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## Design of a simple control strategy for a community-size solar heating system with a seasonal storage

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### Abstract

The presented paper focuses on the design of different control strategies of a cold climate community-size solar thermal system located in Finland. The system was designed on TRNSYS software in order to perform dynamic simulation. A solar thermal system operating with various control strategies has been designed with an integrated ground source heat pump and a seasonal borehole storage to provide domestic hot water (DHW) and space heating (SH) for community-size demand. The system has two short term storage tanks, a hot tank and a warm tank. The impact of the considered system solutions on electricity consumption has been evaluated and compared as a function of the different collector control modes and different tank configurations (short term tanks sizes). Results have shown that the proposed system was able to provide a 78-83% renewable energy fraction. Total electricity consumption of the heating system varied by 20% between the best and the worst cases. Furthermore, system performance was better when solar energy was mainly stored in the warm tank. During a 5-year simulation, the annual seasonal storage efficiency improved from 0.23 to 0.31, whereas the heat pump electricity consumption reduced from 57.17 MWh to 45.93 MWh. The demand in winter was met mainly through ground heat and the rest was provided by the heat pump compressor. However, the demand in summer was met almost completely by solar energy.

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**Nomenclature**

BTES	Borehole thermal energy storage	HP	Heat pump
COP	Coefficient of performance	SH	Space heating
DHW	Domestic hot water	ST	Solar thermal

**1. Introduction**

Buildings are one of the largest energy consumers and emitters of CO<sub>2</sub>, representing 40% of the European Union's total energy consumption. Indeed, the Directive 2010/31/EU and the Council on 19 May 2010 of the European Parliament [1] have prioritized the reduction of energy consumption of the building sector, under the “20-20-20” objectives. Similarly, recent developments on the knowledge about global warming have led to explore alternative technologies for cleaner energy production by using renewable sources. Solar thermal system, especially in the building sectors at a community or district scale, is a key alternative technology to achieve this goal, and indeed such systems are spreading in the European countries [2]. Solar communities are a potential approach for heating dominated buildings in cold regions [3]. They are not yet commonly built at high latitudes in cold regions such as Finland. The cold temperature and the low irradiation in winter limit the operation of these systems in building heating requirements; however, solar thermal energy can be used in an effective way by designing such systems smartly. Furthermore, system designs from other countries cannot be transferred directly to a new location [4] [3]. Several crucial factors need to be considered to evaluate the community-sized solar thermal system energy performance in any region. These include the efficient long term seasonal storage, the effective back up system and a good control strategy of the whole system. Hence, a detailed investigation is needed for such system in Finland.

Firstly, in Finnish conditions, seasonal storage is of great importance in order to store energy for winters. The decision to use a type of seasonal storage depends on the climate and the geological situation of the ground. Studies in various countries [5] [6] [7] have shown that higher solar fraction and savings were obtained with systems with underground storage in most cases. All these studies focused on small scale systems and design optimization is needed to make such concept feasible [5] [6] [7] [8]. Recently, a working solar community has been developed at Drake Landing, Canada [9], to evaluate the performance of the system. Space heating is provided thorough BTES (Borehole thermal energy storage) and the system was able to provide 97.6% of solar fraction by the end of 6<sup>th</sup> year of its operation [10]. Secondly, as system backup, gas and electric boilers have been used widely to overcome the shortcomings of solar thermal energy [9]. Similarly, alternative design is being discussed where a heat pump is used instead of gas boilers [11]. In fact, solar thermal collectors can supply heat to the ground. This heated ground increases the temperature of the evaporator in the ground source heat pump (GSHP), hence, it improves the heat pump efficiency, in addition to provide building heating energy [12]. This technology combination can be particularly attractive in a cold climate.

Lastly, in order to increase the solar fraction of such systems, a good control strategy for the system is required. Numerous studies on model based control strategies for solar thermal plants have been conducted. Improvements were obtained using control based on critical radiations, variable mass flows and the thermo-hydraulic behaviors in the system [13] [14]. Moreover, fuzzy logic and feedforward control have been tested to estimate the daily amount of energy storage and to determine the consumption profile [15]. Similarly, for smaller system's [16] [17] [18], predictive control strategy has been studied where weather forecasts as well as prediction of the user's needs in terms of tapped water were evaluated to operate the auxiliary heater elements in the tanks for a domestic hot water system. Furthermore, design and control of storage tank and its connection with heat pump showed a significant influence on the performance of heat pump and whole system [19]. Detailed studies were carried out for the system performance as function of control strategies and results obtained through simulation showed a reduction of auxiliary energy demand and an increase in solar fraction [20] [21].

In spite of many studies being carried out in the past, however, most of the findings are limited to the particular system configuration considered. Thus, not many community sizes solar heating system has been deliberated. A strong motivation behind this study is to maximize the effective use of the solar energy by giving the priority to building heating energy (domestic hot water and space heating) when solar thermal collectors are used. Therefore an

investigation of a system has been carried out which can drive solar energy to the storage tank, supplying heating energy to the building and into the ground. Moreover, the new proposed control strategy between solar thermal field, ground and heat pump is hierarchical and priority is given to the storage tank loading. Furthermore, it is also important to mention that the performance of the solar heating system strongly depends upon the operating temperatures and parameters. Two solar output controls will be examined in conjunction with three storage tank connection options. The impact of a particular control strategy of the system on the electricity consumption, overall system and borehole performance has been discussed.

## 2. Methodology

TRNSYS simulation environment was the main tool used to analyze the behavior of the solar system. The weather and demand data used in TRNSYS are defined in sections 2.1. System configuration, energy flows, and parameters are defined in section 2.2. System controls strategies along with set points are defined in section 2.3.

### 2.1. Weather and demand profile

The analyzed community is located at 60 °N, Finland. It is a 50-house community with 100 m<sup>2</sup> area covered for each house. Regarding the weather data, Finnish test reference year data [22] has been used in TRNSYS through Type 15 [23]. The total radiation and the external temperature are shown in Fig. 1a. Whereas, Fig. 1b shows the monthly energy demand for space heating (SH) and domestic hot water (DHW) for the analyzed 50 buildings. Furthermore, the characteristic demand for SH is 35 kWh/m<sup>2</sup>a and for DHW 33 kWh/m<sup>2</sup>a for all buildings.

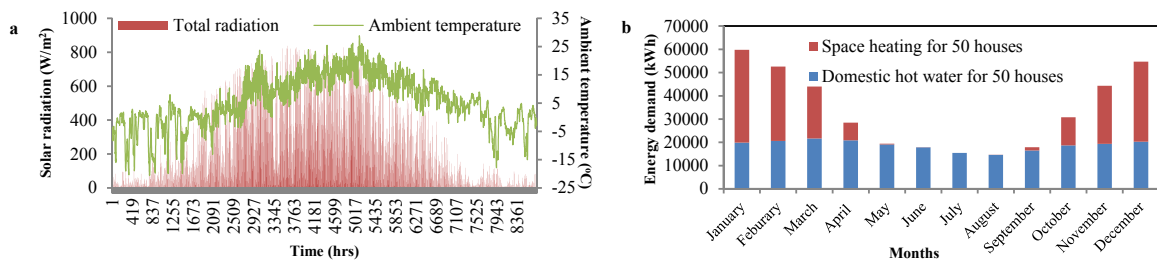


Fig. 1. Finland (a) Hourly solar radiation and ambient temperature; (b) 50 houses monthly energy requirements.

### 2.2. System configuration

The system includes the solar thermal collectors, short term storage tanks, borehole storage and heat pumps. The solar thermal energy is charged into tanks, which in turn supply heating energy to the houses and drive surplus heat into the borehole thermal energy storage (BTES), according to the implemented operating strategy. A schematic representation of the system is shown in Fig. 2. Solid blocks refer to system components, while the continuous lines represent the types of energy flows and their directions.

The control strategy between solar thermal field, hot and warm tanks, and borehole storage is hierarchical. Solar thermal pump draws the cold water from the tank bottom and into the heat exchanger to collect heat from solar collector loop. Meanwhile, heated water from collector transfers heat to the tank via heat exchanger after attaining the desired temperature based on the set point. The tanks can be charged in parallel or in series. Depending upon the control mode selection, water is diverted to charge either short term tank, till that tank's set point value is reached.

When the tank temperature exceeds the desired set point, the short term storage tank transfers the energy to the seasonal storage (ground storage), till the tank's temperature reduces to the desired level. During the winter season when there is not enough energy from the solar collectors, the warm tank and hot tank temperature drops and, at a certain lower limit, the heat pump (HP) provides the energy to the tank from the borehole storage.

The space heating is provided by passing the space heating water through warm tank and then to the houses at temperature between 20 °C to 40 °C depending upon the outdoor temperature. Domestic hot water is provided by

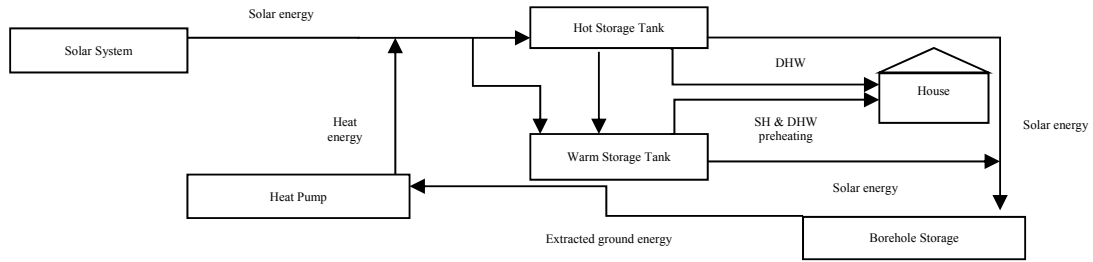


Fig. 2. Solar thermal system components and energy flows.

preheating the cold water in the warm tank and then by heating the water further in the hot tank till it reaches the desired temperature of 60 °C. The hot water is then supplied to the houses. There is also a DHW recirculation circuit in the system to ensure that DHW is always available without delay. The operating and control mode of above system is described in section 2.3 in this paper.

2.2.1. Solar thermal system and short term storage tanks

Solar panels are mounted at 40° tilt angle facing south. The design features of the solar thermal collectors [24] including the storage tanks (hot and warm tank) are shown in Table 1a and 1b respectively. The connections of collector to the tanks are series, parallel or automatic mode.

Table 1. Design characteristic of (a) Solar thermal system design features [24] (b) Short term storage tanks model.

a Solar thermal collector		Value
Net surface	1500 m <sup>2</sup>	
Maximum flow rate	11.11 kg/s	
Intercept efficiency	0.857	
Efficiency slope	3.083 W/m <sup>2</sup> .K	
Efficiency curvature	0.013 W/m <sup>2</sup> .K <sup>2</sup>	

b Short term storage tanks (hot and warm tank)	
Volume	50 m <sup>3</sup> , 100 m <sup>3</sup> , 150 m <sup>3</sup>
Heat exchanger effectiveness	0.9
Insulation U-value	0.3 W/m <sup>2</sup> .K

2.2.2. Borehole thermal energy storage

The seasonal storage plays a key role in the solar energy storage and as thermal source for the heat pump. The seasonal storage behavior has been simulated utilizing Type 557a model that is available in the GHP TESS library of TRNSYS. Table 2 shows the main borehole and soil characteristics.

Table 2. Main BTES characteristics.

Borehole thermal energy storage, Vertical- U tube system	
Volume	60 000 m <sup>3</sup>
Depth	45 m
Number of boreholes	144
Pipe distance	3.4 m
Pipe thermal conductivity	0.472 W/m.K
Soil undisturbed temperature [25]	5 °C

2.2.3. Heat pump

A heat pump (HP) is connected to the system and it operates when the short-term tank’s temperature drops low.

The heat pump meets the heating load in the network through the storage tank. It takes energy from the ground and then supplies it to the short term tanks. The nominal power consumption of the HP is 30 kW, maximum flow rate of water through the HP condenser is 1.94 kg/s and the COP of the HP is 2-6, depending on the BTES and the desired output temperature.

### 2.3. Operating modes

The system is designed to maximize the fraction of solar heat. Solar energy is used primarily for DHW and SH supply through the storage tanks and secondarily for charging the ground. The control is designed in a hierarchical pattern. In order to minimize the use of heat pump, charging set points of the tanks are higher for solar thermal collector than for the heat pump. When the tanks need charging, the first option is using the solar collector. If the warm tank temperature is lower than 40 °C, it will be heated to 45 °C and for hot tank, if temperature is lower than 65 °C, it will be heated to 70 °C by solar collectors. If energy from solar collectors is not available, heat can be transferred from BTES into the tanks through heat pump in order to charge the tanks. If the warm tank temperature is lower than 35 °C, it will be heated to 40 °C and if the hot tank temperature is lower than 60 °C, it will be heated to 65 °C by the heat pump. Heat pump (HP) is the most energy intensive unit of the system; hence, it is important to reduce the operation of the HP to meet the heating demand of the building. This will improve the overall system performance. The set points of tanks charged by the solar collectors are higher as compared to the HP in order to maintain the tanks temperature at higher values. Since the tanks are charged at a higher level, therefore HP is used less. This control strategy will slightly reduce the efficiency of the collectors due to higher operation temperature of the collector; however, it will improve the overall performance of the system due to less utilization of the HP.

Heat is transferred to BTES to avoid overheating of short term tanks. Heat from warm storage tank is transferred when tank temperature reaches 50 °C and stopped once the temperature drops to 45 °C. From hot storage tank, heat is transferred when tank temperature reaches 75 °C and stopped once the temperature is below 70 °C. There are many possibilities to connect the storage tanks and also the flow through the solar thermal collectors. Several control modes can be used in different combinations. Optimal control mode may depend on the energy generation and storage capacities. There are different control possibilities for ST output temperature described in section 2.3.1. Different options for the ST-short term tank connection modes have been described in section 2.3.2. The selection of which tank to charge has been described in section 2.3.3.

#### 2.3.1. Solar collector output control

The solar thermal output temperature is controlled by adjusting the flowrate through the collector. In this study, two flowrate control strategies are tested: temperature difference control and temperature tracking control.

- Temperature tracking control: The collector always aims for an outlet temperature which is higher than the temperature at the top of the target tank.
- Temperature difference control: The solar collector always aims for a constant temperature increase by adjusting the flowrate. In this control, it is important to note that if the temperature difference setting is too small, it may cool the top of the tank due to low inflow temperature. Table 3 shows the set point for the solar thermal collector for each control mode.

Table 3. Solar collector set points and operation modes.

System configuration	Set point (°C)	Description
Temperature tracking control for all tank connection modes	$T_{top} + 1$	Desired temperature in ST over the tank top temperature, where $T_{top}$ = Short term storage tank top temperature
Temperature difference control for series mode	$T_{in} + 45$	Desired constant temperature increase in series mode, where $T_{in}$ = Collectors inflow temperature
Temperature difference control for parallel mode	$T_{in} + 15$	Desired constant temperature increase in parallel mode, where $T_{in}$ = Collectors inflow temperature

2.3.2. Tank connection modes

These describe the connection of the tanks with regard to solar collector. The tanks may be connected in three modes: parallel, series and automatic mode.

- Series mode: Tanks are connected as if they are a single tank. ST inflow comes from the bottom of the warm tank and outflow goes to the top of the hot tank. It allows the operation of the system with lower flow rates.
- Parallel mode: The tanks are completely separate. The inflow for ST comes from the bottom of either tank and the outflow is sent to the top of the same tank.
- Automatic mode: There is automatic switching between the series and parallel mode, depending on the flow and temperature conditions. If the ST output temperature significantly exceeds the set point, but the flowrate is already at maximum, the tank connection switches from parallel to series mode. If the flow rate later drops below 1/3 of the maximum flow, the connection switches back to parallel.

2.3.3. Primary energy storage tank

Both thermal storage tanks are to be kept above certain temperature limits by the solar thermal system, to prevent unnecessary heat pump activation. If both tanks are at an adequate temperature, all available solar heat will be stored in the chosen primary tank, which can be either the warm tank or the hot tank.

2.4. Simulated cases

The simulations were carried out yearly to determine the performance of each system, starting from April to maximize the use of stored energy in the borehole system. Here, various representative system configurations and control modes have been selected and the results obtained are presented and discussed in the paper in order to carefully deliberate the system behaviour. Table 4 and Table 5 describe the configurations and the control modes used in the simulations respectively. The renewable energy fraction is defined in equation (1) as follows:

$$\text{Renewable energy fraction} = 1 - \frac{\text{HP electricity consumption per year} + \text{Pumping electricity consumption per year}}{\text{SH demand per year} + \text{DHW demand per year}} \tag{1}$$

Table 4. Solar collector and short term storage tanks configurations for the simulations and results.

System configuration	ST Area (m <sup>2</sup> )	Warm tank volume (m <sup>3</sup> )	Hot tank volume (m <sup>3</sup> )
A	1500	150	50
B	1500	100	100
C	1500	50	150

Table 5. Case summary for simulations.

System configuration	Control mode (Case number)	Tank connections			ST control		Primary storage	
		Series	Parallel	Automatic	Temp. difference	Temp. tracking	Warm tank	Hot tank
A,B,C	1		x		x			x
	2		x		x		x	
	3		x			x		x
	4		x			x	x	
	5	x			x			x
	6	x				x		x
	7			x	x			x
	8			x	x		x	
	9			x		x		x
	10			x		x	x	

### 3. Results and discussion

#### 3.1. Control system effects

In Case 2 and in Case 8, when the warm tank is the priority tank, the electricity consumption was the lowest and they were generally the best cases in Fig. 3. This was caused by lower HP electricity demand. When warm tank is used as a priority tank, it gets charged frequently by the collectors each time it loses its energy to ground or to demand. As the warm tank receives low temperature energy from the collectors even during low sunshine hours, which occur throughout the year, the system benefits from this abundantly available low temperature energy each year. Furthermore, as the warm tank gets charged more by solar energy, the seasonal storage will take most of its energy from this warm tank, as shown in reference case in Fig. 4. Therefore, the net energy value of BTES will be high at the end of each year as in Fig. 4. Henceforth, heat pump consumes less total electricity each year to generate heat during winters, because a high source temperature improves its COP. However, this changed with different tank priority. In Case 1 and in Case 7, with hot tank as priority, the electricity demand is maximum (Fig. 3). When hot tank is used as priority tank, the solar collectors mostly provide high temperature heat. This decreases solar efficiency and reduces the total energy stored in the tanks and consequently the charging of the BTES, as shown in Fig 4. The heat demand of the buildings was independent of the control mode.

In Case 1 and in Case 2, and similarly in Case 7 and in Case 8 when system performance is compared (Fig. 3), the electricity consumption reduces by 20% when warm tank is set as priority. This phenomenon is explained above, where there is a clear advantage to use warm tank as priority over hot tank. Therefore, it is recommended to use the warm tank as priority storage tank. It indicates that system was able to utilize yearly high and low radiation solar energy available effectively for both parallel and automatic tank-ST controls. Moreover, the discharging of BTES (Fig. 4) is slightly less in case of warm tank as priority. However, one drawback when warm tank is used as priority tank, since it collects more yearly energy from ST collector, the BTES is charged more which increases the yearly losses from the BTES compared to hot tank as priority as shown in Fig. 4.

In Case 5 and in Case 6 with series connection, the energy consumption was slightly higher than those of Cases 2, 4 and Cases 8, 10 since system has to supply energy to hot tank each time at higher temperatures and also solar collector efficiency is less at higher temperatures (Fig. 3). Furthermore, in series mode the temperature tracking Case 6 has higher electricity demand than temperature difference control of collector Case 5. This is because in Case 5 system consumes less energy to charge the hot tank. Therefore, in general for all series, parallel and automatic ST-tank connections it is suggested to use temperature difference control. As for tanks sizes, it is recommended to have warm tank and hot tank sizes as 100 m<sup>3</sup>, as the energy consumption is less as demonstrated in most individual cases shown in Fig. 3. It requires less heat pump energy to charge a small 100 m<sup>3</sup> hot tank to 65 °C compared to a large 150 m<sup>3</sup> hot tank to 65 °C. Moreover, the losses from small sized hot tank will be less.

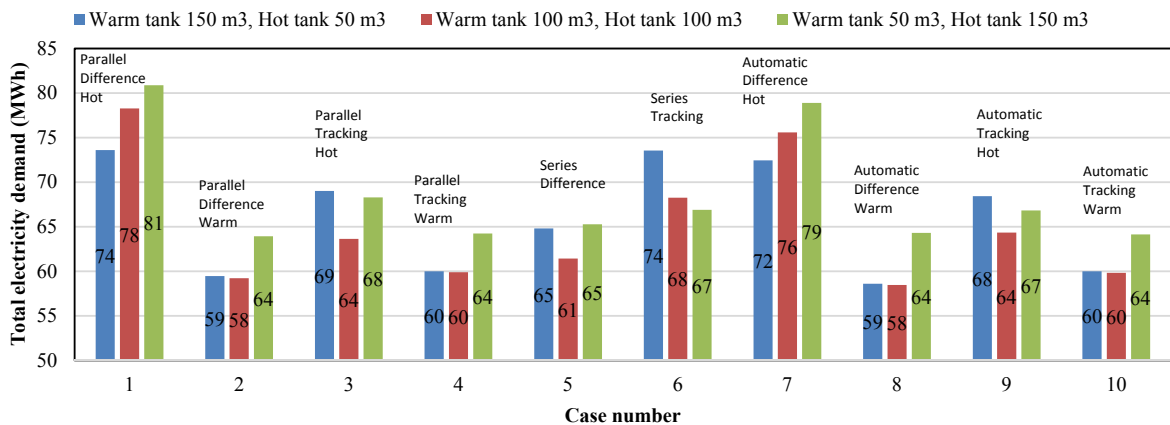


Fig. 3. Total electricity demand of the system, for the simulations based on Table 5.

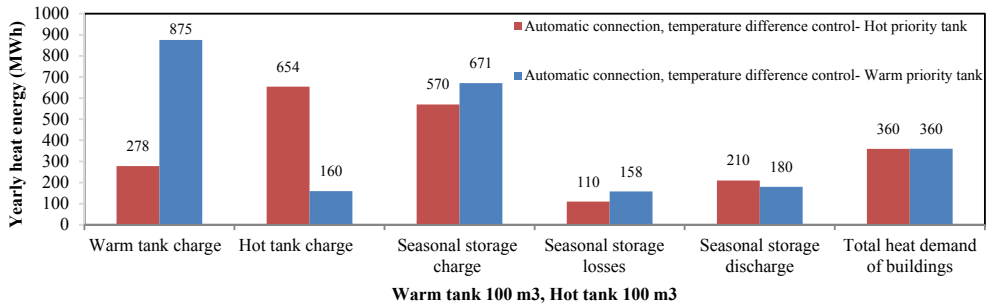


Fig. 4. Heat energy flows in the system during first year, reference case (B7 and B8): warm tank 100 m<sup>3</sup> and hot tank 100 m<sup>3</sup>.

3.2. Detailed system performance

In Fig. 5, we see a detailed analysis of the seasonal storage behavior, taking automatic ST-tank connection with temperature difference control (B8) as reference. During summer, a large amount of energy is used to charge the ground, however, as the energy input and therefore, the ground temperature increases, the losses also get higher. The heat loss of the BTES is given as an output by the BTES- TYPE 557a in the simulation and it is the sum of the heat losses from the top, the bottom and the sides of the BTES. Heat losses depend on the storage temperature and the temperature of the surrounding layer. Both these temperatures change gradually as solar energy is injected to the ground. Discharging of BTES mainly takes place from November to February, when no energy is injected to the ground. March is the only month with a significant amount of both charging and discharging. The efficiency of the BTES is defined in equation (2) as follows:

$$\eta_{BTES} = \frac{\int_0^{8760} BTES\ discharge(t) dt}{\int_0^{8760} BTES\ charge(t) dt} \tag{2}$$

The yearly BTES efficiency based on Equation (2), improves from 0.23 to 0.31 in 5 years of its operation. Furthermore, the average BTES ground temperature increase from 5 °C to 30 °C in 5 years of the simulation.

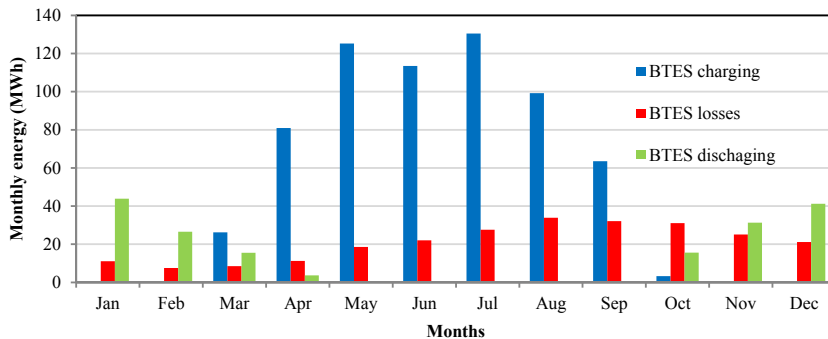


Fig. 5. Yearly seasonal borehole storage behaviour, reference case (B8): automatic ST-tank connection with temperature difference control.

As shown in Fig.6, in summer the demand for DHW is met by the solar energy and as expected, due to the absence of solar thermal energy, in winter, the demand (SH and DHW) is met through heat pump and ground storage. Most of the energy is provided by the heat pump from the ground, while the rest is met by the compressor.



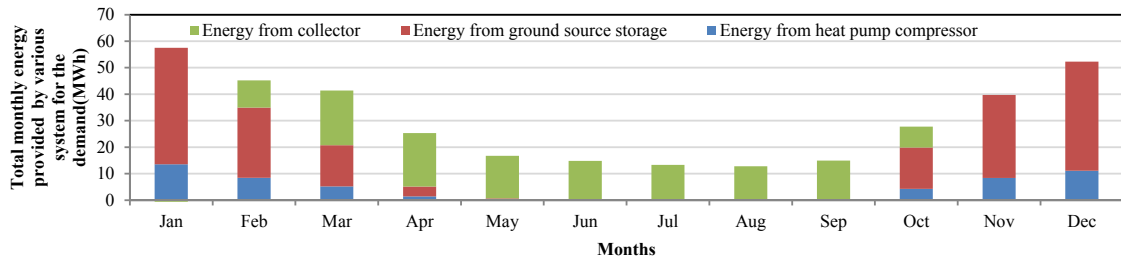


Fig. 6. Yearly system performance, reference case (B8): automatic ST-tank connection with temperature difference control.

To shed light to the effectiveness of these systems in terms of final electricity consumption, we can refer to Table 6. It shows the yearly electricity consumption of the heat pump and the pumps for each circuit using automatic ST-tank connection with temperature difference control (B8) as reference. The most energy intensive unit is the heat pump. Since, the borehole is charged yearly, the energy required by the heat pump to meet the annual demand of the system is reduced yearly, from 57.17 MWh to 45.93 MWh in 5 years.

Table 6. Yearly electricity consumption of the system, reference case (B8): automatic ST-tank connection with temperature difference control.

Heat pump (MWh)	ST pump (MWh)	Pump for HP (MWh)	Ground pump (MWh)	SH pump (MWh)	DHW pump (MWh)	DHW recirculation pump (MWh)
57.17	1.15	0.13	0.29	1.79	0.26	0.003

#### 4. Conclusions

Ground source heat pump integrated with the solar thermal collector is a suitable solution for both DHW and SH demands in Finland for the community requirements. In such a system, seasonal storage plays a fundamental role to increase the system efficiency. In this study, different control strategies were implemented in order to achieve high renewable energy fraction and minimum electricity demand of the system. In parallel/automatic setup, with temperature difference control of collector and warm tank as priority, the renewable energy fraction increased from 78% to 83% and the electricity consumption reduced by 20%, compared to hot tank as priority. This was because the system was able to effectively utilize the available low radiation solar energy annually. Additionally, the use of 100 m<sup>3</sup> warm tank as priority tank is recommended and hot tank 100 m<sup>3</sup>, since they are able to reduce the HP energy consumption. For better performance in series connection, it is also recommended to have temperature difference control for collector and small hot tank 100 m<sup>3</sup> can be used instead of 150 m<sup>3</sup>. The BTES efficiency showed an increasing trend during 5 years of its operation. Moreover, the average BTES temperature increased from 5 °C to 30 °C and as a consequence, the COP of the heat pump increased. The high ground source temperature thus reduced the annual HP electricity consumption from 57.17 MWh to 45.93 MWh in 5 years of simulation. This approach allowed less usage of grid electricity in each following year of the system operation. Therefore, the overall system performance improved with time. Additionally, if the temperature of the ground is high enough, the heat pump may in some cases be completely bypassed, reducing the energy demand significantly. On the other hand, each progressing year when the BTES net energy increases, it might be necessary to change the control strategy where hot tank can be used as priority tank in order to charge the BTES at higher temperatures. The major challenge in building the solar community in Finnish conditions is the BTES heat loss to the environment, which increases as the ground temperature increases. The study showed the methodology and interaction between the BTES, heat pump and system controls and their effect on the overall solar system performance. In this paper, the simulated period was limited to 5 years to reduce computation time. Although, ground temperature and system efficiency kept on increasing even after that, however the improvement rate slowed. An extended study could be made with longer simulated periods and with control parameters that change with the ground conditions.

## Acknowledgements

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