

Design and optimization of a De-centralized community sized solar heating system for Nordic Region

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Abstract

There is a need to accelerate the application of advanced clean energy technologies to resolve the challenges of climate change. Solar heating is a feasible solution among clean energy technologies. These technologies are not yet highly used in high latitudes due to various challenges. This paper focuses on the community sized solar district heating system configuration for cold climates. The proposed configuration consists of a partially de-centralized heating system. Each individual house heat pump was connected between large centralized solar-charged low temperature tank and smaller de-centralized individual high temperature tank in each house. Additionally, the large centralized tank was directly charged by solar-charged borehole storage during winters. Dynamic simulation approach was used through TRNSYS software coupled with MOBO (multi-objective building optimizer) for NSGA-II optimization algorithm. The purchased electricity and investments were two objectives minimized. The impact of the energy system on the renewable energy fraction, purchased electricity and investments as a function of the building heating demand, collectors and photovoltaic areas, short-term tanks storages and boreholes volumes were evaluated. Results showed that purchased electricity varied 47 kWh/m²/yr—25 kWh/m²/yr and renewable energy fraction 75%—91%.

Keywords: De-centralized solar district heating, multi-objective optimization, cold climate, seasonal storage.

1. Introduction

Buildings are one of the largest consumers of the energy in European Union (EU). They consume around 40% of the total energy (Nielsen, 2012). Buildings in the urban and community setup play a significant role in the energy demand of the community. Furthermore, in Finland huge amount of energy is being used by space heating and domestic hot water for the residential buildings. This causes large emissions of CO₂ (Official Statistics of Finland (OSF), 2016). Therefore, with increase in the emissions, and interest on the environmental impact of residential areas, there is an increased interest in using of renewable energy for the buildings. Solar communities can provide a good alternative to the conventional communities that are being provided with fossil based heat energy. These community concepts have not been built at high latitudes in cold regions such as Finland. The cold temperature, demand and supply mismatch and expensive storage system does limit the operations of such systems in building heating requirements. On the contrary, solar thermal can be used effectively if designed properly. It is important to mention that designs and parameters cannot be used directly from other locations as each location has different conditions and climate (Flynn & K.Siren, 2015).

Solar district heating is a very promising alternative to fossil fuel district heating. Solar thermal (ST) systems are key technologies for achieving emission reduction goals. Their use is spreading in European countries. In Europe, there are around 141 heating plants which have more than 500 m² solar collector area (Dalenbäck & Werner, 2012). Since 1979 onwards several countries have participated in operating central solar heating plants with seasonal storage under IEA Task 7 to boost the progress of large scale heating technologies (International Energy Agency Solar Heating and Cooling Programme, IEA-SHC, Task 7, 2016). Since 1980s onwards, in Germany many plants have been built that provide district heating via solar thermal energy (Schmidt, et al., 2004). In Denmark, due to its competitive price in comparison to biomass and gas there is a boom in the solar district heating market (Nielsen, 2012). Similarly, many solar district networks are built in different parts of the Europe and North America. For instance, there are large scale pilot plants located in Norway, Denmark, Sweden, the Netherlands, Canada and the USA that uses solar energy with seasonal storage (Nielsen, 2012),

(Solar District Heating, 2016), (Mangold, 2007), (M. Lundh, 2008), (Bauer, et al., 2010). It is found that community-scale solar energy systems are economical even without support payments. Community-scale allowed the use of seasonal thermal storage, which is a key technology for achieving a high degree of utilization of solar energy in Finland. However, no such community has been built in Finland yet. Instead of zero energy buildings, the focus should shift to developing zero energy communities, which can benefit from the best features of both distributed and centralized energy systems (Hirvonen, 2017). The reason and the challenges to build such community in Nordic region are: (a) the energy cost is still not yet competitive enough and (b) solar energy is not typically available when needed.

In community sized system, the energy storage plays an important role to improve the performance of the system. Moreover in Nordic conditions where the mismatch between the irradiation and demand is significant, seasonal storage is vital. Using thermal storage for viable solar energy utilization through solar thermal panels to meet building heat loads becomes an important discussion. Excess energy generated during long summer hours can be stored for seasonal periods (Kalaiselvam & Parameshwaran, 2014). Seasonal thermal storage stores thermal energy when solar radiation is abundant. The cost and size of the seasonal storage are important factors that influence the decision while choosing the type of seasonal storage to be used in such solar community concepts. Ground thermal energy storage has cost advantage due to its size and capacities compared to short term tanks storage (Fisch, et al., 1998), (Rad & Fung, 2016). However, ground storages have higher losses issues due to ground conductivity. Therefore, the properties of the ground, time of storage, temperature, location and geometry are critical (Nordell, 2000). Sensible thermal storage collects energy by increasing the temperature of a medium with finite heat capacitance (typically water) (V.Novo, et al., 2010). It is stored in a variety of medium for the use during winters. The most prominent modes of storage found in the literature are: (1) Hot Water Energy Storage (HWTES), (2) Gravel-Water Thermal Energy Storage (GWTES), (3) Aquifer Thermal Energy Storage (ATES), and (4) Borehole Thermal Energy Storage (BTES) (Schmidt, et al., 2004). Each method provides certain advantages such as location, capacity and cost. Among these four methods, BTES is the most flexible storage technique (Rehman, et al., 2017) and therefore is the primary focus of this analysis.

It is found that in most of the existing solar communities the focus is on space heating demand (SPH). This approach minimizes the heat losses in the seasonal storage (Chapuis & Bernier, 2009). This low grade temperature present in the seasonal storage can be increased using a heat pump. Heat pump (HP) can be used with the ground with any combination, i.e. regardless the ground is charged or not via solar energy. It is found that charging of the ground can improve the heat pump performance as the evaporator temperature increases. Hence, it improves the coefficient of performance (COP) of the heat pump (Rehman, et al., 2017). The heat pump can be integrated with the solar thermal system in multiple ways and with varying control strategies. The way and the strategy used to integrate the heat pump can also vary the overall solar thermal system performance and behaviour. In this study, a particular methodology is described to integrate HP with the solar thermal district network.

The novelty in the present study is the proposed partially de-centralized solar district heating system and the multi-objective optimization of such system. The proposed system has a centralized large tank that is at lower temperature and provides most of the space heating. While the de-centralized part consists of a small tank in each individual house that operates at higher temperature, it is being charged by the centralized tank and heat pump, and part of the space heating along with domestic hot water is provided through this tank. In this configuration the placement of the heat pump, hot short term storage tank and the overall control strategy is altered compared to the previous studies (Rehman, et al., 2017), (Sibbitt, et al., 2012). In the previous study carried out, the heat pump is centralized with the two large centralized short term storage tanks charged via solar energy and seasonal storage in parallel (Rehman, et al., 2017). These large tanks are divided into warm and hot tanks in order to meet the space heating (SPH) and domestic hot water demand (DHW) of the community respectively (Rehman, et al., 2017). Whereas in the present study, instead of a large centralized hot tank, a small tank is placed in each of the 100 houses. Similarly, instead of a centralized large heat pump, 100 small sized heat pumps are distributed among the 100 houses to charge the small hot tank. Furthermore, only the large centralized warm tank is charged by the solar energy, and the small hot tank is charged via the heat pump directly instead of the solar energy. Likewise, the difference between the present study and the Drake Landing Solar Community, Canada is that for domestic hot water a dedicated individual collectors and natural gas heaters is installed to provide hot water (Sibbitt, et al., 2012). On the contrary in the present study, the individual

house hot tank is charged via heat pump using energy from the centralized solar heating network. The aim of this research is to design, optimize and assess the performance of such de-centralized solar thermal district heating system in Nordic location. The challenges mentioned above are addressed. The impact of the mentioned configuration of solar and ground loop on the annual energy consumption is evaluated. In particular the influence of varying solar thermal (ST) size, short-term storage tank volume, borehole (BTES) size, photovoltaic (PV) size, and building heating demand on the purchased electricity, investments and renewable energy fraction are evaluated. The energy system is designed by using dynamic simulation software i.e. TRNSYS (Thermal Energy System Specialists, LLC, 2012) and then optimized using multi-objective optimization algorithm (NSGA-II) where the purchased electricity and investments are minimized.

2. Methodology

The paper focuses on the modelling and the multi-objective optimization of the de-centralized community sized solar district heating system. Therefore the energy system is first design on dynamic simulation software i.e. TRNSYS (Thermal Energy System Specialists, LLC, 2012) and then the model is optimized using multi-objective optimization algorithm (NSGA-II) (Hirvonen, 2017) where purchased electricity and investments are minimized together. Renewable energy fraction (Hirvonen, 2017), (Rehman, et al., 2017), final purchased electricity, and investment costs (IC) are calculated to evaluate the system.

2.1. Energy system

The energy system consists of ST collectors, short-term tanks, boreholes, PV modules, heat pumps and buildings. The energy system is designed based on Drake Landing Solar Community (DLSC), Canada (Sibbitt, et al., 2012) as it has shown good performance in cold climatic conditions.

The solar energy system is used to provide DHW and SPH through the network and secondarily for charging the ground. The control is designed in a hierarchical pattern. Solar thermal pump draws the cold water from the large centralized low temperature tank bottom and into the heat exchanger to collect heat from solar collector loop. Meanwhile, heated water from collector transferred heat to the centralized tank directly via heat exchanger after attaining the desired temperature based on the set point. For this study, temperature tracking control mode is selected where the collectors typically aims for an outlet temperature that is one degree higher than the warm tank top temperature connection for charging (ur Rehman, et al., 2016).

If the large centralize tank temperature is lower than 40 °C, it is heated to 45 °C. Excess heat from solar collectors is transferred to BTES to avoid overheating of this large tank. Heat from storage tank is transferred when tank temperature reached 50 °C and stopped once the temperature dropped to 45 °C. If energy from solar collectors is not available, heat can be transferred back from BTES into the centralized tank directly. If the centralized tank temperature is less than 35 °C and the BTES average temperature is higher than the tank top temperature, the energy is transferred via BTES and tank is charged till 40 °C. The cold fluid entered from the cool outer edge of the BTES and exits from the hot centre. Low temperature is maintained in the collectors and centralized tank circuit to improve the collectors' efficiency. The energy from this centralized large tank is distributed in the low temperature space heating district heating network of the community. Moreover, the space heating return network is used by individual heat pump (NIBE, 2017) present in each of the 100 houses in the community to heat each of the small sized hot tanks present in each of the houses. If the hot tank temperature is lower than 60 °C, it is heated to 65 °C by the heat pump.

The space heating is provided by passing the space heating (SPH) water through the warm tank and then through the bottom node of the small hot tank. This heated water is then provided to the houses at temperature between 30 °C to 40 °C depending upon the outdoor temperature. Domestic hot water (DHW) is provided to houses by passing the cold water from the bottom of the hot tank and till the top of the tank until it reached the desired temperature of 60 °C. If the heat pump and solar energy are not enough to meet the temperature needs, backup heating is handled by direct electric heaters. A schematic representation of the system is shown in Fig. 1. The centralized section of the energy system i.e. solar thermal collectors, seasonal storage and warm tank along with de-centralized section of energy system i.e. the heat pump and the hot tank in each house is shown in Fig.1.

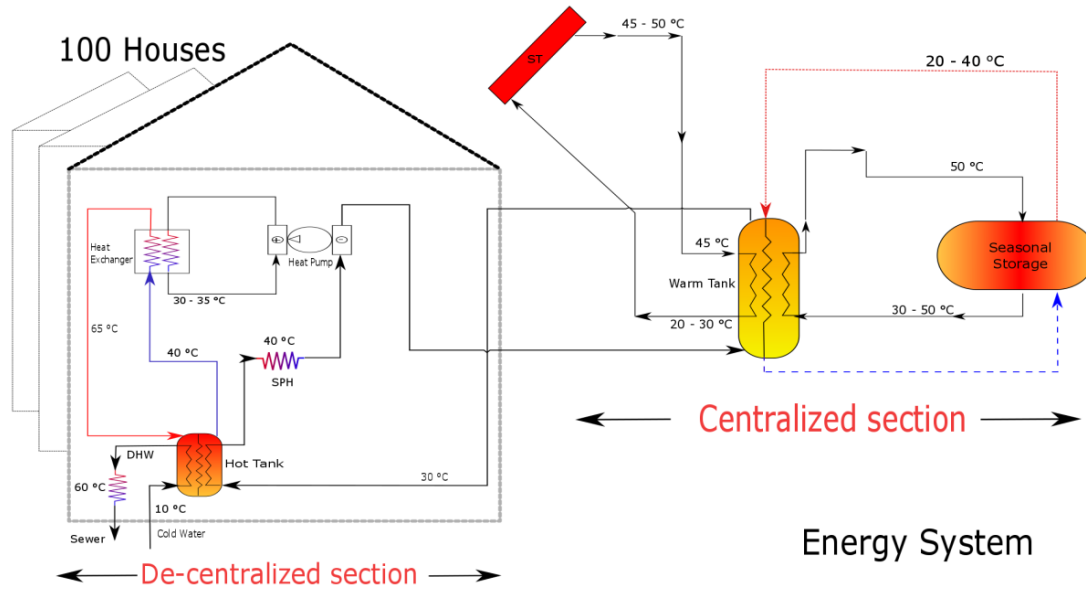


Fig. 1: Simple schematic representation of the partial centralized and de-centralized energy system.

2.2. Simulation environment

A 100-house community is studied, located in Helsinki, Finland. The system is simulated using TRNSYS simulation studio (Thermal Energy System Specialists, LLC, 2012). TRNSYS type 1b, type 543, type 557a, type 668, type 194 and type 15 are used for solar thermal collectors, buffer tanks, boreholes, heat pump, photovoltaic panels and weather data respectively (Rehman, et al., 2017). The buildings are built and simulated in TRNBuild (Thermal Energy System Specialists, LLC, 2012), a subroutine of TRNSYS that generated the thermal loads profile of the building. Each house is a single story house and has pitched roof with a tilted angle of 20°. Three different types of buildings with varying heating demands are selected for the study. Buildings with space heating demand (SPH) of 25, 37 and 50 kWh/m²/yr are selected. The domestic hot water (DHW) demand is 45 kWh/m²/yr and electricity appliances demand is 40 kWh/m²/yr for all three building type cases (Hamdy, et al., 2013). For optimization, TRNSYS simulation model was integrated with the NSGA-II algorithm by optimization integrator software i.e. MOBO also known as multi-objective building optimizer (Hamdy, et al., 2011).

2.3. Optimization problem

In district heating system the optimization problem deals with multiple objectives of conflicting nature. Therefore, in this study the optimization problem consists of minimization of purchased electricity and the investments as both are of conflicting nature.

2.4. Objective functions

In this study, purchased electricity and investment costs (IC) are set as objective functions to be minimized. The purchased electricity and investments costs (IC) are of interest because purchased electricity is in the interest of the user and the investment is in the interest of the contractors and construction companies.

The solar energy system is simulated together with the houses energy demand. Two functions that are analysed are the purchased electricity and the investment costs (IC) together. It is given as:

$$\text{Min, } \{F1(x) = \text{Purchased electricity, } F2(x) = \text{Investment cost(IC)}\} \text{ for all } x = [x_1, x_2, \dots, x_6],$$

where 'x' is the vector of the design variables (x_1, x_2, \dots, x_6) as defined above, F1 is the purchased electricity for the system and F2 is the investment cost of the system. In this problem, the number of considered design variables are six (i.e., $x = [x_1, x_2, \dots, x_6]$). MOBO is integrated with TRNSYS simulation to perform multi-objective optimization. NSGA-II algorithm is used to perform optimization.

The mathematical expression for purchased electricity is,

$$E_{PUR} = E_{PUMP} + E_{HP} + E_{BH} + E_{BUL} - E_{EXP}, \quad (\text{eq. 1})$$

where E_{PUR} is the purchased electricity, E_{PUMP} is the energy consumed by all pumps, E_{HP} is the heat pump energy consumed to heat the hot tank, E_{BH} is the energy use of the direct electric backup heating, used to maintain the temperature in the space heating and domestic hot water network in case heat pump and solar energy is not sufficient, E_{BUL} is appliance electricity demand of buildings and E_{EXP} is the excess electricity that is produced by PV panels and exported.

The second function, investment cost is the sum of the present value of the investments cost of the system. It is expressed as,

$$IC = C_{ST} + C_{PV} + C_{BTES} + C_{WT} + C_{HT} + C_B \quad (\text{eq. 2})$$

where IC is the overall investment cost, C_{ST} is the solar collectors, C_{PV} is the photovoltaic, C_{BTES} is the borehole, C_{WT} is the warm tank, C_{HT} is the hot tank and C_B is the building costs. No maintenance costs are considered. The system is simulated and optimized in parallel for the three years to allow the slow temperature rise in the BTES to take effect.

2.5. Design variables

The energy performance of the energy systems may depend mostly upon the six parameters or design variables which are defined and considered in this paper (Idman, 2013). These are the parameters that can be altered by the designer. The importance of these parameters can vary depending upon the system configuration. The six parameters considered in the system are: (1) ST collectors area, (2) hot tank volume, (3) warm tank volume, (4) BTES volume, (5) photovoltaic area, and (6) building heating demand.

The values of all the design variables and investment costs of design variables are shown in Table 1 including the selected buildings. A constant unit price is used for some energy system components. On the other hand the costs of some design variables are assumed to vary depending upon its size. The cost of the collectors varied as found in the study, large collector field tends to be much cheaper compared to smaller field, caused by economies of scale (Mauthner & Herkel, 2016), (Ahola, 2015), (Dalenbäck & Werner, 2012), (Hirvonen, 2017). The collectors used in the study are roof mounted solar collectors which are expensive compared to ground mounted collectors (Mauthner & Herkel, 2016). Finnish market is still under development therefore higher prices can be assumed for the collectors, tanks and PV panels (including taxes). In Crailsheim, Germany borehole thermal energy storage (BTES) is used as seasonal storage therefore, same cost is used here for BTES cost (Schmidt & Miedaner, 2012). The cost of the BTES is assumed to be constant per unit volume (includes drilling, insulation, construction and taxes) as shown in Table 1. It is computationally expensive to explore all designs. Hence, a multi-objective non-dominated sorting genetic algorithm (NSGA-II) is used to perform the simulation (Hamdy, et al., 2013). MOBO uses NSGA-II algorithm with an initial population of 16 individual for 100 generations i.e. $16 \times 100 = 1600$ simulation run.

Tab. 1: System configuration variations for the simulations and investment cost of the components used in energy systems.

Design variables	Type of variables	Ranges/ Values	Prices (€)	Options
Roof mounted solar thermal area (m ²)	Continuous	50—6000	1000—550 €/m ²	
Warm tank volume (m ³)	Continuous	300—500	825—810 €/m ³	
Hot tank volume /house (m ³)	Continuous	0.5—5	900—810 €/m ³	
BTES volume (m ³)	Continuous	10000—60000	17.19 €/m ³	
Photo voltaic area (m ²)	Continuous	50—6000	450—200 €/m ²	
Building configurations	Discrete	Type 1: space heating demand= 25kWh/m ² /yr	15 628€/building	3
		Type 2: space heating demand= 37kWh/m ² /yr	13 260 €/building	
		Type 3: space heating demand= 50kWh/m ² /yr	12 655 €/building	

2.6. Renewable energy fraction

The renewable energy fraction (REF_{heat}) for heating is defined as (Rehman, et al., 2017),

$$REF_{heat} = 1 - \frac{(HP+backup\ direct\ heating+pumping)electricity\ consumption\ per\ year}{SH\ demand\ per\ year+DHW\ demand\ per\ year}, \quad (\text{eq. 3})$$

the above equation (eq.3) accounts the heat losses through the grid. The household appliances electricity demand is not included in the calculations.

2.7. On-site energy matching (OEM) and on-site energy fraction (OEF)

The onsite-energy matching (OEM) for electricity is defined as the ratio between exported electricity and total on-site electricity generated through photovoltaic panels (Cao, et al., 2013). The OEM provided the values that indicated the portion of the on-site generated electricity that is used in the local demand rather than being dumped or exported. The onsite-energy fraction (OEF) for electricity is defined as the ratio between annual purchased electricity and total electricity demand of the community (Cao, et al., 2013). The OEF provided the values that indicated the portion of the demand covered by the on-site generated electricity through photovoltaic panels. Higher the value of OEF and OEM better is the matching.

3. Results and discussion

The relationship between the purchased electricity and the investments costs of the non-dominated solutions are shown in Fig. 2. In total there are 132 non-dominated solutions for the energy system (red points). All the simulations results cloud is also shown in Fig. 2 (blue points).

The solutions on the Pareto front in Fig.2 (red points) are called non-dominated solutions. All simulations run (blue points) converged on the Pareto front (red points) as shown in Fig. 2. It shows that due to the increase in the investments there is a reduction in the purchased electricity. The solutions on the left side of the Fig.2 are less energy intensive compared to the solutions on the right (red points). The purchased electricity varied from 47.4 kWh/m²/yr to 25.7 kWh/m²/yr, this correspond to the investments cost (IC) from 180.7 €/m², floor area to 526 €/m², floor area. The solution shows that there are wide ranges of the optimal solution available which can be selected by the contactors and the end users based on their expectation and demand. It is found that the left most solutions contained a large photo voltaic and medium sized solar thermal areas. On the other hand the majority of the solutions on the right hand side in Fig.2 contained solutions with smaller photovoltaic panels and solar thermal area. Furthermore, other important design parameters that followed a certain trend on the Pareto front are building heating demand.

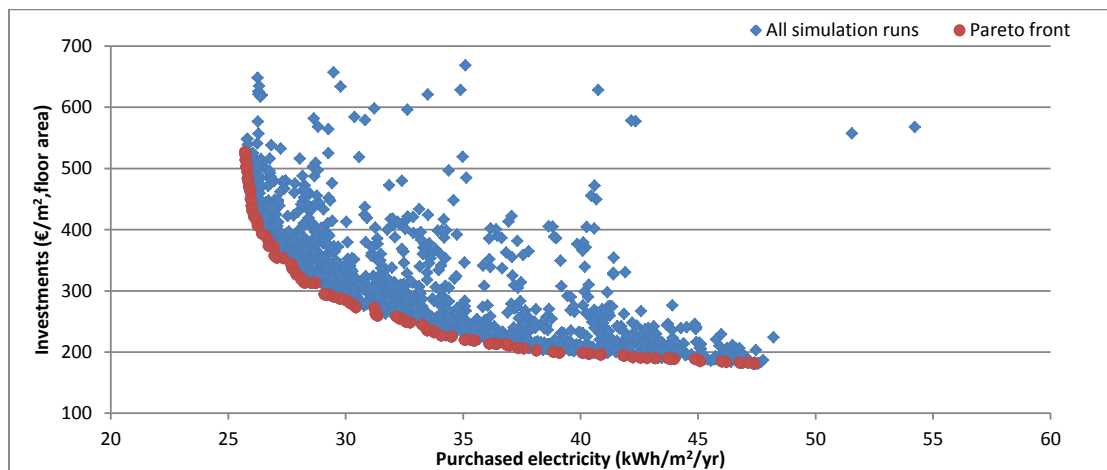


Fig. 2: Purchased electricity versus investments of the non-dominated optimal combinations of the design variables.

The cost breakdowns of the non-dominated solutions are shown in Fig.3.

The solutions on the left hand side of Fig.3 are the least expensive solutions. These solutions have higher purchased electricity. On the contrary the solutions on the right side of Fig.3 are expensive solutions and the corresponding purchased electricity is less.

It is observed that in Fig.3 photo voltaic area, solar thermal area, building heating demand and storage tanks volume played a significant role in the overall investments and also in the change in the purchased electricity. Due to the cheaper cost of the photovoltaics panels compared to the solar collectors, PV area is increased

initially by the algorithm to reduce the purchased electricity, and later solar collectors area is increased. Since hot tank is not charged by the solar thermal energy and it is only charged via the heat pump therefore, there is a large requirement of the electricity compared to the thermal energy. As a consequence, large photovoltaic area played significant role in reducing the purchased electricity compared to solar thermal area. Small-medium ST area is used to charge the warm tank at adequate level in all non-dominated solutions. Large PV panels area is used to provide electricity to the heat pump to charge the hot tank. Nevertheless if hot tank is charged by the solar thermal area then larger ST area would have been beneficial.

Furthermore, the solar thermal area also played important role in the reduction of the purchased electricity. The Fig.3 showed that on the left side, most of the cases has small solar thermal area of around 100—700 m². On the other hand, in the most expensive cases where the purchased electricity is less, the optimization algorithm selected medium sized solar thermal collectors of around 1000—2800 m². A very larger solar thermal area of around 3000 m² and above had minimal advantage in reducing the purchased electricity and also it is expensive, therefore the algorithm did not select a very large solar thermal collectors area. Hot tank is not charged by the solar energy therefore, large collector area had minimal advantage.

Building demand also contributed in improving the performance of the system. Initially, in most of the optimal cases building with heating demand of 50 kWh/m²/yr are chosen because it is the cheapest option among others as shown in Fig.3 (left side). In the cases where the purchased electricity is less, on the right side of the Fig.3, the building with heating demand of 37 kWh/m²/yr and 25 kWh/m²/yr are chosen in majority. With higher investments, building demand could be reduced from 50 kWh/m²/yr to 37 kWh/m²/yr and up to 25 kWh/m²/yr.

The size of the short term tanks also increased gradually from the least expensive to the expensive solution. This indicated that a large tank volume would improve the performance of the system. As this would provide the instantaneous energy needed for the system to meet the heating demand of the buildings. Larger the volume, large is the energy available. Larger tank volumes are also selected in high performing cases due to cheaper cost of the tank.

The solution on the right side of the Fig.3 shows that a combination of medium to large photovoltaic area, medium sized solar thermal area, and large volume of the tanks, energy efficient building and medium size of BTES volume could improve the performance of the energy system. On the other hand, this would have higher cost. A combination of small photovoltaic and solar thermal area, small BTES volume and building with highest heating demand would be the cheapest solution. This resulted in high purchased electricity by the system.

The solution with lowest solar thermal collectors area has minimal renewable energy fraction on left side in Fig.3. The renewable energy fraction increased with increase in the collectors area.

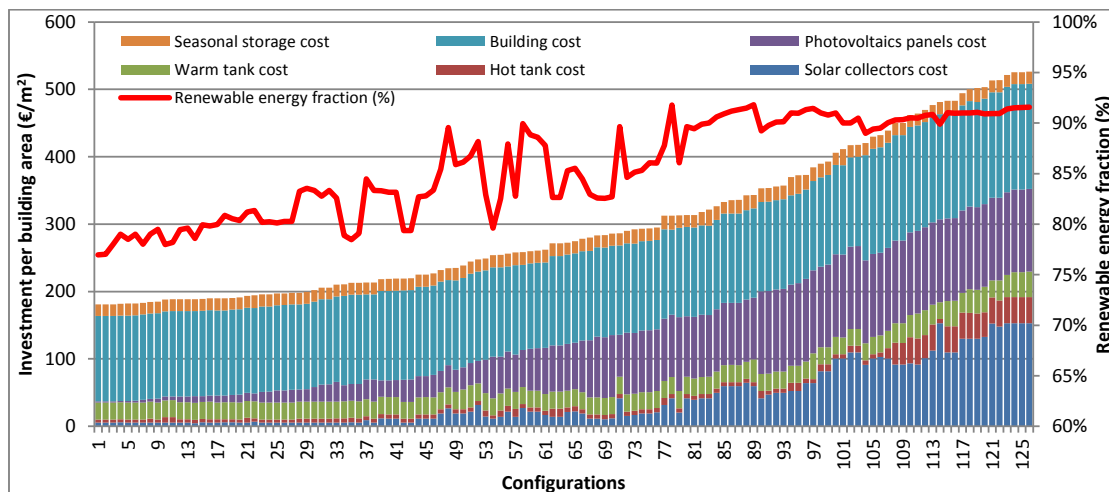


Fig. 3: The cost breakdown of the non-dominated optimal solutions.

The on-site energy fraction (OEF) varied between 2% and 38% as shown in Fig.4. This indicated that PV panels are able to meet 2%—38% of the local demand of the system, depending upon the PV panels size and annual electricity demand. The OEF is less when the PV panels area is less on the left side of the Fig.4, hence the on-

site generation of electricity is not enough to meet the high load. It improved until 38% when the PV and ST areas are large on the right side of Fig.4, resulting in large on-site electricity generation and lesser demand. The maximum OEF is 38% because of the mismatch between the generation and consumption and no electrical storage is considered. Since there is no electricity storage, therefore in the cases where the PV area is large the maximum OEM achieved is 20% as shown in Fig.4. This indicated that in highest performing cases 20% of the on-site generation by PV panels is used locally while the rest of the 80% is exported due to mismatch and lack of electricity storage in the system. On the other hand, the OEM is 100% when the PV area is small (no exported electricity), however this resulted in 2% OEF only.

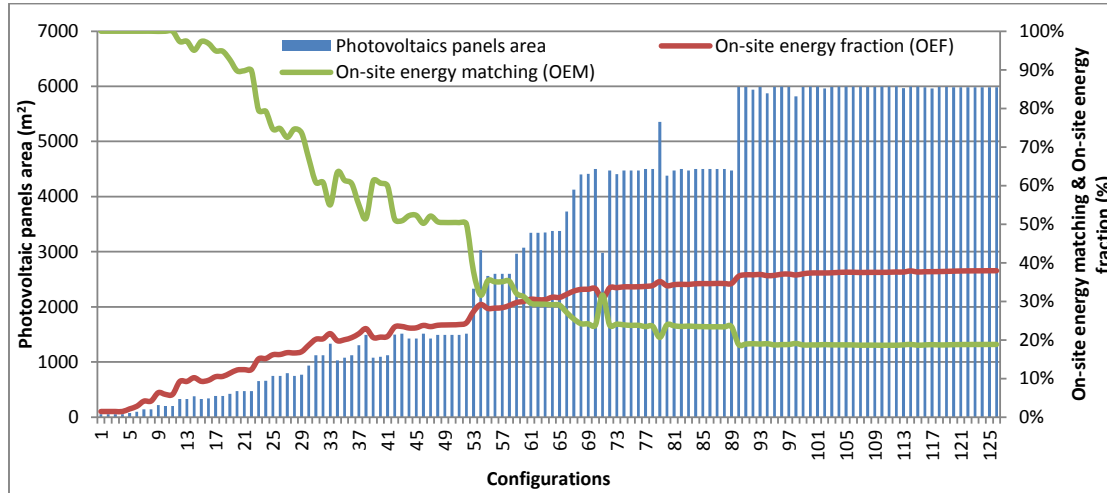


Fig. 4: The On-site energy fraction and On-site energy matching for electricity, correspond to the photovoltaic panels area.

3.1. The benefits of centralized space heating and de-centralized hot water

The simulation results provided some worthwhile findings. Firstly, size of the solar thermal area can be reduced in such system compared to the complete centralized system. It is found that in most of the optimized cases the size of the collectors ranged from 100— 2800 m². Large solar thermal area from 3000 m² onwards is not needed in such partial decentralized system. Because low temperature centralized tank can be charged with small-medium sized collectors and warm tank is used to preheat the space heating water therefore larger areas of collectors are not required. Furthermore, the decentralized hot tank is charged by the heat pump only and not via collectors. This also reduced the need of a larger collectors area in the optimized cases. Due to such partial centralized and decentralized configuration the size of the BTES is around 10700 m³ in majority of the optimized cases. The discharge from the BTES is not significant in the cases where solar thermal capacity is less (cheapest cases), therefore in such cases BTES can be excluded from the system. Only in most expensive cases large volume of BTES (12000 m³) is proposed that slightly improved the performance of the system. However large photovoltaic panels reduced the purchased electricity because hot tank is charged through electricity (heat pump) and not through solar thermal energy (collector) therefore large photovoltaic panels area are proposed.

Secondly, the partial decentralized system can be implemented at lower investment cost because the size of the solar thermal collectors and the BTES are less in most of the optimized cases. Since larger modules of both the solar collectors and BTES are not needed to improve the performance, hence the investment costs are less. Moreover, solar thermal collectors are the most expensive component in the solar community compared to photovoltaic panels. Hence lesser size of collectors is beneficial in terms of cost reduction.

Lastly, the results showed that by having de-centralized high temperature (domestic hot water) system inside houses, the losses through the piping reduced as the length of the high temperature pipe reduced from 4000 m (centralized) to 200 m (decentralized). The reduction in the losses through the domestic hot water piping is around 90%.

4. Conclusion

The goal of the research is to investigate the performance and optimize the solar district heating system for community in Nordic conditions. For this study de-centralized system is proposed. The proposed system

consists of individual house heat pump connected between large centralized solar-charged low temperature tank and smaller de-centralized individual high temperature tank in each house. Additionally, the large centralized tank is directly charged by solar-charged borehole storage during winters. The boreholes are charged by the centralized warm tank during summers. Multi-objective optimization is carried out in order to improve the performance of the system. The two objectives that are minimized are purchased electricity and investments cost.

Generally, it is found that solar energy can be used to provide both DHW and SPH, or also to charge the ground. Balancing the use of the solar energy throughout the year integrated with a HP is effective in energy system. In particular, storing energy in the seasonal storage increases the performance of the system by reducing the purchased electricity. The advantage of using the de-centralized system is that losses through the system and BTES are less. Since the size of the ST area is smaller therefore the temperatures in the seasonal storage is limited and it operates on lower temperature. Furthermore, the losses through the high temperature district heating grid are less compared to the centralized system because the high temperature tank is smaller in size and present inside the houses. This reduced the length of the piping from 4000 m to 200 m for 100 houses, as a consequence the losses through the high temperature DHW piping are reduced.

In terms of energy system, it is found that each component has varied effect on the performance of the system. In order to increase the performance of the system it is essential to have correct combinations of the system. The correct sizing of the design variables like: ST area, photovoltaic area, short-term storages tanks volume, BTES volume and the building heating demand is important. The analysis showed that the highest purchased electricity is 47.4 kWh/m²/yr, on the contrary, the lowest purchased electricity is 25.7 kWh/m²/yr. This is mainly caused by the variation in the heat pump consumption. The heat pump is used only to charge the small sized hot tank while taking energy from the space heating return line instead of the BTES. Hence, the source is relatively warmer on the evaporator side. The system can be implemented with the investments ranging from 180.7 €/m², floor area to 526 €/m², floor area. In most of the best cases, where purchased electricity is minimal, it is found that a combination of small-medium sized solar thermal collectors area, small-medium sized BTES and high energy intensive buildings are proposed in most of the optimal cases. However, purchased electricity can further be reduced by having a combination of medium solar thermal area, large volume of BTES and buildings with lowest heating demand. The results also showed that, photovoltaic area is vital for the overall system performance. Large photovoltaic area reduced the purchase electricity, however due to mismatch excess energy is exported to the grid. No electricity storage is considered in this study. As for the tank sizes, firstly it is beneficial to have small to medium sized decentralized hot tank in most of the optimal cases in each house. Secondly, it is beneficial to have large volume of centralized low temperature tank of around 300—460 m³.

For the solar thermal collectors, a small to medium sized ST area is beneficial in most of the optimal cases. A large area of 3000—6000 m² is not selected in optimal cases. Large ST area had minimal benefit because high temperature is not needed in de-centralized system. In addition to that, the cost of the ST area played important role in selecting the solar thermal area, due to high cost of the collectors the algorithm selected small to medium sized collectors.

The on-site energy fraction (OEF) for electricity varied around 2%—38%. This correspond to the on-site energy matching (OEM) from 100%—20%. Both the OEF and OEM varied based on the PV panels area and the demand of the system. Large PV area and low purchased electricity resulted in higher OEF and low OEM. On the other hand, small PV area and high purchased electricity resulted in lower OEF and high OEM. PV panels installation is beneficial along with the ST collectors because without the PV panels the OEF for electricity would be zero and all the electricity has to be purchased via the grid. This would increase the purchased electricity and the operational cost of the community.

The renewable energy fraction varied from 75%—91%. This again illustrates the significance of the design variables and configuration on the system performance. This study clarified some important aspects of the energy system behaviour. It provides better in-depth understanding of the effect of each individual design variable on the system behaviour. This study gave the methodology and interactions between design variables for a proposed system configuration. In particular, their effect on the system performance is presented. An extended study could be made by changing the controls and other design variables, like the set points of the system in order to optimize the control algorithm. Additionally it is planned to include electricity price (operational cost) and emission price in the energy system optimization to show complete picture in the future

study. With increase in the popularity of the solar community concept in Nordic region, finding the best strategies and combinations would be important. This information is useful for the designers and contractors in making early stage decisions.

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