Heat pump options for low energy office buildings in cold climate

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Introduction

In order to achieve ambitious targets for energy efficiency and zero energy/emission buildings (ZEB), various combinations of energy-efficient technologies have been highly recommended. A trend in Norway is that all new buildings will be built according to the passive building standard. Low-energy buildings require application of energy-efficient technologies like high quality building insulation, energy-efficient building services, and high level of heat recovery. Also, there is a requirement that energy supply systems for the new buildings should be based on renewable energy. Therefore, it is important to analyze energy performance of the building integrated with renewable technologies. To achieve the full potential of energy efficient solutions, it is necessary to study the economic and technical feasibility of the complete energy system.

Heat pump water systems are a promising technology in both residential and commercial applications. Ground coupled heat pump system is also a very effective energy saving technology. The effectiveness of such plant is proven by performing detailed measurements in [1]. There have been several research studies related to solar assisted heat pumps since 1976 [2]. For example, in the work of Trillat-Berdal et al. [3] an experimental study of a ground coupled heat pump combined with a thermal solar collector is presented for residential purposes. The optimally designed solar assisted ground coupled heat pump for domestic hot water and space heating can obtain 36% of the annual space heating from solar and 75% of the annual domestic hot water [4]. However, practitioners and building users are skeptical to novel ideas regardless of the trends for new energy supply solutions, because a lack of documentation on the best practice experience in new technologies [5]. Therefore, it is necessary to study and document such solutions of good practice.

The aim of this study was to define energy supply solutions for a new low-energy office building in cold climates. Heat pump and solar supported heat pump systems were considered relevant energy supply solutions. The following four solutions were analyzed: an air-to-water heat pump, a geothermal water-to-water heat pump, a solar assisted air-to-water heat pump, and a solar assisted geothermal water-to-water heat pump. The working fluid in the heat pumps was R-410A. Since it is not economical feasible to let a heat pump cover all the building heating requirements and heat pump operation is not good under a highly variable load, an electrical boiler was used to cover peak load. The analyzed building is equipped with a variable air volume (VAV) system and a hydronic heating system. In order to minimize the installation cost of the building energy service system, an integrated solution with a VAV box and ceiling heating was implemented. Since *EnergyPlus* is able to simulate heat pump solutions and the building service system, it was chosen as the simulation tool in this study. Improvements in the heat pump and the ventilation control were also analyzed.

Case study

A new low-energy office building located in the south of Norway was analyzed by using *EnergyPlus*. The case study is a 3 000 m² office building on the coast in the Mandal municipality in the south of Norway. The building is in use since recently and the tenants have moved in. The sizing conditions for Mandal are the following: heating degree day is 3 266°C·h at 20°C indoor temperature; the average annual outdoor temperature is 6.9°C; and design outdoor temperature is −19°C [6]. Solar radiation data used for the simulation are provided from [7]. The total solar yearly radiations per m² for different orientations are the following: at the east side 418 kWh/m², at the west side 460 kWh/m², at the north side 262 kWh/m², and at the south side 644 kWh/m². The building was planned for 100 users. The building is shown in **Figure 1** [8].

Figure 1. Office building in Mandal. [8]

The idea in this project was to implement high quality building insulation better than the Norwegian passive building standard, with U-values of 0.71 W/m²K and 0.1 W/m²K for windows and walls respectively. Infiltration was chosen to be 0.5 1/h which was also based on the Norwegian passive building standard [9].

In order to minimize the installation cost of the building energy service system, an integrated solution with a VAV box and ceiling heating was implemented. This way, ventilation and hydronic heating was installed as one device in the ceiling of each office. This installation with the integrated heating and ventilation system has been developed by a contractor company [10]. The water heating system was design to perform with supply/return temperature of 40/35°C. The energy supply system including the heat pump and the electric boiler is shown in **Figure 2**. It was drawn based on a display figure from the building energy management system. Since the building is recently in use, some changes might appear in the future. Therefore, the energy supply solution as in **Figure 2** should not be considered as the final.

In this study, it was assumed that air handling unit consisted of the following elements: an inlet and an outlet damper, a supply and an exhaust fans, filters, a high capacity rotating heat exchanger and a heating coil. Cooling coils were avoided to decrease building energy use and to simplify air handling unit. The idea was to perform night air cooling with the ventilation air. An air flow rate of 6 m³/hm² during working time and 1 m³/hm² during non-working time were assumed, based on the Norwegian passive building standard [9].

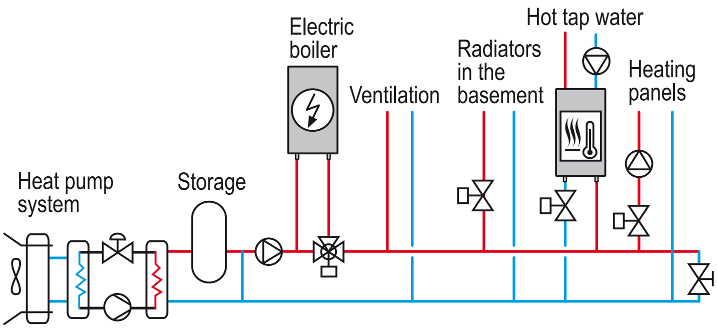

Figure 2. Energy supply system.

Operation of the heat pump in the low energy office building

In order to find suitable energy supply solution for the analyzed low-energy office building, operation parameters and energy use were analyzed. Consequences of the heat pump control strategy on the load duration curve distribution are shown.

Based on the HVAC heating demand and heat pump manufacturer data, the following heat pump performance was chosen: for the air-to-water heat pump a nominal heating capacity of 57.4 kW and COP 3.9, and for the water-to-water heat pump, a nominal heating capacity 50.8 kW and COP 5.6.

Night setback is recommended as a simple energy-efficiency measure. However, dynamic operation with a highly variable load is not preferable for a heat pump. Therefore, control strategies, with night setback and without night setback, were tested. The strategy without night setback assumed a constant indoor temperature. The results of this analysis are shown in **Figure 3** for the air-to-water heat pump.

The night setback strategy required the high peak effect in the morning when the indoor temperature was increased, as shown in **Figure 3**. This peak effect was provided by the additional electricity boiler as explained in Introduction. The constant indoor temperature neither caused a high electricity peak or a high heat pump effect. The consequences of the night setback on the total energy use for the HVAC system can be noticed in the duration curve in **Figure 4**. Further, the results of the control strategy without the night setback are shown in **Figure 5**.

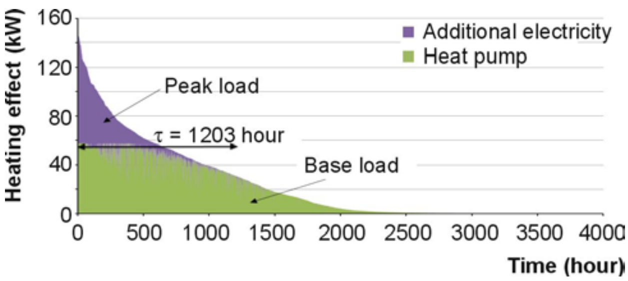

Figure 4. Duration curve for air-to-water heat pump with night setback.

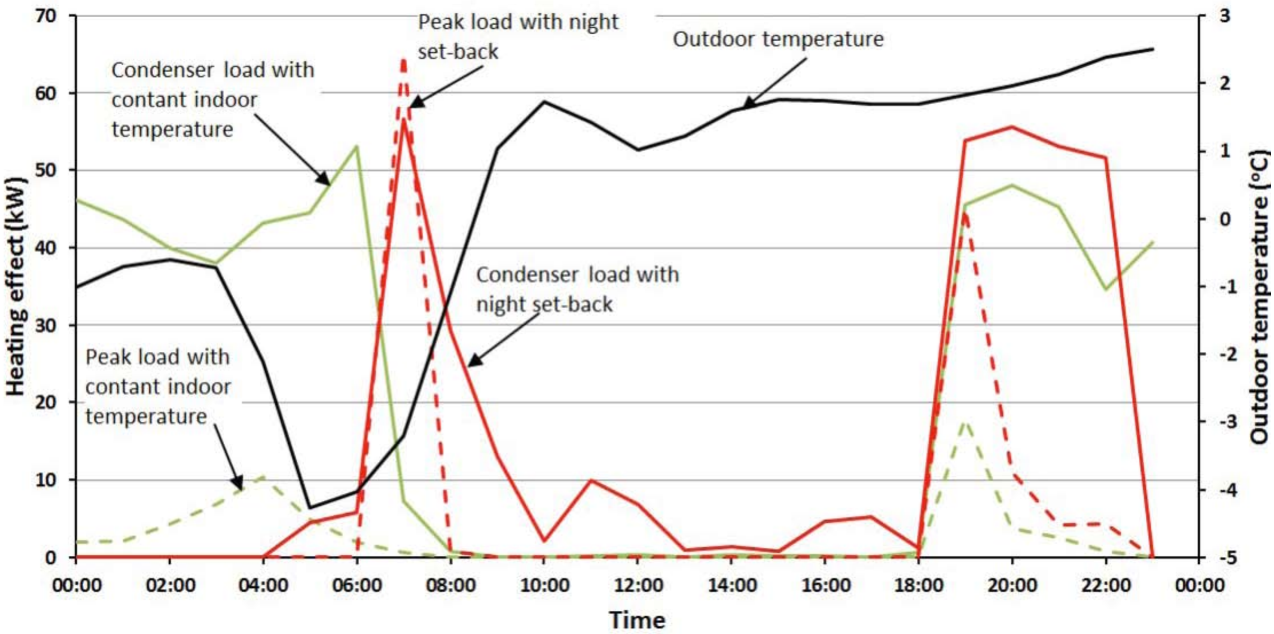

Figure 3. Control strategy for heat pumps.

The duration curve in **Figure 4 and 5** are valid for the air-to-water heat pump. In **Figure 4**, it is possible to notice that the part of energy supplied by the additional electricity boiler is considerably big compared to the total energy use for the HVAC system. Further, the utilization time of only 1203 hours for the heat pump is low. For the same heat pump with constant indoor temperature, the utilization time was 1 775 hours and electricity use was lower as shown in **Figure 5**.

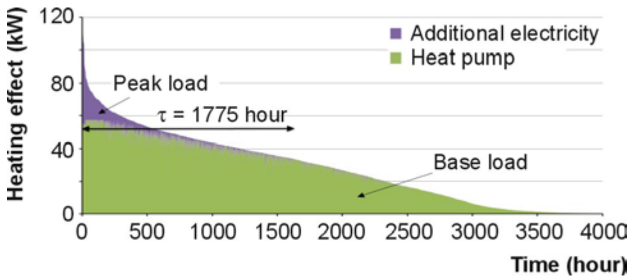

Figure 5. Duration curve for air-to-water heat pump without night setback.

To fully utilize the heat pump technology possibilities and avoid unnecessary use of the electric boiler, the control strategy without night setback was preferable. This conclusion could be relevant for other building types supplied by heat pumps. The summarized results on the utilization time and the total energy use for HVAC for air-to-water and water-to-water heat pumps are shown in **Table 1**.

Since the results in **Table 1** show that the constant indoor air temperature influenced the heat pump operation positively, the constant air temperature was implemented further in the study. The positive influence on the heat pump operation meant that the heat pump utilization time was longer, while the total electricity use for HVAC was lower. The analyzed heat pumps achieved a COP of 2.2 to 5 during a year.

Table 1. Utilization time and total energy use of the heat pumps.

Heat pump	Control strategy	Utilization time (hour/year)	Heat pump electricity use (MWh/year)	Additional electricity use (MWh/year)	Total electricity use (MWh/year)
Air-to-water	Night setback	1203	15.9	21.9	37.8
Air-to-water	No Night setback	1775	24.2	9.1	33.2
Water-to-water	Night setback	1276	15.0	25.1	40.1
Water-to-water	No Night setback	1927	22.8	13.0	35.8

Discussion

The techno-economic analysis of the energy supply solutions was performed by using the net-present value (NPV). The lifetime of 20 years was assumed for the air-to-water heat pump, while 40 years for the water-to-water heat pump because of the borehole installation. The real interest was assumed to be 6%. In the NPV method the complete electric heated building was the reference case. The investments for the analyzed technologies were: 246 000 Norwegian krone (NOK) for the air-to-water heat pump, 425 000 NOK for the water-to-water heat pump including the borehole installation and the heat exchanger, and 3 050 NOK/m² for the solar collectors. The electricity price was about 1 NOK/kWh [11]. 1 EUR = 7.36 NOK at date. To estimate the analyzed solutions, an average global electricity price increase up to 50% was considered. The results on the techno-economic analysis are shown in **Figure 6**.

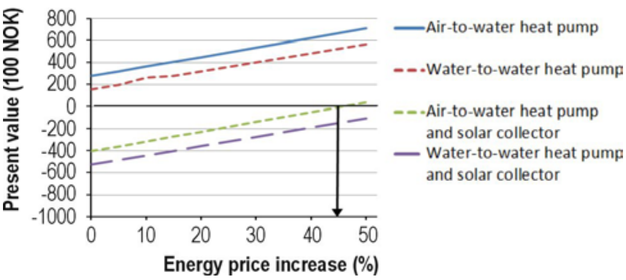

Figure 6. Techno-economic analysis.

The techno-economic analysis showed that the best energy supply solution seemed to be the air-to-water heat pump without solar assistance, **Figure 6**. A 50% increase in the energy price could mean the solution with the solar assisted air-to-water heat pump become attractive. This energy price increase is higher than the predicted of 15% in [14]. A similar trend might be predicted for other building types under the same economic conditions, because the relative ratio between the savings and the total energy use would be similar. A low-energy building has low energy demand, while a building with high energy demand would require a bigger energy supply plants.

Conclusions

The energy supply solutions for a new low-energy office building in cold climates were analyzed. The results show that an increase in ventilation air flow was necessary during the summer in the new low-energy office building. The control strategy without night setback was preferable for the heat pump technology and to avoid unnecessary use of the electric boiler. Since excess solar energy was not injected into the ground as in [3, 4], the potential of the totally received solar energy of 20 MWh/year was not utilized. The techno-economic analysis showed that the best energy supply solution seemed to be the air-to-water heat pump without solar assistance under the assumed economic assumptions, while a 50% increase in the energy price could make the solution with the solar assisted air-to-water heat pump economically attractive. For other building types similar energy supply solutions could be relevant, under the same economic conditions. ■

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