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Techno-economic optimization and analysis of a high latitude solar district heating system with seasonal storage, considering different community sizes

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ABSTRACT

A solar community meets a significant amount of its energy demand through solar energy. In a high latitude country like Finland, the seasonal mismatch of solar availability makes it very difficult to achieve high renewable energy fractions without seasonal storage. In this study, a solar community located in Finland was optimized with respect to energy demand and life cycle cost. To gain better understanding of both technical and economical scaling effects, the optimization was done separately for four cases with 50, 100, 200 and 500 buildings.

The study was performed for Finnish conditions using dynamic TRNSYS simulations and optimized with a genetic algorithm, using the MOBO optimization tool. The modeled energy system had solar thermal collectors and solar electric panels for energy generation, two centralized short-term storage tanks and a seasonal borehole thermal energy storage system (BTES) for energy storage, and a ground source heat pump for additional heat generation.

The larger communities provided noticeable cost-benefits when aiming for high performance. Larger seasonal storages allowed more direct utilization of seasonally stored heat, lowering the need for the heat pump and reducing electricity demand. Comparing the best and worst performing optimal energy system, annual demand for heating electricity was reduced by 80%. Renewable energy fractions close to 90% for heating were possible for all community sizes, but the large communities could obtain them with about 20% lower costs.

1. Introduction

The heating of buildings is a large part of the total European energy demand, especially so in the Nordic countries. For example, in Finland, 87% of energy is consumed by heating (Statistics Finland, 2014). Producing heating through emissions-free renewable energy systems would lower its environmental impact. Such systems might be based on biomass or hybrid solar heating (Modi et al., 2017). Solar energy is a widely available energy source, but suffers from both diurnal and seasonal variation. The diurnal variation is a significant problem for solar electric systems, because of the hourly mismatch between energy generation and demand and the high cost of electricity storage. However, thermal energy storage in hot water tanks is a very mature technology and mostly removes the hourly mismatch in heating applications. It can even partly solve the hourly solar electricity mismatch problem (Hirvonen et al., 2016). Unfortunately, home-scale hot water tanks are of little use in solving the problem of seasonal mismatch, where the heating energy demand is the highest exactly when the solar generation is the lowest, during winter (Fig. 4). This problem is especially difficult in high latitude countries, because the relative difference between summer and winter solar energy availability increases the further we move from the equator.

The problem of seasonal variation can be solved through seasonal thermal energy storage (Xu et al., 2014). Using seasonal storage, energy can be stored in the peak months to be used during times of high energy demand. While technologies are being developed for chemical and latent heat storage, existing seasonal storage systems mostly utilize sensible heat storage, based on changing the temperature of a high heat capacity material. The basic storage types in this group are hot water tank thermal energy storage (TTES), aquifer thermal energy storage (ATES), water pit thermal energy storage (PTES) and borehole thermal energy storage (BTES).

Seasonal thermal energy storage is often utilized in solar communities, where the goal is to meet a significant part of the heating demand by solar energy, that is, to achieve a high solar fraction. The history of solar communities began in the 1970s energy crisis (Reuss, 2015). Many such communities have been built in Europe in the 1980s, 1990s and 2000s, mostly in Denmark (Heller, 2000), Germany (Schmidt

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Nomenclature

Symbol/acronym

BTES	borehole thermal energy storage
DLSC	Drake Landing Solar Community
DHW	domestic hot water
HP	heat pump
PV	photovoltaics
SH	space heating
ST	solar thermal
A_{floor}	heated floor area (m^2)
A_{ST}	solar thermal area (m^2)
h_{ratio}	BTES height vs. width ratio (m/m)
LCC	life cycle cost over 25 years (€/m^2)
$N_{boreholes}$	number of boreholes in BTES (–)
N_{series}	number of boreholes connected in series (–)
REF_{heat}	renewable energy fraction of heating (–)
REF_{total}	Renewable energy fraction of total electricity (–)
SF	Solar fraction (–)
SPF	Seasonal performance factor of heating (kW h/kW h)
V_{BTES}	Seasonal storage volume (m^3)
α_{tilt}	Tilt angle of solar collectors (°)
$\rho_{boreholes}$	Area density of boreholes in BTES ($1/m^2$)

et al., 2004) and Sweden (Lundh and Dalenbäck, 2008). Some of the projects store energy into the ground (BTES), but water-based storage with tanks have also been studied (Tulus et al., 2016). While current efforts in Denmark are towards large solar district heating systems based on water pit storage (Ramboll, 2015), existing solar communities are of many different sizes, as shown in Fig. 1a.

The German Neckarsulm community consists of 200 apartments and a shopping center, school and gym, built in 1997 (Nussbicker et al., 2004). It has a 63 000 m^3 BTES system with a gas boiler and heat pump for backup. The Crailsheim community of similar scale was built in 2007 and has a 37 500 m^3 BTES storage that serves 260 apartments, a school and a gym (Bauer et al., 2010). Backup heating was handled by district heat and a heat pump. The seasonal storage was smaller in Crailsheim than Neckarsulm, but the amount of solar collectors was larger, 7500 m^2 compared to 5670 m^2. The Attenkirchen solar community is much smaller, serving only 30 homes (Reuss et al., 2006). This system utilizes an underground water tank, surrounded by a 10 500 m^3 BTES system. Similar design was used in the only Finnish solar community trial in Kerava (Lund, 1984), though the system was later dismantled and replaced by conventional district heating.

Perhaps the most famous solar community is the Drake Landing Solar Community (DLSC) in Canada, which started operation in 2008 (Sibbitt et al., 2011). It utilizes 2300 m^2 of solar collectors, two water-based buffer storage tanks and 34 000 m^3 BTES system to supply heating to 52 houses. A system of similar scale is the Swedish Anneberg solar community, with a 60 000^3 BTES volume and a 2400 m^2 solar thermal area. The DLSC system has been able to meet 98% of space heating demand through solar energy, while the Anneberg system supplies about 60% of combined space heating and domestic hot water (DHW) demand (Zhu, 2014). On the other extreme of solar communities is the Braedstrup solar district heating system in Denmark (SDH EU, 2012). It was built in 2007 and extended in 2012 to have a 19 000 m^3 BTES volume with an 18 600 m^2 solar thermal area. The system is backed up by an electric boiler and a heat pump and supplies heat to 1200 homes. Because of the large heat demand compared to the solar thermal capacity, the solar fraction is only 20%, but this also ensures minimal waste of available solar energy.

Every solar community has a different amount of buildings, different sizes of short-term and long-term energy storage as well as different solar collector areas, different auxiliary heating systems and different environmental conditions. Thus, even when the communities report different solar fractions, it is hard to tell what is the main reason for the performance. Fig. 1b shows the solar fractions achieved by solar communities, arranged according to their ratio of energy storage to solar capacity and ratio of solar capacity to heated space. All of these systems utilize BTES for their seasonal storage needs. It seems that the highest solar fractions have been achieved by systems with more solar thermal capacity per heated area and more storage capacity per solar thermal capacity. The opposite also holds true for the smallest solar fraction. However, for most samples the correlation is far from clear, which implies other factors are also important.

This article examines the effect of community size on the techno-economic optimization of a high latitude solar community in a heating-dominated climate. Specific environmental challenges include high seasonal variability of solar energy and highly conductive ground. Total system optimizations have not been widely reported in the literature.

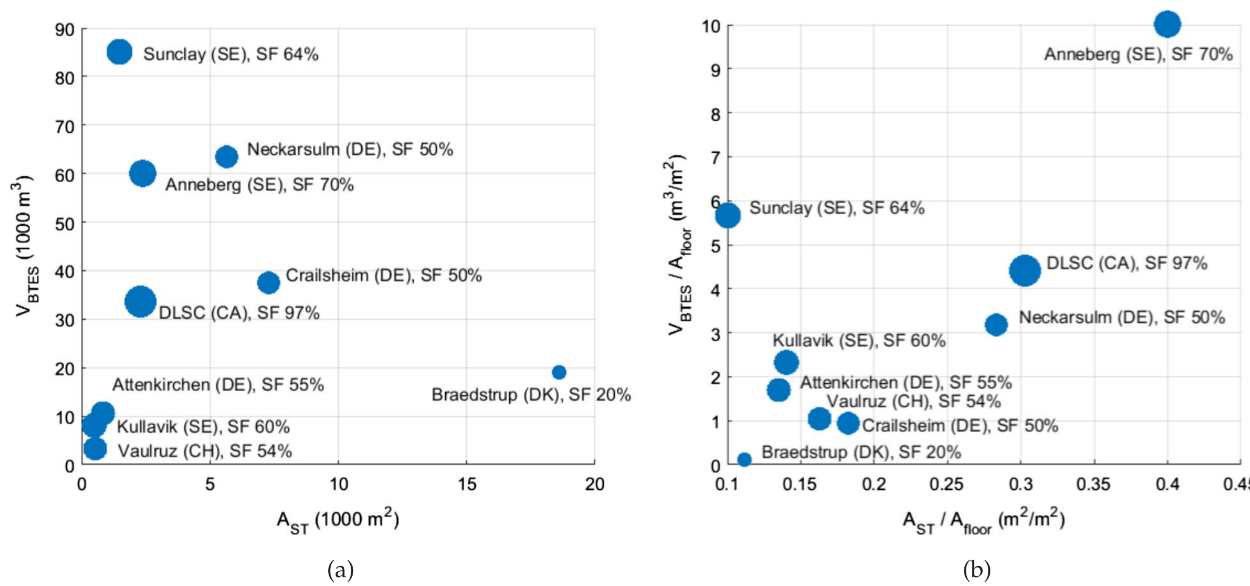

Fig. 1. (a) Solar fraction of some realized solar communities. (b) Solar fraction reported with relative system sizes.