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Influence of location and design on the performance of a solar district heating system equipped with borehole seasonal storage

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ABSTRACT

The solar district heating system combined with borehole thermal energy storage (BTES) in the Drake Landing Solar Community (DLSC) has managed to provide 97% of the community's annual space heating demand with solar power. Following such exceptional results, the focus of this paper is to analyse the influence of location changes on the DLSC. A model of the community is created with TRNSYS and simulations are carried out in five different locations: Helsinki [FI], Hohhot [CN], Dublin [IE], Oviedo [ES] and Perpignan [FR]. To fulfil the specific needs of each location, adaptive measures are taken by modifying key parameters of the system's original design. Results show that insulating the houses and using lower temperature heating systems can significantly increase the system's solar fraction (SF). Despite increasing SF, the use of lower temperature heating systems in well-insulated homes may result in a decrease in the BTES's efficiency (η_BTES), which is also dependent on local ground properties. In hot climates, the BTES may be omitted due to high levels of winter solar radiation. Very high SFs are found to be possible in all studied locations (>95%), as long as appropriate modifications are made to the original design when necessary.

1. Introduction

Solar district heating with seasonal storage is a very promising alternative to fossil fuel heating and has been researched by several entities, such as IEA's Task 32 and Task 45 [1,2], and the German programme Solarthermie [3]. Currently, the solar district heating market is booming in Denmark, not because of subsidies but due to its competitive price in comparison to biomass and gas [4,5].

For designing and analysing the dynamics of such systems, the use of simulation software is continuously on the increase in both building and energy sectors. The software of choice for this current study is TRNSYS 17. In this program, sub-systems are modelled as individual components (called types) which can be cross-linked to one-another in order to create the model in question.

Numerous solar district heating and seasonal sensible thermal storage projects have seen the light of day in Europe and North America. Several reviews have been published, of which the most recent is by Xu et al. [6]. In this review, aquifer, duct, gravel and hot water storage projects are listed and their performances are compared. The solar fraction (SF; see Appendix A for definition) is used as an indicator of performance and the best result, omitting misleading information, has been achieved by the Drake Landing Solar Community (DLSC), established in 2007 in Okotoks, Canada. In the fifth year of operation, an SF of 97% was reached [7]. Due to its outstanding performance, this state-of-the-art design for solar district heating combined with borehole thermal energy storage (BTES) is used as a reference case in this study. The BTES efficiency (η_{BTES}; see Appendix B for definition) is also investigated. Fig. 1 illustrates the concept of the DLSC.

Many reports on the DLSC have been published by its design team, which include simulated and monitored results [7–12]. Chapuis and Bernier [13] have simulated an alternative design where a heat pump is used instead of gas boilers. However, no study on the impact of location changes has yet been undertaken and, as pointed out by Persson and Westermark [14], future research is needed in the area of adapting seasonal thermal energy storages for low energy buildings.

For these reasons, the goal of this paper is to demonstrate the impact of location changes and design modifications on a system such as the DLSC. The studied location changes are Helsinki (Finland), Hohhot (China), Dublin (Ireland), Oviedo (Spain) and Perpignan (France). Design modifications are investigated for the

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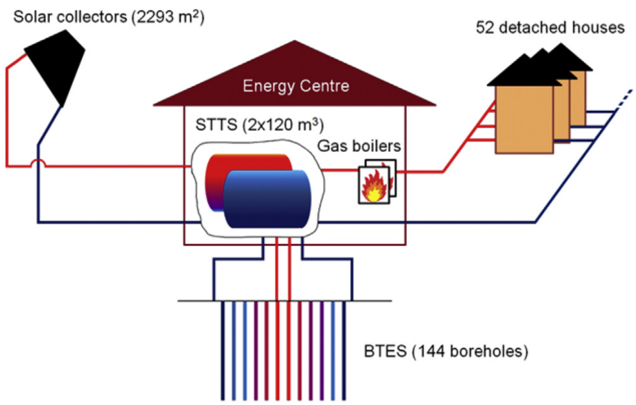

Fig. 1. Simplified diagram of the DLSC.

purpose of increasing the SF whilst minimising the community's need for cooling. These alterations encompass the water supply temperatures, the solar collector area and tilt angle, as well as the houses' insulation, thermal mass and windows. No modifications are made to the thermal energy storages nor to the types and numbers of buildings connected to the heat network (to name but a few possible alternatives) as this would require enough research for a paper of its own. As a reminder to the reader, the district heat in the DLSC is solely used for space heating.

2. Methodology

The methodology of this study is organised as follows:

1) A TRNSYS model is created and three instances are presented: scenarios A, B and C. Scenarios A and B are validated against the DLSC's on-site and predicted results respectively. Scenario C is then introduced as a benchmark for fair comparison between locations.
2) Weather and soil data are changed in order to simulate the DLSC in cold continental/maritime (Helsinki), cold semi-arid (Hohhot), temperate oceanic (Dublin), warm oceanic (Oviedo) and warm Mediterranean (Perpignan) climates.
3) Adaptive measures are taken and modifications are made to the original house design and/or to the solar district heating system in each location depending on the specific need(s), e.g. excessive cooling requirement and/or inadequate SF.

2.1. TRNSYS model of the DLSC

The model is run under three different scenarios. Scenario A is used to compare the TRNSYS model with the real system (DLSC's monitored results) which has undergone various adjustments over the years. Scenario B is used to compare the TRNSYS model with predictive results from the original DLSC design. These two scenarios are used for validation purposes (see section 2.1.2). A third and final scenario is then introduced in section 2.1.3 to effectively compare the influence of location change. To summarise, differences between all three scenarios are presented in a table.

2.1.1. Model description

The entire system can be divided into six modules which have each been implemented into the TRNSYS model: weather and soil data, glycol loop with solar thermal collectors, short-term thermal storage (STTS) tanks, BTES, district heating network, houses. The DLSC design team used an optimisation routine to maximise the economic performance of the system [7], with the full knowledge that the scale was smaller than the economic optimum [9]. The following parameters were varied within the project's limits: the distribution and number of solar collectors, the size of the STTS and the number and depth of holes for the BTES.

Due to the dynamic nature of some of DLSC's components, measurements from certain sensors are taken every minute. However, most of the measurements are taken every ten minutes [12]. For this reason, a compromise is struck and the time step used in all of the presented simulations is six minutes. The covered time span is five years, starting on the 1st of July 2007 and ending on the 30th of June 2012. These settings are used in scenario A. In scenario B, the timespan is the same however the start date is January 1st. System downtime has been reported in the DLSC in late March and early April of 2009 due to maintenance work [9]. A pump was also reported to have failed in December 2009 [15], preventing solar energy from being delivered to the district heating network. As a result, similar downtime is included in scenario A, during which time the gas boilers are used to meet the community's heating demand. Scenario B is spared from downtime.

2.1.1.1. Weather data. There is no weather station in the town of Okotoks, where the DLSC is situated. The only available weather data published regarding the DLSC are annual figures [7] between 2007 and 2012. The closest weather station, Black Diamond [16], is situated 15 km west of the DLSC. However, weather data collection in this station started in December 2008 and no solar radiation records are available. The next closest weather station is Calgary's international airport [17], situated 45 km north of the DLSC. A comparison in annual heating degree days (HDD; see Appendix C for definition) between these three sites shows a closest match between the DLSC and Calgary, with differences within the ±0.2% range. Calgary's temperature, humidity and pressure data are therefore selected for modelling the DLSC's weather.

In terms of solar radiation measurements, the closest weather station is Calgary's international airport. Solar data collection started in 1953 but stopped in 2005 [18], so the closest matching years had to be used. The standard deviation for annual global horizontal radiation over the years 1953–2005 inclusive is relatively low, with a standard deviation of 0.146 GJ/m^2 and a mean value of 4.915 GJ/m^2.

Consequently, solar radiation levels at the DLSC can be simulated by using Calgary solar data with a relatively low level of uncertainty. The difference in annual global horizontal radiation between the data used in scenario A and the reported on-site measurements comfortably lie within a ±1% range, as presented in Table 1.

The DLSC design team's simulation assumed that for the first five years of BTES operation, each year would comprise 5200 HDD and 4.97 GJ/m^2 of global horizontal solar radiation [7]. Since this closely matches the outdoor conditions of DLSC's second year of operation, weather data used for 2008/2009 in scenario A are used for each of the five years in scenario B.

2.1.1.2. Solar collectors. DLSC's 798 flat plate serpentine tube solar thermal collectors are mounted on garage rooftops. The collectors

Table 1
Annual global horizontal radiation for the DLSC and scenario A.

Year of operation	DLSC (Sibbitt et al., [7])	Scenario A
1	4.63 GJ/m^2	4.62 GJ/m^2
2	4.96 GJ/m^2	4.96 GJ/m^2
3	4.65 GJ/m^2	4.65 GJ/m^2
4	4.58 GJ/m^2	4.62 GJ/m^2
5	4.75 GJ/m^2	4.74 GJ/m^2