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Citation for published version:
Renaldi, R & Friedrich, D 2019, 'Techno-economic analysis of a solar district heating system with seasonal thermal storage in the UK', *Applied Energy*, vol. 236, pp. 388-400.
https://doi.org/10.1016/j.apenergy.2018.11.030

Digital Object Identifier (DOI):
10.1016/j.apenergy.2018.11.030

Published In:
Applied Energy

Techno-economic analysis of a solar district heating system with seasonal thermal storage in the UK

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Abstract

Heat demand in buildings is responsible for around 40% of all energy use in middle to high latitude countries. The combination of district heating systems with solar thermal energy and seasonal thermal energy storage has successfully reduced the carbon intensity of heating in different countries, such as Denmark, Germany and Canada. The potentials of such systems to decarbonise the heat demand in the UK has also been highlighted in different reports. Nevertheless, bottom-up quantitative studies to support or dismissive these potentials are very limited. The quantification can be provided by simulating a solar district heating system using UK-specific inputs, such as heat demand and weather profiles. In this study, a validated simulation model is used to study the performance of solar district heating systems with seasonal thermal storage deployed in the UK. The case studies are based on the Drake Landing Solar Community in Okotoks, Canada, which has a relatively high solar fraction. The results show that the system is technically feasible to be implemented in the UK but that it has lower technical performance. A systematic analysis of the influence of the main components on the system performance shows that not only the solar supply and heat demand need to be balanced but also that the long-term storage needs to be appropriately sized. The relatively lower solar fraction could be offset by installing more long-term storage and implementing the system to supply new-built houses with better energy performance rather than the current building stock of older homes. Financially, the system still needs to be supported by encouraging policies to make it competitive with incumbent technologies. The results and the validated model open the possibility to design bespoke solar district heating systems for the UK and other countries in middle to high latitudes.

Keywords: thermal energy storage, district heating, techno-economic, TRNSYS, seasonal thermal energy storage

1. Introduction

District heating has been acknowledged as one of the technological solutions towards decarbonising thermal energy provision in the UK, in addition to repurposing gas grids with hydrogen, electrification with heat pumps, and the implementation of other renewable-based heating technologies, such as biomass boilers and solar thermal [1, 2]. Traditionally, the foundation of district heating was to use local fuel or heat sources that otherwise would be wasted, such as combined heat and power (CHP) plants, waste-to-energy plants, and industrial processes. Recent and future developments of district heating expand this idea by introducing renewable energy sources like solar thermal, biomass, and geothermal energy. This trend has amplified the benefits of district heating beyond financial value to include the environmental, and societal aspect of energy supply [3].

A report by the UK Department of Energy and Climate Change in 2013 identified 1765 district heating networks in the UK [4]. Most installations are small networks, i.e. an average of 35 residential dwellings, and only 75 are classified as large (> 500 homes or 10 non-domestic buildings). Furthermore, the majority of district heating systems are powered by natural gas boilers, with a smaller share of natural gas CHP systems.

In Scotland, district heating implementation is part of the Heat Policy Statement published by The Scottish Government [5]. The statement also highlights key policies in supporting the increase of renewable and other forms of low carbon heat. Similar to the condition in the UK, most of the supply technologies are based on gas boilers and CHP. While natural gas CHP units are a good bridging technology to reduce carbon emissions, the emissions savings vanish for electricity grid emission factors below 200 $g_{CO_2}\,kWh^{-1}$ [6], which have been reached in the UK due to the decommissioning of coal power plants.

Long-term thermal energy storage technology has been mostly installed in district heating applications, particularly solar district heating [7, 8, 9, 10, 11, 12]. An example of these systems is the Drake Landing Solar Community (DLSC) in Canada [13]. Solar district heating combines renewable heat sources with efficient delivery through a heat network. Therefore, it is a potential technology to

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Nomenclature

A area, m^2	T temperature, K
BOI boiler	TES thermal energy storage
C cost	V volume, m^3
$DLSC$ Drake Landing Solar Community	c heat capacity, kJ/kgK
HD heating demand	ch charge
HX heat exchanger	dch discharge
$LCOE$ levelised cost of energy	el electricity
LTS long-term storage	gas natural gas
P electrical power, kW	inv investment
Q thermal energy, kWh	opr operational
R revenue	r discount rate
RHI Renewable Heat Incentive	s soil
$\dot{Q}$ thermal power, kW	sys system
SF solar fraction	sto store
SCO solar collector	t time step
SOC state-of-charge	η efficiency
ST solar thermal energy	ρ density, kg/m^3
STS short-term storage	ϕ standing losses, %

contribute to the decarbonisation of heat in the UK. However, currently, there is no solar district heating or long-term thermal storage installation in the UK.

Most solar thermal installations in the UK are domestic applications with a hot water tank as the storage technology. The potential of long-term storage technologies has been mentioned in recent reports on current situations and future development of energy storage technology in the UK [14, 15, 16, 17]. Nevertheless, the discussions in the literature have been mainly qualitative in nature, while quantitative studies are required in order to determine the feasibility of a technology and to aid the design of viable systems.

Due to its relatively wider implementation in mainland Europe, solar district heating systems with long-term storage have been the subject of various studies. These include, among others, the investigation on the performance of a centralised and decentralised system [18], the integration into existing district heating system [19], the use of flat-plate and parabolic-trough collectors [20], the optimisation of installation in a high latitude location [21], and the thermo-economic sensitivity analysis of a small solar district heating system in Italy [22]. Nevertheless, most of the studies are based on non-UK locations. Location specific characteristics hold significant influence on renewable energy systems, such as a solar district heating system, due to the spatially-dependent resources and energy demand.

Therefore, in order to address this lack of quantitative studies for UK locations, a techno-economic study of a solar district heating system with long-term seasonal thermal energy storage installed in UK locations is presented in this paper. The Drake Landing Solar Community is used as a case study and for the validation of the TRNSYS model. DLSC is chosen as the case study because it aims to provide almost 100% of the heat demand from solar collectors. This is in contrast to most European systems, which supply only around 50-60% of the heat demand from solar collectors. In addition, relevant data related to the design and operational of DLSC are publicly available, which contributes to its use as the case study in several publications (e.g. [23, 24, 25]). While the influence of locations on DLSC has been reported in the literature [26], the previous studies did not consider UK locations and financial aspects nor the influence of the short- and long-term thermal storage configuration on the techno-economic performance. Furthermore, in addition to the techno-economic performance, the present study also investigates the potential of a policy-based subsidy to support the implementation of solar district heating in the UK.

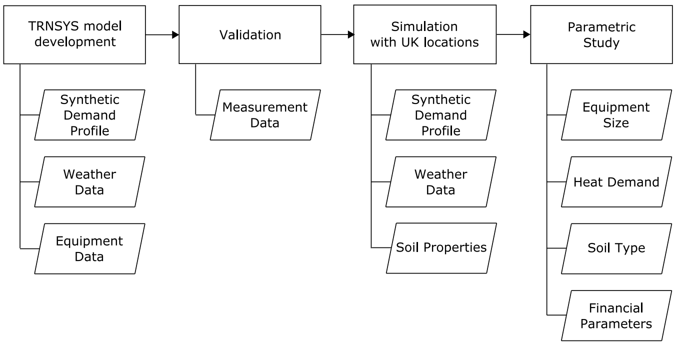


Figure 1: Techno-economic framework.

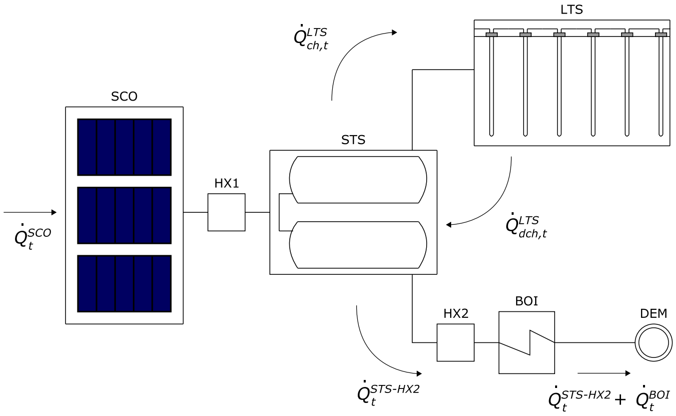


Figure 2: Schematic of Drake Landing Solar Community with the relevant metrics for the techno-economic analysis. Main equipment are solar collectors (SCO), short-term thermal energy storage (STS), long-term thermal energy storage (LTS), and back-up gas boilers (BOI). They are operating to supply the heat demand (DEM) of the connected houses.

2. Methodology

The techno-economic analysis performed in this paper is illustrated in Fig. 1. It starts with the development of a TRNSYS model of DLSC, which is then validated against monitoring results available in the literature. Once the model is validated, location-related input data are modified to represent the selected UK locations. These include weather data, soil properties, and synthetic heat demand input. The simulation results are then used to calculate the techno-economic performance metrics. Performance metrics of the system are then compared further with benchmark values available in the literature.

A parametric study is conducted to investigate the influence of different design parameters on the techno-economic performance of the system. In addition to technical parameters, the influence of financial parameters, such as discount rate and subsidies, are also analysed. Currently available policy-based subsidies for renewable heat in the UK are considered, as well as the required tariff to improve the financial competitiveness of the system.

2.1. Case study: Drake Landing Solar Community

A high-level schematic of the DLSC system showing the main components is given in Fig. 2. Briefly, the system consists of solar collectors (SCO), long-term thermal energy storage (LTS), and demand (DEM), which are connected through the short-term thermal energy storage (STS). The solar collectors are flat-plate glazed collectors with a total area of 2293 m^2. Two horizontal hot water tanks with a combined capacity of 240 m^3 act as the STS, which can be charged by energy from the solar collectors and the long-term storage. The LTS is a borehole thermal energy storage which consists of 144 boreholes of 35 m depth. The system supplies the space heating demand of 52 energy efficient homes which employ water-to-air heat exchanger unit to transfer the thermal energy from the district loop into the house [27].

Metrics relevant to the techno-economic analysis are also shown in Fig. 2. Variable $\dot{Q}_t^{SCO}$ represents the rate of solar energy collected by the collector, while $\dot{Q}_{ch,t}^{LTS}$ and $\dot{Q}_{dch,t}^{LTS}$ correspond to the charge and discharge rate of the long-term storage, respectively. The solar energy transferred to the district comes from the buffered energy in the short-term storage. This buffered energy is a combination of direct solar energy from the collector and the stored solar energy from the long-term storage. The rate of solar energy that goes to the district is represented by $\dot{Q}_t^{STS-HX2}$. Finally, the rate of energy to satisfy the heat demand is a combination of solar and boiler power, $\dot{Q}_t^{STS-HX2}+\dot{Q}_t^{BOI}$.

In this study, the total energy flows are integrated over a yearly period. This approach was considered due to data availability of the important measured metrics, which are publicly available in monthly aggregates form [27]. A more detailed description of DLSC can be found in Ref. [13, 27].

2.2. Performance indicators

2.2.1. Thermodynamic performance

In the analysis, the thermodynamic performance of the solar district heating is described by its solar fraction, system efficiency and long-term storage efficiency. Solar fraction (SF) indicates the proportion of total energy supply that comes from solar thermal energy (Eq. 1). The system efficiency (η_{sys}) illustrates the performance of the system on utilising the collected solar energy (Eq. 2). It also represents the effectiveness of the solar energy collection and storage control in the system. The efficiency of long-term storage (η_{LTS}, Eq. 3) is included in the analysis because the component represents a significant investment cost; thus, its operational performance needs to be monitored and, if required, improved accordingly.

$$SF = \frac{Solar\ Energy\ to\ District}{Total\ Energy\ to\ District} = \frac{\sum_{t=1}^{8760} \dot{Q}_t^{STS-HX2}}{\sum_{t=1}^{8760} \left(\dot{Q}_t^{STS-HX2} + \dot{Q}_t^{BOI}\right)} \tag{1}$$

$$\eta_{sys} = \frac{Solar\ Energy\ to\ District}{Solar\ Energy\ Collected} = \frac{\sum_{t=1}^{8760} \dot{Q}_t^{STS-HX2}}{\sum_{t=1}^{8760} \dot{Q}_t^{SCO}} \quad (2)$$

$$\eta_{LTS} = \frac{LTS\ total\ energy\ discharged}{LTS\ total\ energy\ charged} = \frac{\sum_{t=1}^{8760} \dot{Q}_{dch,t}^{LTS}}{\sum_{t=1}^{8760} \dot{Q}_{ch,t}^{LTS}} \quad (3)$$

2.2.2. Economic performance

In order to evaluate the economic performance of the systems, the following metrics are used in the analysis: Levelised Cost of Energy (LCOE), and Levelised Cost of Solar Thermal Energy ($LCOE_{ST}$). LCOE and $LCOE_{ST}$ are calculated according to Eq. 4 and 5, respectively. Both metrics use the total cost metric as their numerator, while the denominator is the "present value" of total energy for LCOE, and total solar energy for $LCOE_{ST}$. For all economic metrics calculation, unless stated otherwise, the lifetime of the system is 25 years, while the discount rate is 3%. These values, along with the definition of $LCOE_{ST}$, were based on the report of Task 52 Solar Heat and Energy Economics in Urban Environments, IEA SHC Programme [28].

$$LCOE = \frac{C_{inv} + \sum_{t=1}^{N} \frac{C_{opr,t} - R}{(1+r)^t}}{\sum_{t=1}^{N} \frac{Q^{STS-HX2} + Q^{BOI}}{(1+r)^t}} \quad (4)$$

$$LCOE_{ST} = \frac{C_{inv} + \sum_{t=1}^{N} \frac{C_{opr,t} - R}{(1+r)^t}}{\sum_{t=1}^{N} \frac{Q^{STS-HX2}}{(1+r)^t}} \quad (5)$$

The investment cost functions of the main equipment in the considered solar district heating system are shown in Table 1. Equations in Table 1 were taken from the referred studies which are mainly based on experience in European countries. These are deemed to be representative for a case in the UK since most of the equations already consider various climates ranging from Scandinavian to Mediterranean countries. The operational cost consists of a fixed and variable operation and maintenance (O&M) cost. The fixed O&M cost is assumed to be 0.75% of the total investment cost per year [28], while the variable cost is the total electricity and natural gas cost over the year. The pumps are responsible for the electricity consumption, while the back-up boilers utilise the natural gas. The costs of energy inputs to the solar district heating system are given in Table 2.

3. TRNSYS model of Drake Landing Solar Community

The developed TRNSYS model of DLSC is depicted in Fig. 3. It consists of four main loops: solar, STS, LTS, and district loop. The solar loop circulates the collectors' working fluid, which transfers the collected solar energy to the STS through a heat exchanger (HX1). The STS acts as a hub of the entire system by connecting the solar, LTS, and district loop. The LTS loop models the charge/discharge of the long-term storage through the borehole storage itself, underground distribution pipe, a pump, a mixing valve and a diverter. Solar energy from the solar and LTS loop is then transferred to the district loop through another heat exchanger (HX2). When the solar energy is not sufficient to raise the flow temperature to the set-point temperature, the back-up boiler is switched on to supply the missing energy.

An overview of equipment modelling, control, and input data are given in the following paragraphs, while more detailed descriptions can be found in Ref. [33].

3.1. Equipment modelling

The solar collector array is modelled by Type 1a, a flat-plate solar collector model with quadratic efficiency curve and no Incidence Angle Modification. The array is facing southward and inclined at 45°. Its efficiency curve is defined by the performance characteristic given in Eq. 6 [13].

$$\eta_{sco} = 0.693 - 3.835\frac{(T_{in} - T_{ext})}{G} \quad (6)$$

where η_{sco} is the collector efficiency, T_{in} [°C] is the collector inlet temperature, T_{ext} [°C] is the external air temperature, and G [W/m^2] is the total incident solar irradiance.

The short-term storage is modelled with two Type 534 cylindrical storage tanks, along with the connections to other loops. The horizontal storage tanks are modelled with three stratification nodes per tank. The hot STS tank is discharged to charge the LTS and to satisfy the heat demand from the district loop; while it is charged by the solar collector loop and LTS discharge.

The long-term storage is modelled by a Type 557, Vertical U-Tube Ground Heat Exchanger, which was developed based on the duct storage model (DST) [34]. It allows the combined series-parallel configuration of the boreholes, which is the case in DLSC storage with 24 parallel headers and six boreholes per header. The LTS can only be charged or discharged at any given time. This behaviour is modelled by using a mixer, diverter, and a controller.

In the district loop, heat demand is represented by a load flow type, Type 682, which imposes a specified load on a flow stream and calculates the outlet fluid temperature. The specified load is a synthetic heat demand methodology [35, 36].

In addition to the main equipment, two heat exchangers and five pumps are also included in the model. The

Table 1: Investment costs for the solar district heating main equipment. €1 = £0.91.

Type	Costs function	Unit	Reference
Solar collectors	$200 \cdot A_{SCO} + (100 \cdot A_{SCO} - 666.7) + 2 \cdot (40 \cdot A_{SCO} - 10000)$	€	[29]
STS	$403.5 \cdot V_{STS}^{-0.4676} + 250$	€/m^3	[28]
LTS	$20.57 \cdot V_{LTS} - 201841$	€/m^3	[29]
District piping	$L_{pipe} \cdot 345$	€	[30]
Boiler	$24.83 \cdot \dot{Q}_{max} + 31859$	€	[31]

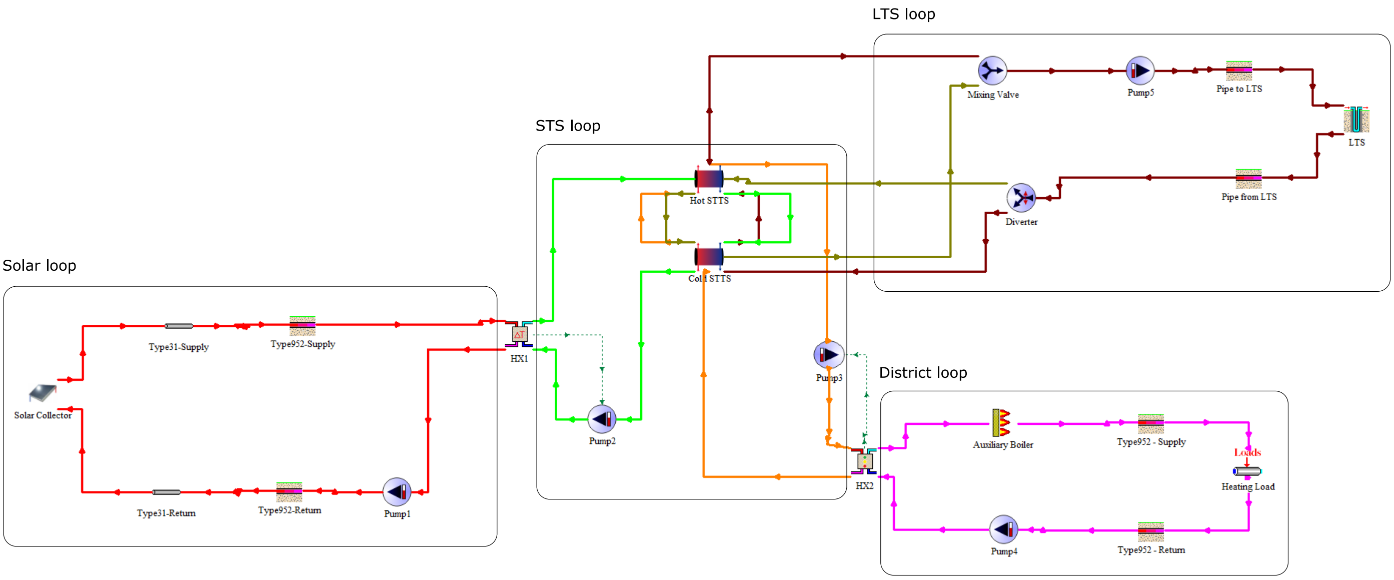


Figure 3: Overview of the developed TRNSYS model of DLSC. The four main loops are shown: solar loop (red), STS loop (light green & orange), LTS loop (brown & olive green), and district loop (magenta).

Table 2: Energy input and maintenance cost of the solar district heating.

Type	Costs	Unit	Reference
Natural gas	0.0379	£/kWh	[32]
Electricity	0.1454	£/kWh	[32]
Maintenance	0.75% $\cdot C^{inv}$	£/year	[28]

first heat exchanger (HX1) connects the solar loop with the STS and is modelled with Type 761, Heat Exchanger with Cold-Side Modulation to Maintain Temperature Difference. The second heat exchanger (HX2) connects the STS with the district loop and is modelled with Type 512, Heat Exchanger with Hot-Side Modulation to Keep Cold-Side Outlet Above its Setpoint. All the pumps in the model are modelled with Type 110, Variable Speed Pump. The heat exchangers and pumps are controlled according to control rules described in the next paragraphs.

3.2. Control assumptions

The key control assumption in DLSC is in the charging/discharging of the LTS. The LTS has lower charge/discharge rates relative to the STS. Thus, its operation needs to be planned well in advance to ensure sufficient energy is available in the STS, minimising the need to operate the back-up boilers. In the original control, it was based on the prescribed value of the required state-of-charge for STS which depends on the time of day and supply set-point temperature [37]. In the field, the control mechanisms have been modified along the operation of DLSC. Along with the non-public nature of the original control assumptions, these make control implementation in the TRNSYS model less straightforward than, for example, sizing the equipment. In this study, the control mechanisms described by Yang et al. [38] were implemented in the developed TRNSYS model.

3.3. Weather data and heat demand

The weather data from Calgary Airport weather station were used in developing the validated model [39], while the solar irradiance data at the DLSC location are

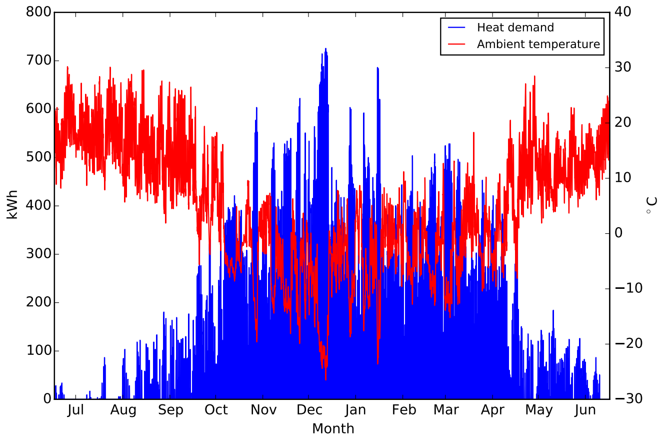


Figure 4: Example of annual demand profile of the DLSC.

gathered from satellite-based measurement [40]. In both cases, the data from July 2007 up to June 2013 were considered as one of the inputs to the simulation and the heat demand model.

The heat demand profile was derived using the method described in Ref. [35, 36]. The annual demand values were calculated by subtracting the district loop loss from the total energy delivered to the loop [13]. The annual values were then distributed into hourly values according to a linear relationship between demand and ambient temperature once the latter decreases below the threshold temperature [35]. An example of the resulting annual hourly profile is given in Fig. 4. A more detailed description on the generation of the synthetic heating demand profile can be found in Ref. [33].

4. Model validation

Representative energy flows and the solar fraction from the developed TRNSYS model are compared with the original simulation results and the measurement data, as illustrated in Fig. 5. The values of annual measurement data from 2007 to 2013 are given in Ref. [33]. It should be noted that the original simulation model was performed with January-December annual time horizon, while the measurement and the developed TRNSYS model in this study were performed with July-June horizon. This is because the DLSC system began operation in late June 2007 and its performance has been monitored since then [13]. Furthermore, the original simulation was developed to illustrate the performance of the system in the first five years; thus the missing values in the sixth year. In the following paragraphs, the term "TRNSYS model" corresponds to the TRNSYS model of DLSC developed in this study.

In general, the TRNSYS model is capable of reproducing the trend and magnitude of the measured energy flows. Prominent discrepancies in several points can be explained by examining the inputs used in developing the TRNSYS model and the operational improvements made in the field.

The differences between the measurement and TRNSYS model in annual solar energy collected range between 1% - 10%. This can be attributed to the solar irradiance data used in the simulation. The data were satellite-based data instead of ground-measured solar irradiance. Moreover, the surface tilt reported in the satellite-based data was based on the latitude (50°). In reality, the solar collectors are installed at an inclination angle of 45°. Satellite-based data were used in the simulation because of the unavailability of ground measured solar irradiance data for the location and years of interest in the public domain. The ground solar data collection from the closest weather station was stopped in 2005 [26], while the satellite-based data are available from Ref. [40]. Furthermore, it has been reported that the variability between ground- and satellite-based data is noticeably lower for the case of the Global Tilted Irradiance (GTI), which is the one used in this study, in comparison with the Direct Normal Irradiance (DNI) [41]. Despite these constraints, the predicted solar energy collected from the developed TRNSYS model is closer to the measured values in comparison with the original DLSC simulation.

For the LTS performance, the TRNSYS model has lower annual charged energy and higher/equal discharged energy than the measurement. Thus, the LTS has higher efficiency in the TRNSYS model than in reality. These discrepancies can be explained by considering that the charge/discharge control of the LTS has been modified during the first five years of operation [13]. The control algorithm implemented in the TRNSYS model is taken from the latest publication from NRCAN CanmetEnergy [38]; thus, it can be assumed to be the latest charge/discharge control of the LTS.

Similarly, the changes in operational control can contribute to the differing values of Solar Fraction. In the early years, the TRNSYS model has significantly higher solar fraction than the measurement, while this trend diminishes from Year 4 onwards. In addition to LTS operational control, adjustments were also made to the set-point temperature in the district loop. These can also contribute to the deviation from the measurement data since higher set-point in the early years means that the boilers are operating more frequently, lowering the solar fraction. Overall, the performance metrics predicted by the TRNSYS model are closer to the measured values in later years due to the control adjustments in the field.

With these factors considered, it is argued that the developed TRNSYS model is sufficiently accurate to investigate the techno-economic performance of a similar system if it is installed in the UK or elsewhere.

5. Simulation of the DLSC in UK locations

The two UK locations selected for the study are Aberdeen, Scotland, and Camborne, England. They repre-

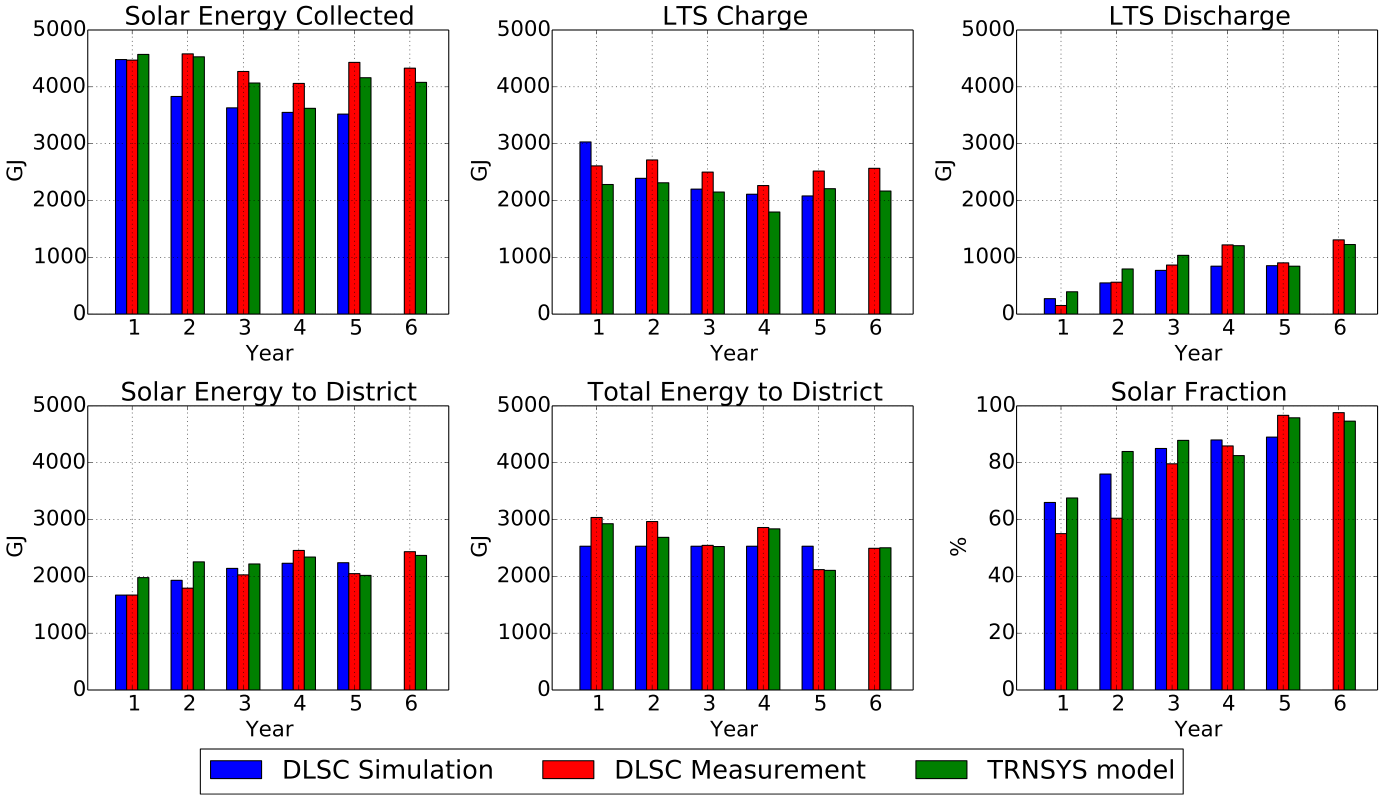


Figure 5: Representative DLSC energy flows and solar fraction in the first six years from the original simulation, measurement, and the developed TRNSYS model.

sent two regions with different supply-demand characteristics: lower solar resource and higher heat demand in Scotland, and higher solar resource and lower heat demand in the South of England.

5.1. *Location specific inputs*

Weather data for these locations were taken from Meteonorm data which are available in TRNSYS. They are typical meteorological year data which were generated using Meteonorm software [42]. Therefore, the yearly data were repeated during the multi-year simulations.

The synthetic heat demand profiles were derived by using the methodology described in Ref. [35, 36]. In generating the synthetic heat demand profiles, the number of houses was increased to 52 from a single dwelling model. This is the same number of houses as in the original DLSC system. For the Aberdeen case, the annual space heating demand of approximately 12000 kWh/y was used in generating the heat demand profile. For the Camborne case, an annual space heating demand value of 8200 kWh/y was considered for a single house. The value was based on an approximation of a typical UK dwelling located in Plymouth, which has similar heating degree days as Camborne [43].

The influence of occupancy profile on the annual energy flows was found to be minimal. This is illustrated in the validation step (Fig. 5) where the developed TRNSYS model with one assumed occupancy profile is able to closely follow the measured values in most cases. Furthermore, since the profiles were based on annual weather data, their implementation in TRNSYS simulations was also repeated accordingly.

In the district heating system, soil thermal properties are relevant not only for calculating losses in underground pipes but also in modelling the borehole thermal energy storage. The soil properties of the two locations are taken from Ref. [44, 45] and shown in Table 3.

5.2. *Technical performance*

The summary of simulation results of the DLSC system in UK locations is shown in Fig. 6 and 7. Overall, the energy flows for UK locations are lower than the original DLSC system. This is due to the lower solar irradiance and lower heat demand in the UK locations. The annual average Global Horizontal Irradiance values are approximately 900, 1100, and 1400 kWh/m^2 for Aberdeen, Camborne, and Okotoks, respectively [46]. The annual district heating demand values are approximately 2200, 1500, and 2500 GJ/y for Aberdeen, Camborne, and Okotoks, respectively.

In the Solar Energy Collected graph in Fig. 6, there is a downward trend in the collected solar energy in the first three years for both locations, despite the same solar irradiance data for every year. This is because the simulations started with empty storage, both STS and LTS. Therefore,

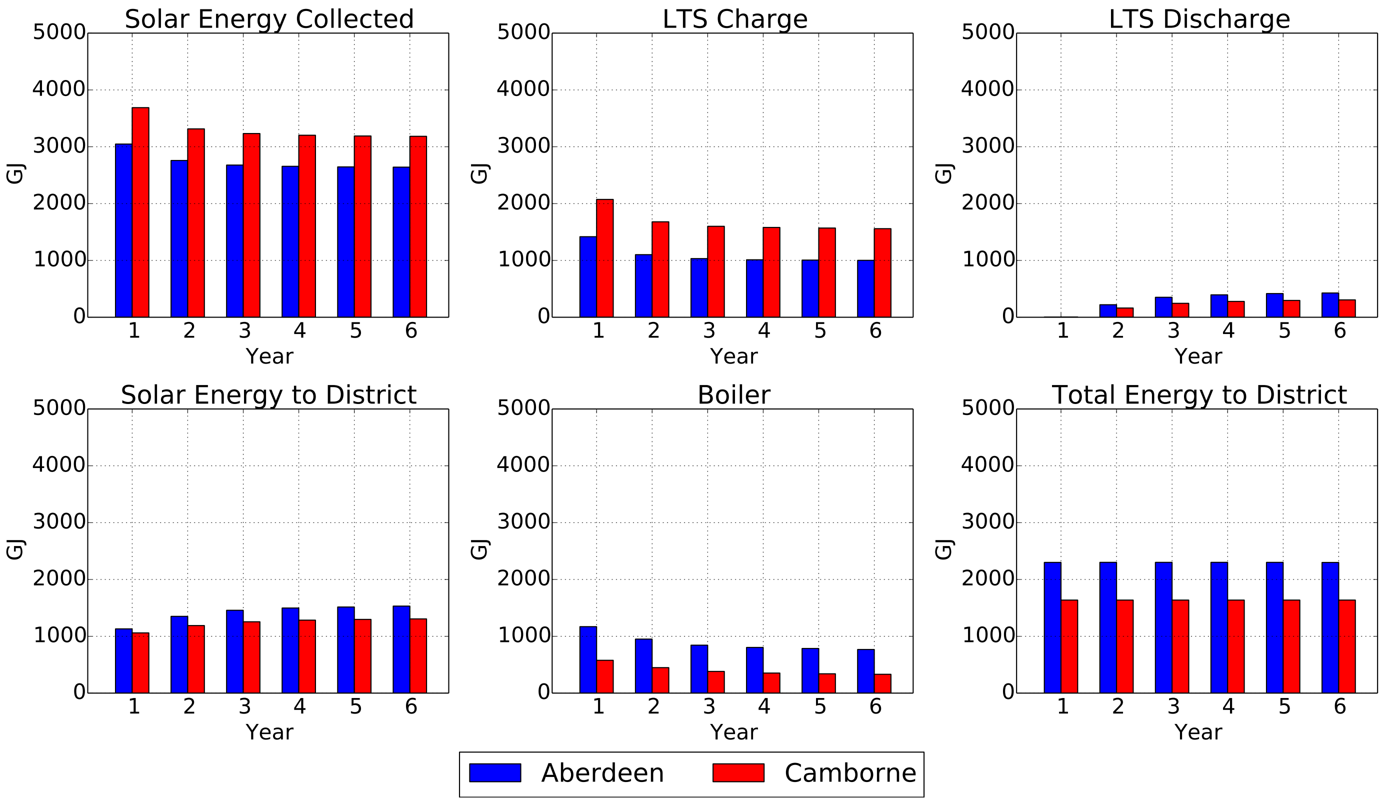


Figure 6: Energy flows of DLSC system in Aberdeen and Camborne, UK.

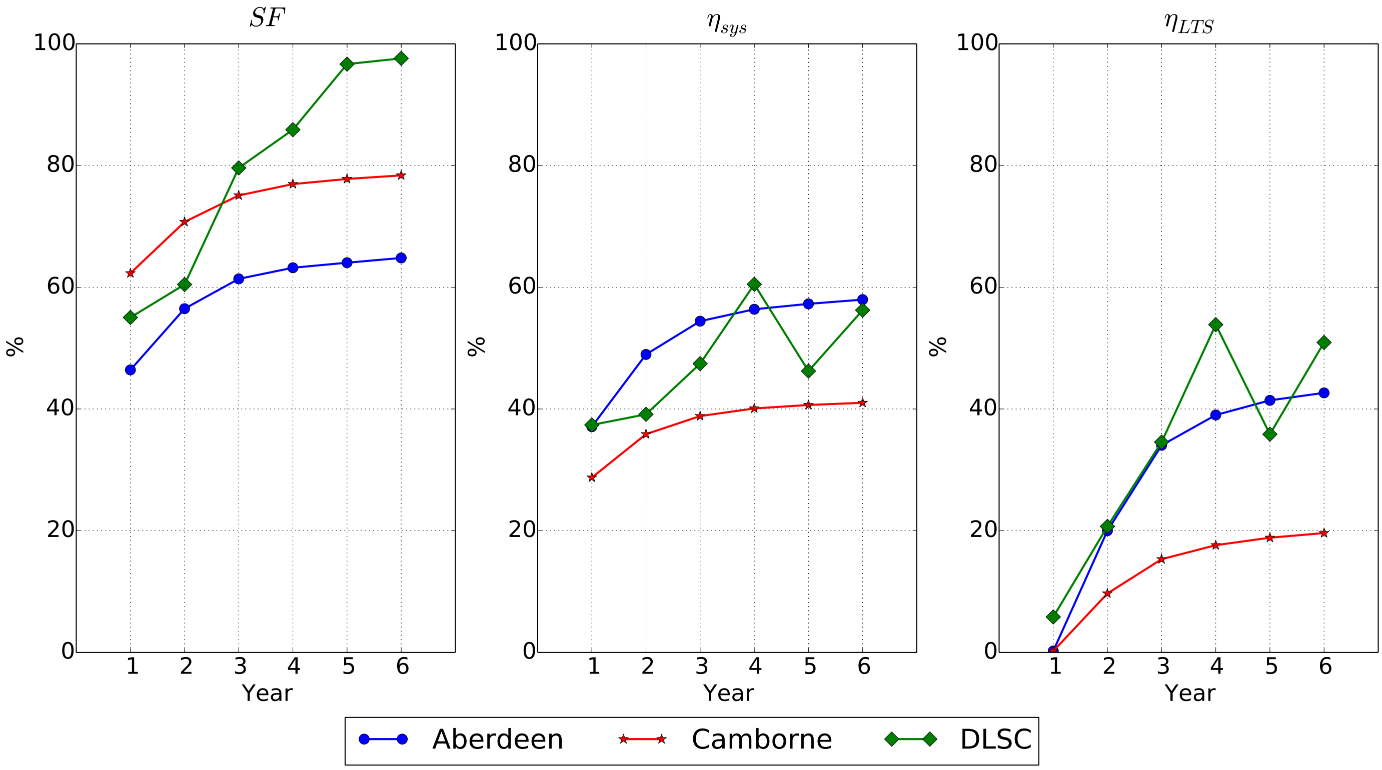


Figure 7: Technical performance metrics for the two UK locations and the original DLSC: Solar Fraction (SF), System Efficiency (η_{sys}), and Long Term Storage Efficiency (η_{LTS}).

Table 3: Summary of the considered parameters of the two UK locations.

Properties	Unit	Aberdeen	Camborne
Global Horizontal Irradiance (Annual average)	kWh/m^2	900	1100
Heating Degree Days	degree-day	2417	1552
Annual space heating demand	kWh/year	12000	8200
Number of houses	-	52	52
Soil properties			
Thermal conductivity	W/mK	1.07	3.76
Specific heat capacity	J/kgK	1014	1169
Density	kg/m^3	1520	1380
Ground temperature	°C	9.3	12.1
Thermal diffusivity	x10^{-6} m^2/s	0.6938	2.3343

more solar energy was collected in the first years to heat up the storage, particularly the LTS which has a large capacity and low charge rate. The collected solar energy started to stabilise beyond the third year as the return temperature from the STS to the solar collectors increases due to the increasing state-of-charge of the LTS relative to the earlier years.

It can also be observed in Fig. 6 that due to its lower latitude, the system in Camborne has more incident solar irradiance, and solar energy collected than Aberdeen. This is also reflected in the amount of energy charged into the LTS. The overall lower trend of Total Energy to District in Camborne is because of its lower heat demand relative to the colder Aberdeen. Due to its higher solar irradiance and lower heat demand, the SF in Camborne is always higher than Aberdeen (Fig. 7). In both cases, the SF curve has a sharp increase in the early years, and it starts to level off after approximately five years due to the borehole storage reaching its operational temperature. The SF curve of the original DLSC is less smooth than the SF curve of Aberdeen and Camborne case. The curves of the original DLSC shown in Fig. 7 are based on the measurement data. Thus, the weather profile and heat demand are not the same for every year. Furthermore, various improvements have been made during the operation of DLSC. These factors contribute to the resulting non-monotonous profiles for the measured metrics.

It should be noted that the LTS was at the original ground temperature at the beginning of simulations, i.e. no pre-heating was prescribed. This is different than in historical operation of DLSC where the LTS was pre-heated up to 25 °C. The effect of pre-heating can be seen in the LTS efficiency curve in Fig. 7, where the original DLSC has a higher efficiency in the first year relative to the other two cases.

It is interesting to note that although the LTS in Camborne is charged more than Aberdeen, it is always discharged less (Fig. 6). This leads to lower LTS efficiency (η_{LTS}) for Camborne (Fig. 7). The lower efficiency can be attributed to the higher thermal diffusivity of the ground in Camborne (see Table 3) which means higher LTS losses to the surrounding ground. Because of this, the system in Camborne has lower efficiency (η_{sys}) than Aberdeen, despite its higher solar fraction.

The system efficiency (η_{sys}) of the Aberdeen case is higher than the original DLSC for most of the time in the first six years of operation. This illustrates that with the latest control rules, a DLSC-like system installed in Aberdeen can have favourable performance in managing the collected solar energy, despite its lower solar fraction.

5.3. Economic analysis

Table 4 summarises the relevant costs and LCOE of the system at the two UK locations. The investment costs for both of them are the same, while the variable operational costs depend on the TRNSYS simulation results, e.g. the gas costs decrease with the increasing solar fraction.

The slightly higher electricity cost in Camborne can be attributed to the higher availability of solar irradiance and more active charging and discharging operation of the LTS. These lead to higher electricity demand from the pumps. Furthermore, the significantly higher gas cost in Aberdeen is due to the lower solar fraction in this case. The gas cost for both cases decreases from the shown upper values to the lower values as the solar fraction of the system increases along the simulated years.

Aberdeen has lower LCOE and LCOE_{ST} than Camborne, despite the latter having better solar resource. This can be related to two aspects: lower heat demand and higher LTS loss in Camborne. The lower heat demand means that the system is highly likely to be oversized, which leads to higher than necessary investment cost. The higher loss means that there are wasteful operational costs in storing the solar energy in the LTS.

5.4. Comparison with similar systems

In order to evaluate the relative techno-economic performance of the system, a comparison with benchmark values has been made and summarised in Table 5. The benchmark values are based on roof-mounted solar thermal systems connected to block heating grids in Central European climate [28].

Table 4: LCOE calculations for UK locations. €1 = £0.91

	Unit	Aberdeen	Camborne
Investment cost			
Solar collector	£	783,449	783,449
STS	£	63,993	63,993
LTS	£	447,052	447,052
Boiler	£	40,289	40,289
Distribution	£	627,900	627,900
Operational cost			
Maintenance (Fixed)	£/year	18,235	18,235
Electricity	£/year	5444	5639
Gas	£/year	8980 - 13676	3875 - 6754
Financial parameters			
Discount rate	%	3	3
Technical lifetime	year	25	25
Economic metrics			
LCOE	£/kWh	0.22	0.30
$LCOE_{ST}$	£/kWh_{solar}	0.34	0.39

Table 5: Comparison of techno-economic metrics between the benchmark case and DLSC-Aberdeen. The benchmark case values are taken from Ref. [28], with an assumed currency exchange value of €1 = £0.91.

	Solar block heating	DLSC-Aberdeen
Technical metrics		
Typical size per unit (m^2-gross)	5000	2320
- range	(1000 - 10000)	
Typical storage volume per unit (m^3 water-equivalent)	12000	15800
Typical annual production per unit (MWh/a)	1500	638
Typical solar energy yield (kWh/m^2/a)	300	183
- range	(260 - 340)	
Typical solar fraction	50%	46-65 %
- range	(40-75%)	
Technical life time (years)	25	25
Economic metrics		
Specific investment cost, material only (£/m^2)	490	845
- range	(365-610)	
Fixed O&M per unit (£/m^2/a)	3.6	6.6
Variable O&M per unit (£/m^2/a)	1	6.5-8.5
$LCOE_{ST}$(£/kWh_{solar})	0.12	0.34
- range	(0.09 - 0.15)	

It is clear that the installation of a DLSC-like system in Aberdeen will result in a more expensive system, albeit with a better solar fraction, compared to typical systems in continental Europe. This can be attributed to several reasons. For example, Aberdeen has lower solar resource than locations in Central Europe. This significantly influences the solar energy yield and, therefore, the $LCOE_{ST}$. Another reason is related to the design of the system. The original DLSC was designed with technical performance in mind, i.e. achieving solar fraction beyond 95%. Thus, the equipment tends to be oversized in order to achieve the target solar fraction, which leads to a more expensive system. Finally, from the heat demand viewpoint, it should be noted that the DLSC and the reported solar block heating systems in Ref. [28] are designed to supply new and renovated low-energy neighbourhoods. On the other hand, the heat demand for the DLSC-Aberdeen is derived from the typical heat demand of a semi-detached dwelling in Scotland, which is mostly part of older, less energy-efficient building stock.

From the analysis in this section, it is apparent that several key design parameters could have a significant influence on the techno-economic performance of the system. For instance, the size of relatively expensive equipment (i.e. solar collectors and LTS) and the soil type may have a larger influence on the LCOE values than other parameters. As stated earlier, the heat demand may play a role in determining the feasibility of a solar district heating system. In the following paragraphs, this hypothesis is explored further by performing a parametric study using the validated TRNSYS model.

6. Parametric study

The Aberdeen case is investigated further by examining the influence of different parameters on the techno-economic performance. Four parameter categories are considered in the study, namely equipment size, heat demand, soil properties, and financial parameters. All figures in this section are based on the Aberdeen case study. It should be noted that only one parameter is changed for one evaluation, while maintaining fixed values as per original system description for other parameters.

6.1. Equipment sizing

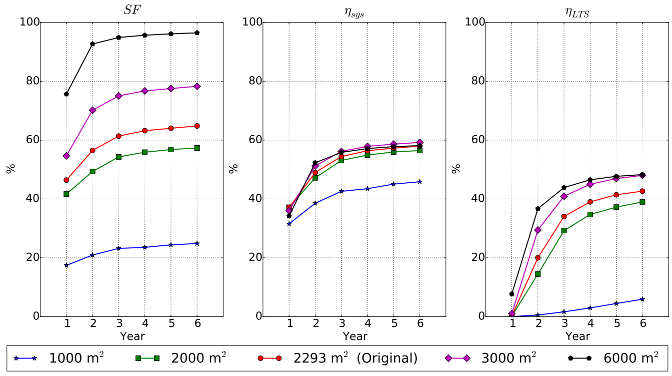
Main equipment types included in the parametric study are the solar collector and long-term storage. The size of the short-term storage was found to be less influential toward the metrics; thus, it is not reported in this paper. Interested readers are referred to Ref. [33] for more detailed results.

6.1.1. Solar collector

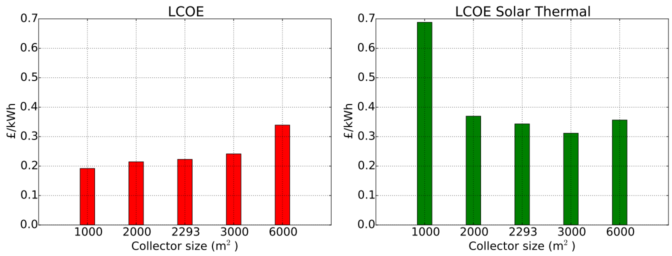
The influence of collector area on the techno-economic metrics is illustrated in Fig. 8(a) and 8(b), for the efficiencies and LCOEs, respectively. The collector area was varied from 1000 to 6000 m^2, with the original value included in both figures.

In all cases, the trend in the technical performance metrics is similar to the original: a rapid increase in the first three years before starting to taper off. A slight exception can be observed in the case of 1000 m^2 collector area. Among the tested collector areas, the 1000 m^2 case has the worst performance in all metrics. This can be seen as a case of under-sizing of the solar collector, which results in lower solar fraction and efficiencies, as well as higher $LCOE_{ST}$.

As expected, systems with larger collector area have higher solar fraction, with SF close to 97% for the system with 6000 m^2 collector area. Nevertheless, the influence of collector size on system and LTS efficiency appears to be minimal. The system efficiency is relatively constant as the collector size increases, while although there is an increase in LTS efficiency, it is not as large as in the solar



(a) Technical performance metrics.



(b) LCOE values.

Figure 8: Parametric evaluation for various solar collector sizes.

fraction. The increase in LTS efficiency in the early years for the case of 6000 m^2 can be attributed to the faster warming up due to the large collector area.

From a financial perspective, an increase in collector area is followed by the LCOE value, while the $LCOE_{ST}$ has a minimum value between 3000 and 6000 m^2 beyond which the $LCOE_{ST}$ starts to increase. This can be explained by the fast growth in solar energy to the district as the collector size increases. In the case of 1000 m^2, the solar energy to the district is too low, and the $LCOE_{ST}$ becomes relatively high. At some point, the produced solar energy cannot justify the investment cost that comes with larger collector area, as illustrated with the 'extreme' case of 6000 m^2. Furthermore, the trend in LCOE shows that the thermal energy from the solar collectors is more expensive than from the gas boilers.

6.1.2. Long-term storage

The modification of the LTS volume in the TRNSYS simulation is performed by changing the borehole number or the borehole depth. The borehole number considered was 90, 180, and 300, while its depth was changed to 15, 70, and 100 m. Both the energy storage capacity and power are directly affected by the change in LTS volume.

The influence of borehole number on the techno-economic metrics is shown in Fig. 9(a) and 9(b). It is clear that the increase in borehole number has a positive correlation with all metrics, both technical and financial. The increase in solar fraction and efficiency metrics can be explained by considering that a larger borehole storage with more boreholes in the central area will have improved performance due to reduced losses and better thermal stratification.

In the case of increasing borehole depth, it appears that the overall trend is not as obvious as in the borehole number, as can be seen in Fig. 10(a) and 10(b). The system with the shallowest borehole, i.e. 15 m, suffers from insufficient storage capacity and larger losses to the surrounding due to an unfavourable shape factor. These contribute to the relatively low values of solar fraction and efficiencies, as well as a slightly higher LCOE solar thermal compared to the original. Furthermore, as the depth increases beyond 35 m, the technical performance and LCOE solar thermal are also growing. It is interesting to note that the solar fraction and system efficiency are relatively constant in the case of 70 and 100 m depth, while the LCOE values are increasing. Thus, it can be concluded that there is an optimal value of borehole depth beyond which the performance does not improve further, or even deteriorate due to larger surface to volume ratio. This is in-line with the analytical result showing that the optimal form factor, i.e. ratio between diameter and depth, for minimal heat losses is equal to 2 [47].

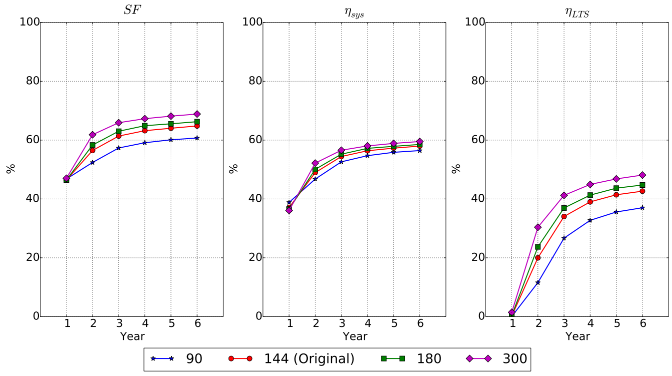
From the comparison between the results of increasing borehole number and depth, it can be concluded that the best way to improve the techno-economic performance through LTS modification is by increasing the borehole number rather than its depth. Indeed, this is also the most practical way to expand a borehole storage installation.

Another option in LTS modification is to remove it altogether from the simulation, thus modelling a system which has only a short-term storage. This was performed by excluding the borehole storage and its corresponding connections in the TRNSYS model. The resulting technical performance metrics given in Fig. 11(a) show a significant reduction in solar fraction, while the LCOE calculations produced values of £0.179/kWh and £0.342/kWh for LCOE and $\mathrm{LCOE_{ST}}$, respectively. These values are similar to the original system (Fig. 11(b)); thus, LTS can increase the solar fraction of the system without significantly degrading the economic metrics.

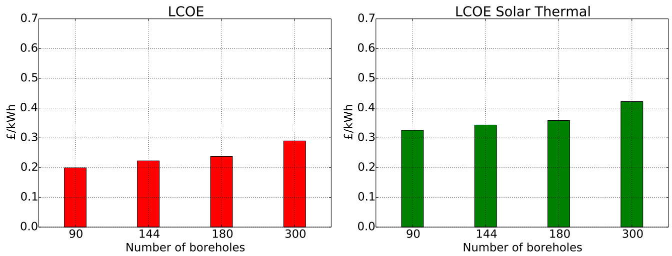
6.2. Heat demand

The original DLSC system in Canada supplies space heating demand to 52 houses with Natural Resources Canada's R-2000 Standard energy efficiency certification. The average annual space heating energy consumption per house is approximately 115 kWh/m^2/year. This was calculated with the average total energy delivered to the district loop of 3000 GJ/year, and floor area of 140 m^2.

In the case of UK locations, assuming a floor area of 96 m^2,which corresponds to the average floor area for the whole building stock in England [48], the space heating consumption is approximately 120 and 85 kWh/m^2/year for Aberdeen and Camborne, respectively. These values correspond to the available building stock, which is mostly older buildings with relatively poor energy performance. For instance, a design calculation for a new built which complies with 2010 Scottish Building Standard (SBS) produces the value of 33.7 kWh/m^2/year for the annual space heating [49].

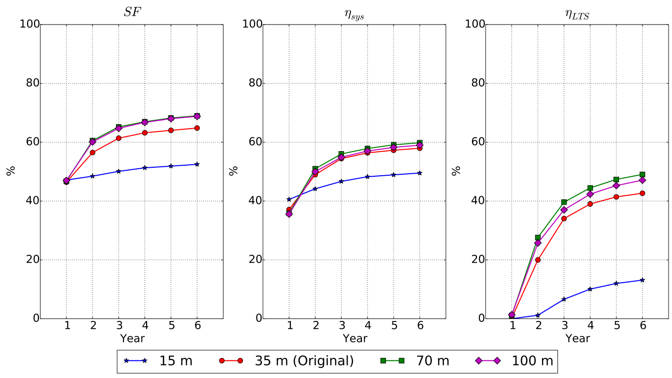


(a) Technical performance metrics.

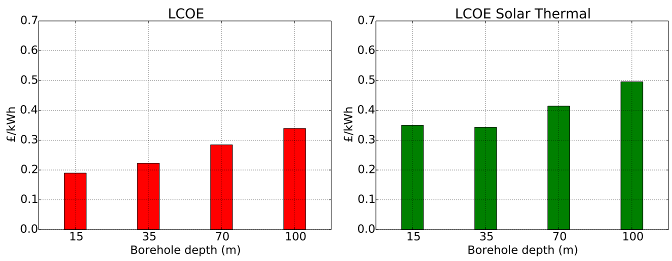


(b) LCOE values.

Figure 9: Parametric evaluation for various number of LTS boreholes.

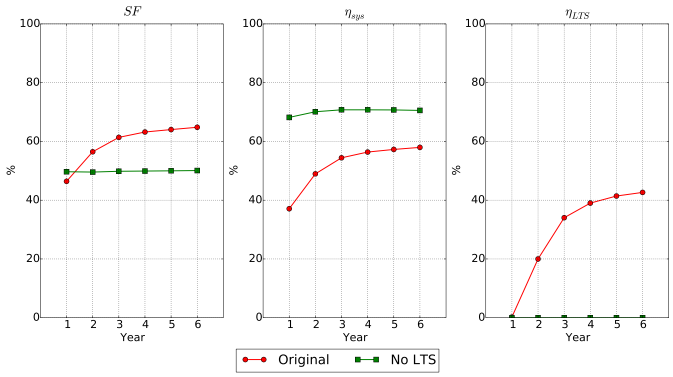


(a) Technical performance metrics.

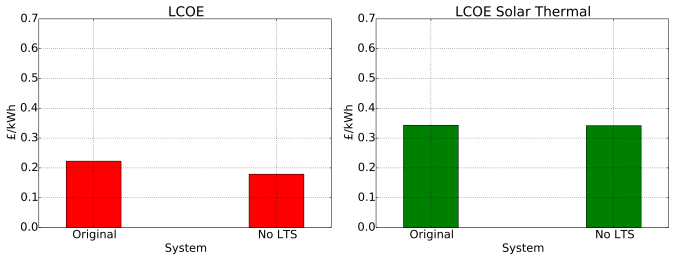


(b) LCOE values.

Figure 10: Parametric evaluation for various depth of LTS boreholes.

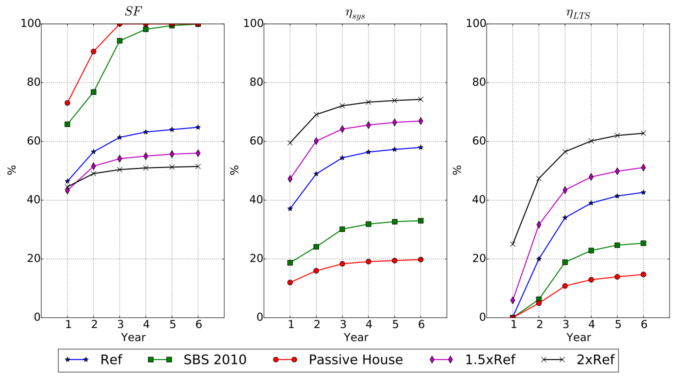


(a) Technical performance metrics.

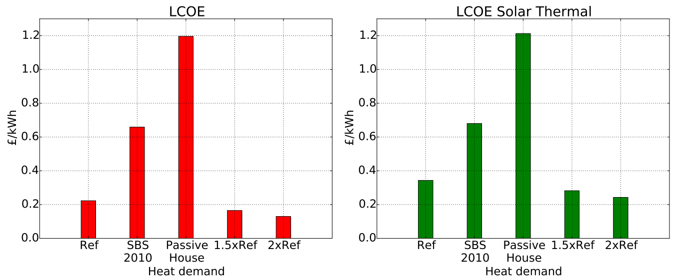


(b) LCOE values.

Figure 11: Parametric evaluation for LTS availability.



(a) Technical performance metrics.



(b) LCOE values.

Figure 12: Parametric evaluation for different heat demand.

The influence of heat demand on the techno-economic performance of the system is investigated by modifying the heat demand input. Two annual space heating demand values are considered: 33.7 and 15 kWh/m^2/year, which corresponds to the SBS 2010 and Passive House specification, respectively. These were taken from the study of Bros-Williamson et al., which compared the energy performance of two Scottish homes built according to SBS 2010 and Passive House [49]. Furthermore, another two additional demand values were assessed, which correspond to a 50% (1.5×Ref) and 100% (2×Ref) increase from the original Aberdeen heat demand.

Figure 12(a) and 12(b) summarise the influence of heat demand on the performance of the system. Both SBS 2010 and Passive House case can reach 100% solar fraction, but this is mainly due to equipment oversizing. As can be seen from the system efficiency and LTS efficiency, the reference case performs better because it simply utilises a larger share of the collected solar energy.

In order to minimise the effect of oversizing, simulation runs with increased heat demand were performed. The results are shown in Fig. 12(a) and 12(b) with "1.5×Ref" and "2×Ref" legend. The increase of 50% and 100% in heat demand translates into approximately 280 and 375 of SBS 2010 houses, respectively. From a performance viewpoint, although the solar fraction is lower than the reference case, the values are still relatively high for a solar district heating system. The increase in heat demand also has positive correlation with the system and LTS efficiency. A further decrease in the LCOE values are also observed for the case with increased heat demand. This is expected since more energy is being utilised.

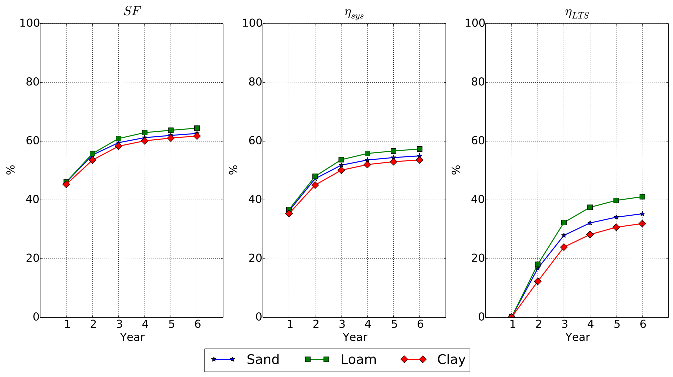
However, it should be noted that the increase in heat demand might entail modifications of the supply systems in order to ensure the district loop supply temperature is reached. Such modifications will have impact on the LCOE values, e.g. increase in total cost due to larger back-up gas boiler. This change in the DLSC supply system to accommodate increasing demand is outside the scope of this paper.

6.3. Soil properties

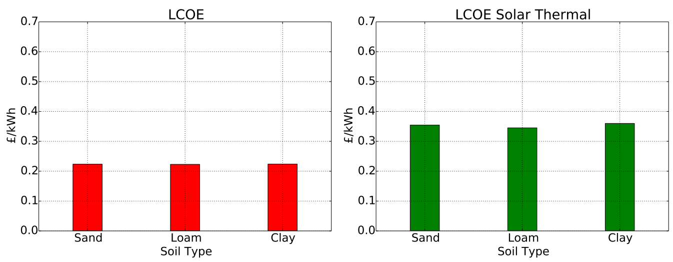
From the results of Camborne, it is clear that the soil properties can have a significant influence on the performance of the system. Three types of soil typically found in the UK are considered in this parametric study: sand, loam, and clay. The thermal properties of each type can be found in Table 6.

The influence of soil types on the techno-economic metrics is illustrated in Fig. 13(a) and 13(b). Despite having little influence on the LCOE values, the soil type can affect the technical performance of the system, particularly on the storage and system efficiency. Among the three soil types, loam has the best technical performance for the investigated system, with higher LTS efficiency than the other two soil types.

It should be noted that the thermal properties considered are median values. In the case of Camborne, the un-



(a) Technical performance metrics for systems with different soil type: Solar Fraction (SF), System Efficiency (η_{sys}), and Long Term Storage Efficiency (η_{LTS}).



(b) LCOE values for systems with different soil type.

Figure 13: Parametric evaluation for different soil type.

favourable properties are outliers within the Clay soil type. This illustrates the importance of using the thermal properties of the particular soil type where the system will be installed, rather than the median or average values. Furthermore, soil thermal properties are only highly relevant if borehole TES was used as the long-term storage technology. Their importance is foreseen to be lower when a pit or tank TES is implemented, for example.

Because of the outlier thermal properties used in the Camborne case, it is interesting to evaluate the system performance if more average thermal properties were used. In order to illustrate this case, a simulation run of the Camborne case but with the soil characteristics of the Aberdeen case was performed. The resulting performance metrics for the sixth year are as follows: solar fraction (90%), system efficiency (52%), and LTS efficiency (43%). However,

Table 6: Thermal properties of typical soil types in the UK. These are median values from the data in Ref. [45]

Properties	Unit	Sand	Loam	Clay
Thermal conductivity	W/mK	1.56	1.15	1.81
Specific heat capacity	kJ/kgK	1.014	1.267	1.398
Density	kg/m^3	1520	1280	1250
Thermal diffusivity	$x10^{-6}$ m^2/s	0.9961	0.7173	1.0295

the financial metrics are only slightly improving at 0.29 and 0.33 £/kWh for LCOE and $LCOE_{ST}$, respectively. The results illustrate that given a suitable soil condition for BTES, a relatively high technical performance can be achieved for a solar district heating system located in the southern UK.

6.4. Financial parameters

Currently, domestic RHI for solar thermal only applies to domestic hot water application and excludes space heating application. The annual payment is calculated based on the estimated annual generation on Microgeneration Certification Scheme (MCS) certificate. On the other hand, non-domestic RHI includes all applications of solar thermal systems and prescribes an upper capacity limit of 200 kW_{th}. The subsidy tariffs are 0.2006 and 0.1044 £/kWh of thermal energy for domestic and non-domestic RHI, respectively. Domestic RHI is tenable for seven years, while non-domestic RHI can be claimed for 20 years.

A system like DLSC is currently ineligible for both domestic and non-domestic RHI due to the space heating application and large thermal capacity. Nevertheless, it is interesting to see the influence of such subsidies on the LCOE values and whether a modified policy-based subsidy can be used to improve the financial attractiveness of the system.

The results of implementing both RHI schemes can be seen in Fig. 14. The solar energy generated was used to calculate the paid subsidy in this figure, as opposed to a fixed value based on certificates. Between the domestic and non-domestic RHI, the latter has slightly larger influence in reducing the LCOE values due to the significantly longer payment period.

It is interesting to identify the required non-domestic RHI tariff for solar thermal in order to make it more competitive with the incumbent technology. For instance, it has been reported that the range of LCOE values for biomass district heating in 2020 is in the range of £0.058-0.11/kWh, depending on the heat density of the location [50]. If the top end of this range is used as a reference, then the required non-domestic RHI tariff is approximately £0.2/kWh to achieve an LCOE value of £0.11/kWh.

The 'cost threshold' concept can also be used to evaluate the required support for a DLSC-like solar district heating system. It is the aggregate LCOE of the main counterfactual heating options at building level, e.g. gas boilers [50]. It is calculated using a 15 year timeline and takes into account the total costs and the cost of carbon emissions. A cost threshold of £0.079/kWh for the year 2020 is employed in Ref. [50]. Using this value as a reference, it requires £0.7/kWh of domestic RHI and £0.35/kWh of non-domestic RHI (15 years) to make a DLSC-like system to reach the cost threshold when it is installed in Aberdeen and supplies 52 houses with the reference heat demand.

Thus, it requires the implementation of a relatively high RHI tariff or a longer subsidised time horizon in or-

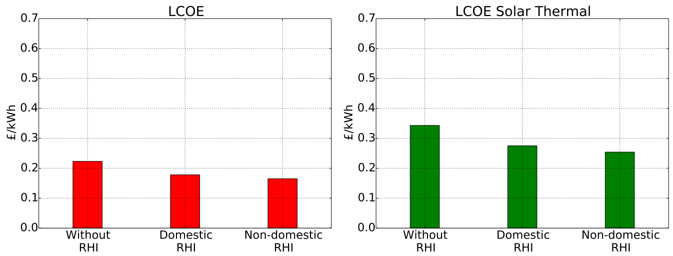


Figure 14: LCOE values for different subsidy types.

der to significantly improve the financial competitiveness of DLSC-like solar district heating systems if it is located in Scotland. It should also be noted that the payment calculation was based on measured energy production and without maximum capacity limit. Clearly, this needs to be re-evaluated from a policy perspective, but such treatment is outside the scope of this study.

7. Conclusions

The techno-economic performance of a solar district heating system installed in two UK locations has been quantified in this study. The case study was based on the Drake Landing Solar Community in Okotoks, Canada, which has a relatively high solar fraction. In supporting the techno-economic analysis, a TRNSYS model of DLSC was developed and validated using the publicly available annual monitoring data.

In general, a DLSC-like system installed in the UK will have a lower solar fraction and higher levelised cost of energy than the original system. Among the two studied locations, a system in Aberdeen has lower solar fraction than the one installed in Camborne. However, Aberdeen has better system efficiency and LCOE. The low system efficiency in Camborne can be attributed to the unfavourable soil properties for borehole thermal energy storage. This signifies the importance of not only solar resource, but also soil properties in designing a solar district heating system with borehole thermal energy storage.

From the parametric study, it is evident that solar collector and long-term storage size have a more significant influence on the techno-economic metrics than the short-term storage. Furthermore, expanding the long-term storage size by increasing the borehole number is not only more feasible in the field, but can also produce a higher improvement in performance than increasing the borehole depth. It has also been shown that a system without long-term storage has little influence over the economic metrics, while it reduces the solar fraction relative to the system with long-term storage.

Apart from equipment size, heat demand can also influence the techno-economic performance of the system. It can be concluded that better financial performance and system efficiency can be achieved by minimising the system oversizing and sacrificing the solar fraction.

Due to the implementation of borehole thermal energy storage, soil properties have high relevance in determining the system performance. As shown in the case of Camborne, unfavourable soil thermal properties can lead to an excessive loss in the long-term storage, lowering the system efficiency despite the relatively high solar fraction. It has also been demonstrated that all major soil types in the UK have similar performance for DLSC system. Nevertheless, it should be noted that median values of soil properties were used in the simulation, and outliers such as in Camborne case do exist.

Although a system like DLSC is not eligible for either domestic or non-domestic RHI, it has been shown that the non-domestic RHI tariff has better capability to reduce the LCOE values. Furthermore, in order to significantly increase the financial competitiveness of DLSC-like systems, the non-domestic RHI tariff needs to be increased up to the level of domestic one, and the payment has to be calculated based on the produced energy rather than a theoretical value.

Several options can be considered to improve the performance of a DLSC-like system and enhance its feasibility in UK locations. For example, Model Predictive Control could be used for the optimisation of the system operation. This is also an interesting possibility to test the interactions between optimisation and simulation models on a larger energy system. Furthermore, the use of a ground source heat pump in combination with the solar collectors could improve the utilisation of the boreholes by increasing the usable temperature range of the thermal energy. These options should be considered in further studies of solar district heating system feasibility. Comprehensive sensitivity and uncertainty analysis can also be considered in the extension of this study.

All in all, a solar district heating system such as DLSC is technically feasible to be implemented in the UK. The relatively lower solar fraction can be offset by installing long-term storage and implementing the system to supply new-built houses with better energy performance rather than older homes. Financially, the system still needs to be supported by encouraging policies, such as renewable heat incentive or carbon tax, in order to make it competitive with incumbent technologies.

Acknowledgements

Support from the School of Engineering, University of Edinburgh in the form of a PhD scholarship to Renaldi Renaldi is greatly appreciated.

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