Techno-economic performance of community sized solar heating systems in Nordic conditions

Hassam ur Rehman
Techno-economic performance of community sized solar heating systems in Nordic conditions

Hassam ur Rehman

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall 216 in Otakaari 4, K1 building of the school on 17 December 2018 at 12:00.

Aalto University
School of Engineering
Department of Mechanical Engineering
Energy Efficiency and Systems, HVAC group
Supervising professor
Professor Risto Kosonen, Aalto University, Finland.

Thesis advisor
Professor Kai Siren, Aalto University, Finland.

Preliminary examiners
Professor Ivo Martinac, Royal Institute of Technology (KTH), Sweden.
Associate Professor, Natasa Nord, Norwegian University of Science and Technology (NTNU), Norway.

Opponents
Professor Per Kvols Heiselberg, Aalborg University, Denmark.
**Author**
Hassan ur Rehman

**Name of the doctoral dissertation**
Techno-economic performance of community sized solar heating systems in Nordic conditions

**Publisher**
School of Engineering

**Unit**
Department of Mechanical Engineering

**Series**
Aalto University publication series DOCTORAL DISSERTATIONS 238/2018

**Field of research**
Energy Engineering

**Permission to publish granted (date)**
29 October 2018

**Language**
English

<table>
<thead>
<tr>
<th>Monograph</th>
<th>Article dissertation</th>
<th>Essay dissertation</th>
</tr>
</thead>
<tbody>
<tr>
<td>☑</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Abstract**
Regional size solar heating systems allow an efficient use of clean energy technologies and passive buildings. The objective of the thesis is on the design, techno-economic performance, optimization and comparisons of various solar heating system architectures in Nordic conditions for regional demand. These systems provide space heating, domestic hot water and electricity to the community.

Detailed simulation is crucial to study the combined effect of renewable energy sources, mechanical components, storages and buildings. In the study, TRNSYS and TRNBuild are used for energy systems and building dynamic simulation respectively. MOBO is used for multi-objective optimization.

The thesis includes four publications. The publications contain following topics: developing of control strategies for a basic system, long term parametric study of three systems alternatives, influence of technical failures on the performance of an optimized system, and comparison between centralized and semi-decentralized systems designs. The results showed that parallel short-term storage tanks charging, with temperature difference control at collector outlet, reduced the energy consumption by 20%, compared to serial charging of the tanks. It is found that by placing a heat pump connected between two short term tanks, using solar charged borehole storage to charge the tank, improved the system performance. Additionally, seasonal storage charging and heat demand played an important role on the performance and investments. However, these systems are sensitive to certain technical failures, inversely they may not be sensitive to certain issues. Results showed that de-stratification, solar circulation pump control and heat pump COP can cause large deviations from the ideal conditions. Semi-decentralized system, where low temperature grid is centralized and high temperature grid is decentralized can clearly outperform centralized system, in terms of the life cycle cost by 35%. Shape of the seasonal storage varies depending on the stored heat and distribution network typology. The renewable energy fraction of up to 92% can be attained.

The thesis shows that it is technically possible to build high performing solar heating networks in Nordic climate. A simulation based optimization problem of solar district and buildings together can reach an optimal or close to optimal solution set, useful for decision makers. Large size of the community allowed the effective use of the seasonal storage and solar energy. Control of each component and optimization is necessary to gain benefits of such concept. Large systems are much cheaper by unit price because of economics of scale. With decreasing trend of the collector and PV cost, economics of such system can be altered with cheap thermal storage. The technical uncertainties should be considered while realizing these systems. To validate the system a pilot project is needed. Life cycle assessment can be done to rationalize its societal impact.

**Keywords**
Solar district heating, multi-objective optimization, seasonal storages, Nordic climate

**ISBN (printed)**
978-952-60-8323-0

**ISBN (pdf)**
978-952-60-8324-7

**ISSN (printed)**
1799-4934

**ISSN (pdf)**
1799-4942

**Location of publisher**
Helsinki

**Location of printing**
Helsinki

**Year**
2018

**Pages**
193

**urn**
Preface

This doctoral thesis has been made in the HVAC group of the Department of Mechanical Engineering, which is part of the Aalto University School of Engineering. The work has mainly been funded by the Academy of Finland, within the project ‘Solar community concept (SCC) in Nordic climate’, but also by the K.V. Lindhols stiftelse, Energy efficiency and systems (EES) doctoral program, and Doctoral Education Network in Energy Technology (DENET). I gratefully acknowledge the financial support of all funders.

I give sincere thanks to my supervisor Professor Risto Kosonen. His support, direction and counsel have been of great help to the success of this endeavour. I would especially wish to express my deep gratitude towards my research supervisor Professor Kai Siren. His excellent guidance, advice and support at each step during these years have been invaluable. As well, I want to thanks Dr. Janne Hirvonen for his continuous support and challenge to improve. Without the support of all the above mentioned persons this thesis would not exist. Their drive for quality has been fundamental for this process. This research team has set a high standard for me, which I intend to follow and convey.

I would also like to thanks Seija Erander-Luukkanen, Ritva Viero, Jenni Lehtonen, Katja Lehto, Paula Thomsson, Mirka Seppälä, and Maija Pero for all the support given in administrative issues. Thanks to Professor Sanna Syri, Juha Jokisalo, Simo Kilpeläinen and Matti Palonen for the support. In particular, I thank the HVAC research group for the exchange of ideas and mutual support. Special thanks to Professor Bruno Lacarrière and Professor Moussa Mohsen, who originally gave me the idea of becoming a doctoral candidate.

Last, but not least I wish my deep gratitude and thanks to Almighty and my family for their continuous and unconditional love and support. Special thanks to Zubair Rehman (father), Dr. Ayesha Sarwat (mother), Ibad ur Rehman (brother), Rehan ul Haq and Shabnam Rehan. I would also give credits to my loving wife, Dr. Yamna Rehman for her unconditional love, support and patience. You all have been and will always be a great source of inspiration to me. I dedicate this thesis for a better future and for a sustainable world.

Espoo, Finland, 7 August 2018
Hassam ur Rehman
Contents

Preface................................................................. 1
List of Abbreviations and Symbols.................................... 5
List of Publications...................................................... 7
Author’s Contribution................................................... 8
1. Introduction .......................................................... 9
  1.1 The background and the importance of the community concept ........................................... 9
  1.2 Solar district heating community concepts: Practical cases .............................................. 11
  1.3 The importance of seasonal storage in solar district communities ........................................ 14
  1.4 Technical failures, errors and issues with solar district heating systems ................................. 15
  1.5 The objective, hypothesis and research questions ............................................................... 16
  1.6 The scope of the thesis .................................................. 17
  1.7 The thesis and publications structure .................................................................................. 18
  1.8 The novelty of the work ................................................... 19
2. Introduction: The analysed solar district heating systems .... 21
  2.1 The reference case: The Finnish context ................................................................. 21
  2.2 The boundary conditions for all the simulated systems .................................................. 21
  2.3 Energy system configurations and control strategies ...................................................... 22
    2.3.1 A simple solar-based community-sized district system design ...................................... 22
    2.3.2 The controls of the collector temperatures ............................................................. 23
    2.3.3 Control of the tanks connections and charging ....................................................... 24
    2.3.4 Energy system types and typologies ........................................................................... 24
    2.3.5 The centralised systems’ generic control strategy .................................................... 24
    2.3.6 The semi-decentralised system’s generic control strategy ....................................... 27
3. Introduction: Simulation and optimisation tools ............... 31
  3.1 The simulation tool ....................................................... 31
    3.1.1 TRNSYS dynamic simulation software ................................................................. 32
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.2</td>
<td>IDA ICE software</td>
<td>32</td>
</tr>
<tr>
<td>3.1.3</td>
<td>A comparison between TRNSYS and IDA ICE software</td>
<td>32</td>
</tr>
<tr>
<td>3.2</td>
<td>The exhaustive search and multi-objective optimisation methods</td>
<td>33</td>
</tr>
<tr>
<td>3.3</td>
<td>The parametric search and exhaustive search methods</td>
<td>34</td>
</tr>
<tr>
<td>3.4</td>
<td>The simulation-based optimisation method</td>
<td>34</td>
</tr>
<tr>
<td>3.4.1</td>
<td>The genetic algorithm: NSGA-II</td>
<td>35</td>
</tr>
<tr>
<td>3.4.2</td>
<td>The hypervolume of the Pareto front</td>
<td>35</td>
</tr>
<tr>
<td>4.</td>
<td>Methodology</td>
<td>37</td>
</tr>
<tr>
<td>4.1</td>
<td>The input parameters and design variables for simulated systems and</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>optimisation</td>
<td></td>
</tr>
<tr>
<td>4.1.1</td>
<td>ST collectors and short-term storage tank design</td>
<td>37</td>
</tr>
<tr>
<td>4.1.2</td>
<td>The piping system</td>
<td>38</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Heat pump design</td>
<td>38</td>
</tr>
<tr>
<td>4.1.4</td>
<td>PV panel design</td>
<td>39</td>
</tr>
<tr>
<td>4.1.5</td>
<td>Weather profile: Finland</td>
<td>39</td>
</tr>
<tr>
<td>4.1.6</td>
<td>The building’s heating demand in the community as an input parameter.</td>
<td>39</td>
</tr>
<tr>
<td>4.2</td>
<td>Input parameters for seasonal storage</td>
<td>41</td>
</tr>
<tr>
<td>4.2.1</td>
<td>The background of the seasonal storages</td>
<td>41</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Types of TES</td>
<td>42</td>
</tr>
<tr>
<td>4.2.3</td>
<td>BTES as seasonal storage in the Finnish context</td>
<td>43</td>
</tr>
<tr>
<td>4.3</td>
<td>The multi-objective optimisation methodology</td>
<td>45</td>
</tr>
<tr>
<td>4.3.1</td>
<td>The optimisation algorithm and MOBO</td>
<td>45</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Problem definition</td>
<td>46</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Objective functions</td>
<td>46</td>
</tr>
<tr>
<td>4.4</td>
<td>Issues, errors and technical failures: Solar district heating systems</td>
<td>48</td>
</tr>
<tr>
<td>5.</td>
<td>Results</td>
<td>51</td>
</tr>
<tr>
<td>5.1</td>
<td>The effect and importance of controls on system performance</td>
<td>51</td>
</tr>
<tr>
<td>5.1.1</td>
<td>System behaviours and energy flows</td>
<td>53</td>
</tr>
<tr>
<td>5.2</td>
<td>Building performance and its importance as a design parameter in</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>energy systems</td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>Analysis of different centralised energy system configurations</td>
<td>57</td>
</tr>
<tr>
<td>5.4</td>
<td>Identification of the main failures and errors, and the influence of</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>the failures on an optimised, centralised district system</td>
<td></td>
</tr>
<tr>
<td>5.4.1</td>
<td>The multi-objective optimisation-base case</td>
<td>64</td>
</tr>
</tbody>
</table>
5.4.2 Analysis on the non-dominated solutions ......................... 66
5.4.3 The influence of system failures and errors on an optimised system: A centralised solar district system in a Finnish context ............... 67
5.4.4 The influence of combined failures and their effect on the centralised energy system performance: The Finnish context ....... 71
5.5 Comparison between centralised and semi-decentralised solar district heating systems ........................................................................... 72
5.5.1 Multi-objective optimisation of the centralised and semi-decentralised systems ........................................................................... 72
5.5.2 The influence of the system designs on various design variables .......................................................................................................................... 75
5.5.3 The sensitivity of the systems with respect to electricity and components prices ................................................................................................. 81
5.6 A summary of the results .................................................................................................................... 83
6. Discussion ............................................................................................................................................. 85
6.1 Comparison between the system typologies, control strategies and design variables ........................................................................................................... 85
6.1.1 The importance of the system control strategies ................. 85
6.1.2 The importance of the energy system typologies............. 86
6.1.3 The importance of the building’s design ......................... 88
6.1.4 The importance of the design variables ......................... 89
6.2 Practical implications ......................................................... 90
6.3 Failures, errors and sensitivity issues with solar district systems ................................................................................................................................. 93
6.3.1 Economic consequences ................................................. 95
6.4 The reliability and validity of the proposed systems ............ 96
6.5 Recommendations for further research .............................. 98
7. Conclusions ........................................................................................................................................ 101
References ................................................................................................................................. 105
Publications ............................................................................................................................... 117
## List of Abbreviations and Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_e$</td>
<td>Discounting factor</td>
</tr>
<tr>
<td>AHU</td>
<td>Air handling unit</td>
</tr>
<tr>
<td>BHE</td>
<td>Borehole heat exchanger</td>
</tr>
<tr>
<td>BTES</td>
<td>Boreholes thermal energy system</td>
</tr>
<tr>
<td>$C_B$</td>
<td>Building investment cost ($\text{€}/\text{m}^2$)</td>
</tr>
<tr>
<td>$C_{BTES}$</td>
<td>Boreholes cost ($\text{€}/\text{m}^3$)</td>
</tr>
<tr>
<td>$C_{\text{Fins}}$</td>
<td>Building floor insulation cost ($\text{€}/\text{m}^3$)</td>
</tr>
<tr>
<td>$C_{\text{HR}}$</td>
<td>Building heat recovery cost ($\text{€}$)</td>
</tr>
<tr>
<td>$C_{\text{HT}}$</td>
<td>Hot tank cost ($\text{€}/\text{m}^3$)</td>
</tr>
<tr>
<td>$C_{\text{PV}}$</td>
<td>Photovoltaic panels cost ($\text{€}/\text{m}^2$)</td>
</tr>
<tr>
<td>$C_{\text{Rins}}$</td>
<td>Building roof insulation cost ($\text{€}/\text{m}^3$)</td>
</tr>
<tr>
<td>$C_{\text{ST}}$</td>
<td>Solar thermal collectors cost ($\text{€}/\text{m}^2$)</td>
</tr>
<tr>
<td>$C_{\text{WIND}}$</td>
<td>Building windows cost ($\text{€}/\text{m}^2$)</td>
</tr>
<tr>
<td>$C_{\text{Wins}}$</td>
<td>Building walls insulation cost ($\text{€}/\text{m}^3$)</td>
</tr>
<tr>
<td>$C_{\text{WT}}$</td>
<td>Warm tank cost ($\text{€}/\text{m}^3$)</td>
</tr>
<tr>
<td>$\text{CO}_2$</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of performance</td>
</tr>
<tr>
<td>DHW</td>
<td>Domestic hot water</td>
</tr>
<tr>
<td>DLSC</td>
<td>Drake Landing Solar Community</td>
</tr>
<tr>
<td>$E_{\text{BH}}$</td>
<td>Backup heater electricity consumption ($\text{kWh/m}^2/\text{yr}$)</td>
</tr>
<tr>
<td>$E_{\text{BUL}}$</td>
<td>Building appliances electricity consumption ($\text{kWh/m}^2/\text{yr}$)</td>
</tr>
<tr>
<td>$E_{\text{DEM}}$</td>
<td>Total electricity demand of the system ($\text{kWh/m}^2/\text{yr}$)</td>
</tr>
<tr>
<td>$E_{\text{EXP}}$</td>
<td>Exported electricity to the grid ($\text{kWh/m}^2/\text{yr}$)</td>
</tr>
<tr>
<td>$E_{\text{HP}}$</td>
<td>Heat pump electricity consumption ($\text{kWh/m}^2/\text{yr}$)</td>
</tr>
<tr>
<td>$E_{\text{ONC}}$</td>
<td>On-site electricity demand, met by photo voltaic ($\text{kWh/m}^2/\text{yr}$)</td>
</tr>
</tbody>
</table>
\[ \mathbf{E}_{\text{PUMP}} \quad \text{Auxiliary pumps electricity consumption (kWh/m}^2/\text{yr)} \]
\[ \mathbf{E}_{\text{PUR}} \quad \text{Purchased electricity from the grid (kWh/m}^2/\text{yr)} \]
\[ \mathbf{E}_{\text{PV}} \quad \text{Electricity produced by the photovoltaic panels (kWh/m}^2/\text{yr)} \]
\[ \text{ESTIF} \quad \text{European solar thermal industry federation} \]
\[ \text{EU} \quad \text{European Union} \]
\[ \text{F}1 \quad \text{First objective function (purchased electricity)} \]
\[ \text{F}2 \quad \text{Second objective function (investment costs)} \]
\[ \text{FC} \quad \text{Full cost} \]
\[ \text{HP} \quad \text{Heat pump} \]
\[ \text{HVAC} \quad \text{Heating, ventilation, and air conditioning} \]
\[ \text{IC} \quad \text{Investment costs} \]
\[ \text{IEA} \quad \text{International energy agency} \]
\[ \text{KPI} \quad \text{Key performance indicator} \]
\[ \text{LCC} \quad \text{Life cycle costs} \]
\[ \text{LCOE} \quad \text{Levelized cost of electricity} \]
\[ \text{MOBO} \quad \text{Multi-objective building optimizer} \]
\[ \text{NSGA-II} \quad \text{Non-dominated Sorting Genetic Algorithm II} \]
\[ \text{nZEB} \quad \text{Nearly zero energy building} \]
\[ \text{nZEC} \quad \text{Nearly zero energy community} \]
\[ \text{OEF} \quad \text{On-site energy fraction} \]
\[ \text{OEM} \quad \text{On-site energy matching} \]
\[ \text{OSF} \quad \text{Official statistics of Finland} \]
\[ \text{PO} \quad \text{Pareto optimal} \]
\[ \text{PV} \quad \text{Photo voltaic panels} \]
\[ \text{REF} \quad \text{Renewable energy fraction} \]
\[ \text{SPH} \quad \text{Space heating} \]
\[ \text{SHC} \quad \text{Solar heating cooling} \]
\[ \text{ST} \quad \text{Solar thermal collectors} \]
\[ \text{TC} \quad \text{Total cost} \]
\[ \text{TES} \quad \text{Thermal energy storage} \]
\[ \text{ZEC} \quad \text{Zero energy community} \]
List of Publications

This thesis consists of an overview of the following publications which are referred to in the text by their numerals

https://doi.org/10.1016/j.egypro.2016.06.183

https://doi.org/10.1016/j.renene.2017.06.017.


Author’s Contribution

**Publication 1:** Design of a simple control strategy for a community-size solar heating system with a seasonal storage

Hassam ur Rehman was the main author in the publication, handling, system modelling, programming, analysis and writing of the whole journal paper. Co-author, Janne Hirvonen provided assistance in developing the model, in discussions, in collection of data and in paper reviewing process. Kai Siren provided essential advice, supervision, helping with ideas, reviewing and writing direction.

**Publication 2:** A long-term performance analysis of three different configurations for community-sized solar heating systems in high latitudes

Hassam ur Rehman was the main author in the publication, handling, system modelling, programming, analysis and writing of the whole journal paper. Co-author, Janne Hirvonen provided assistance in developing the model, in discussions, in collection of data and in paper reviewing process. Kai Siren provided essential advice, supervision, helping with ideas, reviewing and writing direction.

**Publication 3:** Influence of technical failures on the performance of an optimized community-size solar heating system in Nordic conditions

Hassam ur Rehman was the main author in the publication, handling, system modelling, programming, analysis and writing of the whole journal paper. Co-author, Janne Hirvonen provided assistance in developing the model, in discussions, in collection of data and in paper reviewing process. Kai Siren provided essential advice, supervision, helping with ideas, reviewing and writing direction.

**Publication 4:** Performance comparison between optimized design of a centralized and semi-decentralized community size solar district heating system

Hassam ur Rehman was the main author in the publication, handling, system modelling, programming, analysis and writing of the whole journal paper. Co-author, Janne Hirvonen provided assistance in developing the model, in discussions, in collection of data and in paper reviewing process. Kai Siren provided essential advice, supervision, helping with ideas, reviewing and writing direction.
1. Introduction

1.1 The background and the importance of the community concept

Climate change is one of the main challenges that exist at the present time. Climate change can affect many people around the world and their livelihoods; for instance, climate change can cause poverty, a reduction in agricultural output, the melting of glaciers etc. The main reason for climate change is largely fossil fuel consumption and the emissions caused by this. In order to tackle such challenges, the European Union (EU) has given a 20-20-20 target. The objective is to reduce emissions by 20%, improve efficiency by 20% and increase the share of renewable energy by 20% until 2020 (The European Commission, 2009). The goals are indeed quite challenging, and to reach the goals, extensive research is needed. Europe needs to reduce the emissions of greenhouse gases in order to increase the economic growth, maintain technology leadership and keep climate change at acceptable levels. The largest contributors to the emissions are energy plants and energy generations setups. The largest consumers of the generated energy are buildings. Around 40% of the energy is consumed by buildings for heating, cooling and electricity (The European Commission, 2012). This may even be over 50%, as mentioned by Menzes et al. (Menezes, et al., 2014), in some European countries. This means that buildings' energy demand can be reduced or improved in order to provide a larger impact on the emissions. In Europe the ambitious target is to achieve nZEBs (nearly zero-energy buildings); this means that by the end of the year 2020, all new buildings should be nZEBs (The European Parliament and the Council of the European Union, 2010). The main concept is to establish nZEBs that consume as small an amount of energy as possible, and a significant fraction of that energy should be produced through renewable means. Renewable energy is usually considered to be emission free; therefore, if renewable energy is used for buildings, nZEB can be realised. This is certainly true for energy sources such as wind and solar power. However, with bio energy there is still some debate. A 100% bio-based renewable energy system means the combustion of biomass and hence emissions of carbon dioxide (CO₂) (H.Lund & B.V.Mathiesen, 2009; A.Corcoran, et al., 2012).

After minimising energy demand, some energy generation is added in the system. An nZEB needs to be equipped with state-of-the-art efficiency features, such as insulation, windows, heat recovery (for ventilation and domestic hot water [DHW]), as well as passive heating and cooling technologies (Cao, et
Solar energy may be used to provide energy in the buildings. The energy is produced using photovoltaic (PV) panels or a solar thermal (ST) collector that are usually installed on the rooftop of the building. The challenge in utilising solar energy is the diurnal and seasonal nature of solar energy. While energy demand exists throughout the day and night from a fixed location, solar energy may only be generated during the daytime. This issue creates a mismatch problem between the generation and the demand, if daytime generation isn’t sufficient to cover the daily requirements (Cao, et al., 2013). Most of the time the panels and the collector produce insufficient energy to meet the demand; on the other hand, when they produce, it is more than needed. If the issue is considered regarding places in the high latitudes, the situation aggregates. The mismatch can be seasonal in nature (Photovoltaic Geographical Information System - Interactive Maps, 2016). In Nordic countries like Finland, the amount of daylight can change from 20 hours per day in summer to five hours per day in winter. In addition to that, the solar radiation received during winter is less compared to summer. During winter, energy demand rises because of heating needs, but solar energy generation drops to a minimum just when it is needed the most. Therefore, a seasonal mismatch problem exists. The prices of the PV panels and ST collectors have been getting lower, thanks to growing panel and collector production and installation, motivated by governmental policies (The European Technology Platform on Renewable Heating and Cooling (RHC-Platform), 2013; Wirth, 2018). Due to these policies, many people started installing panels and hence sold excess energy to the electrical grid. This solved the economical part of the mismatch problem for the system owners. However, in actuality this mismatch is shifted towards the electrical grid. When the total capacity of uncontrolled energy in the grid reaches a certain fraction, it becomes difficult for the grid operator to manage the grid and compensate for excess generation by reducing generation of the conventional power plants. Fast variations in generation are difficult and many variations cause a blackout in the grid. The problem should not be shifted; a system should be designed that can increase the self-consumption of any energy generated. Therefore, this requires new technological development. There are three technical solutions to the diurnal or seasonal problem: energy storage, demand response and clustering. Energy storage allows storing excess energy during the day and using it later, when consumption is more than generation. Many homes already have an energy storage system in the form of hot tanks and batteries. In buildings with an ST collector, the tank can be used to store solar heat to alleviate the daily mismatch. However, home-scale tanks are unable to meet the seasonal mismatch as the tank has size limitations and losses. On the other hand, a battery system for electric storage has a higher cost, and a limited life cycle (Nataf & Bradley, 2016; Chalise, et al., 2016). Demand response or demand-side management means shifting energy demand from one time to another time; especially during the peak hours, it is shifted to those hours when demand is less (Aghaei & Alizadeh, 2013). This means using appliances during low-demand hours. Clustering means the connection of the building’s energy system in such a way that it becomes a com-
munity (Kayo, et al., 2016). When different users are connected together, their aggregated energy-use profile differs from that of individual profiles. This allows averaging out the demand, hence increasing the base load and avoiding sudden peak loads (A.Corcoran, et al., 2012). This makes it easier to avoid overcapacity and delay immediate investments when balancing local renewable energy generation with demand. Building clustering also benefits from the economy of scale. Hence, a neighbourhood might make a joint order of renewable energy systems in order to reduce unit cost. In Finland, instead of nZEBs, the focus should shift to developing nearly zero-energy communities (nZECs) which can benefit from the best features of both distributed and centralised energy systems.

Since 40% of energy is consumed by buildings for heating, cooling and electricity, this energy could be provided via a renewable source. The renewable source that has the highest potential is solar energy. The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) in the upper atmosphere. Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans and land masses (Intergovernmental Panel on Climate Change, 2007). The spectrum of solar light at the Earth’s surface is mostly spread across the visible and near-infrared ranges, with a small part in the near-ultraviolet range. The amount of solar energy reaching the surface of the planet is so vast that in one year it is about twice as much as will ever be obtained from all of the Earth’s non-renewable resources of coal, oil, natural gas, and mined uranium combined (Stanford University: Global Climate and Energy Project (GCEP), 2017).

### 1.2 Solar district heating community concepts: Practical cases

A solar district heating system is a very promising alternative to fossil fuel heating. These systems are key technologies for achieving emission reduction goals and they are increasing in European countries (European solar thermal industry federation (ESTIF), 2018). By combining the positive side of clustering and solar energy generation, a sustainable solution can be achieved (Kılıç, et al., 2017; Kayo, et al., 2016). District heating systems are here defined as solar heating systems designed to provide heat to large building areas (in other words, residential building areas) via central block and district heating plants (Wang, et al., 2015).

In Europe about 11.1 million m² of solar collectors had been installed by 2000, which provide the equivalent to 5500 MW of thermal power (Solar District Heating, 2016). In Europe, from 1979 to 2011 around 141 large-scale solar heating plants have been built (Dalenbäck & Werner, 2012). Quite a lot of investment has been made in Germany to explore the potential of solar district heating (T.Schmidt, et al., 2004). Currently the solar district heating market is booming in Denmark due to its competitive energy prices in comparison to biomass and gas heating (Solar District Heating, 2016). Large-scale solar heating has increased during recent years, especially in Germany and Austria. However, Sweden is still the leading country with the highest number of solar...
district heating plants in Europe (Dalenbäck, 2003). There are plants being built in Marstal, Denmark (1996), Kungäv, Sweden (2000), Nykvarn, Sweden (1985), Falkenberg, Sweden (1989), Neckarsulm, Germany (1999), AerØskØping, Denmark (1998), Rise, Denmark (2001), Friedrichshafen, Germany (1996), Ry, Denmark (1990), Hamburg, Germany (1996), Brandaris, the Netherlands (1999), and Innsbruck, Austria (1999) (Dalenbäck, 2003). Additionally, there are 28 systems with individual collectors of about 1000–2700 m² and 27 systems with collector areas between 500 and 1000 m² in Europe (Solar District Heating, 2016). The first demonstration plants of solar district heating networks were operated in Hamburg and Friedrichshafen, Germany, during 1996 and in Neckarsulm, Germany, during 1999. The systems also included various types of seasonal storage. The simulation results of these systems show that an up to 50% solar fraction can be achieved by such systems in German conditions. In the first years of the operation of the generation plants, they showed that the solar fraction was lower than expected due to various reasons (T. Schmidt, et al., 2004), explained in the following section of the thesis.

These large-scale solar district heating systems have also been realised in North America. The Drake Landing Solar Community (DLSC) is a master-planned neighbourhood in the town of Okotoks, Alberta, Canada, that has been successfully built to integrate renewable sources with building clusters. This new community is North America’s first major implementation of seasonal ST energy storage. The 52 houses involved are provided with space heating (SPH) via solar energy captured by 800 panels on the garage roofs. There are five main components of the DLSC project: the collector system, the short-term tank, seasonal storage, the district heating supply system and the houses. Figure 1 shows a simple system schematic. The design of the system is able to provide up to 90% of the SPH from ST collector (McDowell, et al., 2008).

![Figure 1. System schematic of the Drake Landing Solar Community, Canada (McDowell, et al., 2008).](image)

In Finland, most of the population lives in areas receiving more than 5.3 GJ/m² total solar radiation annually (Pasonen, et al., 2012). Hence there exists the potential to foster this solar energy. As discussed above, district heating represent 40% of the total energy consumption. Solar district heating is a very

Two community concepts at a small scale had been built and tested in Finland during the 1980s in Kerava and Eko-Viikki (Faninger-Lund, 2003). One pilot project was built at Kerava solar village, located 30 kilometres north of Helsinki at Savio, Kerava. This project was launched by Sitra (the Finnish Innovation Fund) in January 1979 by starting a pilot survey of local heating systems that mainly use solar energy for heating and a heat pump for backup heating. The design included 44 houses in a neighbourhood that receives 75% of its heating energy from solar energy. The rest of the heating energy was provided with a heat pump or district heating. The objective was to find an economically profitable solution for seasonal storage so that a solar collector could also be used with the old district heating networks (Lund & Mäkinen, 1982). Solar energy was collected with a solar collector that had a surface area of 1100 m². Collected solar energy was transferred to heat storage that was located in the central energy building (Kauppa ja teollisuusministeriö, 1986). The Kerava solar village was monitored during the years 1983–1985. The first year was spent building the system; only during the second year was it operational and data were recorded. The year after the plant was commissioned, the system faced major technical problems with the heat pump. The energy storage showed excellent energy efficiency of 85%. The major problem with Kerava solar village was the size of the storage. The retrospective simulations showed that by changing the control parameters, separation of the seasonal storage circuit from the solar generation, using better collector and by increasing the size of the storage, the performance of the system could have been improved (Oosterbaan, et al., 2017).

Eko-Viikki is a test site for ecological construction, located in southern Lato-kartano in Helsinki (SOLPROS, 2004; Hakaste, et al., 2008). The apartment buildings were constructed during 2000–2004 and they house about 2000 people. Thermal insulation in the buildings exceeded the directives of the time C3; (C3 NATIONAL BUILDING CODE OF FINLAND,MINISTRY OF THE ENVIRONMENT, Housing and Building Department, 2002) by 10–30%. C3 is a Finnish building code that deals with the regulations that concern buildings where energy is used for heating and, in addition, possibly for cooling, in order to achieve an appropriate indoor temperature. It provides the standard thermal insulation values for the building envelope that are to be used in Finland; details are provided in the methodology section. Some buildings utilised a new type of heat recovery system where outdoor air is drawn in through the windows so that the inlet flow is heated between the window plates by heat escaping from the room. Many of the Eko-Viikki buildings had ST systems installed. During the study period of 2001–2003, 8–10% of all heating energy, or 30% of DHW energy, was generated by the solar collectors. The solar heating systems suffered from leakages in the piping and from the incompatibility of the field equipment’s automation and control system. There were some issues with the sensors and their compatibility with the control algorithm, therefore the system was unable to perform at optimal levels. Roughly 10% of all heating energy
in Eko-Viikki was generated by solar energy. The calculated design energy demands were estimated in an overly optimistic manner and the realised energy consumption was, on average, 14% higher than could have been achieved by the proper use and maintenance of the systems (SOLPROS, 2004) (Hakaste, 2008). This caused the plant to be undersized, and hence reduced the performance of the heating plant. To achieve the desired energy demand levels, it would require retrofitting. Optimising the inlet water temperature controls of SPH, more efficient heat discharge from the water tank, a higher collector tilt angle, increasing the collector area and increasing the size of the water tank are proposed. Using the current setup, the desired goals are difficult to attain. With optimal operation of the system, the minimum requirement level could be increased (SOLPROS, 2004; Hakaste, et al., 2008). Neither of the Finnish experiments in Kerava and Eko-Viikki have been very successful.

There is no single best universal solution to build a solar thermal based district heating system. Using an integrated approach of generation, storage, demand and smart controls, together with optimisation, might be the most effective approach. Within a cluster and larger systems, unit price can be reduced and controls can be centralised, which can offer new options. For example, large storages can be used to allow a large capacity for a longer duration as the losses are inversely related to the volume. Additionally, a large seasonal storage would allow minimising the effect of the seasonal mismatch issue.

1.3 The importance of seasonal storage in solar district communities

In a community-sized solar energy system, heat storage plays a vital role due to the mismatch between irradiation and heating demand (the low irradiation in winter when demand is high and the high irradiation in summer when demand is low). Storage can reduce the mismatch issue. Ground thermal storage is technically and economically viable compared to short-term storage due to the cost advantage (due to the size and high capacities) and the ability to operate on a large seasonal timescale. However, storage heat loss is an issue (Honkonen, 2016). Seasonal thermal energy storage (TES) stores heat in a sensible form. The goal of TES is to maximise the efficiency of the storage, and this is done by minimising heat loss. Therefore the thermal properties of the storage medium, the time of storage, storage temperature, location, storage geometry and volume are critical. Many researchers (Bauer, et al., 2010; Andersen, et al., 2013) have presented the four main types of sensible seasonal energy storages that have been in operation. They are: (1) hot water TES (HWTES), (2) aquifer TES (ATES), (3) gravel water TES (GWTES), and (4) borehole TES (BTES).
1.4 Technical failures, errors and issues with solar district heating systems

Solar district heating systems with seasonal storage form a promising alternative to fossil fuel heating systems. Due to the sustainability and environmentally friendly application, numerous projects have been built (Mangold, 2007; Lundh & Dalenbäck, 2008; Sibbitt, et al., 2011; McDowell, et al., 2008).

Due to uncertainty and new technology, a complete understanding and the acceptability of such systems are still under development. Although the performance of the plants may live up to expectations, this is not usually the case. In some cases, the collector performance is overestimated and in some cases heat losses are underestimated. The main reasons for this are incorrect input values, the incorrect application of simulation tools, validation issues and optimisation issues related to costs and sizing (Neves & Silva, 2014). It is not surprising that technical performance has not continually met the expectations. Underperformance in the plants is due to the incorrect usage of the technologies. Several authors have discussed about simulation-based solar heating plants. Publications related to monitored data are rare and the ones available are often restricted to a laboratory scale (Hahne, 2000). There has been very little research carried out on comparing real measured results with predicted results in order to identify the discrepancies in the performance of solar district networks. It is interesting to find that the measured and estimated values mostly had discrepancies, which resulted from a variety of reasons (Bauer, et al., 2010). It is crucial to identify and quantify these causes as they can affect the performance of systems and cost.

It has been found that many plants in Germany are unable to reach the expected performance levels. For instance, the measured results from a solar district heating plant in Friedrichshafen showed that the solar fraction varied from 21% to 33%. However, it was estimated that the solar fraction could reach 43%. The set value has not yet been reached because of the higher than expected heating demand, higher thermal losses and the higher water temperature in the SPH network, resulting in lower collector and heat exchanger efficiencies (Bauer, et al., 2010). Similarly, in plants in Neckarsulm, Rockstock, Eggenstein, Crailsheim and Hamburg, the measured and estimated performance showed discrepancies. The common issues identified in these plants were: the higher than expected return temperature of SPH in the networks, efficiency issues in the heat exchangers and collectors, losses through storage, losses through seasonal storage and wrongly sized components (Bauer, et al., 2010; Urbancek, et al., 2015; Nussbicker-Lux, 2012). Another report related to the performance of the Canadian project in the DLSC showed lower actual performance than expected. The reasons behind the underperformance of the system were ground thermal properties, tank stratification issues, pump controls and heat losses due to high return temperatures in the SPH network (Sibbitt, et al., 2012). Similar issues were found in the projects in Denmark (Heller, 2000; Tordrup, et al., 2017) and in Sweden (Dalenbäck, 2005).

In Finland, Eko-Viikki is a test site for ecological construction in Finland. The apartments were constructed during 2000–2004 (Hakaste, et al., 2008).
Introduction

It was found that average energy demand of the solar district heating exceeded expectations. The main reasons behind the underperformance were the higher heating demand of the buildings than predicted, component sizing issues, the higher return temperature of the SPH network, the tilt angle of the collectors and overall optimisation issues.

Hence, the above-mentioned studies showed that all these plants faced technical challenges. There are some common issues reported in these plants that caused the underperformance of solar heating networks during real applications.

1.5 The objective, hypothesis and research questions

The general objective of this research is to find scientifically based methodologies and solutions for the major challenges and obstacles in the implementation of a regional-sized solar district heating concept in the Finnish (Nordic) environment, where less solar radiation is available during the wintertime, where the building practices are established and conservative, where the business models related to renewable energy are undeveloped and where the consumers are largely unaware about the utilisation of solar energy. It is also important to note that the design benchmark is to maintain the thermal comfort of the end users at acceptable levels in the occupied buildings. Integrated models for generation, the supply network and demands are designed at regional level. The energy systems architectures are designed to provide the end users with cleaner, cost-effective and energy-efficient services.

The broad question is what are the reasons for Finland to be so far behind in this evolution? And how can the utilisation of solar technology in Finland be accelerated? Finland is of course located in Northern-Europe and the climate is cold. Therefore, the thesis focuses on finding the most suitable technical solutions for Nordic conditions.

The thesis looks into the problem of the utilisation of ST energy in Nordic conditions, the generation and demand mismatch, the heat demand (of buildings) and energy storage. It also explores the economic aspects of the solar community. The set research questions are:

1. What is the optimal control strategy for a simple ST energy system in buildings integrated with heat pumps and seasonal storage? (Publication 1)

2. What different solar energy system configurations and architectures can provide long-term solar energy in Nordic conditions? How much do a building’s technical properties (passive measures), as design variables, contribute to cost and performance variation (while the thermal comfort of the end users are at acceptable levels)? (Publication 2)

3. What is the techno-economic feasibility (multi-objective optimisation) of solar district heating systems in Nordic conditions? How much can technical uncertainties and failures
cause the system to vary from its optimal performance? (Publication 3)

4. Compared to centralised and decentralised solar district heating distribution networks, which heating grid distribution typology is techno-economically optimal? What design and shape of seasonal storage is optimal in Finnish conditions and has a reasonable cost? (Publication 4).

The utilisation of renewable energy is needed for future energy systems. To study and analyse the use of solar energy as the main source of energy for community-sized solar heating demand in Nordic conditions, four hypotheses are made and tested in this thesis. In challenging Nordic conditions, the first hypothesis of this research is that the control strategy of the solar district heating system would have a substantial effect on the energy demand and performance of the system (Publication 1). The second hypothesis is that the demand and energy system architecture can vary the cost and performance of the solar energy systems (Publication 2). Therefore, it is essential to find the best architecture in terms of techno-economic criteria. The third hypothesis assumed that when any considered system design is optimised under ideal conditions, it performs ideally. However, in real conditions the performance of the system may vary due to non-ideal conditions (Publication 3). Therefore, it is important to find the deviations under non-ideal conditions. The last hypothesis assumed that different combinations of the optimised solar district heating network can vary the life cycle cost (LCC) and, at the same time, reduce the purchased electricity (Publication 4).

1.6 The scope of the thesis

The scope of the thesis is limited to the simulation and modelling of various types of ST-based district heating systems in Finnish conditions. The boundary of the model includes the heat production, thermal storages, seasonal storage, building heat demands and distribution networks. The main focus is on the heat energy flows and heat demands for the district heating. The external systems are the electricity grid and photovoltaic, from which only electricity flows through the boundary to the analysed systems and no electric storage is included. The detailed analyses and modelling are carried out on the typologies, layouts and control strategies of the heat production systems, thermal storages, seasonal storages, piping, heat pumps and building heat demands. The heat distribution network and piping are also included in the network in order to include the overall heat losses from the network in the simulations; however, no detailed pressure losses are analysed from these networks. The district heating grid consists of SPH, DHW and collector piping. All the proposed systems are evaluated based on their technical and financial performance and criteria. Due to the technical and financial limitations, the experimental studies are not included in this thesis; moreover, no such solar-based district heating systems exist in Finland with which a certain section of the model could be
validated against. Nevertheless, errors and sensitivity analyses are carried out in detail in order to provide the uncertainty and performance deviations of such systems in Nordic conditions with respect to the input parameter errors and cost sensitivity.

1.7 The thesis and publications structure

The thesis is structured as follows. Section 1 has presented the existing literature on the topics covered in this thesis and the research questions, and will present the novelty of the thesis. Section 2 introduces all the energy system typologies and architectures proposed, designed and analysed in this thesis. Section 3 introduces the simulation and multi-objective optimisation tools. The methodology of the research work is described in Section 4. The results of the publications are described in Section 5. The results are explained in chronological order publication vice. Section 6 contains discussion and recommended course of action that would provide answers to the research questions, are summarised. Section 7 is the conclusion.

In total four papers were published to answer the research questions and hypotheses, as mentioned in Section 1.5. The objective of the study reported in Publication 1 was to design and compare different control strategies for the solar collector and short-term storage tanks. This was done to identify the best control strategies that can lower the electricity demand of the auxiliary. The best strategy found in Publication 1 was later used in Publication 2.

The objective of the study reported in Publication 2 was to design and compare different energy system configurations. The configurations involved different arrangement of the heat pumps, collector and seasonal storage. This was done to compare and identify the best configuration in terms of cost and performance. The building was also designed and included as a design variable in order to identify the impact of different heating demands as a design variable of the overall performance of the energy systems. The best energy system configuration and three different heating demands were selected from Publication 2 and later used in Publication 3.

The objective of the study reported in Publication 3 was to identify the impact of different failures and technical issues on the performance of an energy system. The energy system and heating demand from Publication 2 was initially optimised based on dual objectives and later reference cases from the Pareto front were tested under different technical failure scenarios.

In the study reported in Publication 4, two different energy system typologies (i.e. centralized and semi-decentralized systems) were designed, optimised and compared based on their technical and economical performance. It was found that by decentralising a certain section of the energy system, the cost of the energy system can be reduced and, at the same time, high technical performance can be achieved. The design variables involved the physical components’ sizes, as well the control’s set points.

The research structure, connections and insight between the published papers of all the four publications are shown in Figure 2.
1.8 The novelty of the work

The novel concept of a self-reliant solar community in a Finnish context is proposed in the thesis. Largely, the thesis proposes an integrated approach to simultaneously studying the near-zone solar energy generation and the energy demand of buildings. At present, energy generation is mainly the concern of energy companies, while buildings are the concern of real estate companies. These two entities have their own interests, limitations and business models which halt a unified approach to addressing climate change issues. Moreover, these are the core challenges in developing successful and well-working solar-based communities and district networks that can address the growing issue of the utilisation of solar energy on a large scale. Here, the challenge of developing a techno-economic community-sized solar district network is divided into sections. Each section is studied separately. Similar methods and dynamic simulation tools are used to address the questions that are proposed in the thesis.

The novelty of this dissertation relies on the detailed technical design and simulation of the control strategies, the integration of generation components and demand, the integration of various building types, investigations into the failures of various proposed community-sized solar district heating and electricity networks, and the economics of the energy systems. Publication 1 examined different control strategies for the solar collectors, storages, and energy harvesting and its further storage in tanks. The novelty lies in having designed and evaluated these different controls strategies for the community-sized heating solution in order to maximise the performance of the district network, integrated with seasonal storage, for Finnish conditions. Publication 2 examined three different energy system typologies, based on economics and technical performance. The novelty lies in having designed three different configura-
tions and typologies for a solar district heating system in Nordic conditions. Additionally, buildings with various heating demands were modelled and later integrated with the district energy system in order to study its impact on the feasibility of the energy system. The focus was to investigate and assess the long-term performance of such different ST district networks in a challenging environment, based on the technical and economic aspects. Publication 3 estimated the influence of failures, errors and defects in the technical components on the performance of the optimised solar energy system. The novelty in this paper is having detailed and systematic failure analysis of a solar district heating system used for a community-sized heating demand. The failure analysis was done based on real-condition defects that can occur during the lifetime of the system’s operation. Publication 4 examined the differences in the techno-economic performance and the design variables variations of two different concepts (i.e. centralised and semi-decentralised solar district heating). The novelty lies in having analysed the solar-based district heating systems typologies for Nordic conditions in such a way that both the centralised and semi-decentralised systems were closely comparable. At the same time, both the systems were multi-objective optimised. The motivation was to reduce the overall LCC of the energy systems while keeping similar technical performance or having better performance.
2. Introduction: The analysed solar district heating systems

Various energy system architectures, reference models, component integrations and control strategies are proposed and discussed in this section. This section of the thesis summarises the different solar district heating systems’ configurations and architectures proposed in all four publications.

2.1 The reference case: The Finnish context

The reference case consists of a typical single building, integrated with a ground source heat pump (3 kW), in Finnish conditions. It has no seasonal storage and has renewable energy generation sources, namely, a collector and photovoltaic. The building has a heating demand of 50 kWh/m²/yr. It is situated in Finland and it meets the minimum requirements of the C3 National Building code of Finland (C3 NATIONAL BUILDING CODE OF FINLAND, MINISTRY OF THE ENVIRONMENT, Housing and Building Department, 2002). The appliance electricity demand of 40 kWh/m²/yr was used, as used by Hamdy et al. (Hamdy, et al., 2013). The building contains a hot tank of 1 m³ to store hot water to meet the heating demand. A ground source heat pump was integrated with the ground (at a depth of 50 m) to charge the hot tank.

2.2 The boundary conditions for all the simulated systems

The border of the simulated systems consists of energy production systems, short- and long-term thermal storages, a heating grid and buildings. The impact of the considered system solutions on the heating renewable energy fraction, the on-site electrical energy fraction, purchased energy and LCC as a function of the building heating demand and energy system have all been evaluated in all the configurations. It was assumed that within the studied boundary, the energy system components (like the collector, short-term storage, seasonal storage, heat pumps and the heat piping network) and buildings were included; furthermore, the heat losses from the heating grid and storages were included and calculated as an output via simulation software. All the heat energy flows to the buildings via distribution networks were also included within the boundary of the energy system analyses. However, no detailed analyses
were carried out on the pressure losses in the network. The PV electrical system and electrical grid were outside the boundary. Any excess electricity from the photovoltaic was exported to the grid, while shortfall was imported from the grid. The electricity flows via the electricity hub, through the boundary in order to supply the building appliances and the energy system auxiliaries. The boundary, energy flows and components are shown in Figure 3.

![Diagram of solar thermal system](image)

**Figure 3.** The studied solar thermal system boundary, components and energy flows (Publication 1) (Rehman, et al., 2016).

### 2.3 Energy system configurations and control strategies

#### 2.3.1 A simple solar-based community-sized district system design

A simple solar-based district heating system consists of an ST collector, short-term storage tanks, seasonal storage and a heat pump. A solar heating system may not contain seasonal storage. The solar energy is charged into the short-term tanks, which then supply heat to the house. Any excess energy can be transferred into the seasonal storage. Figure 3 shows a schematic representation of a simple solar-based district heating system. The solid blocks refer to system components while the arrows represent the types of energy flow and their directions.

The control strategy between solar fields, tanks and seasonal storage was hierarchical. The collector charged the working fluid (water) from the short-term
tanks and then heated water was transferred to the tanks. The tanks were charged based on the outlet temperature from the collector. The hot tank was charged at higher temperatures while the warm tank was charged to lower temperatures. Both tanks could be charged in parallel or in series.

When the tank temperature exceeded a certain set point, the heat energy was transferred to the ground storage or seasonal storage. The transfer of the heat energy was done until the tanks’ temperatures were at the desired levels. During the winter season, when solar energy availability was less, the short-term tanks’ temperature drops, then the heat was taken from the boreholes’ seasonal storage to charge the tanks.

The SPH (ventilation + radiator) was provided by passing the SPH water through a warm tank and then onto the houses at temperatures between 27°C and 40°C, depending upon the outdoor temperature. DHW was provided by preheating the fresh water in the warm tank and then further heating it in the hot tank until it reached the desired temperature of 60°C. Constant circulation was provided in the DHW network to ensure that hot water was always available with no delays.

### 2.3.2 The controls of the collector temperatures

The ST outlet temperature was controlled by adjusting the flowrate through the collector. Two flowrate control strategies were tested: temperature difference control and temperature tracking control.

- Temperature difference control: The solar collector always aims for a constant temperature increase over the collector by adjusting the flowrate. In this control, it was important to note that if the temperature difference setting was too small, it could cool the top of the tank due to low inlet temperature.
- Temperature tracking control: The collector aims for an outlet temperature which was higher than the temperature at the top of the target tank. Table 1 shows the set point for the solar collector for each control mode.

<table>
<thead>
<tr>
<th>System configuration</th>
<th>Set point (°C)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature tracking control for all tank connection modes</td>
<td>( T_{\text{top}} + 1 )</td>
<td>Desired temperature in ST over the tank top temperature, where ( T_{\text{top}} ) = Short term storage tank top temperature</td>
</tr>
<tr>
<td>Temperature difference control for series mode</td>
<td>( T_{\text{in}} + 45 )</td>
<td>Desired constant temperature increase in series mode, where ( T_{\text{in}} ) = Collection inlet temperature</td>
</tr>
<tr>
<td>Temperature difference control for parallel mode</td>
<td>( T_{\text{in}} + 15 )</td>
<td>Desired constant temperature increase in parallel mode, where ( T_{\text{in}} ) = Collectors inlet temperature</td>
</tr>
</tbody>
</table>
2.3.3 Control of the tanks connections and charging

The connection and charging temperature of the short-term storage tanks with the collector needed to be controlled. There were two tanks operating at different temperature levels, therefore the tanks could be connected with the collectors in various ways. The tanks could be connected in three modes: in parallel, in series and in automatic mode.

- Series mode: Tanks are connected in such a way that they form a single tank. The solar collector inlet comes from the bottom of the warm tank and the outlet leads to the top of the hot tank.
- Parallel mode: The tanks are completely separate. The inlet for the collector comes from the bottom of either tank and the outlet was conveyed to the top of the same tank.
- Automatic mode: There was automatic switching between series and parallel modes, depending on the flow and temperature conditions.

2.3.4 Energy system types and typologies

The solar district heating systems for community-sized demand can be designed in various ways. The use of the heat pumps is becoming more and more sensible for such systems in order to reduce dependency on fossil fuels. It allows improving the quality of the heat due to the coefficient of performance (COP) of the pump. The different configurations proposed in this study were divided into two main categories:

- The centralised system: The generation, storage and distribution network are centralised and conducted from a single energy centre. These system concepts were inspired from German, Canadian and Danish studies (T.Schmidt, et al., 2004; Sibbitt, et al., 2011).
- The semi-decentralised system: Either one or several of the components of the system (e.g. the generation, storage or distribution network) can be partially present in the energy centre and partially in the buildings in the community. This concept mixes the idea of an SPH network from the Canadian project and the outcome of the present study (Sibbitt, et al., 2011; Hirvonen, 2017; Rehman, et al., 2018).

2.3.5 The centralised systems’ generic control strategy

Firstly the boundary and main features of the energy systems are described and lastly the control and flow strategy of the network is described.

The main features and boundary of the energy system were:

- A central collector (ST) field
- Centralised PV panels
- Two large centralised short-term storage tanks (i.e. warm and hot tanks) are present at a centralised energy building
- The warm and hot tanks were charged in parallel by the collector during the summer
- BTES was located in the energy centre at a centralised location and was charged via the warm and hot tanks if excess energy was available in the tanks
- A central heat pump (HP) was used to charge the hot tank by taking heat energy from the warm tank during periods when solar energy was not available
- DHW and SPH were provided through this centralised system via 4 km of piping for the DHW and 4 km of piping for the SPH

The energy system was designed in a hierarchical pattern. In order to minimise the use of the heat pump, the charging temperature set points of the tanks should be higher for the collector than for the heat pump.

When the tanks needed charging, the first option was to use the collector. If the warm tank temperature was lower than 40°C, it was heated to 45°C, and for the hot tank, if the temperature was lower than 65°C, it was heated to 70°C by the solar collector. If both the temperatures of the tanks were at adequate levels, the solar heat was sent to the boreholes to maximise energy efficiency. Depending on the energy system configuration, if no energy was available from the collector, heat could be directly transferred from the BTES into the tanks or through the heat pump in order to charge the tanks. The cold fluid entered from the cool outer edge of the BTES and exited from the hot centre, as shown in Figure 4.

![Figure 4. The fluid flow in the BTES during winter-discharging of the seasonal storage (Underground Energy, LLC, 2018).](image)

If the warm tank temperature dropped lower than 35°C, it was heated to 40°C, and if the hot tank temperature was lower than 60°C, it was heated to 65°C by the heat pump or directly from the BTES, depending on the system type and explained later. Since the tanks were charged at a higher temperature level, the heat was used less. This improved the overall performance. Generally, excess energy from the tank was transferred to the BTES to avoid overheating the tanks. When the warm tank temperature reached 50°C, the heat was trans-
ferred to the BTES until it reached 45°C. Similarly, when the hot tank temperature reached 75°C, the heat was transferred to the BTES until it reached 70°C.

The SPH and ventilation were provided by passing the SPH water through the warm tank, or through both the warm and hot tanks, subject to the energy system configurations. The provided temperature was between 27°C and 40°C, depending upon the outside temperature. DHW was provided by passing the cold water through the warm and hot tanks until it reached around 60°C. Recirculation of DHW was also provided in the circuit. If the energy from the heat pump and collector were inadequate to meet the temperature needs, backup heating was provided by direct electric heaters.

The three different centralised energy systems are shown in Figure 5. The distinguished features of each energy system are described in the following sub-sections.

Energy architecture: Energy System I
In this setup, boreholes were charged by solar heat from the collector and the heat pump was directly connected to the boreholes’ outlet. The energy from the seasonal storage was used by the heat pump to charge the short-term tanks in need of energy when the solar energy was less. The heat pump was used to maintain the temperature in both the hot and warm tanks. If the BTES outlet temperature was high enough, it could be directly utilised for heating the tanks through a bypass. Excess solar energy from the tanks was transferred to the BTES to avoid overheating. SPH was provided by the warm tank and DHW was provided by both the warm tank and hot tank. A schematic representation of Energy System I is shown in Figure 5.

Energy architecture: Energy System II
In this setup, the boreholes were charged by solar energy and the heat pump evaporator was directly connected to the short-term warm tank (instead of the borehole outlet, compared to Energy System I). When there was less ST energy, energy from the warm tank was used by the heat pump to heat the hot tank when needed. The warm tank was directly charged from the BTES. If the warm tank temperature was less than 35°C and the BTES’s average temperature was higher than the warm tank’s top temperature, the energy was transferred via the BTES. The warm tank was charged from the BTES every time that the heat pump was used to charge the hot tank. Excess solar energy from both the tanks was transferred to the BTES to avoid overheating. SPH was provided by both the warm and bottom nodes of the hot tanks when the warm tank was at an inadequate temperature level. DHW was provided by both the tanks. A schematic representation of Energy System II is shown in Figure 5.

Energy architecture: Energy System III
In this system, boreholes were not charged by the solar energy, unlike Energy Systems I and II. Moreover, there were two heat pumps used. The depth of the borehole heat exchanger (BHE) was increased to 300 m, compared to Energy Systems I and II, where the depth was around 45 m. This contributed by providing a larger contact area for the BHE in regard to its surroundings, thus
the BHE could be charged naturally. Moreover, it was simulated that larger depths can be discharged for a longer time compared to shallower depths because the average BHE temperature variation between charging and discharging is less. During winters, when solar energy is less, one heat pump evaporator was directly connected to the BHE outlet and it was used to charge the warm tank. The available natural energy from the BHE was used by the heat pump to heat the warm tank when there was less ST energy. The second heat pump evaporator was directly connected to the warm tank and it was dedicated entirely to charging the hot tank by taking energy from the warm tank. The heat pumps were used to maintain the temperature in both the hot and warm tanks. SPH and DHW were provided by both the warm and hot tanks. A schematic representation of Energy System III is shown in Figure 5.

![Figure 5](image.png)

**Figure 5.** Schematic representation of the Energy system I, II and III (Publication 2) (Rehman, et al., 2016).

### 2.3.6 The semi-decentralised system’s generic control strategy

Firstly the boundary and main features of the energy systems are described and lastly the control and flow strategy of the network is described.

The main features and boundary of the energy system were:

- A central (ST) collector field
- Centralised PV panels
- The low-temperature warm tank is large and centralised in the energy building, while small hot tanks were distributed in each house; both types of tank were also known as *short-term storage tanks*
- The ST collector only charged the warm tank during summer
- The BTES was located in the energy centre at a centralised location; it was only charged via the warm tank if excess energy was available in the tanks
- Distributed heat pumps (HPs) were used to charge the distributed hot tanks by taking heat energy from the SPH return network
- DHW was provided through the decentralised hot tanks via 400 m of piping and SPH was provided via 4 km of piping, mainly from the centralised warm tank

The concept of a semi-decentralised system was based on a low-temperature heating network. It has a decentralised DHW and centralised low-temperature seasonal storage. The difference between the Canadian DLSC project (Sibbitt, et al., 2012) and the present study was that DHW was not integrated in the Canadian system. However, in the present work, DHW was integrated with the centralised system and included in the performance calculations. Additionally, the Canadian project had a boiler as a backup instead of a heat pump.

The decentralised system was a semi-decentralised system; for ease of understanding it is referred to as a decentralised system. The schematic representation is shown in Figure 6. The centralised section of the system (i.e. the ST collector, seasonal storage and warm tank), along with the decentralised section of the system (i.e. the heat pump and the hot tank in each house), is shown in Figure 6.

In this setup, a centralised warm tank was only charged via a collector. If the warm tank temperature was less than 4°C, it was heated to 45°C by the collector. The BTES was only charged by the warm tank (in contrast to the centralised energy system, where the BTES was charged by both short-term tanks). If the warm tank temperature was higher than 50°C, excess heat was transferred to the BTES until it was at 45°C. When there was less solar energy, the warm tank was charged via the BTES directly. If the warm tank temperature was less than 35°C and the BTES’s average temperature was higher than warm tank’s top node temperature, the tank was charged via the BTES (Rehman, et al., 2018).

The decentralised hot tank in each building was charged via the decentralised heat pump in each building. The energy from the centralised warm tank was distributed to the low temperature SPH network of the community. Each heat pump in the building took energy from the SPH return line to charge the hot tank. Usually the hot tank was charged up to 65°C by the heat pump if the hot tank’s temperature was lower than 60°C.

The SPH was provided by passing the water through both the centralised warm tank and the bottom node of the decentralised hot tank. The heated water was then provided. The DHW was heated up to 58°C before being supplied to the tap (Publication 4) (Rehman, et al., 2018).
Due to the long simulation calculation time, a five-year simulation was unfeasible. Therefore, as a compromise, the system was simulated for three years and used for estimating the performance of the system. Three- to five-year-long simulations were needed because the BTES’s average temperature becomes steady and the change in temperature is insignificant in the following years.

The renewable energy fraction for the heating was calculated as a performance indicator and it was defined according to the equation of Rehman et al. (Rehman, et al., 2016):

\[
Renewable\ energy\ fraction_{heat} = 1 - \frac{Electricity\ consumption}{SH\ demand+DHW\ demand}. \tag{1}
\]

The on-site energy fraction (OEF) of the electricity was calculated. The OEF indicates the proportion of the electrical load covered by the on-site generated electricity (Cao, et al., 2013). Since grid electricity was the only external energy source, the OEF was therefore defined as the ratio of annually purchased electricity versus the total electricity demand of the community, including the building appliances’ demand.
Introduction: The analysed solar district heating systems
3. Introduction: Simulation and optimisation tools

3.1 The simulation tool

A computer simulation is an attempt to model a real-life or hypothetical system on a computer so that it can be studied in order to get insights into how the system works. It is a tool used to virtually investigate the behaviour of the system. Simulation is used in many contexts. It can be used to simulate the eventual real effects of alternative conditions and courses of action. It is used when a real system cannot be engaged with because it is inaccessible or it may be dangerous (Sousa, 2012). Key issues in the simulations include the acquisition of valid source information about the important selection of key characteristics and behaviours. Within the simulations, simplification, approximations and assumptions are made. Afterwards the simulation outcome needs to be validated.

Energy and building simulation software is an important tool that is used by designers to analyse system feasibility and cost. The energy simulation software allows a designer to predict, measure, optimise and design systems and buildings with some accuracy. It also allows designers to identify important variables that can support their decisions when building a new or redesigning an existing system (Sousa, 2012).

The tools can be useful in building complex systems and simulations without investing a lot in actually building such systems (Clarke, 2001). Nowadays, tools are needed to answer very specific questions during the initial phase. Designers can also predict the behaviour of the energy system and building before they are constructed, and simulate the investments and operational costs of the systems in their current and future conditions.

Energy simulation software can also consider all the regulations in force and provide appropriate suggestions for a better energy system design. Energy simulation software tools have developed over the years. At the moment, there are many energy simulations tools with different complexity and responses to different variables (Sousa, 2012). Generally, in all energy simulations software tools, three steps have to be performed (for instance: creation of the model, building simulations and analysis of the results). Different commercially available simulation tools are available, such as IDA Indoor Climate and Energy (IDA ICE), Integrated Environmental solutions (IES), Energy Plus and TRNSYS (stands for transient system simulation programme). These software tools have been used in various studies (Behrendt, et al., 2011).
3.1.1 TRNSYS dynamic simulation software

TRNSYS is a complete and extensible simulation. The software has been used since 1975 (Thermal Energy System Specialists, LLC, 2006). It is quite a flexible tool, especially in performing transient simulation of an energy system. TRNSYS was first developed jointly by the University of Wisconsin-Madison’s Solar Energy Lab and Colorado State University’s Solar Energy Applications Lab in the 1970s (Thermal Energy System Specialists, LLC, 2006).

TRNSYS is an algebraic and differential equation solver in which components are connected graphically in the simulation studio. The software has a modular structure that has been designed to develop complex systems. The components may range from a heat pump to the multi-zone of a building complex. The components are configured through the graphical user interface known as TRNSYS Simulation Studio (Crawley, et al., 2005). In solar district heating network simulations, all the mechanical components are solved simultaneously at each time step. The time step may vary from an hour to 0.1 of a second. The library in the software tool allows the use of various components like, solar panels, PV panels, HVAC (heating, ventilation and air conditioning) systems, cogeneration systems etc. It also provides different weather data. The simulation results can show the performance of an individual component which can be selected from the simulation studio. It assists understanding complicated systems. Logical programming or simple equations can be written on open source code to accomplish system control strategies.

In the simulation tool, the construction of the building can be achieved by the introduction of data on a dedicated visual interface known as TRNBuild. TRNSYS also provides TRNEdit, which is an editor for reading and writing TRNSYS inputs and outputs. TRNEdit can also perform parametric TRNSYS simulation and plot data (B.Crawley, et al., 2008; Thermal Energy System Specialists, LLC, 2006; Price & Blair, 2003). In addition, this energy simulation tools allows the user to incorporate other components developed in software tools, such as Matlab, Excel, and Visual Basic (VBA) etc.

3.1.2 IDA ICE software

IDA ICE

The modular dynamic multi-zone simulation tool, IDA ICE, is a commercial program which was released around 1998. It can be used for the study of the thermal indoor climate of individual zones, as well as for the study of the energy consumption of a building. The modular nature of IDA ICE makes it possible to write individual models, extending its capabilities as needed by the individual users (Crawley, et al., 2005).

3.1.3 A comparison between TRNSYS and IDA ICE software

Each software tool, TRNSYS and IDA ICE, has certain characteristics and specific applications. In order to understand the features of IDA ICE and TRNSYS, Table 2 presents a summary table of the features of both of the software tools presented above.
Table 2. The Comparison of the features of the various simulation software tools (B.Crawley, et al., 2008).

<table>
<thead>
<tr>
<th>Simulation characteristics</th>
<th>IDA ICE</th>
<th>TRNSYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation of loads</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Iterative solution of nonlinear</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Simultaneous selection of building systems</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Walls, roof and floors</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Solar analysis</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Calculations of the building in general</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Airflow via windows</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Daylighting controls</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Natural and mechanical ventilation</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Window control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>CAD software integration</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Solar energy</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Photovoltaic panels</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Energy production</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Management of electric power load</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>HVAC system</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>User interface</td>
<td>Better</td>
<td>Need understanding</td>
</tr>
<tr>
<td>Controls</td>
<td>Difficult</td>
<td>Easy</td>
</tr>
<tr>
<td>Scheduling</td>
<td>Difficult</td>
<td>Easy</td>
</tr>
</tbody>
</table>

Based on Table 2, in order to provide flexibility, the best simulation software suitable for this thesis is TRNSYS. Additionally TRNSYS provides an easier and detailed platform with which to design energy systems and buildings together. Multi-objective optimisation software can also be integrated with TRNSYS through a .dck file. As a benchmark, the TRNSYS software has been validated and used to design the DLSC in Canada. TRNSYS was used to design and predict the performance of the community energy system (Sibbitt, et al., 2011).

### 3.2 The exhaustive search and multi-objective optimisation methods

According to Laseau (Laseau, 2000), problem solving in an energy system design problem involves the following steps: 1) definition of the design problem, 2) generation of the simulated results, 3) evaluation of the results, 4) selection of the appropriate results, and, 5) communication of the results. To design and evaluate a candidate design solution, the designer has to create several combinations of values for the available variables and assess their performance with respect to the objective. With the huge number of possible solutions and designs for energy systems and buildings, a trial and error method can be a tedious task. There are various methods of performing a simulation in order to find solutions for the system based on certain selected criteria/objectives. The two broad methodologies used are exhaustive search and multi-objective optimisation. In this thesis, both the methods are used to gain benefits from the positives elements of both methodologies.
3.3 The parametric search and exhaustive search methods

Publications 1 and 2 focused on investigating the performance of the systems by using the exhaustive search method. It is a method in which all possible solutions are evaluated. There is no search direction or formal identification of the optimal solutions. The best solutions are identified through the post-processing of all solutions. It has certain advantage over other methods. Firstly, the maximum possible amount of information is gathered in order to be used in decision-making, subsequently all probable and uncertain performance conditions are evaluated. Moreover, it is important for a progressive decision-making approach wherein the design criteria may change within the decision-making process (Wright, et al., 2016). A conventional optimisation may require a re-run of the optimisation process. Secondly, multi-objective optimisation algorithms are used to find an optimised solution using two objectives, since several optimisation algorithms are unsuccessful in resolving ‘many objective’ optimisation problems (Wright, et al., 2016). A parametric search is immune to the computation difficulties and complex algorithms of finding good solutions in many-objective search spaces, and it is scalable. Thirdly, the results can be post-processed in order to know the sensitivity of the decision variables. It is a method used to define how various independent design variables impact on a particular outcome under a given set of assumptions (Investopedia, 2016). Lastly, an exhaustive search can be used to decide which parameters need more in-depth analysis and those for which standard values could be used. These significant parameters, which are more influential, can be used later for optimisation (Idman, 2013). It simply helps to decide which parameters should be optimised accurately.

There are certain limitations of the exhaustive search method. The number of solutions that need to be evaluated increases as the product of the number of values for each variables increases (Wright, et al., 2016). In this thesis the motivation for the parametric analysis is to provide a complete analysis of the system under different conditions.

3.4 The simulation-based optimisation method

When a large number of possible designs are offered, trial and error explorations may not guarantee finding optimal solutions and may need a long time and a lot of effort. Instead of the exhaustive search method, simulation-based optimisation has been used for finding optimal energy and building design solutions (Hai, 2016). In simulation-based optimisation, a simulation model is used to evaluate the performance of a building for each trial solution of the optimisation.

Optimisation is used to improve the performance of a product or a process (Wang, et al., 2017; Wang, et al., 2016). In this method a large set of different design variables are needed as optimisation guides the process towards the best combinations through various algorithms (Hamdy, et al., 2016).

In the case of multi-objective, the objectives are usually conflicting in nature. Such solutions are called Pareto optimal (PO) solutions or non-dominated
solutions (Miettinen, 1998). Together, all the PO solutions form a Pareto front. The front can be a continuous curve with discrete point collection on the axis plane. All the solutions points on the Pareto front are optimal in different ways and one solution cannot be better than another. There are many algorithms and methods used for optimisation.

An automatic simulation-based optimisation method was done in Publications 3 and 4. Table 3 shows the comparison of NSGA-II (Non-dominated Sorting Genetic Algorithm II) with other optimisation algorithms. NSGA-II is used because it can handle multi-objective problems, while at the same time handling both the discrete and continuous design variables. Furthermore, NSGA-II provides a parallel computing facility that can reduce the time needed to reach optimal solutions. NSGA-II is used by combining TRNSYS and MOBO (multi-objective building optimiser) software. MOBO avoids the repetition, keeps all the iterations in an archive and sorts them.

Table 3. Comparison of the NSGA-II algorithm with other optimization algorithm (Attia, et al., 2013).

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Features</th>
<th>Single objective</th>
<th>Multi-objective problem</th>
<th>Constrained handling</th>
<th>Handling discrete variables</th>
<th>Handling continuous variables</th>
<th>Parallel computing</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSGA-II</td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Brute Force</td>
<td></td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Random search</td>
<td></td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Hooke-Jeeves</td>
<td></td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>OMNI optimizer</td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

3.4.1 The genetic algorithm: NSGA-II

Optimisation methods work for problems which are clearly defined by equations, especially those for which gradient information is available (Capitanescu, et al., 2015). In complex black box models, an analytical formulation is unavailable and it is infeasible to use classical methods.

With such a problem, meta-heuristic methods can be used, such as a genetic algorithm. A genetic algorithm is an optimisation method that is based on the evolution principle. After a set of solutions has been found, they are compared and the best ones are combined by way of exchanging some of their variable values. After this the solutions are compared with new variables to find the better solution set. NSGA-II is a popular genetic algorithm that utilises solution sorting based on function values. It helps to find solutions on the Pareto front (Deb, et al., 2002).

3.4.2 The hypervolume of the Pareto front

A hypervolume is a volume or an area enclosed by the current non-dominated front and some reference point. The hypervolume indicates the speed of convergence of the optimisation. The distribution of points on the Pareto front has an effect on the hypervolume. If the points on the generated front are sparsely
distributed, the enclosed area will not match that of the true Pareto front, even if all the points are on the Pareto front.
4. Methodology

The tools used in the modelling and in the simulation of the proposed solar district heating energy systems and buildings were TRNSYS and TRNBuild (Thermal Energy System Specialists, LLC, 2006). Moreover, MOBO (Palonen & Hasan, 2017) was used for multi-objective optimisation of the proposed energy systems. In MOBO, NSGA-II (Deb, et al., 2002) was used to generate PO solutions.

4.1 The input parameters and design variables for simulated systems and optimisation

In general, the energy performance of the energy systems depends on the input or design parameters. These parameters were the variables that could be determined by the designers. The significance and the nature of these parameters can be different for varying systems. In general, the energy performance of the energy systems may mostly depend on the following parameters (which are those that were considered): (1) the solar collector area, (2) the short-term storage tank volume (for both warm and hot tanks), (3) BTES volume, (4) the BTES aspect ratio, (5) BTES density, (6) the PV area, (7) the charging temperature set points of the hot and warm tanks and (8) the building’s heating demand. These design variables are important because they can affect the optimal points on the Pareto front. Each parameter is described below:

4.1.1 ST collectors and short-term storage tank design

The solar panels used in the energy systems were mounted at a 50° tilt angle, facing south. They were flatbed collectors, connected in series. The design features of the collectors and the storage tanks (the hot and warm tanks) are shown in Table 4 and Table 5 respectively. TRNSYS Type 1b and Type 543 (Solar Energy Laboratory, University of Wisconsin-Madison, 2012) were used for collector and buffer tanks respectively.

The efficiency of ST collectors varies, depending on the solar radiation, outside temperature and collector fluid temperature. Efficiency is not a constant – it depends strongly on the temperature difference between the collector and the outside air (Build it solar, 2006). The intercept efficiency was calculated as the point on the efficiency curve when there was no difference between the collector temperature and ambient temperature (Struckmann, 2008).
Methodology

Table 4. Design characteristic of ST system design features (GREENOneTEC Solarindustrie GmbH, 2015).

<table>
<thead>
<tr>
<th>ST collector</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net aperture area</td>
<td>Variable</td>
</tr>
<tr>
<td>Maximum flow rate</td>
<td>11.11 kg/s</td>
</tr>
<tr>
<td>Intercept efficiency</td>
<td>0.871</td>
</tr>
<tr>
<td>Efficiency slope</td>
<td>3.611 W/m².K</td>
</tr>
</tbody>
</table>

Heat exchanger efficiency was defined as the ratio of the heat transferred in the actual heat exchanger to the heat that would be transferred in an ideal heat exchanger. Efficiency was a comparison between the actual (real) and ideal (best) performance and was typically defined as being less than 1, or at best, equal to 1. The ideal behaviour was generally known from modelling and the limitations dictated by physical laws, particularly the second law of thermodynamics (Fakheri, 2006).


<table>
<thead>
<tr>
<th>Short-term storage tanks (hot and warm tank)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>Variable</td>
</tr>
<tr>
<td>Heat exchanger effectiveness</td>
<td>0.9</td>
</tr>
<tr>
<td>Insulation U-value</td>
<td>0.2-0.3 W/m².K</td>
</tr>
</tbody>
</table>

4.1.2 The piping system

The piping network was included in TRNSYS using Type 709 (Solar Energy Laboratory, University of Wisconsin-Madison, 2012). The diameter of the pipe was chosen based on the pressure drop, so that the loss from the pipe was below 100 Pa/m. The insulation thickness was selected based on the available commercial products (Vital Energi, 2016). The polyurethane (PUR) insulation was used with insulation conductivity of 0.023 W/m.K. The district heating grid includes SPH, DHW and collector piping in the simulations. However, the scope of the piping was limited to the inclusion of the heat losses in the network (given by Type 709 as an output); no analyses were carried out on pressure losses.

4.1.3 Heat pump design

The heat pump was connected to the system as a backup for charging the short-term tanks. TRNSYS Type 668 (Solar Energy Laboratory, University of Wisconsin-Madison, 2012) was used to model the heat pump. The heat pump meets the heating load in the network through the storage tank. Several heat pumps can be connected in order to get higher capacities. The thermal power was 60 kW in the energy systems. The maximum flow of brine-water through the heat pump’s condenser was 1.94 kg/s and the COP of the heat pump was 4–6, depending on the BTES and the desired outlet temperature.
4.1.4 PV panel design

PV panels were integrated with the system in order to provide electricity to the system and to reduce the purchased electricity from the supply grid. TRNSYS Type 194 (Solar Energy Laboratory, University of Wisconsin-Madison, 2012) was used to model the electricity produced by the PV system according to its specification, using the same reference year’s weather data. The specifications (AXITEC Solar, 2012) of the PV panels used in the simulations are described in Table 6. The on-site energy generation was used to meet part of the demand while the rest was imported from the grid. Excess energy was exported to the grid in all the publications (Publications 1, 2, 3 and 4). No electricity storage was considered in the study. The area of the panels was variable in the study.

Table 6. PV panel (AXITEC Solar, 2012).

<table>
<thead>
<tr>
<th>Photovoltaic, polycrystal-line modules (at standard conditions)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>AC-250/156-60S</td>
</tr>
<tr>
<td>Area</td>
<td>Variable</td>
</tr>
<tr>
<td>Nominal output (Pmpp)</td>
<td>250 Wp</td>
</tr>
<tr>
<td>Nominal voltage (Vmpp)</td>
<td>30.7 V</td>
</tr>
<tr>
<td>Nominal current (Impp)</td>
<td>8.18 A</td>
</tr>
<tr>
<td>Short circuit current (Isc)</td>
<td>8.71 A</td>
</tr>
<tr>
<td>Open circuit voltage (Voc)</td>
<td>37.80 V</td>
</tr>
<tr>
<td>Module conversion efficiency</td>
<td>15.37 %</td>
</tr>
</tbody>
</table>

4.1.5 Weather profile: Finland

The chosen location for the solar community was situated in southern Finland. Regarding the weather data, Finnish test reference year data (Finnish Meteorological Institute, 2010) was used in TRNSYS through Type 15 (Solar Energy Laboratory, University of Wisconsin-Madison, 2012). The total radiation and the external temperature are shown in Figure 7.

![Figure 7. Hourly solar radiation and ambient temperature in Finland (Publication 1, 2, 3 and 4) (Finnish Meteorological Institute, 2010).](image)

4.1.6 The building’s heating demand in the community as an input parameter

A community energy system has many benefits compared to an individual building-sized energy system. Each building has a unique energy demand pro-
file, even if buildings are similar in function and design, due to the different schedules of people’s lives. Thus, the peak demand moments of each building tend to be at different times, even though some general daily trends do exist due to weather and work schedules. When such demand profiles are aggregated, the peak of the demand per building tends to go down. This results in the smaller generation and storage needs for a community compared the needs of all the buildings considered individually. A community also allows an increase in the self-consumption of the on-site generation with optimal energy system size. The controlling of the community energy system should happen centrally so that it allows the balancing of generation and demand (Hirvonen, 2017). The house designed for modelling the houses in the community under study is defined under.

A 100-house community was studied, located in Helsinki, Finland (60.19N, 24.94N) (World Geodetic System WGS84 Standard, 2012-2016). Each house had a single zone that has a pitched roof (that of an attic) with a tilt angle of 20°. The building’s thermal model was built in TRNBuild (Solar Energy Laboratory, University of Wisconsin-Madison, 2012), which was a TRNSYS subroutine that was able to provide the thermal heat load, various user profiles and the properties of the building envelope. The heated area of the houses was 100 m² each. The internal height was 2.7 m. The windows’ glazing area was 14% of the total wall area. To avoid summer overheating, different types of shading were provided. Because of the mild climate in summer, most of the houses in Finland have no (or little) mechanical cooling. Hence, mechanical cooling was not considered in the study. Each house was ventilated by one air handling unit (AHU) that supplies outdoor air and removes exhaust air from the house. The AHUs had heating coils that kept the supplied air temperature at 18°C when the incoming outdoor air temperature was lower than this temperature. The building envelope has an airtightness (n50) of 2 l/h, where n50 was the number of air changes per hour that is equivalent to an air leakage rate with a 50 Pa pressure difference over the envelope (Hamdy, et al., 2013; Ministry of the Environment, Department of the Built Environment, 2010). The average exhaust air flow rate was equal to a 0.65 air change per hour (1/h) (Pal, et al., 2016). The dynamic changes of DHW, lighting and appliance power demand were considered by using profiles based on the typical Finnish lifestyle (Jokisalo, et al., 2009). The DHW profile was balanced for the buildings to avoid too high peak loads. The same profile was used for all the buildings in the simulations. The internal heats gain due to people, lighting and appliances were 10.3, 7.8 and 17.8 kWh/m²/yr respectively, according to D5-2012 (Hamdy, et al., 2013; Ministry of the Environment, Department of the Built Environment, 2010).

The design variables were selected in order to comply with the national building code C3 (C3 NATIONAL BUILDING CODE OF FINLAND, MINISTRY OF THE ENVIRONMENT, Housing and Building Department, 2002). The variables selected included external walls, the roof’s and floor’s insulation thicknesses, three windows types and three rotary-type heat recovery units. The main data of the house and the envelope’s thermal properties of the house
are shown in Table 7. The cost of each building design variable is also shown in Table 7.


<table>
<thead>
<tr>
<th>Parameters</th>
<th>Alternatives</th>
<th>Prices</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall insulation (mineral wool)</td>
<td>U-value=0.17 W/m² K, insulation thickness=0.210m</td>
<td>65 €/m²</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>U-value=0.13 W/m² K, insulation thickness=0.282m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>U-value=0.10 W/m² K, insulation thickness=0.375m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof insulation (wool)</td>
<td>U-value=0.09 W/m² K, insulation thickness=0.42m</td>
<td>37 €/m²</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>U-value=0.08 W/m² K, insulation thickness=0.475m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>U-value=0.07 W/m² K, insulation thickness=0.545m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor insulation (Polyurethane)</td>
<td>U-value=0.17 W/m² K, insulation thickness=0.221m</td>
<td>114 €/m²</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>U-value=0.13 W/m² K, insulation thickness=0.294m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>U-value=0.10 W/m² K, insulation thickness=0.385m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window type</td>
<td>U-value=1 W/m² K, q-value 0.5%</td>
<td>252 €/m²</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>U-value=0.8 W/m² K, q-value 0.6%</td>
<td>290 €/m²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>U-value=0.6 W/m² K, q-value 0.4%</td>
<td>350 €/m²</td>
<td></td>
</tr>
<tr>
<td>Ventilation heat recovery efficiency</td>
<td>Efficiency=80 %</td>
<td>4138 €</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Efficiency=70 %</td>
<td>3835 €</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Efficiency=60 %</td>
<td>3533 €</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Input parameters for seasonal storage

4.2.1 The background of the seasonal storages

Energy storage allows the utilisation of excess energy generated from energy sources. However, at the moment electricity storage is widely uneconomical and has degradation issues (Thygesen & Karlsson, 2014); this study focuses on thermal storage systems.

There are three main forms of thermal storage: sensible, latent and chemical thermal storage (Aneke & Wang, 2016). Sensible energy storage is the most common and the cheapest way to store heat energy. In sensible thermal storage the temperature of the storage material changes in order to store heat (Dinçer & Rosen, 2011). Typically, many households use water tanks for energy storage. Thermal losses to the environment make it difficult to store heat for long time periods. In latent heat storage, the storage medium changes state between solid, liquid and gaseous states. Each state absorbs or releases heat when undergoing a state change. The volume or mass of the storage medium changes due to the state change (Pomianowski, et al., 2013). Chemical
storage stores or discharges heat by the reversible exothermic or endothermic chemical reactions of two different chemicals. It has no apparent thermal losses (Pardo, et al., 2014); however, it requires more development in order to be commercially available.

4.2.2 Types of TES

Short-term thermal storage can typically provide 20% of the annual heating needs of residential buildings through solar energy. With seasonal storage, it can be increased by 50% or more (Bauer, et al., 2010). In Finland most of the annual solar energy is available during summer. During these months energy demand for heating purposes is low. The problem caused by this mismatch is solved with the seasonal storage of thermal energy. The storage duration of seasonal storage is several months, and during those months, stored energy is consumed for heating purposes. In this study, seasonal storage based on sensible heat energy storage has been considered. There are around four well-known technologies that have been developed for seasonal storage since the 1970s, apart from traditional tank storage (Novo, et al., 2010):

- ATES
- Cavern thermal energy storage (CTES)
- Pit storage (PTES)
- BTES

ATES

ATES uses an underground layer of water-permeable rock, rock fractures or unconsolidated materials. Energy is charged and discharged with the pairing of hot and cold wells. There can be more than one pairing of wells in one aquifer. When charging the aquifer with heat, water is pumped from the cold well to the heat exchanger that heats up the circulating water, which is then injected back to the aquifer through the hot well. The direction of the water flow is simply reversed when discharging heat from the ATES system (Schmidt, et al., 2004).

CTES

Cavern storage uses a massive underground space for water storage. The water that is stored in the cavern is used as storage media for thermal energy. The initial cost of the cavern is high. Old abandoned mines and oil storages can be modified to act as a reservoir for such systems. Ground water leakage should be minimised to reduce the losses.

These storages are located deep in the ground so they are less affected by seasonal fluctuations in air temperature. Heat losses occur by heat convection through the surrounding rock masses. Thermal stratification and aspect ratios are important factors in CTES design (Lee, 2012).

PTES

In a PTES system, a large pit is excavated in the ground and filled with water. This large water reservoir acts as the storage media for stored heat. PTES is similar to tank TES but the main difference is that the storage walls are natural
material and have no supporting structures as the pit is excavated from soil or hard rock. The pit has to be made waterproof to prevent leakage as the escaping water reduces the storage volume and energy. Moreover, PTES has a floating cover that insulates the storage from the top. The floating cover is the most expensive component of the storage (Andersen, et al., 2013).

**BTES**

BTES utilises hard rock or soil as a storage medium and uses heat exchanger pipes installed into a drilled borehole field. Pumping hot fluid through the pipes transfer heat to the surrounding ground and pumping cold fluid absorbs heat from the ground. The heat exchanger system is installed into drilled boreholes and can be either an open or closed system.

BTES is more attractive than other methods of storage for the following reasons: the simplicity of its storage, its adaptability (by additionally drilling more boreholes if the demand increases), its flexibility in terms of location, its cost effectiveness and the favourable ground conditions in Finland (Honkonen, 2016). Therefore, in the present study BTES is used as seasonal storage for further analysis.

Two major local ground properties that affect storage efficiency and losses from BTES are (1) the thermal conductivity and (2) the groundwater level and its movements. Major challenges with the BTES systems are that they can only be cost-effectively insulated from the top. Stored heat escapes from the sides, bottom and even from the insulated top of the storage. The heat escapes because of the temperature difference between the storage and the surroundings. In the early charging period, heat energy losses to the surrounding ground and bedrock are large, but they reduces after a few years, when the surrounding bedrock is hot enough (Gao, et al., 2015; Bauer, et al., 2010).

### 4.2.3 BTES as seasonal storage in the Finnish context

A successful example of BTES implementation is the DLSC in Canada, which is able to provide 97% of the annual SPH via solar energy (Sibbit, et al., 2012). This validated example was used as the starting point for the energy system in all the publications because the rocky ground was well suited for borehole systems.

As mentioned above, BTES does not only depend on ground properties. The shape of the storage volume, and the number of boreholes and their interconnectivity, as well as the energy demand, affect its performance. Solar insolation and ground properties need to be analysed before using BTES in order to meet local conditions. For example, the average ground thermal conductivity in Finland is 3.5 W/m.K, while in Drake Landing it is 1.37 W/m.K (Flynn & Sirén, 2015). This means higher losses to the environment in Finland. The groundwater level plays an important role in thermal conductivity. The groundwater level in Finland is usually located at the depth of 1–4 m below the surface; however, it can be located as deep as 20 m in ridges and bedrock. Most of the bedrock in Finland is unbroken and has little or no ground flow (Honkonen, 2016; GTK Geologian Tutkimuskeskus, 2005). The volumetric heat capacity of
Finnish ground is 2240 kJ/m³K, while in Drake Landing it is 3200 kJ/m³K. This means that less thermal energy can be stored in the same volume.

If the BTES is arranged in series, so that the outlet flow from one borehole is the inlet for another borehole, the heat transfer can be arranged to run from the centre to the outer side. To charge the storage, hot fluid flows from the centre to the outer edge to transfer heat to the ground. To discharge the storage, cold fluid flows from the outer edge to the centre to collect heat from the ground. This strategy of charging and discharging was proposed in order to create radial temperature distribution and maintain temperature stratification in the ground.

The size of the BTES is important because it was found that the temperature of the borehole varies with the size of the BTES. The smaller the storage size, the larger the seasonal temperature variations. Usually, with each charging and discharging cycle, the average BTES’s temperature increases until it reaches a steady state condition where any additional temperature gains are offset by increasingly larger losses. The efficiency of the seasonal storage can be defined as the ratio of energy taken out of the storage to the energy injected into the storage (Flynn & Sirén, 2015):

\[
\eta_{BTES} = \frac{E_{\text{discharge}}}{E_{\text{charge}}}, \tag{2}
\]

The seasonal storage played a key role in all the systems. In a few systems solar energy was stored in BTES and in a few systems it was used directly as a thermal source for the heat pump. To extend the scope of the study, and therefore to assess the benefits of using seasonal storage with ST energy, different volumes and shapes of seasonal storage were considered. The seasonal storage behaviour was simulated utilizing a Type 557a model that was available in the library of TRNSYS (Solar Energy Laboratory, University of Wisconsin-Madison, 2012). Table 8 shows the main borehole and soil characteristics used in each energy system. The volume and shape of the BTES was used as design variables in the thesis. The values given in Table 8 are used in Publication 2 and shown for reference.

**Table 8.** Main BTES characteristics (Schreiner, et al., 2015).

<table>
<thead>
<tr>
<th>Borehole thermal energy storage, vertical-U tube system</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (energy system I, II and III)</td>
<td>33650, 67300, 134600 m³</td>
</tr>
<tr>
<td>Diameter (energy system I and II)</td>
<td>30.9, 43.6, 61.7 m</td>
</tr>
<tr>
<td>Diameter (energy system III)</td>
<td>11.95, 16.9, 23.9 m</td>
</tr>
<tr>
<td>Depth (energy system I and II)</td>
<td>45 m</td>
</tr>
<tr>
<td>Depth (energy system III)</td>
<td>300 m</td>
</tr>
<tr>
<td>Boreholes density (energy system I and II)</td>
<td>0.191, 0.096, 0.048 borehole/m²</td>
</tr>
<tr>
<td>Boreholes density (energy system III)</td>
<td>1.283, 0.641, 0.32 boreholes/m²</td>
</tr>
<tr>
<td>Pipe thermal conductivity</td>
<td>0.472 W/m.K</td>
</tr>
<tr>
<td>Soil undisturbed temperature</td>
<td>5°C</td>
</tr>
<tr>
<td>Insulation conductivity (expanded glass granules)</td>
<td>0.04 W/m.K</td>
</tr>
</tbody>
</table>
4.3 The multi-objective optimisation methodology

4.3.1 The optimisation algorithm and MOBO

In the present approach, the TRNSYS system models and MOBO were combined to perform the optimisation. MOBO (Palonen & Hasan, 2017) is freeware optimisation software that can handle both discrete and continuous variables and it allows the use of evolutionary and classical optimisation algorithms. For this study, NSGA-II was selected (Deb, et al., 2002). NSGA-II was selected because it can solve a multi-objective problem, while handling the constraints, and the discrete and continuous variables. Furthermore, parallel computing was possible with this algorithm (Deb, et al., 2002). It was computationally expensive and time consuming to explore all designs. Hence, a multi-objective NSGA-II was used to perform the exploration (Hamdy, et al., 2013).

An automated simulation-based optimisation method was performed using NSGA-II, combined with TRNSYS. It avoids repetition, keeps all the iterations in an archive and uses them in a non-dominated sorting process. An initial population of 16 individuals was selected in MOBO (Alajmi & Wright, 2014). Figure 8 shows a flow diagram of the multi-objective optimisation process. Deb at al. (Deb, et al., 2002) provides a detailed description of the algorithm. All the design variables’ random values were generated by the algorithm in order to be evaluated in the TRNSYS simulation software, and later the results were sorted by MOBO, based on the objective functions. Post-processing of the results in text files was carried out in Microsoft Excel 2010.

![Diagram](image-url)

**Figure 8.** The flow diagram of the multi-objective optimization process and its integration with the simulation (Publication 4) (Rehman, et al., 2018).
4.3.2 Problem definition

In a solar district heating system, an optimisation problem deals with multiple objectives of a conflicting nature. The objective functions are usually related to the technical performance of a system or cost-related parameters. Therefore, in the current study, the problem includes the minimisation of purchased electricity, investments and the LCC.

4.3.3 Objective functions

In this study, purchased electricity and investments costs (ICs) were used as the objectives to be minimised (Publication 3); purchased electricity and the full cost (FC) or LCCs were used as the objective functions to be minimised (Publications 2 & 4). It is important to note that for Publications 2 and 4, LCC or FC was used to describe the cost function. Both LCC and FC use the same variables (i.e. investments + operational costs). In Publication 3 only ICs were used to describe the cost function.

The motivation for using purchased electricity, ICs (Publication 3) and FC/LCCs (Publication 2 & 4) was of primary interest because purchased electricity and LCCs were of interest to the end user and the IC was of interest to the contractors and investors. The companies building such systems were more interested in the ICs than the LCCs (Publication 3). On the other hand, end users were more interested in the FC/LCC (Publications 2 and 4). Therefore, it was important to evaluate all these quantities in order to provide the overall performance of the system. For Publications 1, 2, 3 and 4, various design variables were considered. The selected design variables used in each publication are described in the individual subsections of Chapter 5 that describe their results.

The two objective functions that were minimised in Publication 3 were the purchased electricity of the system, and the IC. These were given as:

\[ \text{Min} \{ E_{\text{PUR}} (x) = \text{Purchased electricity, IC} (x) = \text{Investment costs} \}, \text{ for all } x = [x_1, x_2, \ldots, x_n], \]

where \( x \) is the vector of the design variables \( (x_1, x_2, \ldots, x_n) \), as defined in the above section, \( E_{\text{PUR}} \) is the purchased electricity for the system, together with the houses appliances, and \( IC \) is the IC of the system (Publication 3).

The mathematical expression for purchased electricity was

\[ E_{\text{PUR}} = E_{\text{PUMP}} + E_{\text{HP}} + E_{\text{BH}} + E_{\text{BUL}} - E_{\text{Self}} \]  \hspace{1cm} (3)

where \( E_{\text{PUR}} \) is the purchased electricity, \( E_{\text{PUMP}} \) is the energy used by all the pumps, \( E_{\text{HP}} \) is energy consumed by the heat pump, \( E_{\text{BH}} \) is the backup electric heater consumption, \( E_{\text{BUL}} \) is the appliances’ electricity consumption and \( E_{\text{Self}} \) is the self-consumption of the on-site generation. It was assumed that the electricity produced by the PV panels was used by the energy system and also by building appliances. The electricity production of the PV panels faces the same problem as heat production by the collector: the match between supply and demand curves. In this thesis, for the heat and electricity supply, the energy
flows were balanced for every time step. All heat demand was met by the local system. However, for the electricity system any excess energy generated via PV panels was exported to the grid due to the lack of an electrical storage device in the present study. Any shortfall was balanced by importing electricity from the grid.

The second objective function was the IC – it was the sum of the present value of the IC of the system. It was defined as:

\[ IC = C_{ST} + C_{PV} + C_{BTES} + C_{WT} + C_{HT} + C_{B}, \]  

(4)

and

\[ C_{B} = C_{Wins} + C_{Rins} + C_{Wind} + C_{HR}, \]  

(5)

where IC is the overall IC, \( C_{ST} \) is the cost of the collector, \( C_{PV} \) is the cost of the PV panels, \( C_{BTES} \) is the cost of the BTES, \( C_{WT} \) is the cost of the warm tank, \( C_{HT} \) is the cost of the hot tank and \( C_{B} \) is the cost of the building costs. The building cost includes the costs of the insulation material – like \( C_{Wins} \) (the walls), \( C_{Rins} \) (the roof) and \( C_{Wind} \) (the floor) – and the cost of windows, \( C_{HR} \) (as in Publications 2, 3 and 4). No maintenance costs were considered. In Publication 3, the multi-objective optimisation was carried out using NSGA-II. It was done by combining TRNSYS and MOBO (Hamdy, et al., 2011) software.

In Publications 2 and 4, the two objectives that were minimised were purchased electricity and LCC or FC. Instead of IC, LCC was included because life cycle was an interest of the building owners. The LCC was the sum of the present value of the investments and the net energy cost for 25 years (Fan, et al., 2009; Voltas Technologies (Pty) LTD, 2010). Maintenance, replacement and plant disposal costs were not included in the calculations. In Publications 2 and 4 it was expressed as

\[ \frac{LCC}{FC} = C_{ST} + C_{PV} + C_{BTES} + C_{WT} + C_{HT} + C_{B} + \sum_{n=1}^{25} a_e C_i E_{PUR} - \sum_{n=1}^{25} a_e C_e E_{EXP}, \]  

(6)

\[ E_{EXP} = E_{PV} - E_{DEM}, \]  

(7)

where \( LCC \) was the LCC (Publication 4) or FC was the FC (Publication 2), \( C_i \) was the imported electricity cost and \( C_e \) was the exported electricity cost. The electricity import price (in euro cents) of 11.10 c/kWh and the export price (in euro cents) of 4.04 c/kWh were used. All energy prices include tax and distribution costs. These prices were based on electricity prices in Finland in 2016 (Nord Pool, 2016). The discounting factors were represented by \( a_e \), which considered the effect of the interest rate and the escalation of electricity prices (Pal, et al., 2016; Hamdy, et al., 2013). Discounting was done with the real interest rate of 3% (European Commission, 2011). Moreover, the price escalation of 1% was used because of the decreasing trend in the prices of electricity in
the Nordic market (Nord Pool, 2016). The discounted operation cost was estimated over a period of 25 years. In Equation (7), $E_{\text{EXP}}$ was the excess electricity that was produced by PV panels and exported, $E_{\text{PV}}$ was the electricity produced by the PV panels, and $E_{\text{DEM}}$ was the total electricity demand of the system that includes pumps, heat pumps, backup heating and building appliances. To calculate the LCC, $E_{\text{EXP}}$ was used, as shown in Equation (7).

4.4 Issues, errors and technical failures: Solar district heating systems

The energy performance of the solar district heating network was sensitive to various technical parameters, as explained in many earlier studies (Hakaste, et al., 2008; Ochs, et al., 2008; Dalenbaeck, 1998; Nielsen, 2012; Truong & Gustavsson, 2014; Boyaghechi, et al., 2015; Faninger-Lund, 2003). The significance and nature of these parameters can be different for various systems. Some of the most common parameters that can alter the performance of the system in real conditions follow: (1) heat exchanger efficiency, (2) solar collector intercept efficiency, (3) tank stratification, (4) the heat pump coefficient, (5) SPH network temperature difference, (6) hot tank set points, (7) warm tank set points, (8) SPH inlet water temperature, (9) the ST circulation pump and (10) the thermal conductivity of the borehole’s boundary. All the mentioned issues and technical failures were explained in Publication 3 (Rehman, et al., 2018).

In ideal conditions, when everything is running well, state-of-the-art values were considered. For other cases, when the system was underperforming, the above ten parameters were altered and its performance was compared to the base case. The base case values and the altered scenario values are shown in Table 9. From the literature, there were no clear hints as to the number/quantity of defects or failures for every technical parameter. Therefore, the number/quantity of defects for each parameter was assumed to be in a reasonable range in order to show real scenarios.
Table 9. Technical parameters considered for the system performance deviations (Publication 3) (Rehman, et al., 2018).

<table>
<thead>
<tr>
<th>Technical parameters</th>
<th>Values before defects (optimized case)</th>
<th>Values after defects (deviation case)</th>
<th>Possible reasons behind failures/errors</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat exchanger</td>
<td>0.9</td>
<td>0.7</td>
<td>Fouling and breakage issues</td>
<td></td>
</tr>
<tr>
<td>efficiency</td>
<td></td>
<td></td>
<td>(Hannaschöck, 2016; Lundh &amp; Daalenbäck, 2008; Dincer &amp; Rosen, 2007)</td>
<td></td>
</tr>
<tr>
<td>Solar collector</td>
<td>0.9</td>
<td>0.7</td>
<td>Fouling, dirt accumulation, air lock and aging issues</td>
<td>ESTIF – the European Solar Thermal Industry Federation, 2006; Nussbicker-Lux, 2012</td>
</tr>
<tr>
<td>intercept efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank stratification</td>
<td>Stratified</td>
<td>Fully mixed</td>
<td>Flow variations, internal design and nodes distribution issues</td>
<td>(Koppen, et al., 1979; Sibbitt, et al., 2012)</td>
</tr>
<tr>
<td>Heat pump (COP)</td>
<td>5-6</td>
<td>3-4</td>
<td>Controls, auxiliary heater controls issues, lower evaporator inlet temperatures</td>
<td>NIBE, 2017; Nussbicker-Lux, 2012</td>
</tr>
<tr>
<td>SH temperature</td>
<td>7-3 K</td>
<td>5-1 K</td>
<td>Building heating system designs issues, HVAC design and district network design issues.</td>
<td>Ministry of the Environment, Department of the Built Environment, 2010; Nussbicker-Lux, 2012; Dincer &amp; Rosen, 2007; Rehman, et al., 2017</td>
</tr>
<tr>
<td>difference- between supply and return temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot tank set</td>
<td>70°C</td>
<td>75°C</td>
<td>Controls malfunction and error in control algorithm</td>
<td>Nussbicker-Lux, 2012; Rehman, et al., 2017</td>
</tr>
<tr>
<td>point</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm tank set</td>
<td>45°C</td>
<td>50°C</td>
<td>Controls malfunction and error in control algorithm</td>
<td>Nussbicker-Lux, 2012; Rehman, et al., 2017</td>
</tr>
<tr>
<td>point</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>point</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar thermal</td>
<td>Variable pump circulation control</td>
<td>On/off pump circulation control</td>
<td>Controls malfunction, error in control algorithm and issues in the pump device</td>
<td>(Sibbitt, et al., 2011)</td>
</tr>
<tr>
<td>circulation pump</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>3.5 W/m.K</td>
<td>4.5 W/m.K</td>
<td>Ground water flow through rocks fracture</td>
<td>(Tordrup, et al., 2017; Hakala, et al., 2014)</td>
</tr>
</tbody>
</table>
5. Results

5.1 The effect and importance of controls on system performance

A simple solar district heating network (as depicted in Figure 3) was simulated for a five-year time period. A simple energy system configuration and the various control modes of the ST collector and tank charging controls were analysed and the results obtained were presented and discussed in order to provide insights into the system behaviour. Table 10 and Table 11 show the design variables selected and the control modes used in the simulation. The control strategies were already explained in Chapter 2. In this simulation study, the following design variables – collector area, warm tank volume, hot tank volume, the solar collector outlet controls and collector outlet temperature control – were used to analyse the effect on the technical performance of the proposed system (Figure 3). In total, there were altogether 30 combinations and cases that were simulated. The heat demands of the buildings were the same in all the cases. The values selected for the simulations were based on the DLSC (Sibbitt, et al., 2012), as shown in Table 10. However, the collector area used in this study was 30 m²/building. It was found that increasing the size of the collector from 30 m²/building to 40 m²/building (as used in the DLSC) (Sibbitt, et al., 2012) only provided a minimal advantage for the present energy system.

Table 10. Solar collector (ST) and short term storage tanks configurations for the simulations and results (Publication 1) (Rehman, et al., 2016).

<table>
<thead>
<tr>
<th>System configuration</th>
<th>ST area (m²)</th>
<th>Warm tank volume (m³)</th>
<th>Hot tank volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1500</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>B</td>
<td>1500</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>C</td>
<td>1500</td>
<td>50</td>
<td>150</td>
</tr>
</tbody>
</table>
Table 11. Case summary for simulations (Publication 1) (Rehman, et al., 2016).

<table>
<thead>
<tr>
<th>System configurations</th>
<th>Control mode (Case number)</th>
<th>Tank connections</th>
<th>ST control</th>
<th>Primary storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>A,B,C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 9 shows the simulation results of all the cases, as described in Tables 10 and 11. Figure 9 shows the total electricity demand of the energy systems in various cases. Figure 9 shows the heat flows in the energy system for selected cases as a reference. In Case 2 and Case 8, when the warm tank was the priority tank, the electricity consumption was the lowest (Figure 9). This was caused by lower heat pump electricity demand. When the warm tank was used as the priority tank, it was charged frequently by the collector each time it had energy losses to the ground or due to demand. As the warm tank received low temperature from the collector during low solar radiation hours, which occur throughout the year, the system benefits from this abundantly available low temperature energy.

In Case 1 and Case 7, the electricity demand was highest, as shown in Figure 9. This was because when the hot tank was used as the priority tank, the collector efficiency decreased and reduced the total energy stored in the tanks and consequently the charging of the BTES.

In Case 1 and in Case 2, and in Case 7 and in Case 8 when system performance is compared, the electricity consumption was reduced by 20% when the warm tank was set as the priority tank. The phenomena was explained above, where there was a clear advantage to using the warm tank as the priority tank over the hot tank. The performance resulted in better effectiveness for both parallel and automatic tank ST controls.

In Case 5 and in Case 6, in series connection, the energy consumption was slightly higher than those of Cases 2, 4, 8 and 10 since the system had to supply energy to the hot tank at higher temperatures each time and also solar collector efficiency was less at a higher temperature (Figure 9). In series mode, the temperature tracking in Case 6 had 10% higher electricity demand than the temperature difference control of the collector in Case 5. This was because in Case 5, the system consumed less energy to charge the hot tank.
As a reference, to show the difference in the heat energy flows in different cases, Case B7 and Case B8 were compared and are shown in Figure 10. It shows that when the warm tank was made the priority tank, the warm tank was charged more by solar energy and the seasonal storage took most of its energy from this tank, as shown in the reference case in Figure 10. Therefore, the net energy value of BTES was high at the end of each year. Hence, the heat pump consumed less electricity each year to generate heat during winters, because a high source temperature improved its COP. However, one drawback when the warm tank was used as the priority tank was that, since the BTES was charged more, it caused an increase in the yearly losses from the BTES compared to when the hot tank was the priority tank, as shown in Figure 10.

5.1.1 System behaviours and energy flows

In Figure 11, in the best case, B8, was further analysed in order to observe the behaviour of the system; it was observed that in summer the demand for the building was met by the solar energy and, due to the absence of ST energy in winter, the energy demand for the building was met through use of the heat pump and ground storage. Most of the energy was provided from the ground, the remaining energy was provided via the compressor.
As a reference, case B8 was again selected in order to analyse the energy consumption of different components in the energy system. The consumption breakdown of the system is shown in Table 12. It was found that the most energy-intensive unit was the heat pump.

### Table 12. First year electricity consumption breakdown of the system, reference case (B8): automatic ST-tank connection with temperature difference control (Publication 1) (Rehman, et al., 2016).

<table>
<thead>
<tr>
<th>Heat pump (MWh)</th>
<th>ST pump (MWh)</th>
<th>Pump for HP (MWh)</th>
<th>Ground pump (MWh)</th>
<th>SH pump (MWh)</th>
<th>DHW pump (MWh)</th>
<th>DHW recirculation pump (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.17</td>
<td>1.15</td>
<td>0.13</td>
<td>0.29</td>
<td>1.79</td>
<td>0.26</td>
<td>0.003</td>
</tr>
</tbody>
</table>

In Figure 12 it was found that with each year that the BTES was charged, the heat pump annual demand of the system was reduced, dropping from 57.17 MWh to 45.93 MWh in five years, as shown in Figure 12.

### Figure 12. Yearly heat pump consumption of the energy system (B8) (Publication 1) (Rehman, et al., 2016).

Overall the study shows that, compared to temperature tracking control, the temperature difference control of the collector reduced the total electricity demand of the system by up to around 20% when the warm tank was chosen as the priority tank for both the series, automatic and parallel controls. Hence temperature difference control performed better for series, parallel and automatic ST tank connections. In terms of the charging of the tanks, parallel and automatic control performed better compared to series charging. They allowed better control of the tanks’ temperatures and could charge the tanks individually when needed.
5.2 Building performance and its importance as a design parameter in energy systems

The importance of a building and its heating demand can play a significant role in the performance of the overall system (Publications 2, 3, 4). In order to generate various building heating demand profiles, TRNBuild was used to generate the hourly profile of the building for SPH and ventilation. The heating demand of the building depends on different design variables, as mentioned above in Section 4.1.6 and as detailed in Table 7.

The parametric search method was used to evaluate building performance based on various design variables, as detailed above in Table 7. The IC was also included in the techno-economic evaluation of the building. The cost of the relative changes of the variables was considered in the economic calculation, assuming that all the other costs for the construction of the houses were constant.

The simulation results for the building heating demand of a 100 m² area situated in Finland was carried out. Each building heating demand was varied by changing the design variables, as detailed in Table 7. The heating demands of the building, set against the IC of the design variables, are shown in Figure 13 (Rehman, et al., 2017). The graph shows that when the investments were high, the building’s heating demand was low. By increasing the investment in the building by 40%, the heating demand of the building can be reduced by 62%. Moreover, the best-points front was generated as an outcome of the simulations in Figure 13. It was observed (in Publication 2) that the majority of the points that exist on the best-points front contains solutions that have high insulation thickness of the walls and roof, less thickness of the floor and higher heat recovery efficiency. Furthermore, it was found that the points that strayed from the front contained solutions, the majority of which, featured a higher thickness of floor insulation and lower efficiency of the heat recovery unit. It was also observed that the heat recovery unit had a higher influence on the heat demand. The airflow rate was controlled to maintain 18°C at the outlet of the heat recovery unit. With a small change in the cost of the recovery unit, the heating demand varied a lot.

![Figure 13](image_url)

Figure 13. The 243 combinations of building energy demand vs the building investment costs (Publication 2) (Rehman, et al., 2017).
Out of the 243 cases shown in Figure 13, 17 of the best cases (on the best-points front) were selected for further analysis of the performance of the building. The IC breakdown of the building is shown in Figure 14. It was observed that as the energy performance of the building improves, the heat recovery unit cost increases immediately in most cases, while the cost of the floor insulation remains almost the same. These results again demonstrate that the highest heat recovery efficiency, along with the lowest insulation thickness on the floor, was favourable in most of the best cases. More than half of the best cases contained inexpensive windows. Moreover, the highest thicknesses of the wall and roof insulations were proposed because the cost of these insulations forms a small portion of the total cost in all solutions.

![Figure 14](image_url)

**Figure 14.** The investment analysis of the selected best combination of Figure 13 (Publication 2) (Rehman, et al., 2017).

Building Cases 5, 13 and 17, with heating demands of 50, 37 and 25 kWh/m²/yr respectively, were further chosen from Figure 13 and Figure 14 in order to analyse both the energy systems (i.e. centralised and semi-decentralised systems, as mentioned in Chapter 2 of the thesis). These buildings were selected in order to provide a wide range of building representations in the energy systems. The next section provides information on the importance of building heating demand as a design variable in the energy system’s overall cost and performance.

It was assumed that in a new community, the buildings would have the minimum basic construction cost for the structure. This basic construction cost was assumed to be 0 and was used as a reference. Any additional cost for building efficiency components was given as an addition to the reference cost 0. The optimal building configurations selected for further energy simulations are shown in Table 13.

**Table 13.** The selected building cases for energy systems simulations (Publication 2, 3 and 4) (Rehman, et al., 2017).

<table>
<thead>
<tr>
<th>Building configuration</th>
<th>SPH demand (kWh/m²/yr)</th>
<th>Wall (W/m²)</th>
<th>Floor (W/m²)</th>
<th>Roof (W/m²)</th>
<th>Windows (W/m²)</th>
<th>Heat recovery efficiency (%)</th>
<th>Price (£/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>0.17</td>
<td>0.17</td>
<td>0.09</td>
<td>1</td>
<td>60</td>
<td>126.65</td>
</tr>
<tr>
<td>2</td>
<td>37</td>
<td>0.17</td>
<td>0.17</td>
<td>0.09</td>
<td>1</td>
<td>80</td>
<td>132.60</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>0.13</td>
<td>0.17</td>
<td>0.07</td>
<td>0.6</td>
<td>80</td>
<td>156.28</td>
</tr>
</tbody>
</table>
To analyse the variation caused in the system’s performance by the building heating demands, a reference case of the centralised system was used to observe the effect on both the technical and cost performance of the system. Figure 15 shows that when the building heating demand was reduced from a 50 kWh/m\(^2\)/yr to 25 kWh/m\(^2\)/yr, the purchased electricity was reduced by 6%, while the corresponding LCC increased by 9%. Hence the nZEB building has an impact on both the cost and technical performance of the energy systems. The figure shows that the building has an impact on the technical and financial performance. Building design and efficiency have to be considered while designing such systems in Nordic conditions.

![Centralized solar thermal system](image)

**Figure 15.** Purchased electricity and LCC, sensitivity of the centralized energy system (reference case) with respect to the various building heating demands in Finnish conditions.

### 5.3 Analysis of different centralised energy system configurations

The three different configurations of the centralised energy system were: (I) a heat pump connected to two tanks in parallel, using charged borehole storage, (II) a heat pump connected between two tanks, using charged borehole storage to directly charge the lower temperature tank and (III) two heat pumps used in series, one between the tanks and the other between the lower temperature tank and ground. In Energy Systems I and II the vertical borehole field was used as a seasonal storage, in Energy System III it was only used to extract heat. The systems were compared against its FC (investments + operational cost) or LCC and purchased electricity costs. The design solutions and the ICs of the design variable are shown in Table 14. This analysis includes six variables: the collector area, the PV area, the warm tank volume, the hot tank volume, the BTES volume and the building’s heating demand. These design variables were important to consider as they can affect the best-point front. In order to simulate the three energy systems configuration, an exhaustive search
method was employed. The numbers of possible design variables were 729 for each system. Therefore, for the three energy systems (I, II and III) the total number of simulations was 2187. The simulations were carried out on TRNEd-it, which is a subroutine of TRNSYS used for parametric analysis.

For parametric analysis, due to the long simulation calculation time, a five-year simulation was unfeasible. Therefore, the system was simulated for the fifth year – since during the fifth year the BTES average temperature becomes steady and change in temperature was insignificant in the following year – and used to estimate the energy performance. The average temperature at the end of the fourth year was used as the starting temperature of the BTES for the fifth year simulation. Each energy system was simulated for five years to identify the fourth-year BTES average temperature based on different collector areas. Afterwards, the average temperature of the BTES was chosen based on the collector areas (Energy Systems I and II) and borehole heat exchanger volume (for Energy System III) for the rest of the simulation cases. A linear equation was used to provide the fifth-year starting temperature of the BTES.

Table 14: System configuration variations for the simulations and investments cost of the component used in the energy systems (Hamdy, et al., 2013; Hamdy, et al., 2011; Haantela & Kïras, 2013).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Alternatives</th>
<th>Prices (£)</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar thermal area</td>
<td>Area = 2000 m²</td>
<td>365 €/m²</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Area = 4000 m²</td>
<td>347 €/m²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area = 8000 m²</td>
<td>312 €/m²</td>
<td></td>
</tr>
<tr>
<td>Warm water tank volume</td>
<td>Volume = 120 m³</td>
<td>500 €/m³</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Volume = 240 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volume = 480 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot water tank volume</td>
<td>Volume = 120 m³</td>
<td>500 €/m³</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Volume = 240 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volume = 480 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BTES volume</td>
<td>Volume 33650 m³</td>
<td>17.19 €/m³ and 13.86 €/m³ without insulation</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Volume = 67300 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volume = 134600 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photovoltaic area</td>
<td>Area = 1000 m²</td>
<td>230 €/m²</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Area = 2000 m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area = 4000 m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building configurations</td>
<td>Type 1: heating demand 25 kWh/m²/yr</td>
<td>156.28 €/m² (investment cost)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type 2: heating demand 37 kWh/m²/yr</td>
<td>132.60 €/m² (investment cost)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type 3: heating demand 50 kWh/m²/yr</td>
<td>126.55 €/m² (investment cost)</td>
<td></td>
</tr>
<tr>
<td>Energy systems</td>
<td>Energy system I</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy system II</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy system III</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total combinations</td>
<td></td>
<td>2187</td>
<td></td>
</tr>
</tbody>
</table>

The relationships between purchased energy and FC for all the solutions of the three systems are shown in Figure 16. In Figure 16 each energy system’s performance is shown separately. Generally it was observed that as the FC of the systems increased, the purchased electricity value decreased. The bold points in Figure 16 were the best-point front, where the FC and the purchased elec-
tricity were at their minimum. The slope of these points shows the change in the purchased energy between different systems. Energy System III performed worst compared to the other two systems. The minimum purchased energy of Energy System III was 44–47% more compared to Energy Systems I and II. This was caused by higher energy consumption of the heat pump since the BHE was not charged by solar energy. On the one hand, Energy System II performed better compared to Energy Systems I and III. This was due to the arrangement of the heat pump and system control. In this system, the heat pump was only used to charge the hot tank while taking energy from the warm tank. This configuration provided relatively warm temperature on the evaporator side compared to the other two cases.

In Energy System I, the purchased electricity varied between 27 kWh/m²/yr and 47.3 kWh/m²/yr, as shown in Figure 16. It was found that the points outside the front could be divided into three subsections. Subsection IA contains the majority of the points that had smaller-sized seasonal storage, subsection IB contains the majority of the points that had medium-sized seasonal storage and subsection IC contains the majority of the points that had large-sized seasonal storage. Due to the utilisation of the heat pump between the BTES and tanks, larger BTES was not needed to reduce the purchased electricity. A smaller BTES volume was enough to provide the required temperature for the heat pump on the evaporator side. A combination of smaller BTES size with a medium to large ST area can be beneficial for performance. However, a combination of large BTES with a large ST area can slightly improve performance.

In Energy System II, the purchased electricity varied between 26 kWh/m²/yr and 34 kWh/m²/yr, as shown in Figure 16. Energy System II can be implemented at a lower FC compared to Energy Systems I and III. In this system the purchased electricity dropped down from 34 kWh/m²/yr to 26 kWh/m²/yr. It was found that points outside the best-point front can roughly be divided into three subsections. In subsection IIA the majority of the points contained seasonal storage of a smaller size, in subsection IIB the majority of the points contained seasonal storage of a medium size and in subsection IIC the majority of the points contained seasonal storage of a large size. Due to the utilisation of the heat pump between the warm tank and hot tanks only, larger BTES reduced the purchased electricity in subsection IIC. It allowed storing more energy during summer. On the contrary, in subsection IIA, due to the smaller size of the BTES, the purchased energy increased as the smaller BTES volume was not able to meet the demand of the warm tank in the absence of a heat pump. As a result, the backup heat increased. A combination of large BTES with a medium-sized collector area can be more beneficial. On the other hand, a combination of large BTES with a large collector area can improve performance slightly further.

In Energy System III, the purchased electricity varied between 39 kWh/m²/yr and 63 kWh/m²/yr, as shown in Figure 16. Energy System III can be implemented with purchased energy falling down to 41 kWh/m²/yr, after which the reduction was low; it was further reduced to 39 kWh/m²/yr, although the FC increased, as shown in Figure 16. It was found that a large collev-
tor area provided a minimal advantage in terms of the reduction of purchased electricity in this configuration. A large collector area increased the temperature in the short-term tanks, causing higher losses from the tanks to their surroundings as excess energy cannot be stored in the seasonal storage in Energy System III. In this system, the BHE was not charged by the excess energy. Therefore, the sizes of the short-term tanks varied the purchased energy; large short-term tanks tend to reduce the purchased electricity. It was found that points outside the best-point front can roughly be divided into three subsections. In subsection IIIA the majority of the points contained a BHE of a smaller size, in subsection IIIB the majority of the points contained a BHE of a medium size and in subsection IIIC the majority of the points contained a BHE of a larger size. In Energy System III, a BHE was not charged by the solar energy; therefore, in subsections IIIB and IIIC, larger BHE were selected in system configurations compared to subsection IIIA. In addition to that, for a longer duration of the system operation it was more beneficial to use a large-volume BHE because it can be discharged for a longer time and the average temperature variations between natural charging and discharging is less. A combination of medium-sized to large BHE with a small to medium-sized collector area can be beneficial. However, a large collector can reduce the performance due to losses, the reduction in collector efficiency and stagnation issues.

![Graph](image)

**Figure 16.** Purchased energy vs full cost, the 2187 combinations for energy system I, II and III (Publication 2) (Rehman, et al., 2017).

The FC analysis and renewable energy fractions of the selected best cases (from the best-points front) identified in Figure 16 for Energy Systems I, II and III are shown in Figures 17, 18 and 19 respectively.

In Figure 17, three sizes of collector area were shown in the best cases equally. The smallest volume of BTES was used in the majority of the cases; only in the two most expensive cases was a larger volume of seasonal storage selected. These results again indicated that a smaller-sized seasonal storage was favourable in most cases in Energy System I. Half of the solutions contain the largest PV area. The operational cost was also significant when the investments were
low. Due to fewer investments, the purchased electricity increased because the on-site generation lacked the capacity to meet the demand of the system. The cost of the tank was a small portion of the total cost in all the solutions. The renewable energy fraction varied between 65–75%. The on-site energy fraction (OEF) varied between 16–40%, indicating that PV was able to meet 16–40% of the total demand of the community. The OEF was low because of the mismatch between generation and consumption and as no electrical storage was considered in the study.

As mentioned in Sections 4.1.6 and 5.2 of this thesis, regarding the building demand as a design variable, it was important to note the significance of the building heating demand in the overall energy system performance. In Figure 17, as the performance of the system improves, the investment on the building increases that corresponds to the building with higher efficiency. It shows that the building, as a design parameter, can play an important role in the performance of the energy system. The building design and its efficiency assisted improving the performance of the system. Therefore, in order to plan, design and optimise such a solar district heating network, the building needs to be designed in an energy-efficient way. An integrated approach has to be considered in order to provide a carbon neutral community.

![Figure 17](image_url)

**Figure 17.** The cost breakdown of the selected best combinations of energy system I as mentioned in Figure 16 (Publication 2) (Rehman, et al., 2017).

In Figure 18, two sizes of the collector area divided the solutions, and the medium size occurred most frequently, hence the large collector had no advantage in Energy System II. A medium- to large-sized volume of BTES was used in the majority of the cases compared to Energy System I. These results again indicated that medium to large sizes of the seasonal storage were favourable in most cases. The PV area and building efficiency increased as the purchased electricity decreased. The renewable energy fraction varied between 68 and 81%. The OEF varied between 19 and 40%.
In Figure 19 two sizes of the collector area divided the solutions, and the small size occurred most frequently; however, a medium-sized collector area improved the system performance slightly in Energy System III. It was evident that the small volume of the BHE was selected in many cases due to cost; nevertheless, a larger BHE improved the system performance. These results again indicated that medium to large sizes of seasonal storage were favourable. The large volume of the short-term storage tanks may be beneficial due to the fact that excess energy is not shifted to the ground. Such large storage tanks can retain energy for a longer duration. The PV area and building efficiency increased as the purchased electricity decreased. The renewable energy fraction varied between 53 and 64%. The OEF varied between 11 and 26%. The OEF was less because the electricity demand was higher in Energy System III compared to the other two systems.

Table 15 shows the comparison between Energy Systems I, II and III, based on purchased electricity, the renewable energy fraction and cost. On a system level, the results showed that Energy System II performed better in terms of the
renewable energy fraction (81%), cost and purchased energy (26 kWh/m²/yr).
On the other hand, Energy System III performed poorest compared to the other two systems in terms of the renewable energy fraction (64%) and purchased energy (39 kWh/m²/yr). Therefore, system configuration and controls can play an important role when designing such systems.

Table 15. Comparison of the Energy system I, II and III.

<table>
<thead>
<tr>
<th>Energy system</th>
<th>System type</th>
<th>Purchased electricity (kWh/m²/yr)</th>
<th>Full cost/life cycle cost (£/m²)</th>
<th>Renewable energy fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy system with heat pump between solar charged BTES and tanks</td>
<td>Centralized with BTES charging</td>
<td>47-29</td>
<td>400-800</td>
<td>65-75%</td>
</tr>
<tr>
<td>Energy system with heat pump between tanks only, with solar charged BTES</td>
<td>Centralized with BTES charging</td>
<td>50-26</td>
<td>311-694</td>
<td>68 – 81%</td>
</tr>
<tr>
<td>Energy system with heat pumps between tanks and between ground and warm tank</td>
<td>Centralized with no sea-sonal charging</td>
<td>63-39</td>
<td>400-680</td>
<td>53 – 64%</td>
</tr>
</tbody>
</table>

The change in purchased energy (sensitivity) due to an increase in ST area (while keeping all other parameters constant) and the corresponding costs are shown in Figure 20. It was found that by increasing the ST area from 2000 m² to 4000 m², the reduction of purchased energy was around 6–15%, depending upon the system. Excessively increasing the ST area from 4000 m² to 8000 m², the purchased energy is reduced by around 5–9%, depending upon the system. Therefore, it was unprofitable, in terms of purchased energy reduction, to have a very large ST area.

Figure 20. The purchased energy comparison between energy system I, II and III as function of ST area-sensitivity analysis (Publication 2) (Rehman, et al., 2017).
5.4 Identification of the main failures and errors, and the influence of the failures on an optimised, centralised district system

5.4.1 The multi-objective optimisation-base case

In this section the TRNSYS model of a centralised system (Energy System II) was selected for simulation. It consists of centralised warm tank, charged directly from solar-charged BTES during winter. The centralised hot tank was charged by the heat pump, taking energy from the warm tank. All excess solar energy from the hot and warm tanks was transferred to the BTES. The SPH was provided by passing water through the warm tank and the bottom level of the hot tank. Energy System II performed better in terms of purchased electricity, as analysed and explained in the previous section; therefore, the same design was further optimised. MOBO was combined with the TRNSYS model of Energy System II (the centralised system) in order to perform multi-objective optimisation. The two objectives that were minimised were purchased electricity and IC. In MOBO, NSGA-II was selected for optimisation, as explained in Chapter 3. In NSGA-II the initial population of 16 individuals for 100 generations (i.e. 16 x 100 = 1600 simulation runs) was selected (Alajmi & Wright, 2014).

The design variables and their corresponding prices that were used for the optimisation are shown in Table 16. A specific price was used for some energy components, as shown in Table 16. The cost of the collector (Figure 21), PV (Figure 21) and tanks (Figure 22) were assumed to go down per m². The lowering of the cost was due to the economics of scale, as supplier companies tend to sell more at a slightly lower price per m². For each selected size of the collector, PV and tanks by the optimiser, the corresponding price of the components were selected from Figures 21 and 22. No incentives were included in the calculations.

![Figure 21. Cost profile of the rooftop ST (Mauthner & Herkel, 2016) and solar electric panels system (Ahola, 2016) (Publication 4).](image-url)
Table 16. System configuration variations for the simulations and investments cost of the component used in the energy system (Publication 3) (Rehman, et al., 2018).

<table>
<thead>
<tr>
<th>Design variables</th>
<th>Alternative/values</th>
<th>Prices (£)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST area (m²)</td>
<td>500-5000</td>
<td>600-500 €/m²</td>
<td>(Mauthner &amp; Herkel, 2016)</td>
</tr>
<tr>
<td>Warm tank volume (m³)</td>
<td>50-500</td>
<td>825 €/m³</td>
<td>(Mauthner &amp; Herkel, 2016; Solar district heating, 2012)</td>
</tr>
<tr>
<td>Hot tank volume (m³)</td>
<td>50-500</td>
<td>825 €/m³</td>
<td>(Mauthner &amp; Herkel, 2016; Solar district heating, 2012)</td>
</tr>
<tr>
<td>BTES volume (m³)</td>
<td>70000-150000</td>
<td>17.19 €/m³</td>
<td>(CIT Energy Management AB, EU report, 2011)</td>
</tr>
<tr>
<td>PV area (m²)</td>
<td>500-5000</td>
<td>230 €/m²</td>
<td>(Mauthner &amp; Herkel, 2016; Solar district heating, 2012)</td>
</tr>
<tr>
<td>Building configurations</td>
<td>Type 1: heating demand= 25 kWh/m²/yr</td>
<td>156.28 €/m²</td>
<td>(Hamdy, et al., 2011; Hamdy, et al., 2013; Haahela &amp; Kiiaras, 2013)</td>
</tr>
<tr>
<td></td>
<td>Type 2: heating demand= 37 kWh/m²/yr</td>
<td>132.60 €/m²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type 3: heating demand= 50 kWh/m²/yr</td>
<td>126.55 €/m²</td>
<td></td>
</tr>
</tbody>
</table>

Figure 23 shows the relationship between the purchased electricity and the ICs of the non-dominated optimal solutions (the red points) and also all simulation runs (the green points) for the energy system.

The solutions on the Pareto fronts were called non-dominated solutions (the red points). In total there were 153 non-dominated solutions for the energy system. The solutions on the right side of Figure 23 were energy intensive, while the solutions on the left side were less energy consuming. The purchased electricity varied between 49 kWh/m²/yr to 25.9 kWh/m²/yr, which corresponds to the ICs ranging from 202 €/m² of floor area to 624 €/m² of floor area. The results show that purchased electricity increased by 50% when IC was reduced by 68%. All the red points on the Pareto front in Figure 23 were optimal points and it is up to the decision makers to choose a point based on their objectives and constraints. In Figure 23 the leftmost points contain solutions with a large collector area compared to the right-hand side. The discon-
Results

Continuous behaviour on the Pareto front was caused by the change in the building heating demand.

The Pareto optimal point that was closer to the ideal point could be interpreted as the single optimal point. The ideal point was a theoretical point where both the objectives were at their minimum values (i.e. 25.9 kWh/m²/yr and 202 €/m²). The single optimal point was therefore point 77, shown in Figure 23. The corresponding values of the purchased electricity were 34 kWh/m²/yr and IC was 367 €/m² at this point on the Pareto front.

![Figure 23. Purchased energy vs investments of the non-dominated optimal solutions (Publication 3) (Rehman, et al., 2018).](image)

### 5.4.2 Analysis on the non-dominated solutions

The cost breakdown of the non-dominated optimised solutions is shown in Figure 24. The solutions on the left side were expensive solutions; on the other hand, solutions on the right side were the cheapest solutions.

Figure 24 show that the collector played a significant role in the investments. In the least-expensive solutions, a smaller collector area was selected as the cost of the collector was significant. However, the size of the collector area increased as the system performance improved by lowering the amount of purchased electricity.

Buildings with a higher heating demand were selected for the least expensive solutions, where the performance was the worst. However, as the performance improves (i.e. the purchased electricity decreased), the buildings with lower heating demand were selected. This again indicates that building performance can affect the energy system’s performance. Building was the cheapest option, and it also has a rather significant effect on energy system performance; therefore, the algorithm first changed the building design variable in optimal cases.
The warm tank’s volume also increased gradually as the investments increased, from right to left in Figure 24. This indicates that a large warm tank volume would improve the performance of the system as it allows more instantaneous availability of energy.

The left side of Figure 24 shows that a combination of a medium- to large-sized collector area, an energy-efficient building, a large warm tank volume and medium-sized BTES volume can improve the performance of the system. A combination of a small collector area, an energy-efficient building, a medium-sized warm tank, smaller BTES volume and a larger PV area can provide medium-range performance in the system. The building costs included all the building design variables, as detailed in Table 13.

![Figure 24](image)

**Figure 24.** The cost breakdown of the non-dominated optimal solutions and renewable energy fraction (red line) (Publication 3) (Rehman, et al., 2018).

#### 5.4.3 The influence of system failures and errors on an optimised system: A centralised solar district system in a Finnish context

Failures, issues and technical defects were mentioned in Section 4.4 of this thesis and are specified in Table 9. Some optimised system configurations were selected from Figures 23 and 24 for further analysis of the effect of non-ideal conditions on the performance of the proposed optimised system. From Figure 24, configuration numbers 1, 12, 55, 77, 96, 121 and 153 were chosen for a base case (an optimised case) in the following text and failure case analysis.

As explained in Section 4.4, the performance of the solar district heating system was sensitive to various technical parameters. The significance of these parameters can be different for varying systems. The most common parameters that can alter the system performance in real conditions were considered in this paper: (1) heat exchanger efficiency, (2) ST collector intercept efficiency, (3) tank stratification, (4) annual average heat pump COP, (5) SPH network temperature difference, (6) hot tank set points, (7) warm tank set points, (8) SPH supply temperature, (9) a ST circulation pump and (10) the thermal conductivity of a boreholes’ boundary.
For the base case, the parameters in Table 9 were considered to be the default values when the system was performing well. For the other cases, these ten parameters were altered in such a way that the system underperformed and its performance was compared against the base case. For reference, one case of failure (for instance, tank stratification) is discussed in more detail below. The results of other failure cases are summarized in Table 17.

**Tank stratification**

The buffer tanks were the most important part of the stratified thermal energy system. Stratification was a natural buoyancy process: the warmth and density of the water were inversely proportional. It was found that stratification allowed low-temperature working fluid to enter at the collector inlet, which increased its efficiency (Koppen, et al., 1979). Although stratified TES was inexpensive, there were still problems with low energy density and complexity in designing the storage tanks (Araner, 2016). Due to flow variations, the wrong internal tank design can cause the loss of stratification. In a stratified tank, the cold water enters the tanks from the bottom node, while hot water flows enter from the top node. In a mixed tank it was assumed that all the entry and exit nodes of the tanks were present at the top node of the tank.

In this study, the simulated tanks were divided into five equally spaced nodes vertically. The tank was designed in a way that the temperature variation and distribution between the top and bottom of the tank was 10°C in the stratified condition. In the failure case, the tank was assumed to be fully mixed and the results were compared with the stratified cases. In this case all the nodes were at the same node, with the same inlet and outlet.

The energy system was simulated for both the stratified and mixed conditions of the tanks, as shown in Figure 25. Due to the loss of stratification, the optimised points shifted in each case. Figure 25 shows that the selected optimal points of the base case (the blue points) shifted towards the right (the red points). This shift was due to the fact that the lowest temperature from the tank was unavailable for the collection of heat from the collectors. Moreover, due to mixing, the return temperature from the heating grid changed the whole tank temperature. This fault increased the purchased electricity from 25.9–49 kWh/m²/yr to 35–60 kWh/m²/yr. Therefore, Figure 25 shows the importance of the tank performance for the whole operation.

![Figure 25](image-url)  
**Figure 25.** Purchased electricity versus investments deviation caused by the mixing of water in thermal energy storage (Publication 3) (Rehman, et al., 2018).
Due to the high inlet temperature in the solar collector circuit, the efficiency of the collector was reduced. Figure 26 shows the reduction in the solar yield by the collector due to the high temperature in the collector circuit. Therefore, it was important to maintain the stratification in the tanks in order to provide a low temperature inside the collector circuit and to reduce the purchased electricity by collecting more solar energy. This low performance cuts the solar collector production by around 5%, as shown in Figure 26. Heat losses from the tanks, pipes and boreholes were also increased due to the high temperature and mixing in the tank. Moreover, during winters the return water from the SPH network was cold and the tank was not stratified. This water enters the top node of the tank or the single node of the tank. It causes mixing of the cold water with the whole hot tank; this result in an increase in the purchased electricity, caused by the heat pump and the backup heaters. The range of the renewable energy fraction was reduced from 65–90% (the base case) to 36–77%, as shown in Figure 26.

![Figure 26. ST yield and renewable energy fraction caused by the stratification issues (Publication 3) (Rehman, et al., 2018).](image)

Table 17 shows that the following factors have a greater effect on the overall system performance (ranging from the highest- to lowest-ranked deviations in purchased electricity): tank stratification, ST circulation pump setting (on/off), heat pump COP, solar collectors’ intercept efficiency, the BTES boundary layer’s thermal conductivity, the SPH inlet temperature set point and the hot tank charging set point.

Only the temperature change of the warm tank charging set point slightly improved the performance of the system. The charging set point of the warm tank was increased from 45°C to 50°C. This increase in performance due to the change in the warm tank charging set point was due to higher charging temperatures in the tank via the collector. This means that the warm tank can provide better preheating of the water used for SPH and DHW before it enters the hot tank for heating to final temperatures. This results in less consumption of electricity by the heat pump and the backup heaters. It was important to consider all these factors during the design and practical application of an ST district heating system. This result gives a better and deeper understanding of the effect of each individual design variable (including its failure) on system behaviour.
It was found that with one fault, depending on the optimal case on the Pareto front and its design variable combination, the deviation in the performance was non-linear. This can vary from the least-performing to highest-performing cases. For instance, in the case of failure of the ST collector pump’s circulation, the deviation in the performance from the ideal condition (the base case) varied because in each optimal case selected, the collector size varied. Therefore, in the cases where the collector area was large, the magnitude of deviation caused by pump control failure was large and when the collector area was small, the magnitude of deviation caused by pump control failure was small. In another example, an increase in the BTES boundary layer’s conductivity can slightly increase the solar yield, because of the availability of low-temperature working fluid caused by losses through the BTES boundary layer. However, it can reduce the performance of the system because of the increase in losses. All the extra collected energy from the collector was ultimately lost into the environment.

Overall Table 17 shows that the largest adverse impact was achieved by mixing the thermal stratification in the storage tanks to a uniform temperature. There was a 23–35% increase in purchased electricity. The second largest adverse impact was achieved by change in the ST circulation pump setting from variable to on/off control. There was a 1–22% increase in purchased electricity. Lastly, the third largest adverse impact was achieved by a reduction in the heat pump COP. There was a 7–21% increase in purchased electricity. The generic reasons behind such issues are discussed in detail in Sections 4.4 and 6.3 (in the discussion section).
Table 17. Overall summary of the defects in the technical parameters, and the deviations in system performance resulting from those defects (Publication 3) (Rehman, et al., 2018).

<table>
<thead>
<tr>
<th>Technical parameters</th>
<th>Values before defects</th>
<th>Values after defects</th>
<th>Increase in purchased electricity</th>
<th>Renewable energy fraction before defects (ideal conditions)</th>
<th>Renewable energy fraction after defects (non-ideal conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank stratification</td>
<td>Stratified</td>
<td>Mixed</td>
<td>23-34%</td>
<td>65-90%</td>
<td>36-77%</td>
</tr>
<tr>
<td>Solar thermal circulation pump</td>
<td>Variable pump circulation control</td>
<td>On/off pump circulation control</td>
<td>1-22%</td>
<td>65-90%</td>
<td>53-73%</td>
</tr>
<tr>
<td>Heat pump (COP)</td>
<td>5-6</td>
<td>3-4</td>
<td>7-21%</td>
<td>65-90%</td>
<td>48-85%</td>
</tr>
<tr>
<td>Solar collectors intercept efficiency</td>
<td>0.9</td>
<td>0.7</td>
<td>2-9%</td>
<td>65-90%</td>
<td>62-86%</td>
</tr>
<tr>
<td>Thermal conductivity of boreholes boundary layer</td>
<td>3.5 W/m.K</td>
<td>4.5 W/m.K</td>
<td>3-7%</td>
<td>65-90%</td>
<td>63-86%</td>
</tr>
<tr>
<td>SPH supply set point</td>
<td>40-30°C</td>
<td>50-40°C</td>
<td>2-6%</td>
<td>65-90%</td>
<td>61-87%</td>
</tr>
<tr>
<td>Hot tank set point</td>
<td>70°C</td>
<td>75°C</td>
<td>3-6%</td>
<td>65-90%</td>
<td>65-87%</td>
</tr>
<tr>
<td>SPH temperature difference</td>
<td>7-3°C</td>
<td>5-1°C</td>
<td>3-5%</td>
<td>65-90%</td>
<td>63-87%</td>
</tr>
<tr>
<td>Heat exchanger efficiency</td>
<td>0.9</td>
<td>0.7</td>
<td>3-4%</td>
<td>65-90%</td>
<td>52-83%</td>
</tr>
<tr>
<td>Warm tank set point</td>
<td>45°C</td>
<td>50°C</td>
<td>1-3% (slight improvement in performance)</td>
<td>65-90%</td>
<td>68%-89% (slight improvement in performance)</td>
</tr>
</tbody>
</table>

5.4.4 The influence of combined failures and their effect on the centralised energy system performance: The Finnish context

The main reasons for the deviation of the design variable from the base case can be the incorrect design of the control system, heating system equipment, maintenance issues, the malfunctioning of control devices and incorrect sizing of the HVAC and district network, as discussed in Section 4.4. It is possible that multiple issues exist at the same time. This could have a domino effect when one event sets off a chain of similar events. Therefore, the overall performance would be drastically reduced. These faults and defects caused a deviation in the value of purchased electricity of 150% compared to the base case, as shown in Figure 27. The blue points in Figure 27 were the base cases. The red points in Figure 27 were the failure cases.
5.5 Comparison between centralised and semi-decentralised solar district heating systems

5.5.1 Multi-objective optimisation of the centralised and semi-decentralised systems

In this section, the TRNSYS model of a centralised system (Energy System II) and decentralised system were selected for simulation. The centralised system consisted of two centralised short-term tanks operating at different temperature levels, charged by a solar collector and heat pump. BTES was also charged via these two centralised tanks. In contrast, the semi-decentralised system consisted of one centralised low-temperature tank charged by a solar collector and BTES and a decentralised high-temperature tank, charged by an individual heat pump in each house. In this case, BTES was only charged by the centralised warm tank.

Energy System II performed better in terms of purchased electricity, as analysed and explained in Section 5.3; therefore, the same design was further selected and optimised. The semi-decentralised system was the system that was explained briefly above and in detail in Section 2.3.6. Both the systems were optimised and compared based on the technical and economic criteria.

MOBO was combined with both the TRNSYS model of Energy System II (the centralised system) and the decentralised system in order to perform multi-objective optimisation. The two objectives that were minimised were purchased electricity and LCC.

The design variables and their corresponding prices, which were used for the optimisation, are shown in Table 18.
Table 18. System configuration variations for the simulations and investments cost of the component used in the energy system (Publication 4) (Rehman, et al., 2018).

<table>
<thead>
<tr>
<th>Design variables</th>
<th>Types of variables</th>
<th>System type</th>
<th>Alternative/Values</th>
<th>Prices (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST area (m²)</td>
<td>Continuous</td>
<td>Decentralised</td>
<td>50-6000</td>
<td>1000-550 €/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Centralised</td>
<td>500-6000</td>
<td>600-550 €/m²</td>
</tr>
<tr>
<td>PV area (m²)</td>
<td>Continuous</td>
<td>Decentralised</td>
<td>50-6000</td>
<td>450-200 €/m²</td>
</tr>
<tr>
<td>Hot tank volume /house (m³)</td>
<td>Continuous</td>
<td>Decentralised</td>
<td>0.5-5</td>
<td>900-810 €/m³</td>
</tr>
<tr>
<td>Warm tank (m³)</td>
<td>Continuous</td>
<td>Decentralised</td>
<td>1-5</td>
<td>850-810 €/m³</td>
</tr>
<tr>
<td>BTES aspect ratio</td>
<td>Continuous</td>
<td>Both systems</td>
<td>0.25-5</td>
<td>3 €/m² (excavation for insulation and piping)+ 33.5 €/m (drill)+ 88 €/m² (1.5 m thickness insulation)</td>
</tr>
<tr>
<td>BTES borehole density</td>
<td>Continuous</td>
<td>Both systems</td>
<td>0-05-0.25</td>
<td></td>
</tr>
<tr>
<td>BTES volume (m³)</td>
<td>Continuous</td>
<td>Both systems</td>
<td>10 000-70 000</td>
<td></td>
</tr>
<tr>
<td>Hot tank charge set points (°C)</td>
<td>Continuous</td>
<td>Decentralised</td>
<td>60-70°C (for heat pump)</td>
<td></td>
</tr>
<tr>
<td>Warm tank charge set points (°C)</td>
<td>Continuous</td>
<td>Both systems</td>
<td>50°C</td>
<td></td>
</tr>
<tr>
<td>Building heating demand, (kWh/m²/yr)</td>
<td>Discrete</td>
<td>Both systems</td>
<td>Type 1: heating demand = 25 kWh/m²/yr</td>
<td>156.28 €/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Type 2: heating demand = 37 kWh/m²/yr</td>
<td>132.60 €/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Type 3: heating demand = 50 kWh/m²/yr</td>
<td>126.55 €/m²</td>
</tr>
</tbody>
</table>

The relationship between the purchased electricity and the LCC of the non-dominated optimal solutions of both the centralised and semi-decentralised systems are shown in Figure 28. Figure 28 also shows the reference building case. The red points were for the centralised system and the blue points were for the decentralised system. The green point was the reference building case. In the reference case, neither seasonal storage nor solar generation were considered. Comparing the two fronts of the centralised and decentralised systems against the reference case, it was found that both the community-sized solar heating networks performs better in terms of the purchased electricity and LCC. This demonstrates that instead of investing in single building solutions, the focus should be on community-sized solar heating networks in order to have a lower LCC and better performance, as shown in Figure 28 (the green point).

In total there were 141 and 112 non-dominated solutions for centralised energy systems (the red points) and decentralised energy systems (the blue points) respectively in Figure 28. The solutions on the right side of Figure 28 were energy intensive, while the solutions of the left side were less energy consuming. The purchased electricity for the centralised system (the red points) varied between 46 kWh/m²/yr and 27 kWh/m²/yr, which corresponds to the LCC variance of 311 €/m² of floor area to 694 €/m² of floor area. On the other hand, the purchased electricity for the decentralised system (the blue points) varied between 40 kWh/m²/yr and 25 kWh/m²/yr, which corresponds to the LCC variance of 270 €/m² of floor area to 500 €/m² of floor area. All the red
points on the Pareto front in Figure 28 were optimal points and it is up to the
decision makers to choose a point based on their objective.

Figure 28 demonstrates that the resulting Pareto front in the decentralised
system was better than in the centralised system. The decentralised Pareto
front shows that this type of system can be implemented at a lower cost. How-
ever, the purchased electricity variations were more or less similar in both the
systems. The decentralised system performed slightly better in terms of pur-
chased electricity. In the decentralised system the cost of the system can be
reduced because the size of the components can be reduced. The renewable
energy fraction varied between 57 and 89% in the centralised system, and for
the decentralized system it varied between 75 and 92%.

![Graph](image)

**Figure 28.** Pareto front of the centralised and decentralised energy system (Publication 4) (Rehman, et al., 2018).

Certain irregularities can be observed in both the Pareto fronts in Figure 28.
There was a slight irregularity in Case 74 and Case 75, in the middle of the cen-
tralised system front (red points). This was caused by the reduction in the PV
area by 744 m² (i.e. from 5906 to 5162 m²). This sudden change in the PV area
corresponds to the price change of PV from 121 €/m² to 105 €/m², as shown in
Figure 29. All the other prices were more or less similar between Case 74 and
Case 75 in Figure 29, only the PV price changed drastically, caused by random
selections of NSGA-II. Similarly, in Figure 28 there is a small gap between
Case 41 and Case 42 in the decentralised system front (blue points). This was
caused by the decrease in the collector area from around 1000 m² to 450 m²,
causing a cost reduction in the collector area. This sudden decrease in the col-
lector area corresponds to the price change of the collector from 40 €/m² to 16
€/m², as shown in Figure 30. All the prices were similar in Case 41 and Case
42, only the collector’s price changed drastically. The irregularities in both the
optimisation fronts (blue and red points) in Figure 28 are explained in Figures
29 and 30. Figures 29 and 30 explain the weakness of NSGA-II when conti-
uous variables are used as design variables. In an ideal situation, the front
should be continuous (with no gaps).
Figure 29. Analysis on the irregularities in the centralised system Pareto front cause by the NSGA-II for multi-objective optimization (Publication 4) (Rehman, et al., 2018).

Figure 30. Analysis on the irregularities in the decentralised system Pareto front cause by the NSGA-II for multi-objective optimization (Publication 4) (Rehman, et al., 2018).

5.5.2 The influence of the system designs on various design variables

Various design variables considered in this study (as detailed in Table 18) were further analysed in order to provide insight into each design variable and into the impact of system design on each design variable. In results analysis for each of the design variables, the centralised system design variables are explained first and the decentralised system design variables are explained last.

Figure 31 shows the ST area design variable. Figure 31a depicts the centralised system and Figure 31b depicts the decentralised system. Both the figures are explained in the same order.

The collector area for the centralised system (Figure 31a) shows that the collector area was 500 m² in 30% of the cases. The other 70% was of an increas-
ing order, ranging from a medium- to large-sized collector area. This indicated that a large ST area was beneficial in a centralised system. Among the design variables, the ST area was the highest contributor to varying the LCC and the purchased electricity (depicted in the next figure, Figure 32). This was because the 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 centralised system the collector was used to charge the hot tank and warm tank to higher temperatures, the large collector was selected in the best performing cases.

The collector area for the decentralised system (Figure 31b) shows the collector area was 50 m² (0.5 m²/m² building area) in 50% of the cases. The other 50% was of an increasing order, ranging from a small to medium-sized collector area. This indicated that a large collector was selected in the best performing cases.

Both systems show that the collector area increased as the performance improved and that the collector played as important role in system performance. A large collector area tends to collect a large amount of heat energy from the environment. Therefore, a large collector area also reduces the purchased electricity. However, for the centralised system, the increase in the collector area can be seen to start earlier, compared to the decentralised system, as optimisation progresses from left to right in Figures 31a and 31b. Moreover, the largest collector area in the best performance case (Case 1) for both systems was 5400 m² and 3000 m² for the centralised and decentralised systems respectively.

![Figure 31. ST collector area (a) centralised and (b) decentralised in the non-dominated optimal solutions (Publication 4) (Rehman, et al., 2018).](image)

The change rate of the purchased electricity with respect to the change in the collector area was estimated in Figure 32. The collector was the main source of energy and the most expensive component of the system; therefore, the impact on the change rate of the purchased electricity was estimated for both the centralised system and decentralised system. To evaluate both the systems, only the collector area was changed in both the energy systems, while other parameters were kept 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 32. It was found that by increasing the collector area from 500 m² to 4000 m², the reduction of purchased energy was around 17% in the centralised system and by increasing the collector area from
500 m² to 4000 m², the reduction of purchased energy was around 12% in the decentralised system. This shows that in centralised system, a large collector area has a larger impact on the purchased electricity. The cost functions in both the systems varied by 34% due to the increase in the size and the corresponding cost of the collector.

![Graph showing the comparison between centralised and decentralised systems in terms of purchased electricity and life cycle cost per building floor area.](image)

**Figure 32.** Sensitivity of the purchased electricity and cost function between centralised and decentralised system as function of solar collector area thermal collector area (Publication 4) (Rehman, et al., 2018).

It was found that for the PV panels, the NSGA-II selected large area of panels for both the centralised and decentralised systems, as shown in Figure 33. This was because the costs of the PV panels were less compared to the collector and this affects the overall system performance. However, in the decentralised system, around 6000 m² of panel area were selected in the majority of the optimal cases (Figure 33b) compared to centralised system (Figure 33a) where the maximum size of the panels in the majority of the cases was slightly less than 6000 m² (i.e. around 5800 m²).

![Graph showing the comparison between centralised and decentralised systems in terms of photovoltaic panels area.](image)

**Figure 33.** Photovoltaic panels area (a) centralised and (b) decentralised in the non-dominated optimal solutions (Publication 4) (Rehman, et al., 2018).
The volume of the BTES increases as the performance of the system improves, as shown in Figure 34. Figure 34a depicts the centralised system and Figure 34b depicts the decentralised system. The corresponding red lines show the collector area. It can be observed that as the collector area increases, the corresponding BTES volume also increases. In the centralised system, the maximum BTES volume was around 38,000 m³, whereas in the decentralised system the maximum BTES volume was around 10,700 m³.

Figure 34. Seasonal storage volumes and collector areas (a) centralised and (b) decentralised in the non-dominated optimal solutions (Publication 4) (Rehman, et al., 2018).

Figure 35 shows the depth of the boreholes, the number of boreholes and the corresponding collector area. Figure 35a is for the centralised system and Figure 35b is for the decentralised system. Figure 35a and Figure 35b are explained in the same order.

The depth of the boreholes, the number of boreholes and the corresponding collector area in the centralised system (Figure 35a) show that the seasonal storage was deeper than it was wide when the system performance was poor (in Case 141). In the cases where the BTES volume was small (Figure 35a, Case 141), the height of the BTES was greater, as shown in Figure 35a. On the other hand, in the cases where the BTES volume was large (Figure 35a, Case 1), the height of the BTES was less, as shown in Figure 35a. In the worst performing cases, the depth of the boreholes was greater because this increases the heat transfer through the sides of the storage. The depth of the boreholes was also relative to the area of the ST collector. When the solar collector area was less, the depth of the boreholes was more. Performance improvement was related to the increase in the ST collector area, a decrease in the depth of the boreholes and an increase in the width of the BTES, as shown in Case 1 of Figure 35a. The BTES was only insulated from the top, hence wider storage was 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 boreholes, the number of boreholes and the corresponding collector area for the decentralised system (Figure 35b) shows that the seasonal storage was deeper than it was wide when the system performance was poor (in Case 112). The behaviour and the relation between the borehole depths, borehole storage volume and collector area were similar to those explained in the centralised system above. When the solar collector area was less, the depth of the boreholes was greater, as shown in Figure 35b (Case 112). When the col-
lector area was less, the injected energy was less, and hence there was no need for large seasonal storage. Moreover, with a greater depth, the BTES was naturally charged from its surroundings. The performance of the system improved when the depth was reduced and the collector area increased from Case 112 side to Case 1 in Figure 35b, along with the borehole storage volume (Figure 34b).

In addition to the borehole depth and collector area, it can be observed in Figure 35a and 35b that with a wider shape, more boreholes can be added to the storage as can be seen by comparing Case 1 to Case 141 in Figure 35a and Case 1 to Case 112 in Figure 35b. In both energy systems, the number of boreholes increased with the increase in the performance in both Case 141 and Case 112 compared to Cases 1. The increase in performance was caused by the increase in the solar collector area and number of boreholes. However, the height of the borehole decreases, as shown in Case 1 in Figure 35a and 35b. Therefore, it implies that higher performance was achieved by having many shallow boreholes over a wide area compared to having fewer, deeper boreholes over a narrow area. The temperature gradient also improves by having many boreholes over a wide area. In all the cases the BTES was insulated from the top. In the centralised system the depth of the borehole changes from around 80 m to 30 m. In the decentralised system the depth of the borehole changes from 68 m to 45 m, and then to 20 m. This was because the size of the collector area increases quickly compared to decentralised system. Additionally, in the centralised system, the size of the collector area was relatively large compared to the decentralised system, therefore it resulted in a larger number of boreholes in the centralised system.

![Figure 35](image.png)

**Figure 35.** Borehole length (single hole), number of boreholes and corresponding collector area (a) centralised and (b) decentralised in the non-dominated optimal solutions for all buildings (Publication 4). Red bars are the depth of each borehole, blue bars are the number of the boreholes and green line is the corresponding collector area (Publication 4) (Rehman, et al., 2018).

For the tank charging set points, there was no clear trend in the set point design variable’s value in either a decreasing or increasing order that corresponds to a change in the performance or LCC. The charging set points’ values
for both the hot and warm tanks in both the centralised and decentralised energy systems were distributed randomly.

When the values of the set points for both the warm and hot tanks in the centralised and decentralised energy systems were arranged based on the frequency of the value, the frequency shows that increasing the charging set point of the warm tank from the existing 45°C to around 47–50°C allows the storage of more solar energy. As for the hot tank’s charging set point, when the hot tank was charged via the collector (in the centralised system), algorithm proposed increasing the charging set point from 71°C to 71–73°C. However, when the hot tank was charged via the heat pump (in the decentralised system), algorithm proposed decreasing the charging set point from 65°C to 60–63°C in the majority of the cases.

The set points of the short-term storage tanks, charged via the collector and heat pump, were also used as design variables. Generally it was found that when short-term tanks were charged by the collector, a higher set point is favourable for increasing the renewable energy fraction. This also improves the system performance by reducing the purchased electricity. It helps in charging the borehole to higher temperatures, thereby reducing the electricity consumption of the heat pump and backup heaters. For instance, the warm tank charging set point for the reference system (the decentralised system) is shown in Figure 36. It shows that the majority of the set point values were in the range of 44–47°C, compared to the 45°C of the reference. On the other hand, it was found that when short-term tanks were charged by the heat pump, a lower set point was favourable. This allows reducing the overall energy consumption of the heat pump in order to meet the lower set point target. This improved the system performance by reducing the purchased electricity. For instance, the hot tank charging set point for the reference system (the decentralised system) is shown in Figure 37. It shows that the majority of the set point values were in the range of 60–63°C, compared to the 65°C of the reference. Therefore, the set points values change with respect to the energy system typology. Figures 36 and 37 show the importance of the set points as design variables. These design variables might have an insignificant direct impact on the investments. However, they can have a significant effect on system performance and operational costs.
5HVXOWV

\( \text{Figure 36. Warm tank charging set point frequency for decentralised system in the non-dominated optimal solutions (Publication 4) (Rehman, et al., 2018).} \)

\( \text{Figure 37. Hot tank charging set point frequency for decentralised system in the non-dominated optimal solutions (Publication 4) (Rehman, et al., 2018).} \)

5.5.3 The sensitivity of the systems with respect to electricity and components prices

The sensitivity of the optimised systems was carried out with respect to the key economical parameters, for instance electricity, PV panels and collector prices. In the future, it is assumed that electricity prices may increase in line with the global trend (Peak oil news, 2013). The prices of the PV panels and collector may be reduced in the future as a result of increased competitiveness in the market, in turn caused by the increase in the demand and supply of these components (Sanchez, 2012). In both the centralised and decentralised systems, the electricity price was assumed to increase by 25%, the PV panels and collector prices were assumed to decrease by 25%. These values were used to estimate the sensitivity of the optimised systems to the prices.

As a reference, Figure 38 shows the sensitivity of the optimised centralised system with respect to electricity, PV panels and collector prices. It can be ob-
erved that with the increase in the electricity price, the LCC of the system increased, making the system less economical. The Pareto front was more sensitive to the electricity price (the brown line in Figure 38) in the worst performing case (Case 141), where purchased electricity was large. The front was more sensitive to the component prices (the purple and green lines in Figure 38) in the best performing case (Case 1), where component sizes were relatively large compared to the worst performing case.

It was observed that with the 25% increase in the electricity price, the reference Pareto front moves (the red line in Figure 38), forming a new front (the brown line in Figure 38). This change causes a 2–8% (Case 1 to Case 141) increase in the LCC with respect to the reference line. With an increase in the PV price of 25%, the Pareto front moves to form a new front (the green line in Figure 38). This change causes a 1–4% decrease in the LCC with respect to the reference line. The increase in the collector price of 25% also moves the Pareto front to form a new front (the blue line in Figure 38). This change causes a 2–11% decrease in the LCC with respect to the reference line.

Two phenomena were observed in Figure 38. First it was found that in the worst performing case (Case 141) the increase in the electricity price causes a larger change in the front compared to the best performing case (Case 1). This was because in the worst performing case the purchased electricity was large and any change in the electricity price also had a large impact on the LCC compared to the best performing case where the purchased electricity was less. This shows that in the best performing case, even if the electricity price fluctuates, there will be less impact on the LCC. Therefore, the benefits of the best case were that the LCC changed insignificantly, even if the electricity price became higher, so the operational cost is similar to that expected. Secondly, in the PV price (the green line in Figure 38) and collector price (the purple line in Figure 38) it was noted that the change in the LCC was relative to the sizes of the PV panels and collector. Solutions close to the worst performing case (Case 141) has smaller PV panels and collector, therefore the purple and green lines were close to the red reference line. In these cases, a reduction in the collector and PV panels prices has less impact on the LCC. The solutions close to the high performing case (Case 1) have a large collector and PV area, resulting in more deviation from the red reference line. Therefore, in the best performing case, if any tax or subsidies were provided, the LCC was reduced.
5.6 A summary of the results

The results of the study in Publication 1 showed that different control strategies within the same energy system architecture can affect the technical performance of the system. The study showed that the temperature difference control of the collector reduced the total electricity demand of the system by around 20% when the warm tank was chosen as the priority tank for both the series, automatic and parallel controls. Hence, the temperature difference control with either a parallel or automatic control was recommended for such systems.

The results of the study in Publication 2 showed that at the system level, when a heat pump was connected between two tanks and using charged borehole storage to directly charge the lower temperature tank (Energy System II), the renewable energy fraction of 81% can be achieved when compared to the Energy System III where two heat pumps were used in series, one between the tanks and the other between the lower temperature tank and the ground, and where the ground was not charged via solar energy. In such Energy System III a renewable energy fraction of 64% can be achieved. Furthermore, heating demand can also vary the performance of the system.

The results of the study in Publication 3 showed that different failures and technical issues can vary the techno-economic performance of an optimised energy system. The results showed that the largest adverse impact was caused by thermal stratification issues in the storage tanks; this issue can increase the purchased electricity by 23–35% compared to the reference optimised case. The second largest adverse impact was caused by the on/off control setting of the ST circulation pump setting; this issue can increase the purchased electricity by 1–22% compared to the optimised reference case.

The results of the study in Publication 4 compared and showed two different energy system typologies (i.e. centralised and semi-decentralised systems). It was found that by decentralisation of the energy system, the cost of the energy system can be reduced by 35% in best performing cases compared to a completely centralised system, and at the same time, high technical performance.
can be achieved. Optimal sizes of the design variables also changed due to the change in the architectures. Therefore, for every case, optimisation was essential in order to reach optimal results.
6. Discussion

6.1 Comparison between the system typologies, control strategies and design variables

Several different energy configurations and architectures are proposed in the thesis. The main sub-systems needed in order to construct a community-sized solar district network are: an ST collector, PV panels, short-term storage tanks, seasonal storage, heat pumps, a distribution network and the technical systems of buildings. By combining all these sub-systems in optimal ways and with optimal methods, a high renewable energy fraction is possible.

The energy systems have four important factors that need to be addressed from the beginning, which are as follows:

1) System control strategies
2) The energy system typology
3) The energy demand and technical systems of buildings
4) The importance of design variables (physical and control design variables)

6.1.1 The importance of the system control strategies

The controls of each sub-system have a significant influence on the total performance of the whole energy system. Without a proper control system, a system is unable to perform well and efficiently. Solar energy has an intermediate characteristic, and to resolve such issue, a proper control strategy is needed. In a conventional energy system, generation and demand are matched. If the demand increases, the generation increases and if the demand decreases, the generation decreases. It is found that two important and basic controls are required to operate the systems properly. These are following:

- A tank charging mode for the warm and hot tank
- A solar collector outlet control

A tank charging mode is a control which controls the series or parallel charging of the tanks charging via solar thermal energy. In series mode, the collector always charges the hot tank first and then the remaining energy goes to the warm tank. In parallel mode, the collector charges either the hot or the warm tank when needed. As solar energy is the main source of free energy, an outlet temperature control is necessary in order to attain certain operating temperatures of the tanks and the circuit. Both the tanks operate at different temperature levels, therefore it is important to have a good working control so that,
firstly, the tanks do not cool down and, secondly, the collector performance is not reduced. In series mode, the collector has to charge the hot tank each time when the tank needs charging, even during low radiation periods, and this may reduce the collector efficiency. Therefore, the study shows that having parallel/automatic controls for the tanks and a temperature difference control for the collector can improve the performance of the system.

6.1.2 The importance of the energy system typologies

The energy system configuration and typology can affect the performance of the system. In the present study it was found that different energy systems had different techno-economic performance. Table 19 shows the comparison between the different typologies that are considered in this thesis. A single building as a reference case shows that a single building solution may not be cost effective. A typical building in Finnish conditions might end up being more expensive and highly energy intensive. Current practices in the Finnish market, where each building is integrated with a heat pump, might be an unfeasible solution in terms of both sustainability and cost. Therefore, to reduce the overall cost and to gain the benefits of storage and sharing, a community-scale solar district system is necessary, as shown in Table 19. Furthermore, within the community-scale solar district network, a semi-decentralised system is the best strategy for achieving a better techno-economic solution.

The Table 19 shows the three main categories of the systems. These categories can broadly divide systems based on major differences among them. These categories are: a centralised system with no charging of seasonal storage, a centralised system with solar charging of BTES and a decentralised system with solar charging of BTES. All three categories are discussed briefly.

Table 19. Comparison of the proposed ST district heating systems (Publication 1, 2, 3 and 4).

<table>
<thead>
<tr>
<th>Energy systems</th>
<th>System types</th>
<th>Purchased electricity (kWh/m²/yr)</th>
<th>Life cycle cost (€/m²)- including building+energy system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Building</td>
<td>Reference</td>
<td>98</td>
<td>684</td>
</tr>
<tr>
<td>Energy system with heat pump between solar charged BTES and tanks</td>
<td>Centralised with BTES charging</td>
<td>47-29</td>
<td>400-800</td>
</tr>
<tr>
<td>Energy system with heat pump between tanks only, with solar charged BTES</td>
<td>Centralised with BTES charging</td>
<td>50-26</td>
<td>311-694</td>
</tr>
<tr>
<td>Energy system with heat pumps between tanks and between ground and warm tank</td>
<td>Centralised with no seasonal charging</td>
<td>63-39</td>
<td>400-680</td>
</tr>
<tr>
<td>Energy system with distributed DHW and heat pump between tanks and solar charged BTES</td>
<td>Decentralised with BTES charging</td>
<td>40-25</td>
<td>270-500</td>
</tr>
</tbody>
</table>
Firstly, it is observed that when seasonal storage is not charged with solar energy, the system performance is rather poor compared to the systems where seasonal storage is utilised in Table 19. In an energy system where BTES are not charged, the technical performance is poor. This occurs because heat pump energy consumption increases when the temperature on the evaporator side is less. In this system, there are two heat pumps connected as a cascade. One heat pump is connected with the BHE, which is not charged via solar energy during summer. The other heat pump is connected between the two short-term storage tanks operating at different temperature levels. Since the first heat pump is connected with the ground, this can cause cooling of the ground. This causes the reduction of the COP from 6–4 to 1–2 (Rehman, et al., 2017). To charge the warm tank, the heat pump takes energy from the ground; this causes cooling of the ground. Since the ground is not charged by ST energy, the ground temperature reduces. This may cause issues in heat pump performance and it can also cause thermal imbalances in soil in seasonal storage. It is also discussed by You et al. (You, et al., 2016) and a similar phenomenon is observed in the proposed system. In such a setup it is found and recommended that a very large volume and depth are needed for the boreholes in order to charge the seasonal storage naturally from its surroundings. Large depths allow a greater contact area with the surroundings, hence balancing the natural charging and discharging of the boreholes. This may require larger investments for the drilling and piping of the BTES. Therefore, it is recommended to charge the ground with excess solar energy, especially during summers.

Secondly, the centralised system with solar charging of the BTES performed better than the centralised system that did not charge the BTES. In this setup two configurations are proposed. In the first configuration the heat pump is between the seasonal storage and the short-term storage tanks. In the second configuration the heat pump is between the short-term storage tanks. In general, both the systems are better solutions compared to the system where seasonal storage is not charged. It is observed that when the heat pump is placed between the short-term tanks, the purchased electricity was reduced compared to the system where the heat pump is between the seasonal storage and the short-term storage tanks. In this strategy the heat pump takes energy from the warm tank and heats the hot tank during low solar radiation periods. This strategy allows the heat pump to have a stable evaporator temperature of 35–40°C at the source inlet. In the other system the heat pump has to charge both the warm and hot tanks to different temperatures while taking energy from the BTES. BTES usual operates at lower temperatures and the losses are high as well. Hence it reduced the heat pump performance, resulting in a higher amount of purchased electricity from the grid. Therefore, in the Finnish context, centralised systems with BTES charging are better in terms of performance and costs.

Lastly, the semi-decentralised system with solar charging of the BTES clearly outperformed the centralised system with solar charging of the BTES. In this setup the centralised section of the energy system consists of the ST collector,
PV panels, seasonal storage and the warm tank, whereas the decentralised section of the energy system consists of a heat pump and hot tank in each house. In this setup, the central collector only charges the warm tank and the seasonal storage; the decentralised hot tank is charged by the heat pump. It is found that when the high temperature network is decentralised and the hot tank is placed inside the house instead of in the central energy centre, this allowed reducing the losses from the network. In addition to this, it was also revealed that in the decentralised system the area of the collector can be reduced as it is only needed to charge the warm tank to lower temperatures. In this system, the BTES is only charged via the warm tank, compared to the centralised system where BTES is charged via both the hot and warm tanks. This reduced the losses from the BTES compared to the centralised system where the boreholes are charged to higher temperatures. Therefore these are the main reasons why the decentralised system performed in a more or less similar manner to the complete centralised system, but at lower cost. Hence, it is recommended to charge the BTES and utilise a decentralised system in order to reduce the cost of the system, while at the same time achieve higher technical performance. Similar findings were found in Germany, where the Danish centralised concept was compared to a newly proposed community system in Germany (Best, et al., 2017). The community in Germany consisted of 131 buildings with a total area of 115 000 m². It was shown that the decentralised system had lower losses and was more economical. It is possible to use a completely PV-based decentralised system instead of the collector-based decentralised system. A similar semi-decentralised system can be used, wherein the collector is replaced by the PV panels. The electricity generated by the PV panels can be supplied to the heat pump directly. This heat pump can convert the electricity into heat energy and charge the short-term storage tanks as well the seasonal storage.

The techno-economic performance of the solar district heating network can be increased by semi-decentralisation. The low-temperature network can be centralised, which can operate at up to 40°C outside, while the high-temperature network can be decentralised, which can operate at up to 60°C inside the building. Inside each building the final temperature (up to 60°C) can be reached based on the individual demand of the building. This system could provide an individual owner of the house with a sense of control regarding her or his choice and decisions. It is assumed that all the buildings are built at the same time and are new buildings. The individual could control his or her set points according to his or her desire and comfort. This energy architecture would also reduce the cost of the system as a smaller surface area of the collector is needed to meet the demand. The collector is the most expensive component of the solar community, therefore its size affects the overall feasibility of the system.

6.1.3 The importance of the building’s design

All the above-mentioned factors are significant when designing a solar district heating network in a challenging environment. Another important factor is
formed of the buildings in the community. In most of the cases and in previous studies (Bauer, et al., 2010; T.Schmidt, et al., 2004; Lundh & Dalenbäck, 2008), it has been found that an energy system has been designed by different bodies to those who have designed the building. However, to successfully integrate such systems the hourly demand has to be estimated precisely. It was found that buildings can contribute to reducing the purchased electricity, as shown in the results of the thesis. In most of the high-performing cases, high-efficiency building solutions are selected in the model and optimisations. Therefore, to make such a solar district heating network feasible in Nordic conditions, the building has to be designed with a lower heating demand. The lower the demand, the higher the renewable energy fraction and performance are for the energy system. The limiting factor is of course the cost of the technical solutions. This may prevent customers from investing in more energy-efficient buildings. Both the LCCs and the efficiency of the building need to be considered while designing such systems.

In the present study 100 buildings were considered in the community. However, it is also estimated that larger communities would provide noticeable cost benefits when aiming for high performance. Communities with 500 buildings can achieve a 90% renewable energy fraction with 20% less cost in Finnish conditions. This is caused by large seasonal storages in large communities that allow more direct utilisation of seasonally stored heat (Hirvonen, et al., 2018). Therefore it is important to consider the size of the community and the building performance. Moreover, building utilisation and purpose can also influence the performance of such systems. Public buildings like schools, universities and hospitals etc. may vary the solar fraction because of the varying energy demand of such kinds of building.

6.1.4 The importance of the design variables

It is proposed that these generic combinations are used to achieve a certain level of performance at a certain cost. In this study, the collector area of 0.05–0.35 m²/m², floor area and a BTES volume of 1–4 m³/m², floor area are proposed in most of the optimised cases. Additionally, it is proposed that buildings have a heating demand of 25 kWh/m²/yr in most of the optimised cases.

Another important design variable is the depth and the number of boreholes, and borehole density, as these can play an important role in the overall design and performance of the system. It is observed that, in the worst-performing cases, the depth of the boreholes is greater and the numbers of boreholes are fewer. On the one hand, in the high-performing cases, the depth of the boreholes is less and the numbers of boreholes are higher. 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. Therefore, it implies that higher performance is achieved by having many shallow boreholes over 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. In general, a borehole depth of 20–80 m, and a number of boreholes between 15 and 250 are proposed in most of
the optimised cases in Finnish conditions. All the above-mentioned values depend on the system typology. This behaviour may also change when a different type of seasonal storage is used instead of BTES.

The set points of the short-term storage tanks charged via the collector and the heat pump are used as design variables. The results showed that when the short-term tanks are charged by the collectors, the charging set points increased compared to the reference points. On the other hand, when the tanks are charged by the heat pump, the optimisation results showed a higher frequency of set points at lower values compared to the reference points. This means that in order to improve the technical performance, as well as LCC, the system control strategy has to be designed in a smarter way. The energy system set points needs to be adjusted in a way that can accommodate, utilise and store more of the free available energy (i.e. the solar energy). This methodology would allow reducing the dependency on the grid and would also improve the renewable energy fraction.

6.2 Practical implications

The seasonal mismatch between the generation from renewable energy systems and demand makes solar district energy systems infeasible in Nordic conditions without seasonal storage. A solar district network with high renewable energy fractions can be built in Finland. However, to reach such high fractions, thermal storage is necessary. Thermal storage can be used to utilise on-site energy; however, heat losses are high. A large community energy system can benefit from the economy of scale and less losses (as losses are inversely related to the size of the system). In order to validate the performance of the community as simulated and to make the prices more competitive, practical experience is needed. Companies should actively participate in developing such a community concept in Finland. Land development by the government should be focused on this in the future so that private companies can invest and build renewable communities. Due to many benefits in terms of performance and economy of scale, companies should invest in pilot projects and, at the same time, be supported by the government. This would also help to reduce the prices of the components further due to demand and supply law. Lower pricing would also attract customers who are otherwise less interested in such costly solutions. Instead of selling individual renewable energy systems to each customer – like collectors and PV panels for meeting building heating and electricity demand – the focus of the future businesses and companies should be on new renewable communities in which buildings have shared energy generation, storage, distribution and controls.

A feed-in tariff can provide a good incentive to the communities to build solar district heating systems. At the moment the feed-in tariff (Energy Authority, 2018) benefit is unavailable for solar-based systems in Finland, partly due to legislation issues and energy company policies. The disadvantage of a feed-in tariff is that it only increases the deployment of renewable energy systems. On the other hand, it can reduce the motivation for self-consumption,
storage and efficiency that can cause fluctuations in the grid. Therefore, a mechanism and policy should be made in order to reduce excess renewable energy system installation and inefficiencies.

The focus should be on storage of energy in order to avoid oversizing, undersizing or the shifting issues of fluctuations to the grid. It is least beneficial to either waste the renewable energy, by dumping it, or to sell it to the grid at either a lower cost or at the time when grid is already saturated. The economical use of the renewable energy system is achieved by maximizing self-consumption. The support mechanism should be designed in a way it promotes new nearly zero-energy communities (nZECs). These communities should be supported via a mechanism on the basis of renewable energy installation, energy storage installation and energy efficiency considered together. Furthermore, the challenge lies with already built areas and how to connect existing areas with new renewable-based district heating systems so that it is technically and economically feasible. The study of this issue may need further analysis as well.

Renewable energy in the grid can cause price fluctuations. Thermal storage allows levelling out these fluctuations. During solar peak generation, most of the energy is provided via solar energy and during the low solar peak and high demand, most of the energy is provided via storage. In Finland, due to the seasonal mismatch between the demand and supply, short-term storage utilisation is limited. During summer, Finnish energy generation has relatively low emissions due to the use of nuclear power. The profile of emissions of electricity and district heating are quite different. However, during the winter season, when the heating demand is quite high, the overall emissions are also quite high as most of the demand is met by fossil fuels. This causes the Finnish district network for buildings to be one of the greatest contributors to CO₂ emissions in Finland (Statistics Finland, 2016). In order to reduce the emissions, especially during winters, renewable energy is needed. Solar energy can help in reducing these emissions and meeting the emission reduction goals. Much less solar energy is available during winters in Finland. Therefore, seasonal thermal storage, integrated with ST generation and a heat pump for heating the buildings, would reduce the energy demand in the winter. This would ultimately reduce the emissions during the winter. Seasonal storages are one of the significant components needed in order to achieve both carbon-neutral societies and urban areas.

Electricity or heat energy can both be stored for a seasonal period, depending on the size and technology of the storage. Usually electricity is stored in electrical batteries and thermal energy is stored in tanks. It was found that batteries are more expensive than thermal energy, as shown in Table 20. The cheapest solution is sensible storage.
Table 20. Cost of the energy storage component (International Renewable Energy Agency (IRENA), 2013; D’Aprile, et al., 2016).

<table>
<thead>
<tr>
<th>Thermal energy storage system</th>
<th>Cost (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible (hot water)</td>
<td>0.1-10</td>
</tr>
<tr>
<td>PCM (Phase change material)</td>
<td>15-50</td>
</tr>
<tr>
<td>Chemical reactions</td>
<td>8-100</td>
</tr>
<tr>
<td>Batteries</td>
<td>400-450</td>
</tr>
</tbody>
</table>

Some of the estimated reference prices of different sensible storage technologies are shown in Table 21. It shows that tank TES is the cheapest option. But it is difficult to store energy for a long time in insulated tanks. Therefore, the alternative is BTES. It is lower in cost and it is flexible in terms of its installation. Therefore, boreholes are selected for seasonal storage in this thesis. BTESs are underdeveloped concept for seasonal storage. It has been proposed and experimented with in some pilot projects around the world, namely in Canada and Germany (Sibbitt, et al., 2011; T.Schmidt, et al., 2004). The average BTES efficiency in the present study is around 40%. An experimental setup is needed in order to estimate the performance of the borehole storage when integrated with solar energy and district heating in Finland. It is also possible to have combi-storage, wherein two technologies can be combined to reduce the losses from the storage.

Table 21. Cost of different storages (Honkonen, 2016)

<table>
<thead>
<tr>
<th>Thermal energy storage system</th>
<th>Cost (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank thermal energy storage</td>
<td>167.19</td>
</tr>
<tr>
<td>Pit thermal energy storage</td>
<td>96.22</td>
</tr>
<tr>
<td>Borehole thermal energy storage</td>
<td>0.06-2</td>
</tr>
<tr>
<td>Aquifer thermal energy storage</td>
<td>8.55</td>
</tr>
<tr>
<td>Caravan thermal energy storage asp</td>
<td>41.46</td>
</tr>
</tbody>
</table>

It is important to promote such a solar-based district network concept in Finnish society. Traditionally it is believed that solar technology, especially ST energy, may not work optimally in local conditions due to the mismatch and cold climate. However, if the correct solar energy concept is promoted logically by the researchers, media and companies, along with governmental support, society can change its attitudes towards solar energy. The myth regarding solar energy application in Finland can be fragmented and society will accept and build its communities based on solar energy. Lastly, the heat price for the end user has to be decided upon; the question is whether the cost of the heat should be similar to the district network price of around 60–80 €/MWh (Helen Oy, 2017) or if it should be cheaper. The pricing for heat may be a strong driving force to attract people to choose such a concept.
6.3 Failures, errors and sensitivity issues with solar district systems

The technical issues and failures discussed in the thesis are all real issues that are reported in the studies and publications. In many European and North American projects, it has been found that there is some discrepancy in the estimated and real operation. This discrepancy occurs in the projects because, during the designing and simulation phase, it is usually difficult to predict the technical issues a project can face in a real environment. This leads to the underperformance of a solar district heating network compared to what was predicted and designed. Interestingly, many issues that are mentioned in the publications from different parts of the world had quite similar issues. Some of the common issues are a higher net temperature in the district network, the higher energy demand of the buildings than the demand for which the system was designed, lower collector efficiency, tank stratification issues, pumping control issues, higher losses from the storage than the losses for which the system was designed etc. (Dalenbäck, 2005; Bauer, et al., 2010; Schmidt, et al., 2004; Sibbitt, et al., 2012). However, in most of the publications, the failures and performance data are just mentioned qualitatively and quantitative discussions are less detailed. These quantitative data could provide an insight to the issues related to the components and the behaviour of the components in the system under such conditions.

It is also found that in many projects (Bauer, et al., 2010; Haahtela & Kiiras, 2013), the correct sizing of the components is of significant importance before constructing a plant. Either the size of the collectors, tanks or the building demands have been underestimated or overestimated. This has ended up in either the lower generation of heat energy from the collector, the lower energy storage capacity of the tanks or higher demands from the building. Due to this incorrect sizing, many projects that are built are found to underperform. Hence it can be concluded that optimisation of the whole system is necessary.

The comparison between the estimated and measured performance of some the projects is shown in Table 22.

<table>
<thead>
<tr>
<th>Plant name</th>
<th>Year</th>
<th>Estimated solar fraction</th>
<th>Measured solar fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friedrichshafen</td>
<td>1996</td>
<td>43%</td>
<td>21-33%</td>
</tr>
<tr>
<td>Neckarsulm</td>
<td>1997</td>
<td>50%</td>
<td>18-44%</td>
</tr>
<tr>
<td>Rostock</td>
<td>2000</td>
<td>62%</td>
<td>32-56%</td>
</tr>
<tr>
<td>Eko-Vilikki</td>
<td>2004</td>
<td>20-25%</td>
<td>8-10%</td>
</tr>
<tr>
<td>Attenkirchen</td>
<td>2005</td>
<td>50%</td>
<td>40%</td>
</tr>
<tr>
<td>Eggenstein</td>
<td>2008</td>
<td>40%</td>
<td>No results yet</td>
</tr>
</tbody>
</table>

In general, the performance of the system is sensitive to various technical parameters, as explained earlier. In addition, the significance and nature of these parameters can be different for varying systems. A brief discussion follows on the different technical issues that can occur in these energy systems.
It is found that heat exchanger efficiency affects the overall performance of the system. The fouling of the heat exchanger surface leads to a reduction in the transfer of solar heat from the solar network to the tanks and from the tanks to the district heating network. This causes very high temperatures in the collector circuit and thus reduced collector performance. Therefore, the proper sizing and cleaning of the heat exchanger is necessary in order to avoid such issues.

The efficiency of the solar collectors varies depending on the solar radiation, outside temperature and collector fluid temperature (Build it Solar-the renewable energy site for do it yourself, 2007). The common reasons for the performance degradation are fouling inside the collector, dirt accumulation on the surface, trapped air (air lock) in the collector and the ageing of the collector. Therefore, cleaning of the surface, oxidization of the surface from inside, priming the collector circuit and maintenance are all necessary in order to avoid these problems.

The buffer tanks are an important part of the energy system. Tank stratification is a natural process in a tank where water is stratified based on its temperature and density. The stratified storage tanks are inexpensive, but they have a complex design compared to a normal tank (Araner, 2016). Due to flow variations, incorrect internal tank design and node distribution can cause the loss of stratification. It is observed that as the performance of the system improves, the effect of this failure increases. In the best performing cases, where the collector size is large, the effect of this failure is also large. In such expensive cases, this failure has to be dealt with seriously as it can significantly reduce performance.

The heat pump performance (COP) in a solar district heating network depends on the BTES’s temperature, the desired outlet temperature and collector size. The issue with a heat pump might be in the controls and inlet temperature. The use of a heat pump is not maximised in the worst-performing cases where the collector size is smaller; therefore, the effect of this failure is large. Because in this case, the energy stored in the BTES is less, it results in more energy consumption by the heat pump in order to charge the tanks. In worst-performing cases, this failure has to be dealt with seriously as it can significantly reduce performance.

The SPH network plays an important role in overall system performance. Ideally the temperature difference between the supply and return temperature should be higher in order to provide a low temperature to the heating plant for higher efficiencies. However, most of the plants face the issue of a higher return temperature in the district network (Sibbitt, et al., 2012; Dincer & Rosen, 2007; Nussbicker-Lux, 2012). The main reasons for the higher return temperature are incorrect design of the building heating system, the HVAC and the district network. This causes the return temperature to be higher than the designed temperature.

As discussed earlier, the SPH network plays a significant part in the overall system performance. The increase in the supply temperature to the SPH network can affect the performance of the system. The main reason for the in-
crease in supply temperature’s set point is the incorrect design of the control system or a malfunction in the controls.

Hot and warm tank–charging set point temperatures can also vary the performance of the system. The main reason for the change in the tank-charging set point temperature is a malfunction in the control or an error in the control algorithm or device.

The ST circulation pump control plays a significant part in overall system performance. Typically, during the early morning hours, evenings and during low solar irradiation periods, heat cannot be extracted from the ST collector field quickly enough and at a high enough temperature to meet heat demands. Therefore, the flow through the collectors is reduced or adjusted in order to provide the set point temperature for the tanks in need. A defect can arise in the control, which can cause a malfunction in the control algorithm or control system of the collector’s pump. This malfunction can result in the continuous operation of the pump, which is either on or off. The maximum flowrate of the pump is based on the collector’s area (i.e. the larger the area, the larger the flow rate). Therefore, in the best-performing cases where the collector size is large, the effect of this failure is also large.

Lastly, the dimensioning of large-scale BTES is inherently uncertain because of the natural variation in thermal conductivity and heat capacities of the ground. The average thermal conductivity of the ground is estimated to be around 3.5 W/m.K (Honkonen, 2016). However, the thermal response tests carried out in Finland showed that the ground conductivity can be as high as 4.5 W/m.K in the presence of water (Hakala, et al., 2014). The main reason for the increase in the overall effective thermal conductivity is due to the ground water flow through rock fractures. The higher conductivity of the BTES increases the losses from the BTES to the surroundings, resulting in a reduction in performance.

When designing such systems, all the technical errors need to be considered in order to achieve maximum performance for these systems.

### 6.3.1 Economic consequences

The energy system performance can have a great influence on the economy of the plant. The economic consequences can be either due to (a) hardware replacement or (b) software maintenance.

**Hardware replacements: Additional investment**

Some of the issues discussed above can only be maintained by additional investments. For instance, ST collector efficiency, heat exchanger efficiency, tank stratification, SPH network temperature difference, BTES boundary layer thermal conductivity and heat pump performance can be improved by replacing or maintaining the relevant devices. Replacement can be moderately or very expensive. Therefore, the plant owners any have to bear the high cost of the new equipment and, as a result, the total investment cost of the plant will increase.
Software maintenance: No additional investment

Some of the issues discussed above can be maintained by no (or insignificant) additional investment. For instance, the warm tank, hot tank, SPH supply temperature set points and solar collector circulation pump control can be improved by just changing the set point on the controller. This may have no (or very little) impact on the investments as only set points or the controller need to be adjusted via the controller (unless there is a defect in the measurement instrument). This kind of investment is inexpensive compared to hardware investments. The plant owners have less costs to bear compared to the hardware issue. However, these defects may increase the operational cost of the plant. This additional operational cost may need to be paid by the end users. However, a technician may need to be hired to adjust and maintain the system.

In the future, with the increasing popularity of the solar community concept, finding the best combinations and tackling certain issues will be important. Therefore, this information is useful for designers and engineers who are making preliminary decisions about designing and building such systems.

It is observed that the solar district heating systems are slightly more sensitive to the collector area and then to the PV area, as shown in Figures 20 and 32.

Overall it is found that technical errors can cause a deviation in Pareto optimal solutions, as shown in Figures 25, 26 and 27 and in Table 17. The results show that largest adverse impact is achieved by mixing the thermal stratification in the storage tanks to a uniform temperature. There is a 23–35% increase in purchased electricity. The second largest adverse impact is achieved by changing the ST circulation pump setting from variable to on/off at the control. There is a 1–22% increase in purchased electricity. Lastly, the third largest adverse impact is achieved by a reduction in the heat pump COP. There is a 7–21% increase in purchased electricity.

The sensitivity of the solutions with respect to the cost of the electricity, PV panels and collector are shown in Figure 38. It was found that in the worst-performing optimised cases, the energy system is sensitive to electricity prices. On the other hand, in the best-performing optimised cases, the energy system is sensitive to the collector and PV prices. Hence, it is recommended to predict the future prices and incentives in order to propose certain optimised systems. Moreover, the errors and failures discussed in Section 5.4., need to be accounted for in the modelling.

6.4 The reliability and validity of the proposed systems

This research was done based on modelling and assumptions, and this has an effect on the final results. Additionally, an experimental pilot project is needed to match the simulations with reality. Validation is needed to compare the technical performance and the investments and maintenance costs of the components in the Finnish context. However, the scope of the study is limited to the computational study. The purpose was to provide basic knowledge and a computational model for a future, real plant in Finland; as no such solar dis-
District heating network project exists in Finland, it is currently not possible for it to be validated. In order to validate such a model, an identical experimental setup, with similar climatic and ground properties, is needed. Furthermore, the initial cost and investments are quite high for such a system and it may require assistance or financial support. Validation of the proposed simulation models, seasonal storage, solar collector and PVs performance through experimentation in the future has been planned. Future research grant applications have been made to different funding bodies for the experimental setup.

The increase in the electricity prices makes renewable energy systems more feasible. However, it was found that after 2010 the trend in the prices of electricity has a decreasing trend (Nord Pool, 2017). Due to this change in prices, it is difficult to predict an escalation rate of the electricity price. Therefore, a conservative escalation rate (1%) is used.

Reasonable and accurate ICs and technical data for some components are difficult to find. Moreover, it is difficult to discover if the increase or decrease in the prices corresponds to the size of the components. Businesses are usually reluctant to publish the costs and prices of sub-systems due to business reasons and bargains. In many project reports some of the costs can be found, but mostly they are given as totals in which the cost of individual sub-systems and components are usually unavailable. Mostly, higher prices are used in order to avoid optimistic results for the costs. This means that the real system might be cheaper than estimated in this thesis. Lastly, maintenance costs are not included, as it is difficult to predict the maintenance costs of such systems in the Finnish context.

The building heating demand used in the calculations is simulated for a single-zone building; it may vary from the exact demand of a real typical building of a similar type. It is also assumed that all the buildings in the community have a similar hourly demand profile and that the building type is also the same (i.e. a residential building – no commercial or public service buildings are considered).

The BTES boundary layer’s conductivity is assumed to be 3.5 W/m.K, which is a mean value of the ground conductivity in Finland. However, its value can range from 2–4 W/m.K (Huang, et al., 2011). Therefore, the calculation of the performance and costs in this thesis may vary in practice. The exact value of the conductivity will depend on the thermal response test of the specific site at which the actual BTES is to be built. The seasonal storage component used in the calculation is a predefined model in TRNSYS. It is assumed that the BTES is cylindrical in shape and that boreholes are arranged in a circular pattern. The complex designs, shapes and borehole arrangements cannot be changed in TRNSYS and this may also vary the calculations.

The quantified values used in the calculations of the impact on the performance of the energy system caused by technical defects are reasonably assumed values. It is difficult to quantify the values and ranges of the failures and defects because these are mostly unavailable or not reported in detail in publications. It is possible that none of the defects mentioned may happen, or alternatively, different combinations of defects may occur together. All this
may affect the performance differently. These values can only be quantified experimentally or when reported from experience and are mostly unavailable.

NSGA-II – used to provide the multi-objective optimised solutions – is near to the global optimised values of the systems. It is possible that due to the randomness of the algorithm, certain values of the design variables may not change in a way that it provides a better front. However, NSGA-II provides reasonably good results for the optimisation, as validated in previous studies (Hamdy, et al., 2013).

6.5 Recommendations for further research

The community approach allowed the utilisation of solar energy in an efficient manner. More work should be carried out to further develop the seasonal storage technology. The study showed that integration of a heat pump and seasonal storage can provide a good solution to the issue of the mismatch between demand and generation via solar energy. It is important to perform a thermal response test in order to identify the ground properties that can be used to accurately design the seasonal storage. A hybrid model of the seasonal storage can also be tested where an underground tank can be surrounded by boreholes to integrate them together and reduce the losses from the seasonal storage. Moreover, this system could be modelled and tested for the different climatic conditions of Finland.

It is important to build and study this system in real conditions in order to validate the simulation model and to know the real costs of the system. In the initial stages, investors are reluctant to invest; therefore, an experimental setup can assist in opening up this market and showcasing the performance in real conditions. It has been observed that the cost of the components reduces as the sizes increases, due to the economy of scale. Therefore, large communities could be more feasible economically. To enable the construction and promotion of such a large community, new business models and governmental support might be needed. However, the main objectives of the renewable energy integration should be to maximise the on-site matching and minimize the costs.

The concepts of large-scale solar district heating networks are still considered unrealistic by many individuals in Finland. New research should be done on business models and social acceptance in order to motivate people and communities to invest in community concepts. Either the people can invest in the projects in order to own the whole energy plant, or people can buy the services at a cheaper price while the plant is owned by an experienced management board and expert company.

On an energy level, it seems that semi-decentralisation of the system can provide better results in terms of performance and cost. Therefore, further analysis could be carried out by changing the arrangements of the centralised and decentralised components in order to identify the best combination and control strategies. The largest cost of the energy system is the collector; therefore, any alternate system can be tested for charging the seasonal storage that
is more economical than the collector, for example, PV panels. PV panels are cheaper than a collector. PV panels can be tested for charging the short-term storage (via electric heaters or heat pumps) by converting electricity to heat energy. Excess electricity from the PV panels can run several heat pumps in order to charge the seasonal storage. PV panels are usually integrated with batteries (electricity storage). Nevertheless, the cost of thermal storage is less and the technology is more developed compared to electrical storage, therefore emphasis should be placed on thermal storage in this case as well. Another possibility is to integrate electric vehicles in which the car batteries can act as storage for excess electricity from PV panels. The question would be how the user behaviour and car usage can affect the storage capacities.

Research could also be done on the possibilities of integrating seasonal storage and a district network in existing urban areas. There is an increase in the cooling demand, especially in the commercial sector in Finland (Finnish Energy, 2018). The study can also be conducted to identify the usefulness of hybrid solar district cooling/heating networks for commercial building application in Finnish context. These models can also be tested for different climatic and ground conditions.

On the policy level, there is a need for support schemes that can enable sustainable development. Such policies should promote renewable communities towards efficient self-consumption, the minimisation of load on the grid by reducing net primary energy demand and encourage storage technologies, rather than only focus on maximising renewable energy capacities. In addition to the renewable-based energy systems, importance should be placed on building efficiency, where special tax benefits can be provided to the building owners based on their building energy performance levels. These benefits can be provided to the communities and individuals that perform better in terms of building efficiency and on-site matching. However, it might be tedious to identify the contribution of an individual to meeting self-consumption and building efficiency goals at a community level. So the question remains whether the benefits should be divided equally among those who participate in community concepts, regardless of their contribution, or divided based on achieving a certain percentage on some KPI (key performance indicator) regarding an individual and her or his contribution towards the renewable community.

On the business level, it can still be analysed for the effect of tax benefits on the economic feasibility of solar district networks in the Finnish context. An economic model can be tested wherein the selling price of different energy (heat and electricity) is the same, so the companies willing to invest do not reduce their revenues, but the VAT or other taxes are lowered. To test the willingness and motivation of the investors and energy distribution companies, a higher carbon taxation scheme can be examined.
7. Conclusions

In this thesis solar energy harvesting was considered as an alternate to the traditional district heating and electricity network in Nordic conditions. It was seen that there exists a significant mismatch between solar energy generation and the demand in Finland. Due to this mismatch, in buildings such solar energy–based systems become uneconomical in this environment. The import of energy from the grid is usually expensive, while at the moment exporting electricity to the grid is uneconomical as the financial gains are insignificant. A feed-in tariff may solve such issues; however, it might not promote energy efficiency. Self-consumption and storage are more effective solutions as they also encourage active energy management and energy efficiency on the user’s side. Therefore, seasonal storage, integrated with solar-based district heating, can play a significant role in Nordic conditions. The economic issues of on-site renewable energy systems can be mitigated by community energy systems. However, the integration of energy generation, storage, demand, seasonal storage and control strategies should be done centrally for the community in order to maximise their benefits.

This dissertation describes how, in Publication 1, the importance of control strategies, their design and selection, can affect the overall performance of a system. In a simple system, the heat pump takes energy from the solar-charged seasonal thermal storage and charges the hot and warm tanks. During winters, most of the energy was provided via seasonal storage and the heat pump, while in the summer the heating demand was mostly met directly via the collector. Publication 2 introduced three different solar district energy system architectures and compared them against each other based on purchased electricity, FC and the renewable energy fraction. Publication 2 also simulated and showed the importance of community demand as a design variable in the overall solar district energy system’s performance. Publication 3 argued and introduced various technical issues, failures and defects that usually occur in the real application of such solar-based heating networks. A centralised solar district heating network was modelled, simulated and multi-objective optimised under ideal conditions. Lastly, selected typical failures and technical issues were introduced to the optimised system in order to predict the behaviour of the system under various non-ideal conditions. Publication 4, introduced two different concepts of community-sized solar heating systems: the centralised and the decentralised energy systems. In the centralised system the generation, storage and distribution networks were in one place. In the semi-
decentralised system, generation and seasonal storage were centralised while distribution and part of the storage were decentralised. Publication 4 compared both these energy systems and found the best-performing optimised system based on the minimum purchased electricity and minimum LCC. All the design variables, including physical components and set points, were closely compared in detail. The main conclusions of the present thesis are summarised in the following:

- The control strategy plays an important role in varying the overall performance of the solar district heating network. In simple solar district heating systems with hot and warm tanks, it was found that with a parallel/automatic setup – with temperature difference control of the collector and the warm tank set as the priority tank – the renewable energy fraction increased from 78% to 83% and the electricity consumption was reduced by 20% compared to when the hot tank was set as the priority tank.
- The BTES efficiency showed an increasing trend during the five years of its operation. Moreover, the average BTES’s temperature increased from 5°C to 30°C and, as a consequence, the COP of the heat pump increased.
- Maximising the performance of these systems was a matter of selecting the best combinations of the ST area, the PV area, short-term storage tank volume, BTES volume, BTES shape, charging set points and the building’s configuration (as building design can alter the system’s performance).
- The shape of the boreholes, the depth of the boreholes, building heating demand and the collector area were important design variables for all energy systems.
  - In the best-performing optimised cases in the centralised system, the solutions contained the following values: borehole volume: 38000 m³; borehole depth: 30 m; the number of boreholes: 242; collector area: 5400 m²; and heating demand: 25 kWh/m²/yr.
  - In the best-performing optimised cases in the decentralised system, the solutions contained the following values: borehole volume: 11000 m³; borehole depth: 20 m; the number of boreholes: 144; collector area: 3100 m²; and heating demand: 25 kWh/m²/yr.
  - It was found that when the building heating demand was reduced from 50 kWh/m²/yr to 25 kWh/m²/yr, the purchased electricity was reduced by 6%, while the corresponding LCC increased by 9%.
- The results showed that in the centralised system, a heat pump connected between two tanks, using solar-charged borehole storage to directly charge the lower temperature tank, performed better in terms of the renewable energy fraction, cost and purchased energy
when compared to the energy system where the heat pump was connected between short-term storage tanks and seasonal storage, using solar-charged borehole storage and also when compared to the energy system where seasonal storage was not charged by solar energy and heat pumps were used between the two tanks and also between the seasonal storage and tanks.

- The results showed that when the BHE was not charged via solar energy, such a system performed poorest compared to systems where the boreholes were charged.
- In an optimised centralised energy system with solar charging of the seasonal storage, the purchased electricity varied from 49 kWh/m²/yr to 25.9 kWh/m²/yr, which corresponds to the renewable fraction from increasing from 65 to 90%.
- In terms of LCC and purchased energy, the decentralised system clearly outperforms the centralised system. With a similar energy performance, there was an up to 35% reduction in LCC for the decentralised system. The renewable energy fraction can be 92% in such a system.
- The various failures and defects in the technical parameters discussed in the thesis show the importance of all the non-ideal aspects.
- The largest adverse impact of errors was achieved by mixing the thermal stratification in the storage tanks in order to form a uniform temperature. There was a 23–35% increase in purchased electricity.
- The second largest adverse impact of errors was achieved by changing the ST circulation pump setting from variable to on/off at the control. There was a 1–22% increase in purchased electricity.
- The Pareto fronts were more sensitive to the electricity price in the worst-performance cases where the amount of purchased electricity was a large (i.e. around a 2–8% increase in LCC), if electricity prices increase in the future. The Pareto fronts were more sensitive to the component prices in the best-performing cases, wherein component sizes were relatively large compared to the worst-performing cases. This can decrease the LCC by 2–11% if the future component prices decrease.
Conclusions
References


cooling, heating and power cycle driven by geothermal and solar energies using 

Available at: http://www.builditsolar.com/References/Measurements/CollectorPerformance
 hentai#Efficiency

Build it Solar—the renewable energy site for do it yourself, 2007. *Solar Collector 
[Accessed 2018].

C3 NATIONAL BUILDING CODE OF FINLAND, MINISTRY OF THE 
Available at: https://www.edilux.fi/data/rakentamismaaraykset/c3e_2003.pdf

Cao, S., Hasan, A. & Sirén, K., 2013. Analysis and solution for renewable energy load 

Cao, S., Hasan, A. & Sirén, K., 2013. On-site energy matching indices for buildings 
with energy conversion, storage and hybrid grid connections. *Energy and 

Cao, X., Dai, X. & Liu, J., 2016. Building energy-consumption status worldwide and 
the state-of-the-art technologies for zero-energy buildings during the past 

Capitanescu, F. et al., 2015. Some efficient approaches for multi-objective constrained 
optimization of computationally expensive black-box model problems. *Computers 
& Chemical Engineering*, Volume 82, pp. 228-239.

of remote microgrids considering battery lifetime. *The Electricity Journal*, 
29(6), pp. 1-10.

management.se/ http://sunstore4.eu/download/member-
area/wps5/EU%20report-WP5-
deliverable%205%204_Feasibility%20simulation%20studies.pdf

worth-Heinemann.

capabilities building energy performance simulation programs*. [Online] 
Available at: https://sbi.dk/bsim/Documents/PDF-
docs/Contrasting%20the%20capabilities%20of%20building%20energy%20per-
formance%20simulation.pdf

[Online]


Idman, T., 2013. Parametrization of energy simulation and development of energy-efficient building design analysis and decision making process, Espoo, Finland: Aalto University, School of Engineering, Department of Energy Technology.


Koppen, C. V., Thomas, J. & Velkamp, W., 1979. The actual benefits of thermally stratified storage in a small and medium size solar systems. Atlanta, s.n.


SOLPROS, 2004. Ekoviiink EU-aurinkolämpöjärjestelmien jatkoseuranta, s.l.: s.n.


114


Climate change is one of the biggest challenges in the present time. Efficient houses and solar energy are some of the solutions to prevent climate change. The challenge in the Nordic region is the mismatch between the production and consumption of the solar energy. The goal of the thesis is to design, optimize and compare several solar district heating architectures and control strategies for the community in the Nordic climate. Various components and controls design variables are nominated to provide multi-objective optimized simulated systems. The thesis indicates that the focus should be at the district level instead of focusing on the single building solutions. Such systems benefits from economy of scale, reduction in energy consumption and lower operational cost. The communities maybe designed to maximize the onsite energy generation and consumption. The onsite consumption can be increased by integrating the seasonal storages and efficient buildings with the solar district. Moreover, such systems are sensitive to the failures, errors, economic and operating conditions.