heat were used in combination with heat pumps. When the temperature at the bottom of the DHW storage tank was above the specified limit of 60°C, the extra solar heat was used to charge the GSHP boreholes. Any heat which could not be used either for heating of DHW or charging the boreholes was transferred to the SH tank during the heating season. Design parameters for the energy supply system are shown in Table 1.

Table 1. Basic energy system design parameters

Indoor/outdoor design temperatures		20°C/ -17 C	
Boreholes	Number	Depth	
	1	80 m	
GSHP	COP	Heating capacity	
	4.6	3 kW	
Solar collector	Collector area	Efficiency	
	16.75 m^2	60%	
EAHP	Air/air	Air/water	
COP	4.6	3.9	
Heating capacity	2.0 kW	1.2 kW	
DHW tank	Volume	Electrical supply	
	180 L	1.5 kW	
SH storage tank	Volume	Electrical supply	Heat loss
	325 L	3.0 kW	2.0 kWh/day
PV panel	Size	Efficiency	
	37.75 m^2	20%	

4. Results

For the reference case, simulations showed a total electricity demand of 5 869 kWh/year, or 29 kWh/m^2. Heating contributed with 17.8 kWh/m^2 of this. This was used to size the PV panels, which were set to cover the entire yearly electricity energy demand. This was accomplished at a PV area of 37.75 m^2. The configuration of the energy supply system was unchanged for the different scenarios, and the areas of the STCs and the PV panels were the same for all the scenarios. The heat energy distribution for the reference scenario can be seen in Fig. 3. Solar heat could cover more than the heat demand was, and therefore it covered 100% of the heat demand from May to August.

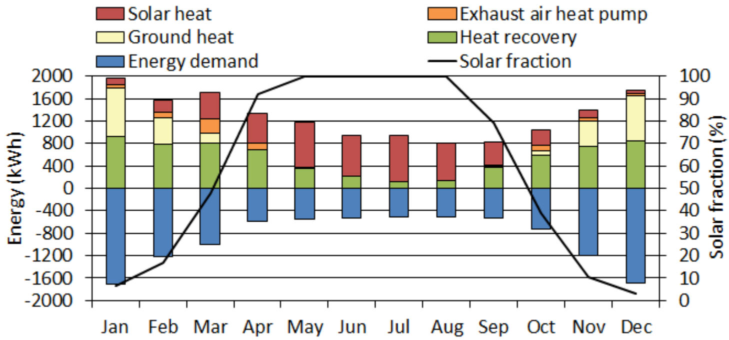

Fig. 3. Heating demand and renewable heat production in reference building

The electricity use and production was distributed as shown in Fig. 4. The monthly mismatch factor, the ratio of electricity production per electricity use, is also shown in Fig. 4. The monthly mismatch factor was varying from almost zero in winter months to 2.7 in the summer months, and the resulting annual average mismatch factor was 1.

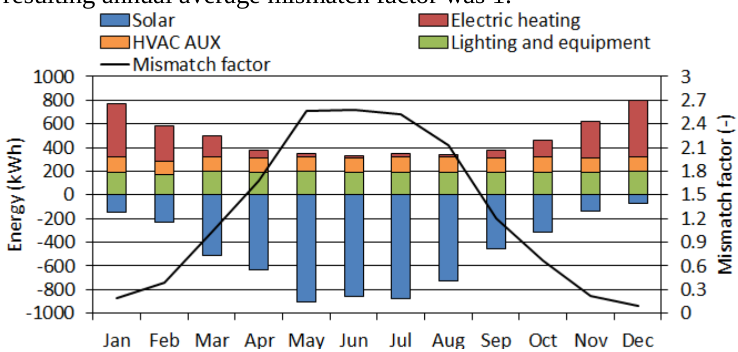

Fig. 4. Electricity use and electricity production in reference building

In Fig. 5 and Fig. 6 hourly distribution of electricity use, production, and mismatch factor for design winter and summer days are shown.

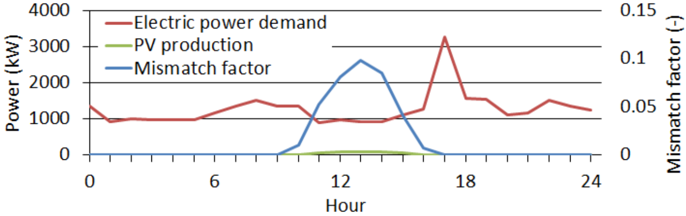

Fig. 5. Electricity use and electricity production in reference scenario on design winter day

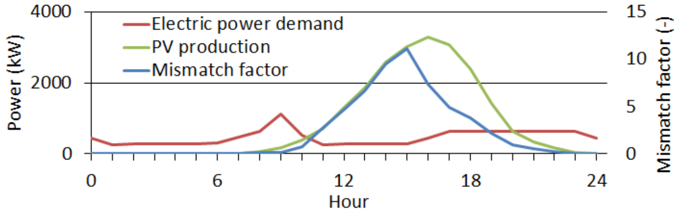

Fig. 6. Electricity use and electricity production in reference scenario on design summer day

It can be seen that the mismatch factor varied greatly since production occurred only during the day hours. The electric grid should be able to manage this sporadic export of power [15] or otherwise it would be exposed to a big stress. In winter, the building would not be able to produce more than a small fraction of its energy demand, and its behavior would be closer to a non-producing building in this period.

3.1 Influence of setpoint temperature on ZEB performance

The standards set minimum requirements for indoor temperature, which were used when calculating the standard energy performance, see results in previous section. However, studies show that many users tend to choose higher or lower temperatures to increase comfort or to save energy. The scenarios therefore included a range of indoor temperatures from 19-25°C. The relevant changes in the energy flows caused by the changes in the indoor temperature are shown in Fig. 7. In this context, free heat refers to heat collected from the ambient. Fig. 7 shows that the impact on the electricity use was small in comparison to the increase in heating demand, since most of the energy was covered by an increase in solar and geothermal heat utilization. A 4 K increase of the indoor temperature induced an increase in the heating demand by 12.1 kWh/m^2, while the electricity use increased by 2.8 kWh/m^2. The change in free heat utilization mainly comes from the air handling unit heat exchanger (25-45%) and from ground heat (55-70%), with solar heat only contributing a minor amount (0-5%). Since the indoor temperature was higher, an increase in heat gain from the heat recovery should be expected.

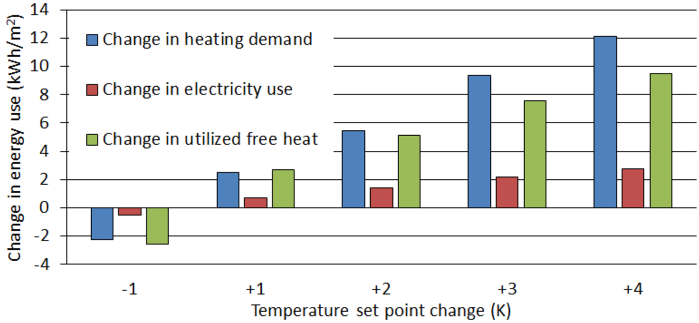

Fig. 7. Influence on energy use by change in temperature set points

As a result, the impact of an increased indoor temperature was reduced due to the heat recuperation in the air-handling unit. Change in the yearly average mismatch factors for the different temperatures was small as shown in Table 2.

Table 2. Mismatch factors at different temperature set points

Scenario	-1K	Reference	+1K	+2K	+3K	+4K
Mismatch factor	1.02	1.00	0.98	0.95	0.93	0.91

3.2 Influence of DHW use on the ZEB performance

Use of DHW is known to vary depending on user habits, thus a variation of ±10-20% in DHW usage was simulated. Since variations up to 50% have been observed, this was also included. For DHW, no heat is transferred to the indoor environment as heat gain, so the heating demand was not influenced by the change in DHW use. In Fig. 8 the change in DHW use, as well as the change in electricity use and free heat utilization are shown.

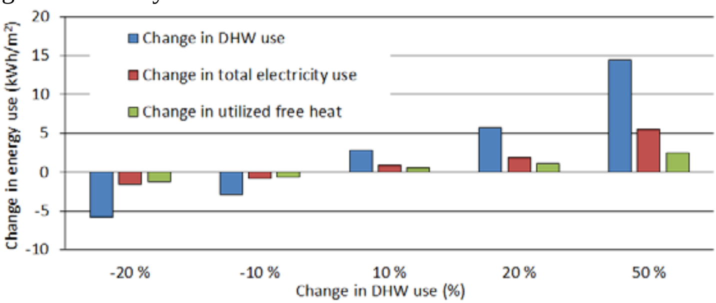

Fig. 8. Influence on energy use by changes in DHW use

Free heat was used to cover some of the extra DHW demand, while electrical heat covered the rest. In all the cases in Fig. 8, 97% of the change in free heat was observed to come from the STCs, which were best suited to deliver heat at this temperature level. For the case of 20% increased DHW use, the building only experiences an increase in electricity use of 1.9 kWh/m^2 with an increase in DHW use of 5.8 kWh/m^2. The influence of DHW use on energy performance may be seen as limited, and highly dampened by the efficiency of the energy system. Change in the yearly mismatch factor for the different scenarios was small as shown in Table 3.

Table 3. Mismatch factor at different levels of DHW use

Scenario	DHW -20%	DHW -10%	Reference	DHW +10%	DHW +20%	DHW +50%
Mismatch factor	1.06	1.03	1.00	0.97	0.94	0.84

3.3 Influence of electrical equipment use on the ZEB performance

To simulate electrical equipment in IDA-ICE, 60% of the energy use was included as heat gains in the building. Therefore, the change in electrical equipment use would influence the heat demand in the building. A variation of ±10-20%, plus the 50% case, was simulated to investigate this effect and the results for heating and energy use are given in Fig. 9.

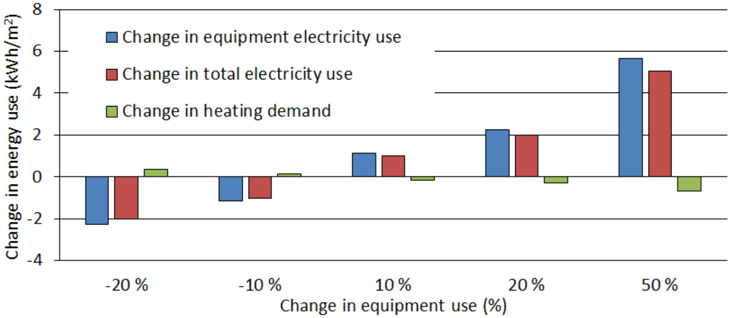

Fig. 9. Influence on energy use by changes in equipment use

It can be seen that the change in electricity use was smaller than the change in equipment electricity use, because the equipment use contributed partially to the heat gains and influenced the heat demand. Still, the impact of equipment use was more direct than that of the DHW use and indoor temperature change. This may be because the heat gain from equipment use replaces free heat from renewable sources, so the heat gain does not contribute to reduce the electricity use for equipment. The yearly average mismatch factor for the five scenarios is given in Table 4.

Table 4. Mismatch factor at different levels of equipment use

Scenario	EQ -20%	EQ -10%	Reference	EQ +10%	EQ +20%	EQ +50%
Mismatch factor	1.07	1.04	1.00	0.97	0.93	0.85

Since the energy use for electricity equipment was already very low in this building, the influence on the specific energy use was limited to an increase of 2 kWh/m^2 at a 20% (or 2.27 kWh/m^2) increase in equipment use.

3.4 Overall influence of occupant behavior on ZEB performance

Users who increase their energy use in one area have a tendency to increase the energy use in other areas, too. To investigate the effects of this, scenarios with conservative and wasteful user behavior were simulated. In the conservative scenario, the electricity equipment and DHW use was reduced by 20%, while the set point temperature was reduced by 1 K. In the wasteful scenario, equipment and DHW use was increased by 20%, and the temperature increased by 2 K. In Fig. 10, the impact on the monthly mismatch factor for these scenarios and the reference case is shown.

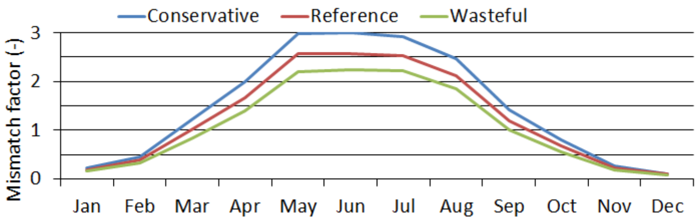

Fig. 10. Mismatch factors for different user behavior profiles

In Fig. 10, it can be seen that the annual mismatch factor was significantly influenced, decreasing from 1.0 to 0.85 in the wasteful case, and increasing to 1.16 in the conservative case. The decrease in the wasteful case is slightly smaller than the sum of the change in the individual cases, indicating that the effects to some degree were compensated. For the conservative case, the increase in mismatch factor is slightly larger than the sum of the change in the three individual cases.

5. Conclusion

The results show that user behavior can influence the performance of a ZEB building both positively and negatively. The results showed that even moderate, but simultaneous changes in temperature set points, DHW use, and electricity equipment use could have a large impact on the electricity mismatch factor, varying from a 15% reduction in a wasteful case to a 16% increase in a conservative case. The installed energy supply system showed to be robust, because some of the effects were compensated among each other, but only if the changes were small. For larger changes, the influence on the ZEB performance would be greater. The impact on electricity use at higher indoor temperature could be decreased as some of the additional energy was recovered through the ventilation heat recovery exchangers. The DHW use required a higher temperature level, which was supplied by solar collectors. The increase in tap water use was shown to be handled well by the energy system, providing approximately 60% of the extra energy from renewable sources. The use of electrical equipment had the most direct impact on the energy performance of the building, since the energy system is unable to adjust the electricity production accordingly. In scenarios where users generally made choices to conserve energy, the annual mismatch factor was shown to increase significantly. Consequently, the occupant influence on the performance of ZEBs should not be underestimated.

Acknowledgment

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