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A novel fully electrified solar heating system with a high renewable fraction - Optimal designs for a high latitude community

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ABSTRACT

Solar energy use in Nordic countries suffers from a high seasonal mismatch of generation and demand. However, given a large enough community, seasonal thermal storage could be utilized to store summertime heat gains for use in winter. This simulation study examined a Finnish case of fully electric solar heating, where heat pumps (HP) powered by photovoltaic (PV) panels were used for generating heat for both immediate use and for seasonal storage through a borehole thermal energy storage (BTES) system.

Multi-objective optimization of LCC and energy use was performed by a genetic algorithm and TRNSYS simulations. Comparison was done between communities of a 100 and 500 buildings. The need for purchased electricity was between 40 and 26 kWh/m^2 per year for the optimal configurations. For the same cases the life cycle cost was between 220 and 340 €/m^2. Up to 98% renewable energy fraction was obtained for heating, showing that even in Finland it is possible to provide practically all heating by solar energy. The PV-type heating system was also compared to a solar thermal heating system from a previous study and it was found that the new design had as much as 36% lower life cycle cost.

Nomenclature

Abbreviation	Explanation
AW-HP	Air-to-water heat pump
BTES	Borehole thermal energy storage
DLSC	Drake Landing Solar Community
DHW	Domestic hot water
HP	Heat pump
LCC	Life cycle cost
PV	Photovoltaic
REF_{total}	Renewable energy fraction of total electricity
REF_{heat}	Renewable energy fraction of heating
SH	Space heating
ST	Solar thermal
WW-HP	Water-to-water heat pump

1. Introduction

Heat generation for space heating and hot water is a significant source of energy demand and in the Nordic countries. In Finland, district heating provides a large portion of the required heating, but this energy is mostly generated by conventional combustion of fossil fuels and biomass. On an annual level, solar energy potential in Finland is similar to that of Northern Germany, however, the seasonal difference of solar insolation is greater. The amount of solar energy available in the brightest summer month can be 20 to 30 times greater than what is available in the middle of winter, which is the time that energy is needed the most.

Zero energy building design can reduce the need for heating and thus the solar capacity needed for meeting the demand. Further advantage can be gained from neighborhood level design, as different types of buildings can benefit from shared energy generation [28]. Larger scale solutions also make it possible to utilize seasonal thermal energy storage, which is not feasible on the single building level. Seasonal thermal energy storage can be used to store energy for several months, allowing the use of solar energy even in winter. Two popular methods for seasonal storage are pit thermal energy storage (PTES) and borehole thermal energy storage (BTES) [29]. PTES uses a large pool of water to store heat and is useful in locations where the ground is easy to dig. In a BTES, the heat is stored directly in the ground, by circulating hot liquids through heat transfer pipes inside boreholes that are drilled to the ground. BTES may be used even in locations where the bedrock is close to the surface.

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Seasonal thermal storage systems have been combined with solar thermal energy generation in several solar communities built around the world, such as those in Germany [2], Sweden [14] and Canada [27]. In the Canadian Drake Landing Solar Community 98% of space heating demand was met by solar thermal energy. Similar performance was obtained in a simulation study in Finnish conditions, though a larger solar thermal area was required [8]. One issue, along with the selection of the seasonal storage type, is the degree of centralization vs. decentralization in the energy generation. While a centralized ground installation of solar collectors is cheaper than distributed rooftop installation in principle, the cost of the land may change the economic end result [3]. An alternative to solar energy generation is to charge the BTES with waste heat from cooling, such as was done in a Swedish university campus [17].

To provide not only space heating (SH), but also domestic hot water (DHW) requires higher storage temperatures. This is very challenging using BTES, which suffers from significant thermal losses. However, in typical conditions, modern heat pumps (HP) can generate space heating and hot water with a coefficient of performance (COP) of 3–5 [26]. A study about solar heating for a Finnish district found that 60% self-sufficiency was possible using low temperature BTES and heat pumps [20]. Another study about a Finnish solar community with heat pumps and a solar thermal system found it possible to obtain a 95% solar fraction when providing both SH and DHW [11]. However, such a high solar fraction came at a high cost. Solar thermal collectors and auxiliary solar electric panels were the most expensive individual components in the system, which guides us to look into alternative solutions. Heat pumps, on the other hand, have been found to be a cost-effective technology for reducing energy demand in Finnish apartment buildings [18].

Solar photovoltaic (PV) panels can be used for supplying electricity for lighting and appliances, but also for running electrical heating systems, specifically heat pumps. An Italian experimental study looked into combining PV panels with HP to supply heating and cooling from a ground loop [9]. Unfortunately, the HP was oversized compared to the PV system, which caused inefficient operation with a low COP, and the system could not provide all the heat required in winter. In Finnish conditions, the seasonal differences in solar energy potential would make such a plan even more infeasible. However, air-source heat pumps linked to solar electric systems could provide energy to a BTES system during summer, to provide heating in winter. Typically, PV panels are used to run appliances and to balance out the purchased electricity through net metering, as was done in an Irish solar heating study [5]. However, in many countries, such as Finland, net-metering or solar feed-in tariffs are not available and the value of solar energy exported to the grid is lower than self-consumed energy. The trend in Finland is to increase both the use of solar PV panels and heat pumps, making their integration a natural progression. Using excess solar electricity to generate heat is a way to increase self-consumption and improve the economics of a solar energy system. A review on solar heat pump technology found that there is a lack of studies which consider the combination of PV and HP systems [22]. It also highlights the importance of system boundaries when using free solar electricity to run all components of a heating system. Heating of buildings is a significant source of carbon emissions in Finland, which is why research on emission-free heat generation is of great importance. Using solar electricity to charge a seasonal thermal storage has not been reported before.

This paper aims to fill the research gap and study the potential of a fully electric solar district heating system in cold conditions with high seasonal variability in solar insolation. The studied solar heating system consists of a centralized energy storage system with large water tanks and a seasonal borehole thermal energy storage system, as well as air-source and water-source heat pumps and solar electric panels. A range of solar community designs will be obtained through multi-objective optimization, which minimizes grid energy demand and life cycle cost. The research questions are: What kind of renewable energy fraction can be achieved with PV-based solar heating systems in Finland? What are the optimal designs when aiming at low cost or high performance? What is the benefit of the solar electric system compared to a solar thermal system?

2. Methodology and system description

This is a simulation study that was performed using a dynamic TRNSYS model. The modeled system was a solar community with 100 low energy residential buildings connected to a local heating grid and the national electric grid. Solar electricity was used to meet as much of the energy demand as possible. The weather conditions used for simulation of solar generation and heating demands corresponded to the Helsinki Test Reference Year 2010 [13], which has the annual mean ambient temperature of 5.6 °C. For each examined case, the simulated time period was 4 years and the timestep was 0.125 h.

2.1. Energy system

The energy system for the community is shown in Fig. 1. The core of the energy system was the centralized thermal storage system, consisting of two water tanks (Type 534) and the borehole thermal energy storage (BTES) system (Type 557a). The tanks provided energy to the local heating grid and were charged by heat pumps. An air-to-water heat pump (AW-HP) was used to charge the warm tank (kept at 40 °C), which served as the main provider of space heating (SH) and preheated the domestic hot water (DHW). A water-to-water heat pump (WW-HP) used the warm tank as its heat source to provide thermal energy to the hot tank (kept at 60 °C), which was used to superheat the DHW to above 55 °C, as required by the Finnish building code [30]. The houses were heated with a low temperature floor heating system, using a temperature of 30–35 °C, depending on ambient air temperature. The local heating grid was the main source of energy for the buildings' space heating and domestic hot water needs, but a direct electric backup heating system was available at each house in case the temperature was too low.

Each house in the community was setup with rooftop solar panels to provide electricity to the community. Any generated solar electricity was first used to run electric appliances in the house. If any solar electricity remained after that, it was used to run the centralized heat pumps to heat up the water tanks. The heat pumps were modeled as ideal systems for which the COP was a function of the heat source temperature and load-side inlet temperature. The minimum part-load state for the heat pumps was 10%, but otherwise they could be operated on any power level. No efficiency losses due to part-load or ramping were considered. The COP properties of the heat pumps are shown in Figs. 2 and 3.

The WW-HP was operated first so that the hot tank temperature was raised up to 70 °C. If this temperature was reached or there was further excess solar electricity available, the AW-HP was used to charge the warm tank as much as possible. The WW-HP used the warm tank as its heat source. The cooled down return flow lowered the temperature in the warm tank, thus increasing the COP of the AW-HP. Whenever the temperature in the warm tank was 5 °C higher than the average temperature of the BTES ground storage, the energy from the tank was used to charge the seasonal storage. Any excess solar electricity remaining after heat pump use was sold