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ENERGY MANAGEMENT SYSTEM IN CLIMATE-NEUTRAL DISTRICT HEATING

Summary of the Doctoral Thesis

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

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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 Science is my own. I confirm that this Thesis has not been submitted to any other university for the promotion to ascientific degree.

Ilze Siliņa ……………………………….. (signature)

Date ……..

The Doctoral Thesis has been written in English. It consists of an introduction, three chapters, Conclusions, 35 figures, 11tables; the total number of pages is 155. The bibliography contains 95 titles.

CONTENTS

INTRODUCTION

Across all levels of energy sector, there is a clear consensus that the decarbonization of Europe's energy supply relies on the expansion of district heating (DH). The ideological framework of the deployment and maintenance of the DH system is the development of sustainable energy systems, reducing the consumption of fossil energy resources in energy generation, and reducing overall energy consumption by implementing energy efficiency measures on both supply and consumption sides. It includes energy generation from fluctuating sources like solar and wind and waste heat, e.g., from industry, data centres, and supermarkets, which the DH system can utilize and store. The regulatory framework promoting these changes is already in place as part of the European Union's (EU) Clean Energy Package, including the Energy Efficiency Directive and the Renewable Energy Directive.

Due to the increased energy efficiency of buildings and stricter environmental impact requirements, the DH system is beginning to change. The traditional 3rd generation DH system with high heating network temperature and combustion heat source should transform towards a low-temperature 4th generation transmission and heat source. One of the most important challenges is the development of a non-fossil district heat supply system and integration of RES, which will be a sustainable energy system [1]. The future energy and climate policy is based on increasing RES and ensuring the coupling of the heating, power and transport sectors to reduce primary energy consumption and greenhouse gas (GHG) emissions.

The Latvian National Energy and Climate Plan 2021–2030 aims to increase the share of RES to 54 % and improve energy efficiency by 2030 in the district heating sector [2]. According to central statistics data, in 2020, there were 529 boiler houses and 162 combined heat and power plants (CHP) in Latvia [3]. In recent years, Latvian district heating companies have significantly developed the infrastructure and reduced fossil fuel consumption by using available European Union funds. By 2020, in total 106 energy efficiency and RES projects were implemented in heat sources and heating networks [4].

There is a wide range of different energy sources available for heat supply in DH systems. The most often-used RES in energy systems is biomass [5], [6], wind [8], geothermal [7], and solar energy. The integration of thermal solar energy in DH systems has become more popular in recent years because solar collectors use unlimited solar energy and have relatively low maintenance costs [8]. Solar collectors are emission-free technology, therefore, appropriate to reduce the environmental impact of the DH system. The largest thermal solar energy plants are in Denmark [9], where there are similar climate conditions to those in Latvia. Solar energy is a high potential for use in district heating [5], [6], [7]. The first large-scale solar collector field in the Baltic States started the operation in the DH system in 2019. The active area of a particular solar collector field is 21 672 m^2 with an integrated heat storage water tank of 8000 m^3.

One of the future development tasks will be to integrate DH into a common energy system by interacting with the district cooling, power, transport, and industrial sectors. Such a future system is referred to as a smart energy system, i.e., an energy system in which smart grid, heating 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 the common energy system. This combination results in polygeneration systems or multi-energy systems with higher efficiency. To achieve this, it is necessary to coordinate the operation of several infrastructures such as energy storage facilities, demand-side management, IT solutions, and other innovative technologies.

Research Topicality

District heating companies have one of the biggest potentials for reducing energy consumption, improving efficiency, and eliminating CO_2 emissions due to well-developed infrastructure and a high potential for flexibility increase to cover the heat load. It is possible to decrease the primary energy consumption and CO_2 emissions through various measures, for example, installing boilers with higher efficiency, and integrating various types of RES, such as solar systems or heat pumps, reducing heat transmission losses due to isolating the heating pipes or reducing heat carrier temperatures. The wide variety of more efficient heat supply options and development of innovative technologies requires system thinking and continuous actions for DH operators to follow up on the latest developments. Therefore, the implementation of an energy management system (EnMS) is one of the ways to efficiently control and reduce primary energy consumption in the organization.

To achieve the energy efficiency goals, the Energy Efficiency Law was issued in Latvia in 2016, which obligated large companies to implement a certified EnMS or conduct an energy audit to identify the energy efficiency measures. Therefore, the 20 largest heating companies in the country, which produce 80% of the total heat consumption in DH executed these criteria in Latvia. Through the implementation of different development projects, these companies are rapidly switching to RES. In recent years, there have been reconstructed wood chip boiler houses cogeneration plants developed, and other types of energy efficiency measures performed. However, DH companies are looking for broader innovative solutions. A variety of sustainable energy sources are used in DH in the EU – solar energy, heat pumps, and waste heat or surplus heat from the commercial and industrial sectors. The system is moving towards the 4th generation system concept by implementing low-temperature heat sources, lowering network temperature, integrating smart grid technology, different storage technologies, and interacting with prosumers.

Within the more complex multi-source heat supply system it is important to follow energy efficiency indicators and a clear methodology to determine these indicators to achieve the highest possible performance of the operation. It is important that the EnMS is suitable for complex systems and is constantly evolving.

Hypothesis

The hypothesis of the research is that the transition to renewable energy can be successfully integrated into the EnMS, which increases the company's energy efficiency and reduces its environmental impact.

Aim and Objectives

The aim of this dissertation is to evaluate the possibilities of expanding the EnMS for future innovative DH solutions by integrating the transition to RES in the system, with an emphasis on solar collector systems.

The main objectives for achieving the goal are:

1. Analyse energy efficiency and environmental indicators at the national and the company level.
2. Develop a simplified methodology to compare the energy efficiency and environmental performance of DH companies.
3. Develop steps to simplify the implementation of energy management in both municipalities and DH companies.
4. Perform a multi-criteria analysis using the TOPSIS method to evaluate the most suitable RES technology for DH companies.
5. Evaluate influencing factors for the solar collector field operation by using multivariate regression analysis.
6. Assess the opportunities to improve solar system performance in DH system.

Scientific Novelty

The methodology proposed in the dissertation helps to evaluate the possibilities of improving the existing EnMS framework for DH companies by integrating RES technologies. To achieve the goal, a number of methods have been compiled and described in detail in several publications. The method is designed to fill the information gap in the industry and to develop the model of EnMS suitable for district heating companies with the development of technologies. The methods to achieve the goal are summarized in Fig. 1.

Publication	Method			
	Regression analyses	**Composite index method**	**Multicriteria assessment**	**Multifactor regression analyses + Pearson correlation method**
"Application of ISO 50001 for Implementation of Sustainable Energy Action Plans"	To evaluate energy efficiency indicators			
"Energy Reduction Potential of the District Heating Company Introducing Energy Management System"	To evaluate energy efficiency indicators			
"Multi-Criteria Analysis to Select Renewable Energy Solution for District Heating System"			To select the most suitable RES technology for DH	
"Is it possible to obtain more energy from solar DH field? Interpretation of solar DH system data"	To evaluate performance of solar DH system			
"Climate Index for District Heating System"	To identify influencing factors of heat tariff	To compare performance of heating companies at national level		
"Optimizing large-scale solar field efficiency. Latvia case study"				To identify the most important influencing factors and optimisation potential for solar system

Fig.1. Methods used in the rsearch

The important part of the methodology is the evaluation of heat supply operation and performance, which within the proposed methodology is divided into the evaluation of energy efficiency indicators and related influencing factors for DH operation and resulting heat tariff. A regression method was chosen to evaluate the relationship between different technical and economic parameters of heat generation and supply.

The national heat supply level is also considered in the research. In order to perform the evaluation and comparison of various DH systems with different heat generation technologies and characteristics of heat transmission system, the author suggests using the composite index method which merges the main performance indicators of sustainable heat supply.

An important contribution of the developed EnMS framework is the proposal on the way to select the most suitable RES technology for DH systems. Great emphasis is placed on new technologies that are rapidly entering the heat supply solutions, such as the solar collector system. When integrating a new system, it is important to identify the most important influencing factors and evaluate the possibilities of its optimization. The combination of this method provides a structured model to assess the potential of an EnMS to extend it and be more suitable for future innovative DH systems.

Practical Significance

The Thesis has practical significance at three different levels: national, municipality, and company level. The effects on each level are summarized in Fig. 2.

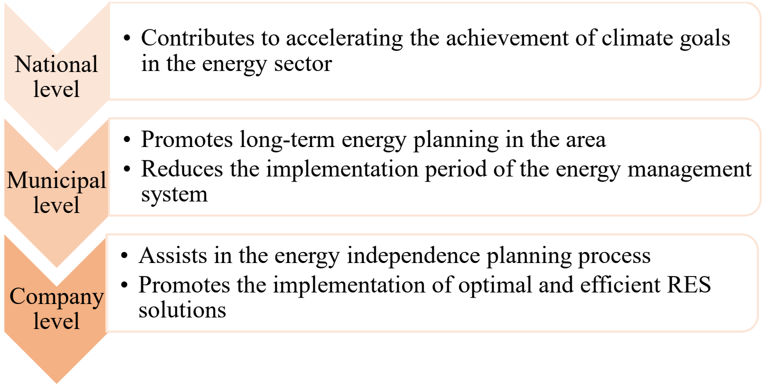

Fig. 2. Practical impact of research on sectors.

The significant emphasis is on the level of DH companies, as the proposed methodology will assist in implementation of innovative pilot projects in heat transmission and heat generation. The improved EnMS with additional performance indicators allows to identify the energy efficiency measures more accurately and implement follow-up actions to optimise the implemented solutions.

At the municipality level the proposed indicators allow to evaluate the local heat supply solutions and indicate the necessary support or restrictions for the DH operator improving the long-term planning process of heat supply development.

Integrating RES technologies into the EnMS will speed up the achievement of national climate goals and improve the transparency of overall heat supply by highlighting sustainability indicators of DH companies.

Approbation of the Research Results

1. Ilze Dzene, Ilze Poļikarpova, Līga Žogla, Marika Rošā. Application of ISO 50001 for Implementation of Sustainable Energy Action Plans. Energy Procedia, 72, (2015), 111–118.

2. Ilze Poļikarpova, Marika Rošā. Energy Reduction Potential of the District Heating Company Introducing Energy Management System. Energy Procedia, 128, (2017), 66–71.

3. Ilze Poļikarpova, Dace Lauka, Dagnija Blumberga, Edgars Vīgants. Multi-Criteria Analysis to Select Renewable Energy Solution for District Heating System. Environmental and Climate Technologies, vol. 23, (2019), 101–109.

4. Roberts Kaķis, Ilze poļikarpova, Ieva Pakere, Dagnija Blumberga. Is it possible to obtain more energy from solar DH field? Interpretation of solar DH system data. Environmental and Climate Technologies, vol. 25, 2021, 1284–1292.

5. Ieva Pakere, Dace Lauka, Kristiāna Dolge, Valdis Vītoliņš, Ilze Poļikarpova, Stefan Holler, Dagnija Blumberga. Climate Index for District Heating System. Environmental and Climate Technologies, vol. 24, (2020), 406–418.

6. Ilze Poļikarpova, Roberts Kaķis, Ieva Pakere, Dagnija Blumberga. Optimizing large-scale solar field efficiency. Latvia case study. Energies, 14, (2021).

Reports at Scientific Conferences

1. Ilze Dzene, Ilze Poļikarpova, Līga Žogla, Marika Rošā. Application of ISO 50001 for Implementation of Sustainable Energy Action Plans. International Scientific Conference "Environmental and Climate Technologies – CONECT", 2014, Riga, Latvia.

2. Ilze Poļikarpova, Marika Rošā. Energy Reduction Potential of the District Heating Company Introducing Energy Management System. International Scientific Conference "Environmental and Climate Technologies", CONECT 2017, 10–12 May 2017, Riga, Latvia.

3. Ilze Poļikarpova, Dace Lauka, Dagnija Blumberga, Edgars Vīgants. Multi-Criteria Analysis to Select Renewable Energy Solution for District Heating System. International Scientific Conference "Environmental and Climate Technologies", CONECT 2018, 16–18 May 2018, Riga, Latvia.

4. Roberts Kaķis, Ilze poļikarpova, Ieva Pakere, Dagnija Blumberga. Is it possible to obtain more energy from solar DH field? Interpretation of solar DH system data. Environmental and Climate Technologies, CONECT 2020, 13–15 May 2020, Riga, Latvia.

5. Ieva Pakere, Dace Lauka, Kristiāna Dolge, Valdis Vītoliņš, Ilze Poļikarpova, Stefan Holler, Dagnija Blumberga. Climate Index for District Heating System. Environmental and Climate Technologies, CONECT 2021, 12–14 May 2021, Riga, Latvia.

Structure of the Research

The structure of the research is based on the energy management cycle – plan, do, check, and act. The traditional EnMS framework has been supplemented with an analysis for transition to RES. The structure of the research is shown in Fig. 3.

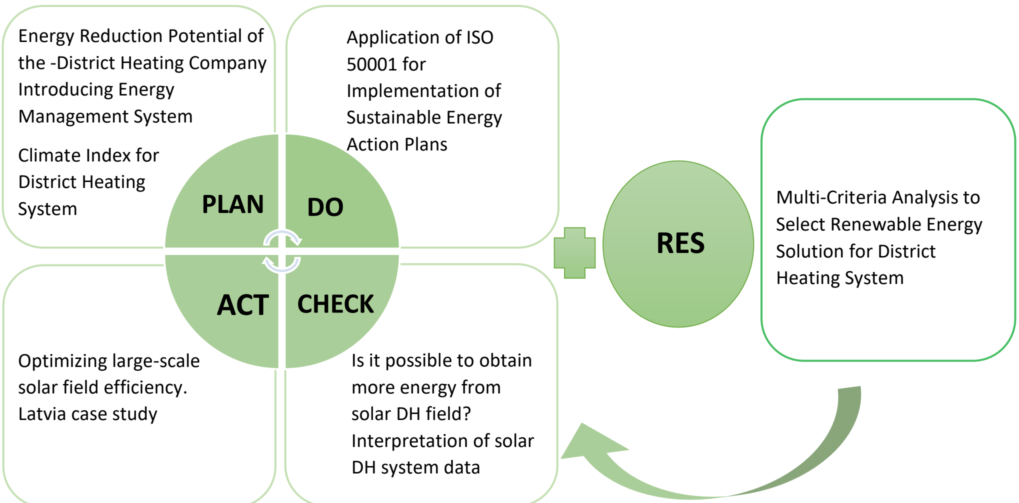

Fig. 3. Structure of the research.

The Thesis is based on 6 related scientific publications summarizing different methods and results, which together create a new methodology for determining the possibilities of expanding the EnMS for DH systems by integrating the transition to RES in the system, with an emphasis on solar collector systems. Each step of EnMS has been supported by at least one scientific publication of the author, as indicated in Fig. 3. Two scientific articles are related to the planning stage because it is an important part of the implemented energy management in a DH system.

The Thesis consists of an introduction, literature review, research methodology and results, and conclusions.

1. METHODOLOGY

In general, EnMS implementation steps are defined based on the Deming cycle – Plan, Do, Check, and Act. However, there is no common methodology how to apply the EnMS standard for DH system with emphases on integration of RES technologies. In addition, there is currently an active transition from the 3rd generation DH systems to the 4th generation heating solutions based on low temperature heat transmission and heat sources, such as waste heat and solar collectors. It is, therefore, important to improve the existing methodology of energy management for it to be applicable for energy-efficient integration of RES technologies and innovative solutions.

The standard steps of energy management are considered in the development of the methodology of this work. The first step of the assessment examines the environmental impact and energy efficiency in DH companies at the national level by identifying several sustainability indicators. As a result, a national climate benchmark has been created to assess the performance of DH systems. It can be used as an external benchmark in the EnMSs of DH companies.

The next step is to summarize and identify energy management indicators and influencing factors at the DH company level to evaluate their performance. In this step, internal benchmarks are established by data collection to define vulnerabilities and identify the potential for RES technologies. In the second stage, different benefits of implementation of EnMSs are analysed, including economic performance.

The next stage is a selection and comparison of renewable energy solutions for the DH system. This methodology summarizes possible indicators and uses multi-criteria analysis to find a more appropriate RES technology solution for a particular case study. The next steps are to integrate the chosen technology – a solar collector system with an accumulation tank – and to develop the monitoring system within the EnMS. In these steps, optimization options are evaluated for the implemented RES measures and supplementation, because the EnMS is an ongoing process.

1.1. Development of a national level sustainability assessment method for district heating system

A methodology was developed to determine the performance of DH companies' sustainability at the national level. To compare the companies objectively, various sustainability indicators are covered by creating the climate benchmark – a composite index characterising the main operational parameters of DH system.

The main steps for climate benchmark determination can be seen in Fig. 1.1. The author uses the data set from 20 DH companies for the evaluation.

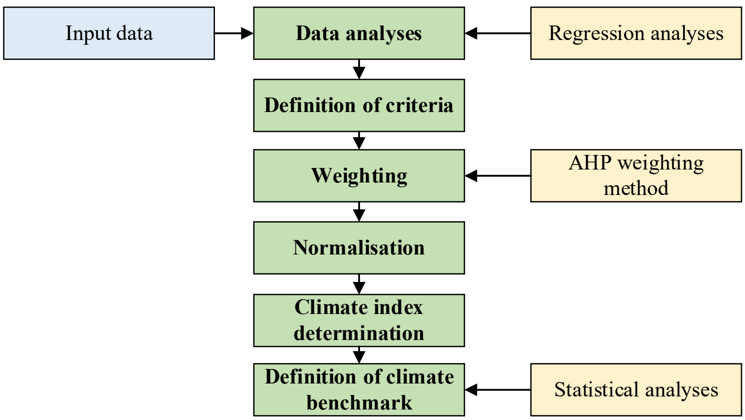

Fig. 1.1. Main steps and methods for determination of climate benchmark.

After the detailed data assessment, the author defines the main criteria for further analyses. Seven different criteria are used (see Fig. 1.2) for calculation of the Climate index in the case study. Several sustainability criteria are used to evaluate the used energy production technologies and energy sources. Therefore, the author has identified three different criteria: the share of RES, the share of heat produced in RES CHP, and the share of heat purchased from industrial enterprises.

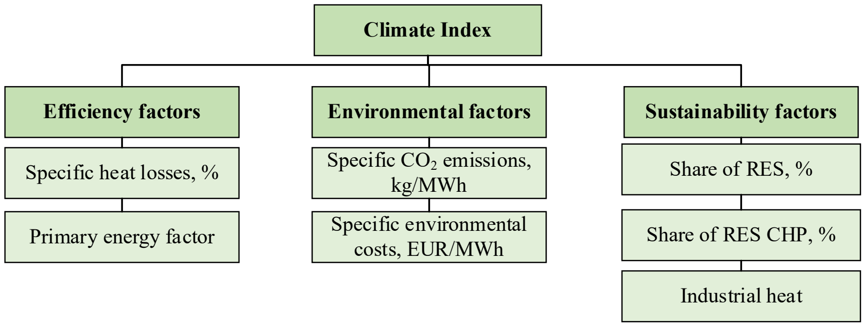

Fig. 1.2. Criteria merged within the Climate index.

The criteria are prioritized to better reflect the use of sustainable development opportunities. The weights for each criterion are calculated according to the analytic hierarchy process method (AHP). The base of the method application is a pairwise comparison matrix, which reflects the relative importance of the criteria [10]. The normalized and weighted values of the criteria are summed up to obtain the Climate index for each DH operator.

1.2. Identify energy management indicators and influencing factors at the district heating company level

EnMS should be introduced to determine the possible measures for energy consumption reduction in the DH company. Its focus is to identify the weak points in energy use and identify energy efficiency measures. An objective method for such a comparison of energy use in the organization is the selection of precise energy efficiency indicators.

The DH company energy efficiency assessment system, which is based on the indicator method, is carried out in the following basic steps:

- Identifying all energy consumers.
- Defining the major energy consumers.
- Determining the incoming resource flows.
- Determining the effectiveness of the heat source (each incoming flow compared to net output flow).
- Regression analyses to determine if there is a correlation of the indicator with certain factors.
- Grouping of simple and complex indicators.

- Verifying if the established indicators also perform the function of an operational indicator.
- Selection of the necessary collection periods for each indicator (24 hours, a month, or once per three months, etc.).

Creating an indicator that objectively reflects the energy efficiency of the company, can be used as a tool to identify the places for improvement and implementation of energy efficiency measures.

1.3. Selection of renewable energy solution for district heating system

When moving towards climate and energy efficiency goals, it is important to introduce the transition to RES in the DH company, determining the most suitable and profitable technology.

Multi-criteria analysis is used to identify the most suitable RES technology for the company, which allows evaluation of alternatives from several aspects: technical, environmental, economic, and social factors.

Energy technologies are evaluated according to four criteria. The indicators chosen are: the total investment, resource costs, reduction of GHG emissions, and impact on land use. The experts chose the importance of the criteria from 0 to 5 in order of importance, 0 – without impact to 5 – with extremely high impact.

To evaluate the RES technology for DH, the TOPSIS method is chosen. The TOPSIS procedure consists of five main steps: development of the normalized decision matrix, development of weighted normalized decision matrix, calculation of the positive ideal solution, calculation of the negative ideal solution, and determination of the relative proximity to the ideal solution.

1.4. Evaluation of the implemented RES measures and supplementation of the EnMS indicators

When introducing a new technology in a company, it is important that it fits into the existing system. One of the essential aspects of an EnMS is that performance is objectively reflected. This research evaluates the influencing factors of solar collector systems and their importance when reaching higher efficiency.

The analysed case study is on a large-scale solar collector system installed in Salaspils, Latvia. The total active area of collectors is 21 672 m^2 with an integrated thermal accumulation tank of 8000 m^3. The system is operating since September 2019, and it is the first large-scale solar collector field for district heating in the Baltic States.

Operation of a solar thermal system is mainly affected by two factors: the intensity of solar radiation and the set temperature. However, the solar field performance is also impacted by the following factors:

- collector area;
- optical efficiency of the collector;
- system losses;
- ambient air temperature;
- DH return temperature – inlet temperature;
- outlet temperature of the collector.

The next step is to understand which factors in a particular system can be affected by the system operator and which cannot. As this is the first project in the Baltic States, the solar radiation is analysed as well to identify how the intensity of solar radiation affects the overall system performance. Therefore, the solar collector yield is evaluated depending on the solar intensity, DH heat carrier return temperature, and the heat carrier flow rate.

1.5. Optimization of EnMS in a district heating company with a large solar field

After the first year of operation of the solar technology, the evaluation of results and the examination of optimization options in line with the EnMS was performed. The data on the first-year results allows to estimate and analyse the influencing factors of the large-scale solar collector field in Latvia, the Baltic region. The heating plant consists of two wood chip boiler houses (7 MW + 1.68 MW flue gas condenser and 3 MW + 0.5 MW flue gas condenser) and 3 gas boilers (capacity of 10 MW, 10 MW, and 3 MW) for peak load coverage. The overall heat production scheme is shown in Fig. 1.3.

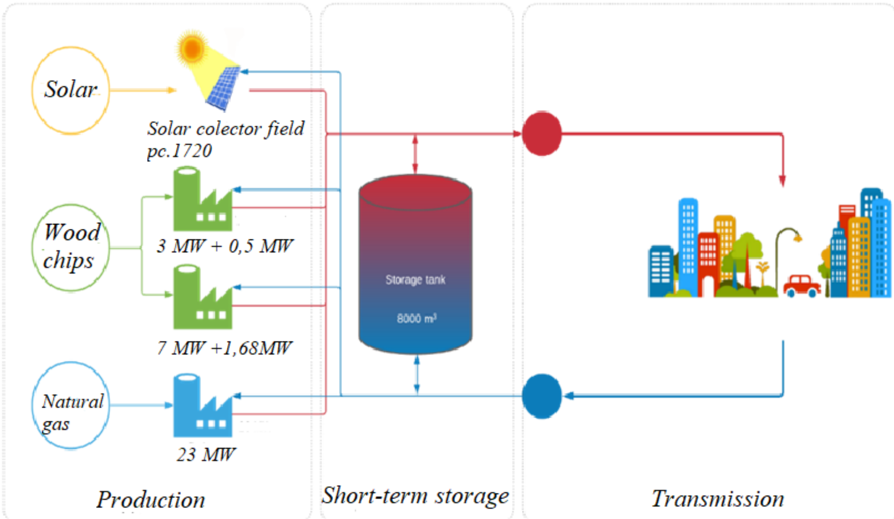

Fig. 1.3. Case study scheme.

Statistical analysis and regression analysis methods were used to obtain objective results because of the availability of comprehensive monitoring data of solar field operation. The use of regression analysis clearly shows the influencing factors that should be optimized to reach higher efficiency of the solar field. The regression analysis is divided into three steps: data collection and compilation, the analysis of influencing factors, and multi-regression analysis. The statistical data analysis was performed using the Statgraphics 19-X64 software.

Three efficiency influencing factors of solar collectors were evaluated, apart from solar radiation as a direct influencing factor. These include the DH system’s return and supply temperature, the return flow temperature difference, and the flow rate. These factors were chosen based on the analysed results from previous studies of laboratory experiments and simulations.

To perform a statistical analysis of the data, the author used the Statgraphics Version 19.2.01 software. The software program for data analysis and visualization includes more than 230 data analysis functions. Multiple variable analysis and multiple regression analysis were used to determine the influence of variable factors on the solar collector field efficiency.

2. RESULTS

2.1. Development of a national level sustainability assessment method for DH system

The developed methodology and results allow to gain confidence that the DH company is energy efficient and sustainable or on the contrary, it is necessary to pay attention to several aspects that should be improved.

The author has analysed the performance of 20 DH operators in 2017. The analysed DH systems differ a lot. The produced amount of annual heat ranges from more than 500 GWh in Riga, the capital city of Latvia, to less than 1 GWh in smaller towns.

Table 2.1 shows the overview of normalized values of each criterion for analysed DH systems. Value 1 indicates the best-ranked system, but value 0 is the lowest obtained value. As it can be seen, only two DH systems have purchased heat from industrial enterprises.

Table 2.1

Normalised Values of Obtained Values of Criteria

DH location	RES	RES CHP	CO_2 emissions	Environmental costs	Heat losses	Primary energy factor	Industrial heat
Rīga	0.15	0.13	0.19	0.48	0.57	0.95	0.00
Daugavpils	0.16	0.00	0.09	0.40	0.09	0.49	0.00
Jelgava	0.92	0.97	0.36	0.97	0.42	0.95	0.00
Liepāja	0.63	0.30	0.81	0.56	0.30	0.81	0.00
Ventspils	0.90	0.93	0.90	0.87	0.53	0.92	0.00
Jūrmala	0.47	0.00	0.21	0.30	0.00	0.55	0.00
Rēzekne	0.00	0.00	0.47	0.18	0.26	0.42	0.00
Valmiera	0.25	0.00	0.00	0.20	0.66	0.56	0.46
Jēkabpils	0.82	0.23	0.83	0.53	0.56	0.86	1.00
Salaspils	0.61	0.00	0.35	0.41	0.69	0.78	0.00
Saldus	0.86	0.60	0.80	0.73	0.08	0.86	0.00
Sigulda	0.94	0.30	0.95	0.42	0.39	0.87	0.00
Ludza	0.96	0.00	1.00	0.50	0.50	0.98	0.00
Gulbene	1.00	0.74	1.00	0.87	0.09	0.99	0.00
Alūksne	1.00	0.00	1.00	0.51	0.41	1.00	0.00
Ķekava	0.21	0.00	0.39	0.00	0.26	0.00	0.00
Broceni	0.95	1.00	0.97	1.00	0.42	0.99	0.00
Iecava	0.58	0.61	0.39	0.18	1.00	0.57	0.00
Mārupe	0.00	0.00	0.39	0.00	0.74	0.24	0.00
Saulkrasti	0.70	0.00	0.67	0.21	0.44	0.75	0.00

Figure 2.1 shows the results of obtained Climate index values with and without application of criterion weights. As it can be seen, the application of weights has a small impact on the DH systems with highest and lowest Climate index values. The highest rank is obtained for the DH systems where the heat is produced by using a biomass cogeneration plants (CHP) technology or the heat is purchased from industrial enterprises. The lowest Climate index values are for the DH systems where natural gas is the main energy source for heat production.

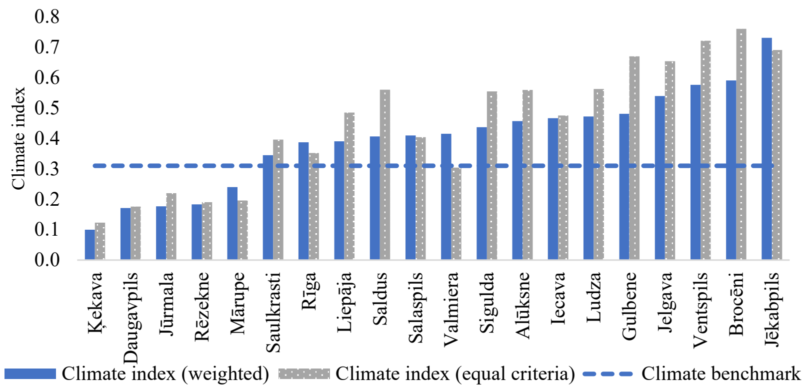

Fig. 2.1. Results of ranked Climate index values and obtained climate benchmark.

For the analysis, the benchmark is obtained according to the Pareto principle by analysing the frequency of particular obtained Climate index values. The benchmark is determined as the most frequent minimal value of the index. To demonstrate sustainable heat production, the Climate index value should be above the determined benchmark value, which is 0.31 for this particular case study.

The analyses show that five DH systems are below the obtained benchmark. These companies should review their strategic plans with an emphasis on energy efficiency and sustainability. Introducing this benchmark at the company level would allow recording of progress.

The determined Climate index has a potential for further development and application for system performance evaluation at the international level. The methodology can be adjusted for country-specific conditions by using additional technical, economic, and environmental indicators.

2.2. Energy management indicators and influencing factors at DH company level

When implementing an EnMS for a DH system, the company specification must be considered. It is important to select the appropriate energy efficiency indicators at the planning stage. In Table 2.2, the most important energy efficiency indicators and influencing factors for a DH company are summarized [11], [12].

Table 2.2

The Most Important Energy Efficiency Indicators and Influencing Factors

Energy performance indicator (EnPI)	Unit	Influencing factors	Unit
Boiler efficiency coefficient or Specific fuel consumption	% or MWh_{in}/MWh_{out}	Amount of produced heat	MWh
Relative heat loss in heat pipes	%	Amount of realised heat	MWh
Specific electricity consumption	kWh/MWh	Amount of produced heat	MWh
The flue gas condenser efficiency	%	Network water reverse temperature	°C
		Wood chips humidity	%

One of the most important energy performance indicators of a DH company is the specific fuel consumption or boiler efficiency coefficient. It is relatively easy to calculate the specific fuel consumption for a gas boiler because there is mostly a gas consumption meter and produced heat meter installed at the boiler house, and these meters have high accuracy. But woodchips boiler is more complicated because it is difficult to determine the amount of the woodchips input; however, it is possible to obtain reliable monthly data and calculate the average boiler efficiency.

One of the aims of EnMS is to find out the weak points in the company's energy consumption and identify potential energy efficiency measures. These vulnerabilities can be identified if appropriate indicators and influencing factors are defined. There are two ways to choose the appropriate energy-efficiency measures:

- Analyse the consumer or the consumer group, which has the highest recorded energy consumption.
- Implement measures that are economically reasonable. The first measures will be implemented with no need for investment or a small investment. Further, the measures that have a significant impact on consumption can ensure the biggest energy savings.

The following identified measures should be introduced in the analysed DH system to raise the efficiency of the heat production process:

- Develop and implement operational indicators and procedures to ensure an daily control system and production process analysis.
- Create incentive measures for the control of the operator of work.
- Ensure regular training for the boiler operator.
- Introduce automatic boiler control system for the optimal setting and regular check-ups.

The introduction of energy efficiency measures identified in the DH system could save about an average of 4 % per year of energy.

2.3. Selection of renewable energy solution for DH system

The result of the multi-criteria analysis allows the company to choose the most suitable solution for the transition to RES. The data reflect the operation of a medium-sized DH company. This study presents a multicriteria decision-making to prioritize three situations. The study evaluated the current situation when the DH operator used a gas boiler in summer period and 2 alternative RES scenarios:

- Planned situation – installation of solar collectors with a thermal accumulation tank for summer load coverage.
- Alternative situation – installation of a heat pump with PV panels.

In Table 2.3, the main criteria for the current situation and future alternatives have been collected. The best solution is when resource costs, GHG emissions, land utilisation, and total investments are minimal, but the share of RES is maximal.

Table 2.3

Original Decision-making Matrix

	Resources costs	Reduction of GHG emissions	The share of RES	Impact on the utilized land	Total investments, kEUR
Current situation	35	0.2	50	0	0
Planned situation	0	0	90	2	375
Alternative situation	0	0	90	3	613
	min	min	max	min	min
Weights	0.25	0.23	0.2	0.14	0.18

After normalizing values, the matrix where the values are from 0 to 1 is obtained, which is easier to compare in a single score (see Table 2.4).

Table 2.4

Normalized Decision Matrix

	Resources costs	Reduction of GHG emissions	The share of RES	Impact on the utilized land	Total investments
Current situation	0.00	0.00	0.37	0.95	0.93
Planned situation	0.71	0.71	0.66	0.32	0.36
Alternative situation	0.71	0.71	0.66	0.00	0.00

In TOPSIS method application, the important part is the determination of the weight of indicators, which in this case is chosen by DH experts. There can be one criterion with higher priority, and all criteria can be equivalent. In this case study, the weight of resources costs is slightly higher because the DH company can gain energy independence and changes in energy prices have less impact on overall heat production costs. The second most important criterion is the reduction of CO_2 emissions, as reducing GHG is an important aspect when choosing RES.

The obtained TOPSIS result of this case study for the most suitable energy technology for a medium-sized DH company is presented in Table 2.5. It indicates that the prior is a planned alternative-solar collector with an accumulation tank, and the second-best is an alternative with heat pump installation and PV panels.

Table 2.5

TOPSIS Result of the Ideal/Anti-Ideal Points and the Closeness Coefficients for Analysed Scenario

	di+	di–	ci	Result rank
Current situation	0.25	0.21	0.46	3.00
Planned situation	0.14	0.26	0.66	1.00
Alternative situation	0.21	0.25	0.54	2.00

A total of five decision-making indicators covered economic and environmental aspects. The best option is the planned scenario where solar collectors and storage tanks are installed (see Fig. 2.2).

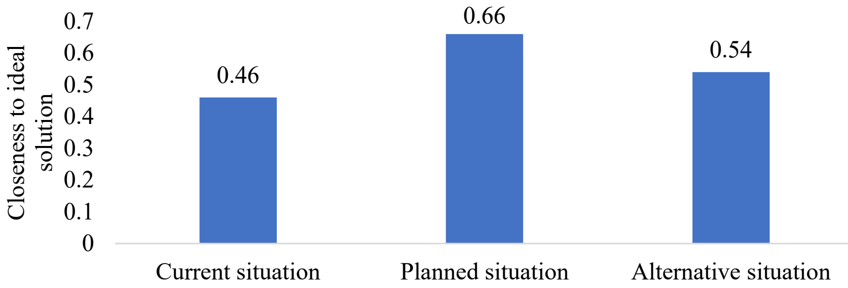

Fig. 2.2. Obtained multi-criteria analysis results for analysed DH solutions.

2.4. Evaluation of the implemented RES measures and supplementation of the EnMS indicators

After integrating a new RES system into an existing DH system, it is important to monitor and analyse the obtained results of the operation. It is crucial to compare performance with the planned results and refer to it as the basis for future optimisation.

In the first year since solar collectors have been installed in the analysed DH system of Salaspils, the annual share of thermal energy produced by solar collectors is about 20 % of the total produced amount of heat. The amount produced using solar collectors was 11088 MWh, while the total produced amount of thermal energy in Salaspils heating plant was about 58 GWh. The highest share of solar field production was observed in June, July, and August, when the solar energy share reached 46–49 % compared to the total production.

During the high solar radiation periods when the sun shines at high intensity for several days, the installed 8,000 m^3 storage tank cannot accumulate all the produced solar energy, and the overheating protection of the solar field is started. But there are also moments of low solar irradiation and cloudy weather for several days in which all the stored heat is consumed and the production by solar collectors is insufficient. In these moments, natural gas boilers are used for heat production the operation of which is more efficient than biomass of boilers when switched on for a shorter time.

Another operational parameter, which can be regulated by the operator, is the solar field set point. The set point is a manually adjusted temperature mark at which the solar collector field circulation pumps start their operation and move the heat carrier towards the heat exchanger, where heat is removed. In the summer months, the ambient air temperature and solar radiation are much higher than in spring, which results in higher solar thermal energy production, but the demand for thermal energy on the consumer's side is lower compared to May and April. In such cases, the set point should be increased, thus reducing the amount of energy produced and adjusting it to the heat consumption. The opposite situation is in spring when the demand for thermal energy is high enough and all solar energy is either consumed or stored. Consequently, the set point is adjusted lower, sometimes even under the network flow temperature to reduce the load from the biomass boilers and decrease the fuel consumption.

The obtained monitoring data are analysed by using the regression analysis method by determining the correlation between different parameters. The data presented have been collected throughout the sunny season, which in Latvia's case is from April until August. Figure 2.3 shows that solar radiation is the main impacting factor of produced solar thermal energy. Of all the parameters studied, which may affect the performance of solar collectors directly, solar radiation has the highest correlation coefficient with average value reaching 0.6112. Similar results have been observed in the studies carried out in large-scale solar DH systems in Denmark [13]. The largest data distribution has been observed in July, which is due to the regulation of the already mentioned set point. At high productivity over several days and insufficient heat demand, the set point was raised by reducing the produced thermal energy. But the highest correlation was observed in May because solar collectors are placed in such a position that they produce heat energy with the highest efficiency and productivity in May. This analysis approves it. If the correlation between the solar radiation and solar collector productivity is the strongest in May, the most appropriate conditions have therefore been created to make production the most efficient at this time.

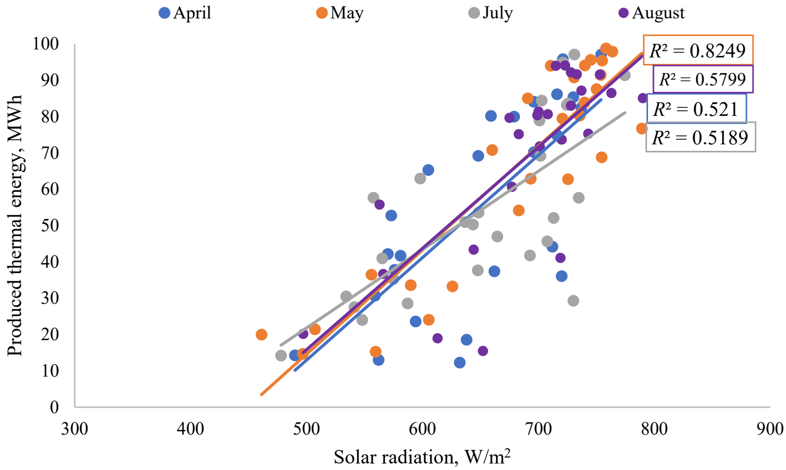

Fig. 2.3. Dependency of the produced solar energy on solar radiation.

Figure 2.4 presents the correlation between ambient air and produced thermal energy. The correlation between these parameters is lower in June, July, and August, but higher in April and May. The average correlation between ambient air temperature and produced thermal energy is 0.2837, which means that the correlation islow and other conditions have higher impact on the performance of the solar collector.

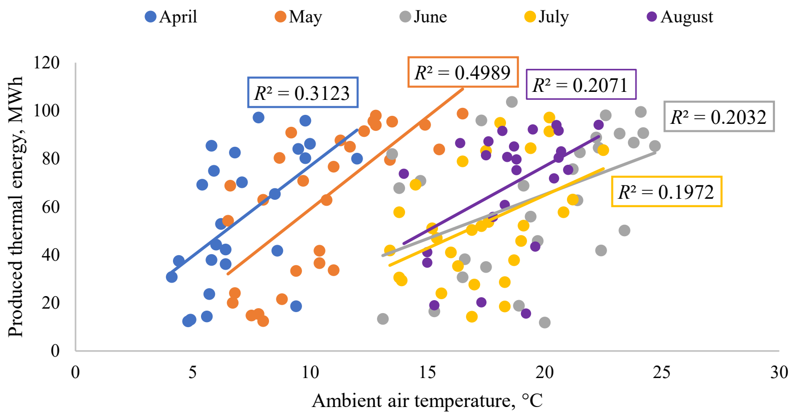

Fig. 2.4. Dependency of solar collector efficiency on ambient air temperature

Another analysed impacting parameter that was examined in this study was the flow and return temperature of heat carrier. The study showed that the correlation between these parameters and the produced thermal energy with solar collectors is very low. The data was very distributed, and knowing that the set point value was changed regularly, several times a day, the analysis of these parameters was very complicated. When the temperature difference changes several times a day, it is difficult to register and divide the data on how much heat energy was produced with each specific temperature difference between the supply and return temperatures.

Figure 2.5 shows the comparison of the performance of numerous solar heating plants in Denmark and the particular solar DH plant in Salaspils. All the heating plants, which were included in this comparison, are using the same solar collector technologies from Arcon-Sunmark A/S, HTHEATstore 35/10. The data were calculated as average solar performance and solar radiation results during the period from 2012 to 2016, presented in [14]. It is clear that the Salaspils solar heating plant has achieved a high solar yield. The specific solar performance (511 kWh/m^2) is high compared to other solar DH systems with similar average solar radiation.

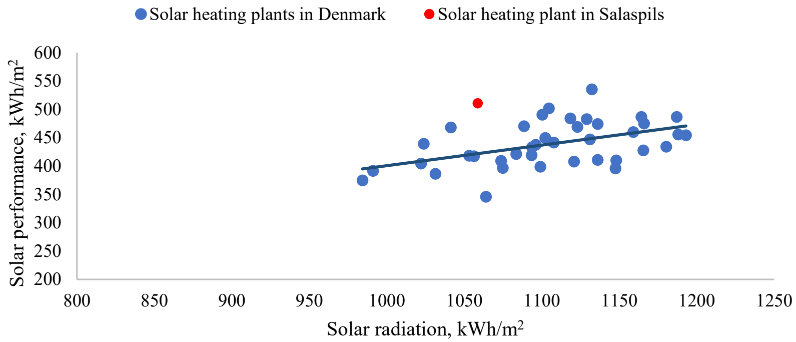

Fig. 2.5. Comparison of a solar heating plant performance depending on solar radiation in Denmark (average data of 2012–2016) [14] and a solar heating plant installed in Salaspils (2020).

The difference between the results could arise because the solar heating plant in Salaspils has active operation only in the first year, when the equipment and technologies are the most effective, although the efficiency of solar collectors does not fall so significantly during the years. The monitoring of system performance will be continued, and more driving factors will be identified in the future.

Overall, the solar performance of the solar collector field installed in Salaspils is high; however, it would be possible to produce even more thermal energy, if the plant had more storage to store the energy, or if the demand were higher. But the problem is that the weather cannot be controlled and the demand shrinks at times when the production (with solar collectors) is the most productive – warm and sunny days. In further research, the author analyses the efficiency of solar collectors by excluding the influence of solar radiation in order to better identify the effect of other factors, which impact efficiency less than solar radiation.

2.5. Optimization of EnMS in a DH company with a large solar field

When installing the system, it was planned to cover 100 % of the demand with solar collectors in the summer months. However, in the summer months of 2020, it covered 90 % of the demand, while the rest was produced by using a natural gas boiler. The overview of actual heat production by primary energy source in 2020 can be seen in Fig. 2.6. It is, therefore, essential to investigate whether there is a potential for improvement.

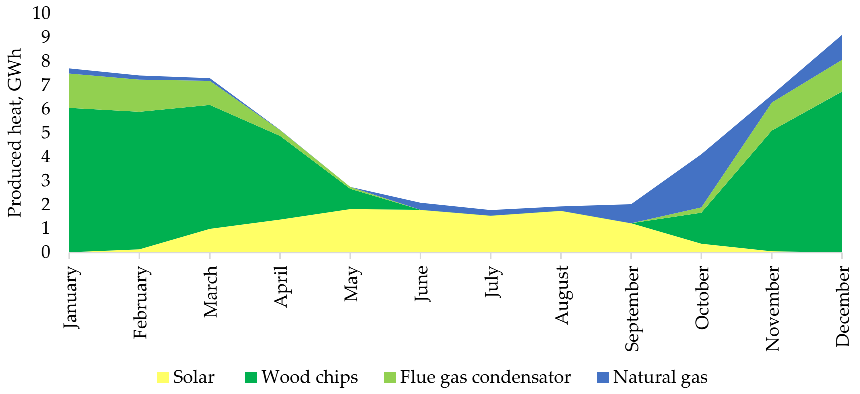

Fig. 2.6. Produced heat by used fuel in 2020.

The data on solar heat production was processed in two steps. In the first step, the four influencing factors on the efficiency of the solar collector were evaluated separately. The considered factors were return temperature, flow rate, supply and return temperature difference, and ambient temperature.

The author firstly assessed how the primary flow changes the efficiency of the solar collector field. The obtained results show that the higher the flow, the higher is the efficiency. The obtained results of the regression analysis are summarized in Fig. 2.7.

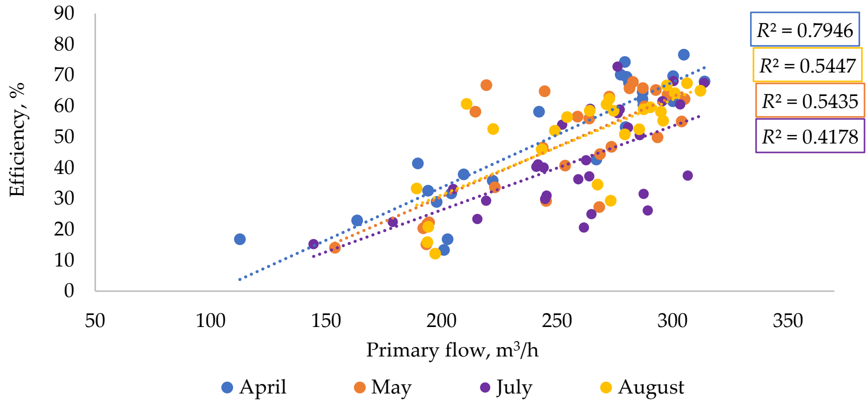

Fig. 2.7. Correlation of heat carrier primary flow rate and solar field efficiency.

The flow depends on the solar radiation, and it is adjusted to reach the required supply temperature. If the solar field produces more thermal energy than the actual heat demand, the excess heat is stored in the accumulation tank.

When comparing the data of four analysed months, the highest efficiency dependence on the flow rate can be observed in April (correlation coefficient = 0.7946). Due to a higher heat demand in April than in the summer period, because is still needed space heating . The efficiency is reduced when there are many sunny days and no demand is forecasted, and the storage tank is full. The efficiency reduction is ensured by increasing the inlet temperature of the solar collector, and as a result, the secondary side of the water in the inlet mixes with the flow of warm water. Accordingly, in July, the regression coefficient is about 0.41. As can be seen from the dotted points in the graph, the efficiency was reduced at these points and therefore was less dependent on the primary flow rate. By optimizing the system, it is possible to increase efficiency and obtain more solar energy. The optimization of the primary flow rate is also necessary due to the high-power consumption of circulation pumps. The obtained data analysis shows that it was possible to reach higher solar efficiency with a lower flow rate on some days. Therefore, further investigation could focus on the specific days with higher solar field efficiency and lower primary flow rates.

The second influencing factor in this case study is the supply and return temperature difference. The obtained regression analysis data is shown in Fig. 2.8.

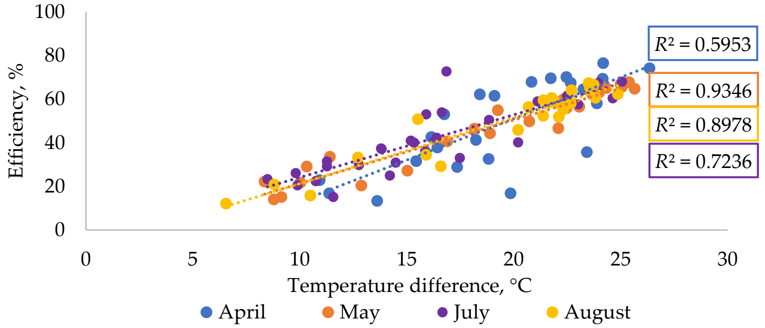

Fig. 2.8. Dependency of solar collector efficiency on the temperature difference.

The results show that the higher the temperature difference, the higher is the efficiency of the solar collector. The inlet temperature depends on the return temperature of the heating network, but the set point regulates the outlet temperature from the solar field. The highest efficiency regression coefficient with the flow rate is in April, but at the same time, lower dependence on the temperature difference was identified. This clearly shows that quantitative heating network regulation occurs in spring, while qualitative regulation occurs in summer. The results show that further optimization could be performed if a suitable heating network regulation mechanism is chosen by seeking the equilibrium between the pumping costs, heat losses, and solar field efficiency.

The literature states that outdoor air temperature is an influencing factor [4] because it affects the flow rates and heat carrier temperatures. The average daily outdoor air temperature fluctuations were from +1.7 °C to +12.1 °C. Figure 2.9 shows that in April, there are days with the highest solar field efficiency because the temperature differences can be maintained higher. Moreover, in July, some points could be optimized. The set temperature (the temperature of the heat carrier before the heat exchanger) was changed based on weather forecasts for the coming days. When days with higher solar irradiation were upcoming, this set point was increased, thus decreasing the solar collector efficiency. Future studies should consider the impact of accurate weather forecasts on the overall solar field performance. It can be seen from the data analysis that the changing set temperature causes fluctuating conditions of solar energy production. The highest correlation coefficient was in May (R^2 = 0.93) because the solar radiation was stable, and the settings of the solar field were not changed.

The third analysed factor is the effect of ambient air temperature changes on the solar field efficiency (Fig. 2.9).

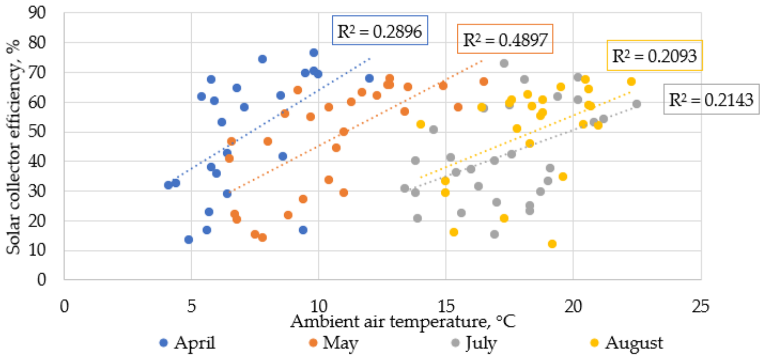

Fig. 2.9. Solar collector efficiency dependency on ambient air temperature.

It can be clearly seen that the average daily outdoor air temperature in Latvia from April to August is in the range from +1.7 °C to +22.3 °C. Compared to other influencing factors defined as significant, the ambient air temperature is an ancillary factor that may explain the deviation of the significant factors. However, comparing all the months, the highest outdoor temperature and solar field efficiency correlation was observed in May (R^2 = = 0.4897).

Therefore, the outdoor air temperature is not a significant factor. However, it influences the return temperature from the consumers and thus the temperature difference.

Multiple regression analyses using Statgraphics functions were carried out to determine the relationship between the analysed variables. The output shows the results of fitting a multiple linear regression model to describe the relationship between efficiency and three independent variables. The equation of the fitted model is:

$$E = -31{,}617 + 0.135 \times w_1 + 2.32794 \times \Delta t + \ 0.091657\ t_a,$$

where w_1 is primary flows, Δt is the temperature difference, and t_a is the ambient air temperature.

According to the obtained equation, by changing the influencing factors, the efficiency of the solar collector can be calculated. Therefore, this equation can be used to plan the solar field performance and forecast the heat production. When planning the system's operation, the main task is to reach the highest possible efficiency during periods when there is a higher demand and maintain the efficiency when there is no more reserve in the storage tank.

Correlations and matrix plot functions were used to estimate the correlation between variables and to then visualize this correlation. The data are summarized in Fig. 2.10.

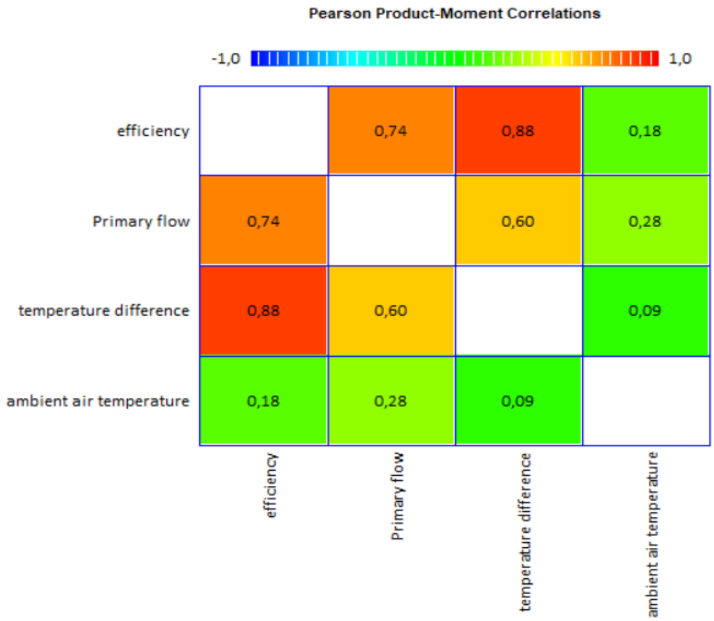

Fig. 2.10. Correlation plot.

Figure 2.10 shows Pearson product-moment correlation between each pair of variables. These correlation coefficients range between −1 and +1 and measure the strength of the linear relationship between the variables. The number of pairs of data values used to compute each coefficient is also shown in parentheses. The third number in each cell location is a p-value that tests the statistical significance of the estimated correlations; p-values below 0.05 indicate statistically significant non-zero correlations at the 95.0 % confidence level. The following pairs of variables have p-values below 0.05:

- efficiency and primary flow;
- efficiency and temperature difference;
- the primary flow and temperature difference;
- the primary flow and ambient air temperature.

The strongest correlation is between the efficiency and temperature difference, with a correlation coefficient of 0.88. The weakest correlation is between the efficiency and ambient air temperature. However, ambient air temperature also affects the flow.

CONCLUSIONS

In the Thesis, a methodology has been developed, which allows to plan, implement, evaluate, and optimise RES solutions in heat supply through the EnMS framework, which increases the company's energy efficiency and reduces its environmental impact. The energy management planning process has been applied at the national, municipality and company level.

National heat supply evaluation

The Climate index has been introduced as a common rating to evaluate the performance of DH system efficiency, environmental impact, and sustainability. Seven criteria are used for the evaluation: share of RES, share of RES CHP, specific CO_2 emissions, environmental costs, specific heat losses, primary energy factor, and share of heat delivered by industrial enterprises. The composite index framework has been applied and the criteria are prioritized and weighted according to the AHP method.

The use of Climate index could improve the competition among DH operators and promote moving towards more sustainable solutions. The determined Climate index could also be a criterion for the heat tariff calculation. DH companies with the highest Climate index could be allowed to have a higher profit share, easier heat tariff approval process, or obtain other benefits. The method was applied for 20 different DH operators. The obtained Climate index values for 15 DH Companies are above the estimated average reference level. Five DH systems were below the determined benchmark due to the use of natural gas as the main energy source.

Energy management at municipality level

The standardized energy management procedures are flexible and can be also successfully applied in organisations, including municipalities. The availability of energy data is crucial for planning the actions and for monitoring their implementation. Lack of data can be solved through implementation of integrated data management procedures as part of an EnMS. Information should be further used for calculating measurable energy indicators.

The EnMS will work only in case when an integrated part of the overall organisational and administrative model of the municipality exists. Therefore, use of standardised procedures (as stated in ISO 50001) is key for the implementation of a successful, functioning and efficient EnMS at the municipal level. In the meantime, it will also promote more efficient implementation of sustainable energy action plans. To facilitate the implementation of energy management standard in municipalities, comprehensive guidelines with step-by-step procedures and examples would be very useful. These guidelines should also contain a set of energy indicators that should be used to evaluate the state of art and to identify the critical parts of the municipal energy system.

EnMS in DH

The Thesis proposes a method for DH companies to select the appropriate renewable energy technology, complementing the EnMS model. A multi-criteria analysis method was used to objectively compare several alternatives for the transition to RES. Key indicators for DH companies performance evaluation are the existing heating boiler efficiency depending on the amount of heat produced, condenser efficiency coefficient depending on the return temperature and wood chips moisture content, specific power consumption. The share of renewable resources in the total amount of energy used is an important indicator of EnMS.

According to EnMS framework, it is crucial to check the performance of both implemented energy efficiency measures and RES projects. Within the Thesis this stage is presented as the performance evaluation of the solar system. The operational data analysis is performed for the first large-scale solar collector field in Latvia, connected to DH network and depending on several factors.

The results of the analysis show that the system's productivity is mainly depending on solar radiation and the strongest correlation between these parameters is in May. The solar collector performance is strongly affected by an adjusted set point, which sometimes must be settled on a seemingly unbeneficial value, but it is done with the long-term aim to keep the solar collector system safe. The correlation between solar radiation and collector productivity is linear.

In the energy management acting step, the optimization possibilities of the solar collector were analysed. The performance of solar collector field installed in Salaspils is high; however, it would be possible to produce even more thermal energy, if the plant had larger energy storage capacity or if the heat demand were higher.

When introducing measures that increase the share of RES in a company, it is important to check its compliance with the goals set at the planning stage. By ensuring a continuous EnMS when introducing new solutions in the company, the performance indicators need to be improved. To ensure continuous improvement of the system operation, it is important to identify optimization opportunities and set new goals.

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