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Performance comparison between optimized design of a centralized and semi-decentralized community size solar district heating system

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Abstract

Solar thermal energy is widely recognized as one of the most important renewable energy resources. However, in high latitudes, due to various climatic and mismatch challenges, such solar district heating networks are difficult to implement. The objective of the paper is to optimize and compare two different design layouts and control strategies for solar district heating systems in Finnish conditions. The two different designs proposed are a centralized and a semi-decentralized solar district heating system. The centralized system consists of two centralized short-term tanks operating at different temperature levels charged by a solar collector and heat pumps. Borehole thermal energy storage is also charged via these two centralized tanks. In contrast, the semi-decentralized system consists of one centralized low temperature tank charged by a solar collector and a borehole thermal energy storage and decentralized high temperature tank charged by an individual heat pump in each house. In this case, borehole thermal energy storage is charged only by the centralized warm tank. These systems are designed using the dynamic simulation software TRNSYS for Finnish conditions. Later on, multi-objective optimization is carried out with a genetic algorithm using the MOBO (Multi-objective building optimizer) optimization tool, where two objectives, i.e. purchased electricity and life cycle costs, are minimized. Various design variables are considered, which included both component sizes and control parameters as inputs to the optimization. The optimization results show that in terms of life cycle cost and purchased electricity, the decentralized system clearly outperforms the centralized system. With a similar energy performance, the reduction in life cycle cost is up to 35% for the decentralized system. Both systems can achieve close to 90% renewable energy fraction. These systems are also sensitive to the prices. Furthermore, the results show that the solar thermal collector area and seasonal storage volume can be reduced in a decentralized system to reduce the cost compared to a centralized system. The losses in the centralized system are 40 – 12% higher compared to the decentralized system. The results also show that in both systems, high performance is achieved when the borehole storage is wider with less depth, as it allows better direct utilization of seasonally stored heat. The system layout and controls varied the performance and life cycle cost; therefore it is essential to consider these when implementing such systems.

Keywords: Solar community; seasonal storage; centralized solar district; decentralized solar district; cold climate; multi-objective optimization.

Nomenclature

a_e	Discounting factor
BTES	Borehole thermal energy system
C_B	Building investment cost (€/m ²)
C_{BTES}	Borehole cost (€/m ³)
C_E	Exported electricity price (c/kWh)
C_{Fins}	Building floor insulation cost (€/m ³)
C_{HR}	Building heat recovery cost (€)
C_{HT}	Hot tank cost (€/m ³)
C_I	Imported electricity price (c/kWh)
C_{PV}	Photovoltaic panels cost (€/m ²)
C_{Rins}	Building roof insulation cost (€/m ³)
C_{ST}	Solar thermal collectors cost (€/m ²)
C_{WIND}	Building windows cost (€/m ²)
C_{Wins}	Building walls insulation cost (€/m ³)
C_{WT}	Warm tank cost (€/m ³)
CO_2	Carbon dioxide
COP	Coefficient of performance
DHW	Domestic hot water
DLSC	Drake Landing Solar Community
e_p	Electricity price escalation rate
E_{BH}	Direct electric backup heater electricity consumption (kWh/m ² /yr)

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E_{BUL}	Building appliances electricity consumption (kWh/m ² /yr)
E_{DEM}	Total electricity demand of the system (kWh/m ² /yr)
E_{EXP}	Exported electricity to the grid (kWh/m ² /yr)
E_{HP}	Heat pump electricity consumption (kWh/m ² /yr)
E_{ONC}	On-site electricity demand, met by photo voltaic panel generation (kWh/m ² /yr)
E_{PUMP}	Auxiliary pumps electricity consumption (kWh/m ² /yr)
E_{PUR}	Purchased electricity from the grid (kWh/m ² /yr)
E_{PV}	Electricity produced by the photovoltaic panels (kWh/m ² /yr)
ESTIF	European solar thermal industry federation
EU	European Union
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
i_r	Interest rate
IEA	International energy agency
LCC	Life cycle costs
LCOE	Levelized cost of electricity
MOBO	Multi-objective building optimizer
NSGA-II	Non-dominated Sorting Genetic Algorithm II
OE_{elec}	Onsite energy fraction for electricity
OSF	Official statistics of Finland
PV	Photo voltaic panels
REF_{heat}	Renewable energy fraction for heating
SPH	Space heating
ST	Solar thermal collectors
TES	Thermal energy storage

1. Introduction

Global energy consumption has been growing in the last few decades. Moreover, the combustion of fossil fuels for energy production has resulted in a huge environmental problems and emissions. Therefore, the increase in energy prices, the reduction in fossil fuel resources, and the impact on climate change have forced the masses to explore alternative and renewable sources in order to provide a sustainable future. On any sunny day, solar energy systems collect more energy than is needed for direct use [1]. Solar thermal is one of the most attractive renewable energy technologies and has huge market potential. . It has been predicted that by 2020, the European Union (EU) will reach a total operational solar thermal capacity of around 320 GW [2]. However, the challenge is to develop efficient methods to collect, convert, store and utilize solar energy at affordable cost [3]. There are two main drawbacks in developing solar heating systems in Nordic region: (1) the resulting energy costs are not yet competitive and (2) solar energy is not available when needed. Research efforts are being made to develop methodologies that can help to overcome these challenges-developing low cost solar energy system architecture is one of those methodology [4].

The key to develop a low cost and high performing solar heating system is to build a large scale community sized solar heating networks, instead of a small or single building level heating system. Generally the main advantage of community sized district heating systems is their environmental benefits compared to a single building heating system [5]. It is found that a community-scale system and district heating are more beneficial than a single-house scale [6], as each building has a unique energy demand profile due to the different schedules in people's lives. This means that for a building cluster, a local energy generation or storage system can be sized to a lower capacity than for a single building [7]. A community has more controllable loads than a single building, therefore the matching is better. One option for a communal energy system is the centralized design where many buildings utilize a shared system. In a single-scale design, each building has its own generation and storage [8]. Joining single-building generation and energy storage units and controlling them centrally can improve the energy performance of the community [9]. Micro-girds are also proposed as an alternative to single building energy systems, where a micro grid can be built within the neighbourhood to share the energy [10]. A probabilistic portfolio-based model for financial valuation of community solar is proposed by Shakouri et al. and they found that community sized systems has shortest payback period [11]. The benefit of community is that the unit price is lower for large systems than for small systems [12], and large seasonal storage is feasible in large-scale applications [13].

In a community-sized solar energy system, heat storage can play an important role due to the mismatch between the demand and the generation. The cost advantage, due to the size and ability to operate at a seasonal scale allows ground thermal storage to be feasible technically and economically compared to short term storage [14]. Moreover, the integration of seasonal storage in district heating network has the potential to mitigate the CO₂ [15]. Among many types

of ground storage, borehole thermal energy storage (BTES) is more attractive than other methods of seasonal storages. The main reasons are: its simplicity of design, its adaptability, its flexibility in term of the location and its cost effectiveness [16]. The issue with ground thermal storage is the heat loss [17]. The ground stores the heat in sensible form. To maximize the performance of the storage the heat loss needs to be minimized. The losses through the BTES depend on two main ground properties which are (1) thermal conductivity of the boundary layer and (2) groundwater level. Therefore, it is necessary to estimate the ground storage temperature to predict the losses and thermal conductivity of the ground. Beier et al. [18] provided an analytical model to estimate the vertical temperature profile of the ground storage. Numerical model is proposed to optimize the BTES operation by simulation, the objective is to minimize the losses through the BTES [19]. Spitler et al. [20] modelled techniques to reduce the losses in the BTES. They proposed that instead of low permeability grout, groundwater is filled in the annular space between the U-tube and the borehole wall. Welsch et al. [21] performed simulation to investigate the environmental and economic benefits of integrating borehole thermal energy storage in district heating network. It is found that with growing share of renewable energy mix, a combination of solar thermal, combined heat and power plant and borehole thermal energy storage can be economical with no subsidies. In the present study borehole thermal energy storage is used as seasonal storage. The average thermal ground conductivity of rocks in Finland is around 3.2-3.5 W/m.K, the ground water is located at the depth of 1-4 m below the surface and, the bedrock in Finland is unbroken with little or no ground water flow [22].

Majority of the solar heating networks are designed to meet the space heating demand only. This approach allows lowering the losses in the storage [23]. The lower temperature can be raised using a heat pump (HP) depending on the demand. Heat pumps are economical [24] and the primary energy consumption of heat pump is lower than coal-fired boiler, gas boiler, direct electric heating mode therefore it is environmentally friendly [25]. Heat pump can be used with or without solar charged ground storage [24]. It is beneficial to charge the ground with solar energy as it can provides higher temperature at the evaporator side of the heat pump. Many simulations are done to analyse solar district heating systems. A solar-assisted heat pump heating system is modelled using TRNSYS software and compared to a traditional solar domestic hot water system and an electric domestic hot water system. The results showed that a dual tank indirect-style solar-assisted heat pump system is energy efficient and had the lowest annual operating costs [26]. It is also found that by utilizing solar energy and a heat pump, the system could provide 83-97% and 50% of the hot water demands in summer and winter, respectively [27]. Two TRNSYS simulation models of heating network with heat pumps are compared by Poppi et al. [28] and it is found that heat pump integrated with solar thermal collector performed better than the one without solar collector. In China, studies showed that a solar-assisted air source heat pump can provide up to 60% of the heat via solar energy in cold regions [29]. In cold regions, if heat pump is used without solar thermal heat stored in the ground it can cause soil thermal imbalances in seasonal storage [30], and it can greatly deteriorate the system practical performance as well. Therefore, a system has to be designed with optimum control strategies to maintain better soil thermal balance [30]. The ground storage connection controls can also alter the heat pump performance [31]. Many strategies can be used to integrate heat pump with solar energy. In Finland, heat pumps integrated with solar thermal collector and seasonal storages have not yet been widely used for a community size, and this approach has been considered in present study.

Another important parameter in the community is the building. Buildings can play a significant role in the early design stage of such solar district heating systems. The building needs to be constructed according to the advance standards to improve the efficiency [32]. Especially in the cold regions, where the heating demands are high, energy efficiency is an important design parameter while designing solar energy systems [33]. Usually buildings are studied separately while district energy systems are designed separately [34]. Therefore, when such large solar heating systems are integrated with the actual buildings, the performance is not up to the expectations [34]. An integrated design approach is needed where both the buildings as a design variable and the solar district heating networks are modelled and simulated together for the Nordic Conditions to estimate the behaviour of the whole system.

In addition to modelling and simulation, a few solar district heating plants have been built for real applications in the world. In Europe since 1970s till 2011 around 141 large scale solar heating plants have been built. All these plants have solar collector area of 500 m² or above [35]. There are pilot scale plants located in Germany [36] and Sweden [37]. For instance, in Germany, four types of storage units have been developed for seasonal storage. The first pilot systems for a solar district heating supply with long-term heat storage went into operation in 1996 in Hamburg. Similar projects had been built in Neckarsulm to provide solar district heating to the community. The differences between these projects are the process layouts and storages [38]. Currently the solar district heating market is on the rise in Denmark due to its competitive price in comparison to the gas [39]. Hybrid solar district heating plant with collector and parabolic trough collector are designed and tested in Denmark [40]. At Marstal, Denmark, a 9,000 m² solar collector has been used to provide heat to 1,469 end users with a yearly demand of 28,000 MWh. The system is able to provide a solar fraction of 30%. Here the solar fraction is defined as the ratio between the solar heat generated and the heat demand [40]. It is found solar fraction can vary seasonally. Experiments show that the solar fraction can be very high in the summer when the heat load is low and the weather is sunny. On the other hand, during winters, when solar radiation is low, the

collector produces low quantity of solar heat. Therefore, the solar fraction in the winter can be very low. This phenomenon is usual for the Nordic regions [40]. The whole system is centralized with a back wood chip boiler [41]. Several small-scale solar district heating systems with various seasonal storages have been built and put into operation, e.g. in Bilbao, Spain and Warsaw, Poland. The system in Bilbao provides space heating for a building of around 1,000 m². It has ground hot water storage integrated with a heat pump and gas boiler to provide heating for the buildings [34]. Similarly in Warsaw, a small-scale district heating network is built to provide space heating for a hospital building. It also has a hot water tank integrated with a heat pump and gas boiler [34]. Various district heating systems have been realized in Northern America, for instance in Drake Landing Solar Community, Canada [42]. In China it is also being studied to utilize solar based energy system for the future demand [43]. In Finland, Eko-Viikki is a test site for ecological construction located in southern Latokartano, Helsinki. The apartments are provided heat via solar energy. However, reports are found that mentioned that the average energy demand of the solar district heating demand exceeded expectations [44]. Therefore, the system did not perform as expected.

It is found in the literature that solar district heating energy systems are widely divided into two broader typologies, i.e. centralized and decentralized systems. First, in the centralized system, all the heat generation, storage and supply are at a central location. Most of the plants built in Germany and Denmark are centralized plants. The solar district heating network plants are mostly operated at higher temperatures [45]. The storage and distribution network are usually centralized. Secondly, the system can be partially decentralized (decentralized system), where usually the heat generation and seasonal storage are centralized, while supply and short term storage tanks are decentralized. A new housing area is proposed in Zum Feld lager, Germany. The area consists of 131 buildings on a land area of 115,000 m². To provide the buildings with space heating a semi-decentralized district network is proposed by the authors instead of a complete distributed system [46]. In proposed study the distribution supply temperature in semi-decentralized system is assumed to be 40 °C, which is lower than 70 °C supply temperature if the system is assumed to be completely centralized. The simulation results showed that in the centralized district heating network ≈ 18 % distribution heat losses occur within one operating year. On the other hand, in the decentralized district heating network ≈ 5.5 % distribution heat losses occurs [46]. District networks has an advantage to the economy of scale, where large size components that can be installed at a district scale can be cheaper compared to smaller size components that can be installed at a building scale level. Moreover, to make the district network competitive the distribution network needs to be highly efficient (lower losses) in order to ensure economic feasibility. Another study [47] simulated two cascade heat pump system without solar energy, where central heat pump distributed low temperature in central network while small booster heat pump is used to provide high temperature in the building. This improved the heat pump performance and reduced the losses in the network [47]. Similarly, in the Drake Landing Solar Community in Canada, space heating is provided through a centralized system, where distribution, generation and storage are centralized [42], while domestic hot water is provided through separate distributed collector and storage tanks in each house. In present study both concepts of the centralized and semi-decentralized solar heating systems are designed and compared against each other for Nordic conditions.

A community sized solar district heating network integrated with heat pump, buildings and borehole thermal energy system has neither been fully investigate nor applied in Finnish conditions [14]. As discussed above the challenges in developing such systems in Nordic conditions needs to be taken into account. Moreover, systems from other countries cannot be transferred directly to a new location due to different weather and ground conditions [48]. Therefore, such issues call for a system that is adapted to the local conditions and designed accordingly. It is also important to optimize the system based on the local conditions. Due to the complexity of the energy system design, variation in the energy production by the solar collector and the costs, it is difficult to find the best combinations of the design variables. Therefore, multi-objective optimization is needed to resolve such issues [49].

The novelty in this paper is the design of two novel solar district heating networks typologies i.e. centralized and semi-decentralized solar district heating systems and their control strategies in Nordic conditions. In the proposed architectures, controlled changes are made such that both centralized and semi-decentralized systems are closely comparable. At the same time both the systems are multi-objective optimized. The objective and aim of this research is to optimize, compare and investigate the differences in the performances of two different concepts in Northern European conditions—i.e., centralized and semi-decentralized solar district heating. Two different types of configurations are proposed, and the impact of each particular configuration on the final energy consumption has been evaluated. Purchased electricity and life cycle cost (LCC) are the two objectives that are minimized. In addition, the heating renewable energy fraction and onsite energy fraction for electricity are also evaluated to analyse overall performance. Both the physical and control parameters are considered as design variables. Additionally, the sensitivity of both the proposed systems with respect to the prices and the physical components are carried out and compared. The design variables considered for the optimization are solar thermal (ST) area, photovoltaic panels area, short-term storage tank volume, borehole volume, borehole aspect ratio and density, hot and warm tank charging set points, and building design. Furthermore, a detailed focus is on the set points and the borehole shapes. The study is performed

using the dynamic simulations approach using TRNSYS [50] due to the complexity of the proposed system. MOBO (multi-objective building optimizer) [51] is used to run the NSGA-II algorithm and TRNSYS model together for the optimization of the two objectives. The scope of the study is limited to the computational study. The purpose is to provide basic knowledge and computational model for the future real plant in Finland, as no such solar district heating network projects exists in Finland. However, to verify and compare the TRNSYS model in Finnish conditions, the presented simulation model is compared against three real projects, namely in Neckarsulm-Germany [52], in Carlsheim-Germany [36], and in Drake Landing Solar Community-Canada [42]. The simulation result is compared against these real projects because, no such solar community district heating network project exists in Finland at the moment and these projects are somehow close to the working principles of the presented models.

2. Energy systems

Two distinct large scale solar district heating networks typologies are designed for cold climate in the paper. In order to show the benefits of the proposed community sized solar district heating networks a reference case is also used.

2.1. Proposed community sized solar district network: Centralized and Semi-decentralized systems

The study is performed for a virtual Finnish community with two different and dedicated solar district heating networks. It is modelled on TRNSYS 17 introduced earlier in [53], and dynamic simulations are performed.

The community consists of 100 houses with a heated area of 100 m² each. Generally, in both the energy systems, solar thermal collectors are used to collect heat and store it in short-term tanks operating at two temperature levels. Excess energy is stored in the borehole thermal energy storage (BTES) system. A heat pump is integrated to provide heat energy in the absence of solar energy. The on-site electricity is generated through photovoltaic (PV) panels. The on-site demand of the energy system (pumps, heat pumps and backup electric heaters) and building appliances are primarily met through locally generated solar electricity. Furthermore, electricity is imported or exported via a grid to compensate for the mismatch between electricity demand and generation. The main features and differences between the two proposed energy systems are described below. In addition to the two proposed energy systems a reference case is simulated for the comparisons.

The first concept introduced in this paper is inspired by a previously published study, a Danish project in Braedstrup and a German project in Carlsheim [54] where borehole are used as seasonal storage. However, the difference is in the seasonal storage and heat pump integration in this study. In this paper, the word ‘centralization’ and ‘semi-decentralization’ is used to define the heating network and thermal heat generation typology. Photovoltaic panels and electricity generation are centralized in both the cases. The schematic representation is shown in Figure 1. The energy system consists of:

- Centralized system (Figure 1):
 - A central collector (ST) field.
 - Centralized photovoltaic panels (PV) in an open central field.
 - Two large centralized short-term storage tanks, i.e. warm and hot tanks present at a centralized energy building.
 - Warm and hot tanks also known as short term storage tanks, are charged in parallel by the collector during the summer.
 - Borehole thermal energy storage (BTES) is located in the energy centre at a centralized location. It is charged via the warm and hot tanks if excess energy is available in the tanks.
 - A central heat pump (HP) is used to charge a hot tank by taking heat energy from a warm tank during periods when solar energy is not available.
 - Domestic hot water (DHW) and space heating (SPH) is provided through this centralized system.

Figure 1. Simple schematic representation of the centralized energy system.

The second concept is a semi-decentralized concept based on a low temperature district heating network. It has decentralized domestic hot water and centralized low temperature seasonal storage. It is based on the Canadian experience regarding centralized low temperature networks [42]. However, the difference in both systems is that in the Canadian project, domestic hot water is not integrated with the centralized energy system and therefore is not included in the system performance calculations. In the current paper, the decentralized hot water is integrated with the system and included in the overall system performance calculations. Although the decentralized system is a semi-decentralized system, for ease of understanding, it is referred to as a decentralized system in the manuscript. The schematic representation is shown in Figure 2. The centralized section of the energy system (i.e. the solar thermal collector, photovoltaic panels, seasonal storage and warm tank) along with the decentralized section of the energy system (i.e. the heat pump and the hot tank in each house) is shown in Figure 2. The heat supply system consists of:

- Semi-decentralized system (Figure 2):
 - A central collector (ST) field.
 - Centralized photovoltaic panels (PV) in an open central field.
 - It is a semi-centralized system where the low temperature warm tank is large and centralized in the energy building while small hot tanks are distributed in each house. Both the tanks are also known as short term storage tanks.
 - Solar thermal collector (ST) charges the warm tank only during summer.
 - Borehole thermal energy storage (BTES) is located in the energy centre at a centralized location. It is charged via the warm tank only if excess energy is available in the tanks.
 - Distributed heat pumps (HP) are used to charge distributed hot tanks by taking heat energy from space heating (SPH) return network.
 - The domestic hot water (DHW) is provided through the decentralized hot tanks, and space heating (SPH) is provided mainly from the centralized warm tank.

Figure 2. Simple schematic representation of the decentralized energy system.

2.2. The system controls description

Both the centralized and decentralized system is designed to maximize the use of solar energy. Solar energy is used to meet the heating demand and also to charge the borehole thermal energy storage. The overall control strategies of both systems are described here. The individual features of each of the energy systems are described in the following subsections of the paper (2.2.1 and 2.2.2).

2.2.1. Centralized system

The solar thermal is first used to charge the short-term tanks, and if solar energy is not available, the borehole and heat pump are used to charge the short-term tanks, while the short-term tanks are used to provide space heating and domestic hot water (DHW) to the buildings. If the warm tank temperature is lower than 40 °C, it is heated to 45 °C. Similarly, if the hot tank temperature is lower than 65 °C, it is heated to 70 °C by the collector. If no energy is available from the collector, the heat is transferred directly from the BTES to the warm tank. If the warm tank temperature is lower than 35 °C and the BTES average temperature is higher than the warm tank top temperature, the tank is charged via the BTES. For the hot tank, if the temperature is lower than 60 °C, it is charged to 65 °C by the centralized heat pump. The heat pump takes energy from the warm tank. Any excess energy is transferred to the BTES from both the hot and warm tanks in order to charge the seasonal storage. BTES is charged by both tanks. If the warm tank temperature is higher than 50 °C, the heat is transferred to the BTES until it reaches 45 °C. Similarly, if the hot tank temperature is higher than 75 °C, the heat is transferred to the BTES until it reaches 70 °C [53].

Space heating is provided by passing the water through the warm tank and through the bottom node of the hot tank to provide space heating to the houses between 27 °C to 40 °C, depending on the outdoor temperature. The domestic hot water (DHW) is provided by passing the cold water through both the warm and hot tanks [53]. The water is heated up to 58 °C before being supplied to the tap. There is also backup heating provided by a direct electric heater in case the system is not able to provide sufficient heat. The schematic representation is shown in Figure 1.

2.2.2. Decentralized system

In this setup, a centralized warm tank is charged only via a collector. If the warm tank temperature is lower than 40 °C, it is heated to 45 °C by the collector. The BTES is charged only by the warm tank (in contrast to the centralized energy system, where the BTES is charged by both the warm tanks and the hot tanks). If the warm tank temperature is higher

than 50 °C, excess heat is transferred to the BTES until it reaches 45 °C. When solar energy is not available, the warm tank is charged via the BTES directly. If the warm tank temperature is lower than 35 °C and the BTES average temperature is higher than the warm tank top node temperature, the tank is charged via the BTES [53].

The decentralized hot tank in each building is charged only by the decentralized heat pump in each building. The energy from this centralized warm tank is distributed in the low temperature space heating district heating network of the community. The heat pump takes energy from the space heating return line to charge the hot tank. Generally, in the base case scenario, if the hot tank temperature is lower than 60 °C, it is heated to 65 °C by the heat pump. However, in this study, the hot tank charging set point via the heat pump is used as a design variable [53].

The space heating is provided by passing the water both through the centralized warm tank and the bottom node of the decentralized hot tank when the warm tank is not at an adequate temperature level to maintain the supply temperature [53]. The heated water is then provided to the buildings at a temperature between 27 °C and 40 °C, depending on the outdoor temperature. The water is heated up to 58 °C before being supplied to the tap. The schematic representation is shown in Figure 2.

3. Simulation methodology

A dynamic simulation software (TRNSYS) is used for the simulations of the proposed energy systems. A time step of 0.125 hours is used. The time step is small to have accuracy in the calculations; however it is not too small to increase the simulation time. It is found that 1 hour simulation can take 485 seconds. While 0.1 hour takes 983 seconds. Therefore as a compromise 0.125 hours is taken which takes 582 seconds for single simulation. TRNSYS [50] Type 1b, Type 543, Type 557a, Type 668, Type 194, and Type 15 are used for the solar thermal collector, buffer tanks, borehole thermal energy storage (BTES), heat pump, photovoltaic panels, and weather data, respectively [53]. These input parameters have already been defined in [53]. The application of both the centralized and decentralized systems is for the residential community with 100 houses each of 100 m² floor area. No commercial, high density buildings or public buildings are considered. The TRNSYS simulation tool has been validated by Drake Landing Solar Community, Canada. The simulation results showed conformity with the measured data of the real plant [42].

3.1. Piping networks

The distribution piping for domestic hot water for 100 buildings is assumed to be around 4000 m for the centralized system and 400 m for the decentralized system. In centralized system the hot tank is assumed to be present at a central location or plant, therefore it has longer distribution network to connect each building. The length for the domestic hot water network in decentralized system is reduced because it is assumed that each decentralized hot tank is placed inside the building. A commercially available pipe type DN40 is used, with polyurethane (PUR) insulation having insulation conductivity of 0.023 W/m.K [55]. The piping network is simulated in the TRNSYS using Type 709 [50]. The losses through the pipes are simulated as an output by the Type 709 in TRNSYS [55].

3.2. Weather profile and demand profile

The weather profile chosen for the simulation is of Southern Finland. Regarding the weather data, Finnish test reference year is used in TRNSYS through Type 15 [53]. The ambient temperature and total radiation are shown in Figure 3a. Figure 3b shows the hourly demand for space heating (37 kWh/m²/yr) and DHW (45 kWh/m²/yr) demand for the analysed building. An appliance electricity demand of 40 kWh/m²/yr is used [56].

Figure 3. Finland (a) Hourly solar radiation and ambient temperature; (b) building hourly energy demand (37 kWh/m²/yr space heating demand).

3.3. Reference case

The reference case consists of a typical single building, integrated with a heat pump (1.8 kW) in Finnish conditions. It has no seasonal storage and renewable energy generation sources namely, collector and photovoltaic. The building has a heating demand of 50 kWh/m²/yr situated in Finland and it meets the minimum C3 National Building code of Finland [57]. An appliance electricity demand of 40 kWh/m²/yr is used [56]. The building contains a hot tank of 1 m³ to store hot water for heating demand. The heat pump is integrated with the ground (depth 50 m) to charge the hot tank.

4. Optimization methodology

4.1. Problem definition

The focus in this paper is to optimize, compare and investigate the differences in the performances of two different concepts in Northern European conditions—i.e., centralized and semi-decentralized solar district heating. The application of the proposed energy systems is for the residential buildings. Therefore, firstly, both the energy systems are modelled and then optimized using a multi-objective optimization algorithm (NSGA-II), where purchased electricity and life cycle costs are minimized together in ideal conditions. Lastly, both systems are compared to analyse the differences between the two systems based on various criteria. The renewable energy fraction [53], final purchased electricity, and life cycle costs (LCC) are calculated to evaluate the system.

In this kind of building optimization problems, the use of two (contradictory) objective functions has proven to be a good approach [58]. The objective functions are usually representing the system performance (purchased electricity) and cost (LCC). The better performing system, the less energy needs to be purchased but the higher is the cost and vice versa. Therefore, both the objectives i.e. system performance (purchased electricity) and cost (LCC) are contradictory and does not follow same trend of development. Furthermore, in this way a Pareto front including numerous non-dominated solutions (Pareto-optimal set) is achieved. Using LCC, single-objective optimization leads to only one optimal solution. This minimum cost solution is one amongst the multi-objective results (Pareto-optimal set). So, the multi-objective approach is giving dozens of optimal solutions with different technical performance and different cost. On the contrary, the LCC single optimal approach is giving only one of these solutions. The benefit of multi-objective approach is evident in such problems and therefore used in present study.

4.2. Objective functions

In this study, purchased electricity and life cycle costs (LCC) are set as the objective functions to be minimized. The motivation to use purchased electricity and the life cycle costs (LCC) are of primary interest because purchasing electricity and operational costs (and environmental issues in general) are of interest to the end users and the contractors. Therefore it is important to evaluate all these quantities in order to provide the overall performance of the system.

The optimization problem can be formulated as follows:

Min $\{E_{PUR}(x) = \text{Purchased electricity}, LCC(x) = \text{Life cycle costs (LCC)}\}$, for all $x = [x_1, x_2, \dots, x_n]$,

where E_{PUR} is the purchased electricity for the system together with the building appliances, and LCC is the life cycle costs of the system, and 'x' is the vector of the design variables ($x_1, x_2, \dots, x_n$) as defined in Subsection 4.3. In this problem, there are ten design variables that are considered. To provide an overall performance of the community that includes both the energy system and building appliances demand. The purchased electricity includes both the factors. Additionally, photovoltaic panels are used to supply electricity to both the system and houses electricity demand. The mathematical expression for purchased electricity is:

$$E_{PUR} = E_{PUMP} + E_{HP} + E_{BH} + E_{BUL} - E_{ONC}, \quad (1)$$

where E_{PUR} is the purchased electricity, E_{PUMP} is the energy consumed by all flow circulation pumps, E_{HP} is the heat pump energy, E_{BH} is the energy used by the direct electric backup heating (used to maintain the temperature in the space heating and domestic hot water network in case the heat pump and solar energy are not sufficient), E_{BUL} is the appliance electricity demand of buildings, and E_{ONC} is the on-site electricity demand that is met by the PV panels. It is assumed that the electricity produced by the PV is used by the energy system and also by the building appliances. The electricity production by the PV panels faces the same problem as heat production by the collector: the mismatch between supply

and demand curves. In this paper the energy flows (for the heat and electricity) are balanced for every time step. All heating demand has to be met by the local system. However, for electricity, excess energy generated via PV is exported to the grid due to the lack of electrical storage device in present study. Any shortfall is balanced by the imported electricity from the grid, while excess is exported.

The second function—life cycle costs—is the sum of the present value of the investment cost of the system and discounted energy cost for 25 years. It is expressed as:

$$LCC = C_{ST} + C_{PV} + C_{BTES} + C_{WT} + C_{HT} + C_B + \sum_{n=1}^{25} a_e C_I E_{PUR} - \sum_{n=1}^{25} a_e C_E E_{EXP}, \quad (2)$$

the C_B , E_{EXP} and a_e used in Eq. (2) is defined as,

$$C_B = C_{Wins} + C_{Rins} + C_{Fins} + C_{WIND} + C_{HR}, \quad (3)$$

$$E_{EXP} = E_{PV} - E_{DEM}, \quad (4)$$

and,

$$a_e = 1 - (1 + r)^{-25} / r \quad (5)$$

where r in Eq. (5) is defined as,

$$r = (i_r - e_p) / (1 + e_p), \quad (6)$$

in Eq. (2) LCC is the life cycle cost, which includes the investments and operation costs for 25 years. C_{ST} is the solar collector investment, C_{PV} is the photovoltaic, C_{BTES} is the borehole (includes excavation and drilling costs), C_{WT} is the warm tank, C_{HT} is the hot tank, and C_B is the building investments. C_I is the imported electricity price, and C_E is the exported electricity price. The import electricity price of 11.10 c/kWh and export electricity of 4.04 c/kWh is used. All these prices are based on 2016 electricity prices [59]. The ' a_e ' is the discounting factor that takes into account the interest rate ' i_r ' and price escalation ' e_p '. The discounting factor ' a_e ' is explained in Eq. (5) [60]. The factor ' r ' in Eq. (5) is calculated by using ' i_r ' and ' e_p ' and it is explained in Eq. (6) [60]. The price escalation rate ' e_p ' of 1% is used because of the decreasing trend in electricity prices in the Nordic market [61]. The interest rate ' i_r ' of 3% is used [62]. In Equation 2 and 3, the C_B is the building investment, which includes the cost of the building's insulation material, wall (C_{Wins}), roof (C_{Rins}), and floor (C_{Fins}), and the cost of windows (C_{WIND}) and building heat recovery (C_{HR}) as defined in Table 1 and in Table 2. The variables explained in Eq. (3) changes with respect to the type of the building quality selected in each optimization case. A detailed explanation regarding building cost is provided in Table 1 and in Table 2. In Equation 4, the E_{EXP} is the excess electricity that is produced by PV panels and exported, E_{PV} is the electricity produced by the PV panels, and E_{DEM} is the total electricity demand of the system that includes pumps, heat pump, backup heating and building appliances. E_{EXP} is used to calculate the LCC as shown in Eq. (2). No maintenance costs replacement or disposal costs are considered in LCC, as the presented calculation is an economical life cycle analysis as proposed [63]. As the application is computationally expensive, a five-year simulation is not feasible. Therefore, as a compromise, the system is simulated for three years for estimating the performance of the system.

The solar fraction is also known as renewable energy fraction (REF) or on-site energy fraction of solar utilization [64]. The renewable energy fraction for heating i.e. REF_{heat} and onsite energy fraction for electricity i.e. OEF_{elec} are calculated separately.

In this system solar district network is supported by ground-source heat pump (HP), seasonal storage and short term tanks, therefore total solar energy generation couldn't be used directly for the calculation of renewable energy fraction. Instead, REF for heating or REF_{heat} is calculated indirectly to avoid confusion. Due to the utilization of short-term tank and seasonal storage, as well as heat pump, the total solar energy generation could not be used for the calculation of the REF_{heat} because there are significant losses and energy conversion from electricity to heat. Therefore, REF_{heat} is calculated by determining the electricity consumption of all heat related systems (heat pumps, back up heating and pumping) and assuming remaining energy is generated by solar thermal collector for heating demand. For heating the renewable energy fraction is defined as a ratio of total electricity needed to run the heating system and the total heating demand met by the system. Any onsite produced electricity by PV is not compensated for the calculation of REF_{heat} . This is done to show the impact of the heat related system on the heating demand.

The renewable energy fraction for heating is defined as [65],

$$\text{Renewable energy fraction}_{\text{heat}} (REF_{\text{heat}}) = 1 - \frac{(\text{HP} + \text{backup direct heating} + \text{pumping}) \text{ electricity consumption per year}}{\text{SPH demand per year} + \text{DHW demand per year}}, \quad (7)$$

the above Eq. (7) accounts the direct-use and ground stored heat energy as it reduces the need for the direct electric backup heating and heat pump compressor operation. It also accounts the heat losses through the grid. SPH in Eq. (7) is the space heating demand (SPH) as mentioned in Table 2. It includes both the ventilation heating and space heating. DHW in Eq. (7) is the domestic hot water (DHW) demand. Solar electricity produced by PV is not considered in the calculation of the REF_{heat} in Eq. (7) and accounts only the heating energy, therefore any electricity produced by PV and consumed on-site is not included in the REF_{heat} calculation. The household appliances electricity demand is also not included in the calculations. In the optimization, varying of the solar thermal area, tanks volume, seasonal storage shape and volume, also vary the REF, until it reaches certain saturation level. After this saturation level there is no further increase or decrease in the purchased electricity and REF simultaneously. All the design variables mentioned in Section 4.3 has an effect on the heat pump performance and back up heating, which ultimately vary both the purchased electricity and REF. Purchased electricity is used as an objective to be reduced instead of REF.

The onsite energy fraction (OE_{elec}) of electricity is also calculated. OE_{elec} indicates the portion of the electricity demand met by the onsite electricity generation i.e. by PV [64]. In the present study, grid electricity is the only external source, the OE_{elec} for the whole system is defined using the ratio of annually purchased electricity vs. the total electricity demand of the community. This includes both the house appliance and energy system demands. No electrical storage device is considered for electricity in present study.

4.3. Design variables

The performance of the energy system depends on the ten design variables that are defined and considered in this paper, namely: (1) the ST collector area, (2) warm short-term storage tank volume, (3) hot short-term storage tank volume, (4) BTES volume, (5) photovoltaic area, (6) the building's heating demand, (7) BTES aspect ratio, (8) BTES borehole density, (9) hot warm tank charging set point, and (10) warm tank charging set point. The reference point for the design variables values are from Drake Landing Solar Community, Canada [42]. Similar values are used in the optimization. However, the mentioned project has fixed values for all the design variables. To provide a wide range of possible optimal solutions a wide range of design variables are assumed for the simulation and optimization.

It is assumed that in a new community, the buildings would have minimum basic construction cost for the structure which needs to be paid. This basic construction cost is assumed to be '0' and used as a reference. Any additional cost of building efficiency components are given as a difference to this reference cost '0'. Costs of building efficiency components are reported in Table 1 and the optimal building configurations selected for further energy simulations are shown in Table 2 [53].

Table 1. Cost of building efficiency components [56], [66].

Parameters	Details	Prices	Variables used in Equation (3)
External wall insulation	Mineral wool	65 €/m ³	C_{Wins}
Roof insulation	Blow in wool	37 €/m ³	C_{Rins}
Floor insulation	Polyurethane	114 €/m ³	C_{Fin}
Windows type	U-value= 1 W/m ² .K	252 €/m ²	C_{WIND}
	U-value= 0.8 W/m ² .K	252 €/m ²	
	U-value= 0.6 W/m ² .K	252 €/m ²	
	Efficiency= 80%	4138 €/house	
Ventilation heat recovery efficiency	Efficiency= 70%	3835 €/house	C_{HR}
	Efficiency= 90%	3533 €/house	

Table 2. Building configurations used as possible options in the community optimization [53].

Building configuration	SPH demand (kWh/m ² /yr)	Wall (W/m ²)	Floor (W/m ²)	Roof (W/m ²)	Windows (W/m ²)	Heat recovery efficiency (%)	Price (€) /building
1	50	0.17	0.17	0.09	1	60	12,655 €/building
2	37	0.17	0.17	0.09	1	80	13,260 €/building
3	25	0.13	0.17	0.07	0.6	80	15,628 €/building

The values or range of the design variables are shown in Table 3. The investment costs are related to the design variables, which are also shown in Table 3. All the values of the design variables defined in Table 3 are the total values for all the 100 buildings. Only hot tank volume is specified as volume/house. In order to provide a wide range of solutions very small to large values of the variables are used to find best combinations of the design variables. A constant price unit is used for some components as shown in Table 3. The cost of the collector (Figure 4), photovoltaic panels (Figure 4), and tanks (Figure 5) are assumed to go down with larger sizes. The lowering of the costs is due to economies of scale as supplier companies tend to sell more at slightly lower price. For each selected size of the collector, photovoltaic and tanks by the optimizer, the corresponding price of the components are selected from Figures 4 and 5 respectively, by the simulation. All the costs used are market prices and no incentives are included in the calculations.

There are two major changes in the design variables selection in the centralized and decentralized systems in Table 3. The two changes are in the solar collector area and the hot tank charging set point. First, in a decentralized system, the solar collector area design variable can be reduced to 50 m² as a starting point, compared to a centralized system where the lowest collector area is 500 m². It is adjusted because in a decentralized system, only a warm tank is charged via the collector at lower temperatures, hence there is leverage to reduce the collector area. Secondly, in a decentralized system, the hot tank is charged via a heat pump; and in a centralized system the hot tank is charged mainly via the collector. Therefore in both cases, the design variables are different for the hot tank charging set point.

Figure 4. Cost profile of the rooftop solar thermal [67] and solar electric panels systems [68].

Figure 5. Cost profile of the hot and warm tanks [67].

Table 3. System configuration variations for the simulations and investment cost of the components used in energy systems.

Design variables	Types of variables	System type	Range/ Values (total for 100 houses)	Prices (€)	References
ST area (m ²)	Continuous	Decentralized	50-6000	1000—550 €/m ²	[67]
		Centralized	500-6000	600—550 €/m ²	[67]
PV area (m ²)	Continuous	Both systems	50-6000	450—200 €/m ²	[68]
Hot tank volume/house (m ³)	Continuous	Decentralized	0.5-5/house	900—810 €/m ³	[67]
		Centralized	1-5/house	850—810 €/m ³	[67]
Warm tank volume (m ³)	Continuous	Decentralized	300-500	900—810 €/m ³	[67]
		Centralized	150-500		
BTES aspect ratio			0.25-5	3€/m ³ (excavation for insulation and piping)	
BTES borehole density	Continuous	Both systems	0.05-0.25	+33.5€/m(drill)+88€/m ³ (1.5 m thick insulation)	[66, 69]
BTES volume (m ³)			10,000-70,000		
Hot tank charge set points (°C)	Continuous	Decentralized	60-75 °C (for heat pump)		
		Centralized	68-83 °C (for collector)		
Warm tank charge set points (°C)	Continuous	Both systems	35-50 °C		
Building quality/configuration	Discrete	Both systems	Type 1: heating demand= 25kWh/m ² /yr	15,628 €/building	[53]
			Type 2: heating demand= 37kWh/m ² /yr	13,260 €/building	
			Type 3: heating demand= 50kWh/m ² /yr	12,655 €/building	

4.4. Optimization algorithm

In the present approach, the TRNSYS system models and multi-objective building optimizer (MOBO) are combined to perform the optimization. MOBO [70] is freeware optimization software that can handle both discrete and continuous variables and allows the use of evolutionary and classical optimization algorithms. For this study, the NSGA-II algorithm is selected [58]. The NSGA-II algorithm is selected because it can solve a multi-objective problem, while handling the constraints, discrete and continuous variables. Furthermore, parallel computing is possible with this algorithm [58]. It is not only computationally expensive to explore all designs, it is computationally infeasible. Hence, a multi-objective non-dominated sorting genetic algorithm (NSGA-II) is used to perform the exploration [56].

An automated simulation-based optimization method is performed using the NSGA-II algorithm combined with TRNSYS. It avoids the repetition, keeps all the iterations in an archive, and uses them in a non-dominated sorting process. An initial population of 16 individuals is selected in MOBO [71]. Figure 6 shows the flow diagram of the multi-objective optimization process. Deb et al. [58] provides a detailed description of the algorithm. All the design

variables random values are generated by the algorithm to be evaluated in the TRNSYS simulation software and later the results are sorted by MOBO based on the objective functions.

Figure 6. The flow diagram of the multi-objective optimization process and its integration with the simulation.

The speed of convergence of an optimization method can be determined by using the hypervolume indication as explained in [72]. Hypervolume describes the area or volume enclosed by the non-dominated front and some reference point. The distribution of points on the Pareto front has an effect on hypervolume. The smaller the hypervolume value is, the closer the Pareto front is from the global/true optimal front. In Figure 7, the vertical axis shows the hypervolume (area enclosed by the Pareto front, correspond to that generation number), and the horizontal axis shows the number of generations (in each generation 16 simulations are done). It is found that the hypervolume of the Pareto front reduced by increasing the number of generations, as shown in Figure 7. However, after 300 generations, there is no progress on the Pareto front, i.e. the hypervolume remained almost constant after 300 generations. Therefore, for the given optimization problem, 300 generations are used in optimization.

Figure 7. Hypervolume of the Pareto front of the decentralized system as a function of generations.

4.5. Sensitivity analysis

In addition to the optimization, two types of sensitivity analysis are carried out to provide an in-depth analysis of the system behaviors under key parameters. The two sensitivities carried out are 1) price sensitivity and 2) physical design variable sensitivity.

4.5.1. Price sensitivity

In the future it is assumed that electricity prices may increase due to global trend [73]. While the prices of the PV and collector may reduce in the future, as a result of increase competitiveness in the market caused by increase in the demand and supply of these components [74]. In both the centralized and decentralized systems, the electricity price is assumed to increase by 25%, the PV and collector prices are assumed to decrease by 25%. These values are used to estimate the sensitivity of the optimized systems to the prices.

4.5.2. Physical design variable sensitivity

Physical design variable sensitivity is carried out to define how various independent design variables can impact the performance under a given set of assumptions [75]. The results can be post processed to identify the sensitivities of the decision variables. It is a useful tool that can be used to decide which parameters need more in-depth analysis and has larger impact on the objectives. These significant parameters, which are more influential, can be used for further studies, while the standard values can be used for the least influential parameters. The two most important physical design variables in both the community district networks are collector and photovoltaic. These two variables are the main sources for generation and also expensive. In the present study a single representative random case for each of the centralized and decentralized systems are simulated, where either the collector or photovoltaic sizes are varied at a time, while all the other design variables are kept constant. This analysis and comparison can provide a deep understanding about the variable that has the highest contribution in varying the LCC and the purchased electricity.

5. Results and discussions

5.1. Optimal solutions

Figure 8 shows the relationship between LCC and the purchased electricity of the non-dominated solutions of the two different systems and reference building case. Red points are for the centralized system and blue points are for the decentralized system. Moreover, green point shows the reference building case.

The solutions on the Pareto fronts are called non-dominated solutions. Generally, the solutions on the right side of the figure 8 are the least expensive optimal solutions with the worst optimal performance, while the solutions on the left side of the figure 8 are most expensive solutions with best optimal performance. By comparing the two fronts of the centralized and decentralized systems against the reference case, it is observed that both the community sized solar heating networks perform better in both the objectives i.e. in the purchased electricity and in the LCC. This shows that instead of investing and focusing on the single building solutions the focus should be on the community sized heating networks to have better LCC and lower purchased electricity. In reference case (green point), no seasonal storage and renewable energy sources are considered, therefore the LCC and purchased electricity values are higher.

In total, there are 141 and 112 non-dominated solutions for the centralized (red points) and decentralized (blue points) energy systems, respectively, as shown in Figure 8. For the centralized system (red points), the purchased energy varied from 46 kWh/m²/yr to 27 kWh/m²/yr, which corresponds to a LCC from 311 €/m² to 694 €/m², respectively, as shown in Figure 8. On the other hand, for the decentralized system (blue points), the purchased energy varied from 40 kWh/m²/yr to 25 kWh/m²/yr, which corresponds to a LCC from 270 €/m² to 500 €/m², respectively, as shown in Figure 8. The solution shows a wide range of optimal solutions that can be selected based on the needs of the customers and investors.

Figure 8. Comparison between the Pareto fronts of the centralized and decentralized energy system along with the reference point.

Certain irregularities are observed in both Pareto fronts in Figure 8. In Figure 8, there is a slight irregularity in Case 74 and Case 75 in the middle of the centralized energy system front (red points). This is caused by the reduction in the PV area by 744 m², i.e. from 5906 m² to 5162 m². This sudden reduction in the PV area, corresponds to the price change of PV from 121 €/m² to 105 €/m² as shown in Figure 9. All the other prices are similar between Case 74 and Case 75 in Figure 9, only PV price changed drastically, caused by the random selections by the NSGA-II algorithm. Likewise, in Figure 8, a small gap in Case 41 and Case 42 in the decentralized energy system front (blue points). This is caused by decrease in the collector area from around 1000 m² to 450 m², and thereby a cost decrease caused by the change in the collector area. This sudden decrease in the collector area, corresponds to the price change of the collector from 40 €/m² to 16 €/m² as shown in Figure 10. All the other prices are similar between Case 41 and Case 42 in Figure 10, only collector price changed drastically. The irregularities in both the optimization fronts (blue and red points) in Figure 8 are explained in Figure 9 and in Figure 10. These Figures 9 and 10, shows the weakness of the NSGA-II algorithm, when continuous variables are used as a design variable. In an ideal scenario, the front points should be continuous without any gaps between them, with each design variable's value changing in a continuous manner in smaller steps.

Figure 9. Analysis on the irregularity in the centralized system Pareto front, caused by the NSGA-II algorithm for multi-objective optimization.

Figure 10. Analysis on the irregularity in the decentralized system Pareto front, caused by the NSGA-II algorithm for multi-objective optimization.

The resulting Pareto front in the decentralized system is better than in the centralized system in Figure 8. The decentralized Pareto front shows that this type of system can be implemented at a lower cost. However, the purchased electricity variations are more or less similar in both energy systems, with the decentralized system performing slightly better in terms of purchased electricity. Figure 8 shows that by having centralized low temperature space heating network and decentralized high temperature domestic hot water, the cost of the system can be reduced, since the size of the expensive components (solar collector) can be reduced. A representative case is selected from the Pareto fronts of both the energy systems to compare the district network temperatures of both the systems. The purchased electricity are same in both the representative cases i.e. around $28 \text{ kWh/m}^2/\text{yr}$, however the LCC are different. Figure 11 shows the differences in the network temperatures and the corresponding life cycle cost of both systems. Both the systems are able to reach similar levels of performance i.e. purchased electricity, while the cost function is different mainly due to the costs of the collector and PV as shown in Figure 11.

Figure 11. Average yearly operating temperature of the centralized and decentralized system central district heating network.

5.2. Sensitivity analysis of the Pareto front with respect to the prices

Sensitivity of both the optimized centralized and decentralized systems as shown in Figure 8 are carried out with respect to the key economical parameters, for instance electricity, PV and collector prices. Figure 12 and Figure 13 shows the sensitivity of the optimized centralized system with respect to electricity, PV and collector prices. Overall, in both Figure 12 and in Figure 13 the increase in the electricity price increased the LCC of the system, making the systems less economical. On the other hand, reduction in the components prices reduced the LCC of the system, making the systems more economical. The Pareto fronts are more sensitive to the electricity price (brown line) in worst performance cases (Case 141 or Case 112 for centralized and decentralized systems respectively) where purchased electricity is large. While the Pareto fronts are more sensitive to the component prices (purple and green lines) in best performing cases (Case 1), where component sizes are relatively large compared to the worst performing cases.

Figure 12 shows the sensitivity of the optimized centralized system with respect to electricity, PV and collector prices. It is observed that with the increase in the electricity price by 25%, the reference Pareto front moves (red line) to form a new Pareto front (brown line). This change causes 2~8% (Case 1 to 141) and an average 4% increase in LCC (brown line) with respect to reference LCC (red line). It is also observed that with the increase in the PV price by 25%, the reference Pareto front moves (red line) to form a new Pareto front (green line). This change causes 4~1% and an average 5% decrease in LCC (green line) with respect to reference LCC (red line). With the increase in the collector price by 25%, the reference Pareto front moves (red line) to form a new Pareto front (purple line). This change causes 11~2% and an average 6% decrease in LCC (purple line) with respect to reference LCC (red line).

Two phenomena can be observed in Figure 12. First, when reference Pareto front (red line) is compared against the Pareto front where electricity price is changed (brown line). It is found that in worst performing cases (Case 141) the increase in the electricity price cause larger change in the front compared to the best performing cases (Case 1). This is because in the worst performing cases the purchased electricity is large, and any change in the electricity price will also have large impact on the LCC, compared to the best performing cases where the purchased electricity is less. Secondly in PV price (green line) and collector price (purple line), it is noted that the change in LCC is relative to the sizes of the PV and collector in a particular solution. Solutions close to the least performing cases (Case 141) has less PV and less collector, therefore purple and green lines are close to the reference red line. This means that in these cases reduction in collector and PV prices has less impact on the LCC. On the other hand, solutions close to high performing cases (Case 1) has large amount of collector, therefore the purple line is farthest from the reference red line, compared to the green line. Hence in these cases reduction in collector price compared to PV price has slightly more impact on the LCC.

Figure 12. Sensitivity of the multi-objective optimized solutions of the centralized system, with respect to electricity, PV and collector prices.

Figure 13 shows the sensitivity of the optimized decentralized system with respect to the electricity, PV and collector prices. It is observed that with the increase in the electricity price by 25%, the reference Pareto front moves (blue line) to form a new Pareto front (brown line). This change causes 2~8% (Case 1 to 112) and an average 5% increase in LCC (brown line) with respect to reference LCC (blue line). It is also observed that with the increase in the PV price by 25%, the reference Pareto front moves (blue line) to form a new Pareto front (green line). This change causes 7~1% and an average 6% decrease in LCC (green line) with respect to reference LCC (blue line). With the increase in the collector price by 25%, the reference Pareto front moves (blue line) to form a new Pareto front (purple line). This change causes 9~2% and an average 4% decrease in LCC (purple line) with respect to reference LCC (blue line). Similar phenomena can be observed in Figure 13 as explained above for the centralized system, regarding the sensitivity of the prices as solutions moves from (Case 1) to (Case 112).

Figure 13. Sensitivity of the multi-objective optimized solutions of the decentralized system, with respect to electricity, PV and collector prices.

The design variables of both the centralized and decentralized systems are compared in detail in the following sections.

5.3. Analysis of the non-dominated solutions

Both Figure 14 and Figure 15 show the cost breakdown of the non-dominated optimized solutions in Figure 8 for the centralized and decentralized systems, respectively. Generally, the solutions on the left side near (Case 1) are the most expensive solutions and are therefore high performance solutions in both Figure 14 and Figure 15. On the other side, the solutions on the right side near (Case 141) and (Case 112), respectively, are the least expensive solutions and are therefore the lowest performance solutions. For the optimal solutions, the initial investment cost is around 65-90% of the total LCC, and the other is the operational cost as shown in figures 14 and 15. First, a centralized system (Figure 14) is explained and later a decentralized system (Figure 15) is explained

Figure 14 shows that the solar thermal collector formed the biggest part of the investment, followed by buildings, and then PV for the centralized system in (Case 1). In Figure 14, the buildings form the biggest part of the investment, followed by the solar thermal collector in (Case 141). The highest part of the investments goes to the buildings in the solutions in (Case 141). As the simulation progresses towards (Case 1) in Figure 14, where the performance improves, the initial investments are made in the photovoltaic panels due to lower cost. After saturation of the PV panels area and its benefits, the investments are then made in the buildings and solar thermal area, which further benefits the system by reducing the purchased electricity demand of the system. It is also important to note that parallel to the increase in the area of the collector from (Case 141) to (Case 1) in Figure 14, the volume of the borehole storage also increases. It is evident that in order to improve the centralized system performance, the solar thermal collector played a significant role as the photovoltaic panels get saturated. The overall solar thermal collector area, the photovoltaic panels area, and the buildings' heating demand played a significant role in the reduction of purchased electricity.

Generally the solutions near (Case 1) had a medium-large size solar thermal collector and a large size photovoltaic panels area. This combination reduced the purchased electricity to around 27 kWh/m²/yr. Buildings with a heating demand of 25 kWh/m²/yr are selected in the majority of the cases, especially in the cases where the purchased electricity is less. The life cycle cost is higher in the solutions close to (Case 1) of Figure 14, with a large part going to the investment cost while a small proportion going to the operational cost. The renewable energy fraction for heating (REF_{heat}) varied between 90% and 57%. The onsite energy fraction (OEF_{elec}) for electricity varied between 36% and 11%.

Figure 14. Life cycle cost breakdown of the non-dominated optimal solutions of centralized system.

Figure 15 shows that the solar thermal collector and buildings formed the biggest part of the investment, followed by PV for the decentralized system in (Case 1). In Case 112 in Figure 15, the building forms the largest part of the investment, followed by the warm tank and photovoltaic panels. The largest part of the investments goes to the buildings in (Case 112). As the simulation progresses towards (Case 1) in Figure 15, where the performance improves, the initial investments are made in the photovoltaic panels due to lower cost and more benefits. This phenomenon occurs up till the middle of the optimization front (Case 46). After saturation of the PV panels area, investments are then made in the solar thermal area and later in the buildings, and that further benefits the system by reducing the purchased electricity demand of the system. It is also important to note that in parallel to the increase in the area of the collector from (Case 112) to (Case 1) in Figure 15, the volume of the borehole storage also increases marginally. Figure 15 shows that, to improve the decentralized system performance, the photovoltaic panels area played a significant role, followed by the solar thermal collector area, as investments are initially made on the PV panels and later on the collector. Overall photovoltaic panels area, the buildings' heating demand and the solar thermal collector area played an important role in the reduction of purchased electricity.

Generally the solutions close to (Case 1) had a medium sized solar thermal collector and a large photovoltaic panels area. This combination reduced the amount of purchased electricity to around 25 kWh/m²/yr. Buildings with a heating demand of 25 kWh/m²/yr are selected in fewer cases because of the higher cost compared to the PV. The cost of the building is 156 €/m² whereas the cost of the PV is 121 €/m². Therefore, the algorithm selected first the PV and then the building. In addition, since the individual building heat pump electricity demand is higher in a decentralized system, PV is given priority, which significantly reduced the amount of purchased electricity. The life cycle cost is higher in the solutions close to (Case 1) in Figure 15, with a large part for the investment cost and a small part for the operational cost. The renewable energy fraction for heating (REF_{heat}) varied between 92% and 75%. The onsite energy fraction (OE_{elec}) for electricity varied between 41% and 12%.

Figure 15. Life cycle cost breakdown of the non-dominated optimal solutions of decentralized system.

The common features in both the centralized (Figure 14) and decentralized (Figure 15) systems are the trends. As the systems solutions progresses from (Case 141) or (Case 112) to (Case 1) in Figure 14 and Figure 15 respectively, the cost of the system increases while the performance improves. In both systems, the solar thermal collector, photovoltaic panels and buildings make up the major part of the investment cost. Moreover, the purchased electricity and renewable energy fractions are similar in the best performance cases for both systems.

However, when comparing the centralized system (Figure 14) with the decentralized system (Figure 15), three major differences can be observed. Firstly, when comparing centralized system (Figure 14) and decentralized system (Figure 15), the solar collector cost is relatively large in the best performing optimized cases (Case 1) in Figure 14 compared to the (Case 1) in Figure 15 respectively. This means that the collector area is relatively smaller in the decentralized system than in the centralized system. Moreover, the change in collector area done by the algorithm from small to medium comes earlier in the centralized system. It shows that in the centralized system, the solar thermal area needs to be large to benefit the system. Since the hot tank needs to be charged at a higher temperature by the collector to reduce the purchased electricity consumption, the collector area is large in the best performing Case 1 in the centralized system. Higher temperatures cannot be reached in the hot tank without a medium or large collector area. Secondly, in the decentralized system, the PV panels cost increased to the saturation up till Case 46, while the collector cost remained the same. This means that the PV panels area increased to saturation until Case 46, while the collector area remained less. This shows that in a decentralized system, the performance of the system can be improved by initially adding a cheaper option, i.e. PV panels, compared to the collector. Lastly, the cost of the borehole in the best performing Case 1 of the centralized system (Figure 14) is higher compared to the decentralized system (Figure 15) Case 1. It corresponds to the larger size of the borehole storage needed in the centralized case to achieve better performance.

It is also found that by having a decentralized high temperature (domestic hot water) system and a hot tank inside the buildings, the losses through the piping are reduced, as the length of the high temperature domestic hot water pipe is reduced from 4,000 m (in the centralized system) to 400 m (in the decentralized system). The losses through the pipes in the centralized system are 40% higher compared to the decentralized system in the best performing optimized cases. Similarly, the losses through the pipes in the centralized system are 12% higher compared to the decentralized system in the least performing optimized cases.

5.4. Influence of system design on various parameters of the non-dominated solutions

5.4.1. Physical component design parameters

In total, there are 141 non-dominated optimal solutions for a centralized system and 112 non-dominated optimal solutions for a decentralized system that resulted from each optimization run. Figures 16 to 25 shows various design

variable values of the non-dominated solutions for the energy systems. Each figure provides insight into each design variable. In the results analysis for each of the design variables, first the centralized system design variable is explained and secondly the decentralized system design variable is explained.

Figure 16 shows the solar thermal collector area design variable. Figure 16a is for the centralized system and Figure 16b is for the decentralized system. Both figures are explained in the same order.

The solar thermal collector area for the centralized system (Figure 16a) shows that around 30% of the solar thermal area is 500 m². The other 70% is in increasing order from a medium- to large-sized collector area. This indicated that a large solar thermal area is beneficial in a centralized system. Among the design variables, the solar thermal area is the highest contributor to varying the life cycle cost and the purchased electricity. This is because the solar collector acts as the main source for collecting energy from the sun and providing it to the system to meet the demand. Since in the centralized system the collector is used to charge the hot tank and warm tank to higher temperatures, the large collector is selected in the best performing cases.

The solar thermal collector area for the decentralized system (Figure 16b) shows that around 50% of the solar thermal area is 50 m². The other 50% is in increasing order, from small to medium sized collector area. This indicated that a large solar thermal area is not always beneficial in a decentralized system.

Both systems show that the collector area increased as the performance improved and that the collector played an important role in system performance. However, for the centralized system, the increase in the collector area started earlier compared to the decentralized system, as the optimization progressed from (Case 141) to (Case 1) in Figures 16a then from (Case 112) to (Case 1) in Figure 16b. Moreover, the largest collector area in the best performance Case 1 for both systems is 5400 m² and 3000 m² for the centralized and decentralized systems, respectively. It clearly shows that in the centralized system, a larger collector area is needed to reach similar performance levels i.e. purchased electricity as the decentralized system.

Figure 16. Solar thermal collector area (a) centralized and (b) decentralized in the non-dominated optimal solutions.

The change rate of the purchased electricity with respect to the change in the collector area is estimated in Figure 17. Collector is the main source of energy and most expensive component of the system, therefore the impact on the change rate of the purchased electricity is estimated for both the centralized system and decentralized system. To evaluate both the systems, only the collector area is changed in both the energy systems, while keeping other parameters similar. The change in purchased energy due to an increase in collector area while keeping all other parameters constant and the corresponding costs are shown in Figure 17. It is found that by increasing the collector area from 500 m² to 4000 m², the reduction of purchased energy is around 17% in the centralized system. On the other hand by increasing the collector area from 500 m² to 4000 m², the reduction of purchased energy is around 12% in the decentralized system. This shows that in centralized system large collector area has larger impact on the purchased electricity. The cost functions in both the systems varied by 34 %, due to increase in the size and the corresponding cost of the collector.

Figure 17. Purchased electricity and cost function comparisons between centralized and decentralized system as function of solar collector area.

Figure 18 shows the photovoltaic (PV) panels area design variable. Figure 18a is for the centralized system, and Figure 18b is for the decentralized system. Both figures are explained in the same order.

The photovoltaic panels area for the centralized system (Figure 18a) shows that more than 70% of the solution shows a medium to large panels area in this system. As the area of the panels increases, performance improves. The largest area proposed in the decentralized system is around 5800 m². However, due to the non-availability of electricity storage in the designed system, most of the electricity would be exported to the grid due to a mismatch in the cases where the PV panels are large.

The photovoltaic (PV) panels area for the decentralized system (Figure 18b) shows that more than 50-70% of the solution shows large panels area in this system. The other 20-30% of the solutions contains a medium to small panels area. Among the design variables, PV panels contributed to the change in the purchased electricity. Large panels would aid in the reduction of purchased electricity. The largest area proposed in the decentralized system is around 6000 m². Moreover, compared to the collector area (Figure 16b) in the decentralized system, a larger PV panel area is selected in most of the optimized cases (Figure 18b) due to the lower cost of the PV panels compared to the collector. Hot tanks are not charged by solar thermal energy, they are only charged via the heat pumps. Therefore there is a large amount of electricity required compared to the amount of thermal energy required in the decentralized energy system. As a consequence, the large photovoltaic area played a significant role in reducing the purchased electricity compared to the solar thermal area, as shown in Figure 18b.

Figure 18. Photovoltaic panels area (a) centralized and (b) decentralized in the non-dominated optimal solutions.

The change rate of the purchased electricity with respect to the change in the photovoltaic area is estimated in Figure 19. Photovoltaic is the main source of energy and an expensive component of the system, therefore the impact on the change rate of the purchased electricity are estimated for both the centralized system and decentralized system. To evaluate both the systems, only the photovoltaic area is changed in both the energy systems, while keeping the other parameters similar. The change in purchased energy due to an increase in photovoltaic area while keeping all other parameters constant and the corresponding costs are shown in Figure 19. It is found that by increasing the photovoltaic area from 500 m^2 to 4000 m^2 , the reduction of purchased energy is around 15% in the centralized system. On the other hand by increasing the photovoltaic area from 500 m^2 to 4000 m^2 , the reduction of purchased energy is around 18% in the decentralized system. This shows that in decentralized system large photovoltaic area has larger impact on the purchased electricity. The cost functions in both the systems varied by 4 %, due to increase in the size and the corresponding cost of the photovoltaic panels.

Figure 19. Purchased electricity and cost function comparisons between centralized and decentralized system as function of photovoltaic area.

Overall, by comparing Figures 16, 17, 18 and 19, it can be observed that decentralized system favours a PV-based district heating network, as the largest panels area proposed by the algorithm is slightly larger than in the centralized system. On the other hand, the centralized system favours a solar thermal-collector-based district heating network. This shows that by changing the energy system layout and control strategies, the importance of any design variable can change, and as a result it can significantly affect the overall optimization of the system.

Figure 20 shows the hot tank volume design variable, where Figure 20a is for the centralized system and Figure 20b is for the decentralized system. Both figures are explained in the same order.

The hot tank volume for the centralized system (Figure 20a) shows that more than half of the solutions contained a hot tank size of more than 150 m³. The large hot tank is used to store large energy available from the large collector area in the centralized system, as shown in Figure 20a.

The hot tank volume for the decentralized system (Figure 20b) shows that around 50% of the solutions contain a small hot tank volume. The other 50% of the solutions contain a medium sized tank. Only a few of the solutions contained a tank larger than 2m³ per house. The hot tank is used in the energy system to heat the DHW and SPH water up till the final supply temperature. The increase in volume of the hot tank assisted in reducing the purchased electricity because it provided instantaneous energy to the building heating grid, thereby reducing the backup electricity heating, as shown in (Case 1) of Figure 20a.

Compared to the decentralized system (Figure 20b), the maximum hot tank volume proposed in the centralized system is 470 m³ in most cases, as shown in (Case 1) of Figure 20a. Whereas, in the decentralized system, the maximum hot tank volume proposed is less than 400 m³, as shown in Figure 20b. This occurs because in the centralized system, the size of the collector area is larger and the hot tank is charged by the collector. Therefore, the larger hot tank benefits the system by reducing the purchased electricity in such a system.

Figure 20. Hot tank volume (a) centralized and (b) decentralized in the non-dominated optimal solutions.

Figure 21 shows the warm tank volume design variable. Figure 21a is for the centralized system, and Figure 21b is for the decentralized system. Both figures are explained in the same order.

The warm tank volume for the centralized system (Figure 21a) shows that a large tank volume of around 400 m³ or more is proposed in the cases with the least purchased electricity, where the large collector area is selected as shown in Figure 16a in (Case 1). As the collector area increases from (Case 141) to (Case 1) in Figure 16a, the warm tank volume also increases from (Case 141) to (Case 1) in Figure 21a. Compared to the decentralized system, less volume of the warm tank is proposed because the energy from the collector area is divided into a hot and warm tank. Hence the size of the warm tank volume is less in most cases shown in Figure 21a compared to the decentralized system shown in Figure 21b.

The warm tank volume for the decentralized system (Figure 21b) shows that a medium tank volume of around 300 m³ is proposed in most of the cases. The best performing case (in Case 1 of the figure) contain a tank size of around 300 m³. The results indicated that a medium size for the centralized warm tank is beneficial in most of the optimal cases. This is because in a decentralized system, high temperatures are not needed; and only in the first few cases where the solar thermal collector area is relatively large, a higher tank volume is proposed.

Figure 21. Warm tank volume (a) centralized and (b) decentralized in the non-dominated optimal solutions.

Figure 22 shows the borehole thermal energy storage (BTES) volume design variable. Figure 22a is for the centralized system, and Figure 22b is for the decentralized system. Both figures are explained in the same order.

The borehole seasonal storage volume for the centralized system (Figure 22a) shows that the volume of the borehole thermal energy storage (BTES) increased as the performance improves from (Case 141) to (Case 1). It indicates that the performance of the energy system is linked to the size of the BTES. Here there also exists a relation between the collector area and the BTES volume, as shown in Figure 22a. It is observed that as the collector area increases, the volume of the BTES also increases, as shown in Figure 22a.

The borehole seasonal storage volume for the decentralized system (Figure 22b) shows that the volume of the borehole thermal energy storage (BTES) increased slightly as the performance improves, as shown in (Case 1) Figure 22b. In the solutions where the purchased electricity is less, the seasonal storage volume is high, and vice versa. Another important relation is between the collector area and the BTES volume, as shown in Figure 22b. It is again observed that as the collector area increases, the volume of the BTES also increases.

Both energy systems show a similar behaviour regarding the relationship between system performance and BTES volume. However, compared to the centralized system, the maximum BTES volume (Figure 22b) is less than the maximum BTES volume (38,000 m³) of the centralized system, as shown in Figure 22a. This is because in centralized system, the solar thermal collector area is larger than the collector area in the decentralized system. This causes higher temperatures in the seasonal storage as it is being charged by the hot tank compared to the decentralized system. Therefore, higher BTES volume is proposed by the algorithm in the case of the centralized system.

In both of the cases for the centralized and decentralized energy systems, the volume itself doesn't give the whole truth. Figure 23a and Figure 23b show the number of boreholes and the depth of the boreholes. Here is observed the opposite trend of the total borehole depth decreasing while performance improves. Clearly, BTES volume is not the only factor that determines total system efficiency.

Figure 22. Seasonal storage volumes and collector areas (a) centralized and (b) decentralized in the non-dominated optimal solutions.

Figure 23 shows the height or depth of the borehole, number of boreholes and corresponding collector area. Figure 23a is for the centralized system and Figure 23b is for the decentralized system. Both figures are explained in the same order.

The depth of the borehole, number of boreholes and corresponding collector area in the centralized system (Figure 23a) shows, that the seasonal storage is deeper than wide when the system performance is poor in (Case 141). In the cases where the BTES volume is small (Figure 22a, Case 141), the height of the BTES is more, as shown in Figure 23a. On the other hand, in the cases where the BTES volume is large (Figure 22a, Case 1), the height of the BTES is less, as shown in Figure 23a. In the least performing cases, the depth of the borehole is more because this increases the heat transfer through the sides of the storage. The depth of the borehole is also relative to the area of the solar thermal collector. When the solar collector area is less, the depth of the borehole is more. Performance improvement is related to the increase in the solar thermal collector area, the decrease in the height of the borehole, and the increase in the width of the BTES, as shown in (Case 1) of Figure 23a. The BTES is insulated from the top, hence wider storage is beneficial with lower depths. A wide shape also allows the BTES core to obtain higher temperatures and retain more energy in the centre.

The depth of the borehole, number of boreholes and corresponding collector area for the decentralized system (Figure 23b) shows that the seasonal storage is deeper than wide when the system performance is poor in Case 112. The behaviour and the relation between the borehole depths, borehole storage volume and collector area is similar to that explained in the centralized system above. When the solar collector area is less, the depth of the borehole is more, as shown in Figure 23b (Case 112). When the collector area is less, the injected energy is less, and hence there is no need for a large seasonal storage. Moreover, with a larger depth, the BTES is charged naturally from the surroundings. The performance of the system improves when the depth is reduced and the collector area increases from (Case 112) side to (Case 1) in Figure 23b, along with the borehole storage volume (Figure 22b).

In addition to the borehole depth and collector area in Figures 23a and 23b, it is observed that with a wider shape, more boreholes can be added in the storage from (Case 141) and (Case 112) to (Case 1) in both Figures 23a and 23b respectively. In both energy systems, the number of boreholes increased with the increase in the performance from (Case 141) and (Case 112) to (Case 1) respectively. The increase in performance is caused by the increase in the solar collector area and number of boreholes. However, the height decreases, as shown in (Case 1) in Figures 23a and 23b. Therefore, it implies that higher performance is achieved by having many shallow boreholes on a wide area compared to having fewer deep boreholes over a narrow area. The temperature gradient also improves by having many boreholes over a wide area.

When comparing the decentralized system (Figure 23b) to the centralized system (Figure 23a), the decrease in the height of the borehole is sooner when the solutions move from (Case 141) to (Case 1) in centralized system (Figure 23a). In centralized system in Figure 23a the depth of the borehole changes from around 80 m to 30 m suddenly. While in decentralized system in Figure 23b, the depth of the borehole changes from about 68 m to 45 m and then to 20 m. This is because the size of the collector area increases quickly in centralized system in Figure 23a from (Case 141) to (Case 1), compared to the decentralized system from (Case 112) to (Case 1). It is also important to note that in the centralized system, the size of collector area is relatively large compared to the decentralized system (Figure 23b) therefore the number of boreholes is also large in the centralized system (Figure 23a). This would allow retaining higher temperatures in the large volume of the seasonal storage and keeping the core temperature high, avoiding losses to the surroundings.

Figure 23. Borehole length (single hole), number of boreholes and corresponding collector area (a) centralized and (b) decentralized in the non-dominated optimal solutions.

5.4.2. Control design parameters

From Figure 24 to Figure 25, the results show the behaviour of the control set points. Each figure provides insight into each control design variable. In the results analysis for each of the design variables, first the centralized system design variable is explained and lastly the decentralized system design variable is explained.

For the hot tank charging set point design variable, there is no clear trend in the set point design variable value, either in decreasing or increasing order, that corresponds to the change in the performance or life cycle cost. The hot tank charging set point design variable is distributed randomly in the solutions for both the centralized (charged via solar thermal collector) and decentralized (charged via heat pump) energy systems.

However, in the centralized system, for the hot tank set point the highest frequency occurs in the range of 71-74 °C, as shown in Figure 24a. It implies that set point for the tank charging through the solar thermal collector can be increased from 70 °C to 71-74 °C. This would assist in increasing the borehole core temperature and reducing the electricity consumption of the backup heaters and the heat pump by providing higher temperatures in the system, especially in the warm tank during winters via seasonal storage.

In the decentralized system, for the hot tank set point, the highest frequency occurs in the range of 60-63 °C, as shown in Figure 24b. It implies that the set point for the tank charging through the heat pump can be reduced from 65 °C to 60-63 °C in the decentralized system shown in Figure 24b. This would assist in reducing the losses through the tanks, and it would also reduce the electricity consumption of the heat pump by heating the hot tank at lower temperatures. It is also interesting to note that since the hot tank is not being used to charge the seasonal storage, it is enough to charge the tank up to 60-63 °C. This temperature is reasonable for mainly providing the building with the domestic hot water at around 58-60 °C.

Figure 24. Hot tank charging set point frequency (a) centralized (charged via collector) and (b) decentralized (charged via heat pump) in the non-dominated optimal solutions.

There is no clear trend in the increasing or decreasing order for the warm tank charging set point design variable. The warm tank charging set point design variable is distributed randomly in the solutions for both the energy systems.

In the centralized energy system, for the warm tank set point, the highest frequency occurs in the range of 47-50 °C, as shown in Figure 25a. It implies that the set point for the tank charging through the collector can be increased slightly from 45 °C to around 47 °C. This would assist in increasing the performance of the system. The higher temperature could also be used to charge the BTES with higher energy.

In the decentralized energy system, for the warm tank set point, the highest frequency occurs in the range of 44-47 °C, as shown in Figure 25b. It implies that the set point for the tank charging through the collector can be increased slightly from 45 °C to 44-47 °C. This would assist in increasing the performance of the system, since the warm tank is used to mainly provide the space heating and heating for the heat pump evaporator. Hence, the higher tank temperature would assist in reducing the backup electric heating in the space heating network and higher COP of the heat pump. In addition to that, the excess high temperature heat can be transferred to the seasonal storage in case there is less need for the heat pump and space heating.

Figure 25. Warm tank charging set point frequency (a) centralized and (b) decentralized in the non-dominated optimal solutions.

For the centralized system, as shown in Figure 24a and Figure 25a, it can be concluded that first the charging set point of the hot tank and then the warm tanks can be increased from the previous default values. Since both tanks are charged by the collector, the higher set point would be favourable in increasing the renewable energy fraction. This would also improve the system performance by reducing the purchased electricity. It would help in charging the borehole at higher temperatures, thereby reducing the electricity consumption of the heat pump and backup heaters.

For the decentralized system as shown in Figure 24b and Figure 25b, two main trends are observed. First, for the hot tank charging set point (Figure 24b), most of the solutions contained a lower value of the set point. It means that when the hot tank charging set point is reduced, the overall energy consumption of the heat pump is reduced in order to meet the lower set point target. This improved the system performance by reducing the purchased electricity. Secondly, for the warm tank charging set point via the collector, most of the solutions contained a higher set point value, as shown in Figure 25b. This means that to achieve better performance, it is recommended to charge the warm tank at a higher value so that space heating is provided at a higher temperature to the houses, which corresponds to lower utilization of any backup direct electric heater and less energy usage from the hot tank bottom node. Furthermore, the heat pump COP would improve in a decentralized system, as heat pump takes energy from the space heating network to charge the hot tank, and borehole can be charged at higher temperatures.

Figures 24 and 25 shows the importance of the set points as a design variable in such systems. These design variables may not have a significant direct impact on the investments. However, they can have a significant effect on system performance and operational costs.

5.5. Comparison and validation of the simulation model to other real plants

As no such solar community project exists in Finland at the moment, therefore the presented simulation model is compared and verified against three different real projects from various regions. Two projects are situated in Germany and one project in Canada. As a reference case, centralized system model (Case 1) is compared against the German projects in Neckarsulm [52], Carlsheim [36] and also against the Canadian project in Drake Landing Solar Community (DLSC), Alberta [42]. It is compared because these projects are somehow close to the presented models. The comparison of the simulated system against the three real systems is shown in Table 4. The renewable energy fractions are very favourable compared to some German solar communities as shown in Table 4. Even in the low performing cases the REF_{heat} exceeded both the Crailsheim and Neckarsulm communities. The main difference in this study compared to Neckarsulm community is the heat pump and demand. With the heat pump and lower demand, higher renewable energy fraction can be achieved. However, the Crailsheim community also contained a heat pump. The difference between the Crailsheim and present study can partly be attributed to higher solar thermal area compared to heat demand, but it may not be the sole reason. The BTES volume vs demand ratio is also large in the present study compared to Crailsheim. Moreover, configurations in present simulated study are optimized, so the results can reasonably be expected to be

better than those from non-optimal real case studies. The Drake Landing Solar Community (DLSC) is also compared against the presented model. It is found that DLSC and the presented simulated studies in Finnish conditions are reasonably comparable, with some differences. These differences occur broadly because of two main factors. Firstly, the heating energy demand is higher in simulated Finnish case, as it includes both space heating and domestic hot water demand, while in DLSC case only space heating is included. Secondly, the ground thermal conductivity in DLSC is around 1.5-2 W/m.K [76], where as in Finnish case it is 3.5 W/m.K [22], this may reduce the performance of the overall system. This explains why the REF_{heat} is better in DLSC compared to the Finnish case.

The technical comparison of the simulated system against the real system shows (Table 4) that the simulated model is reasonably comparable. In addition, simulated studies are always optimistic compared to real systems. A real system may suffer from many problems, for instance component failures, non-ideal efficiencies, unexpected ground flows and uncertain environmental conditions. No cost comparison is done against the real system as the ratios of the cost vs. performance of these studies are not known.

Table 4. Comparison of other studies (real systems), Neckarsulm [52], Carlsheim [36], and Drake Landing Solar Community, Canada [42], with centralized system (simulated system), Finland.

	Centralized system, Finland (simulated)	Neckarsulm, Germany (BTES+boiler)	Carlsheim, Germany (BTES+HP)	Drake Landing Solar Community, Canada (BTES+boiler)
Heat demand (MWh/yr)	700	1891	4100	650
ST area (m ²)	5400	5007	7300	2300
BTES volume (m ³)	38000	63360	37500	34000
ST/Heat (m ² /MWh)	7.7	2.65	1.78	3.5
BTES/Heat (m ³ /MWh)	54.2	33.5	9.1	52.5
REF_{heat}	90	39	50	97

6. Conclusions

Two different types of solar district systems based on simulation models are developed and optimized for a solar community design problem. The two proposed systems are centralized and decentralized systems. In the centralized system, two centralized short-term tanks are charged by solar energy, the heat pump connected between two tanks, using solar charged borehole storage. In the decentralized system, a warm tank is centralized and charged by solar energy, while the decentralized hot tank is charged by the heat pump; moreover, the borehole is charged only by the warm tank. The study is performed using dynamic simulation software (TRNSYS) where a model is prepared. In addition, a multi-objective building optimizer is integrated into the model to perform Non-dominated Sorting Genetic Algorithm (NSGA-II). The objective functions are to minimize the purchased electricity and life cycle cost. The design variables selected for the optimization are physical component size and control set points. A brief summary of the key findings are the following:

- Overall the community sized solar district heating systems performed better in terms of the purchased electricity and the cost function, against the single reference building in Finnish conditions.
- In terms of life cycle cost and purchased energy, the decentralized system clearly outperforms the centralized system. With a similar energy performance, the reduction in life cycle cost is up to 35% for the decentralized system.
- For the centralized system, the purchased energy varied from 46 kWh/m²/yr to 27 kWh/m²/yr against the life cycle cost from 311 €/m² to 694 €/m², which corresponds to a renewable fraction (REF_{heat}) from 57% to 90%. The onsite energy fraction (OEF_{elec}) for electricity varied from 11% to 36%.
- For the decentralized system, the purchased energy varied from 40 kWh/m²/yr to 25 kWh/m²/yr against the life cycle cost from 270 €/m² to 500 €/m², which corresponds to the renewable fraction (REF_{heat}) from 75% to 92%. The onsite energy fraction (OEF_{elec}) for electricity varied from 12% to 41%.
- The study also showed the irregularities in the Non-dominated Sorting Genetic Algorithm (NSGA-II) algorithm caused by the random selection of the design variables by the algorithm.
- Sensitivity analysis of the systems against the prices shows that both the systems are equally sensitive to the electricity price. While centralized system is slightly more sensitive to the collector price than photovoltaic

price. On the other hand, decentralized system is slightly more sensitive to the photovoltaic price than collector price.

- The Pareto fronts are more sensitive to the electricity price in worst performance cases where purchased electricity is large. While the Pareto fronts are more sensitive to the component prices in best performing cases, where component sizes are relatively large compared to the worst performing cases.
- The purchase electricity in the centralized system is slightly more sensitive to the collector size than the photovoltaic size. While, the purchased electricity in the decentralized system is slightly more sensitive to the photovoltaic size than the collector size.
- In the centralized system, the collector area varied around 500-5400 m². In the decentralized system, the collector area varied around 50-3000 m².
- As the performance of the systems improved from worst to best optimized cases, the borehole thermal energy storage tends to be wider and shallow, the numbers of boreholes increased, and the borehole thermal energy storage volume increased. The increase in the volume also corresponds to the increase in the area of the collector and the number of boreholes over a wider area.
- It is found that in the best performing optimized cases, the borehole thermal energy storage volume is larger in the centralized system, i.e. around 38,000 m³, compared to the decentralized system, around 10,700 m³.
- The set point of the hot tank in the centralized system increased from 70 °C to 71-74 °C because the collector is used to charge the centralized hot tank, and this improved the performance of the system, while in the decentralized system it decreased from 65 °C to 60-63 °C because the heat pump is used to charge the individual hot tank in buildings instead of the collector.
- The warm tank set point in the both systems increased from 45 °C to around 47-50 °C, as it allowed more solar energy to be stored in the tanks from the collector.
- The losses from the distribution network in the centralized system are around 40% to 12% higher compared to the decentralized system due to the high temperature distribution network.

The present study can be useful in the real applications of such community sized district heating networks, especially in the cold climatic regions of the world, for instance in the Northern European countries, and in North America. It is demonstrated that instead of focusing on the single building energy system, the focus should be on the community sized energy systems as it is less costly due to economies of scale and better in performance. Two different energy systems architectures for a 100 houses community located in Nordic conditions are designed and optimized. It is found that multi-objective optimization of the system is highly important in order to find right combinations of the design variables sizes and values. Without this step the system can either be oversized or undersized. Multi-objective optimization provides best combinations of the design variables that are technically and economically best, under the given problem.

In real applications, it is important to know that such solar based community energy systems are sensitive to the fluctuating market prices of the electricity and components. Therefore some sort of incentives and governmental support is needed to make these community systems economically feasible. Due to high costs of the collector any support to reduce the price of the collector can reduce the overall cost of the systems. However, the incentives in the future should be given based on the self-consumption efficiency of the community rather than on increasing only the renewable energy capacity. Storage in solar district networks plays a significant role in reducing the purchased electricity from the grid, in other terms it improves the self-consumption. Due to seasonal mismatch in cold regions, seasonal storage can play an important role in increasing the renewable installed capacity and its utilization.

Both the centralized and semi-decentralized systems are proposed in this study. Both the system can be built in Nordic conditions based on the requirement. However, it is found that compared to complete centralized system a semi-distributed system can be built at a lower cost, where the central district network is operated at lower temperature, while the high temperature network is distributed within the building. It is demonstrated that the centralized system is more sensitive to the collector size whereas the decentralized system is less sensitive to the collector size. Moreover, the shape of the borehole seasonal storage is an important design parameter. The design and shape of the borehole thermal energy storage should always be investigated simultaneously while choosing the collector size. The set points for the tanks, collectors and controls should also be designed in an optimum way, to increase the overall performance of the systems.

This study has served as a proof of concept for different types of district heating networks for high latitudes. The analysis shows that both systems performed differently in different control strategies. Hence it is highly important to consider the control strategies, layouts, buildings and placement of each component while designing such systems. In the future studies it is planned to perform experimental verification of the proposed systems because no such solar community district heating network project exists in Finland at the moment and other studies cannot be directly

compared against the present study, due to many technical differences. It is also planned to estimate levelized cost of electricity (LCOE) of the components. Estimated heat prices of the energy from such district networks can also be included in the calculations and compared against the reference prices for the interest of the end consumers, additionally, sensitivity analysis can be carried out. New policies should be designed around the world that can promote community scale solar heating networks. This would allow building carbon neutral communities around the world that would ultimately reduce the impact on the climate change phenomenon. In the current environment where business competitiveness is a high priority, along with various environment-related policies, it is likely that the cost of the solar thermal collector would go down, thus making such systems much more attractive for investors and resulting in higher investments. This study can be essential for policy makers, designers and businesses when choosing and proposing better policies, technical designs and business models that can better serve stakeholders.

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