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Heating buildings with direct electrical heating by storing heat in the thermal mass during off-peak hours using predictive control

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Abstract

In future, a large share of the electricity production will come from fluctuating energy sources such as wind, which will produce lots of excess electricity in periods with low consumption. A smart and flexible energy system is therefore crucial in future applications so that different energy demands are matched with productions from fluctuating energy sources. This paper focuses on the possibility to use direct electricity for space heating in off-peak hours between 00:00-06:00 and store enough heat in the thermal mass (i.e. floor construction) to cover the space heating demand for next 24h. The study found that it is possible to supply heat during night and store enough heat in the concrete floor element to cover the space heating demand the upcoming 24h without compromising with the comfort temperatures even in the coldest period of the year ($T_{operative}$ > 20°C). Even during night when heat is supplied the operative temperature does not exceed 22°C.

Keywords - flexible buildings; smart buildings; predictive control; heating with direct electricity

1. Introduction

In future, a large share of the electricity production will come from fluctuating energy sources such as wind [1,2], which will produce lots of excess electricity in periods with low consumption. In 2014 the electricity production from wind accounts for 39% of the total electricity production in Denmark [3]. The goal is that wind should cover 52 % in 2020 [4] and between 60-80 % in 2050 [5]. Already with the installed capacity today negative prices has been seen on the market due to an overproduction of wind power at times with low demand [6,7]. A smart and flexible energy system is therefore crucial in future applications so that different energy demands are matched with productions from fluctuating energy sources. Energy usage in buildings will play a significant role in the future energy system and it is therefore important to focus on how to create flexible energy usage in buildings that uses surplus energy in off-peak hours [8]. One way of creating flexible energy demands in buildings is to store heat in the thermal mass of the building, for instance by the use of direct electricity in off-peak hours [9,10]. A study [11] investigated the potential of demand response of electrical space heating in Swedish single family dwellings. They concluded that it was possible to shift up to 1% of the total Swedish electricity demand, which can reduce peak production and help overcome the challenge of surplus electricity production in off-peak hours.

From an exergetic point of view it is very inefficient to use direct electricity for space heating. Exergy combines the first and second law of thermodynamics and exergy analyses can be used to optimize and improve energy conversion efficiency on a system level [12]. The exergy roughly expresses the quality of energy. Energy flows with matching qualities will result in less destruction of exergy (and less creation of entropy). Electricity contains a high energy quality (exergy factor = 1), which is why it should not be used for a low quality demand such as space heating (exergy factor ≈ 0.05), seen from an exergetic point of view [13]. However, under the circumstances of surplus electricity production, solutions that utilize the excess electricity should be found and one could argue that exergy in this context has less importance. In non-district heated areas with limited alternative low exergy sources, installation cost may be more important. Surplus electricity from wind power plants could also be considered to have less “quality” than electricity during high peak consumption periods.

To optimize control of the building energy systems the use of predictive control using weather forecasts has been in focus in many studies, among other in [14-19]. Combining price signals for electricity and weather forecast will optimize both the energy consumption and lower the energy costs since the electricity is used when there is an overproduction, which results in lower prices.

This paper focuses on the possibility to use direct electricity for space heating in off-peak hours between 00:00-06:00 and store enough heat in the thermal mass (i.e. floor construction) to cover the space heating demand for next 24h. The stored heat will then be released during the upcoming day ensuring comfortable temperatures at all times. Numerical simulations are performed in the building energy simulation software IDA ICE for hourly heating demand and comfort temperatures. This paper only contains the pre-investigation ensuring that the concept provides comfort temperatures at all times. Future work will include onsite tests of the concept using real weather forecasts for predictive control of the floor heating system.

2. Method

The method applied for this investigation was divided into 3 steps.

Step 1: A simulation model of the test house was created with IDA ICE software to determine the heating demand on daily, monthly and yearly basis. An electrical floor heating system is applied with a set point temperature of 21°C. The floor heating system is controlled based on a thermostatic control and the room air temperature. *Step 2:* Based on the simulation results the daily heating demand required for the following day was determined. Heating profiles was established based on the heat demand for the upcoming day so that heat (electrical floor heating) only was supplied in off-peak hours from 00:00 to 06:00. *Step 3:* Simulation with the heating profiles implemented in the IDA ICE model was carried out for one week in February to analyses the concept and whether comfort temperatures could be obtained.

The method is applied on a case-study on a test house placed in Frederikssund, Denmark.

A. Desctiption of the test house and IDA ICE model

The house is a one floor single family house placed in Frederikssund, Denmark. The house has a floor area of 146 m^2. As seen from Fig. 1 there is one big kitchen/living room, five rooms, and two bathrooms. Furthermore Fig 1 shows a picture of the house and the model constructed in IDA ICE. As seen from the figure the shadows have been modelled as “walls” around the house. Table 1 describes the construction materials and their properties.

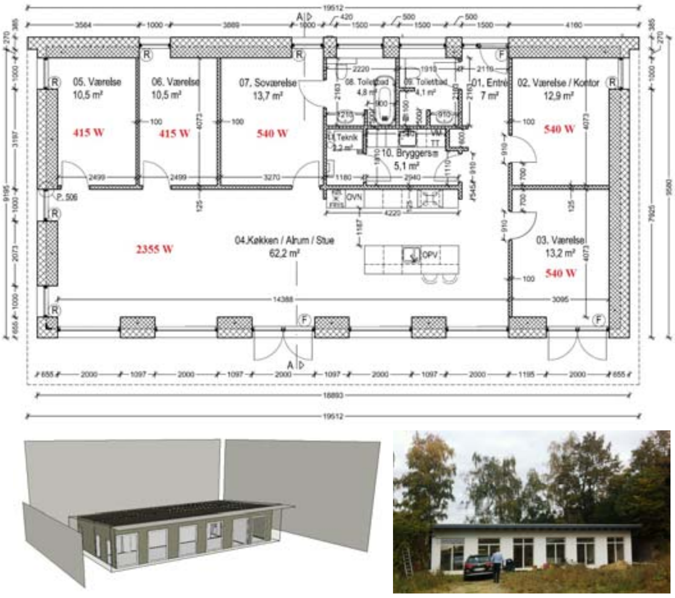


Fig. 1 Top: Floor plan of the test house (www.passivbolig.dk). Bottom left: IDA ICE model of the test house. Bottom rigth: Foto of the actual house in Frederikssund, Denmark.

Table 1. Material properties for the building elements

	Construction	λ [W/mK]	ρ [kg/m^3]	C_p [J/kgK]	d [m]
External walls	Render	0.35	1800	790	0.01
	insulation	0.042	115	1300	0.28
	Concrete	0.083	340	1050	0.365
Internal walls	Light weight concrete	0.15	500	1050	0.125
Floor	Wood	0.14	500	2300	0.014
	Floor coating	0.13	1100	920	0.015
	Concrete	2.1	2300	880	0.1
	Extruded polystyrene	0.036	20	1200	0.45
Roof	Render	0.8	1800	790	0.01
	Insulation	0.037	20	750	0.52
	Air space	0.4	1.2	1006	0.05
	Plywood	0.2	500	2300	0.21

	g-value [-]	T, Solar transmittance [-]	T_{vis}, visible transmittance [-]	U-value [W/m^{2}K]
Windows	0.63	0.6	0.74	0.8

The house has a mechanical ventilation system with heat recovery of 85% and a constant air flow rates corresponding to an air change rate of 0.5 h^{-1}. The air infiltration rate is set to 0.05 h^{-1}. The internal gains are set to a constant value of 2.1 W/m^2 for equipment and person load assuming a constant presence of 55% for 4 persons. The heating supply is based on an electrical floor heating system with installed heating capacities as indicated on Fig. 1. The floor heating system is controlled by an on-off thermostat and the room air temperature. The on/off approach have been used in order to control the amount of heat stored in the floor (installed power times on-time)

Domestic hot water supply has been neglected in this investigation.

B. Modelling of electrical floor heating system in IDA ICE

To investigate the concept of storing heat in the floor element during night time using direct electricity an electrical floor heating system has been applied in the IDA ICE model. IDA ICE assumes an average distribution of heat stored in the floor construction implying no actual cables, and thereby no local differences of heat over the floor. The electrical floor heating is modelled in the concrete layer of the floor construction in a depth under the floor surface of 0.04m. The temperatures in the upper and middle layer of the concrete have been logged (see Fig. 2) together with the room air and operative temperature in each room.

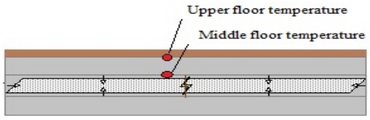


Fig. 2 Model of floor heating system in IDA ICE.

3. Results and discussion

C. Calculaed space heating demand

The annual space heating demand has been calculated to 21.5 kWh/m^2 with a room temperature set point of 21°C. Fig. 3 shows the monthly space heating demand and the daily space heating demand for the first week in February.

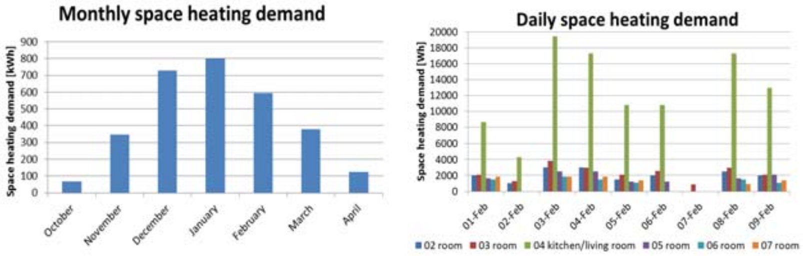


Fig. 3 Left: Monthly space heating demand for the test house with 24h floor heating operation. Right: Daily space heating demand for one week in February with 24h floor heating operations

The air temperature and operative temperatures in each room over the year can be seen in Fig 4. As seen the operative temperature is slightly above the air temperature due to the floor heating and warmer floor surface. As seen room 3 and the kitchen/living room reach high temperatures all year around. The reason for this is that the rooms are orientated towards south and has large glass areas and solar radiation heats up the rooms during day time. However, the air temperatures stay below 26 °C except few hours during summer.

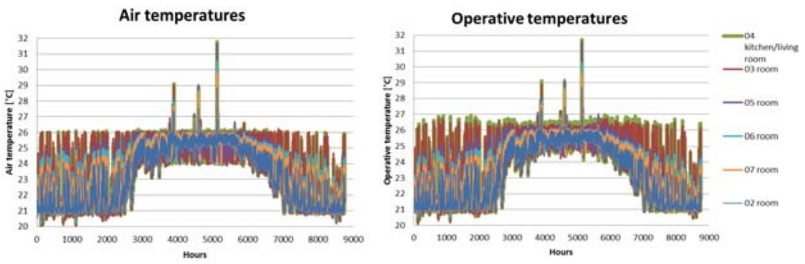


Fig. 4 Hourly air temperature and operative temperature for each room over a year.

D. *Heating profiles for heat supply in off-peak hours*

Based on the daily space heating demand, heating profiles was established for each room for the first week of February. The heat is supplied and stored in the floor construction from 00:00-06:00 each night covering the heat demand of the following day. Table 2 shows an example of the heating profile for the kitchen/living room.

Table 2. Floor heating profile for the kitchen/living room based on space heating demand for the following 24h.

	Space heating demand [Wh]	Floor heating system on per hour in 6 hours [min/h]
February 1st	8,640	37
February 2nd	4,320	18
February 3rd	19,440	60
February 4th	17,280	60
February 5th	10,800	46
February 6th	10,800	46
February 7th	0	0
February 8th	17,280	60
February 9th	12,960	55

E. *Operative temperatures and floor temperatures by storing heat in the floor element during night*

Fig. 5 shows the operative temperature and floor temperatures together with the heating profile and weather data (solar radiation and temperature) when heat is supplied and stored in the floor element during night time for the kitchen/living room. As seen from the figure the floor heating system is active from 00:00-06:00 each night. The 3rd, 4th, 8th and 9th the floor heating system is active for all six hours, mainly due to low solar radiation the following day. As seen the floor heating system is completely off the 7th, which is due to an increase in the outdoor temperature, together with a high level of solar radiation. From Fig. 5 the effect of the heat supply during night time can also be seen in the floor temperature of the middle layer. During night when heat is supplied and stored in the floor element the temperature increases and peaks at 06:00 after which the floor releases heat during the day and the temperature decreases. The upper floor temperature varies with the room temperature and is slightly higher since heat is released to the room. However, during day when the solar radiation is high the room temperature increases above the upper floor temperature resulting in a heat flow from the room to the floor element.

It is seen that even during very cold periods (1st: -18°C and 6th: -12°C) it is possible to obtain comfort temperatures above 20°C at all times. Furthermore, by storing the heat during night the figure also shows that even though the temperature of the middle floor layer increases up to 27°C, the surface temperature and operative temperature does not exceed 22°C during night when the heat is supplied. The operative temperature only increases with approximately 1°C during the six hours supply.

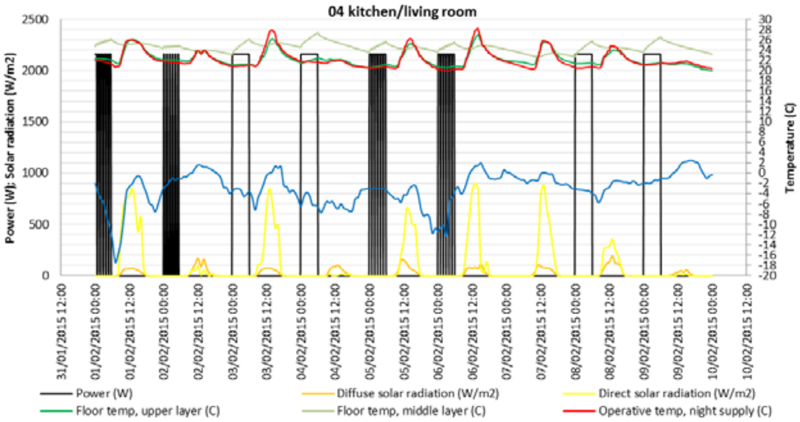
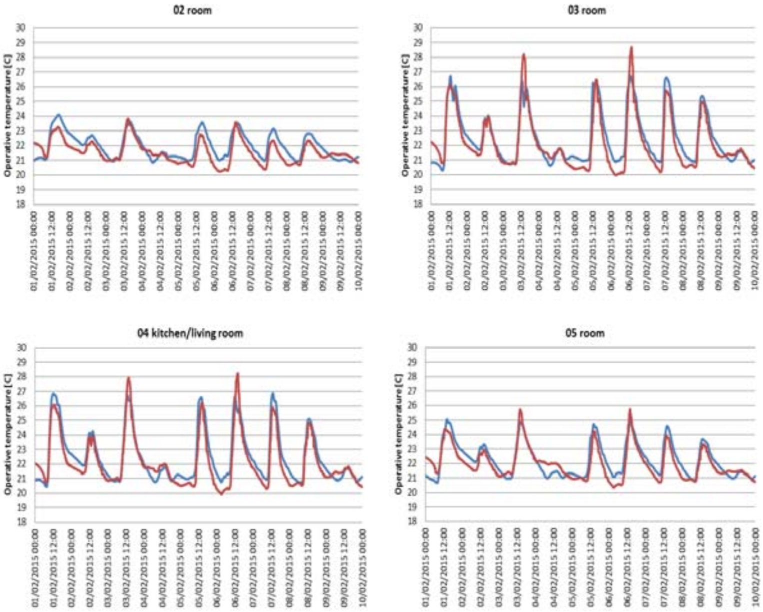


Fig. 5 Electricity supply, operative temperature and floor temperatures together with weather data (direct and diffuse solar radiation and outdoor temperature) for 04 kitchen/living room from February 1st –February 9th.

Fig. 6 shows the operative temperatures in each room for the two situations: a) 24 hour supply and b) night supply in off-peak hours from 00:00-06:00. As can be seen from the figure the operative temperatures for the situation where the floor heating system can supply 24h are generally higher compared to when the supply is limitted between 00:00-06:00. This is due to the fact that for the 24h supply the floor heating system is activated as soon as the temperature decreases below the setpoint temperature, 21°C. When the floor heating supply is limitted to operation only during night the temperature might drop below 21°C and only from 00:00 the system is activated. During very cold periods it might be difficult to reach the 21°C during the six hours supply period, but what can be seen from the figure is that the temperature never drops below 20°C even in the coldest period of the year. These results only represent a theoretical study based on the reference year, implying that the following days space heating consumption is known. However, in real cases where only weatherforecasts are avaiable, heat demand is calculated based on thoese, and large deviation from how the actual heat demand is can occur. This might result in a lower or higher temperature at 24:00 than expected and it is therefore important to correct the actual measured room temperature to be the starting point for the calculations of heat demand for the following 24h. If actual measured temperatures are not used as the starting point, errors might accumulate over time, which will provide wrong calculated heating demands and thereby an unacceptable thermal indoor environment.



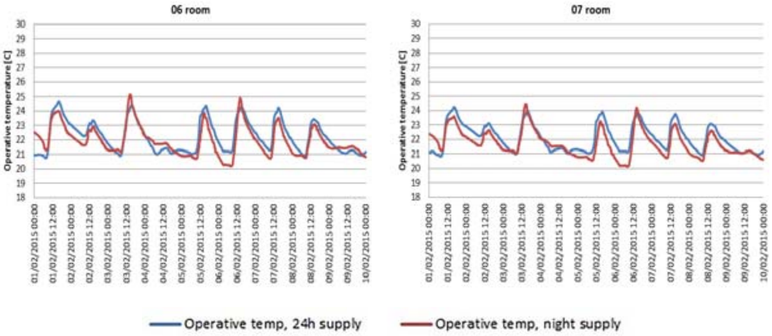


Fig. 6 Operative temperature for each room shown for a 24h floor heating operation and for night operation only.

4. Conclusion

This paper presented a method of how to use direct electricity for space heating purpose in off-peak hours (00:00-06:00) when the electricity production from wind power will be highest compared to the electricity consumption. The study found that based on a theoretical study using numerical simulations and the Danish Design Reference Year it is possible to supply heat during night time and store enough heat in the concrete floor element to cover the space heating demand the upcoming 24h without compromising with the comfort temperatures even in the coldest period of the year ($T_{operative} > 20°C$). Even during night when heat is supplied the operative temperature does not exceed 22°C.

These results only represent a theoretical study based on the reference year, implying that the following days space heating consumption is known. Future work will include onsite tests of the concept using real weather forecasts for predictive control of the floor heating system.

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