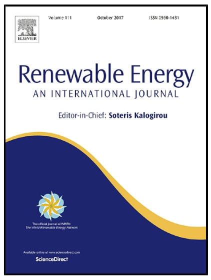
Accepted Manuscript



A long-term performance analysis of three different configurations for community-sized solar heating systems in high latitudes

Hassam ur Rehman, Janne Hirvonen, Kai Sirén

PII:	S0960-1481(17)30518-9
DOI:	10.1016/j.renene.2017.06.017
Reference:	RENE 8881
To appear in:	*Renewable Energy*
Received Date:	04 February 2017
Revised Date:	31 May 2017
Accepted Date:	02 June 2017

Please cite this article as: Hassam ur Rehman, Janne Hirvonen, Kai Sirén, A long-term performance analysis of three different configurations for community-sized solar heating systems in high latitudes, *Renewable Energy* (2017), doi: 10.1016/j.renene.2017.06.017

A long-term performance analysis of three different configurations for community-sized solar heating systems in high latitudes

Hassam ur Rehman*, Janne Hirvonen, Kai Sirén

Aalto University, School of Engineering, Department of Mechanical Engineering, HVAC group, PO Box PL 14400/Vi 351,00760 Aalto, Finland

Abstract

This paper proposes various community-sized solar heating systems configurations for cold climate. Three configurations were proposed, (I)a heat pump connected to two tanks in parallel, using charged borehole storage, (II)a heat pump connected between two tanks, using charged borehole storage to directly charge the lower temperature tank, and (III)two heat pumps used in series, one between the tanks and the other between the lower temperature tank and ground. In configurations (I) and (II) the vertical borehole field is used as a seasonal storage, in (III) it is used to extract heat only. The studied energy flows are heat and electricity. The border consists of energy production systems, heating grid and buildings. The impact of the considered system solutions on the heating renewable energy fraction, on-site electrical energy fraction, purchased energy and full cost as a function of the demand, solar thermal and photovoltaic areas, tanks and borehole volumes has been evaluated. The dynamic simulations results shows that an average renewable energy fraction of 53–81% can be achieved, depending upon the energy systems' configuration. Furthermore, Energy System II utilizes less energy compared to other systems. In all three systems medium-sized solar thermal area is more beneficial instead of large area.

Keywords: Solar community; seasonal storage; solar assisted heat pump; cold climate; district heating and domestic hot water; exhaustive parametric search

1. Introduction

Huge environmental problems are an increasing worldwide issue due to fossil fuel consumption. Efforts are being made to develop and introduce energy-efficient and environmentally friendly systems through the utilization of renewable energy [1]. Buildings are one of the largest energy consumers and emitters of CO_2, representing 40% of the European Union's total energy consumption [1]. Moreover, in Finland more than 80% of residential energy consumption is used for space heating and domestic hot water heating, which has increased by 5% since 2015 [2, 3] , causing CO_2 emissions to have increased by 8% per year [4]. Therefore, there is presently renewed interest in the use of renewable energy due to the environmental impact [5]. In Finland most of the population lives in areas receiving more than 5.3 GJ/m^2 total solar radiation annually. Hence, there is substantial potential for harvesting solar energy [6, 7].

Solar district heating with seasonal storage is a very promising alternative to fossil fuel heating and has been researched by several entities, such as the IEA's Task 32 and Task 45 [8]. Solar thermal (ST) systems are key technologies for achieving emission reduction goals and their use is spreading in European countries [9]. In Europe, from 1979 to the 2011 there have built 141 large-scale solar heating plants, all of them have more than 500 m^2 solar collector area [10]. Schmidt et al. made a detailed review of the advances in seasonal thermal energy storage (TES) in Germany [11, 12]. Since 1979 several countries have participated in operating central solar heating plants with the seasonal storage working group operating under IEA Task 7 [13] to boost the progress of large-scale solar heating technologies. Since this program eight plants have been built in Germany (since 1996) [14]. Currently, the solar district heating market is booming in Denmark, due to its competitive price in comparison to biomass and gas [15, 16]. Numerous solar district heating and seasonal sensible thermal storage projects have been realized in Europe and North America. There are large-scale pilot plants located in Germany, Sweden, and Canada [17, 18] that use solar energy with the help of seasonal storages. Several new solar communities have been built in Germany, Denmark, Sweden and are in operations [19]. Two community concepts at a small scale had been build and tested in Finland in Kerava (1980s) and Eko-Viikki (without seasonal storage) [20]. The Drake Landing Solar Community (DLSC) project was established in 2007 in Okotoks, Canada [21, 22].

One of the greatest scientific and technological challenges we are facing is to develop efficient methods to collect, convert, store, and utilize solar energy at affordable costs [5]. There are two main drawbacks to solar energy systems in the Nordic region: (a) the resulting energy costs are not yet competitive and (b) solar energy is not typically available when needed. Considerable research efforts are being devoted to techniques that may help to overcome these drawbacks—control strategy of the solar thermal system is one of those techniques [23, 24] [24].

* Corresponding author: tel. +358 46 90 55 270; email: hassam.rehman@aalto.fi

In a community-sized solar energy system, heat storage plays a vital role due to the mismatch between irradiation and demand (the low irradiation in winter when demand is high and high irradiation in summer when demand is low), and the storage volumes are relatively large. The cost advantage (due to the size and high capacities) and the ability to operate on a large timescale is the reason that allow ground thermal storage to be technically and economically viable compared to short-term storages [25, 26, 27] . However, storage heat loss is an issue [22]. Seasonal TES store heat in a sensible form. The goal of TES is to maximize efficiency, and this is done by minimizing heat loss. Therefore the thermal properties of the storage medium, time of storage, storage temperature, location, storage geometry, and volume are critical [25]. Many researchers [28, 29, 30] have presented four main types of sensible seasonal energy storages that have been in operation. They are (1) hot water TES (HWTES), (2) aquifer TES (ATES), (3) gravel water TES (GWTES), and (4) borehole TES (BTES). ATES is the cheapest solution, in small to large scale applications it can acquire more storage volume by adding additional wells that penetrate additional ground volume, however, it is site specific as it requires a suitable aquifer available nearby and this limits the flexibility of the location [30]. Furthermore, other methods may require very large storage volumes to be feasible, and the initial costs are high [30]. BTES is more attractive than the other methods of seasonal storage for the following reasons, because of the simplicity of its storage, its adaptability (through drilling additional boreholes if there is increased demand for stored heating energy), its flexibility in terms of location, its cost effectiveness, and the favorable ground conditions in Finland [30]. Therefore, BTES is chosen in this study. One of the main disadvantages of ground seasonal storages like ATES and BTES is heat loss to the surroundings. Two major local ground properties that affect the storage efficiency and the losses from BTES are (1) the thermal conductivity and (2) the groundwater level and its movements. Finland is located in the Fennoscandia Shield and suitable for BTES [30]. The mean thermal conductivity of rocks in Finland is 3.24 ± 1.00 W/m·K [31]. Secondly, the groundwater level plays an important role in thermal conductivity [30]. The groundwater level in Finland is usually located at a depth of 1–4 meters below the surface, however, it can be located as deep as 20 meters in ridges and bedrock [32]. Most of the Finnish bedrock is unbroken and has little or no groundwater flow [30, 32]. The size of the borehole storage is also important for heat loss. Vertical borehole lengths are usually in the range of 30–100 m with approximately 3–4m separation [11]. The borehole depths in recent installations have gone as deep as 200m [28]. The cylindrical shape of the storage reduces the losses [30].

The heating distribution systems in the existing solar communities are mostly based on a medium temperature and focus on space heating (SH) demand. This approach allows minimizing the thermal storage heat losses in the seasonal storages [33, 34]. Furthermore, this low-grade temperature can be raised using a heat pump (HP) depending upon the demand. An HP can be used regardless of whether the ground is charged via solar energy or not. Charging the ground with solar energy is beneficial for the heat pump because the evaporator temperature increases. Hence, this helps the HP to have a higher coefficient of performance (COP) [35, 36, 37]. There are many strategies to integrate a HP into ST systems. Many strategies can be used with which an HP can be integrated into ST systems [35, 36]. In cold climate areas such as Finland, they are not yet widely used and this has been considered in this study.

Another important aspect of the residential area is the building itself. It plays a significant role in the residential energy demand [38]. In continental Europe a domestic building constructed according to advanced standards can reduce the energy demand for space heating by 70–80% in comparison with that of the average building in 2005 [39, 40] due to passive measures. Therefore, the building's passive measures have to be integrated with the solar system model in order to understand the behavior of the whole system regarding the energy demand.

A community-sized district heating system with ST system, integrated with an HP and borehole storage, has neither been fully investigated nor applied [27] in Nordic countries. The technical and economic viability of using such a system has also not been investigated. As discussed above, at high latitudes there are three major challenges: (1) the weather is extremely cold during winters, (2) the annual mismatch between irradiation and demand (the low irradiation in winter when demand is high and high irradiation in summer when demand is low), and (3) the losses from the seasonal storage are high due to ground conditions. In addition, system designs from other countries cannot be transferred directly to a new location [41, 42]. Therefore, several crucial factors need to be considered in order to evaluate the energy performance of such a community-sized solar heating system. All these features call for a system that is adapted to local conditions and designed accordingly. Such an integrated approach has not been carried out in the past.

The novelty in the paper is that of the proposed configurations and strategies for an ST district heating system in a Nordic location. Therefore, the aim of this research is to investigate and assess the long-term performance of such ST district heating system in the Finnish climate. The challenges (described above) of this location are addressed and solutions are proposed in this study based on the technical and economic aspects. Three different types of configuration are proposed and the impact of a particular configuration of a solar and ground loop on the final energy consumption has been evaluated. In particular the influence of varying ST size, short-term storage tank volume, borehole size, photovoltaic area, and building design on the renewable energy fraction for heating [43], purchased energy, and full cost (FC) and on-site energy fraction for electricity [44] are evaluated. The objective behind this study is to maximize the effective use of solar energy when different configurations of houses and systems are used. The proposed control strategies for the ST field, the ground, and the storage tank are hierarchical and priority is given to buffer storage tank loading. The study is performed using dynamic simulations approach using TRNSYS [45] due to the complexity of the proposed system [36, 46].

2. System configurations

The solar energy system consists of ST collectors, short-term storage tanks, vertical borehole heat exchanger field (BHE), borehole thermal energy storage (BTES), PV modules and HPs. Three system configurations were evaluated, the main features and differences among each system are described below:

- Energy System I
  - Solar heat from collectors is fed to either the warm tank or the hot tank, and excess heat from the buffer tanks is transferred to the BTES, depending on the temperature
  - The HP extracts heat from BTES and pumps it to either the warm tank or the hot tank
  - Photovoltaic electricity (PV) is used for the HP, circulation pumps, and residential needs; the surplus is exported to the external grid while any shortfall is imported from the external grid

- Energy System II
  - The system is the same as Energy System I except for the following point
  - The HP extracts the heat from the warm tank and pumps it to the hot tank, and the warm tank is charged directly from the BTES

- Energy System III
  - The system is the same as Energy Systems I and II except for the fact that the ground is only used as a heat source without any solar heat injection and the following point below
  - In contrast to Energy Systems I and II, two separate HPs were used: one HP extracts heat from the warm tank and pumps it to the hot tank whereas the second HP extracts the heat from the BHE and pumps it to the warm tank

The energy system I and II are designed based on the Drake Landing Solar Community, Canada as it has shown better performance in cold climates and provided up to 90% of space heating demand through solar energy [21, 22]. However, instead of a boiler, a heat pump is used in different arrangements. In addition to that, domestic hot water is also provided in proposed configurations. Energy system III has a cascade heat pump arrangement. It was based on German experience regarding cascade heat pump arrangements for buildings [47]**.** The three configurations are described in detail in the following subsection, Subsection 2.1.

There were many possibilities of hydraulic interconnection. The optimal control mode may depend on the energy generation and storage capacities. Moreover, there were different control possibilities for the ST output temperature as well. Firstly, for this study the connection between the short-term storage tank and the ST collectors was chosen to be parallel [43]. Secondly, temperature tracking control mode was selected [43] where the collector typically aims for an outlet temperature that is one degree higher than the tank's top temperature. These control strategies were implemented as these strategies together resulted in the reduction of the energy demand of the ST system, as evaluated in an earlier study [43]. The cooling needs in the community were minute, therefore a cooling system was not included.

The technical features of the different components used in the simulations are described in Section 3 of this paper. All components were similar in all the energy systems. However, changes were made to perform the parametric analysis and these are mentioned in Section 4. This was implemented to understand the relation of these components to the renewable energy fraction for heating [43], and on-site energy fraction for electricity, final purchased energy, and full cost (FC).

2.1. The energy system

Energy Systems I, II, and III were designed to maximize the fraction of solar heat. Solar energy was primarily used for domestic hot water (DHW) and SH supply through the storage tanks and secondarily for charging the ground. The control was designed in a hierarchical pattern. The ST pump drew the cold solar fluid (water + glycol) from the tank bottom and into the heat exchanger in order to collect heat from the solar collector loop. Meanwhile, the heated water from the collector transferred heat to the tank via the heat exchanger after attaining the desired temperature based on the set point. The tanks were charged in parallel. Water was diverted to charge either the hot or the warm short-term tank till that tank's set point value was reached. In order to minimize the use of the HP, the charging set points of the tanks were higher for the ST collector than for the HP. When the tanks need charging, the first option was to use the solar collector. If the warm tank temperature was lower than 40 ^{o}C, it was heated to 45 ^{o}C, and for the hot tank, if temperature was lower than 65 ^{o}C, it was heated to 70 ^{o}C by the solar collectors [43]. If both tanks were at adequate temperature levels, all the solar heat was pumped into the warm tank to maximize energy efficiency. Depending upon the energy system configuration, if no energy was available from the solar collectors, heat could be directly transferred from BTES into the tanks or through the HP in order to charge the tanks. Cold fluid entered from the cool outer edge of the BTES and exited from the hot center. If the warm tank temperature was lower than 35 ^{o}C, it was heated to 40 ^{o}C, and if the hot tank temperature was lower than 60 ^{o}C, it was heated to 65 ^{o}C by the HP or directly from the BTES, conditional to the energy system type [43]. The set points of tanks charged by the solar collectors were higher when compared to the HP in order to maintain the tanks' temperature at higher values. Since the tanks were charged at a higher level, the HP was used less. This improved the overall system performance. Depending upon the energy system configuration, excess solar heat present in the buffer tanks was transferred to charge the BTES in order to avoid overheating the short-term tanks. Heat from the warm storage tank was transferred when the tank temperature reached 50 ^{o}C and the process stopped once the temperature dropped to 45 ^{o}C. Heat was transferred from the hot storage tank when the tank temperature reached 75 ^{o}C and stopped once the temperature was below 70 ^{o}C [43]. The SH was provided by passing the SH water through the warm tank or through both the warm and hot tanks, subject to the energy system configuration. This heated water was then provided to the houses at a temperature between 27 ^{o}C and 40 ^{o}C, depending upon the outdoor temperature. DHW was provided to houses by preheating the cold water in the warm tank and then heating the water further in the hot tank until it reached the desired temperature of 60 ^{o}C. There was also a DHW recirculation circuit in the system to ensure that DHW was continuously available without delay. If the HP and solar energy were not enough to meet the temperature needs, backup heating was handled by direct electric heaters. The distinguishing features of each of the energy systems are described in the following subsections of the paper (2.1.1, 2.1.2, and 2.1.3).

2.1.1. Energy System I

In this setup, boreholes were charged by solar energy and the HP evaporator was directly connected to the borehole outlet. The energy from the BTES was used by the HP to heat the short-term tanks in need of energy when ST energy was not available. The HP was used to maintain the temperature in both the hot and warm tanks. If the BTES output temperature was high enough, it could be directly utilized for heating the tanks via a bypass. Excess solar energy from the short-term tanks was transferred to BTES to avoid overheating. SH was provided by warm tank and DHW was provided by both the warm tank (preheating) and hot tank (the final temperature). A schematic representation of the system is shown in Figure 1. All the set points of each of the system components and its operational controls are described in Subsection 2.1.

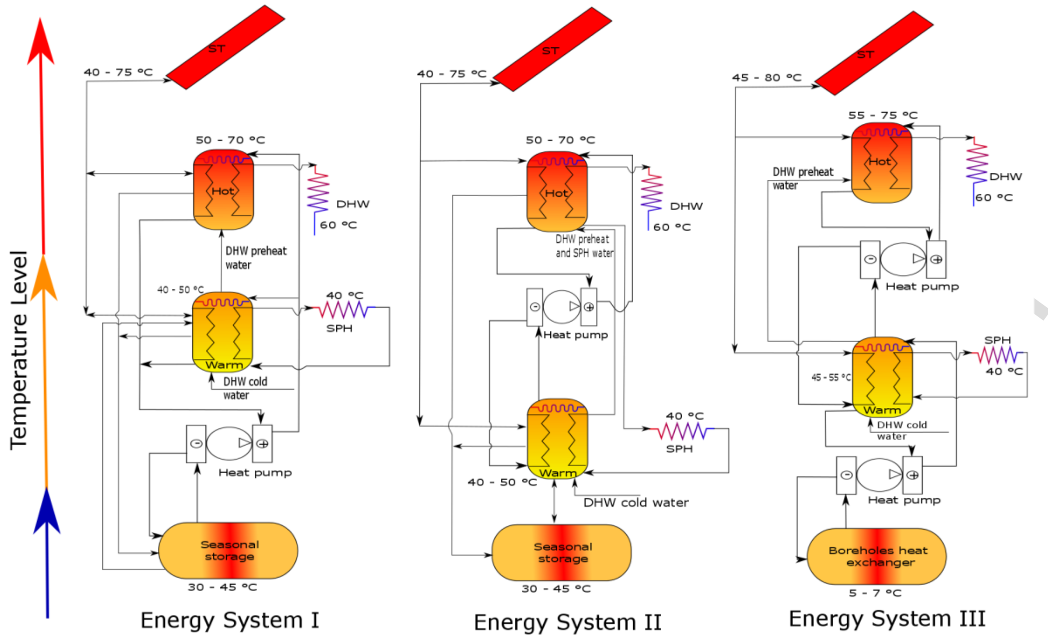


Figure 1. Simple schematic representation of the Energy System I, Energy System II and Energy System III

2.1.2. Energy System II

In this setup, boreholes were charged by solar energy and the HP evaporator was directly connected to the short-term warm tank (instead of the borehole outlet if compared to system I). The energy from the warm tank was used by the HP to heat the hot tank in need of energy when ST energy was not available. Moreover, the warm tank was charged directly from the BTES. If the warm tank temperature was less than 35 °C and the BTES's average temperature was higher than the warm tank's top temperature, the energy was transferred via the BTES. The warm tank was charged from the BTES every time that the HP was used to charge the hot tank. Excess solar energy from the short-term tanks was transferred to BTES to avoid overheating. SH was provided by both the warm and hot tanks when the warm tank was not at an adequate temperature level. DHW was provided by both the warm tank (preheating) and the hot tank (the final temperature). A schematic representation of the system is shown in Figure 1. All the set points of each of the system components and its operational controls are described in Subsection 2.1.

2.1.3. Energy System III

In this setup, boreholes were not charged by the solar energy, unlike in system I and system II. Moreover, there were two HPs used. During the winters, when solar energy was not available, one HP evaporator was directly connected to the BHE outlet and it was used to charge the warm tank. The available natural energy from the BHE was used by the HP to heat the warm tank when ST energy was not available. The second HP evaporator was directly connected to the warm tank and it was dedicated entirely to charging the hot tank by taking energy from the warm tank. The HPs were used to maintain the temperature in both the hot and warm tanks. In this system BHE was not charged by solar heat. SH was provided by the warm tank and DHW was provided by both the warm tank (preheating) and the hot tank (the final temperature). A schematic representation of the system is shown in Figure 1. All the set points of each of the system components and its operational controls are described in Subsection 2.1.

3. System simulation input parameters

In general, the energy performance of the energy systems and buildings described in Section 2 depend upon the input or *design parameters*. These parameters are variables that can be determined by the designers [48]. In addition, the significance and the nature of these parameters can be different for varying systems. In general, the energy performance of the energy systems may mostly depend on six parameters that are considered in this paper, namely: (1) the ST collector's area, (2) the short-term storage tank volumes (warm and hot tanks), (3) BTES volume, (4) the photovoltaic area, and (5) the total building heating demand. Each parameter is described in detail in Subsections 3.1, 3.2, and 3.3.

3.1. ST and auxiliary systems

3.1.1. The ST system and short-term storage tanks

The solar panels used in all three energy systems were mounted at a 50^o tilt angle, facing south. They were flatbed collectors, connected in series. The design features of the ST collectors [49] and the storage tanks [50] (a hot and warm tank) are shown in Tables 1 and 2 respectively. TRNSYS type 1b and type 543 were used for ST and buffer tanks respectively.

Table 1. Design characteristic of solar thermal system design features [49]

Solar thermal collector	Value
Net aperture area	2000, 4000, 8000 m^2
Maximum flow rate	11.11 kg/s
Intercept efficiency	0.871
Efficiency slope	3.611 W/m^2·K
Efficiency curvature	0.013 W/m^2·K^2

Table 2. Design characteristic of short term storage tanks model [50]

Short- term storage tanks (hot and warm tank)	
Volume	120, 240, 480 m^3
Heat exchanger effectiveness	0.9
Insulation U-value	0.2–0.3 W/m^2·K

3.1.2. BTES

The seasonal storage played a key role in all systems. In systems I and II it stored the solar energy, and in systems I and III it was used directly as a thermal source for the HP. To extend the scope of the study and therefore to assess the benefits of using seasonal storage with ST energy, different BTES volumes were considered. In Energy System III, the depth of the BHE was increased to 300 m, compared to Energy Systems I and II where the depth was 45 m. This contributed to providing a larger contact area for the BHE with its surroundings, thus the BHE could be charged naturally. Moreover, it was simulated that larger depths can be discharged for a longer time compared to shallower depths because the average BHE temperature variation between charging and discharging is less. The seasonal storage behavior was simulated utilizing a Type 557a model that is available in the GHP TESS library of TRNSYS [45]. Table 3 shows the main borehole and soil characteristics used in each energy system.

Table 3. Main BTES characteristics.

Borehole thermal energy storage, Vertical- U tube system	
Volume (Energy system I, II and III)	33650, 67300, 134600 m^3
Diameter (Energy system I and II)	30.9, 43.6, 61.7 m respectively
Diameter (Energy system III)	11.95, 16.9, 23.9 m respectively
Depth (Energy system I and II)	45 m
Depth (Energy system III)	300 m
Boreholes density (Energy system I and II)	0.191, 0.096, 0.048 boreholes/m^2 respectively
Boreholes density (Energy system III)	1.283, 0.641, 0.32 boreholes/m^2 respectively
Pipe thermal conductivity	0.472 W/m·K
Soil undisturbed temperature [51]	5 ^{o}C

3.1.3. HP

HP was connected to the system as a backup to charge the short-term tanks. TRNSYS Type 668 [45] was used to model the HP. The HP meets the heating load in the network through the storage tank. Several HPs can be connected to get higher capacities. The nominal power consumption of each HP was 60 kW. The maximum flow rate of water through the HP's condenser was 1.94 kg/s and the COP of the HP was 4–6, depending on the BTES and the desired output temperature.

3.1.4. PV

PV solar panels were integrated with the system at a tilt angle of 40^o in order to provide the electricity to the system and to reduce the purchased electricity from the supply grid. TRNSYS Type 194 [45] was used to model the electricity produced by the photovoltaic system according to its specification using the same reference year's weather data. The specifications [52] of the photovoltaic panels used in the simulation are described in Table 4. The on-site energy generation was used to meet part of the demand while the rest was imported from the grid. Excess energy was exported to the grid. No electricity storage was considered in this study.

Table 4. Photovoltaic panels system for the simulations [52].

Photovoltaic, polycrystalline modules (at standard conditions)	
Type	AC-250/156-60S
Area	1000, 2000, 4000 m^2
Nominal output (P_{mpp})	250 Wp
Nominal voltage(V_{mpp})	30.7 V
Nominal current (I_{mpp})	8.18 A
Short circuit current (I_{sc})	8.71 A
Open circuit voltage (V_{oc})	37.80 V
Module conversion efficiency	15.37%

3.2. *Building design variables*

A 100-house community was studied, located in Helsinki (60.19 N, 24.94 E [53]), Finland. Each house is a single-zone house and has a pitched roof (attic) with a tilted angle of 20^o. The buildings' thermal model was built and simulated in TRNBuild [45], which is a TRNSYS subroutine that is able to generate the thermal loads profile of a building. The energy efficiency of houses can strongly influence overall energy use in the building sector and the overall energy consumption of the solar system. The heated area of the houses was 100 m^2 each. The internal height was 2.7 m. The windows glazing area was 14% of the total walls area. To avoid summer overheating, different types of shading were provided. Because of the mild climate in the summer, most Finnish houses do not have mechanical cooling. Hence, mechanical cooling was not considered as an option. Each house was a single zone building. Each house was ventilated by one air handling unit (AHU) that supplies fresh air to the house and draws exhaust air from the house. The AHU had heating coils that keeps the supply air temperature at 18 ^{o}C when the incoming outdoor air temperature was lower than this temperature. The building envelope has an airtightness (n_{50}) of 2 1/h, where n_{50} is the number of air changes per hour equivalent to an air-leakage rate, with a 50 Pa pressure difference between the indoors and outdoors [54, 55]. The average exhaust air flow rate is equal to 0.65 air changes per hour (1/h) [56]. The dynamic changes of DHW, lighting, and appliances energy were considered by using profiles based on the typical Finnish lifestyle [57]. The yearly heating demand for domestic hot water was 45 kWh/m^2/yr including the constant recirculation of hot water. The DHW profile has been balanced for the buildings to avoid too high peak loads and to include the effect of simultaneity among various buildings. Same profile for DHW was used for all buildings. An appliance electricity demand of 40 kWh/m^2/yr was used [55, 58]. The internal gains due to people, lighting, and appliances were 10.3, 7.8, and 17.8 kWh/m^2/yr respectively, according to D5-2012 [54, 55].

The design variables were selected to cover packages of measures ranging from compliance with the requirements of the current national building code, C3-2010 [59], to combinations that realize a passive standard house. The variables include the number of external walls, both the roof and floor insulation thicknesses, three window types, and three rotary type heat recovery units. The main data of the house and the envelope's thermal feature of the house are shown in the Table 8, in Subsection 4.2.

3.3. *The weather and demand profiles*

The chosen location for the solar community was in southern Finland. Regarding the weather data, Finnish test reference year data [60] was used in TRNSYS through Type 15 [45]. The total radiation and the external temperature are shown in Figure 2a. Whereas, Figure 2b shows the monthly energy demand for SH (37 kWh/m^2/yr) and DHW (45 kWh/m^2/yr) for the 100 analyzed buildings.

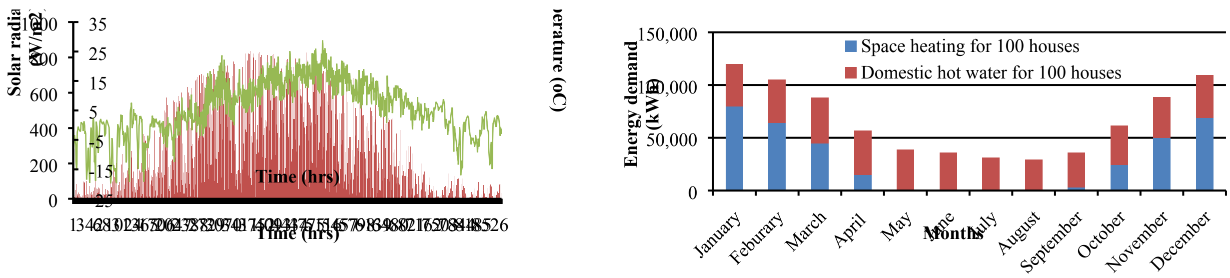


Figure 2. Finland (a) Hourly solar radiation and ambient temperature; (b) 100 houses monthly energy demand (37 kWh/m²/yr space heating demand)

4. Parametric analysis

4.1. The motivation for using parametric analysis vs. optimization

This paper focused on investigating the performance of the presented systems by using an exhaustive search. An exhaustive search is one in which all possible solutions are evaluated. As such, there is no search direction or formal identification of the optimal solutions—the best solutions are identified through the post-processing of all solutions. It has many advantages over other search methods. First, the maximum possible amount of information is gathered in order to be used in decision-making, subsequently all probable and uncertain performance conditions are evaluated. Furthermore, this is particularly important for a progressive decision-making approach where the design criteria may change within the decision-making process. A conventional optimization may require a re-run of the optimization process [61]. Second, many of the multi-objective optimization methods used in present research seek to find an optimized solution between two objectives, since several optimization algorithms are unsuccessful in resolving "many objective" optimization problems [61]. An exhaustive search is immune to the computation difficulties and complex algorithms of finding good solutions in a many-objective search space and it is scalable. Third, the results can be post processed to identify the sensitivities of the decision variables [61]. It is a method used to define how various independent design variables impact a particular outcome under a given set of assumptions [62]. Lastly, an exhaustive search can be used to decide which parameters need more in-depth analysis and those for which standard values could be used. These significant parameters, which are more influential, can be used for further optimization, while the standard values can be used for the least influential parameters [48]. In other words, it helps to decide which parameters should be optimized accurately. The limitation of an exhaustive search is obvious: the number of solutions needing to be evaluated increases as a product of the number of values for each variable [61].

In this paper, the motivation for the parametric analysis of the defined energy system configurations in Section 2 was to provide a complete analysis of the system and the behavior under different conditions. Moreover, the selected system parameters for the studied energy system configurations were changed in each different scenario [63, 64, 65]. These changes are described in Subsections 4.2 and 4.3.

4.2. Design variables – buildings

The current study considers five variables: the insulation thickness of the external wall, roof, and floor; window type; and ventilation heat recovery efficiency. The value of the design variables and investment costs of design variables are shown in Table 8. The number of possible building designs was 243 (3^5). TRNEdit [45], a subroutine of TRNSYS, was used to perform the parametric analysis of the building. TRNEdit runs each set of design variables one by one using the same model, only changing the supplied design variables, as shown in Table 8.

All the building cases (243) were simulated separately to calculate the heating demands of each of the 243 cases and then the three building heating demands were further chosen for the energy system simulations. Firstly, the building with the highest heating demand (50 kWh/m²/yr) was chosen as the worst case. Secondly, the case with half this demand (25 kWh/m²/yr) was chosen as the best case and the final case was taken from their midpoint (37 kWh/m²/yr).

Table 8. Building configuration variations for the simulations and Investment cost data of the building design variables [58, 55, 66].

Parameters	Alternatives	Prices	Options
External wall insulation (Mineral Wool)	U-value= 0.17 W/m²·K, insulation thickness = 0.210 m U-value= 0.13 W/m²·K, insulation thickness = 0.282 m U-value= 0.10 W/m²·K, insulation thickness = 0.375 m	65 €/m³	3
Roof insulation (Wool)	U-value= 0.09 W/m²·K, insulation thickness = 0.42 m U-value= 0.08 W/m²·K, insulation thickness = 0.475 m U-value= 0.07 W/m²·K, insulation thickness = 0.545 m	37 €/m³	3
Floor insulation (Polyurethane)	U-value= 0.17 W/m²·K, insulation thickness = 0.221 m U-value= 0.13 W/m²·K, insulation thickness = 0.294 m U-value= 0.10 W/m²·K, insulation thickness = 0.385 m	114 €/m³	3
Windows type	U-value= 1.0 W/m²·K U-value= 0.80 W/m²·K U-value= 0.60 W/m²·K	252 €/m² 290 €/m² 350 € /m²	3
Ventilation heat recovery efficiency	Efficiency= 80% , Regenerative heat exchanger Efficiency= 70% , Counter-flow heat exchanger Efficiency= 60% , Cross-flow heat exchanger	4138 € 3835 € 3533 €	3
Total combinations			243

4.3. Design variables – energy systems and buildings

The current study considered six system variables: the ST area, the photovoltaic area, the warm tank volume, the hot tank volume, the BTES volume, and the buildings. The values of all the design variables and investment costs of design variables are shown in Table 9, including the selected buildings and energy systems. The buildings were chosen based on the different space heating demands (DHW demand is same for all building types) of the buildings caused by the variations in the design variables, as mentioned in Section 4.3. The highest heating demand obtained in the simulated cases was 50 kWh/m²/yr. The case with half this demand (25 kWh/m²/yr) was chosen as the best case and the final case was taken from their midpoint (37 kWh/m²/yr).

The number of possible designs were 729 (3^6) for each system. Therefore, the three ST systems, combined with the three building types, proposed above for the community had a total number of 2187 simulations (729 x 3). The simulations were likewise done through TRNEdit [45] in order to perform the parametric analysis of Energy Systems I, II, and III. Here, various representative system configurations have been selected and the results are presented and discussed in Section 5.

Table 9. System configuration variations for the simulations and investment cost of the components used in energy systems [52, 49, 50, 67, 68]

Parameters	Alternatives	Prices (€)	Options
Solar thermal aperture area	Area= 2000 m² Area= 4000 m² Area= 8000 m²	365 €/m² 347 €/m² 312 €/m²	3
Warm water tank volume	Volume= 120 m³ Volume= 240 m³ Volume= 480 m³	500 €/m³	3
Hot water tank volume	Volume= 120 m³ Volume= 240 m³ Volume= 480 m³	500 €/m³	3
BTES volume	Volume= 33650 m³ Volume= 67300 m³ Volume= 134600 m³	17.19 €/m³ and 13.86 €/m³without insulation	3
Photovoltaic area	Area= 1000 m² Area= 2000 m² Area= 4000 m²	230 €/m²	3
Building configurations	Type 1: heating demand= 25kWh/m²/yr Type 2: heating demand= 37kWh/m²/yr Type 3: heating demand= 50kWh/m²/yr	15 628€/building 13 260 €/building 12 655 €/building	3
Energy systems	Energy system I Energy system II Energy system III		3
Total combinations			2187

4.4. Energy matching and full cost

The motivation to use purchased energy and the full cost (FC) were of primary interest because purchasing energy (as well as environmental issues in general) is an interest of the end user and the full cost is an interest of the contractor and end user. Therefore it was important to evaluate both quantities in order to provide the overall performance of the system.

The mathematical expression for purchased energy is

$$P_E = E_P + E_{HP} + E_{BH} + E_{BUL} - E_{EXP}, \tag{1}$$

where P_E is the purchased energy, E_P is the electricity consumed by all pumps, E_{HP} is the electricity consumed by the HP, E_{BH} is the backup direct electricity used to maintain the temperature in the SH and DHW network when HP and solar energy is not sufficient, E_{BUL} is the appliance electricity demand of buildings, and E_{EXP} is the excess electricity that is produced by the photovoltaic panels and exported. The electricity production by PV panels faces the same problem as heat production by ST collectors: the mismatch between supply and demand curves. The electricity production by PV panels faces the same problem as heat production by ST collectors: the mismatch between supply and demand curves. In this paper for the heat and electricity supply the energy flows are balanced for every time step of 7.5 mins. All heating demand has to be met by the local system. However, for electricity, excess energy generated via PV is exported to the gird due to the lack of electrical storage device. Any shortfall is balanced by imported electricity from the grid.

The full costs (FC), is the sum of the present value of the investment and net energy cost for 25 years. It is expressed as

$$FC = C_{ST} + C_{PV} + C_{BTES} + C_{WT} + C_{HT} + C_B + \sum_{n=1}^{25} a_e C_I P_E - \sum_{n=1}^{25} a_e C_E E_{EXP}, \tag{2}$$

and

$$C_B = C_{Wins} + C_{Rins} + C_{Fins} + C_{WIND} + C_{HR}, \tag{3}$$

where, FC is the full cost that includes the investments and operations costs (for 25 years), plant disposal and maintenance costs are not included in the FC. C_{ST} is the solar collectors, C_{PV} is the photovoltaic panels, C_{BTES} is the borehole heat exchanger, C_{WT} is the warm tank, C_{HT} is the hot tank, and C_B is the building costs. C_I is imported electricity cost and C_E is exported electricity cost. The import electricity price of 11.10 c/kWh and export electricity of 4.04 c/kWh was used. All energy prices include tax and distribution costs. These prices are based on 2016 electricity prices in Finland [69]. The a_e are the discount factors [56] [55] which take into account the effect of interest rate and effect of escalation of electricity prices as well. Discounting was done with a real interest rate of 3% [70]. Due to the reversing price trend in the Nordic electricity market, the average price increase during the past decade has been low and even negative [69]. Thus, a conservative escalation rate of 1% was used in this study. The discounted operation cost was estimated over a period of 25 years [71] [72]. The building investment C_B includes the cost of the building's insulation material, walls (C_{Wins}), roof (C_{Rins}), floor (C_{Fins}), windows (C_{WIND}), and the building's heat recovery (C_{HR}). Replacement costs were not considered for the building material and heat recovery unit. No maintenance costs were considered for replaced elements for the system. Due to the long simulation calculation time, a five-year simulation was not feasible. Therefore, as a compromise, the system was simulated for the fifth year and used for estimating the performance of the system. The fifth year was selected because the BTES average temperature becomes steady and change in temperature is not significant in the following year. The fifth year was simulated by keeping the fourth-year end average temperature of the BTES as the starting temperature of the BTES for the fifth year simulation. The fifth year starting temperature was chosen based on ST area (for system I and II) and BHE volume (for system III). A linear equation was used to provide this fifth year staring temperature of the BTES for simulation.

The renewable energy fraction for heating is defined as [43],

$$Renewable\ energy\ fraction_{heat} = 1 - \frac{(HP + backup\ direct\ heating + pumping\ )electricity\ consumption\ per\ year}{SH\ demand\ per\ year + DHW\ demand\ per\ year}, \tag{4}$$

the above Eq. (4) accounts the heat losses through the grid. The household appliances electricity demand is not included in the calculations.

The on-site energy fraction (OEF) of electricity was also calculated. OEF indicates the proportion of the electrical load covered by on-site generated electricity [44]. Since grid electricity was the only external energy source, the on-site energy fraction (OEF) for the whole system was defined using the ratio of annually purchased electricity vs. the total electricity demand of the community (including household electricity demand) [44].

5. Results and discussion

5.1. Buildings

The performance of all building simulation cases against the investments are shown in Figure 3. The slope indicates that the building's heating demand was high when the investment was low, the building's heating demand improved with the high investment. The front of the 17 best cases is also shown in Figure 3. It was observed that the majority of the points that lie on the best point-front feature high insulation thickness of the walls and roof, less thickness of the floor, and high efficiency of the heat recovery unit. Furthermore it was found that the points that fell behind the front did so because the majority of them featured a higher thickness of floor insulation and less heat recovery efficiency. The reason is the expensive floor insulation material. Therefore, higher U-value (or thinner floor insulation) were selected for the best cases. On the other hand, the heat recovery efficiency has a greater influence on the heat demand, and the slight change in the cost of the heat recovery units among the different cases allowed the highly efficient heat recovery unit to appear on the best-point front. Therefore, it is proposed that having higher efficiency of heat recovery and less thick floor insulation result in a better performance of the building in terms of heat demand.

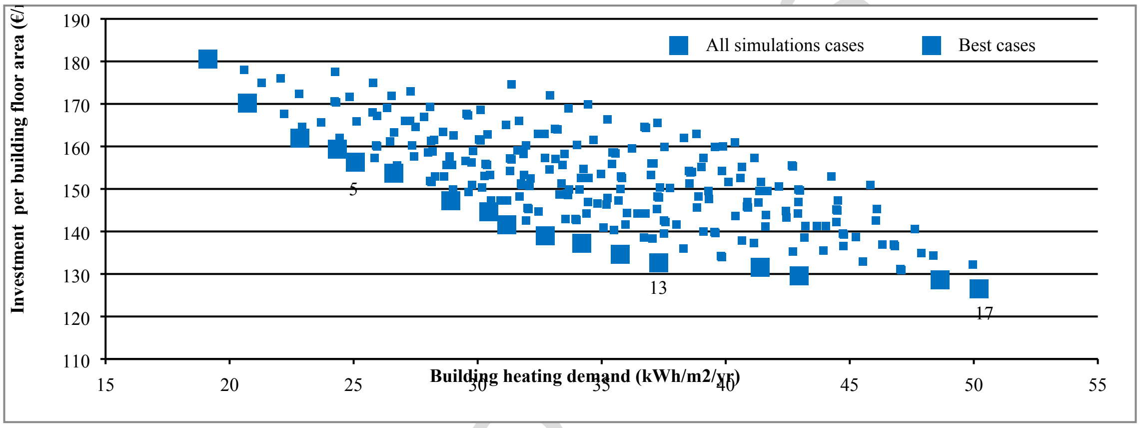


Figure 3. The 243 combinations of building energy demand vs the building investment.

The 17 best cases out of the 243 cases were further selected in order to analyze the performance of the building. The investment analysis of the selected best performing buildings is shown in Figure 4. In Figure 4 the majority of the cases had the highest heat recovery unit cost and lowest cost for the floor insulation. These results again indicate that the highest heat recovery efficiency along with the lowest insulation thickness on the floor was favorable in most of the best cases. More than half of the cases contained inexpensive windows. In addition to that, the cost of the roof and wall insulation was rather a small portion of the total cost in all solutions and varies in each case. This leads to a rather smoothly growing investment.

Buildings 5, 13, and 17—with a heating demand of 50, 37, and 25 kWh/m^2/yr respectively—were further chosen from Figure 3 in order to analyze of Energy Systems I, II, and III. These buildings were selected to offer a wide representation of the buildings in the energy system simulations.

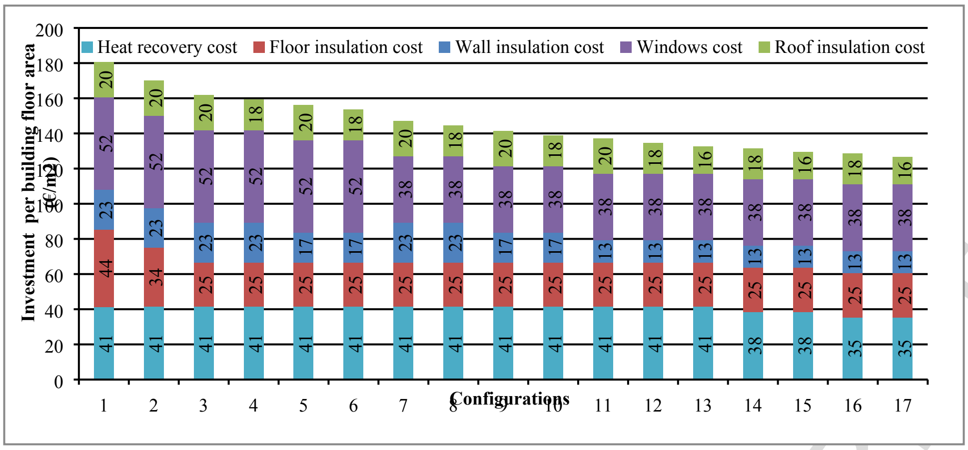


Figure 4. The investment analysis of the selected best combinations of Figure 3.

5.2. Energy system analysis

In order to provide an overall illustration of the energy system, Figure 5 shows the annual thermal energy flows in one of the configurations of the energy system I. As a reference, the energy system I shown in Figure 5, consist of ST area of 4000 m^2, PV area of 2000 m^2, warm and hot tank volume of 240 m^3 each, BTES volume of 33650 m^3 and building with heating demand of 50 kWh/m^2/yr. Most of the heat is provided through the solar thermal collectors to the buffer tanks. The space heating and domestic hot water demand is met through the buffer tanks in order to provide the energy instantly. The excess energy (after meeting the demand) is then transferred from the buffer tanks to the BTES for charging the ground. When solar energy is not available the BTES is discharged via the heat pump to charge the buffer tanks. Majority of the losses from the system to the environment occurred through the BTES and district heating network. Losses are not examined in detail in this study. The electricity flows are shown separately, only imported, exported and self electricity consumptions (produced via PV) are shown. For all energy systems and configurations the Sankey flow diagrams will vary and are not shown in this paper.

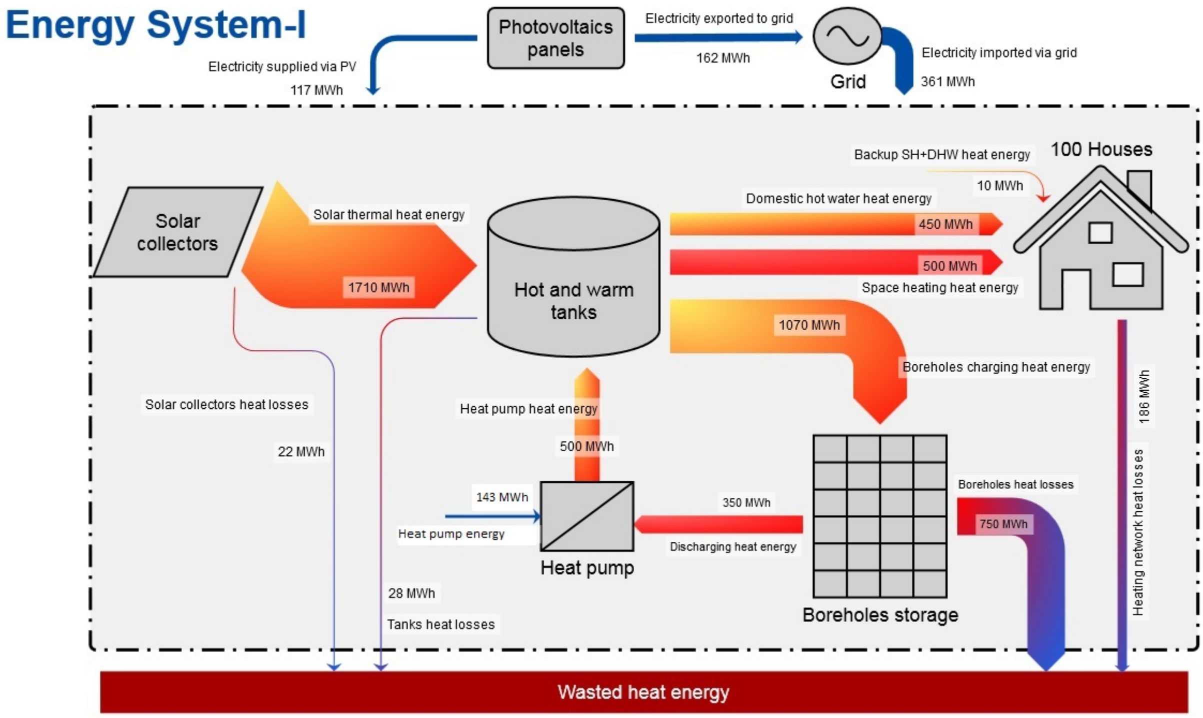


Figure 5. Sankey flow diagram of Energy system-I, annual heat and electricity flows in the system when ST area = 4000 m^2, PV area = 2000 m^2, warm and hot tanks volume = 240 m^3, BTES volume = 33650 m^3 and building heating demand = 50 kWh/m^2/yr.

The relationships between purchased energy versus the full cost (FC) for all the solutions for the three systems proposed in the study are shown in Figure 6. In Figure 6, each energy system performance is shown separately. Generally, it shows that the systems' purchased energy was high when the full cost was low; however, it was reduced when the full cost increased. The best-point fronts (the minimum purchased energy and full cost) out of 2187 cases were exclusively analyzed to compare the overall performance of Energy Systems I, II, and III. They are also shown in Figure 6. The slope of these best-point fronts indicates the change in the purchased energy between different systems. In terms of purchased energy, system III performed the worst compared to the other two systems. The minimum purchased energy (system III's purchased energy) was 44–47 % more compared to energy systems I and II. This was caused by the higher energy consumption of the HPs in system III since the BHE was not charged by solar energy. On the other hand, system II performed better in terms of purchased energy compared to systems I and III and in full cost compared to system I. It was due to the system configuration and the HP arrangement. In this system, the HP was only used to charge the hot tank while taking energy from the warm tank. Hence, the source was relatively warm on the evaporator side when compared to the other two cases.

It was observed in system I that the purchased energy varied from 27.2 kWh/m^2/yr to 47.3 kWh/m^2/yr (shown on the best case front in Figure 6). Furthermore, when analyzed deeply in Figure 6, it was observed that the points outside the front can be roughly subdivided into three subsections. Generally, in section I A the majority of the system configurations contained a seasonal storage of smaller size; in section I B the majority of the system configurations contained a seasonal storage of medium size; and in section I C the majority of the system configurations contained a seasonal storage of larger size. It was found that in section I A, due to the utilization of the HP between the BTES and tanks, larger BTES was not needed to reduce the purchased energy. The use of an HP reduced the need for very large BTES as smaller BTES was enough to provide the required temperature to the HP at the evaporator side. A combination of smaller BTES size with a medium to large ST area can be more beneficial. On the other hand, a combination of large BTES with a large ST area can slightly improve the performance. It is important to mention that stagnation frequency of the solar collectors has not been considered in the present study.

It was observed in system II that the purchased energy varied from 26 kWh/m^2/yr to 34 kWh/m^2/yr on the best-point front in Figure 6. System II can be implemented with remarkably low full cost. In this system the purchased energy dropped down from 34 kWh/m^2/yr (one end) to 28.5 kWh/m^2/yr, after that the reduction in purchased energy was less (as indicated by the slope)—it was further reduced to 26 kWh/m^2/yr although the full cost increased towards higher values, as shown in Figure 6 of the system II. It was revealed that adding a large ST area had a minute advantage on the purchased energy reduction, however, this would increase the temperature in the BTES, causing higher losses to the surroundings from the BTES. Therefore the change in purchased energy declined drastically with very high investment. Furthermore, on the other end of the front, there are no solutions for system II above 34 kWh/m^2/yr because of two main reasons. Firstly, unlike system I the HP's consumption was low because it was only used to charge the hot water from the warm tank instead charging the water of both the tanks. Secondly, since the SH was provided through the warm and hot tanks together, backup SH electricity consumption reduced drastically. Furthermore, in the same system, it was perceived that the points outside the front can be roughly subdivided into three subsections. In section II A the majority of the system configuration contained seasonal storage of a smaller size, in section II B the majority of the system configuration contained seasonal storage of medium size, and In section II C, the general majority of the system configuration contained seasonal storage of a large size It was found that in section II C, due to the utilization of a HP between the warm and hot tanks only, larger BTES reduced the purchase of energy. Larger BTES helped to store more energy in order to recharge the warm tank effectively for a longer duration. On the other side of the Figure 6, in section II A, due to smaller size of BTES, the purchased energy increased as a smaller BTES was not able to charge the warm tank in the absence of an HP. As a consequence the backup electricity increased. In other words it can be stated that when the energy stored in the BTES was used to directly charge the short-term tanks, it was worthwhile having large BTES in most cases. A combination of large BTES with a smaller to medium-sized ST area can be more beneficial. On the other hand a combination of large BTES with a large ST area can improve the performance, however, the change is negligible.

It was observed in system III that the purchased energy varied from 39 kWh/m^2/yr to 63 kWh/m^2/yr on the best case front (shown in Figure 6). System III can be implemented with purchased energy falling down to 41 kWh/m^2/yr, after which the reduction in purchased energy was low (as indicated by the slope)—it was reduced to around 39 kWh/m^2/yr although the full cost increased towards higher values, as shown in Figure 6. It was revealed that adding a large ST area had less advantage in terms of the purchased energy reduction, however, the increased temperatures in the short-term tanks cause higher losses from the tanks to the surroundings as excess energy is not stored in the BHE in system III. Therefore high investments in the ST area had no advantage in this system as the variation in purchased energy declined drastically with very high investments. Furthermore, on the other end of the front, it was observed that the change in the investments was small, however, the purchased energy changed drastically. This is due to the fact that the BHE was not charged by the excess solar energy in this system. Therefore the sizes of the short-term tanks played a role in varying the purchased energy: larger short-term tanks tended to reduce the purchased energy. In the same system, it was observed that the points outside the front can be roughly subdivided into three subsections. In section III A, the general majority of the system configurations contained seasonal storage of a small size, in section III B the majority of the system configurations contained seasonal storage of a medium size, and in section III C the majority of the system configurations contained seasonal storage of a large size. In section III A, due to the utilization of a HP between the BHE and tanks, it was economical to utilize small BHE. The use of a HP maintained the short-term tank temperatures at adequate levels. However, since the BHE was not charged by the solar energy in energy system III, therefore, in section III B and III C larger BHE were selected in the system configurations, which reduced the purchased energy prominently. As larger BHE allowed rapid natural regeneration of the BHE, hence providing higher temperatures at the HP evaporator, causing reduction in HP electricity consumption. Moreover, in the longer run it was more beneficial to use a large size for seasonal storage because it can be discharged for a longer time and the average BTES temperature variation between natural charging and discharging was less. A combination of medium to large seasonal storage with a small to medium ST area can be more beneficial. On the other hand, a large ST area can reduce the performance due to high losses without charging the seasonal storage with excess energy.

In system III, depending upon the ST collector's area, a stagnation frequency of 430 to 700 hours occurred in a year in the collectors due to absence of seasonal storage. Therefore, in such solar heating network it is essential to have seasonal storage to improve the overall performance of the system and to avoid stagnation in the collectors in Finnish conditions. The effect of stagnation was not considered for energy calculations. In system I and II no stagnation occurred, due to the boreholes storage as excess energy was stored in the BTES. Therefore, low temperature water was always available from the buffer tanks to collect solar energy through collectors.

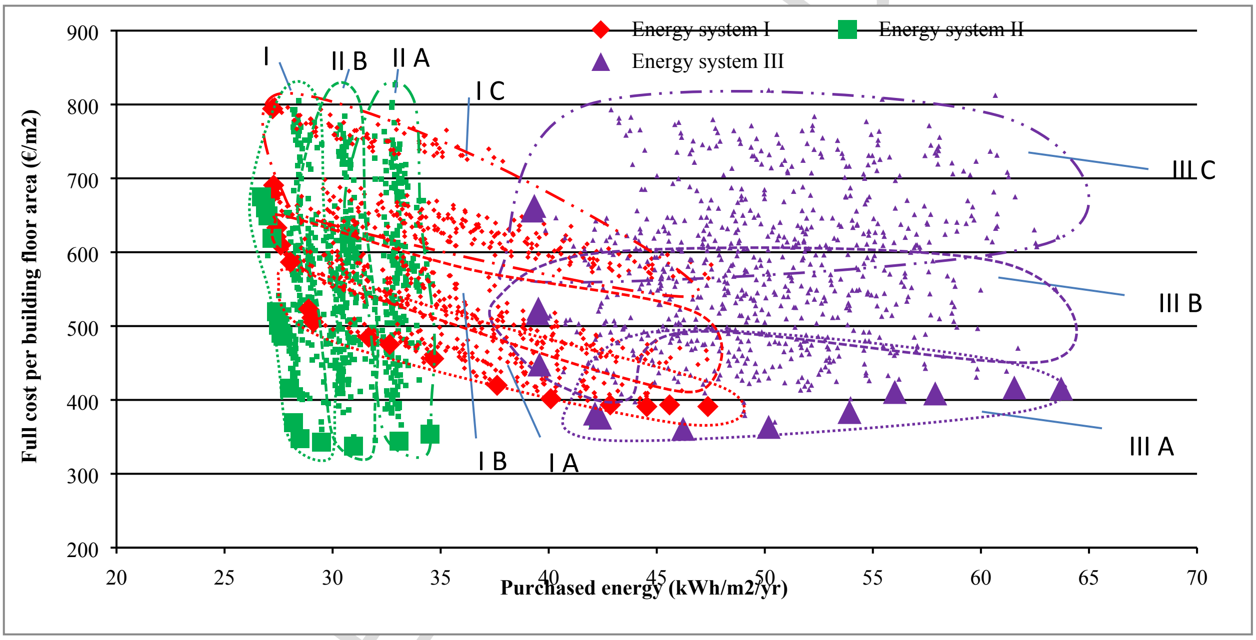


Figure 6. Purchased energy vs full cost, the 2187 combinations as mentioned in section 4.3, for energy system I, II and III.

The full cost analysis and renewable energy fractions of the selected best cases—identified in Figure 6 for systems I, II, and III—are shown in Figures 7, 8, and 9 respectively. Generally it was found that investments had bigger share in full cost compared to the operational cost. The renewable energy fraction varied from 53% to 81% depending upon the energy system configuration. It was observed that system III had the least average renewable energy fraction compared to the other two systems. However, system II had a slightly better fraction compared to system I. This again illustrates that system III is unfavorable compared to the other two systems.

In Figure 7 three sizes of ST area divide the solutions into three equally large groups. Although large ST area is shown in best cases, nevertheless, the reduction in purchased energy was not significant. The smallest BTES were used in the majority of cases. Only the two most expensive solutions used larger seasonal storage. These results again indicated that the lower size of seasonal storage was favorable in most cases in system I. In addition to that, half of the solutions have the largest photovoltaic area. The operation cost or net energy cost (i.e. exported energy price subtracted from the imported energy cost) is also significant when the investments are low. Due to low investments the purchased energy increased as system was unable to meet its all demand, causing increase in the operation cost. The cost of the tanks is a rather small portion of the total cost in all solutions. The renewable energy fraction for heating varied between 65% and

75%. The on-site energy fraction (OEF) varied between 16% and 40% indicating that PV was able to meet 16 to 40 % of the load demand of the system, depending upon the PV size and annual electricity demand. The OEF was low because of the mismatch between the generation and consumption and no electrical storage was considered in the study.

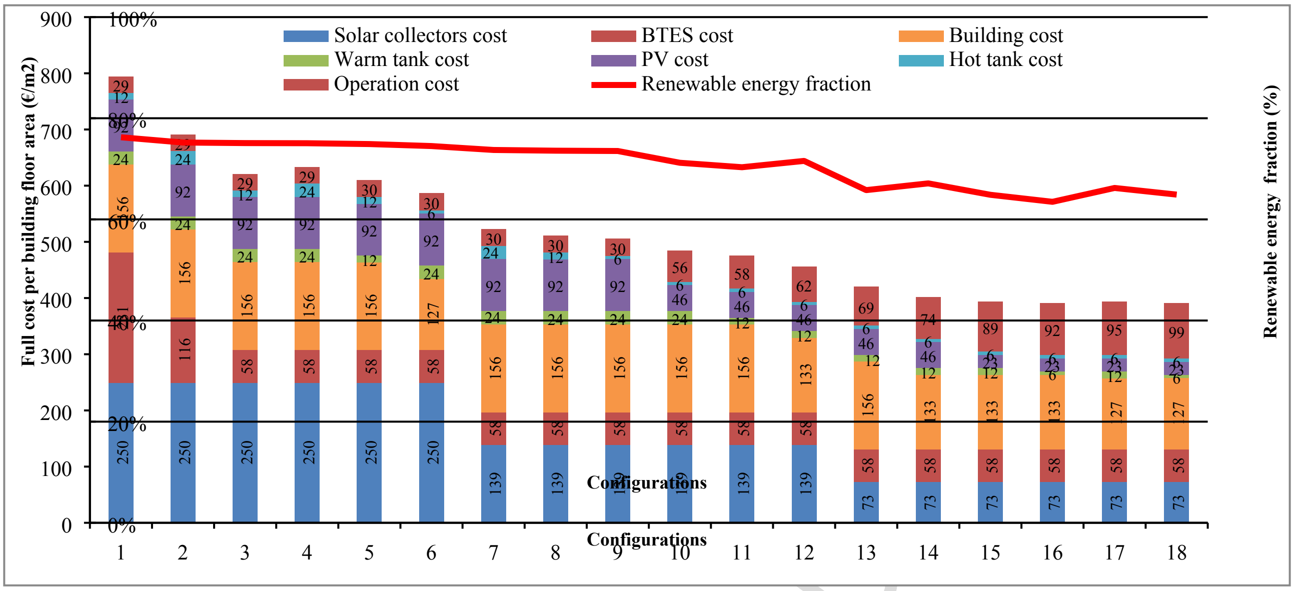


Figure 7. The cost breakdown of the selected best combinations of energy system I as mentioned in Figure 6.

In Figure 8 two sizes of ST area divide the solutions and medium-sized ST occurs most frequently. This shows again that large ST area is not appropriate in this system. Medium- to large-sized BTES was used in the majority of cases compared to system I. These results again indicate that the medium to large size of seasonal storage was encouraging in most cases in system II. The operation cost is also significant when the investments are low. Due to low investments the purchased energy increased as system was unable to meet its all demand, causing increase in the operation cost. More than half of the solutions had a small photovoltaic area due to less purchased energy being needed by this system. The renewable energy fraction for heating varied between 68% and 81%. The on-site energy fraction (OEF) varied between 19% and 40%.

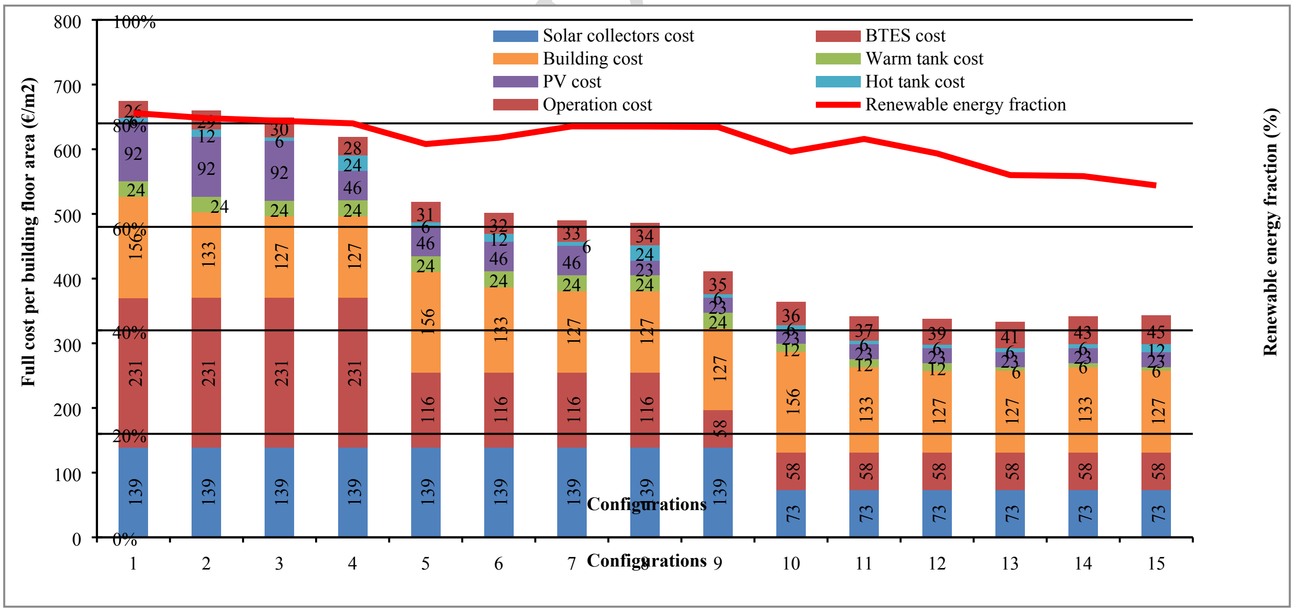


Figure 8. The cost breakdown of the selected best combinations of energy system II as mentioned in Figure 6.

In Figure 9 two sizes of ST area divide the solutions and small-sized ST occurs most frequently. This shows again that a small ST area is favorable in this system, however a medium-sized ST area improved the system performance. The smallest BTES was used in the majority of cases. Only a few of the most expensive solutions used larger seasonal storage. It is evident that the smaller size of seasonal storage was favorable in most cases due to costs—however, larger BTES sizes improved the performance of the system by reducing the purchased energy. The cost of the tanks is a rather small portion of the total cost in all solutions. Larger short-term tanks may be beneficial due to the fact that excess energy was not shifted to the BTES. Therefore, it can store the maximum amount of energy for a longer duration, causing a reduction in purchased energy. The operation cost is also significant when the investments are low. Due to low investments the purchased energy increased as system was unable to meet its all demand, causing increase in the operation cost. In addition to that, more than half of the solutions have a small photovoltaic area due to the low purchased-energy need in this system. The renewable energy fraction for heating varied between 53% and 64%. The on-site energy fraction (OEF) varied between 11% and 26%.

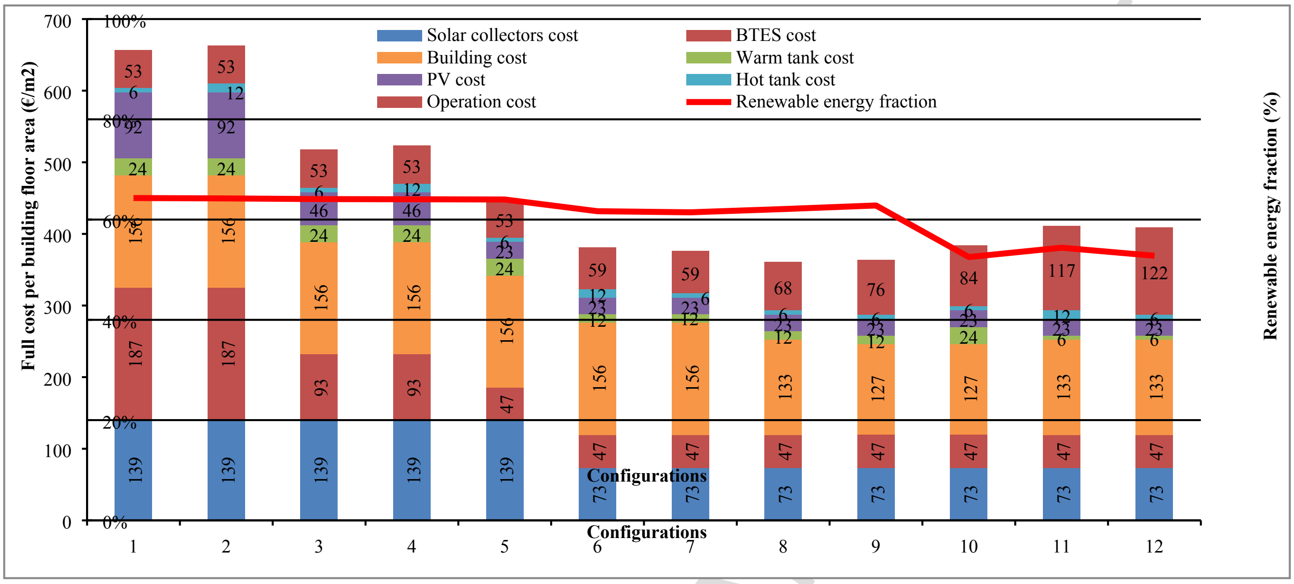


Figure 9. The cost breakdown of the selected best combinations of energy system III as mentioned in Figure 6.

To evaluate the three system configurations the changes in ST areas were focused in all three energy systems, while keeping other parameters similar. The changes in the purchased energy and cost functions were observed. The change in purchased energy due to an increase in ST area while keeping all other parameters constant and the corresponding costs are shown in Figure 10. It was found that by increasing the ST area from 2000 m^2 to 4000 m^2, the reduction of purchased energy was around 6~15% depending upon the system. Excessively increasing the ST area from 4000 m^2 to 8000 m^2, the purchased energy reduced around 5~9% depending upon the system. Therefore, it was not beneficial in terms of purchased energy reduction to have very large ST area. This was due to the fact that large ST areas tend to gain more energy from sun and causing an increase in the temperature of the tanks. This increase in tanks temperature causes an increase in the losses to the environment. One possible solution is to increase the tanks insulation thicknesses, however, this would augment the tanks cost and benefits may not be too high as well. Therefore, a cost effective way is to have smaller size of the ST area in order to reduce the temperatures in the tanks and operate the system at lower temperatures. Furthermore, large ST area increased the stagnation frequency to around 700 hours in a year in system III.

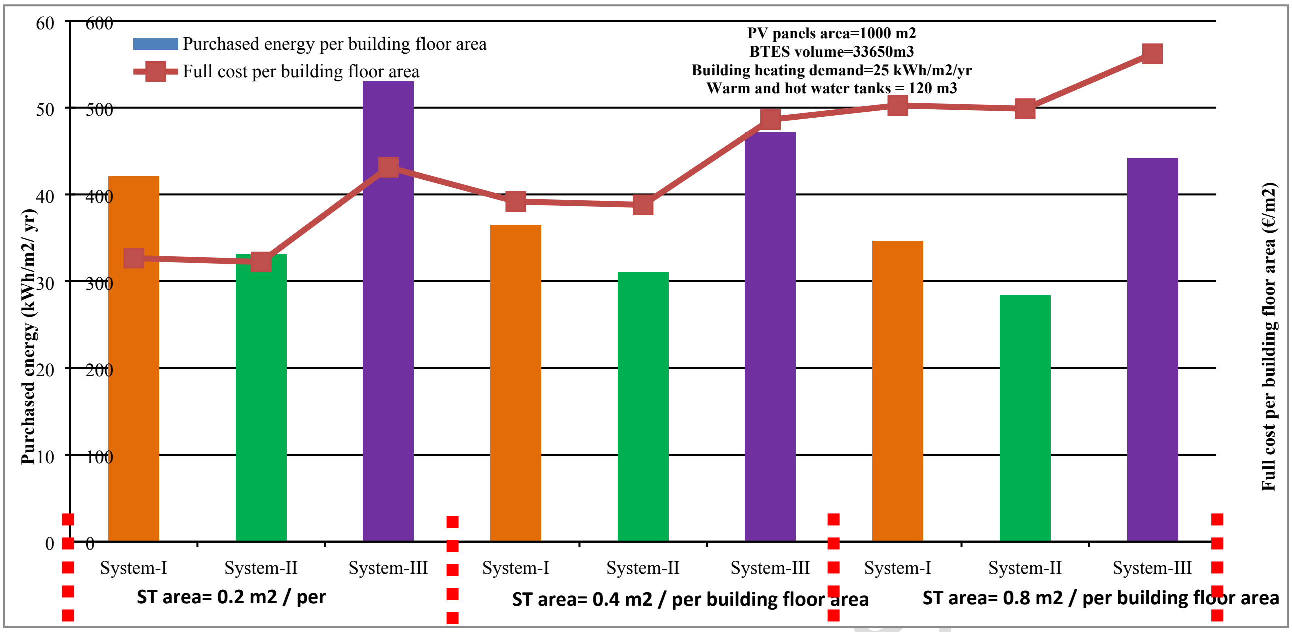


Figure 10. Purchased energy comparison between energy system I, II and III as function of solar thermal area

The advantage of using parametric analysis was that it clarified some important aspects of the energy systems' behavior. Parametric analysis was beneficial in identifying and studying the individual points outside the best point's curves, as discussed earlier regarding the Figures 6 and 10. This gave better and more in-depth understanding of the effect of each individual design variable on the system behavior. In future, with the increasing popularity of the solar community concept in the Nordic climate, finding the best combinations and different systems arrangements is important. Therefore, this information is useful for designers who are making early-stage decisions.

6. Conclusion

The goal of this research is to investigate the performance of a solar community in a Finnish climate. Three different types of ST district heating configurations are proposed in the study. The three proposed configurations are (I) A HP connected to two tanks in parallel, using solar-charged borehole storage as an energy source, (II) A HP connected between two tanks, using solar-charged borehole storage to directly charge the lower temperature tank, and (III) two HPs are used in series, one between the tanks and the other between the lower temperature tank and the uncharged ground. In (I) and (II) the vertical borehole heat exchanger field is used as a seasonal storage. In (III) the field is used to extract heat from the ground only. Moreover in (I) the seasonal storage can charge warm tank directly or via a heat pump. In the paper, these different energy system configurations have been assessed as a function of ST area, photovoltaic area, short-term tank sizes, BTES volume, and building heating demand. The study is performed using a dynamic simulations approach (in TRNSYS).

Buildings with various thermal and energy features were simulated. It was observed that most of the best cases featured high heat recovery efficiency along with low insulation thickness of floor. Windows with high U-values were also selected in the majority of the best cases. Therefore, these three components should be considered more profoundly at the design stage for community houses. On the other hand, wall and roof insulation thickness varied depending upon the heating demand. User behavior plays another important role in varying the building demand profile, but their variation was not modelled. Buildings with a heating demand of 50, 37, and 25 kWh/m^2/yr were further chosen in order to perform the analysis of Energy Systems I, II, and III.

In terms of energy systems, each component had a varied effect on the performance of the system. Maximizing the performance of these systems is a matter of selecting the best combinations of the ST area, the photovoltaic area, short-term storage tank volume, BTES volume, and the building's configuration (as building design can alter the system performance). In most of the best cases, where the system's purchased energy was minimal, highly insulated buildings were selected. On a system level, the results showed that system II performed better in terms of the renewable energy fraction, cost, and purchased energy. On the other hand, system III performed poorest compared to other two systems in terms of the renewable energy fraction and purchased energy. In the broad spectrum, when comparing all three systems it can be stated that solar energy can be directly used to provide both DHW and SH, or used to charge the ground. Balancing and controlling the use of ST energy throughout the year and ground charging and discharging integrated with a HP is effective in energy systems. In particular, storing solar energy in the ground increases the performance of the system by reducing the purchased energy and increasing the renewable energy fraction from around 53% (system III) to 75~81% (systems I & II). However, when the BTES temperature increases, this may cause losses into the ground. The major drawback of BTES is the high losses. It was found that the losses in the ground could be as high as 40-60% in Finnish conditions.

Generally it is found that when a HP is connected to the charged seasonal storage and the HP is used to charge the short term tanks, the system required small BTES sizes in most of the best-cases. Therefore, in system I it is beneficial to have smaller seasonal storage along with medium-sized to large ST area. On the other hand, when a HP is not directly connected to the charged seasonal storage and BTES is used to directly charge the warm tank, the system required larger BTES sizes in most of the best-cases. Therefore, in system II it is beneficial to have larger seasonal storage along with medium-sized ST area. Unlike systems I and II, in system III the BTES is not charged and an HP is used to charge the warm tank. The depth of the BHE needs to be large in all cases and the volume of the BHE could be small. However, larger volume of BHE would improve the performance of the system. This strategy would enhance the natural regeneration of the BHE. Therefore, in system III it is beneficial to have larger seasonal storage along with small to medium-sized ST area. Larger short-term tanks may be beneficial in system III as well. Since excess energy is not transferred to the seasonal storage, larger short-term tanks are noted to reduce purchased energy. Subsequently, it can be concluded that system-II performed better compared to the other two systems. Therefore, regarding the case studies done, system-II could be a preferred system to be further optimized and then built in Finnish conditions.

For the solar thermal collectors, a large ST area can improve the energy collection from the environment. However, in the considered systems a large ST area was not beneficial in terms of purchased energy reduction. The reduction in purchased energy was greater when the ST area changed from small to medium sized. A ST area of 8000 m^2 provides minimal benefits compared to 4000 m^2.

The on-site energy fraction for electricity varied from around 16 – 40 % (system I & II) to 11 – 26 % (system III). Without the PV panels included in the calculations, the on-site energy fraction for electricity would be zero and all that electricity had to be imported via grid. This would increase the purchased energy of each energy system and the operational cost (imported electricity cost) of the systems would also increase.

The study demonstrates the methodology and interaction between the system configurations and design variables (including the buildings). In particular, their effect on system performance and the corresponding full costs are presented. The parametric analysis of different system designs and component sizing show how important a proper system configuration and sizing of the main components are. Poor configuration and design can lead to very poor performance. In this paper, the simulated period was limited to the fifth of five years in order to reduce computation time. An extended study could be made with the optimization of such systems and later using different backup systems, design variables, seasonal storages, and different soil conditions. The results of this study may attract the interest of designers and contractors in using such ST systems in Nordic regions and cold climates.

Acknowledgements

This work has been funded by the Academy of Finland through the New Energy research program.

References

[1] The European Parliament and the Council of the European Union, "Directive 2010/31/EU of the European Parliament and of the council of 19 May 2010 on the energy performance of buildings".

[2] Official Statistics of Finland (OSF), " Energy consumption in households [e-publication]," ISSN=2323-329X, 20 Nov 2015. [Online]. Available: http://www.stat.fi/til/asas/index_en.html. [Accessed 2016].

[3] Official Statistics of Finland (OSF), "Dwellings and housing conditions [e-publication]," ISSN=1798-6761, 24 May 2016. [Online]. Available: http://www.stat.fi/til/asas/index_en.html. [Accessed 2016].

[4] Official Statistics of Finland (OSF), "Energy supply and consumption [e-publication]," ISSN=1799-7976, 22 Jun 2016. [Online]. Available: http://www.stat.fi/til/ehk/index_en.html. [Accessed 2016].

[5] B.Bose, "Global warming: Energy, enviornmental pollution and the impact of power electronics," *IEEE Industrial Electronics Magzine,* vol. 4, no. 1, pp. 6-17, 2016.

[6] K. M. R. A. &. K. S. Riku Pasonen, "Arctic solar energy solutions, VTT Technical Research Centre of Finland, ISBN 978-951-38-7825-2," 2012. [Online]. Available: http://www.vtt.fi/inf/pdf/technology/2012/T15.pdf. [Accessed 2016].

[7] K. Jylhä, K. Ruosteenoja, J. Jokisalo, K. Pilli-Sihvola and T. Kalamees, "Hourly test reference weather data in the changing climate of Finland for building energy simulations," *Data in Brief,* vol. 4, p. 162–169, September 2015.

[8] International Energy Agency Solar Heating and Cooling Programme, IEA-SHC, Task 32, "Task 32 - Advanced Storage Concepts for Solar and Low Energy Buildings," [Online]. Available: http://archive.iea-shc.org/task32/. [Accessed 15 9 2016].

[9] European solar thermal industry federation(ESTIF), "Solar thermal markets in Europe," [Online]. Available: www.estif.org. [Accessed 2016].

[10] J.-O. Dalenbäck and S. Werner, "Market for Solar District Heating, WP2 – European Market Study," CIT Energy Management AB, [Online]. Available: http://solar-district-heating.eu/portals/0/sdh-wp2-d2-3-market-aug2012.pdf. [Accessed 15 9 2016].

[11] S. T, M. D and M.-S. H, "Seasonal thermal energy storage in Germany," in *ISES Solar World Congres*, Goteborg, Schweden, 2003.

[12] S. T, M. D and M.-S. H, "Central solar heating plants with seasonal storage in Germany," *Solar Energy,* vol. 76, pp. 165-174, 2004.

[13] International Energy Agency Solar Heating and Cooling Programme, IEA-SHC, Task 7, "Task 7-Central Solar Heating Plants With Seasonal Storage," [Online]. Available: http://task07.iea-shc.org/. [Accessed 2016].

[14] S. T, M. D and M.-S. H, "Central solar heating plants with seasonal storage in Germany," in *ISES solar world congress*, Adelaide, Australia, 2001.

[15] J. E. Nielsen, "IEA-SHC Task 45: Large Solar Heating/Cooling Systems, Seasonal Storage, Heat Pumps," *Energy Procedia, 1st International Conference on Solar Heating and Coolingfor Buildings and Industry (SHC 2012),* vol. 30, pp. 849-855, 2012.

[16] Solar District Heating, "Ranking List of European Large Scale Solar Heating Plants," [Online]. Available: http://solar-district-heating.eu/ServicesTools/Plantdatabase.aspx. [Accessed 2016].

[17] D. Mangold, "Seasonal storage – a German success story," *Sun Wind Energy,* vol. 1, pp. 48-58, 2007.

[18] M. Lundh and J.-O. Dalenbäck, "Swedish solar heated residential area with seasonal storage in rock: Initial evaluation," *Renewable Energy,* vol. 33, no. 4, p. 703–711, 2008.

[19] D. Bauer, R. Marx, J. Nußbicker-Lux, F. Ochs, W. Heidemann and H. Müller-Steinhagen, "German central solar heating plants with seasonal heat storage," *Solar Energy,* vol. 84, no. 4, pp. 612-623, 2010.

[20] SOLPROS-enhancing sustainability effectively, "Ekoviikin EU-aurinkolämpöjärjestelmien,LOPPURAPORTTI (In Finnish)," SOLPROS, Helsinki, 2004.

[21] T. P. McDowell and J. W. Thornton, "Simulation and Model Calibration of a Large-Scale Solar Seasonal Storage System," in *IBPSA-USA (International Building Performance Simulation Association USA Chapter) Conference Proceedings*, Berkeley, California, August 2008.

[22] B. Sibbitt, D. McClenahan, R. Djebbar, J. Thornton, B. Wong, J. Carriere and J. Kokko, "The Performance of a High Solar Fraction Seasonal Storage District Heating System – Five Years of Operation," *Energy Procedia, 1st International Conference on Solar Heating and Coolingfor Buildings and Industry (SHC 2012),* vol. 30, pp. 856-865, 2012.

[23] S. V. Obydenkova and J. M. Pearce, "Technical viability of mobile solar photovoltaic systems for indigenous nomadic communities in northern latitudes," *Renewable Energy,* vol. 89, pp. 253-267, 2016.

[24] A. Shariah and B. Shalabi, "Optimal design for a thermosyphon solar water heater," *Renewable Energy,* vol. 11, no. 3, pp. 351-361, 1997.

[25] B. Nordell, "Large-scale Thermal Energy Storage, Lulea, Sweden," 2000. [Online]. Available: http://large.stanford.edu/courses/2013/ph240/lim1/docs/nordell.pdf. [Accessed 2016].

[26] M. Fisch, M. Guigas and J. Dalenbäck, "A review of large-scale solar heating systems in Europe," *Solar Energy,* vol. 63, no. 6, p. 355–366, 1998.

[27] F. M. Rad and A. S. Fung, "Solar community heating and cooling system with borehole thermal energy storage – Review of systems," *Renewable and Sustainable Energy Reviews,* vol. 60, p. 1550–1561, 2016.

[28] G. K. Pavlov and B. W. Olesen, "Seasonal solar thermal energy storage through ground heat exchangers –Review of systems and applications," in *6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems*, Dubrovnik, Croatia, 2011.

[29] L. G. SOCACIU, "Seasonal Sensible Thermal Energy Storage Solutions," *Leonardo Electronic Journal, ISSN 1583-1078, http://lejpt.academicdirect.org/A19/049_068.pdf,* no. 19, pp. 49-68, 2011.

[30] M. Honkonen, "Thermal energy storage concepts and their feasibility," Aalto University, Civil engineering,Rock mechanics, Master's thesis(Rak-32), Espoo, Finland, 2016.

[31] I. Kukkonen and S. Peltoniemi, "Relationships between Thermal and other Petrofysical Properties of Rocks in Finland," *Physics and Chemistry of the Earth,* vol. 23, no. 3, pp. 341-349, 1998.

[32] GTK Geologian Tutkimuskeskus, "Pohjaveden synty ja esiintyminen (In Finnish)," 2005. [Online]. Available: http://weppi.gtk.fi/aineistot/mp-opas/pohjav_esiintyminen.htm. [Accessed 1 October 2016].

[33] S. Chapuis and M. Bernier, "Seasonal Storage of solar energy in borehole heat exchangers," in *Eleven International*

IBPSA Building simulation Conference, Glasgow,Scotland, 2009.
[34] D. Qv, L. Ni, Y. Yao and W. Hu, "Reliability verification of a solareair source heat pump system with PCM energy storage in operating strategy transition," *Renewable Energy,* vol. 84, pp. 46-55, 2015.
[35] X. Wang, M. Zheng, W. Zhang, S. Zhang and T. Yang, "Experimental study of a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage in severe cold areas," *Energy and Buildings,* vol. 42, no. 11, p. 2104–2110, 2010.
[36] F. M. Rad, A. S. Fung and W. H. Leong, "Feasibility of combined solar thermal and ground source heat pump systems in cold climate, Canada," *Energy and Buildings,* vol. 61, p. 224–232, 2013.
[37] D. Neves and C. A. Silva, "Modeling the impact of integrating solar thermal systems and heat pumps for domestic hot water in electric systems-The case study of Corvo Island," *Renewable Energy,* vol. 72, pp. 113-124, 2014.
[38] H. U. Rehman, "Experimental performance evaluation of solid concrete and dry insulation materials for passive buildings in hot and humid climatic conditions," *Applied Energy,* Vols. Volume 185, Part 2, p. 1585–1594, 2017.
[39] J.-C. Hadorn, "International Energy Agency Solar Heating & Cooling Programme; Thermal energy storage for solar and low energy buildings – State of the art. IEA Solar Heating and Cooling Programme. Task 32," Edicions de la Universitat de Lleida,ISBN: 84-8409-877-X, Lleida, Edicions de la Universitat de Lleida, 2005.
[40] J. Smeds and M. Wall, "Enhanced energy conservation in houses through high performance design," *Energy and Buildings,* vol. 39, no. 3, p. 273–278, 2007.
[41] C. Flynn and K. Siren, "Influence of location and design on the performance of a solar district heating system equipped with a borehole seasonal storage," *Renewable Energy,* vol. 81, pp. 377-388, 2015.
[42] J.Persson and M.Westermark, "Low energy buildings and seasonal thermal energy storages from a behavioral economics perspective," *Applied Energy,* vol. 112, pp. 975-980, 2013.
[43] H. u. Rehman, J. Hirvonen and K. Sirén, "Design of a Simple Control Strategy for a Community-size Solar Heating System with a Seasonal Storage," *Energy Procedia,* vol. 91, p. 486–495, 2016.
[44] S. Cao, A. Hasan and K. Sirén, "On-site energy matching indices for buildings with energy conversion, storage and hybrid grid connections," *Energy and Buildings,* vol. 64, p. 423–438, 2013.
[45] K. S. e. al., "TRNSYS—a transient systems simulation program, Version 17.1, Solar Energy Laboratory, University of Wisconsin-Madison; 2009–2012.".
[46] C. Montagud, J. M. Corberán and F. Ruiz-Calvo, "Experimental and modeling analysis of a ground source heat pump system," *Applied Energy,* vol. 109, p. 328–336, 2013.
[47] N. Gohl, D. Bauer and H. Drück, "1to10 – a Cost-effective Heat Supply Concept with Low Primary Energy Consumption for Multi-family Houses and Small Residential Areas," *Energy Procedia,* vol. 91, pp. 460-466, 2016.
[48] T. Idman, "Parametrization of energy simulation and development of energy-efficient building design analysis and decision making process, Master Thesis," Aalto University School of Engineering, Department of Energy Technology, Espoo, Finland, 2013.
[49] GREENoneTEC Solarindustrie GmbH, "GK 3000 series large-surface collectors," 9 2015. [Online]. Available: http://www.greenonetec.com/fileadmin/user_upload/downloads/Produktdatenblaetter/3003_en_PDB_2015-09.pdf. [Accessed 2015].
[50] CIT Energy Management AB, EU report, April 2011. [Online]. Available: http://www.energy-management.se/;http://sunstore4.eu/download/member-area/wp5/EU%20report-WP5-deliverable%205%204_Feasibility%20simulation%20studies.pdf. [Accessed 2016].
[51] O. Ozgener, L. Ozgener and J. Tester, "A practical approach to predict soil temperature variations for geothetmal (ground) heat exchangers applications," *International Journal Heat Mass Transfer,* vol. 62, pp. 473-480, 2013.
[52] AXITEC Solar, "AXI Power," [Online]. Available: www.axitecsolar.com. [Accessed 2016].
[53] World Geodetic System WGS84 standard, 2012-2016. [Online]. Available: http://www.latlong.net/place/helsinki-finland-1668.html. [Accessed 2016].
[54] Ministry of the Environment, Department of the Built Environment, "D5 National Building Code of Finland, Calculation of power and energy needs for heating of buildings, Guidelines 2012,DRAFT 28 September 2010," 2010. [Online]. Available: http://www.puntofocal.gov.ar/notific_otros_miembros/fin43_t.pdf. [Accessed 2016].
[55] M. Hamdy, A. Hasan and K. Siren, "A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010," *Energy and Buildings,* vol. 56, p. 189–203, 2013.
[56] S. K. Pal, K. Alanne, J. Jokisalo and K. Siren, "Energy performance and economic viability of advanced window technologies for a new Finnish townhouse concept," *Applied Energy,* vol. 162, p. 11–20, 2016.
[57] J. Shemeikka and A. Laitinen, "Specification of RET-single family house," echnical Research Centre of Finland VTT, Building and Transport, Version 2.0(in Finnish), 2005.
[58] M. Hamdy, A. Hasan and K. Siren, "Applying a multi-objective optimization approach for design of low-emission cost-effective dwellings," *Building and Environment,* vol. 46, no. 1, p. 109–123, 2011.
[59] Ministry of the Environment, Housing and Building Department, "C3 National Building Code of Finland, Thermal

insulation in a building, regulation," Ministry of the Environment, Housing and Building Department,Finland, 2010.

[60] Finnish Meteorological Institute, "Weather and climate in Finland," 31 5 2012 . [Online]. Available: http://en.ilmatieteenlaitos.fi/. [Accessed 3 10 2016].

[61] J. Wright, E. Nikolaidou and C. J.Hopfe, "Exhaustive search: Does it have a role in explorative design?," in *BSO 2016-Building Simulation & Optimization 2016*, Newcastle, UK, 2016.

[62] Investopedia, "Sensitivity Analysis," 2016. [Online]. Available: http://www.investopedia.com/terms/s/sensitivityanalysis.asp. [Accessed 2016].

[63] A. Silva and E. Ghisi, "Uncertainty Analysis of User Behaviour and Physical Parameters in Residential Building Performance Simulation," *Energy and Buildings,* vol. 76, pp. 381-391, 2014.

[64] J. Helton, J. Johnson, C. Sallaberry and C. Storlie, "Survey of Sampling-Based Methods for Uncertainty and Sensitivity Analysis," *Reliability Engineering & System Safety,* vol. 91, no. 10-11, pp. 1175-1209, 2006.

[65] W. Tian, "A Review of Sensitivity Analysis Methods in Building Energy Analysis," *Renewable and Sustainable Energy Reviews,* vol. 20, pp. 411-419, 2013.

[66] Y. Haahtela and J. Kiiras, Talonrakennuksen kustannustieto 2013 (Building construction cost data 2013) in Finnish, Helsinki: Haahtela-kehitys, ISBN:9789525403213 , 2013.

[67] Solar district heating, "Solar district heating guidelines-storage," August 2012. [Online]. Available: http://solar-district-heating.eu/Portals/0/Factsheets/SDH-WP3_FS-7-2_Storage_version3.pdf. [Accessed 2016].

[68] D. Mangold and T. Schmidt, "The next Generations of Seasonal Thermal Energy Storage in Germany," Solites-Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems, http://www.solites.de/download/literatur/07-Mangold_ESTEC%202007.pdf , Stuttgart, Germany .

[69] Nord Pool, "FI-Elspot prices," 2016. [Online]. Available: https://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/ALL1/Hourly/?view=table. [Accessed 20 April 2017].

[70] EUROPEAN COMMISSION, "COMMISSION DELEGATED REGULATION c(2011) 10050," 16 1 2012. [Online]. Available: http://ec.europa.eu/transparency/regdoc/rep/3/2011/EN/3-2011-10050-EN-F1-1.Pdf. [Accessed 20 April 2017].

[71] Mathias Aarre Maehlum, "Energy Informative-The Real Lifespan of Solar Panels," 7 May 2017. [Online]. Available: http://energyinformative.org/lifespan-solar-panels/. [Accessed 20 April 2017].

[72] The Renewable Energy Hub, "Solar thermal system lifespan, maintenance and warranties," [Online]. Available: https://www.renewableenergyhub.co.uk/solar-thermal-information/solar-thermal-system-lifespan-maintenance-and-warranties.html. [Accessed 24 April 2017].

Highlights

- Assessed three different solar district heating typologies for Nordic climate.
- Various parameters of solar heating systems including houses were studied together.
- Large seasonal storage was beneficial in system II and III and less in system I.
- Renewable energy fraction of 53-81% was achieved depending upon system considered.
- Having more than 4000 m^2 solar thermal area had minimal benefits.