RIGA TECHNICAL UNIVERSITY
Faculty of Electrical and Environmental Engineering
Institute of Energy Systems and Environment

Ieva Pakere
Doctoral Student of the Study Programme “Environmental Science”

SOLAR ENERGY IN LOW TEMPERATURE DISTRICT HEATING

Summary of the Doctoral Thesis

Scientific supervisor
Professor Dr. habil. sc. ing.
DAGNIJA BLUMBERGA

RTU Press
Riga 2020

Pakere, I. Solar Energy in Low Temperature
District Heating.
Riga: RTU Press, 2020. 36 p.

Published in accordance with the
decision of the Institute of Energy Systems and Environment of 2 March 2020,
Minutes No.112.

This work has been supported by:

- Project "Development of the Academic personnel of Riga Technical University in the strategic fields of specialization" funded by European Social Fund (No. 8.2.2.0/18/A/017);
- Project "Development of heat supply and cooling systems in Latvia" funded by National Research Programme (VPP) (No. VPP-EM-EE-2018/1-0002);
- Project "Low Temperature District Heating for the Baltic Sea Region" (LowTEMP) funded by the European Commission through the EU INTERREG Baltic Sea Region (No. #R063).

NACIONĀLAIS ATTĪSTĪBAS PLĀNS 2020
EIROPAS SAVIENĪBA
Eiropas Sociālais fonds
IEGULDĪJUMS TAVĀ NĀKOTNĒ

ISBN 978-9934-22-445-4 (print)
ISBN 978-9934-22-446-1 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERISTY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCES

To be granted the scientific degree of Doctor of Sciences (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 8th of June, 2020 at 10 am the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12 k-1 Azenes Street, Room 115.

OFFICIAL REVIEWERS

Professor Dr. sc. ing. Ritvars Sudārs
Latvia University of Life Sciences and Technologies, Latvia

Researcher Dr. sc. ing. Vladimirs Kirsanovs
Riga Technical University, Latvia

Professor Dr. ing. Stefan Holler
HAWK Hildesheim/Holzminden/Göttingen University of Applied Sciences and Arts, Germany

DECLARATION OF ACADEMIC INTEGRITY

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

Ieva Pakere ……………………………….. (signature)

Date ………………………..

The Doctoral Thesis has been written in English. It consists of an introduction; three chapters; Conclusion; 59 figures; 19 tables; the total number of pages is 165. The bibliography contains 123 titles.

CONTENTS

INTRODUCTION

In many countries, including Latvia, providing the heat in buildings and preparation of hot water is one of the basic needs. Currently, there is an ongoing discussion on how to optimize the heat supply to reduce the share of fossil energy resources and to ensure an optimal level of energy costs. The district heating (DH) system`s infrastructure plays an important role to improve the energy efficiency and adapt available RES to energy consumption (Latosov et al., 2017). DH network connects buildings in different areas of cities and other settlements, so different centralized boiler houses or several smaller heat sources can supply the heat to consumers. This approach allows using any heat source integrated into the DH system.

The heat consumption of buildings continues to decrease due to energy efficiency measures and increased building standards of new buildings. Therefore, it is often not economically viable to connect energy efficient buildings to a standard heat supply system because such a DH system has high fixed costs due to high capital investments. When the heat consumption decreases, it is possible to use a heat carrier with a lower temperature in the heat supply system, reduce the diameters of the pipelines, ensuring an optimal flow rate of the heat carrier (Rama & Sipila, 2017; Elmegaard et al., 2016). Therefore, renewable energy sources (solar energy, ambient heat, etc.) and low potential surplus heat from different industrial processes can be used as heat sources more efficiently. Based on these aspects 4th generation district heating (4GDH) system concept has been developed (Fig. 1) (Lund et al., 2014). 4GDH concept provides the reduction of temperature in the heating networks, integration of renewable energy resources and low potential thermal energy in order to provide sustainable heat supply.

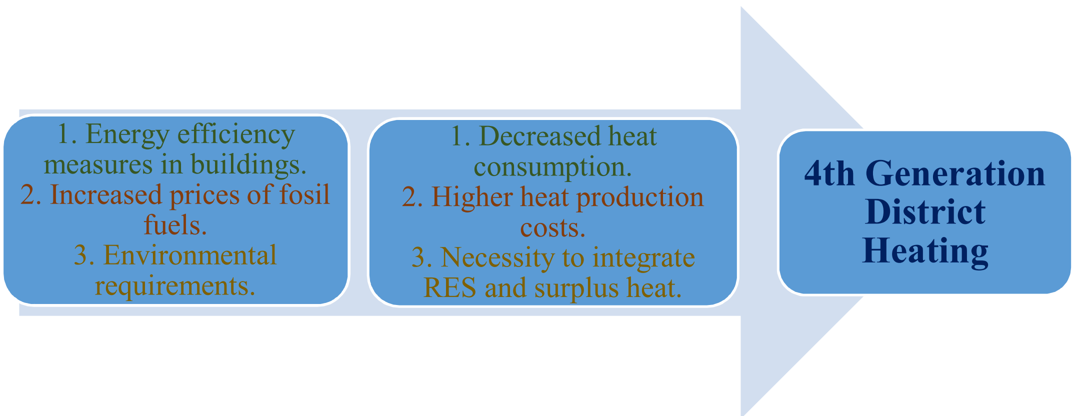


Fig. 1. Driving forces of 4th generation district heating.

Competitiveness of DH system derives from a combination of conditions of heat generation and supply efficiency. An important requirement for optimal heat supply is a concentrated heat demand in order to reduce the distribution costs and the heat losses. An area with low heat density generates relatively higher distribution costs. The DH system will have to address the following challenges, in order to maintain its role as sustainable energy system in the future (Averfalk & Werner, 2017):

- to supply low-temperature heat for space heating and domestic hot water preparation in existing buildings, renovated buildings and new low-energy buildings;

- to supply heat in networks with low heat losses;
- to use heat from the low-temperature sources and to integrate renewable energy sources (RES), including solar and geothermal heat;
- to be an integral part of intelligent energy system, including integrated 4th generation district cooling;
- to ensure appropriate operational planning and costs, as well as strategically plan investment for development.

Research Topicality and Hypothesis

The hypothesis of the research is that the solar energy is a sustainable and cost effective solution for energy production in 4GDH when the long-term planning and appropriate organisation is applied.

Currently, there are the following challenges for the heating system in Latvia and other European Countries:

- large share of heat losses in networks due to installation of too large pipelines, poor insulation of heat pipes, and low heat density;
- inefficient heat production by outdated and low efficiency equipment;
- continuous changes of fossil fuel and biomass prices;
- wide choice of individual heat generating units for consumers which are easy to operate;
- development of prosumer concept offering the energy for other consumers;
- lack of appropriate monitoring and analyses of main heat generation and supply parameters;
- missing strategic planning of future development of heat and cold supply of the local and national policy makers.

All those aspects result in lower heat demand or higher heat generation costs and increase of main indicator − heat tariff. If the DH heat tariff is high, the consumer is free to choose an alternative heat supply option: individual boilers, solar collectors, heat pumps, etc. The circle of interactions continues as each lost customer raises the specific heat costs of DH system. By continuing the traditional heat supply concept, it is easy to destroy the existing DH infrastructure that could be used for sustainable development of energy sector.

DH systems are a great opportunity to increase renewable energy proportion in both heating and cooling sectors. The renewable energy sources (RES) can be integrated into DH for both heat load coverage and power production used for heat generation and transmission. This requires technological and strategic planning changes in energy supply. Installation of solar collectors for the heat production in DH has become a widespread solution in several countries. In addition, solar photovoltaic (PV) panels can be used in DH systems to generate electricity for heat production and transmission. Solar energy is an important element in 100 % cost effective renewable power systems. However, generated solar energy follows the available solar radiation not the actual power consumption that leads to necessity to redesign the operation strategy of energy system.

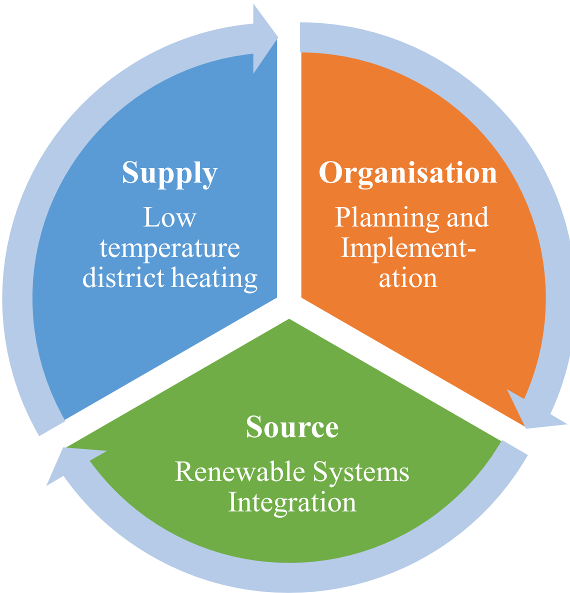


Fig. 2. Three pillars of sustainable development of district heating (Lund et al., 2014).

To maintain the role of DH as an energy efficient and economically justifiable solution for heat supply, further development of DH should be based on three key elements: low temperature heat supply, integration of renewable energy resources, and long-term planning. The Doctoral Thesis includes all of these milestones, evaluating the potential of solar energy integration as a perspective for sustainable DH development.

Aim and Objectives

The aim of the Thesis is to develop the methodology for evaluation of different solar energy integration strategies in low temperature DH systems.

The main objectives for achieving the goal are:

- to perform the particular district heating system analyses by applying regression analyses and developing energy balance model;
- to identify and evaluate long-term transformation paths for DH system;
- to evaluate solar energy potential and test various technical solutions and operation strategies for solar energy integration in DH by using empirical and system dynamics modelling;
- to rank the analysed solar energy system configurations by evaluating different criteria and applying multi-criteria analyses method;
- to determine the main aspects influencing the solar system performance by applying sensitivity analyses;
- to evaluate the operation of first solar power station in Latvia by regression analyses.

Scientific Novelty

The algorithm of developed methodology can be seen in Figure 3. Each step of the methodology has been presented in one or several articles listed in Table 1.

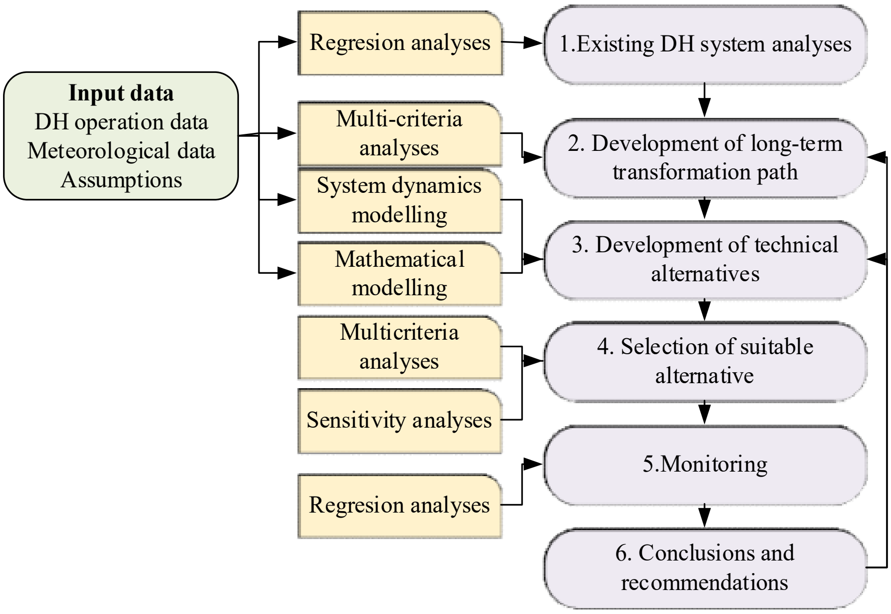


Fig. 3. Research algorithm and methods used in different steps.

Table 1

Scientific Articles Used in the Doctoral Thesis to Represent the Steps of the Developed Methodology

Methodology step	No	Publication title
1. DH system analyses	1	Lowering temperature regime in district heating network for existing building stock.
2. Development of long-term transformation path	2	The future competitiveness of the non-Emissions Trading Scheme district heating systems in the Baltic States.
	3	Introduction of small-scale 4th generation district heating system. Methodology approach.
3. Development of technical alternatives	4	Solar energy use in district heating systems. A case study in Latvia.
	5	Solar power and heat production via photovoltaic thermal panels for district heating and industrial plant
	6	Solar power in district heating. P2H flexibility concept.
4. Suitable alternative selection	7	Solar power or solar heat: What will upraise the efficiency of district heating? Multi-criteria analyses approach.
5. Monitoring	8	The first solar power plant in Latvia. Analysis of operational data.

The first step represents the analyses of existing DH system and the potential for heat carrier temperature lowering (Article 1). For evaluation of the operation data the regression analyses method is used. The second step derives from the obtained results in the first step and therefore represents the comparison of different long-term transformation paths for DH system. Article 2 presents the DH system technological solutions, which are compared by multi-criteria analyses method. Article 3 presents the results for DH temperature lowering in a particular small-scale DH system.

For the analyses of solar energy integration into the DH system (Step 3), three different models were analysed for the particular DH system (Articles 4−6). Each model differs in technological configuration, demand alignment strategy and the used simulation method. To evaluate solar thermal and solar combined system performance the mathematical energy balance models were developed. For the evaluation of dynamic aspects related to solar power technologies, the system dynamics modelling (SD) was used. The results obtained from the solar models are compared by two different multi-criteria analyses methods evaluating different aspects and scenarios (Article 7). In addition, the sensitivity analyses is performed in order to evaluate the possible changes of main variables. It is very important to monitor the developed energy systems and their operation, therefore Article 8 presents the monitoring results of the first larger scale solar power plant in Latvia.

Scientific Significance

The research has high scientific significance as it provides a novel methodology for determining optimal technological and operational strategies for solar energy integration into the low temperature DH system. The method allows choosing the main transformation path for DH development and identifying several technological scenarios for solar energy integration into the 4GDH.

The obtained results of different solar models highlight various aspects that need to be taken into account when planning the solar DH system. Therefore, analyses include both solar heat, solar power and combined solar systems representing different opportunities for solar energy use.

Practical Significance

The existing DH systems face significant changes due to building heat requirements. It enforces the operators search innovative solutions for heat production and transmission. Therefore, the research has high practical significance as it identifies alternatives for the sustainable DH development and evaluates the related technical, economic and environmental aspects.

The presented methodology and the obtained results can be used both at national level in the planning of the energy sector, in the development of local governments' heat supply strategies, and in the heating industry, assessing future development prospects.

Approbation of the Research Results

1. Pakere, I., Blumberga, D. Solar power or solar heat: What will upraise the efficiency of district heating? Multi-criteria analyses approach (2020) *Energy* 198, 117291.
2. Grāvelsiņš, A., Pakere, I., Tukulis, A., Blumberga, D. Solar power in district heating. P2H flexibility concept. (2019) *Energy.* 181, 1023−1035.
3. Pakere, I., Blumberga, D. Solar Energy in Low Temperature District Heating (2019). *Environmental and Climate Technologies.* 23 (3), 147−158.

4. Feofilovs, M., Pakere, I., Romagnoli, F. Life Cycle Assessment of Different Low-Temperature District Heating Development Scenarios: A Case Study of Municipality in Latvia. (2019) *Environmental and Climate Technologies.* 23 (2), 272−290.
5. Tukulis, A., Pakere, I., Grāvelsiņš, A., Blumberga, D. Methodology of system dynamic approach for solar energy integration in district heating. (2018) *Energy Procedia,* 147, 130−136.
6. Pakere, I., Lauka, D., Blumberga, D. Solar power and heat production via photovoltaic thermal panels for district heating and industrial plant. (2018) *Energy*, 154, 424-432.
7. Pakere I., Romagnoli F., Blumberga D.· Introduction of small-scale 4[th] generation district heating system. Methodology approach. (2018) *Energy Procedia,* 149, 549−554.
8. Lauka D., Pakere I., Blumberga D. First solar power plant in Latvia. Analysis of operational data, *Energy Procedia*, 147, 2018, 162−165.
9. Soloha, R., Pakere, I., Blumberga, D. Solar energy use in district heating systems. A case study in Latvia. (2017) *Energy,* 137, 586−594.
10. Pakere, I., Ziemele, J., Blumberga, D. DH company in prosumers role. (2017) *Energy Procedia*, 128, 234−239.
11. Ziemele, J., Pakere, I., Blumberga, D. The future competitiveness of the non-Emissions Trading Scheme district heating systems in the Baltic States. (2016) *Applied Energy*, 162, 1579−1585.
12. Cirule, D., Pakere, I., Blumberga, D. Legislative Framework for Sustainable Development of the 4th Generation District Heating System. (2016) *Energy Procedia*, 95, 344−350.
13. Ziemele, J., Pakere, I., Chernovska, L., Blumberga, D. Lowering temperature regime in district heating network for existing building stock. (2016) *Chemical Engineering Transactions*, 52, 709−714.
14. Ziemele, J., Pakere, I., Blumberga, D. Development of District Heating System in Case of Decreased Heating Loads. (2014) The 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2014): Proceedings, 2044−2055.
15. Ziemele, J., Pakere, I., Talcis, N., Blumberga, D. Multi-criteria analysis of district heating systems in baltic states. (2014) *Energy Procedia*, 61, 2172−2175.

Other Scientific Publications

1. Pakere, I., Lauka D., Blumberga, D. Estimation of Carbon Emission Reduction from Upgrading the DH Network to the 4th Generation. Multivariate Linear Regression Model. (2019) *Environmental and Climate Technologies*, 23 (2), 64−73.
2. Pakere, I., Purina, D., Blumberga, D., Bolonina, A. Evaluation of Thermal Energy Storage Capacity by Heat Load Analyses. (2016) *Energy Procedia*, 95, 377−384.

3. Ziemele, J., Pakere, I., Blumberga, D., Zogla, G. Economy of Heat Cost Allocation in Apartment Buildings. (2015) *Energy Procedia*, 72, 87−94.

4. Ziemele, J., Pakere, I., Talcis, N., Cimdina, G., Vigants, G., Veidenbergs, I., Blumberga, D. Analysis of wood fuel use development in Riga. (2014) *Agronomy Research*, 12 (2), 645−654.

5. Dāce, E., Pakere, I., Blumberga, D. Evaluation of Economic Aspects of the Deposit-Refund System for Packaging in Latvia. (2013) *Management of Environmental Quality: An International Journal,* 24 (3), 311−329.

6. Dāce, E., Pakere, I., Blumberga, D. Analysis of Sustainability Aspects of the Packaging Deposit-Refund System in Latvia. (2013) *Sustainable Development and Planning VI: WIT Transactions on Ecology and the Environment, (173)* New Forest. 729−740.

Reports at Scientific Conferences

1. Pakere, I., Blumberga, D. "Solar power or solar heat: What will upraise the district heating?". *International conference "5th International Conference on Smart Energy Systems"*, Denmark, Copenhagen, September 10−11, 2019.

2. Pakere, I., Lauka, D., Blumberga, D. "Estimating carbon emission reduction from low temperature district heating implementation trough multivariate linear regression model". *International scientific conference of Environmental and Climate Technologies "CONECT 2019"*, Latvia, Riga, May 15−16, 2019.

3. Pakere, I., Blumberga, D. "Solar energy in low temperature district heating". *International scientific conference of Environmental and Climate Technologies "CONECT 2019"*, Latvia, Riga, May 15−16, 2019.

4. Feofilovs, M., Pakere, I., Blumberga, D. "Life cycle analysis of different Low-temperature district heating development scenarios: A case study of municipality in Latvia". *International scientific conference of Environmental and Climate Technologies "CONECT 2019"*, Latvia, Riga, May 15−16, 2019.

5. Tukulis, A., Pakere, I., Blumberga, D. "Solar DH system sustainability and flexibility increase forecast via power-to-heat technology integration. System dynamic approach". *International conference "4th International conference on Smart Energy Systems and 4th generation District Heating"*, Denmark, Alborg, November 13−14, 2018.

6. Pakere, I., Romagnoli, F., Blumberga, D. "Introduction of small-scale 4th generation district heating system. Methodology approach". *International conference "The 16th International Symposium on District Heating and Cooling"*, Germany, Hamburg, September 9−12, 2018.

7. Tukulis, A., Pakere, I., Gravelsins, A., Blumberga, D. "Methodology of system dynamic approach for solar energy integration in district heating". *International conference;*

International scientific conference of Environmental and Climate Technologies "CONECT 2018", Latvia, Riga, May 16−18, 2018.

8. Pakere, I., Ziemele, J., Blumberga, D. "DH Company in Prosumers role". *International scientific conference of Environmental and Climate Technologies "CONECT 2017"*, Latvia, Riga, May, 2017.
9. Pakere, I., Blumberga, D. "Solar collectors versus solar panels in DH". *International conference "3rd International conference on Smart Energy Systems and 4th generation District Heating"*, Denmark, Alborg, September 12−13, 2017.
10. Soloha, R., Pakere, I., Blumberga, D. "Solar Energy Share in DH system. Case study in Latvia" *"2nd International conference on Smart Energy Systems and 4th generation District Heating"*, Denmark, Alborg, September 27−28, 2016.
11. Purina, D., Pakere, I., Blumberga, D., Bolonina, A. "Evaluation of thermal energy storage capacity by heat load analyses". *International scientific conference of Environmental and Climate Technologies "CONECT 2015"*, Latvia, Riga, October 14−15, 2015.
12. Cirule, D., Pakere, I., Blumberga, D. "Legislative framework for sustainable development of the 4th generation district heating system". *International scientific conference of Environmental and Climate Technologies "CONECT 2015"*, Latvia, Riga, October 14−15, 2015.
13. Ziemele, J., Pakere, I., Blumberga, D., Zogla, G. "Economy of Heat Cost Allocation in Apartment Buildings". *International conference "Environmental and Climate Technologies"*. Latvia, Riga, October 14−15, 2014.
14. Ziemele, J., Pakere, I., Blumberga, D. "Development of District Heating System in Case of Decreased Heating Loads". *International conference "The 27th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2014)"*, Finland, Turku, June 15−19, 2014.

Monograph

1. Barisa, A., Blumberga, A., Blumberga, D., Grāvelsiņš, A., Gušča, J., Lauka, D., Kārkliņa, I., Muižniece, I., Pakere, I., Priedniece, V., Romagnoli, F., Rošā, M., Seļivanovs, J., Soloha, R., Veidenbergs, I., Vīgants, E., Vīgants, Ģ., Ziemele, J. Energy System Analysis and Modeling. Riga: RTU Press, 2018. 144 p. ISBN 978-9934-22-037-1.

Thesis Outline

The Doctoral Thesis is based on eight thematically unified scientific articles that are presented, and the results have been approbated in various scientific conferences. All articles are accessible in international citation databases. The articles describe the unified methodology for DH transformation process towards low temperature district heating with integrated solar energy technologies.

This Thesis consists of introduction and three sections:

- literature review,
- research methodologies,
- results and conclusions.

The introduction presents the aim of the Doctoral Thesis, the scientific and practical importance of the work, as well as a brief outline of the approbation of published research results at various scientific conferences. This section also includes publications and monographs related to other areas of research of the author.

The first section of the work includes a literature review on topicality of low temperature DH and integration of solar energy. The second section describes the research methods that are related to the research of sustainable development of DH system and solar energy integration. The section of the results presents the identified long-term transformation paths, solar energy models and sensitivity analyses. Finally, conclusions are given at the end of the Thesis, which answers the question of sustainable development of DH system. The Bibliography contains 123 titles.

1. LITERATURE REVIEW

1.1. Development of Low Temperature DH Concept

Increasing energy efficiency and optimizing power systems has become a key task to promote energy security and reduce the overall environmental impact. Political decisions and regulations at both European and national level contribute to this (EP, 2012; Saeima, 2016). Several scientists have developed the idea of 100 % renewable energy systems (Ostergaard et al., 2010; Ostergaard & Lund, 2011; Lund, 2007). Such conceptual systems are mainly based on the combination of variable RES (wind, geothermal, solar) with more independent resources such as the waste and biomass. However, in order to reduce the need for biomass that should primary be used for the production of higher quality products, the concept of sustainable energy system development should also include energy source diversification, energy efficiency and energy savings.

Henrik Lund, Swen Werner and other authors in 2014 (Lund et al., 2014) defined the hypothesis that DH and cooling play an important role in future sustainable energy systems, but those systems need to adapt and implement new technological and strategic solutions to maintain their competitiveness. Existing heating systems require essential changes by reducing the heat carrier's temperature in networks; adapt to the energy consumption of energy-efficient buildings and become part of a common "smart energy systems". Therefore, the term "4th Generation District Heating" (4GDH) was introduced (Lund et al., 2014).

Smart power systems focus on interaction between the electricity, heating, cooling and transport sectors, as well as on balancing the consumption and energy storage systems. To achieve this, it is necessary to coordinate the operation of a number of smart infrastructures − electricity networks, DH and cooling networks, gas networks and various fuel infrastructures.

Future DH system infrastructure should be developed for the future and not for the current energy system. One of the further development tasks will be to integrate DH into the common energy system by interacting with the electricity and transport sectors (Jiang et al., 2014). Such a future system is defined as an intelligent energy system, i.e. an energy system in which smart electricity, heat and gas networks are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each flow as well as for a common energy system (Lund, 2014).

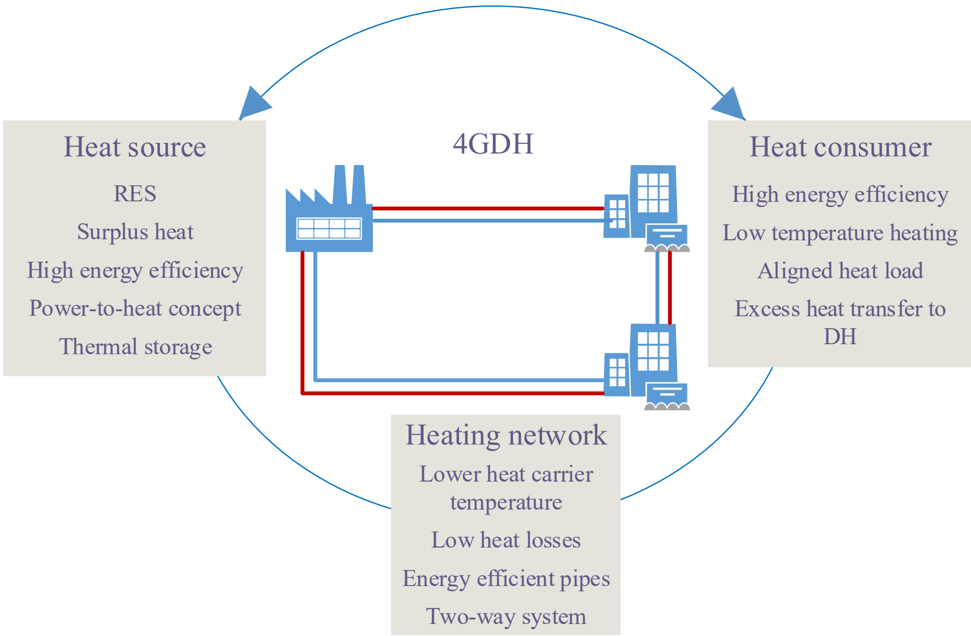


Fig. 1.1. Interaction between the DH system elements.

DH system consists of three main elements (heat source, heating network, and heat consumers), which have a certain role in overall operation of the system. Therefore, there should be certain technical and operational adaptions to develop the 4GDH. Figure 1.1 shows the interaction between all DH system elements. Lowering the heat carrier temperature is possible and beneficial only in cases where the consumer is appropriately adapted.

1.2. Solar Thermal Energy

The integration of solar thermal energy in DH systems is a more and more common practice in many countries all over the world. The general idea for solar collector field integration in DH networks is to partly or fully supply the summer heat demand of a DH system. Previous studies have shown that a high solar fraction in solar DH is feasible only by introducing a large-scale seasonal storage into the system. In general solar DH systems consist of large collector fields integrated into a DH system for supplying heat to residential and industrial areas. The collector field is typically ground mounted in close connection to the conventional DH plant (Tulus et al., 2016).

Solar collector efficiency is strongly influenced by heat carrier temperature. Figure 1.2.1 shows the variety of solar collector efficiency curve as a function of the temperature difference between heat collector and the ambient temperature. The efficiency curve differs for different solar collector types.

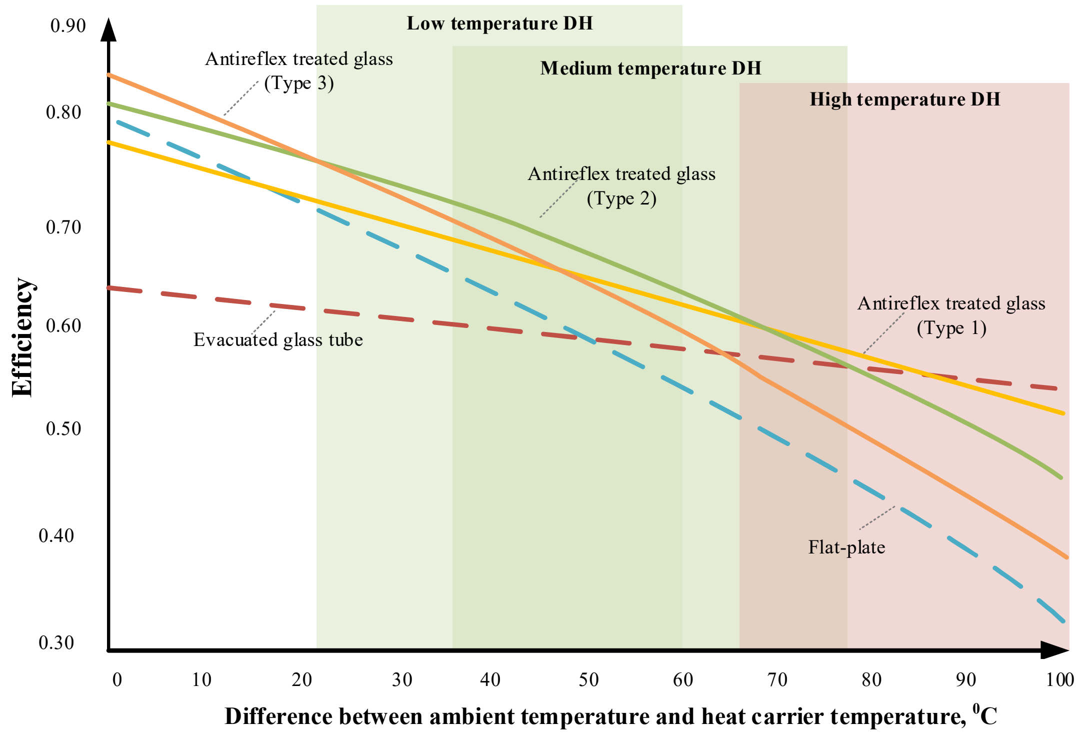


Fig. 1.2. Solar collector efficiency dependence on the temperature difference between the heat carrier and abundant temperature (Rosa et al., 2012).

Figure 1.2. schematically marks the low, medium and high temperature DH system boundaries. It shows the different types of collector efficiency curve but they all have a similar trend. The collector efficiency increases when temperature difference decreases. Therefore, lowering of the heat carrier temperature can significantly increase the efficiency of solar collectors and it is possible to produce more heat.

1.3. Solar Power

One of the opportunities for DH system development is the integration of solar PV panels for self-consumption coverage (Pakere et al., 2018). A stand-alone photovoltaic power system is a complete set of interconnected components for converting solar irradiance directly into electricity and generally consists of the PV generator, battery, charge controller, inverter, and the system load (Sakellariou & Axaopoulos, 2017). The main reason why PV panels start to look interesting in DH system is that their prices are decreasing rapidly. The forecasted price reduction was from an average of 3 % (Dobrotkova et al., 2018) to 7 % (Feldman et al., 2014).

PV cells only convert a certain wave type of the incoming irradiation that can be used to direct conversion of light into electricity. Only 15–20 % of incident solar energy is converted into electricity. The rest of solar energy is converted into heat, which causes heating of the solar cells in PV panels. The surface of the PV panel can be heated up to 40˚C above ambient temperature (Makki & Omer, 2015).

Consumption load management and grid-interactivity are the key factors analysed for more flexible renewable energy system solutions (Elcia et al., 2015). There is an additional solution for utilizing the power from the RES when the power consumption is lower than the production rate. This amount of generated solar power can be defined as a surplus power, which due to legislative or economic reasons cannot be fed into the grid. When such conditions occur, one of the possibilities is to convert power to heat (P2H) via electric boilers or heat pumps (HP) (Averfalk et al., 2017) and used in the local (Hirvoneva et al., 2016) or large-scale heating systems (Salpakari et al., 2016). Figure 1.3 shows the interaction of heat production costs and electricity price for different heat generation technologies. Therefore, P2H concept is feasible when the electricity price is lower than the heat production costs of other heat generation technologies (Moller et al. 2018).

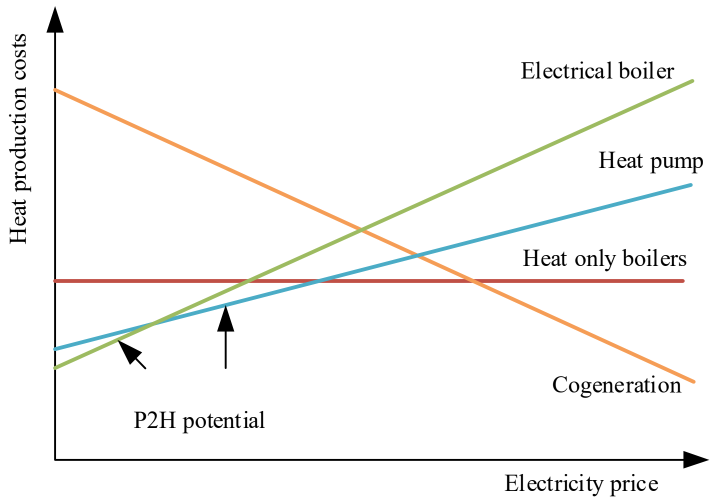


Fig. 1.3. Interaction of heat production costs and electricity price for different heat generation technologies (Moller et al. 2018).

Hypothetically, DH would be a suitable application for the P2H concept because electricity can be directly used for heat generation and transmission in boiler house, while the surplus power can be converted to heat and fed into the heat supply system.

2. METHODOLOGY

There is no single solution for all DH systems how to lower the heat carrier temperature, integrate solar energy and raise the overall operational efficiency. The 4th generation DH systems need to be embedded in an overall energy strategy, which investigates and displays the possibilities on how to apply such a system. Hence, it requires a careful strategic planning process towards the sustainable development of the new generation DH system. For all these reasons this methodology aims to present the steps for a detailed analyses of the existing DH system and future heat consumption forecasting in order to select of most suitable transformation pathways towards a more efficient heat supply by use of solar energy as a heat and/or power source.

Firstly, analysis of the DH system main parameters is carried out to obtain information about the heat demand, temperature levels, heat production efficiency and other operation parameters. Detailed analyses of DH system and available operation data lead to the identification of possible long-term transformation paths. The next step of the research is the definition of technical alternatives. The particular research focuses on temperature lowering, energy efficiency increase in buildings and solar energy integration into the DH system with different technological configurations. When a detailed analyses of each technological alternative is performed, several criterions are determined and compared by use of multi-criteria analyses to indicate the most sustainable solution for particular DH system.

2.1. Analysis of the Existing DH System

The evaluation process starts with the analyses of existing situation of particular DH system. This step includes the analyses of several DH parameters such as energy balance, heat load, system efficiency, used technologies, energy sources, etc.

Operation of DH system includes many technical, economic and environmental parameters, which affects the efficiency of the system. In order to evaluate different scenarios, it is necessary to obtain comparative indicators by using available input data and assumptions. Such calculations would give the necessary answers for most suitable alternatives for further development of DH system.

One of the most important parameters describing the DH system operation is the heat load curve, which shows the amount of produced thermal energy. This curve is used for all technical, economic and statistical calculations. By knowing the heat consumption, it is possible to determine the number of necessary equipment and their capacities. Heat load curve describes the capacity of base and peak loads of DH system. It gives a comprehensive overview of different energy source capacities that can be integrated into the DH system.

2.2. Development of Technical Alternatives

In the particular research, solar energy integration has been identified as a long-term transformation path, and three different hourly solar system energy balance models have been developed within the research (Fig. 2.1).

The first model presents the solar thermal system by solar collectors installed for the coverage of the summer heat load. Solar collectors produce the thermal energy by heating up the heat carrier that circulates within the system. To calculate the solar collector efficiency, the hourly heat supply temperature and ambient temperature is used (Soloha et al., 2017). In the particular research, all of the solar heat can be used directly because the capacity of solar thermal system does not exceed the summer heat load (around 2 MW). It is assumed that the thermal storage tank for daytime load balancing is integrated.

The second model analyses the integration of solar PV panels primarily to cover the electricity consumption of the specific DH plant. Author have developed the system dynamics model for detailed analyses. It is assumed, that in the solar power model, the monocrystalline PV panels will be used. The produced amount of solar power is calculated according to the methodology described by Gravelsins et al. (Gravelsins et al., 2019) and aligned with the power consumption of the DH companies. If excess power which cannot be used on-site is produced, it is either returned to the grid (BTG), if the power price is high, or converted to heat with the HP and used to cover the heat load. The HP capacity is calculated as the maximum excess electricity output. The COP of HP depends on the temperature of heat carrier of the DH system.

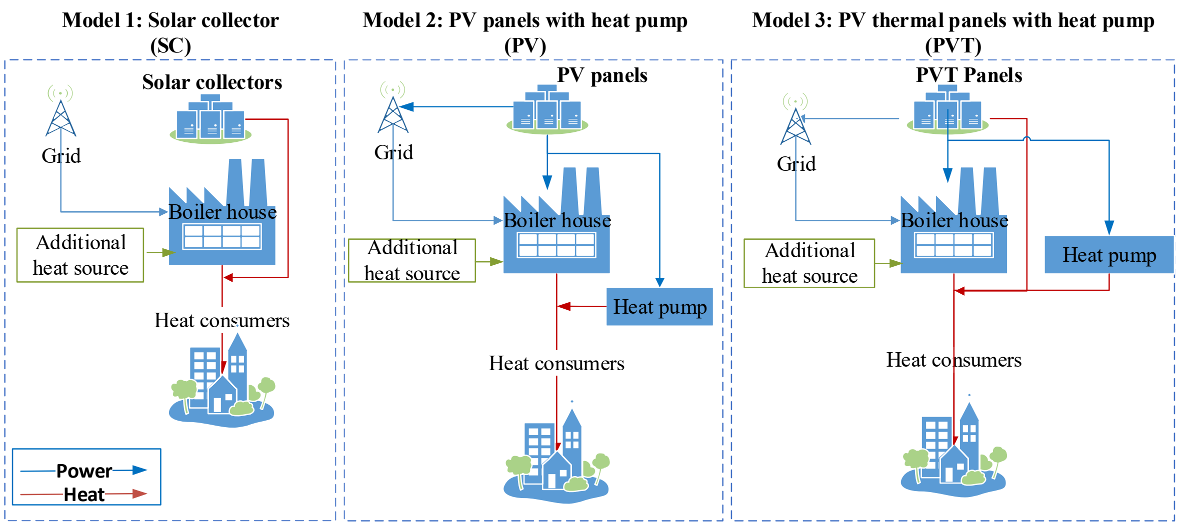


Fig. 2.1. Overview of analysed solar system configurations.

Within the third model, the hybrid system has been analysed. The installation of PVT panels that produce both electricity and heat are modelled according to the methodology described in the author's previous research (Pakere et al., 2018). The power consumption is primarily used onsite in the DH plant but the heat is transmitted to consumers. If excess solar electricity is produced, it is either returned to the grid, if the exchange price is high, or converted to heat via HP and used to cover the heat load.

The solar models provide detailed information on solar energy potential in case of different technological configuration. The produced, consumed and sold amount of solar energy (heat and/or power) is calculated for different scales of the system to obtain more clear view on different system aspects.

2.3. Selection of Suitable Alternative

The obtained results of three different solar models have been compared and ranked using two different multi decision-making tools. Those are TOPSIS and AHP (Dynova et al., 2013; Laurenzutti & Krohling, 2014). The main steps of the multi-criteria decision making method can be seen in Figure 2.2.

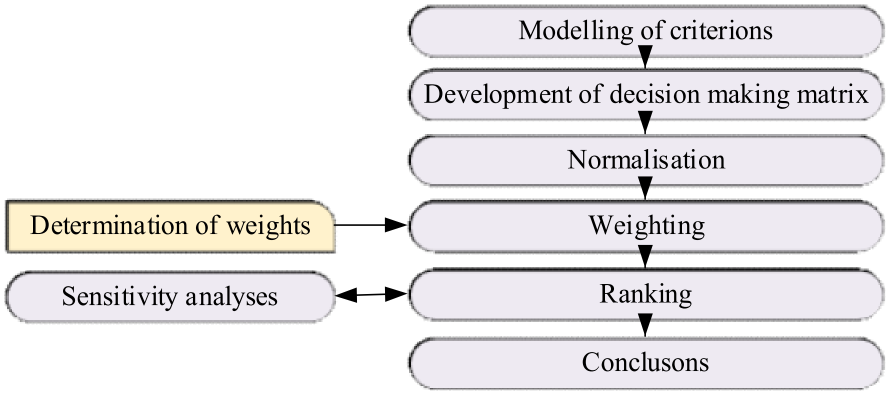


Fig. 2.2. Multi-criteria decision making steps.

Table 2.1

Overview of Analysed Scenarios

Solar technology	Scenario	Installed area, m^2	Power capacity, kW	Thermal capacity, kW	HP power capacity, kW
Model 3 PVT technology	PVT 1	140	24	70	0
	PVT 2	500	85	240	85
	PVT 3	1000	170	480	90
	PVT 4	2000	340	960	230
Model 2 PV technology	PV 1	140	25	n/a	0
	PV 2	500	90	n/a	26
	PV 3	1000	180	n/a	90
	PV 4	2000	360	n/a	247
Model 1 Solar collectors	SC 1	140	n/a	100	n/a
	SC 2	500	n/a	360	n/a
	SC 3	1000	n/a	720	n/a
	SC 4	2000	n/a	1442	n/a

The first step includes identification of all applicable criterions calculated from the developed solar models. The obtained annual results of solar models (produced amount of solar energy, consumed solar heat and power, solar power transferred BTG and power used for heat production) have been estimated for different scenarios in further comparison of most desirable alternative solution (Table 2.1). Author use the installed area of solar technologies as a reference parameter, assuming that the available land could be a limiting factor for decision-making. Different system scales have been analysed from the reference case (140 m^2 of installed technology area) to large-scale system with 2000 m^2 of panels/collectors useful area.

The decision-making matrix and normalization of the obtained values are done according to the methodology described by Loken (Loken, 2007). For the weighting of criterions, the entropy weighting method is applied, which was firstly introduced by Shannon & Weaver (Shannon & Weaver, 1949) and was applied for different kinds of studies. The highest weight value (Fig. 2.3) when applying the entropy weight method is calculated for total savings (TS), specific useful exergy (SUE), LCOE, total specific costs (TC), specific operation costs (SOC), and specific avoided CO_2 costs (C_{CO2}). When determining the weight by AHP method, the highest values are for the NPV, LCOE, PBT and TS criterions.

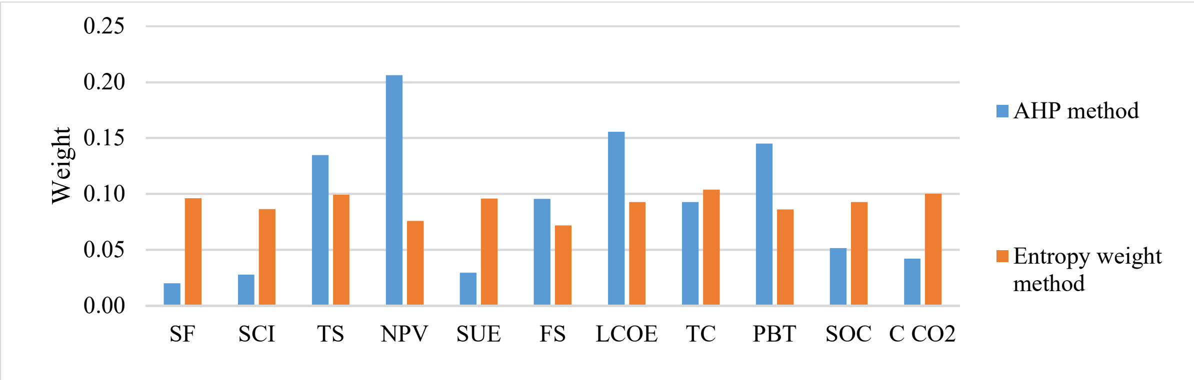


Fig. 2.3. Comparison of determined weight for criterions based on AHP and entropy weight method.

The final rank of alternatives is obtained by multiplying the weight of the criterion with the corresponding alternative rating. In addition, the consistency index is calculated for a consistency check of decision makers' ratings in case of AHP method application (Samal & Kansal, 2015).

3. RESULTS

3.1. DH System Analyses

The developed methodology has been applied for the particular large-scale DH system. The total amount of supplied heat energy is around 61 GWh per year and average heat losses in the DH system network are approximately 12.4 %. The DH system facility supplies heat to local apartment as well as residential and municipal buildings.

Approximately 44 % of the heat supply was produced from wood chips, 7 % from natural gas, but the remaining 49 % was purchased from CHP plant. Average heat load during the summer season when only hot water is consumed is 3 MW. The maximal heat load during the peak period reaches more than 20 MW.

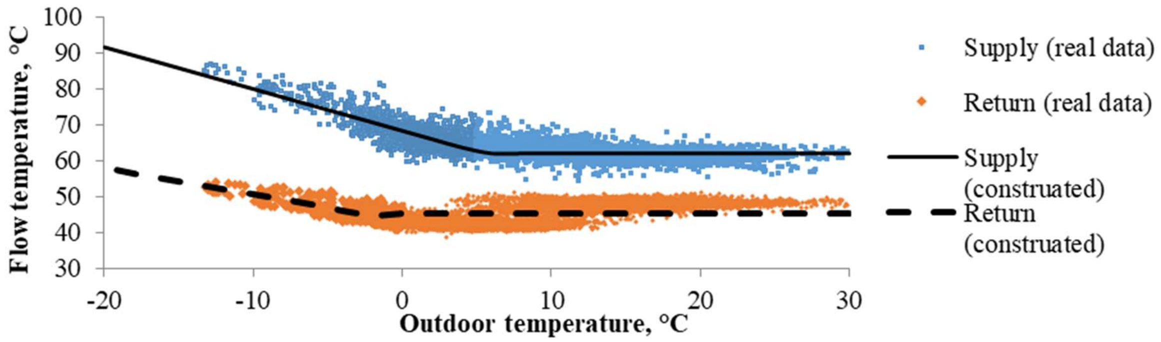


Fig. 3.1. Temperature regime of the DH system.

In Figure 3.1 it can be seen that the DH system operates with the temperature regime 90/60 °C. The average supply and return temperature during heating season is 66 °C and 46 °C. During the summer season, the return temperature is higher than during the heating season and the temperature difference between supply and return temperature is small.

3.2. Evaluation of Technical Alternatives

Solar Thermal Model

The solar thermal energy model evaluates different technical alternatives for solar thermal energy utilisation with and without seasonal energy storage. The first scenario is without seasonal storage system because energy provided by solar energy is less than the actual heat consumption. The second is the base scenario in which solar energy provides the hot water consumption load throughout the year. The remaining four are seasonal storage scenarios. During summer, the energy provided by solar energy is higher than the actual heat consumption. Therefore, it is possible to have surplus solar energy that can be stored.

According to the methodology described in (Soloha et al., 2017) a mathematical optimization model has been developed to simulate various solar thermal system scenarios and determine the most suitable solution from the technical and economic variables. The necessary solar collector area, the amount of stored heat and heat losses from the storage tank have been calculated in corresponding scenarios.

In total, 6 solar thermal system scenarios were compared, by changing the solar collector area and thermal energy water storage tank volume (Table 3.1). The following system dimensions were chosen after analysing monthly and annual heat demands.

Table 3.1

Analysed Scenarios for Solar DH System

Scenario	Solar collector area, m^2	TES volume, m^3
S1	9 000	0
S2	36 500	218 000
S3	45 600	272 000
S4	54 700	327 000
S5	63 800	382 000
S6	72 900	438 000

Figure 3.2.1 shows the existing heat demand and obtained solar DH system results for different scenarios. Solar irradiation increases in summer months and most of solar heat is produced from June to August when heat demand is lower. Nevertheless, as analysis of the large scale system shows, in the case of Scenario 1, it is possible to provide half of the required heat for hot water consumption in summer with 9000 m^2 of solar collectors. The total amount of heat produced from solar energy varies from 6000 MWh per year in Scenario 1 MWh to 23 700 MWh per year in Scenario 6. Therefore, in order to use all of this energy, 30 % to 50 % of heat from solar energy needs to be accumulated in thermal energy storage (TES) (Fig. 3.2).

The solar fraction (SF) has been calculated for all scenarios and it varies from 10 % to 78 %. When calculating SF, it has been determined that the total heat demand can be reduced by applying energy efficiency measures for part of buildings. If heat demand decreases, SF increases and it is possible to provide all of the heat by solar energy in Scenario 6. The necessary thermal water tank volume for such a system is 438 000 m^3.

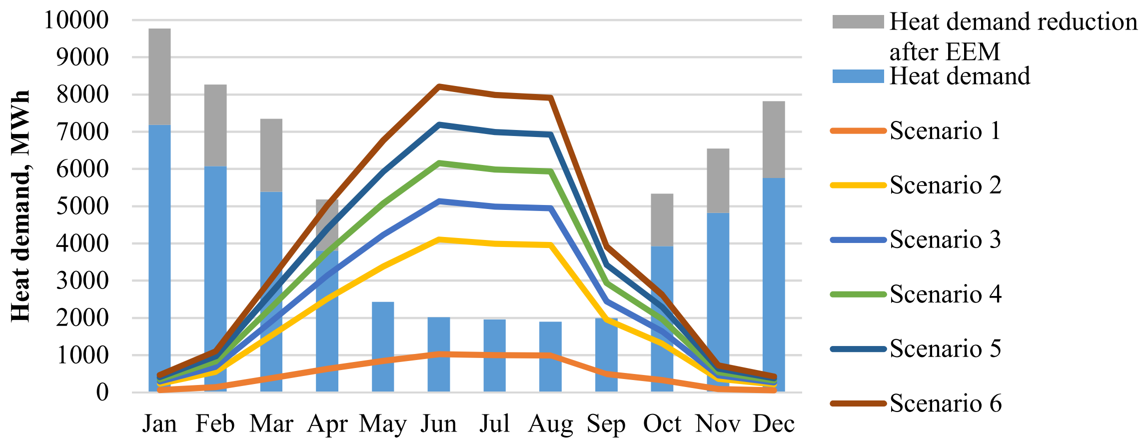


Fig. 3.2. Existing heat demand and amount of heat produced in solar DH system for different scenarios.

The calculated heat losses from TES are negligible and vary from 600 MWh to 1300 MWh per year. This is due to relatively low temperatures in the accumulation tank as maximal temperature is 64 °C in Scenario 6.

Solar Power Model

Another alternative for solar energy use is the solar power generation, which can be used either for DH self-consumption coverage, transferred to the grid or converted to heat. The simulation is conducted by SD modelling for a 10 year period to show the long term dynamic of the obtained results. The developed SD model evaluates different solar power system configurations. Table 3.2 summarizes the analysed scenarios.

Table 3.2

Overview of Analysed Scenarios

Scenario	Initial PV area m^2	HP capacity factor –
Base scenario	1000	0.1
SC 1	100	0
SC 2	1000	0
SC 3	1000	0.05
SC 4	1000	0.2
SC 5	500	0
SC 6	500	0.05
SC 7	500	0.1

The baseline scenario represents the configuration of a 1000 m^2 PV area and the HP with a starting capacity of 20 kW. The solar power production is modelled on an hourly basis according to the available solar radiation. It is further aligned with the hourly power consumption and the market price of electricity.

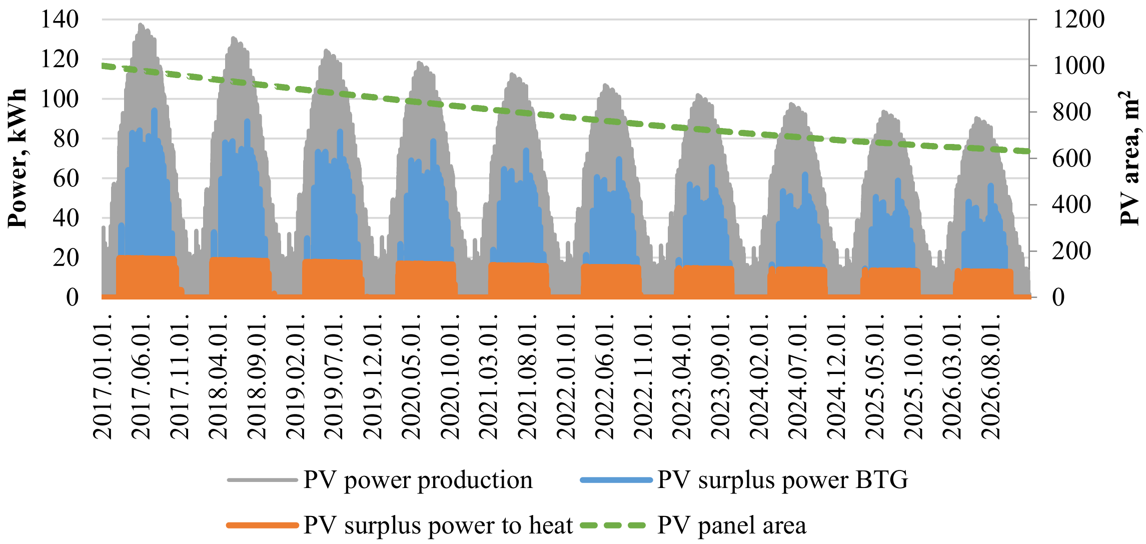


Fig. 3.3. Solar power production, surplus power utilisation and changes of PV area in the Base scenario.

Figure 3.3 shows the results of solar power production and utilisation of surplus solar power. The solar fraction reaches around 20 % of total power consumption in the first year and drops to 13 % in the 10th year. Around 81 % of produced solar power is used directly for self-consumption; therefore, the remaining part is surplus power, which can be either transmitted BTG or converted to heat via HP when the electricity price is low. Around 47 % of surplus power is converted to heat and fed into the DH network, and the rest is transmitted BTG. However, the use of power for heat production is strongly limited by the HP capacity. Part of the surplus power is sold BTG due to insufficient HP capacity.

The PV analyses include scenarios with additional support in the form of subsidies for the PV panel and the HP purchase and installation. Figure 3.4 shows the accumulated profit per installed PV area for different grant policies. The obtained results are compared with the Base scenario. The subsidies for PV panel installations (20 % and 40 %) show higher accumulated profit increase compared with the support for HP. The highest value of 88.25 EUR/m^2 is obtained when the support is considered for both PV panels and HP. Nevertheless, the 40 % subsidies for PV panel installation allow to reach 78.26 EUR/m^2.

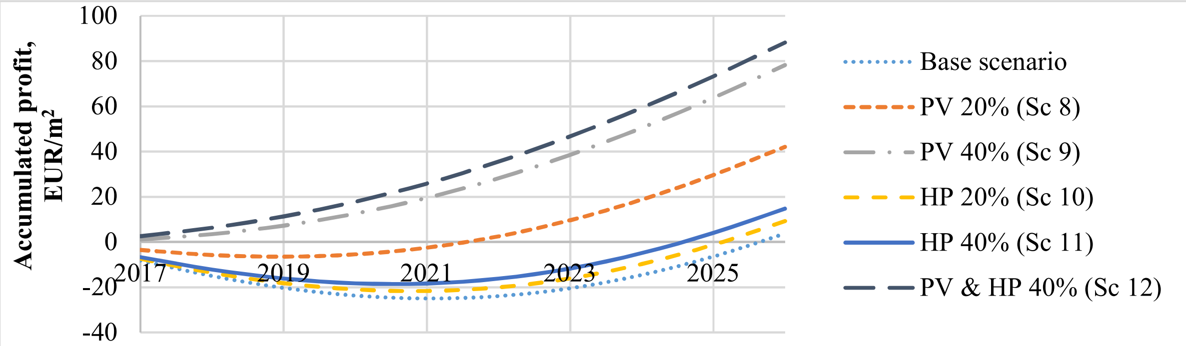


Fig. 3.4. Specific accumulated profit for different scenarios with support policies.

The leading factor that influences profitability of the PV installation is the power costs that are replaced by solar energy costs. The heat tariff and electricity price also significantly affect the benefit of power transformation to heat. Therefore, Figure 3.5 shows the impact of heat and power price increase on the accumulated profit of PV system. If the heat price increases by 20 %, the accumulated profit increases by 71 %.

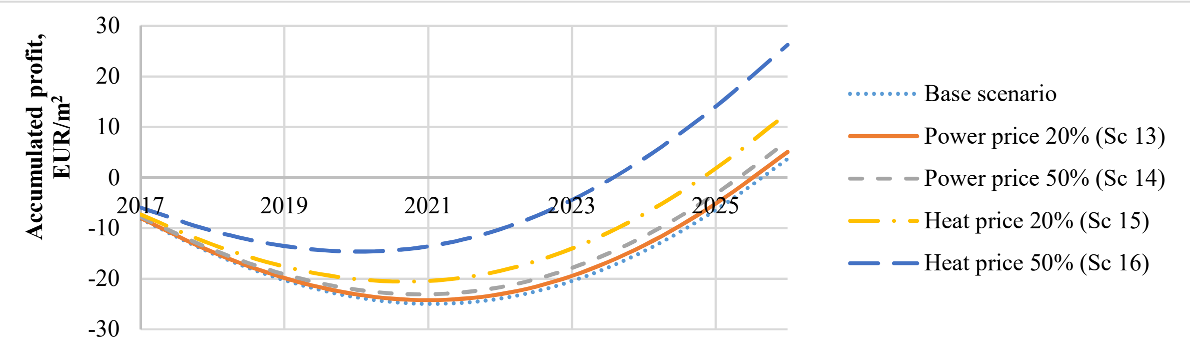


Fig. 3.5. Specific accumulated profit for different scenarios with increased power and heat tariffs.

However, in the specific case the share of surplus power converted to heat does not increase in the case of scenarios with additional support for investment costs and higher heat tariff. This is due to low HP capacity, which is insufficient to convert all the power to heat.

Solar Combined System Model

As an alternative solar DH system author compares several different PVT system scenarios in order to find the optimal design of the solar combi system for a particular case study. The scenarios differ in terms of the size of installed PVT area and an excess power utilization setup (Table 3.3). When installing 1000 m^2 of PVT (S1), the main part (88 %) of generated solar power directly covers the power consumption. Only a small part needs to be exported to the grid or converted to heat. Therefore, the solar fraction for power consumption coverage reaches only 13 %. A different situation is observed in S3 with 3000 m^2 of PVT installed. In this scenario, the maximal generated power in the summer period is almost the same as total power consumption. There are more hours when excess solar power occurs. Therefore 16 % of generated solar power should be converted to heat because in those periods heat tariff is higher than power market price. It would be economically reasonable to export to the grid only 4 % of generated solar power as surplus power occurs mainly when the electricity market price is low.

Table 3.3

PVT System Scenario Overview

Scenario	Installed PVT area *A*, m^2	Heat capacity, kW	Power capacity, kW	Excess power utilization	Battery capacity, kWh
S1	1000	600	150	Exported to grid and converted to heat	–
S2	1500	900	225		–
S3	2000	1200	300		–
S4	2500	1500	375		–
S5	3000	1800	450		–
S6A	2000	1200	300	Accumulated in batteries and exported to grid	250
S7A	2500	1500	375		300
S8A	3000	1800	450		350

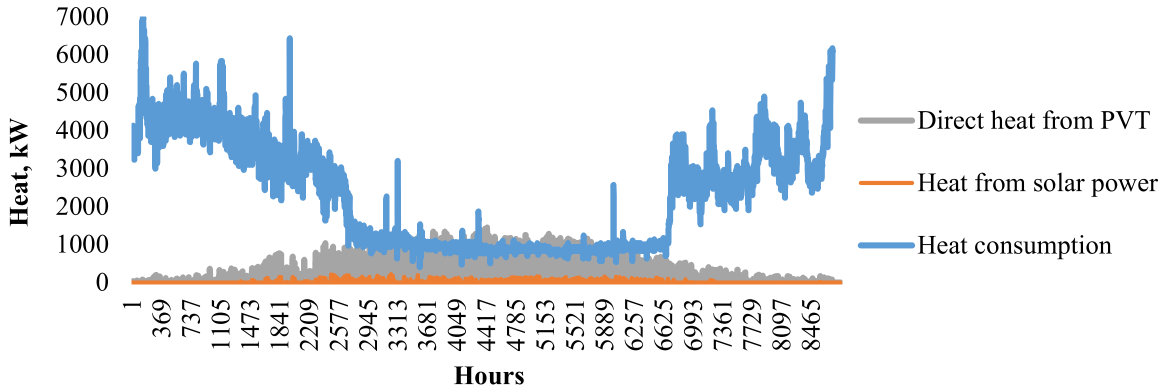


Fig. 3.6. Heat demand and results of solar heat generation for scenario S5.

The solar heat generated by PVT technology directly covers the heat demand. In particular case heat demand is relatively high. Therefore, almost all solar heat even in 3000 m^2 PVT scenario can be used either for space heating in cold season, or for domestic hot water preparation during the summer (Fig. 3.6). Additional heat is prepared from solar power, but only in cases when heat demand is high enough.

The maximal SF for heat demand coverage reaches 7 % in scenarios S5 and S8A. Heat demand rapidly increases in the winter period due to space heating in buildings and it cannot be totally covered by solar energy without additional accumulation technologies.

3.3. Selection of Suitable Technical Alternative

The section presents the energy analyses of the solar thermal, solar power and solar combined system models. The economic and environmental analysis is presented to obtain a more detailed comparison of the analysed systems. The results for solar production and consumption rates of several scenarios are summarized in Table 3.4.

Table 3.4

Overview of Solar Energy Production

Scenario	Produced solar power, MWh	Consumed solar power, MWh	Power BTG, MWh	P2H, MWh	Solar heat, MWh	Heat from solar power, MWh	Useful exergy, MWh
PVT 1	24	24	0	0	69	0	83
PVT 2	86	84	0	1	245	6	300
PVT 3	171	135	2	34	490	150	687
PVT 4	342	189	11	142	980	604	1563
PV 1	25	25	0	0	n/a	0	25
PV 2	91	88	0	2	n/a	10	97
PV 3	181	139	3	39	n/a	174	291
PV 4	362	194	13	156	n/a	683	794
SC 1	n/a	n/a	n/a	n/a	102	n/a	88
SC 2	n/a	n/a	n/a	n/a	364	n/a	313
SC 3	n/a	n/a	n/a	n/a	728	n/a	625
SC 4	n/a	n/a	n/a	n/a	1455	n/a	1251

The results of economic analyses in Fig. 3.7 show that the PV system has the lowest value of simple payback time (PBT) ranging from almost 10 years to almost 12. The PBT increase when additional system capacity is installed. The opposite trend is for the SC system as the PBT decreases for the larger-scale system. The PBT for PVT have small changes when comparing small and large-scale systems.

The lowest value of levelized cost of energy (LCOE) is reached in the case of SC scenarios and it has small dependency on the overall installed system capacity. The opposite results are observed for PV system where LCOE varies a lot for the small-scale system (around 68.59 EUR/MWh) and for the large-scale system (39.21 EUR/MWh). The lowest LCOE for PVT system is 40.28 EUR/MWh in the case of 2000m^2 area of installed PVT panels.

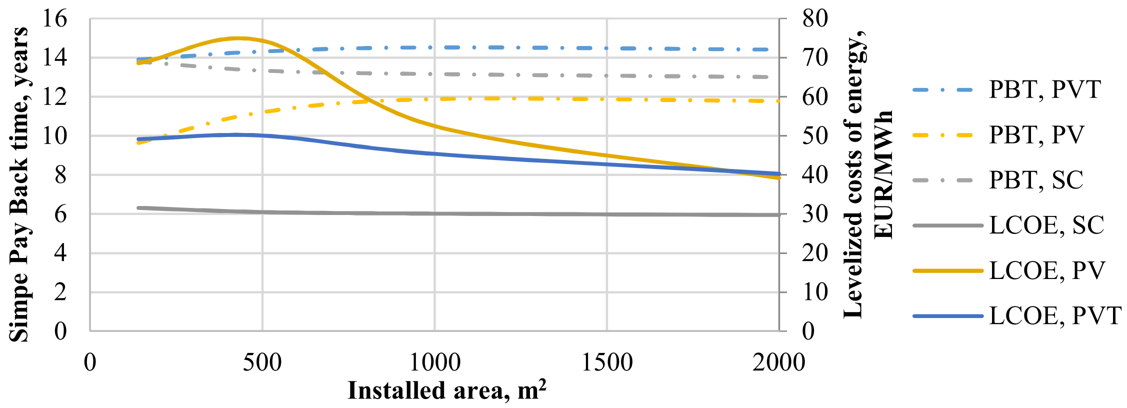


Fig. 3.7. Economic indicators (PBT and LCOE) for different installed solar field areas and technologies.

The specific avoided emissions of CO_2 kg per capital costs (kgCO_2/EUR) are calculated. When evaluating the environmental benefits, it is important to identify the reference energy system, which is replaced by solar energy. Therefore, in the particular research it is assumed that the solar energy will avoid either the use of energy from DH networks and the power grid or the energy produced by natural gas (both heat and power).

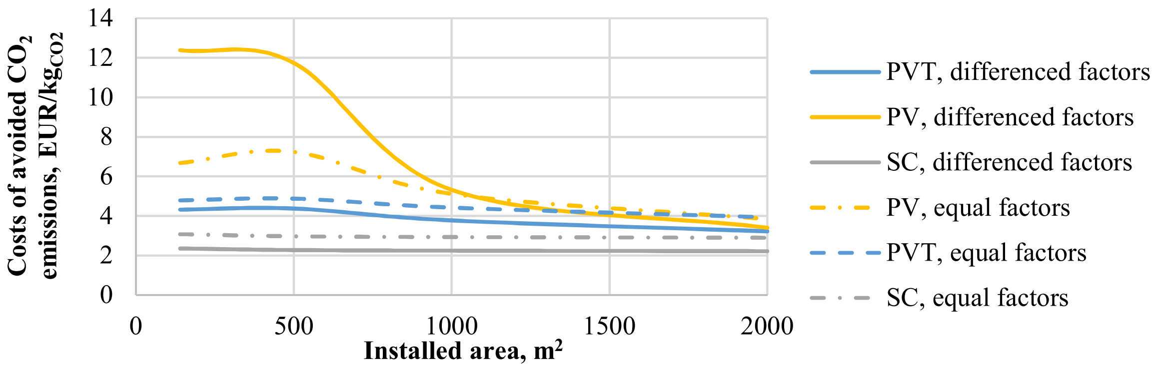


Fig. 3.8. Costs of avoided CO_2 emissions.

Figure 3.8 shows the results for the differentiated emission factor (electricity from grid (109tCO_2/MWh) and heat from DH (264 tCO_2/MWh)) and for equal CO_2 emission factors (natural gas 202 tCO_2/MWh). The highest avoided emission costs are for PV scenarios in cases when differenced factors are applied as the CO_2 factor for power is lower.

The results of economic and environmental analyses are further used in multi-criteria analyses to determine the main criterions.

Sensitivity Analyses

Sensitivity analyses is performed to analyse the impact on the overall system performance in the case of large-scale systems and small-scale systems.

There is an on-going discussion on the necessity to lower the DH network temperature. Therefore, the heat supply and return temperatures have been evaluated as one of the variables affecting the overall solar system performance and economic indicators. Lowering the temperature of the heat carrier affects the efficiency of the solar collectors and the COP of the heat pump. Figure 3.9 shows that the solar thermal panels (especially in PVT3 scenario) are most sensitive, as reduced temperature affects both thermal energy production and surplus power conversion. When decreasing heat supply temperature by 10 °C, the net present value (NPV) in the PVT3 scenario increases by more than 100 %. There is a negligible impact from temperature changes on PV scenarios.

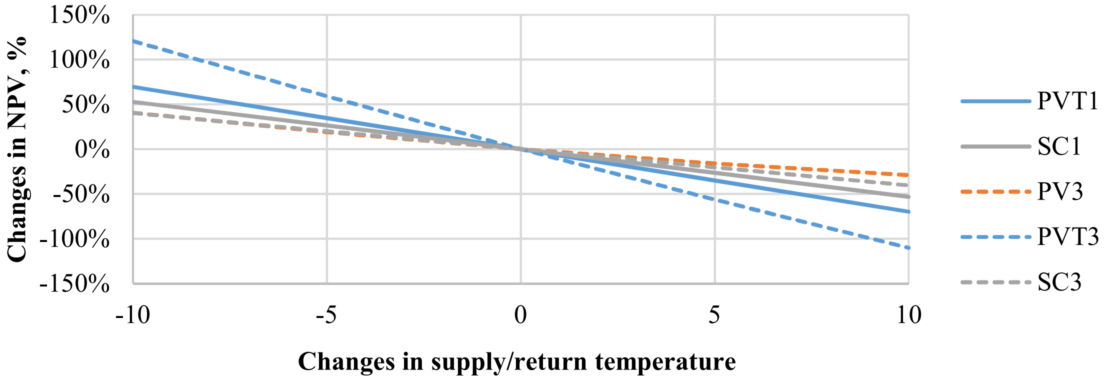


Fig. 3.9. Changes in system NPV value due to changes in heat supply and return temperature.

Different heat tariff levels are analysed within the study, because the value of heat tariff determines the management of surplus power − either it is reasonable to transfer the surplus power BTG or convert to heat. It is assumed that the thermal energy production tariff changes from existing 45 EUR/MWh by 30 %. Changes in the price of heat affect both the economic savings and the share of heat converted. For example, if the price of heat falls by 20 %, most of the surplus electricity from PVT panels is sold rather than transformed to heat (P2H). In contrast, if the heat tariff increases, most of surplus power is converted to heat, because it is more beneficial.

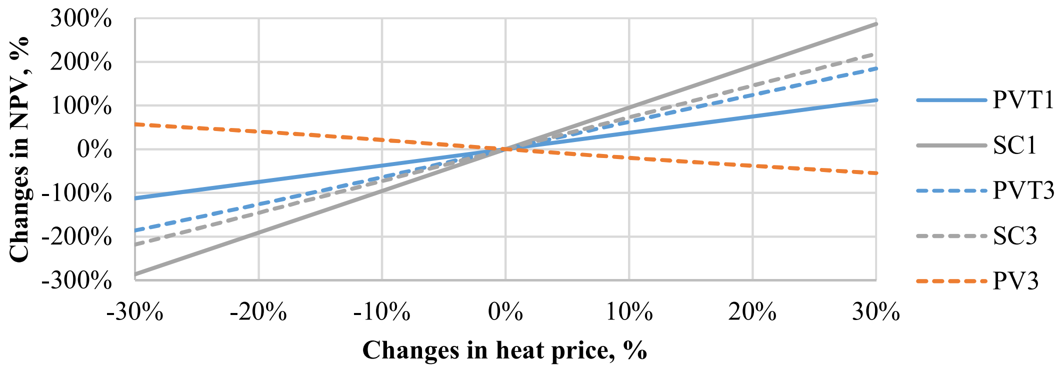


Fig. 3.10. Changes in system NPV value due to changes in the heat tariff.

The heat tariff has been identified as a driving factor affecting the solar thermal system's economic indicators. If the heat price changes by 30 %, the NPV value of solar system can change by even 300 % in SC scenario (Fig. 3.10). The impact is not so major in large-scale PV scenario.

Multi-Criteria Analyses Results

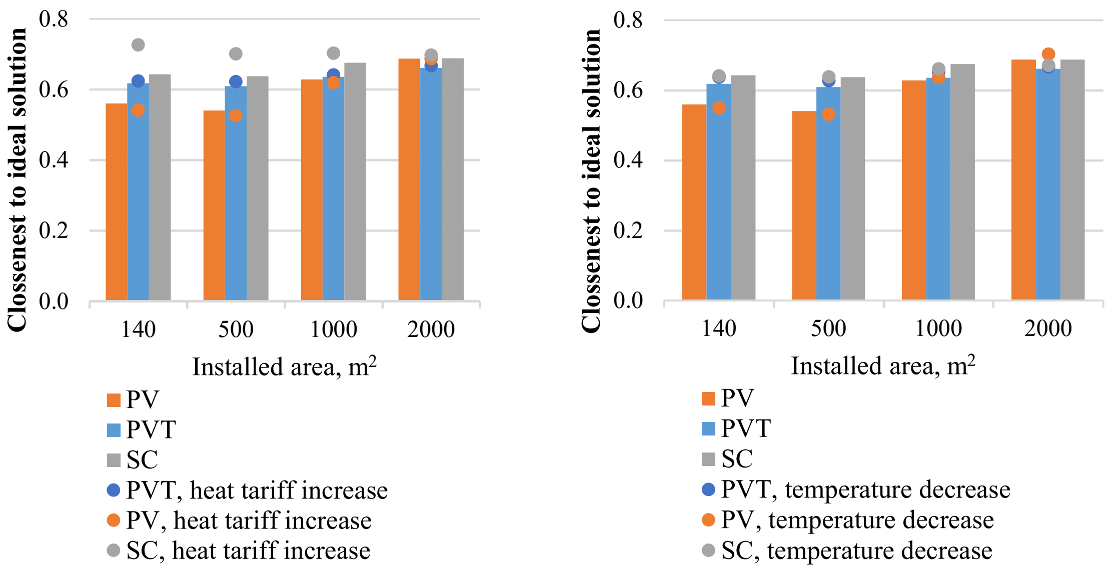
The results from PV, PVT and SC models and sensitivity analyses are used within the multi-criteria analyses to determine different criterions. Those are solar fraction (SF); self-consumption index (SELFCI); total savings (TS); net present value (NPV); specific useful exergy (SUE); flexibility savings (FS); levelized cost of energy (LCOE); total costs (TC); simple payback time (PBT); specific operation costs (SOC); cost of CO_2 avoided ($C_{AV,CO2}$)).

Table 3.5 shows the values of each criterion for different scenarios. The multi-criteria analyses results according to the TOPSIS method (Fig. 3.11) show that the most desirable solution for DH Company differs with the installed technology area. For the system area up to 1000 m^2, the SC technology proves to be the most desirable solution. For the large-scale system (2000 m^2 of installed area), the results are equal for SC and PV technologies.

Table 3.5

Overview of Values of Multi-criteria Analyses Criterions

Criterion	PVT 1	PVT 2	PVT 3	PVT 4	PV 1	PV 2	PV 3	PV 4	SC 1	SC 2	SC 3	SC 4
1. SF	0 %	2 %	4 %	8 %	0 %	0 %	1 %	4 %	0 %	2 %	3 %	7 %
2. SCI	100 %	100 %	96 %	92 %	100 %	98 %	88 %	84 %	100 %	100 %	100 %	100 %
3. TS	46	46	48	49	25	26	27	29	33	33	33	33
4. NPV	116	98	96	109	142	105	101	119	67	83	88	94
5. SUE	0.9	0.9	1.0	1.1	0.7	0.7	0.9	1.1	1.4	1.4	1.5	1.5
6. FS	0.0	0.5	5.9	11.7	0.0	0.8	6.8	13.2	0.0	0.0	0.0	0.0
7. LCOE	49	50	45	40	69	74	52	39	32	30	30	30
8. TC	640	661	694	709	245	287	326	345	452	437	431	426
9. PBT	14	14	15	14	10	11	12	12	14	13	13	13
10. SOC	9.1	8.9	7.4	6.2	24.8	22.4	12.7	8.6	6.9	6.9	6.9	6.9
11. C_{CO2}	4.3	4.4	3.8	3.2	12.4	11.7	5.3	3.4	2.4	2.3	2.2	2.2



a *b*

Fig. 3.11. Results of TOPSIS for reference scenarios and scenarios with increased heat tariff (a), and scenarios with decreased heating network temperature (b).

From the performed sensitivity analyses it can be seen that there are several variables significantly impacting the overall performance of solar systems. Therefore, the ranking of alternatives is repeated for the increased heat tariff scenario (from 45 EUR/MWh to 59 EUR/MWh) and decreased heating network temperature by 10 °C. Figure 3.11 shows the obtained results in the case of heat tariff increase (a) and temperature decrease (b). The impact of heat tariff increase is more significant on closeness to ideal solution for small-scale systems when SC has significant increase compared to other scenarios. In case of temperature decrease, greater differences from the reference scenarios are observed for a large-scale PV system, as the COP of HP is higher.

CONCLUSIONS

The Thesis presents a novel methodology for assessment of solar energy integration into low temperature DH by evaluation of the existing situation, development of long-term transformation path, identification and ranking of different technological alternatives, continuous monitoring, and by driving conclusions for further development.

Three different solar energy models have been developed in order to test the methodology and compare technological solutions for DH application. Multi-criteria analyses are used to compare indicators of different technological solutions of heat and power. The developed methodology is applicable for different DH companies as well as for testing different solar energy integration scenarios.

The system dynamics approach used for solar power system modelling, which allows to evaluate the relationship between various dynamic factors (technology costs, efficiency, energy costs, etc.) and the effect of different policies for solar energy sources in long-term perspective. The sensitivity analyses indicate the main variables affecting the overall solar system performance in the case of different system configurations.

Future Development of DH System

Increased energy efficiency in buildings, heating network temperature lowering and solar energy integration have been identified as long-term transformation paths for DH system. With the development of low-consumption buildings, DH companies will be interested to lower the heat transfer temperature in order to reduce the specific transmission costs. 4GDH system has a high potential in the future, because its implementation is related to increased energy performance of buildings.

The DH system analyses results show that switching to a lower temperature regime can reduce transmission costs and increase solar thermal system efficiency. Therefore, if the heat consumption of buildings decreases, existing DH system with high temperature regime becomes inefficient and specific transmission costs increase by more than 50 %. In order to motivate the existing and newly built buildings connect to DH system it is necessary to reduce the heat tariff by using cheaper energy source and/or decrease transmission costs.

The identified indicators describing the overall development of DH system development include specific fuel consumption, avoided CO_2 emissions, specific costs, specific electric power consumption for heat power transmission, specific heat losses of the network, heat tariffs, motivation of developer or building owner to connect to the DH system, and potential for integration of solar thermal energy.

The research underlined that the shift of a DH company from fossil fuel to renewable solar energy can both reduce the tariff and the amount of emissions, which in turn helps Latvia to attain the required emission reduction in the non-ETS sector.

Implementation of the 4GDH systems in the Baltic States must be incorporated within the strategic measures aimed at elimination of the existing barriers. It means that additional motivation is required for building developers to adjust buildings to the low temperature regime.

Solar Energy Integration into DH System

There are countless technical configurations for solar energy integration into DH system. In the particular research, author compares solar power, solar thermal and solar combi systems for DH with different technological and management configurations and system scales.

The significant decrease of the price of PV panels promotes expansion of solar power integration for different applications. However, the SD model results of solar power show that it is not profitable to install larger PV area than needed for summer electricity consumption. In the Baseline scenario, the total installed PV decreased in total area by 37 % in 10 year period because of insufficient profit from produced power and decommissioning of PV panels. The highest accumulated profit value was obtained for the scenario with a smaller PV area when all the produced solar power was directly used for self-consumption.

The results of solar thermal system with solar collectors show that it would be necessary to install 9000 m^2 to 72 900 m^2 large solar collector field with a properly sized TES in order to produce 6000 MWh per year or up to 23 700 MWh per year. With such a system it would be possible to cover 10 % to 78 % of total heat demand in a particular DH system. If energy efficiency measures in buildings were implemented, it would be possible to reach even 95 % solar fraction. The total capital costs of large-scale solar thermal systems are high, but the calculated specific costs are comparable to reference energy costs. The results show that large-scale solar thermal DH system integration allows reaching higher solar fraction, however it requires high investment and occupies larger land area.

The developed solar combi system model of PVT panels shows that a higher solar fraction (38 %) can be obtained in the scenario of maximal PVT installation with power accumulation added. However, this scenario has also the highest costs. The economic analyses show that the highest NPV value and lowest LCOE is for the scenario with maximal installed PVT area and without accumulation. The calculated value of LCOE for all scenarios is lower than used reference costs of energy but it strongly depends on the assumed system costs. The specific avoided CO_2 emission costs show that the optimal scenario is that which has the 2000 m^2 PVT area installed.

The multi-criteria analyses results show that the most desirable solution in reference scenarios is SC implementation, but for a large-scale system the results are similar for both SC and PV system. However, if the heating network temperature decreases, the most desirable solution in the case of large-scale system implementation is the PV scenario.

Analyses of Factors Influencing Solar Energy Integration into DH System

Different criterions have been determined from the developed solar models – technological (solar fraction, self-consumption index, useful exergy), economical (total savings and costs, simple payback time, net present value, levelized cost of energy, specific operation costs), and environmental (costs of avoided CO_2 emissions). The obtained values of criterions vary for different solar system scenarios. The lowest payback time value is for PV systems varying from 10 to 12 years, but the lowest LCOE value is for SC scenarios 31.56 EUR/MWh to 29.74 EUR/MWh. The highest NPV value (more than 230 000 EUR) has been obtained for the large-scale PV scenario. In addition, the lowest costs of avoided emissions are obtained for SC scenarios around 2.3 EUR/kg CO_2 by applying differenced CO_2 factors for solar heat and solar power.

The scenarios include the solar power production by using the PV or PVT panels, which are coupled with HP for surplus power conversion to heat. Such design allows increasing the overall system flexibility by analysing the hourly power market price, comparing it to heat production costs and making a decision regarding the best surplus heat management strategy – either transfer to grid or convert to heat for DH heat load coverage. The estimated flexibility gains for such a design are estimated as almost 7000 EUR per year in the case of larger scale PV scenario and almost 6000 EUR per year in the case of PVT scenario.

Sensitivity analyses evaluate different solar technology costs, DH heating network temperatures, and heat and power tariff levels. Decreased heating network temperature (heat supply and return) results in the significant increase of NPV value in PVT and SC scenarios. Changes of solar technology costs have greater impact on the results of PVT scenarios because the panel costs account for the largest share of overall capital costs. The power price changes are affecting only the PV and PVT scenarios, but the changes of heat tariff have an impact on almost all analysed solar systems (excluding small scale PV) as it also determines the use of surplus power. The heat tariff increase by 30 % results in NPV value increase by almost 300 % for the small scale SC scenario.

The results show that the implementation of HP and surplus power conversion to heat should be considered if the large-scale solar power stations are implemented. Significant increase of the economic indicator values can be obtained if the solar systems are implemented within the lower temperature DH network.

REFERENCES

Averfalk H., Ingvarsson P., Persson U., Gong M., Werner S. (2017). Large heat pumps in Swedish district heating systems. *Renewable and Sustainable Energy Reviews*, 79, 1275–1284

Averfalk H., Werner S. (2017). Essential improvements in future district heating systems. *Energy Procedia*, 116, 17-225

Dobrotkova P.A., Surana K., Audinet P. (2018). The price of solar energy: Comparing competitive auctions for utility-scale solar PV in developing countries. *Energy Policy,* 118, 133–48

Dynova L., Sevastjanov P., Tikhonenko A. (2013). A direct Interval Extension of TOPSIS Method. *Expert Systems with Applications*, 40 (12), 4841-4847

Elcia M., Oliva A., Herkel S., Klein K., Ripka A. (2015). Grid-interactivity of a solar combined heat and power district heating system. *Energy Procedia,* 70, 560 – 567

Elmegaard B., Ommen T.S., Markussen M., Iversen J. (2016). Integration of space heating and hot water supply in low temperature district heating. *Energy and Buildings*, 124, 255-264

EP (European Parlament and the Council of the European Union) (2012). Directive 2012/27/EU on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. *Official Journal of the European Union*, 315, 1-56

Feldman D., Barbose G., Margolis R., James T. et.al. (2014). Photovoltaic System Pricing Trends Historical, Recent, and Near-Term Projections Edition. Available at: https://www.nrel.gov/docs/fy15osti/64898.pdf [Accessed 07.03.2010]

Gravlsins A., Pakere I., Tukulis A., Blumberga D. (2019). Solar power in district heating. P2H flexibility concept Energy 181, 1023-1035

Jiang X.S., Jing Z.X., Li Y.Z., Wu Q.H., Tang W.H. (2014). Modelling and operation optimization of an integrated energy based direct district water-heating system. *Energy*, 64, 375-388

Kirkerud G.J., Bolkesjø T.F., Trømborg E. (2017). Power-to-heat as a flexibility measure for integration of renewable energy. *Energy*, 128, 776-784

Latosov E., Volkova A., Siirde A., Thalfeldt M., Kurnitski J. (2019) The Impact of Parallel Energy Consumption on the District Heating Networks. *Environmental and Climate Technologies*, 23, 1–13

Laurenzutti R., Krohling R. (2014). The Hellinger Distance in Multicriteria Decision Making: An illustration to the TOPSIS and TODIM methods. *Expert Systems with Applications*, 41, 4414 – 4421

Loken E. (2007). Use of multicriteria decision analysis methods for energy planning problems. *Renewable and Sustainable Energy Reviews*, 11(7), 1584–1595.

Lund H. (2007). Renewable energy strategies for sustainable development. *Energy*, 32, 912-919

Lund H., Werner S., Wiltshire R., Svendsen S., Thorsen J.E., Hvelplund F. (2014) 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy, 68, 1-11

Makki A. S., Omer H. S. (2015). Advancements in hybrid photovoltaic systems for enhanced solar cells performance. *Renewable and Sustainable Energy Reviews*, 41, 658-684

Moller M., Sandberg E., Koduvere H., Olsend O.J., Blumberga D. (2018). Policy incentives for flexible district heating in the Baltic countries. *Utilities Policies*, 51, 61-72

Ostergaard P.A., Lund H. (2011). A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. *Applied Energy*,88(2), 479-487

Ostergaard P.A., Mathiesen B.V., Möller B., Lund H. (2010). A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. *Energy*, 35 (12), 4892-4901

Pakere I, Ziemele J, Blumberga D. (2017). DH company in prosumers role. *Energy Procedia*, 128, 234-239

Pakere, I., Lauka, D., Blumberga, D. (2018). Solar power and heat production via photovoltaic thermal panels for district heating and industrial plant *Energy*, 154, 424-432

Rama M., Mohammad S. (2017). Comparison of distributed and centralised integration of solar heat in a district heating system. *Energy*, 137, 649–660

Rosa D. A., Boulter R., Church K., Svendsen S. (2012). District heating network design and operation toward a system-wide methodology for optimizing renewable energy solutions (SMORES) in Canada: A case study. *Energy*, 45(1), 960-974

Saeima (The Parliament of the Republic of Latvia) (2016). Energy Efficiency Law. *Latvijas Vēstnesis,* 52 (5624)

Sakellariou E, Axaopoulos P. (2017). Simulation and experimental performance analysis of a modified PV panel to a PVT collector. *Solar Energy*, 155, 715–26

Samal R.K., Kansal M.L. (2015). Sustainable development contribution assessment of renewable energy projects using AHP and compromise programming techniques. *International Conference on Energy, Power and Environment: Towards Sustainable Growth (ICEPE)*, Shilling, 1-6

Schweiger G., Rantzer J., Ericsson K., Lauenburg P. (2017). The potential of power-to-heat in Swedish district heating systems. *Energy*, 137, 661-669

Shannon C.E., Weaver W. (1949). The Mathematical Theory of Communication University of Illinois. *Urbana University of Illinois Press*, 85, 24-30

Soloha, R., Pakere, I., Blumberga, D. (2017). Solar energy use in district heating systems. A case study in Latvia *Energy,* 137, 586-594

Tulus V., Boer D., Cabeza L. F., Jiménez L., Guillén- Gosálbez G. (2016). Enhanced thermal energy supply via central solar heating plants with seasonal storage: A multi-objective optimization approach. *Applied Energy* 2016; 181, 549–561