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Integrated ground source heat pumps and solar thermal systems for zero energy buildings

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Abstract
This paper presents a comparative study of different integration strategies between a ground source heat pump and a solar collector system, aimed at enhancing renewable energy sources exploitation to provide space heating and domestic hot water to a net zero energy building. The case building is the Living Lab, a single family house, built by the Norwegian Research Centre on Zero Emission Buildings (ZEB) and located in the campus of the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. Numerical simulations show that the thermal output from the solar panels is significantly increased in the integrated connection (i.e. post-heating through thermal panel of the ground source heat carrier fluid), coupled with a decrease in the temperature of the heat carrier fluid at the outlet of the solar thermal panels. The electricity demand of the heat pump is reduced by around 2.5% in the integrated connection thanks to a higher temperature in the primary ground/solar circuit, compared to a conventional installation, but that this reduction is accompanied by a similar increase in the demand of the circulation pumps. Less energy is withdrawn from the ground through the surface collector. This implies that the integrated solution allows a reduction of the surface collector field to be realized while still meeting the same heat load – with a corresponding reduction of costs and of the environmental impact of the building. The rather limited increase of the performance of the integrated system compared to the conventional one may be due to the relatively low irradiation and not perfect orientation of the solar thermal system.

Keywords – solar thermal collector; ground source heat pump; zero energy building; integrated system

1. Introduction

A net zero energy building is an energy efficient building where the necessary energy demand is met by on-site generation of renewable energy [1]. Active solar energy, such as photovoltaic (PV) modules and solar thermal collectors, are well suited for installation on buildings, and is therefore often used to provide renewable energy zero to energy buildings. In

Northern Europe, solar thermal collectors cannot meet the full annual heat load of a building and need to be combined with other heat sources into hybrid systems [2].

Heat pumps of different types are an energy-efficient way to provide heat. Heat pumps with a liquid heat transfer medium work well in combination with solar thermal systems, since they can be connected to the same hydronic storage and distribution system. The combination between a heat pump and a solar thermal installation is generally named solar-assisted heat pump system [3]. Different types of combinations and integrations of the two systems can be seen under this category.

The study presented in this paper is focused on a building with a ground source heat pump (GSHP) and solar thermal collectors. The objective of the study is to determine whether the thermal output of the solar collectors, and the overall system efficiency, can be increased by using an integrated system with heat pump and solar collectors, compared to a system where they are working independently of each other.

Similar concepts have been the topic of previous research. For example Girard, et al. [4] compared a GSHP system to a solar assisted GSHP (SGSHP) system for 15 cities in Europe. They found that the largest increase in the coefficient of performance (COP) was for mild climates and high irradiation. However, the largest improvement in absolute numbers, as well as the shortest (economic) payback times, were achieved for the locations with cold climates and high irradiation, such as the Alpine region.

2. The case building

The case study building is the Living Lab (Fig. 1), built by the Norwegian Research Centre on Zero Emission Buildings. It is located on the campus of the Norwegian University of Science and Technology (NTNU) in Trondheim. As the name suggests, the building is an experimental facility, where the interaction between people and technology is to be studied. For this purpose, the building is equipped with alternative HVAC systems, as well as an extensive monitoring system. The building, which was finished in 2015, is described in more detail in [5].

The building has around 100 m^2 heated floor area, and a total south-facing roof area of 80 m^2 with a 30° tilt angle. A grid connected photovoltaic (PV) system is installed on the total roof area, with a rated power of 12.48 kW_p. Space heating and domestic hot water (DHW) is provided by a combination of a ground source heat pump and 4.2 m^2 of façade-integrated solar thermal collectors. The heat source for the heat pump is a surface collector field, which consists of 105 m piping at around 1.5 m depth on the north side of the building. A sketch of the heating system is shown in Fig. 2.

Fig. 1. The Living Lab in Trondeim viewed from the South. Solar collectors are integrated in the south-exposed façade, right next to the window.

The heat pump and the solar collectors are connected to a 400 l integrated thermal storage tank, composed of a 240 l DHW tank at the top, and a 160 l buffer tank for space heating at the bottom. In the original system, the heat pump is connected via a coil heat exchanger to the DHW tank, as well as to the buffer tank in a tank-in-flow connection. The solar thermal collectors are connected to the buffer tank via a coil heat exchanger. Different heat distribution systems exist in the building, but only the hydronic underfloor heating system is considered for this study.

3. Method

Two types of configurations between the heat pump and the solar thermal collectors are studied:

- Separate connection to the tank, i.e. the systems working independently of each other
- Integrated system

In the original system, the heat pump and solar collectors are used with separate connections to the tank. In the integrated case (Fig. 3), which is also simulated here, the system can work in different modes depending on the temperatures of the heat transfer fluids in the hydronic circuits. The solar thermal output can be used to directly load the storage tank, or as a direct input to the heat pump; the thermal output from the surface collector field can be post-heated before it feeds the heat pump; and finally, the solar thermal output can be used to recharge the ground during summer, when the heating demand is low. This operation mode has, however, not been tested in this paper.

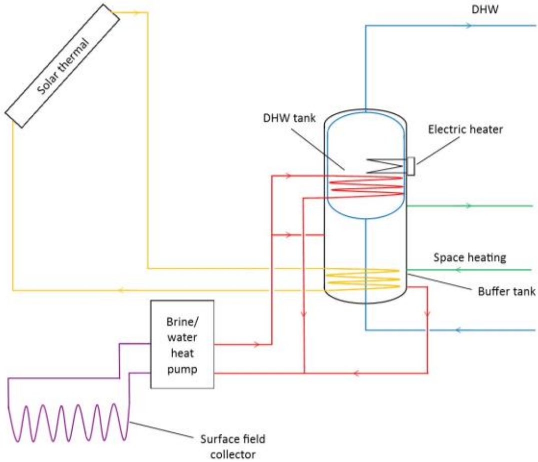

Fig. 2. A simplified sketch of the original heating system on Living Lab.

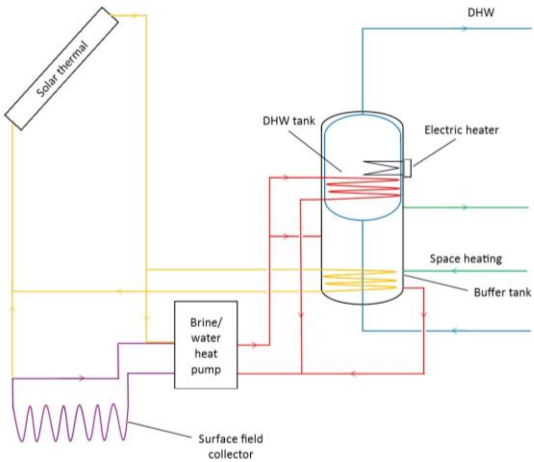

Fig. 3. A simplified sketch of the integrated system option.

The effectiveness of the different concepts are investigated through numerical simulations, performed in the simulation program Polysun from Vela Solaris [6]. This is a dynamic simulation tool for thermal and electric solar energy systems, as well as for hydronic systems and other building equipment components. The heating and DHW loads are obtained from previous publications [5, 7] and used in combination with hourly user profiles. The simulated total energy demand of the building is 80.8 kW h/m^2, divided between space heating (27.9 kW h/m^2), DHW (29.8 kW h/m^2) and electricity-specific (23.1 kW h/m^2) demand. The simulated monthly distribution of the energy demand is shown in Fig. 4. It can be noted that the electricity demand varies slightly in the two connection types, as a result of the varying demand of the circulation pumps. Fig. 4 shows the electricity demand based on the original system with data from [7], where fans and pumps account for about 11%. It should also be noted that the electricity demand of the heat pump is not included in the electricity demand shown in Fig. 4, which shows only the electricity-specific demand of equipment, lighting, fans and circulation pumps.

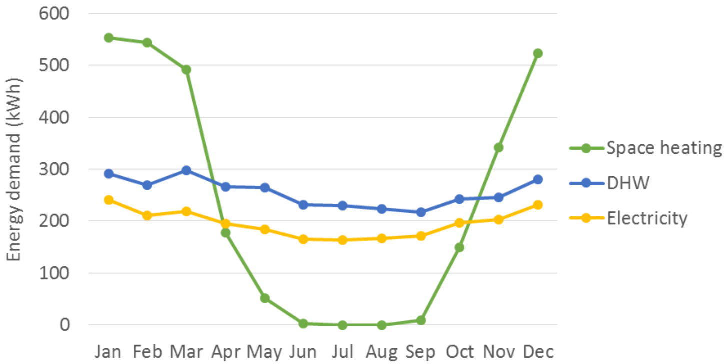

Fig. 4. The simulated monthly distribution of the energy demand for space heating, DHW and electricity.

The original, separate system (Fig. 2) is compared to the alternative, integrated system (Fig. 3) using comparative simulations. Excluding the connection between the heat pump and the solar collectors, the two systems are identical. Some modifications have been made in the simulation model compared to the actual installation in order to simplify the simulation. For example, the connection between the heat pump and the solar panel circuit occurs through a heat exchanger for experimental purposes, but the heat exchanger has not been modelled in these simulations. These simplifications are not expected to have a significant impact on the results.

4. Results

The results show that the integrated connection increases the amount of thermal solar energy that is extracted from the system, as shown in Fig. 5. The annual thermal energy yield is increased by 26 %. The lower absolute values during summertime are a result of the vertical orientation of the modules, which are installed on the south façade. The solar fraction of the building is increased from approx. 14 % to almost 18 %.

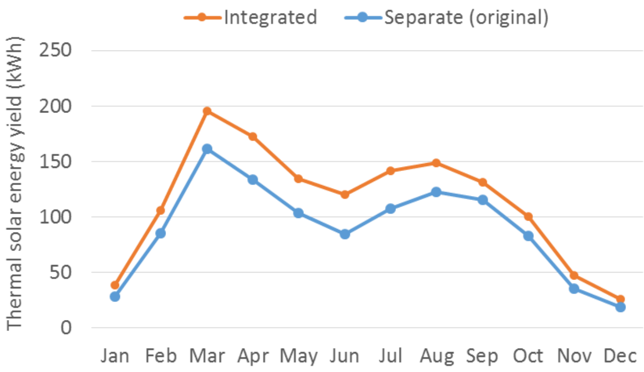

Fig. 5. The simulated thermal solar energy yield from the separate and integrated systems.

The thermal output is increased since the solar collectors operate for a longer time, also when the output temperature is not high enough to be directly useable for DHW preparation. The collector temperature during operation is therefore lower in the integrated system, as shown in Fig. 6. The average collector temperature difference between the two connection options during the year is approximately 13 °C.

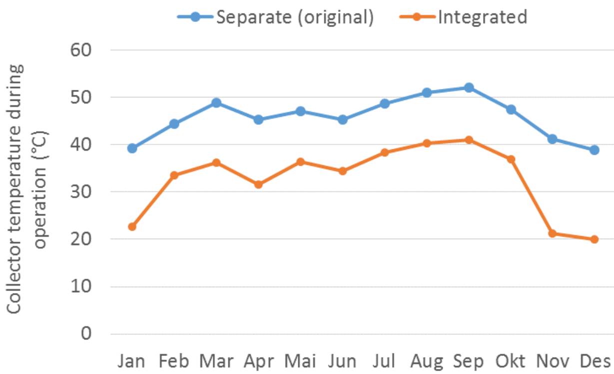

Fig. 6. Collector temperature during operation of the two systems.

In the integrated system, there are two heat sources that contribute to the heat pump operation: the surface collector field and the solar thermal collectors. In this case, the solar collectors contribute to the heat pump operation during the whole year. In addition to the contribution during summer, it also contributes notably during spring and autumn. As a result, the supplied auxiliary energy for heating is reduced by 3.2 %. The electricity demand of the heat pump and the electric heater in the tank is also reduced by 2.5 % over the year, from 2101 kWh to 2049 kWh. The circulation pump electricity demand is, however, increased by 51% from 123 kWh to 186 kWh during the year. This means that in this case the electricity reduction of the heat pump is more or less counterbalanced by the increase in circulation pump electricity demand. This highlights the importance of optimizing the system and using energy efficient equipment. The circulation pumps accounted for approximately 6-8% of the electricity demand of the thermal components.

The energy withdrawn from the surface collector field is reduced by 11 % when using the integrated connection compared to when using separate connection. This indicates that an integrated connection could reduce the required length of the surface collector accordingly. A simulation of an integrated system with drastically reduced surface collector length (50 m instead of 105 m), showed that it was able to meet the heating demand with the same electricity use as the original system. The solar fraction in the system with reduced collector length was 18 %.

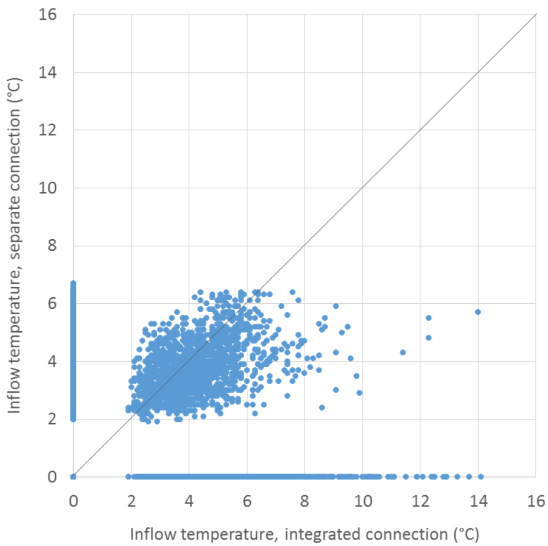

Fig. 7. The inflow temperature to the heat pump during operation for the system with separate connection (y-axis) versus the system with integrated connection (x-axis).

Fig. 7 shows a scatter plot of the inflow temperature to the heat pump during operation. The y-axis shows the values for the separate connection, where the surface collector is the only heat source. The x-axis shows the corresponding values at the same simulation time step for the integrated connection, where both the surface collector and the solar collectors contribute. The diagonal line marks the points where the temperatures are similar in both systems. The figure shows that the integrated connection leads to generally higher inlet temperatures to the heat pump.

A factor that limits the performance of the systems, both in the separate and the integrated connection options, is that they are quite small in relation to the heat load of the building. In Northern Europe, it is common to dimension solar thermal combi-systems (which supply space heating and DHW) to cover the heat load in summer, when there is generally only the DHW load. For a well-designed combi-system, the solar fraction can be in the range 40 % to more than 70 % [8], which can be compared to the solar fraction of 14 to 18 % found in this case. In addition to the size, the vertical orientation of the modules reduces the annual energy output, even though the output during spring and autumn is slightly increased.

A series of simulations of the case building with larger collector areas was performed and showed that at least 3-4 times the original area would be required to give a solar fraction above 30 % - a solar fraction value that is still far from well-designed systems in locations with higher solar irradiation. An example of the influence of the collector area and tilt angle is shown in Fig. 8 for the integrated system (the influence on the separate system is similar). Increasing the collector area by three times (from the original 4.2 m^2 to 12.6 m^2) increases the solar thermal output by 110%, and installing it at the optimal angle increases it by another 13%, but this reduces the yield between October and March slightly. It should be noted that only the collector area was changed in these simulations, and higher outputs would probably have been achieved if also the storage volume had been increased.

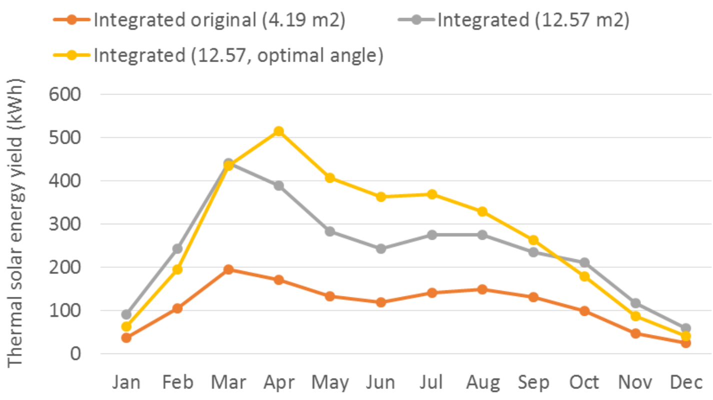

Fig. 8. The energy output of the three versions of the separate system: the original size (4.19 m^2), increased size (12.57 m^2) and increased size with optimal angle (12.57 m^2, 45°).

The solar fraction was increased from 17 % to almost 36 % with the increased area. In the case with optimal angle, the solar fraction is ca. 40 %, and more than 85 % on average during the summer.

5. Discussion

The simulations showed a relatively modest increase in performance of the system with an integrated connection of solar collectors and heat pump compared to the one with a separate connection. The results are, however, in line with the results of previous studies. The reduction in electricity use is only 2.5 %, which is relatively similar to the 2 % reduction found by Girard, et al. [4] for a relatively similar system located in Bergen in Southern Norway. The corresponding increase in electricity demand of the circulation pumps shows the importance of optimizing the system, and of using energy efficient equipment.

The simulations showed that the integrated connection lead to a reduction in the required length of the surface collector field compared to the original separate connection, and it has been demonstrated that a drastic reduction of the surface collector field (-50 %) can be achieved with the same electric energy demand for heating and DHW. This has implications for the cost of the system, but also for the embodied energy and greenhouse gas emissions, i.e. the energy and emissions associated with the production of materials and construction. Previous research in the ZEB Centre has shown that the embodied emissions can account for around half of the total emissions of a building during its lifetime [9]. Reducing the need for materials and construction work is therefore an important entry when the environmental impact of a building is analyzed from a general perspective.

The results presented here are a first step in the study of integrated solar thermal and GSHP for Norwegian conditions. Several improvements could be made to the system which could improve the performance, for example adding a buffer tank between the solar collectors and the surface loop, or connecting the solar thermal output directly to the heat pump evaporator. More work will also be put in to optimizing the operation of the system, and the choice of components such as circulation pumps.

Another topic, which was not analyzed for this paper, is the possibility of recharging the ground with solar energy using an integrated connection, thereby utilizing the ground as a seasonal thermal storage. In a recent review, Hesaraki, et al. [10] concluded that a good seasonal thermal storage should have a high specific heat storage capacity, long term stability under thermal cycling, a stable containment, and low cost. This means that mainly rock, soil or water are used as seasonal storage media. The review found that seasonal storage is a promising technology for energy saving, but that it is not suitable for all types of applications due to high cost and/or complexity [10].

6. Conclusions

The performance of a ground source heat pump and solar thermal system with separate connections for the heat sources was compared to a similar system with an integrated connection. The results show that the solar thermal output is significantly increased in the integrated connection case, although the temperature of the output is decreased. The electricity demand of the heat pump is reduced by around 2.5% when using the integrated connection, and less energy is withdrawn from the ground via the the surface collectors. However, the additional electricity used by the circulation pumps more or less equaled the reduction in electricity demand by the heat pump. This highlights the importance of optimizing the system and using energy efficient equipment.

The simulations also showed that the integrated solution allowed a reduction in the length of the surface field collectors, while still meeting the same heat load. This could reduce the cost as well as the environmental impact of the system. Further developments to the system could include optimizing the control system, adding a buffer tank between the solar collectors and the surface field collector, or investigating the possibilities of utilizing solar thermal energy for seasonal heat storage in the ground.

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