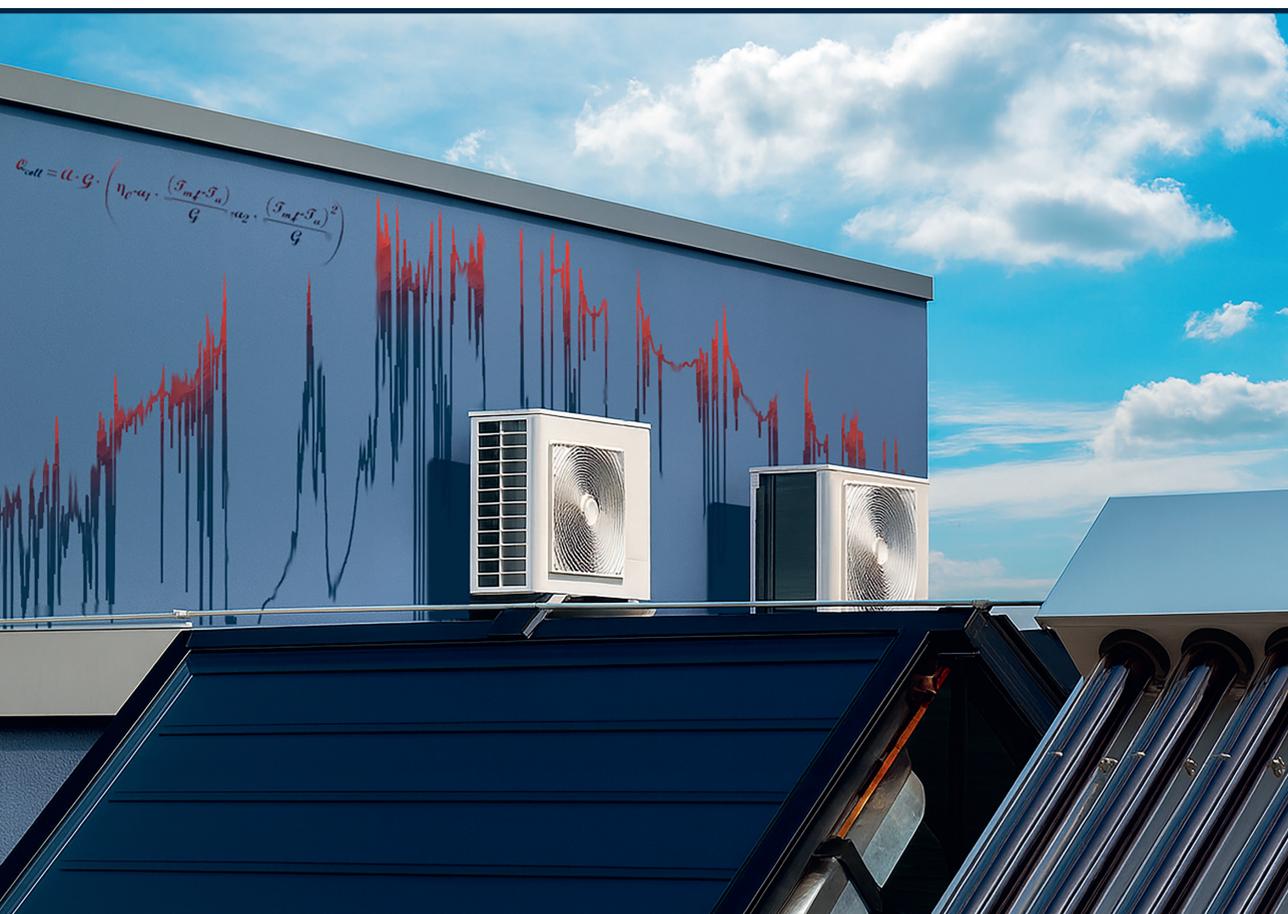


Raimonds Bogdanovičs

PERFORMANCE EVALUATION OF SOLAR THERMAL AND HEAT PUMP TECHNOLOGY IN DISTRICT HEATING

Summary of the Doctoral Thesis



RIGA TECHNICAL UNIVERSITY

Faculty of Civil and Mechanical Engineering
Institute of Sustainable Building Materials and Engineering Systems

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**PERFORMANCE EVALUATION
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Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph.D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on September 18, 2025, at 13.00 at the Faculty of Civil and Mechanical Engineering of Riga Technical University, 6A Ķīpsalas Street, Room 546.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph.D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Raimonds Bogdanovičs (signature)

Date:

The Doctoral Thesis has been written in English. It consists of an Introduction, 4 chapters, Conclusions, 96 figures, and 32 tables; the total number of pages is 133. The Bibliography contains 177 titles.

TABLE OF CONTENTS

NOMENCLATURE	5
INTRODUCTION.....	6
1. Solar energy applications	11
2. Solar district heating system	15
3. Solar-assisted heat pump in district heating system	19
4. Impact of temperature fluctuations on the brine-to-water heat pump performance	23
CONCLUSIONS AND FUTURE STUDIES.....	29
ACKNOWLEDGEMENTS.....	31
REFERENCES.....	32

NOMENCLATURE

AWHP	air-to-water heat pump
BWHP	brine-to-water heat pump
COP	coefficient of performance
DH	district heating
DHW	domestic hot water
ETC	evacuated tube collectors
FPC	flat-plate collectors
LTDH	low-temperature district heating
MAD	mean absolute deviation
HP	heat pump
PV	photovoltaic
PVT	photovoltaic-thermal
RES	renewable energy sources
SD	standard deviation
ST	solar thermal
TRNSYS	the name of dynamic simulation software
ULTDH	ultra-low temperature district heating

INTRODUCTION

This Thesis started with a practical engineering challenge: how to maximize solar energy utilization in the district heating sector. This led to the concept of combining solar energy with brine-to-water heat pumps, raising a key technological question: Do variations in solar energy affect the performance of a solar-assisted heat pump? This, in turn, led to the scientific research question: How to measure and evaluate the influence of heat carrier temperature variations, caused by solar energy fluctuations, on brine-to-water heat pump performance.

Relevance of the study

In recent years, there has been a noticeable rise in scientific research on solar-assisted heat pumps – including thermal, photovoltaic and combined systems. However, limited attention has been given to the integration of these technologies with district heating networks, especially under Northern Europe's climatic conditions.

Achieving carbon neutrality by 2050, as outlined in the Paris Agreement, requires a fundamental shift away from fossil fuels for heat production. Integrating heat pumps and solar energy into low-temperature district heating systems presents a promising solution for producing and storing heat energy in a sustainable and efficient manner. The efficiency of heat pumps can be further improved by utilizing solar thermal heat, while photovoltaic panels can supply renewable electricity to power the heat pumps.

This combination not only enables the generation of heat energy without greenhouse gas emissions but also introduces the possibility of space cooling – an increasingly important consideration as Latvia experiences the impacts of a warming climate. The study's focus on maximizing solar heat utilization within district heating networks directly supports the broader goals of decarbonizing the heating sector and advancing renewable energy integration.

The aim of this Ph.D. Thesis is to investigate strategies for maximizing solar heat utilization in Northern Europe's climatic conditions within district heating systems by integrating solar thermal and heat pump technologies.

The main tasks

1. Assess solar energy potential and variability in Latvia for integration with solar thermal and heat pump-based district heating.
2. Examine solar thermal collector performance under different heat carrier temperature regimes and analyze heat carrier temperature fluctuations under variable conditions.
3. Explore the integration of solar energy into district heating systems and evaluate the effectiveness of using district heating to store heat produced by solar collectors, in order to assess the feasibility of distributing the generated energy to nearby buildings.
4. Evaluate the combination of solar energy, heat pump and district heating system to identify strategies for maximizing solar heat utilization using limited building roof space.
5. Analyse the impact of heat carrier temperature fluctuations on the performance of the brine-to-water heat pump.
6. Examine the effect of solar thermal collector temperature and flow fluctuations on the operation of a brine-to-water heat pump.

Theses to be defended

- The integration of solar energy and heat pump technologies into low-temperature district heating networks is one of the most effective strategies for maximizing solar heat utilization.
- In systems with solar thermal collectors, heat carrier temperature fluctuations are primarily caused by solar irradiance variability and can be reduced by operating at lower temperatures.
- Source-side temperature fluctuations reduce the coefficient of performance of brine-to-water heat pumps, while fluctuations on the sink side have minimal impact.
- The coefficient of performance of brine-to-water heat pumps is particularly sensitive to source-side temperature fluctuations at temperatures below 20 °C. So the findings are specifically relevant when heat pumps are used as booster units in ultra-low-temperature district heating systems or when photovoltaic-thermal collectors serve as the heat source.

The scientific novelty of this Thesis lies in the development of an integrated methodology that combines experimental testing, simulation models and energy performance calculations to evaluate and maximize the performance of solar thermal and brine-to-water heat pump technology in a low-temperature district heating system under fluctuating heat carrier temperatures. Unlike conventional heat sources such as geothermal heat or groundwater, which maintain stable thermal conditions, this study specifically investigates the dynamic temperature variations introduced by solar energy fluctuations, an aspect rarely explored in existing research.

This research examines the dynamic interaction between solar thermal collectors, district heating systems and heat pumps, focusing on how solar-induced temperature variations affect the heat pump's coefficient of performance (COP) at different heat carrier temperatures. Since heat pump manufacturers do not typically test for these conditions, this study fills a critical gap by providing an experimental assessment and a novel methodology for measuring and evaluating their impact under real operating conditions. **It hypothesizes** that temperature fluctuations driven by solar energy integration significantly influence the COP of the brine-to-water heat pump, requiring advanced evaluation techniques beyond standard testing procedures.

The proposed methodology integrates multiple methods, including statistical analysis, literature reviews, field measurements, the development of two experimental test facilities and numerous computer simulations using the TRNSYS 18 dynamic simulation software. By conducting energy performance calculations for different system configurations and temperature regimes, this research demonstrates how the proposed system can maximize solar energy utilization, thereby providing evidence of its feasibility for real-world applications.

The practical implementation lies in supporting the development of the district heating sector by providing valuable insights into the integration of renewable energy sources, particularly solar energy and heat pumps. The results, including statistical analysis, experimental data and simulation outcomes, can inform strategic decision-making processes for modernizing district heating networks, optimizing solar heat generation and improving system efficiency. While the research focuses on Northern Europe and especially Latvian climatic conditions, the proposed methods and findings are adaptable to other regions, offering a broader application for advancing sustainable and resilient district heating systems.

Structure of the Thesis

The Thesis comprises four chapters. Each chapter is solid research with its own methods, results and conclusions. Chapters are connected, so findings of one chapter are used in other chapters according to the developed research methodology. Combined, they provide a bigger scope for the research topic.

Chapter 1: Solar energy applications

- To complete Task 1, statistical and climatic data were analyzed, and field measurements were carried out on a solar collector system installed in a single-family house and at an experimental test facility.
- To accomplish Task 2, a solar collector test facility was designed, constructed and operated under various weather and operating conditions; a computer simulation model of the test facility was developed using the TRNSYS 18 energy simulation software package.

Chapter 2: Solar district heating system

- To complete Task 3, a comprehensive review of scientific literature was conducted, and two computer simulation models were developed using TRNSYS 18.

Chapter 3: Solar-assisted heat pump in district heating system

- To conduct Task 4, an extensive review of scientific literature was done, and three computer simulation models were developed using TRNSYS 18.

Chapter 4: Impact of temperature fluctuations on the brine-to-water heat pump performance

- To fulfill Task 5, a heat pump test facility was designed and constructed, accompanied by a corresponding TRNSYS 18 model.
- To perform Task 6, the heat pump test facility was operated using data collected from the solar thermal collector test facility.

The study contributes to the United Nations Sustainable Development Goals (SDGs), particularly Goal 7, “Affordable and clean energy”, Goal 11, “Sustainable cities and communities”, and Goal 13, “Climate action”.

Research methodology

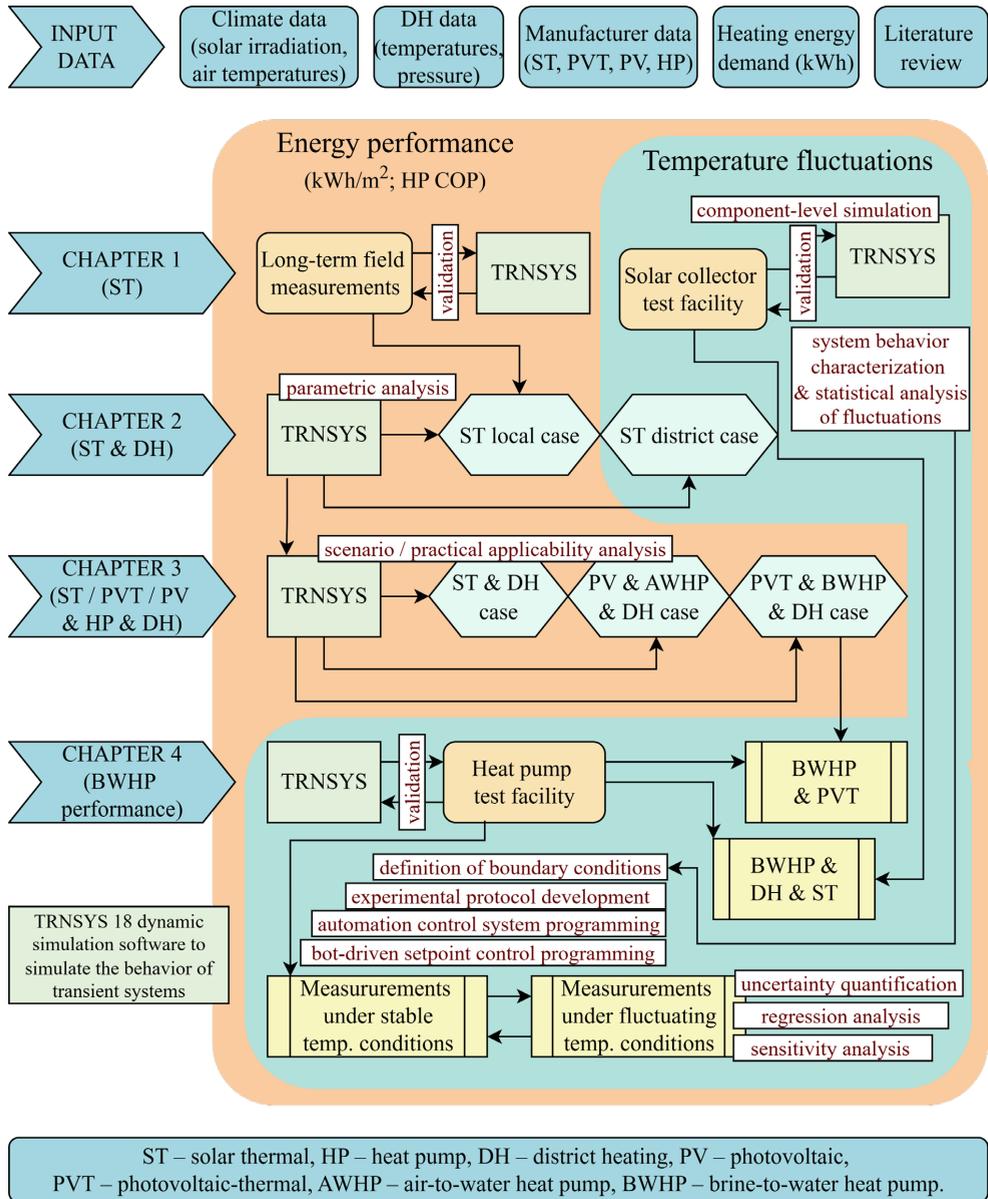


Fig. 0.1. Research methodology.

List of publications related to this study

Articles indexed in SCOPUS:

1. **Bogdanovics, R.**, Zemitis, J., Zajacs, A., Borodinecs, A. (2024). Small-Scale District Heating System as Heat Storage for Decentralized Solar Thermal Collectors during Non-Heating Period. *Energy*. Vol. 298.
2. Zajacs, A., Lebedeva, K., **Bogdanovics, R.** (2023). Evaluation of Heat Pump Operation in a Single-Family House. *Latvian Journal of Physics and Technical Sciences*. Vol. 60.
3. Zajacs, A., **Bogdanovics, R.**, Zeiza-Seleznova, A., Valancius, R., Zemitis, J. (2022). Integration of decentralized solar collectors into a district heating system. *Sustainable Cities and Society*, Vol. 83.
4. Zajacs, A., **Bogdanovics, R.**, Borodinecs, A. (2020). Analysis of low temperature lift heat pump application in a district heating system for flue gas condenser efficiency improvement. *Sustainable Cities and Society*. Vol. 57.

Conference papers indexed in SCOPUS:

1. **Bogdanovics, R.**, Zemitis, J., Zajacs, A., Borodinecs, A. (2025). Optimizing the Integration of Booster Heat Pump with Solar Thermal Collectors and Low-Temperature District Heating System in the Baltic Region: Laboratory Measurements. *2025 ASHRAE Winter Conference*. February 8–12, 2025, Orlando, Florida, USA.
2. **Bogdanovics, R.**, Zemitis, J., Zajacs, A. (2023). TRNSYS model of district heating system used as heat storage for decentralized solar thermal collectors. *18th IBPSA Conference on Building Simulation, BS 2023*, Building Simulation Conference Proceedings. September 4–6, 2023, Shanghai, China.
3. **Bogdanovics, R.**, Zajacs, A. (2022). Supply Temperature Stabilization of Decentralized Solar Thermal Collectors for Integration into District Heating System. *2022 ASHRAE Virtual Winter Conference*. ASHRAE Transactions. January 29–February 2, 2022, online.
4. Zajacs, A., Borodinecs, A., **Bogdanovics, R.** (2020). Assessment of the efficiency and reliability of the district heating systems within different development scenarios. *11th International Conference on Sustainability and Energy in Buildings, SEB 2019*. July 4–5, 2019, Budapest, Hungary.

Conference papers (not indexed):

1. Lebedeva, K., **Bogdanovičs, R.**, Zajacs, D. (2023). Use of Existing Water Tanks for Improvement of Building Heating/Cooling System Using Heat Pumps and Solar Collectors, *International Conference on Innovative Engineering Technologies*, Proceedings of the IRES International Conference. May 23–24, 2023, Barcelona, Spain.
2. **Bogdanovics, R.**, Zeiza-Seleznova, A., Zemitis, J., Zajacs, A. (2022). TRNSYS model with 3-way valve for heat carrier temperature control of solar thermal collectors integrated into district heating system, *BuildSim Nordic 2022 Technical papers*. August 22–23, 2022, Copenhagen, Denmark.
3. **Bogdanovics, R.**, Zemitis, J., Zubovics, A. (2022). Energy balance of solar collector assisted heat pump in 5th generation DHC system in Northern Europe, 2nd International Sustainable Energy Conference (ISEC 2022) Conference Proceedings. April 4–7, 2022, Graz, Austria.

1. Solar energy applications

The investigation of solar energy availability, variability and development potential in Latvia and Northern Europe revealed a steady increase in renewable energy sources and a growing number of installed solar photovoltaic power plants, with the aim of further boosting the share of renewable energy sources in electricity production (Cabinet of Ministers, Republic of Latvia, 2024). But according to the chairman of the board of the distribution system operator JSC “Sadales tīkls” (Delfi.lv news portal, 2024), solar generation capacity had already reached 660 MW by the end of 2024 and is expected to grow to 900 MW by 2025, exceeding Latvia’s electricity demand during the summer season and potentially causing low or even negative electricity prices during sunny weather.

This Thesis is focused on solar thermal collectors, as the use of solar energy for heating purposes remains minimal, presenting a challenge which is addressed in this study – how to make solar heating a more technically and economically attractive solution for consumers. Solar thermal technologies, examined in this Thesis, include flat-plate collectors (FPC), evacuated tube collectors (ETC) and photovoltaic thermal (PVT) collectors, which integrate both solar heat and solar electricity generation within a single device, offering higher energy yields per unit area (Weiss & Spörk-Dür, 2024). The dual functionality of PVT is particularly beneficial when roof space is limited, supporting integrated solar energy solutions essential for achieving a climate-neutral energy supply in residential and commercial buildings.

While this study primarily focuses on Latvia's statistical data, the results are largely applicable to other Northern European countries due to their similar climates, regulatory frameworks and shared emphasis on promoting renewable energy sources.

Thermal performance of solar collectors

One year of field measurements and TRNSYS 18 simulations of solar thermal collectors installed on a single-family house for domestic hot water preparation purposes showed that the actual heat output from ST was at least twice as low as reported in the literature (Lebedeva et al., 2023; Weiss & Spörk-Dür, 2024). The measured solar heat energy utilization of an ST system was 17.5 % lower than the simulated results, with 178 kWh/m² compared to 216 kWh/m²; however heat carrier temperature analysis shows that, in field measurements, temperatures were often higher than expected due to low energy consumption, which may have led to reduced heat utilization. Maximum measured daily solar energy utilization was 2.8 kWh/m², but the maximum solar collector temperature (+86 °C) was detected on 15 July, with daily heat production of 1.4 kWh/m² and on 16 July, 2.2 kWh/m².

A seasonal mismatch was observed, with 76 % of total solar irradiation occurring between April and September, during which 90 % of useful solar thermal energy was utilized in field measurements and 83 % in TRNSYS simulations for traditional 65 °C ST applications. The main amount of heat energy was produced during June and July.

To improve system performance, operating at lower heat carrier temperatures is suggested. Reducing the mean heat carrier temperature from 55 °C to 25 °C can increase energy production by 132 %. However, this also raises the challenge of how to effectively use such low-temperature heat – a question addressed in the following chapters.

Solar collector test facility

To gain more data from solar thermal collectors under different temperature regimes, the test facility (Fig. 1.1) with flat plate and vacuum thermal collectors was designed, constructed and placed on the Riga Technical University roof in Riga, Latvia, providing the location of solar collectors to the south without shading. For additional in-depth component-level analysis, a test facility model was developed by applying the dynamic simulation computer software TRNSYS 18. The first results were presented in the author's Master's Thesis (Bogdanovičs, 2021), later expanded, completed and published in the article by Zajacs et al.(2022).



Fig. 1.1. The view of the test facility (Bogdanovičs, 2021).

Overheating risk and the potential of district heating system utilization

During non-heating periods, thermal energy is used only for domestic hot water preparation. However, hot water demand can be irregular – for example, during vacation periods when usage may significantly decrease, leading to a risk of system overheating. The analysis shows that traditional ST systems with local storage tanks can reach a temperature above 100 °C within 30 minutes of stopped energy consumption in the middle of a sunny summer day. ETC reach high temperatures faster than FPC, making them more exposed to overheating risks.

The suggested solution for making solar heating an attractive solution for consumers and reducing the risk of overheating is to connect collectors to existing or newly constructed district heating systems with significant volume and energy storage potential, if a building already has a connection to DH. Integration of decentralized solar collectors into the networks could be more expensive in comparison to large-scale centralized solar collector plants. However, this solution does not occupy the city's and agricultural lands, and the total potential area for solar collectors on roofs in a city is huge. The decentralized heat source is also located closer to the heat consumer, thus the energy for district heating pumps and heat losses can be reduced.

In Riga, the DH system operates at 65/45 °C during the non-heating season with a defined supply temperature variation of 65 ± 3 °C. Measurements at the solar test facility on such a setpoint showed that small-scale solar collectors can meet the required supply temperature. To ensure a supply temperature of 65 °C for at least 98 % of the time, the setpoint should be 69.6 °C, but in case of a minimum supply temperature of 62 °C for at least 98 % of the time, the setpoint should be 66.5 °C. In this case, the supply temperature will exceed 68 °C for 2–8 % of the time.

The main challenges for thermal solar prosumer units are as follows:

- changing solar intensity during a day;
- the fluctuating differential pressure in the district heating networks;
- the necessity to maintain the stable supply temperature, according to the technical regulations of the district heating operator.

Component-level simulation analysis

To make detailed solar collector performance and temperature fluctuations measurements, the test facility was built, and the TRNSYS computer model was developed and validated. The validation showed that the model predicts similar thermal energy output at high (65 °C) heat carrier temperatures, but at lower temperatures (35 °C), up to 8 % lower thermal energy output for ETC and up to 15 % output higher for FPC.

The system behavior simulation shows that it is possible to make temperature fluctuations in the TRNSYS computer model with a similar fluctuating period, but the standard deviation of simulated fluctuations is 1.7–2.4 times lower. Taking into account all assumptions and simplifications, the model can be used for component-level simulations.

In the results of the simulation, it has been found that the selection of the control algorithm has the most considerable effect on the supply temperature fluctuations. It is suggested to reduce the waiting time of the three-way valve so that the valve responds faster to the temperature change. However, too long an operation time of the valve could contribute to additional fluctuations of the flow and temperature. To reduce fluctuations, it is recommended to select a valve with a lower closing speed and lower hysteresis.

Temperature fluctuation analysis

To describe temperature fluctuations, standard deviation (SD) and mean absolute deviation (MAD) statistical parameters can be used. However, the observed temperature fluctuations show a non-normal distribution, so MAD is preferred for further analysis. SD is sensitive to outliers and assumes a symmetric, bell-shaped (normal) distribution, while MAD is more robust and provides a more accurate representation of variability in skewed or irregular data.

The measured MAD of heat carrier temperature from ST collectors varied based on temperature levels, control regime, and weather conditions. At high temperatures (80/50 °C), MAD ranged from 1.02 K to 2.20 K; at medium temperatures (65/42 °C), it ranged from 1.03 K to 1.61 K; and at low temperatures (50/30 °C), it was between 0.47 K and 0.96 K. In general, MAD is higher during cloudy hours and at the beginning and end of the daytime.

Typical fluctuation period was measured to be about 13–15 minutes in “normal” and about 8–9 minutes in “fast” control mode.

There is no single universal control mode that would be the best in all temperature regimes and weather conditions, but it is clear that with the decreasing supply temperature setpoint, it becomes easier to control the heat carrier temperature.

Limitations

The capacity of the system examined within the scope of this research is very small compared to the systems described in the literature. Smaller systems have lower thermal inertia, which might affect the choice and performance of control algorithms.

Although Schäfer and Thomas (2018) highlight the impact of differential pressure fluctuations in heat networks, such fluctuations could not be physically replicated on the test facility. Instead, they were simulated in TRNSYS software, showing that high pressure variations increase the supply temperature's standard deviation by only 1.2 times compared to “normal” conditions. This aspect should be explored further in future studies using systems connected to actual DH networks.

Measurements were carried out under real outdoor conditions, which varied daily (solar irradiation, air temperature, wind). As a result, control strategies and temperature setpoints could not be tested under identical conditions. However, this variability was mitigated by conducting long-term measurements to ensure reliable results.

Future studies

Further research should involve connecting the solar thermal unit to a real district heating system and conducting long-term performance measurements. Future studies should also explore the use of variable set temperatures and control algorithms based on the time of the day, weather conditions, meteorological forecasts, and differential pressure. Additionally, the potential of machine learning algorithms to improve system control and efficiency should be evaluated.

Based on the current findings, several recommendations can guide future development to enhance solar collector performance and reduce temperature fluctuations.

- The developer of the control algorithm of solar collector systems should take into account not only the temperature difference between the setpoint and actual values but also weather conditions, especially cloud cover.
- Technical regulations issued for connection to the district heating system should consider the limitations of the small-capacity solar thermal collectors. The district heating system operator can consider providing a more flexible temperature schedule by defining a higher temperature deviation. For example, $+65 \pm 5 \text{ }^\circ\text{C}$ instead of $+65 \pm 3 \text{ }^\circ\text{C}$, unless it can compromise the reliability of the whole DH network, which needs to be investigated in the future research.

2. Solar district heating system

The European Union has set ambitious goals to become the first climate-neutral region on the planet by 2050 (European Commission, 2020). There are numerous possibilities for generating and transferring heating energy for domestic and industrial needs. One of the environmentally friendly, financially reasonable and cost-effective solutions for populated areas is a district heating (DH) system (Lake et al., 2017). According to the statistical survey by Euroheat & Power on the district heating and cooling sector, there were around 6000 DH networks in the EU, providing approximately 11–12 % of the total heat demand. Some counties don't have district heating at all, but some provide more than 50 % of heat energy by this system (Buffa et al., 2019; Werner, 2017). DH systems are being proposed as the future solution for urban heating in Europe, with high potential to boost the integration of renewable energy.

In Riga, there is a wide DH system, which provides heating for 70 % of the Riga building sector with an overall energy demand of 3 TWh, which ought to implement energy efficiency improving activities in this field. Latvian mid-term and long-term heating sector planning documents foresee the increase of solar energy use, electrification of the heating sector by increasing the share of heat pumps (HP) and implementation of the renovation measures for building stock (Cabinet of Ministers, Republic of Latvia, 2022; Directorate-General for Communication, 2024; International Energy Agency, 2024).

The existing system in Riga is a 3rd generation system (65 °C during the non-heating period, averaging 70 °C – 80 °C during the heating season, and reaching up to 118 °C during extreme cold conditions). According to Lund et al. (2014, 2021), 4th generation district heating systems are classified as low-temperature district heating (LTDH) networks, operating with heat carrier temperatures of 50 °C – 60 °C in the supply pipe and approximately 25 °C in the return pipe. 5th generation systems are ultra-low temperature district heating (ULTDH) networks, operating at close-to-ground temperatures (below 30 °C) with distributed heat pumps.

While transitioning from the existing 3rd generation to the 5th generation model in the Baltic countries presents challenges, particularly due to the significant investments required, the region's ambitious energy and climate goals (Volkova et al., 2022) open the door to integrating certain key elements from the 5th generation approach. This could improve Latvia's DH system's efficiency without necessitating substantial capital investments.

District heating networks usually have centralized thermal energy production sources at a sole location and energy sources are limited by the installed heating units, while decentralized district heating system allows using and adding multiple energy sources and technologies, such as solar thermal, moderate geothermal resources, industrial waste heat, backup boiler and seasonal storage (Bertelsen et al., 2021). Furthermore, the inclusion of prosumers might be the best way to enhance an existing grid that has been pushed to its technical or economic limits (Lichtenegger et al., 2017). The concept of the 5GDH system includes the possibility to use the network as an energy storage system and simultaneously as a source of heat and cold for buildings' heating and cooling using heat pumps, as well as introducing the concept of "prosumer" – an individual who both consumes and produces energy (Buffa et al., 2019; Millar et al., 2021; Revesz et al., 2020).

The large-scale solar collector plants connected to the district heating (DH) system have been successfully operating for a long time in Denmark, Sweden, Germany, as well as in Latvia, in Salaspils (Lebedeva et al., 2023). However, there are a few examples when households are connected to a district heating system as prosumers. The stagnation and overheating problems are crucial for small-scale solar collector plants in a local system with uneven heat demand and limited heat accumulation capacity. Integration of solar thermal collectors into the 4th or 5th generation district heating system allows to minimize these risks and to provide an opportunity to maximize the capacity of solar collector plants by utilizing all available roof areas.

Integrating decentralized renewable thermal energy sources into DH systems requires robust, reliable solutions with precise temperature control, remote access and low maintenance costs (Brand et al., 2014; Brange et al., 2017; Huang et al., 2020). To minimize heat carrier temperature fluctuations, solar collectors can heat the return pipeline and deliver energy to the supply pipeline according to the defined temperature regime (Lennermo et al., 2019). Since DH systems provide both domestic hot water and space heating, it is essential to consider factors like building energy consumption reduction through renovations (Hamburg et al., 2020), forecast-based control (Cholewa et al., 2022), and combining solar energy with other sources.

District heating system as heat storage for solar thermal collectors

The research presented in this chapter has been published in the article by Bogdanovics et al. (2024).

Converting existing 3rd-generation DH networks to 4th or 5th generation is complex and costly. In Latvia, small-town DH networks often are not operated during the non-heating period due to low demand and high pipeline heat losses, so domestic hot water is heated locally by electric boilers. In such cases, integrating solar thermal collectors could transform DH networks into large heat storage systems, reducing reliance on local electric boilers.

The presented study introduces a method for evaluating the impact of key parameters – including hot water usage profiles, solar collector area, and district heating system pipeline diameter and length – on the useful amount of received solar energy. It conducts a parametric study to assess the efficiency of using an existing small-scale DH system as heat storage for prosumers with decentralized solar thermal collectors in northern climatic conditions during the non-heating period (May–September). By comparing TRNSYS 18 simulation results of the “district” solution with the “local” system (Fig. 2.1), the study highlights the potential for energy sharing with neighboring houses, providing insights for future simulations and system optimization investigations.

In the “local” solution, the heat utilized by solar collectors is stored in a local storage tank. Tap water is preheated by solar collectors through a heat exchanger and then heated up to 55 °C by an electric flow heater.

In the “district” solution, decentralized solar collectors act as the only heat source for the system. As the temperatures in the grid rise, tap water is preheated through a heat exchanger, reducing the need for auxiliary heating on the building side. The network in this scenario functions as a massive thermal storage system.

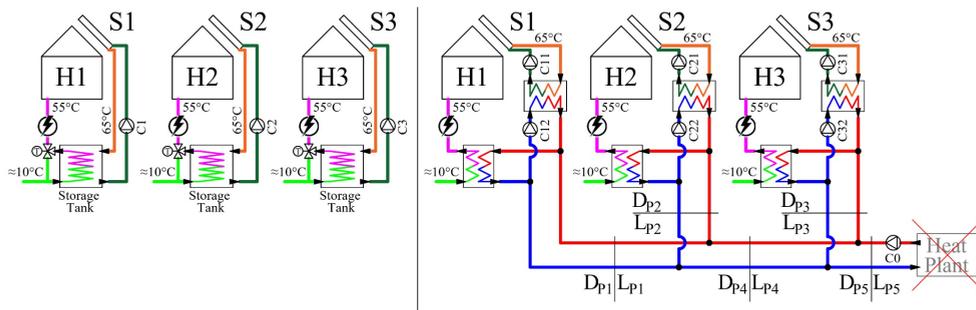


Fig. 2.1. Principal drawing of the studied “local” system (left) and “district” system (right).

Results show that production of useful solar energy depends on the amount of installed solar thermal collectors, the size of thermal storage and the heating load profile and can vary from 55.1 kWh/m² to 164.6 kWh/m² for a 5-month period (May–September) (Fig. 2.2).

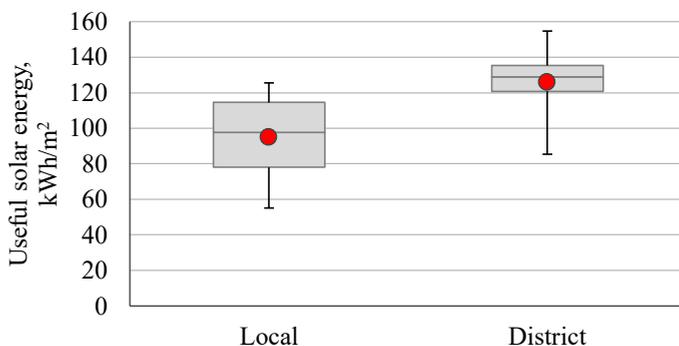


Fig. 2.2. Utilized useful solar energy, kWh/m² collector area. May–September.

Increasing the solar collector area in the “local” solution results in a reduction of energy production per square meter, but this effect can be mitigated by increasing the volume of the storage tank. This means that with limited storage, installing too many collectors leads to overheating and lower overall efficiency.

In the “district” solution, there is no need for a local storage tank due to the substantial volume of the DH system. The useful solar energy received in the “district” solution surpasses that of the “local” solution thanks to the lower heat carrier temperature in the DH system compared to the temperature in the local storage tank. Implementation of a 40 m² collector area on each house in the “district” solution can increase the amount of solar energy received by 13–22 % in comparison to the “local” solution with 40 m² collectors on each house and 1 m³, 2 m³ or 3 m³ storage tank.

The study found that the building domestic hot water demand profile can have an impact on the amount of energy received from the district heating system: it is more beneficial to install solar collectors on a restaurant roof rather than on a residential building, and the difference between residential and restaurant or office building is statistically significant ($p < 0.05$), but the difference between restaurant and office building is not statistically significant ($p = 0.24$).

More solar energy is produced when the collectors are evenly distributed between all buildings. However, even if the building does not have solar collectors, it can receive up to 38 % of solar energy through the district heating system. If this building is located too far (P4 length = 500 m), it will receive only 1–4 %. A larger main pipeline diameter and more compact consumer locations were found to result in higher efficiency. If the neighboring building without solar collectors is located further than 500 m from a prosumer, it receives a very small amount of solar energy through the district heating system.

Limitations and assumptions

During the research, it was concluded that the TRNSYS might not be the best tool to model the entire town DH system because of the high level of detail and the necessity to define parameters for each building. This issue may be minimized by combining several households into groups or using results from TRNSYS simulations in other software. The key objective of the model was to assess relationships between crucial parameters, which was successfully done. This information serves as a foundation for discussions on the practicality of implementing this approach in a case study. It is crucial that the model remains simple enough, providing clear identification of the influence of each parameter on the result.

The study concentrates on three distinct hot water consumption profiles, intentionally avoiding any weekly variations. This approach aims to minimize the number of variables, allowing for a clear examination of the specific profile's influence on the final results. It is crucial to note that the primary emphasis lies in the diversity of these profiles rather than their representation as real residential, office, or restaurant profiles. While future work considers utilizing real case studies with reference profiles for specific buildings, this study employs numerical modeling for the purpose of comparing and analyzing the profiles and their interplay. The model can be easily adapted to any other thermal energy consumption profiles.

The presented model was based on the described situation, with a small-scale DH system in the non-heating period, which is not used, with no defined temperature or pressure requirements. Frequent heat carrier temperature changes may cause unnecessary thermal stress on pipelines that may decrease their lifetime and need to be considered in future studies.

As the model represents a newly proposed solution without real-world examples, system validation is not yet feasible. However, future studies can apply this model using real data on pipeline dimensions and building energy consumption. To simulate a traditional setup where the DH system operates with a main plant and stable heat carrier temperature, detailed data on each building's location and heat demand are required. The absence of some consumers can lead to high pipeline losses and inaccurate simulation results.

Increasing the depth of pre-insulated pipelines has the potential to lower heat losses, but it simultaneously raises the installation costs. Consequently, identifying the optimal solution for each specific situation becomes important. This research focuses on integrating the proposed solution into an existing district heating system. Following recommendations from pipeline manufacturers and based on our real-world experience, pipelines usually range in depth from 0.6 m to 2.0 m, with an average of about 1.0 m. Therefore, a one-meter depth was chosen in the simulation, aligning with the practical limitations of the current infrastructure.

3. Solar-assisted heat pump in district heating system

Around 50 % of heating energy in Riga's district heating (DH) system is produced by burning biomass, but it is planned that 90 % of heat energy will be produced from renewable energy resources by 2030, reducing the dependence on natural gas (Rīgas Siltums JSC, 2024). The new development strategy anticipates that DH needs to be transformed into an energy sharing platform with allowing users to sell excess heat to the system, transforming it into a 4th generation district heating system (Dienas Bizness, 2023).

Therefore, there is a need and potential for greater solar energy integration into DH systems. This can be achieved through large-scale centralized solar parks (Paulick et al., 2018; Sørensen et al., 2012; Winterscheid et al., 2017) or small-scale decentralized solutions (Zajacs et al., 2022) located near consumers, reducing transmission losses and utilizing unused rooftop space. As the roof area is limited, it must be optimized to maximize energy output. To achieve this, lowering DH temperatures is recommended, which requires significant capital investments but can be implemented gradually – through zoning strategies (Lund et al., 2018) and in parallel with the building renovation process.



Fig. 3.1. Zoning scheme of DH system (red lines – main pipelines) for some Riga districts.

As the zoning approach is proposed (Fig. 3.1), a substation is required to isolate the zone from the main DH network. This can be achieved either by installing a heat exchanger to create an independent hydraulic zone or by implementing a mixing system to lower the heat carrier temperature. The zone primarily consists of multi-apartment buildings, with limited ground space due to playgrounds, recreation areas, parking and shading from buildings and trees. Therefore, the study proposes utilizing roof areas for installing solar technologies.

The research question focuses on maximizing solar heat generation within a DH network using limited roof space, with the broader goal of integrating solar energy into DH systems and decarbonizing the heating sector. Analysis focuses on technical potential and performance.

Solar energy can be converted to heat through two methods: (1) directly using solar thermal (ST) collectors, or (2) generating electricity with photovoltaic (PV) panels and using it to produce heat via electric heaters or heat pumps. Photovoltaic-thermal (PVT) systems combine these approaches, simultaneously generating both electricity and heat. It is most effective when PVT is combined with a heat pump.

The produced heat can be supplied to 4th or 5th-generation district heating (DH) systems, where it may be stored and redistributed as needed. This study investigates three configurations for integrating solar energy into DH systems (see Fig. 3.2):

1. Connecting ST collectors to the DH system through a heat exchanger.
2. Using a brine-to-water heat pump powered by electricity and heat from the PVT system.
3. Using an air-to-water heat pump powered by electricity generated by PV panels.

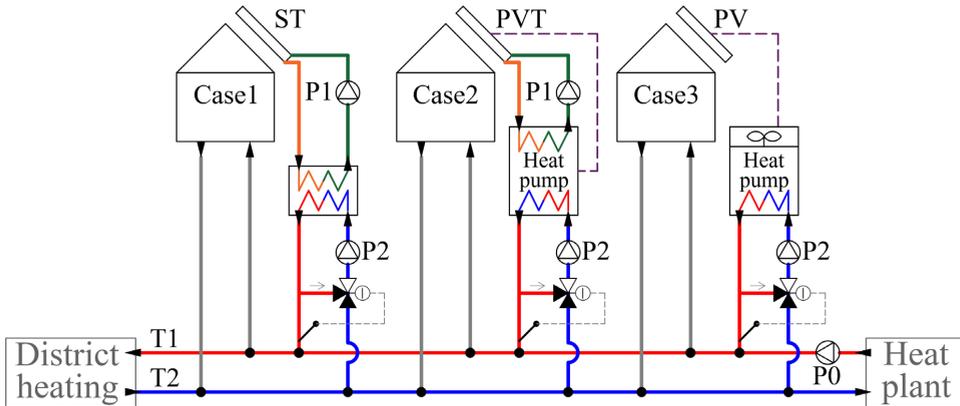


Fig. 3.2. Principal drawing of the studied system with 3 cases.

This study does not investigate the dynamic behavior of the DH system, including temperature and pressure fluctuations or heating capacity of the system. It is assumed that the DH network is sufficiently large to accumulate all produced heat.

To evaluate and compare cases, the following key performance indicators were used:

- produced useful heating energy per unit area of ST, PVT or PV system [kWh/m^2];
- thermal output ratio – the percentage of produced useful heating energy relative to total solar irradiation on the surface;
- system operating hours;
- heat losses in pipes (connect ST with the heat exchanger and PVT with the heat pump);
- circulation pump electricity consumption;
- heat pump coefficient of performance (COP).

Several scenarios were simulated for each case, varying ST, PV and PVT parameters under two DH temperature profiles:

- low-T with supply temperature 30–50 °C and return 20 °C;
- high-T with supply temperature 60–70 °C and return 40 °C.

To maximize the useful usage of the roof space and reduce the mechanical stress created by wind, the slope of the ST, PV or PVT surface is chosen to be 15° with the distance between surfaces of 2 meters, facing south.

The analysis was conducted using dynamic systems simulations in TRNSYS 18 with a one-minute timestep. Figure 3.2 shows the principal drawings of the studied systems. The climate for the Riga location was used from the Meteonorm V 5.0.13. database in TMY2 output format.

According to Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings, “heat pump” means a machine, a device or installation that transfers heat from natural surroundings such as air, water or ground to buildings or industrial applications by reversing the natural flow of heat such that it flows from a lower to a higher temperature. For reversible heat pumps, it may also move heat from the building to the natural surroundings.

Heat pump performance is based on the second law of thermodynamics, so it depends on the system's temperatures and especially on the temperature lift (Meggers et al., 2010). COP can be increased by decreasing the temperature lift – the difference between HP condensation temperature T_H and evaporation temperature T_C – according to Eqs. (3.1) and (3.2).

$$\text{COP}_{\text{ideal}} = \frac{T_H}{T_H - T_C}, \quad (3.1)$$

$$\text{COP}_{\text{real}} = \eta_{\text{Carnot}} \cdot \frac{T_H}{T_H - T_C} = \frac{Q}{E}, \quad (3.2)$$

where

$\text{COP}_{\text{ideal}}$ – maximal (theoretical) coefficient of performance;

COP_{real} – real coefficient of performance;

T_H – condensation temperature, K;

T_C – evaporation temperature, K;

η_{Carnot} – Carnot factor (or Carnot efficiency);

Q – produced heating power, W;

E – consumed electrical power, W.

The performance of air-to-water and brine-to-water heat pumps used in simulation was based on publicly available heat pump manufacturer data. Flat-plate and evacuated tube solar collector parameters are taken from (SPF Institute for Solar Technology, n.d.) database. Photovoltaic-thermal collector parameters are based on the research by Francisco et al. (2024).

Simulation results for Case 1 show that in the low-T system, FPC demonstrate higher performance than ETC, with annual heat utilization reaching up to 592 kWh/m². In the high-T case, the difference between FPC and ETC is minimal, with maximum annual useful heat production reaching 378 kWh/m². Results indicate that lowering the operating temperature can increase heat utilization by 31 % to 88 %, depending on the type and properties of the collectors.

Using PVT as a heat and electricity source for a brine-to-water heat pump, as proposed in Case 2, can maximize solar energy utilization, achieving 1040–1361 kWh/m² in a low-T DH system. This exceeds annual solar irradiation (1033 kWh/m²) on the PVT surface, because the heat carrier temperature in PVT is lower than ambient air temperature, allowing additional energy gains from the surrounding air.

For Case 3, two heat pump operation strategies were evaluated: (1) a constant operation scenario, where the heat pump runs year-round at a constant heat capacity, and (2) a solar availability scenario, where the heat pump operates only when solar energy is available. Despite having approximately half as many operating hours, the air-to-water heat pump achieved a

higher COP in the “solar” mode. In the low-T system, the total energy produced reached up to 977 kWh/m² in the “constant” mode and up to 1183 kWh/m² in the “solar” mode.

Figure 3.3 presents the results of useful energy production for all simulated cases. The data show that Case 2 offers the highest potential for maximizing solar energy output from a limited area. Notably, even under high-T conditions, Case 2 produces more useful energy than Case 1 does under low-T conditions.

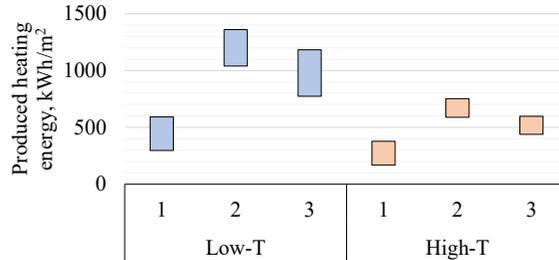


Fig. 3.3. Comparison of produced heating energy for each case; min/max.

This study assumes that the DH system has unlimited heating capacity, meaning it can absorb all produced heat without temperature changes. However, if the proposed system were installed on the roof of every building, total heat production could surpass consumption, leading to temperature increases and efficiency losses. To mitigate this, seasonal heat storage or restrictions on installed solar capacity per zone could be introduced.

Since peak solar heat production occurs in summer, when only domestic hot water (DHW) demand exists in residential areas, system feasibility must align with real consumption needs. Measurement data from multi-apartment buildings in Oslo, Norway (Walnum et al., 2021) shows that DHW heating energy demand ranges from 0.079 kWh/m² to 0.189 kWh/m² per day, averaging 0.127 kWh/m² per 24 hours or 46.2 kWh/m² per year. Assuming the DH system can store heat for a 24-hour period, it is possible to estimate the maximum ST, PV or PVT area.

Calculations show that in a low-T case, a BHP + PVT system can produce 8.39 kWh/m² per day, meaning 1 m² of PVT can provide DHW heating for 66 m² of building area. In the study’s case example, a 153.6 m² PVT system installed on a 530 m² roof could provide DHW for a 19-floor building or almost four five-story buildings. In such a way, it is possible to install both technologies – one building can produce heating energy in one of the ways discussed in this study and another building can produce electricity by using PV panels.

Limitations

This study focuses on the technical side of integrating solar energy and heat pumps into low-temperature district heating. A detailed economic analysis was not included, as it depends on multiple variable factors, like equipment prices, installation costs, energy tariffs, and electricity prices, all of which vary by time and location. Technological advancements may lower equipment costs, while inflation can increase labor and material expenses. District heating tariffs and electricity prices also vary over time, significantly impacting the payback period and influencing system selection. The goal here was to build a solid technical base. The economic side can and should be addressed in future studies using these results as input.

4. Impact of temperature fluctuations on the brine-to-water heat pump performance

As demonstrated in Chapter 1, the heat carrier temperature in solar thermal collectors can be unstable due to solar irradiation fluctuations and imperfect system control. Additional measurements taken by researchers from the Royal Institute of Technology (Francisco et al., 2024) confirm that the heat carrier temperature in photovoltaic-thermal (PVT) collectors also depends on solar irradiation intensity and its variations.

During this study, the heat carrier temperature in an existing 3rd generation DH system was measured in a multi-apartment building over three summer weeks with a 5-second time step. For one day with higher temperature fluctuations, the average supply temperature was 62.7 °C with a SD = 2.2 K, MAD = 2.0 K and a temperature range from 54.4 °C to 66.5 °C, but for the rest of the period, an average supply temperature of 65.0 °C with SD = 0.8 K and MAD = 0.6 K was recorded. Additionally, the district heating supply temperature was recorded in another building with a one-hour time step during a 2-year period. Measurements show that during the non-heating period, the average monthly supply temperature was 59.3–64.1 °C and monthly temperature SD varied from 1.2 K to 6.6 K, while MAD varied from 0.9 K to 3.3 K.

Considering a booster heat pump, the temperature in the district heating system needs to be lower, but this does not necessarily mean that temperature fluctuations become lower too, especially in the case of many small decentralized renewable heating sources with varying heating production load. Heating temperature lift is a key factor in heat pump system performance, but the impact of temperature fluctuations remains unexplored in the literature.

Heat pump manufacturers provide standardized tests under a limited number of controlled conditions, which differ significantly from those in low and ultra-low-temperature DH systems. In particular, high source temperatures (> 20 °C) and temperature fluctuations are not taken into account. As a result, there is very little data on how these fluctuations affect the heat pump's coefficient of performance (COP).

The optimal heat temperature in DH depends on many factors, including network size and consumption profiles, so a universal solution seems to be impossible. However, this study identifies a range of acceptable temperature fluctuations in the grid that are not tied to any specific location, climate or system configuration. These findings can therefore be applied universally to guide better system design and control strategies.

The aim of this study (Fig. 4.1) is to evaluate how fluctuations in heat source (T_{1in}) and sink (T_{2in}) temperatures impact the coefficient of performance (COP) of a brine-to-water heat pump in laboratory conditions by comparing COP at stable and fluctuating temperature conditions.

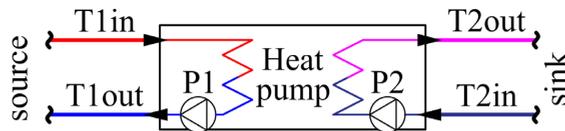


Fig. 4.1. Principal drawing of the studied system. P1, P2 – circulation pumps.

The experimental process

This research tested (Fig. 4.2) a 6-kW brine-to-water heat pump with heat source temperature from 0 °C to 28 °C and heat sink inlet temperature 25 / 30 / 35 / 40 / 45 / 50 / 55 °C under full load conditions with potential application with PVT collectors connected to the source side or as a booster heat pump in ultra-low temperature district heating system.



Fig. 4.2. Heat pump test facility.

To test the system, an experimental protocol was developed. As stated in previous sections, the measured mean absolute deviation (MAD) of heat carrier temperature from solar thermal collectors ranged from 0.47 K to 2.20 K at different temperature levels, control regimes, and weather conditions and the typical fluctuation period was measured to be from 8 to 15 minutes.

To measure the heat pump's COP at stable temperatures, a 25-minute interval was chosen, from which the initial 5 minutes of each measurement period were excluded from analysis to reduce possible errors during flow temperature adjustments. This shows good practice, since it allows for measuring a lot of different temperature combinations within a small time period, but provides good replication of measurements. Each measurement cycle was performed 3 times, and measurement uncertainty was calculated, which, for almost all measurements, were below 1 % (higher uncertainty was at high source temperatures and high sink temperatures).

For COP measurements under fluctuating conditions, a 4-minute interval of temperature setpoint changes was chosen, meaning that the fluctuation period was 8 minutes. One measurement cycle was 40 minutes. Six temperature ranges were used and arranged in non-regular order (± 8 K, ± 6 K, ± 1 K, ± 4 K, ± 0 K, ± 2 K) to avoid bias from a consistent increase or decrease in temperature fluctuations and ensuring that any observed effects on the heat pump's COP could not be attributed to a gradual trend in temperature changes. The MAD of the resulting fluctuations were in the range from 0.05 K (no fluctuations) to 6.00 K. To achieve this, a bot-driven setpoint control computer program was written, which changed the setpoint every 4 minutes and allowed to perform the experiment without interruption during the day and night.

The temperatures T_{1in} , T_{1out} , T_{2in} , and T_{2out} were measured using eight Class A surface temperature sensors (tolerance $\pm 0.15 + 0.002$ t), which were placed on opposite sides of the same cross-sectional area of the metal pipe as specified in EN 14511-3:2022, positioned as close to the heat pump as possible, and then insulated with closed cell flexible elastomeric foam insulation.

Main findings

The results show that the heat pump's (including both circulation pumps) COP is 3.9 % to 9.9 % lower than the COP of the heat pump's compressor (only). This difference is strongly influenced by the customer-side temperature change rather than by the source-side temperature.

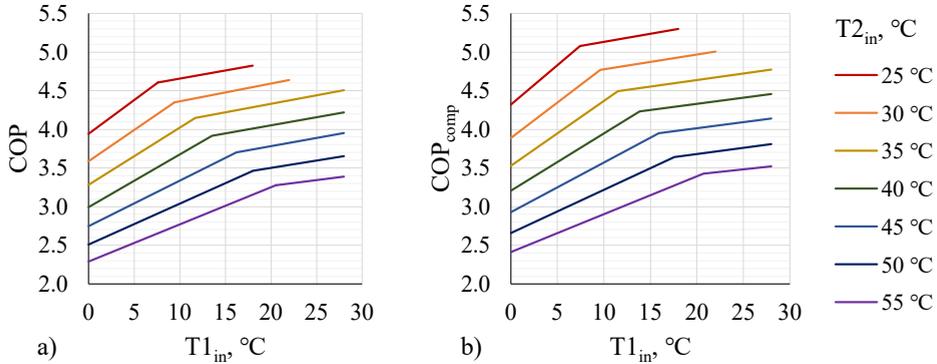


Fig. 4.3. a) COP of the heat pump; b) COP of the heat pump's compressor dependence on $T_{1,in}$ measured temperature at different $T_{2,in}$ temperature setpoints. The regression model.

Regression analysis showed that the relationship between source-side inlet temperature and heat pump COP can be described as a piecewise linear function (Fig. 4.3): a 1 K change in source temperature has a greater impact on COP at lower temperatures than at higher ones. The breakpoint temperature depends on the customer-side temperature (Table 4.1).

Table 4.1

Linear regression function of COP_{HP} dependence on $T_{1,in}$ temperature for different $T_{2,in}$ temperature cases, expressed in the $f(x) = a \cdot x + b$ form as a piecewise function.

$T_{2,in}$ setpoint	Before BP		Breakpoint (BP)	After BP	
	a	b		a	b
25 °C	0.087 ± 0.006	3.942 ± 0.024	7.64 °C	0.021 ± 0.003	4.446 ± 0.035
30 °C	0.081 ± 0.004	3.587 ± 0.024	9.40 °C	0.023 ± 0.001	4.132 ± 0.024
35 °C	0.074 ± 0.003	3.282 ± 0.017	11.69 °C	0.022 ± 0.001	3.890 ± 0.030
40 °C	0.068 ± 0.003	2.993 ± 0.021	13.57 °C	0.021 ± 0.001	3.631 ± 0.025
45 °C	0.059 ± 0.001	2.747 ± 0.012	16.24 °C	0.021 ± 0.002	3.364 ± 0.038
50 °C	0.053 ± 0.002	2.509 ± 0.017	18.00 °C	0.019 ± 0.003	3.121 ± 0.060
55 °C	0.048 ± 0.001	2.289 ± 0.014	20.58 °C	0.015 ± 0.003	2.968 ± 0.069

For further analysis, the COP_{HP} of the heat pump, including circulation pumps, was examined. It is important to note that heat pump capacity and electrical power also depend on source and sink temperatures. The heat pump's heat capacity ranged from 5.25 kW to 9.53 kW, while electrical power varied between 1.51 kW and 2.82 kW. This data was used to develop a heat pump performance dataset for use in the TRNSYS dynamic simulation program for further analysis and can be used in future research to simulate and analyze complex system behavior.

For each 40-minute measurement cycle, the heat pump's COP was calculated (4.1) and is represented as a dot in Fig. 4.4. Since the mean T_{1in} temperatures vary and are not constant, directly comparing COP values between measurement cycles would be misleading. Therefore, the COP for fluctuating cases is compared to a stable baseline case – representing the COP that would be expected at the same mean temperature without fluctuations, according to Fig. 4.3.

$$COP_{HP} = \frac{Q_h}{E}, \quad (4.1)$$

where

COP_{HP} – heat pump coefficient of performance;

Q_h – heat pump produced heating energy, kJ;

E – heat pump consumed electricity, kJ.

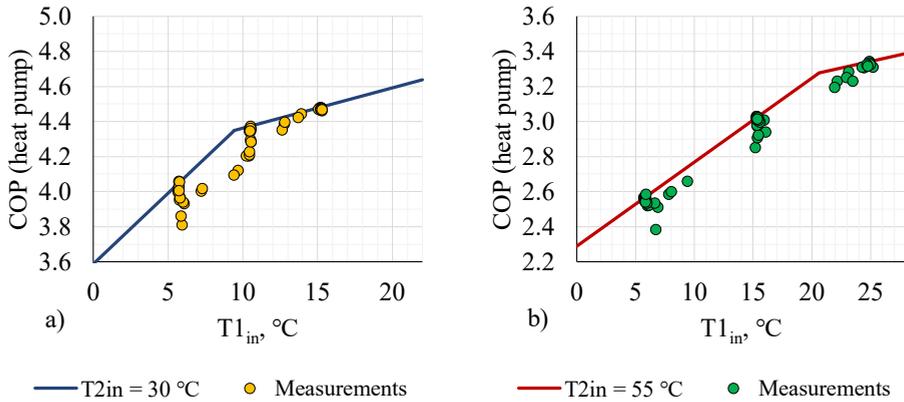


Fig. 4.4. COP dependence on T_{1in} mean temperature. Dots – COP at various temperature fluctuations over a 40-minute interval; line – COP under stable temperature conditions.

From Fig. 4.4, it is clear that COP values under fluctuating conditions do not match the COP values expected at stable conditions. To evaluate the influence of fluctuations on this difference, Fig. 4.5 is provided. Each dot in Fig. 4.4 includes a corresponding mean absolute deviation (MAD) value, and for each dot, the difference (ΔCOP) between the calculated COP and the expected COP at the same mean temperature without fluctuations was determined. The relationships between these differences and the MAD values are shown in Fig. 4.5.

For cases with $T_{2in} = 30$ °C and $T_{2in} = 55$ °C, there are statistically significant correlations ($p < 0.05$) between the MAD of T_{1in} and the ΔCOP at the same mean temperature without fluctuations. The correlation coefficients (r) show strong relationships between MAD and ΔCOP at lower temperatures (5 °C, 10 °C for $T_{2in} = 30$ °C and 5 °C, 15 °C for $T_{2in} = 55$ °C). However, as the source temperature rises above the breakpoint temperature (Table 4.1), the correlation becomes weaker.

For source temperatures below the breakpoint, a 1 K increase in the MAD of source temperature fluctuations results in a COP decrease of 0.027–0.041 (approximately 1 %). Above the breakpoint, the impact of fluctuations is minimal. Sink-side temperature fluctuations had a minimal influence on COP and remained within the measurement uncertainty.

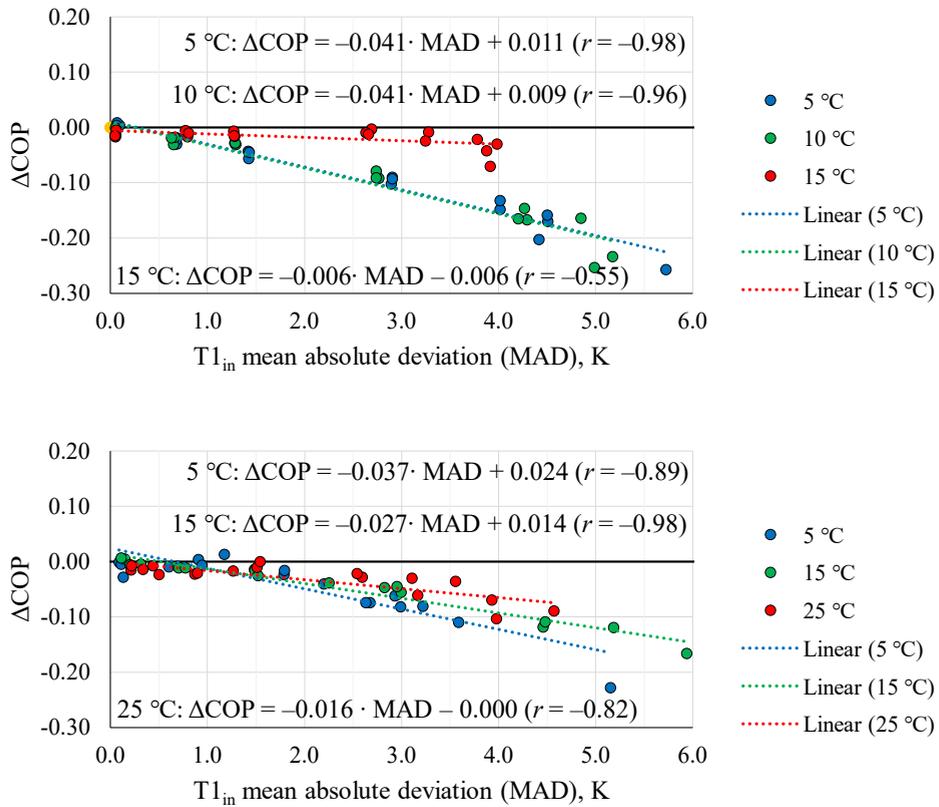


Fig. 4.5. Relationship between $T1_{in}$ MAD measured over 40-minute intervals and the difference between expected COP at the same mean temperature without fluctuations and calculated based on measured data. a) $T2_{in} = 30$ °C; b) $T2_{in} = 55$ °C.

To determine whether temperature fluctuations significantly impact COP value, ΔCOP must exceed the uncertainty of COP under stable conditions. The critical value of $T1_{in}$ MAD at which this occurs was calculated (Table 4.2). Because of uncertainties, it is impossible to determine the precise critical temperature MAD, so the interval in which it lies was provided.

Table 4.2

Heat pump COP and uncertainty (σ_{COP}) at stable temperature conditions, COP decrease slope with 99 % confidence interval and critical T_{1in} MAD when ΔCOP exceeds COP uncertainty.

T_{2in}	T_{1in}	Based on Table 4.1		ΔCOP slope (Fig. 4.5)	T_{1in} MAD _{critical} when $\Delta COP < \sigma_{COP}$
		$COP = a \cdot T_{1in} + b$	σ_{COP}		
30 °C	5 °C	3.992	± 0.031	-0.041 ± 0.006	[0.66–0.89] K
30 °C	10 °C	4.362	± 0.026	-0.041 ± 0.008	[0.53–0.79] K
30 °C	15 °C	4.477	± 0.028	-0.006 ± 0.007	[2.15–28.0] K
55 °C	5 °C	2.529	± 0.015	-0.037 ± 0.013	[0.30–0.63] K
55 °C	15 °C	3.009	± 0.021	-0.027 ± 0.004	[0.68–0.91] K
55 °C	25 °C	3.343	± 0.102	-0.016 ± 0.008	[4.25–12.8] K

When the MAD of temperature fluctuations on a source-side stays below 0.9 K, its impact on COP is within the measurement uncertainty. Taking into account that low-temperature solar collector experiments showed MAD values below 1 K, it can be concluded that solar energy variability under such conditions does not significantly affect heat pump performance.

TRNSYS computer simulations were performed using COP curves measured under stable conditions and temperature data from fluctuating conditions as an input. While the simulations also indicated a drop in COP with increased temperature fluctuation, the influence was weaker. This suggests that computer models do not fully capture all real-world impact on COP under dynamic conditions. Therefore, experimental data is more reliable for performance assessments.

Additional measurements using temperature and flow data from both solar thermal (ST) and photovoltaic-thermal (PVT) test facilities confirmed that when MAD values remain below or close to the critical MAD value (Table 4.2), the observed ΔCOP falls within measurement uncertainty. When MAD exceeds this threshold, a noticeable COP decrease occurs.

Measured data from PVT and ST collectors showed that the heat carrier temperature typically stays near or above the COP curve breakpoint temperature, and temperature MAD remains low. Under these conditions, no significant impact on heat pump COP was observed. However, in the case of widespread installation across a DH grid or poorly configured control algorithms, the COP of booster heat pumps potentially could be negatively affected.

Limitations

This research focused on a single brine-to-water heat pump using R407C refrigerant, with operation limited to source temperatures up to 30 °C. While this approach provided consistency and control, different heat pump models, refrigerants or compressor types may show varied performance, offering a path for future comparative studies. Load fluctuations were not part of this study but will be explored in future work using the experimental methods developed here. Additionally, variations in pressure difference and fluctuations in DH networks could affect circulation pump energy use and system COP because of higher electricity consumption with the pressure increase. To move closer to real-world operation, further testing under variable customer-side temperatures, flow profiles and partial load conditions is recommended using the developed methodology. These next steps will support practical, large-scale implementation.

CONCLUSIONS AND FUTURE STUDIES

The aim of this study was achieved by comparing the performance of different system configurations and operating conditions, showing the significant potential of the development of photovoltaic-thermal systems combined with brine-to-water heat pumps in low-temperature district heating networks. The results not only demonstrate the benefits of this integrated approach but also identify a clear pathway for future research and practical implementation.

The developed research methodology combines experimental measurements, simulations and statistical analysis, offering a flexible framework for future studies focused on evaluating heat carrier temperature fluctuations, calculating system thermal output and testing heat pump performance under varying conditions. This methodology serves as a foundation for further research, including the testing of different heat pump models, exploring additional system layouts and implementing alternative control algorithms.

The main conclusions

1. There is significant potential to expand the use of solar thermal (ST) collectors in Latvia. The key challenges are the seasonal mismatch, with around 75 % of useful ST energy absorbed between April and September, and low performance in traditional applications. This study recommends integrating ST collectors into low- or ultra-low-temperature district heating (DH) networks to utilize more solar energy and reduce overheating risk by utilizing the storage capacity of the network and enable energy sharing between buildings.
2. Heat carrier temperature fluctuations in ST systems are primarily influenced by solar irradiance variations, chosen operating temperature level and control strategy. These fluctuations can be effectively characterized by using the mean absolute deviation (MAD) parameter. Measurements showed that MAD values ranged from 0.47 K to 0.96 K at low temperatures (50/30 °C), 1.03 K to 1.61 K at medium temperatures (65/42 °C), and 1.02 K to 2.20 K at high temperatures (80/50 °C).
3. Large-scale solar collector plants have been successfully implemented in countries like Denmark, Sweden, Germany and Latvia. However, household-scale integration, where consumers also act as prosumers, remains rare. The limited availability of case studies and operational data from real-world applications slows down the development and practical implementation of the concept of decentralized solar integration in DH networks.
4. TRNSYS 18 simulations confirm that small-scale DH systems can effectively act as thermal storage for decentralized ST collectors, reducing reliance on local electric boilers during the non-heating period – a practice commonly observed in small towns in Latvia. Compared to “local” solutions, the “district” configuration showed 13–22 % higher solar energy utilization due to lower operating temperatures and larger storage volume.
5. The study confirms the energy viability of combining solar energy with heat pumps in DH systems. In particular, photovoltaic-thermal (PVT) collectors paired with brine-to-water heat pumps (BWHP) show strong potential to maximize solar heat output from limited areas. This combination enables high solar heat utilization, efficient use of space and improved overall system performance in low-temperature DH networks.

6. TRNSYS 18 simulations showed that PVT + BWHP systems produced the highest annual heat output: 1040–1361 kWh/m² in a low-temperature DH system. This is 1.8 to 4.6 times more than the calculated output from solar thermal collectors directly connected to the DH grid and up to 7.6 times more than the measured output of a traditional solution with local storage in a single-family house. However, to avoid overproduction and efficiency losses, seasonal heat storage or capacity limits must be considered when scaling up the system.
7. The relationship between source-side inlet temperature and BWHP COP is a piecewise linear function. Below the breakpoint (BP), a 1 K increase in MAD reduces COP by up to 1 %; above the BP, the effect is minimal, indicating higher sensitivity to temperature fluctuations at lower source temperatures. When MAD is below 0.9 K, this impact falls within the 99 % confidence interval and cannot be statistically confirmed. Fluctuations on the sink side had minimal influence and remained within the measurement uncertainty.
8. Temperature and flow fluctuations from ST and PVT collectors had little effect on the heat pump's COP, as measured MAD values stayed near or below critical thresholds. However, large-scale implementation or poor control strategies could cause higher variability and reduce heat pump efficiency, highlighting the importance of monitoring and system design.

The hypothesis was confirmed through experimental measurements, showing that heat source temperature fluctuations caused by solar energy variations can reduce the coefficient of performance of a brine-to-water heat pump when the source temperature is low (8–21 °C, depending on sink temperature), as is typical in ultra-low-temperature district heating systems. Under low-temperature DH conditions (≥ 20 °C), temperature fluctuations had no significant impact on COP. It should be noted that these tests were performed on a specific heat pump model, so results may vary with other models. However, the general testing principles and the developed methodology are applicable for evaluating other heat pumps in future studies.

The results of this study have been published in scientific journals and presented at international conferences, with at least two more journal articles planned based on the findings.

These results can aid decision-making in district heating system development, optimizing solar energy integration and heat pump utilization to improve overall efficiency. However, a detailed economic analysis considering real prices and energy tariffs is necessary to determine payback periods, which remains a future research direction. Additionally, the low- and ultra-low-temperature DH concept offers the potential for district cooling development using heat pumps, making this an important area for future research and system optimization.

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DECLARATION OF GENERATIVE AI

During the preparation of this work, the OpenAI “ChatGPT” was used in order to improve readability and language. After using this tool, the content was reviewed and edited as needed.

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