RIGA TECHNICAL UNIVERSITY

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ENERGY MANAGEMENT SYSTEM IN CLIMATE-NEUTRAL DISTRICT HEATING

Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY

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ENERGY MANAGEMENT SYSTEM IN CLIMATE-NEUTRAL DISTRICT HEATING

Summary of the Doctoral Thesis

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ANNOTATION

District heating (DH) has big potential for implementing energy efficiency measures and renewable energy sources (RES) and reducing CO_2 emissions, as the range of RES technologies used is wide: biomass, solar panels, heat pumps and other technologies and their combinations. Because there is such a wide variety of heating options available, systemic thinking and continuous heating operators need to keep up with the latest developments. Therefore, the implementation of an energy management system (EnMS) is one way to effectively control and ensure the primary energy efficiency of an organization.

The dissertation is designed as a set of publications, which consists of 6 thematically unified publications, which have been published in various scientific journals and available in international databases. The aim of this paper is to assess the potential for extending the energy management system to integrate renewable energy technologies, with a particular focus on the solar system.

This work consists of an introduction and three chapters. The introductory part of the work includes: hypothesis, aims and objectives, describes the structure of the work and the methods used. The first chapter analyzes the literature on energy management for total district heating: demand side, transmission and production. As well as literature sources on possible renewable energy resources in district heating. Part of the methodology of the work includes information on the developed methodology and applied methods. The third chapter describes the obtained results - which reflect the energy management system at the national level, the municipality and the district heating company. At the end of the work, conclusions are made about the developed work and the obtained results.

ANOTĀCIJA

Centralizētā siltumapgādei (CSA) ir liels potenciāls energoefektivitātes pasākumu ieviešanai un atjaunojamo energoresursu (AER) ieviešanai un CO_2 emisiju samazināšanai, jo izmantojamo AER tehnoloģiju klāsts ir plašs: biomasa, saules kolektori, siltumsūkņi un citas tehnoloģijas un to kombinācijas. Tā kā ir tik plašs efektīvāku siltumapgādes iespēju variācijas ir nepieciešama sistēmiska domāšana un nepārtraukta siltumapgādes operatoru rīcība, lai sekotu līdzi jaunākajiem notikumiem. Tāpēc energopārvaldības sistēmas (EnPS) ieviešana ir viens no veidiem, kā efektīvi kontrolēt un samazināt primārās enerģijas patēriņu organizācijā.

Promocijas darbs ir izveidots kā publikāciju kopa, kura sastāv no 6 tematiski vienotām publikācijām, kas ir publicētas dažādos zinātniskajos žurnālos un ir pieejamas starptautiskās datu bāzēs. Šī rakstu kopuma mērķis ir novērtēt iespējas paplašināt energopārvaldības sistēmu, integrējot atjaunojamās enerģijas tehnoloģijas, īpašu uzmanību pievēršot saules kolektoru sistēmām.

Šis darbs sastāv no ievada un trīs nodaļām. Darba ievada daļā ir iekļauti: hipotēze, izvirzītie mērķi un uzdevumi, aprakstīta darba struktūra un izmantotās metodes. Pirmajā nodaļā ir veikta literatūras analīze par energopārvaldību kopējai centralizētai siltumapgādei: patērētāju daļai, pārvadei un ražošanas daļai. Kā arī apskatīti literatūras avoti par iespējamie atjaunojamiem energoresursiem centralizētajā siltumapgādē. Darba metodoloģijas daļa ir iekļauta informācija par izstrādāto metodiku un pielietotajām metodēm. Trešajā nodaļā ir aprakstīti iegūtie rezultāti- kuros tiek atspoguļoti energopārvaldības sistēma nacionālajā līmenī, pašvaldības un centralizētā siltumapgādes uzņēmuma. Darba noslēgumā ir veikti secinājumi par izstrādāto darbu un iegūtajiem rezultātiem.

CONTENTS

NOMENCLATURE

4GDH - fourth-generation district heating

a - area

AHP - Analytic Hierarchy Process method

ANN - and artificial neural network

BAT - best available technology

BPNN - Back propagation neural network

CART - classification regression tree

CHP - heat and power plants

COP – coefficient of performance

DH - district heating

DHS - distric heating system

DSA -displacement storage accumulator

DSM - Demand Side Management

EnMS - energy management system

EnPI - energy efficiency indicator

ETS - european trading system

GBDT - Gradient boosting decision tree

GBM - gradient boosting machine

GHG - greenhouse gas

HP – heat pump

MART - multiple additive regression tree

MCDM - Multi-criteria analysis

PEF - Primary energy factor

Pg - guaranteed performance

PUC -Public Utilities Commission

PV - photovoltaic panels

PVT - photovoltaic thermal collector

RES - renewable energy sources

RF - random forest

SVM - support vector machine

SVR - support vector regression

INTRODUCTION

From all levels of the 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 for 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 centers, 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]. In Latvia, there are 529 boiler houses and 162 combined heat and power plants (hereinafter CHP) in 2020 according to central statistics data [3]. In recent years, Latvian district heating companies have significantly developed the infrastructure and reduced fossil fuel consumption by using available European Union funds. In total, 106 energy efficiency and RES projects were implemented in heat sources and heating networks by 2020 [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 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 etc. 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 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 how 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, developed cogeneration plants, and performed other types of energy efficiency measures. 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 toward 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. Important is 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. Analysing energy efficiency and environmental indicators at the national and the company level;
2. Developing a simplified methodology to compare the energy efficiency and environmental performance of DH companies;
3. Developing steps to simplify the implementation of energy management in both municipalities and DH companies;
4. A multi-criteria analysis was performed using the TOPSIS method to evaluate the most suitable RES technology for DH companies;
5. Evaluating 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 this 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, to make the model of EnMS suitable for district heating companies with the development of technologies. The methods to achieve the goal are summarized in Figure 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 indentify 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 work

An important part of the methodology is an 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 work. In order to perform the evaluation and comparison of various DH systems with different heat generation technologies and charecteristics 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 how 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

Work has practical significance at three different levels: nacional, municipality and the company level. The effects on each level are summarized in Figure 2.

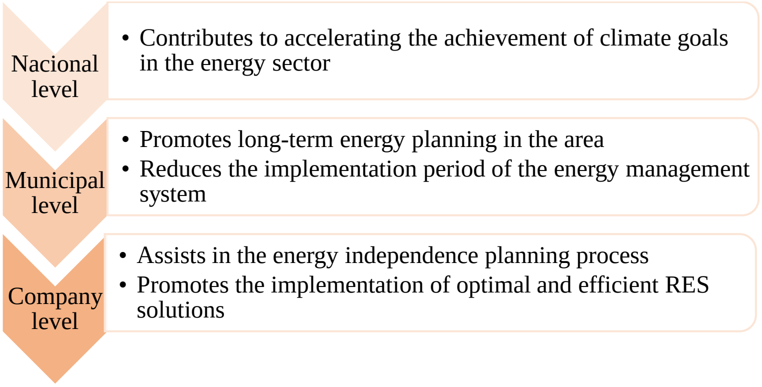

Figure 2. Practical Impact of Work on Sectors

The significant emphasis is on the DH companies level as the proposed methodology will assist in implementation of inovative 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 allows to evaluate the local heat supply solutions and indicates the necessary support or restrictions for 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 Work

The structure of the work is based on the energy management cycle - plan, do, check and act. The traditional EnMS framework has been supplemented with a analyses for transition to RES. The structure of the publications is shown in Figure 3.

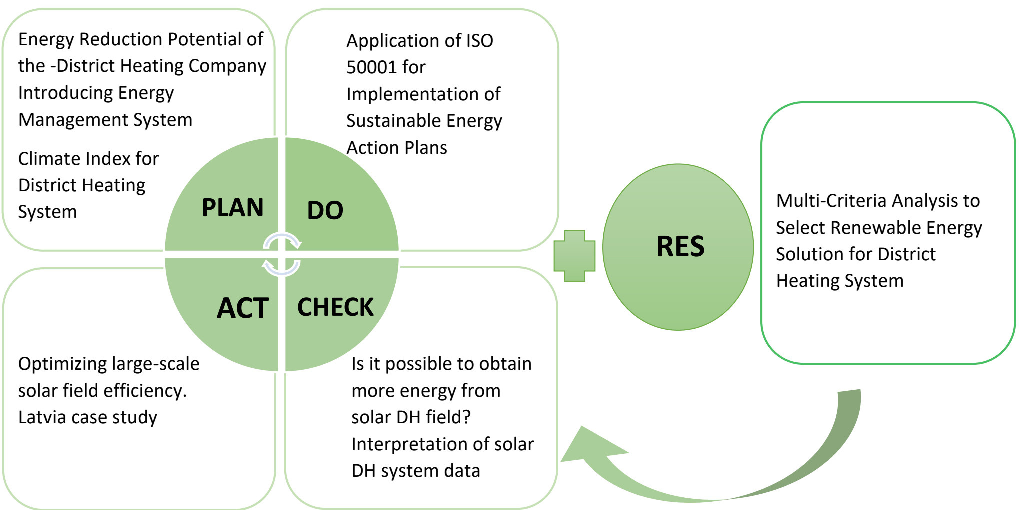

Fig. 3. Structure of the Work

Doctoral thesis is based on 6 related scientific publications summarizing different methods and results, which together create new methodology for determining 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 have been supported by at least one scientific publication of the author as indicated in Figure 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 includes an introduction, literature review, research methodologies and results and conclusions.

1.LITERATURE REVIEW

1.1. Energy management in district heating systems

Demand side management

District heating (DH) companies have a big potential for reducing energy consumption, improving energy efficiency, and reducing greenhouse gas emissions [10].

District heating system includes three main actors: consumer, producer, and transmission. Relation between them is possible to describe by load duration curve (see Fig.1.1.), which presents consumer need, transmission losses and necessary load of heat energy sources during year.

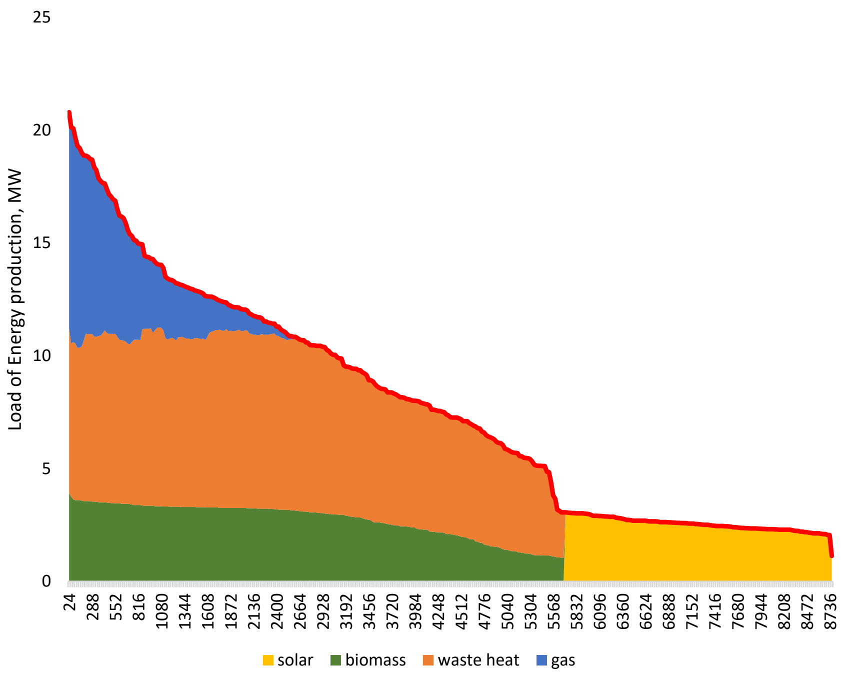

Fig.1.1. Heat load duration curve.

The transition to a future DH system, where renewable and recycled heat is used, can be divided into two steps [11]. The first step considers possible sources of renewable heat energy and their implementation. The second step looks at the redesign of existing systems to make them more suitable for future needs. In the demand side management part, we look at the second step, and the first step is discussed in the next chapter.

How to forecast heat energy consumption in district heating system - energy efficiency improvement influence on energy consumption (duration curve)

DH systems have the potential to optimize operational strategies because most of them are still working in line with reactive control strategies. Systems can be optimized by using predictive strategies which are based on forecasting and real-time data [12].

Energy forecasting is an important method in the transition to future sustainable DH systems since the new energy systems are more complex, and higher energy efficiency is needed. As the share of renewable energy increases, the importance of demand forecasting also. Systems that use renewable energy to produce heat need an accurate prognosis of heat demand in upcoming days to verify if they can accomplish the task only with renewable energy or if they need other energy sources. The heat load forecasts allow to run the systems with higher precision, resulting in more efficient systems, which lowers the system costs. [13]

Factors influencing the heating load can be divided into four main categories: time variables, weather parameters, operation inertia of DH systems, and user social behavior. Time variables are the year, month, day, hour, and others that can show the behavior of users. That kind of data can be used for heat load planning. For example, in an office building, the demand for heat will be greater on weekdays when people have a work. The determining factor for the heating load is the weather conditions like outdoor temperature, outdoor humidity, wind speed, and air quality index. The air quality index indirectly can affect heating load. The operating parameters of the DH system, such as supply and return water temperature, flow rate, and the type of energy used, are also an influential factor. To better understand all leading factors of heating load, historical data should be analyzed. [14]

In the past, DH systems for forecasting used approaches based on physical and mathematical methods, which established the functional relationship between heating load and its influence characteristics. But due to the uncertainty of various factors such as extreme weather and holiday, mathematical modeling methods were not sufficiently accurate. Therefore, data-driven methods are a better choice. [14]

Different forecasting models are developed for this sector, but not one can give the best forecast in every situation, so studies recommend using multiple models. Also, it would be beneficial to use temporal hierarchies to improve forecast accuracy because they give a short-term and long-term prognosis which are useful for operational optimization and long-term planning. [13]

Temporal hierarchies have not been used for heat load forecasting, although they have proven themselves in other sectors, such as tourism and electrical load forecasting. They have different levels and non-overlapping temporal aggregations. These models on different aggregation levels can reveal different behavior in the data. Forecasts are being reconciled at all levels, meaning that the forecast from a higher level is equal to the sum of the prognosis from the lower level. [13]

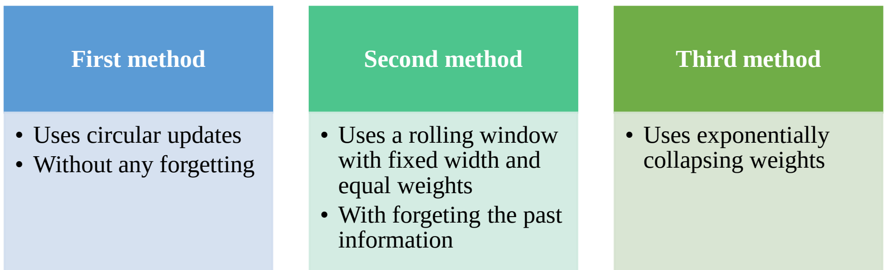

Fig.1.2. Covariance matrix update methods

H. G. Bergsteinsson *et al*. used temporal hierarchies for heat load forecasting in the Danish DH system in Varmelast. The aim was to improve the accuracy of the day-ahead hourly heat load forecasts. In this case, prognoses are generated each day at 23:00 for the next 24 hours. Four year historical data on heat loads were used. In this study, the authors propose three methods to update the covariance matrix. The first approach uses circular updates for the covariance matrix without any forgetting. In the second approach to forget the past information model uses a rolling window with fixed width and equal weights. The third approach uses exponentially collapsing weights on past information to improve the relevance of the recent observations. [13]

Based on the results from the case study [13], authors made observations about the tested methods:

- The first method is suitable for cases when few data points are available because the optimization of the hyperparameters is unnecessary. The covariance matrix expands over time and improves the base forecasts.
- The second method's performance is the worst of all approaches. It will reach the same result as the first method with increasing memory, but it never outdoes it.
- The third method's performance is the best because it always made the best improvements to heat load forecast accuracy.

The system proposed in this study improved the accuracy of forecasts by 15% compared to commercial state-of-the-art operational forecasts [13].

The most used models for forecasting in a DH system are the traditional regression model, support vector machine (SVM), and artificial neural network (ANN) [14]. Soft computing methods such as ANN and SVM are commonly used to forecast short-term natural gas consumption - load per week, per day, per hour, or even less than per hour [15].

Artificial neural network (ANN) covers a large class of models and learning algorithms. The feedforward neural network is generally the most used neural network. It consists of three main layers- input, hidden, and output. The hidden layer can have more than one layer, which depends on the complexity and characteristics of the problem. The input information for the layer comes only from the previous layer. Back propagation neural network (BPNN) is a multilayer feedforward neural network, which is made of two parts: the forward generation of the signal and the back error propagation. ANN can be unreliable because instability issues can create significant variations in the output data due to small changes in the input information. [16]

When SVM is used for regression problems, it is called support vector regression (SVR). The SVR model is obtained from the calculation of a linear regression function but has a high-dimensional feature space where the input data is mapped using a nonlinear function. This model aims to find a function that has the most difference from the obtained target for all the training data but still is as flat as possible. The SVR model has two key parameters: the penalty factor, which is tolerance for the error, and the coefficient of the kernel function, which uncertainly establishes the distribution of the data after mapping to the new space. The biggest disadvantage of this model is the calibration of its hyperparameter. It is difficult but crucial to the accuracy of forecasts. [16]

The base model for random forest (RF) is the classification regression tree (CART). It improves the CART model because, for forecasting, it uses a set of trees, not a single tree. That increases the accuracy and stability of the predictions but makes the model more complex and time-consuming. Regression trees are generated by making repeated samples of the primary dataset. Approximately one-third of samples are not obtained at each repeated sampling, which creates a control data set. The average results of all trees give a final prediction function. [16]

Gradient boosting decision tree (GBDT) is an iterative decision tree algorithm and is also termed multiple additive regression tree (MART) or gradient boosting machine (GBM). For GBDT, numerical optimization is the base way of thinking, and it uses the quickest descent method to find the optimal solution for the loss function. The model operates by adjusting the negative gradient using the regression tree and by determining the step length using the Newton method. It applies the forward distribution algorithm. GBDT can avoid overfitting by reducing deviations, but GBDT is harder to train in parallel than RF model. [16]

Extreme gradient boosting (XGBoos) algorithm is based on GBDT but an improved version. For XGBoos, analytic reasoning is the base way of thinking. This model operates by using the Newton method to find the extreme value of the loss function. To obtain the optimal loss function, the function is expanded to the second-order derivatives to get the analytic solution as the gain to establish trees. XGBoost does parallel learning, is comparably faster in calculations, and prevents over-fitting but at the same time optimizes the computation resources. [16]

Ran Wang *et al*. looked at the advantages and disadvantages of commonly used forecasting models using multiple performance metrics [16]. The accuracy, efficiency, robustness, and interpretability were taken into account while comparing the models. Accuracy describes the difference between predicted and actual value. To evaluate it, they used root mean squared error, mean absolute error, mean absolute percentage error, and coefficient of variation of root mean square error. Efficiency shows the convenience of the use of the prediction model. To measure it, they used data pre-processing, normalization, and cross-validation. The standard deviation of the accuracy was used to indicate the robustness, which is the ability to deliver acceptable accuracy for various problems with inconsistent training datasets. Interpretability was used to define the capability of insight, which the method imparts to model behavior, for example, parameter importance and interaction effects. Five forecasting models were investigated- XGBoost, RF, BPNN, GBDT, and SVR. Input data for models was heating energy consumption from the residential quarter located in Tianjin. That is a city on the east coast of China and is in a cold climate zone. As a result of research, there was not one best model. RF shows the highest overall results, with the best accuracy, robustness, and interpretability. XGBoost performed with optimal efficiency but is slightly less robust and accurate than RF. The BPNN got the lowest results. The sample size greatly affected the precision of the hourly heating energy forecast. When the training data is small size, the accuracy of RF and SVR was higher. But the BPNN and ensemble algorithms showed high precision when the sample size was large. Historical heating consumption and outdoor dry bulb temperature are influential variables because they affect the precision of output data. The obtained results of this research can help better choose the machine learning algorithms in the field of building energy consumption prediction.

As mentioned above, it is necessary to use several models together to get more accurate results. Nima Izadyar *et al*. conducted a study [6] in which the SVM method was coupled with the discrete wavelet transform (SVM-Wavelet), the firefly algorithm (SVM-FFA), and the radial basis function (SVM-RBF). All models were analyzed and used to forecast monthly natural gas consumption in Baharestan town's heating system. To better understand the accuracy of models, they were compared with two other soft computing methods- ANN and Genetic programming (GP). Accuracy was measured using three statistical indicators- root means square error, coefficient of determination, and Pearson coefficient. The results showed that all three SVM models performed slightly better than ANN and GP. SVM models have a relatively high correlation with actual data because the Pearson coefficient is bigger than 0,85. Based on the results, the authors conclude that SVM-Wavelet is the most accurate model from studied SVM models for forecasting the monthly natural gas demand.

Heat load forecasting is an essential part of the transition to future sustainable DH systems. Several methods for predictions already exist. Some are used in practice, but some are in the development stage. There is no single best method that can be used in all cases. The forecasting approach should be chosen depending on the situation. Also, it is recommended to use multiple models to get a more precise forecast of energy load.

Energy demand flexibility - reduction of peak loads

Heat demand of buildings is highly sessional and has more powerful peaks compared to other sectors like electricity and transport [17]. The correlation between demand and production plays an essential role in system efficiency improvement (see Fig.1.3.).

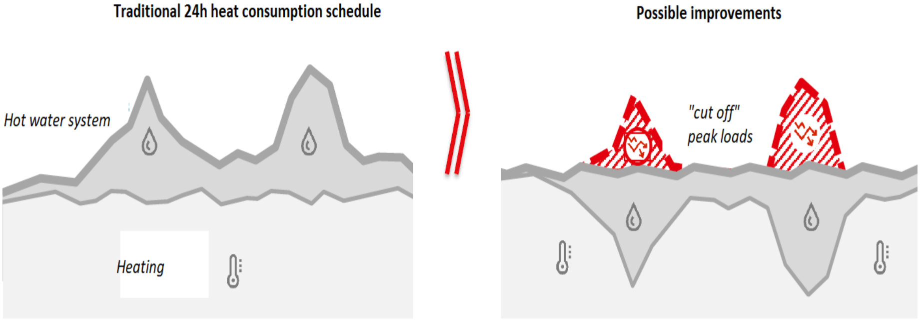

Fig.1.3. Possible system efficiency improvement (info from Danfoss, Ltd)

Because when an unexpectedly high amount of thermal energy is needed, technologies with low efficiency, usually Heat-only-boilers, are used [18]. Heat-only-boilers can be replaced with thermal storage. When there is excess or low-cost energy, it is stored. And it is used when main plants cannot produce enough energy during peak hours, or the energy costs are too high [9]. There are the three main thermal storage methods [18]:

1. Proper heat buffer in DH systems is regular, and they have many advantages. They usually are placed close to the plants or in strategic zones of the network. The main disadvantages of this method are installation space and investment costs. Usually, DH systems are in densely populated areas where space is limited, and the costs of this space are high.
2. Another method is to use the water mass within the network pipelines as storage. The thermal capacity of the network is used as storage by influencing the mass flow rate or the supply temperature. A system whit this kind of storage is more complex because the storing time depends on several variables.
3. As storage, the building envelope also can be used. It is done by delivering heat at a different time than it is needed, which raises the temperature indoors and in the envelope. This method is possible because the thermal capacity of the building is usually important for the thermal balance. Buildings are very different, so it is not a simple task. However, studies show that possible stored heat energy in buildings is 9–54 MW depending on the size and the envelope characteristics. It is when an induced variation of the outdoor temperature is taken up to 6 °C.

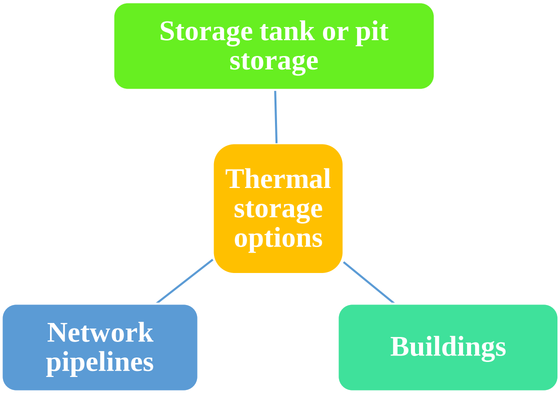

Fig.1.4. Thermals storage options

When comparing the storage tank to a building as storage, storage tanks can hold more than double the amount of heat. However, for DH systems, buildings as heat storage could be an option because various buildings are available as thermal storages, and they can be used separately in different ways. Network pipelines can offer limited contribution as thermal storage in comparison to building envelopes. But the application of the building envelope as storage needs the involvement of the customers because indoor conditions are slightly changed. [18]

Demand Side Management (DSM) can be used in DH systems. DSM includes all the actions at the demand level. These measures aim to reduce energy consumption, costs, and impact on the environment or raise the income from energy sales. Also, they include energy efficiency improvements of the buildings. DMS in DH systems can adjust the thermal demand of the buildings to modify the overall network thermal load. That allows adjusting the parts of the general load profile to create compliance with the production side. While using DMS in DH systems, many goals can be set and achieved, for example, reduction of a thermal peak, minimizing the expense for heat energy, and the best renewable source integration into the network. [18]

Three main actions can be done to change the building thermal demand profiles- retrofitting measures, indirect DMS, and direct DMS. The first action is about modernizing connected buildings in the DH network. The result of this method is an irreversible change in the heat load demand of the buildings, which can decrease the difference between demand and production. The indirect DMS is widely known in the electricity market. This method uses different tariffs for different times of the day to adjust demand. Implementation is easy and does not require high investment costs, but it can deliver very uncertain outcomes. User responses to this method are hard to predict. It can even make the peak loads that are just shifted in time. The direct DMS is directly controlling the heat load to customize it to the optimal profile. This can be accomplished by changing the on/off timetable in buildings or implementing a different regulation strategy. With direct DMS, goal achievement is more controllable. [18]

Elisa Guelpa and Vittorio Verda summarized the use of DSM in DH systems [18]. In this review, they looked at case studies and simulations. A study in Italy's distribution network used DSM and schedule changes lower than 20 minutes in about 35 buildings. Results showed that up to 10% peak load reduction is achievable. Another study about 27 student apartment buildings in Finland used demand response where household hot water demand was prioritized at the cost of the heating. In that case, room temperature lowers when the need for domestic hot water is high. As a result, peak load reduction was 14%–15% during the coldest days. There are also studies in which simulation tests are made for real buildings. They concluded that the peak load could be decreased by about 20–30%. Reviewed studies show that it is possible to reduce peak loads using DMS, but the reduced amount depends on the peak load size, building characteristics, and used methods [17].

To summarize, the DMS can be used in DH to achieve many goals like reduction of peak load. It can be achieved by implementing measures at the demand level. Three main steps can be taken to change the building thermal demand profiles. The literature review showed that peak load can be reduced by up to 30% when using DMS.

Elisabeth Zeyen *et al*. looked at the most cost-efficient ways to lower the heat demand peaks in a design where carbon dioxide emissions are net-zero [8]. They used the least-cost capacity expansion model PyPSA-Eur-Sec to simulate eight scenarios. The simulation was made for all European countries. For heat demand peak reduction, were chosen three options- the thermal envelope retrofitting of buildings, thermal energy storage, and individual hybrid heat pumps with backup gas boilers. All eight possible combinations of these methods were simulated. The scenarios start from flexible, where all three options are used, and end at rigid, where none of the options are used. The model simulates heat demand not only in DH systems but also in rural areas and urban areas with individual heating. The results showed that implementation of these three methods reduced heat demand by up to 51% and peak capacities by up to 55%. Off all three options, retrofitting buildings had the most significant effect on peak capacity reduction. Thermal energy storage also reduced peak capacities but increased general heat energy generation. Hybrid heat pumps with backup gas boilers or building retrofitting decrease the peak capacities significantly more than thermal energy storage. So, it is beneficial if carbon-neutral gas is available. Building renovation is mainly required to address those peaks and not to lower the total energy demand. Results indicate that entire system costs decrease by up to 17% if all three methods are applied.

The reviewed study [17] also performed a thought experiment to discover what part of total costs is from heat peak loads. They looked at the entire expenses of the three sectors- heating, electricity, and transport. They made a scenario where annual thermal demand was distributed evenly over the entire year. So, there was an unchanging heat profile without winter peaks. In this scenario, total costs decreased by 18–30%. That indicates that up to 30% of three sector expenses are made from heat peak demands.

DH systems have higher heat load peaks because demand is more seasonal than in other sectors. There are several ways to reduce those peaks, like thermal storage, management systems, and building renovations. Using these methods peak loads can be reduced significantly. Peak reduction improves efficiency and can lower the overall costs of the system.

Assessment of heat energy tariffs

Creating a resilient DH system can bring financial benefits to DH system owners, operators, customers, and the end user, as improving energy efficiency reduces peak load expenditure at heat plants and reduces maintenance costs [19]. Cost reductions can be realised through lower distribution temperatures, which can also be achieved with renewable and recycled heat sources [20]. An important aspect is the pipeline reconstruction rate to reduce heat loss from the network [21]. With district heating and cooling optimization technologies, reducing energy consumption to 40% [22]. Investments, operational costs, and heat losses also affect the costs of DH [23]. Therefore, reduced costs allow heat producers attract new customers by lowering heat prices and reassuring those customers who are not connected to DH previously.

There are several aspects affecting the efficiency of the DH companies' heating generation and heat tariff. One of most important is the DH regulation mechanism. Limited or non-existing competition that is commonly seen in the natural monopolies of utilities, including the DH production market, create additional challenges for the regulator when it comes to operational efficiency evaluation. The lack of competition does not incentivize DH producers to increase the productivity of their production processes and the integrity of tariff determination [24].

The business and pricing models play an essential role in the DH framework, as they show how the company generates income and customer relationships [19]. DH is a natural monopoly, as there is little room for competition. DH companies can abuse the monopoly and disproportionately increase prices, complicating invoicing, and tariff structure, harming new customers [19]. This abusive method of increasing profits creates neutrality for DH operators and favours individual heat supply.

DH tariff could be comprehensively regulated or unregulated, and each model has advantages and disadvantages [25]. DH tariffs are often two-part tariffs and consist of a fixed fee and a variable fee [26]. Heat tariffs primarily are based on connexion fee, standing cost and unit cost [25]. But there are several DH tariff structure models [25]:

- cost-plus pricing tariff consists of operational cost, annual depreciation and permitted profit;
- marginal-cost pricing tariff components are a cost of one more unit of generation and marginal variable cost as well as the depreciation of fixed cost;

- incremental cost tariff is formed from operational costs of the existing system and discounted costs of future change;
- an integrated model of competitive and regulated methods where heat is integrated from different regions;
- shadow price method tariff is based on willingness to pay for an additional unit of heat production when the market is in equilibrium;
- real-time pricing based on smart metering and is similar to pricing in the electricity sector;
- the equivalent marginal cost method is made of short and long-run marginal costs.

Tariffs for DH systems must also be as low as possible in order to reduce energy poverty, as the EU has 11% of the population unable to afford energy services [27].

Examples of DH tariff methodologies in different European countries

DH tariffs vary not only for different countries due to diverse tariff structures but also for different regions where there is one tariff structure, because each region has its own energy producer, which affects the tariff. Therefore, existing heat tariffs should be regularly reviewed, and the most optimal tariff calculation should be selected depending on the countries capabilities and resources.

The heat tariff is regulated in all Baltic States. In **Estonia,** the heating tariff is approved by showing reasonable sales volume and cost-effectiveness. The heat price limit is determined separately for each DH area showing cost-effectiveness maximum area price. Competition Authority sets it according to technical indicators [28]. In **Lithuania,** heat tariff is based on two variable components and a fixed component. Heat price is determined for three up to five year periods, but tariff components are updated every month or year depending on several conditions[29]:

- variable component – updated every month based on actual fuel costs from the operator's own plants and monthly auctions;
- second variable component - actual energy mix is revised every year by the Regulator to adjust through the year;
- fixed component – includes depreciation and amortisation, staff cost, operation and maintenance, etc. and is revised yearly by the Regulator.

The heat tariff regulation is much more liberal in Nordic countries. The heating prices are not regulated in **Finland** and **Sweden**. The competition in the DH market keeps the price at a reasonable level [30]. In **Norway,** heating price is regulated for mandatory connections. It depends on electricity price with grid tariffs and electricity taxes. In **Iceland**, the heating tariff is regulated by the Ministry of Industry and Innovation. The heat price shows production, distribution, and sales price [30].

Slightly different regulation mechanisms occur in Denmark, where heat tariff is based on the cost-plus principle and regulated by energy market authority [30]. The tariff structure is based on 4 components [30]:

- connection fee (DKK/kW) – paid once for connection and as part of an investment;
- annual fixed term (DKK/kW/y) – depends on capacity;
- variable term (DKK/MWh) – energy consumption, but in future, it could be season tariff to optimise efficiency;
- bonus/malus term (DKK/°C) - depends on return temperature. If it differs from the temperature range 30 - 37°C by 10 %, a bonus or penalty of 1% is applied.

A similar heat tariff determination method by applying variable and fixed components has been used in France, Germany and Spain. The tariff structure in **Germany** consists of two components, and new customers have a connection fee. The fixed component includes capital and operation costs based on maximum capacity (MW), but the variable component is based on consumed MWh. In **France,** the fixed component is affected by installed capacity and consists of energy consumption of auxiliary equipment, cost of operation and maintenance of the network, and yearly capital costs. The variable component is affected by consumed energy, flow in heat exchanger and season. In **Spain,** there are long term and short term tariffs introduced in addition to fixed and variable components. The fixed component is higher for the long term tariff, but the variable component is higher for the short term tariff [10]. In Spain, heating tariffs are reviewed monthly because of national indexes and changes in gas and electricity prices and for new clients, there are connection fees to connect to the network.

Poland has two options for heating tariff – a cost-plus method based on planned incomes and costs and benchmarking method based on Regulator published heat price level [22]. Benchmark for heat tariff is usually set for one year, but it is possible to request a change in tariff before the end.

In **Italy,** DH price is not regulated and is updated every year by a published index from the National Institute of Statistics. DH tariff consists of a variable component and two fixed components. The heat tariff is different for residential and tertiary buildings and depends on the consumed heat and installed capacity [29].

Role of DH tariffs towards smart DH systems

The role of DH tariff from the consumers and DH operator's perspective have been shown in Fig.1.5. An essential aspect of final consumers is the cost of heat, which depends on the heating area and the building efficiency and different operational conditions. If the tariff structure is not based on the customer's actual consumption, it provides little or no incentive to optimise heat consumption [32]. Therefore, tariffs that consider customers' actual consumption allow them to influence their energy bill and consumption and motivate them to find more efficient solutions to their energy consumption [32]. On the other hand, the DH tariff should also be affordable not to raise the energy poverty risk.

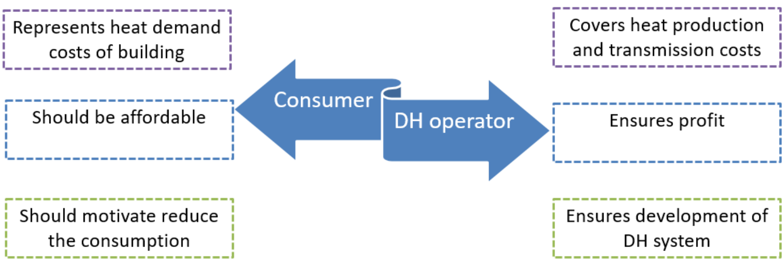

Fig.1.5. Role of DH tariff from the consumers and DH operator's perspective

From the DH operators perspective, DH tariffs should cover the heat production and transmission costs and ensure profit for future development of the DH system. In addition, improving existing DH tariffs allows the implementation of new business models that are more understandable and encourage the involvement of new stakeholders. Finally, tariffs that incentivise both heat producers and end-users are a good tool to apply in DH systems, but countries where DH pricing is regulated, may face political obstacles [19].

Application of the benchmark method in determining the heat supply tariff

Compared to a strictly regulated DH market, in a fully liberalized DH environment, the tariff is determined based on the DH performance benchmarking parameters [33]. It promotes an incentive-based regulation framework [34], [35]. While a strong debate over which of the DH regimes is the most convenient is on-going [36], more and more studies focus on the examination of the effects and benefits of introducing benchmarks in DH market regulation for the operational efficiency evaluation [37]. Benchmarking in a natural monopoly market structure is as useful as in a fully liberalized market since it allows to compare how the performance efficiency of DH production companies differ even though the same service is provided for the end-consumer [38].

A study by Marques et al. [39] concludes that the application of benchmarking for companies operating in the utilities and in a natural monopoly market structure has several advantages. It incentivizes companies to operate more efficiently and implement innovative solutions to increase technical efficiency which results in the optimization of operations and capital expenses, increased return on investment, and improved information transparency to the utility consumers and stakeholders [39].

Several authors have emphasized the possibility of setting heat tariffs using the benchmark method [33], [40], [41]. There are various alternatives for correct benchmarking, including a number of performance parameters [42]. However, several different alternatives can be made to compare existing DH tariffs.

The results of the study conclude that DH operators and DH systems differ significantly, so empirical regression analysis is not sufficient to obtain unambiguous results [43]. Instead, it is necessary to take into account the various explanatory parameters and the relative values of the indicators that would give each DH system a ranking according to its distance to a certain benchmark. However, there is still no consensus in studies to date on the most appropriate comparative methodology. It was concluded that the choice of the benchmark method, including indicators and thresholds, has a significant impact on the performance indicators set and the assessment of the DH companies [44].

There are studies analyzing benchmarking models as tools for evaluating the effectiveness of DH [42]. The benchmark model includes a combination of different technical, structural and economic indicators, such as the type and price of the energy source, the legislation in force, the heat load and installed capacity of the system, the efficiency of heat production and transmission, and others. In addition, the assessment of the economic and environmental parameters of DH systems includes indicators of government decision-making, market structure and management performance.

The type of fuel consumed is an important indicator that is included in the DH benchmark. The share of renewable energy used by DH determines the overall sustainability of an existing DH, as it has a strong impact on greenhouse gas emissions. Setting an appropriate benchmark allows DH operators to be grouped not only by their heat production efficiency, but also by moving towards a carbon-neutral heat supply. Therefore, it allows to highlight those DH companies whose set values are below the benchmark. Such results can contribute to restructuring and improving systems to move towards more sustainable carbon-neutral heat production technologies. In fact, environmental objectives are considered to be one of the predominant long-term objectives of DH, as they promote more sustainable production on both the part of the regulator and the consumer [45].

DH have an important role to play in achieving ambitious global climate change mitigation goals [46], and tools need to be developed to incentivize DH operators to reduce their greenhouse gas emissions. Decarbonisation of DH can be achieved both through more efficient technologies and through less polluting energy sources [47]. Energy efficiency is one of the key factors in mitigating both climate change and lower heat tariffs [48]. DH energy efficiency can be increased by integrating RES and improving the technological efficiency of heat production and transmission networks [49]. Therefore, indicators assessing the performance of DH technical parameters should be included in benchmark-based models.

When analyzing the performance of a DH, the type of heat source (boiler house or cogeneration plant) should be taken into account as an important technological indicator. In addition, the technological condition of boiler houses and cogeneration plants has a strong impact on the efficiency of heat production, so the DH benchmark studies recommend integrating variables that take into account investments in heat source reconstruction activities in the last years of operation. This is particularly important for the assessment of DH infrastructure in Eastern Europe, where, due to a lack of historical investment, DH modernization strategies need to be implemented to ensure the future sustainability of DH [41].

Studies show that the performance and efficiency of DH operators are highly dependent on the energy source, the proportion of different fuels, heat production technologies, and transmission losses in the system [24]. In addition, a more detailed analysis of the technical parameters greatly influences the resulting transmission losses due to the temperature of the heat transfer medium. To maximize the effectiveness of the DH, transmission losses should be kept to a minimum. Therefore, low flow and return temperatures in heating networks are a key factor in increasing the energy efficiency of DH networks [51].

Technological factors are also important for the long-term development of the DH system: introduction of new heat production technologies, digitization of operational processes and services. Diversification of production technologies includes the integration of heat sources such as solar energy, geothermal energy, waste heat from different production and other plants, geothermal energy and other sources that have the potential to increase long-term energy efficiency and optimize production costs for DH operators [42].

The study by U. Sarma and G. Bazbauer introduced a new benchmark for technological efficiency, showing that "best available technology (BAT)" indicators could be used to promote the development of DH infrastructure [53]. By setting efficiency requirements based on BAT, DH could provide incentives and drive for efficiency gains. BAT parameters for the various elements of a DH could be used to generate assessment indices that indicate how the energy efficiency of a particular installation differs from that specified in the BAT reference documents [54].

Another important parameter for DH performance efficiency is the amount of energy produced. If the total amount of energy produced increases, the DH system benefits from a reduction in the total cost per unit of energy produced. As a result, the system operates with higher economic efficiency and can provide a competitive heat tariff [55]. The cost optimization provided by the increase in heat production increases the overall efficiency and competitiveness of the DH. Therefore, the merger of DH operators and the joint expansion of DH business are proposed [56].

1.2. Management of energy resources

As the population continues to grow, so does the need for energy, and it is crucial to develop and use energy-efficient, cost-effective, and sustainable technologies. In 2015 three quarters of the population in Europe lived in cities where mainly district heating and cooling systems are used [24]. The population in cities continues to grow. The priority of the European Union (EU) Strategy on Heating and Cooling is to make heating and cooling more efficient and sustainable [48]. Annual energy consumption for heating and cooling in the EU accounts for 50% of total energy consumption. Main primary energy sources used are natural gas (46%), coal (15%), biomass (11%), and fuel oil (10%), but the remaining 18% are renewable energy [49]. However, renewable energy in heating and cooling systems has not reached full potential in this sector.

Heating and cooling systems need to become more intelligent and increase energy efficiency. Energy costs and CO_2 emissions should be reduced. Biomass, geothermal energy, and solar collectors are popular renewable technologies used in DH systems over the last decade [21]. For DH, the future challenge is a more intelligent energy system because it is a system where together are integrated district heating and cooling, electricity, and transport sectors to achieve the best solution for each sector and all energy sectors [59]. DH needs to transition to low-temperature networks to be part of a smart energy system [40]. The focus is on low-temperature DH as the primary technology with renewable energy sources and waste heat use [60].

To reduce the environmental impact of DH, the redesign of existing systems to make them more suitable for future needs is necessary [11]. To make DH more sustainable, one of the key aspects is renewable energy [61].

Replacement of fossil fuels by renewable energy sources

Between 2015 and 2020, the share of renewable energy in DH globally increased by 1%. However, this share is projected to increase from 8 to 14% by 2025. Every country has a different percentage of renewable energy sources in DH systems depending on natural resources, market drivers, and policies. [61]

Currently, the most used renewable resources in DH systems are solar thermal, geothermal, and biomass. Also, waste heat from industry is another existing heat source supplied to DH systems. All noted heat sources are commercially mature with a technical readiness level of 9 on a scale of 1–9. [61]

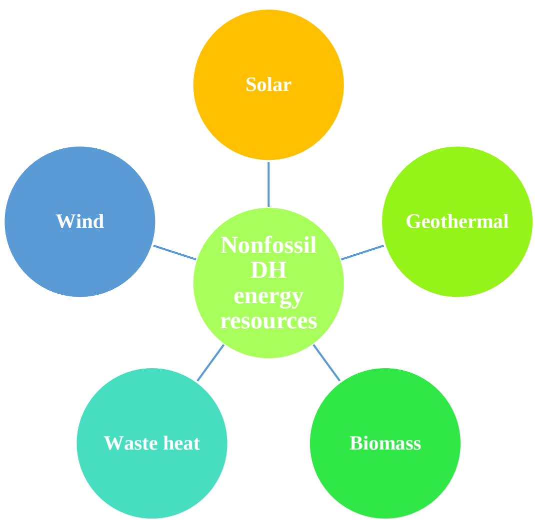

Fig.1.6. Nonfossil energy resources in DH systems

Solar thermal is absorbed heat from sunlight that is further used for heating, cooling, and electricity. Its biggest benefits are high reliability, low maintenance, high efficiency, and flexibility for integration with additional renewable heat sources. However, disadvantages of solar thermal are irregular nature, the necessity of geographic review, mainly available in summer when heat energy for DH is not highly demanded, relatively high capital cost, and physical space is needed. Globally, Denmark has the most large-scale solar-based DH systems. They have about 120 systems, which are larger than 500 m2, and overall cover 1.3 million m^2. However, large solar thermal plants which are providing heat for DH systems now define only about 1% of the installed capacity of all solar thermal systems. Estimations show that this could rise to 4–15%. Solar thermal plants are centralized or distributed. Centralized solar plants are usually large-scale collector parks on the ground that needs a big land site. Distributed plant solar collectors usually are not in the heat supply plants but are located closer to the heat consumption point that provides energy to an individual or building blocks. Also, there is an option to put solar panels on rooftops, which is suitable for urban areas whit high land costs. One of the essential technical aspects of successful solar-based DH systems is seasonal heat storage. [61]

Waste heat is local energy remaining from industrial and commercial uses, and it has already completed its primary function. Its benefits are its usage makes energy savings, significant lowering in GHG emissions, high efficiency in energy utilization, and it is available all year. However, disadvantages of waste heat are the heating site is frequently limited, cannot be used for DH at a national level, can have a lower temperature, is time uncertain, and may induce lock-in of fossil fuels. About 30-60% of industrial energy is directly released into the ambient atmosphere in the form of waste heat. That is why its recovery can improve general energy efficiency while reducing GHG emissions. Waste heat to DH can be delivered using heat pumps or via direct heat exchange. There is a great potential for this resource in DH systems because the estimations show that approximately 750 TWh/year of waste heat could be recovered in the European union. That is one-quarter of the European annual heat needs for the building sector. Waste heat from industries is suitable for a low-temperature DH system with a supply/return of about 50/20 °C because usually, its temperature is in this range. Nevertheless, it is only a cost-effective resource if the industrial site is close to the heating area. Another thing to consider when using waste heat is that industries work according to their own schedules, so the amount of heat cannot be adjusted to demand. [61]

Geothermal is locally accessible earth's inner heat, either highly diffuse or concentrated into deposits. The benefits of geothermal are it is secure and adaptable, it has environmental and economic advantages, it is available all year, and a little geometrical area is needed. Nevertheless, disadvantages are geographic limitations, efficiency dependent on the temperature, and big investment expenses due to the drilling and equipment needed. Geothermal technology is the most mature of all renewable energy technologies in DH systems. They are used in Europe, as there are 240 geothermal-based DH systems in Europe. But the usage depends on the country's geographical location. Iceland has great access to this renewable resource, so around 100% of space heating need is met by geothermal in DH systems. However, only approximately 12% of geothermal heat in the world is applied in DH systems. But almost 75% of total geothermal heat is used for personal ground source heat pumps and spa and swimming pool heating. Extra costs before geothermal installation are surface exploration before drilling. It can include geological and hydrogeological studies, geochemical and geophysical surveys, thermal analysis, and slim and shallow well drilling may also be required. Financing new geothermal DH infrastructure can be difficult, but economic viability increases in cases where installation is near urban areas with higher density or when this technology is implemented in the existing DH network.[61]

Biomass is a raw material produced by photosynthesis like wood or energy crop. Its biggest benefits are less costly, lower GHG emissions compared to fossil fuels, and residues can be used. However, disadvantages of using biomass are a geographic restriction, if not locally accessible, then increased transportation expense, and pollution if burnt. Biomass is an attractive renewable energy source because of its easy usage, as the direct combustion of biomass instead of fossil fuels. In 2010, only 8% of biomass across the world was used in the DH sector, but it is predicted to grow to 1389 TWh by 2030. Because the DH systems are being improved and are moving to lower supply temperatures, biomass could be better used in biorefineries to produce transportation fuels, chemicals, and plastics. Therefore, DH should concentrate more on recovering waste heat from these industries. Also, the improvement of systems will lower system costs, so biomass usage in this sector most likely will decrease. However, it is not predicted to entirely not be used, but biomass is not a long-term answer for heating purposes. [61]

The future network which allows decarbonization of the system is the fourth-generation district heating (4GDH) system [61]. 4GDH systems use low-temperature heat sources. That is achievable using smart energy systems integrated with low-energy buildings and networks with low grid losses. A.M. Jodeiri *et al*. reviewed challenges and technological factors related to the integration of waste heat, solar thermal, geothermal, and biomass energy sources into 4GDH systems [61]. Moving to 4GDH, the economics will vary because usage of renewable energy is highly determined by investment expenses instead of fuel consumption. The low temperatures in the DH network will decrease grid losses, improve the efficiency of the heat generation technology, and reduce supply costs because of renewable resources and waste heat. The authors point out that seasonal heat storage will have an essential role in maximizing renewable energy use. The reviewed energy sources have their specific aspects and challenges.

Solar thermal collectors are an established technology, but the optimization is still under research. Their efficiency would improve whit lower network temperatures. Low-temperature waste heat is less used than solar thermal in DH but would also benefit from the 4GDH system. The disadvantage of geothermal is that if it has a high temperature, then it is available only in specific places. Alternatively, low-enthalpy ground source systems can be established in nearly all ground conditions. Biomass is cost-effective but is not a long-term answer for the heating sector. Capital expenses, availability, and flexibility are critical issues for implementing renewable energy sources into 4GDH systems and require a detailed plan and resource review. Nevertheless, multiple studies have proven the potential of the transition, which would give economic and environmental benefits.

Solar energy integration in district heating systems

Solar thermal is absorbed heat from sunlight that is further used for heating, cooling, and electricity. Its biggest benefits are high reliability, low maintenance, high efficiency, and flexibility for integration with additional renewable heat sources. However, disadvantages of solar thermal are irregular nature, the necessity of geographic review, mainly available in summer when heat energy for DH is not highly demanded, relatively high capital cost, and physical space is needed. [61]

Solar energy appears to be a more favorable sustainable energy alternative to fossil fuel than other renewable energy sources because it can satisfy energy needs to some extent and give environmental benefits. Mainly solar radiation is converted into electrical energy, but it can also be used for thermal energy production and for converting radiation into both energies in the same system. [62]

Solar thermal energy is obtained using heat exchanger collectors that transform solar radiation into thermal energy through a transport medium or carrying fluid. Collectors are the main component of the solar system, and it absorbs the incoming solar radiation and transforms it into heat energy. Then it is transmitted through a fluid that is typically air, water, or oil for practical applications. This system can be used for heating and cooling buildings. [62]

For generating electrical energy from solar radiation photovoltaic is the most used method. In this system, devices that convert sunlight into electricity are solar cells. They are using the photoelectric effect. This system also consists of ancillary components. The typical solar power conversion efficiencies are 15–20%. [62]

Photo thermo conversion is a method when thermal and electrical energy is obtained from solar radiation in the same system. This system uses device called hybrid photovoltaic thermal collector (PVT) [62]. Compared to other solar systems, PVT is economically beneficial because the costs of solar energy are lower, and generated energy amount per area is higher [63].

Solar thermal plants are centralized or distributed. Centralized solar plants are usually large-scale collector parks on the ground that needs a big land site. Distributed plant solar collectors usually are not in the heat supply plants but are located closer to the heat consumption point that provides energy to an individual or building blocks. Also, there is an option to put solar panels on rooftops, which is suitable for urban areas whit high land costs. [61]

A. Behzadi and A. Arabkoohsar proposed a solar-based building energy system that delivers excess energy to an electricity grid and DH system [63]. The system consists of PVT panels and thermal storage but does not have a battery and heat pump. The two components were eliminated to make the system more attractive to building owners because of cost reduction. To better understand the impact of changes in the DH system on this solar-based system, the authors made tree simulations in TRNSYS software. They made a model for existing, low-temperature (4GDH) and ultralow-temperature DH systems. The results indicated that the tested system for buildings would reach the best results in ultralow-temperature district heating. In this scenario, the solar system in the building will provide over 400 m3 of hot water to the DH system and about 1940 kWh of excess electricity to the power grid annually. The overall efficiency of the model achieves maximum values in June for ultralow-temperature system and in May for the two other systems. However, it is impossible for the proposed PVT systems to cover the building's real-time space heating demand because of the low solar availability on cold days.

In the last reviewed study [63], we can see how distributed solar thermal plants can be valuable for the DH system. Buildings with solar systems can provide electricity and domestic hot water for them self, and the excess is given to the district heating. Mutual benefit is formed because this building system cannot fully cover the space heating demand of the building with which DH can help.

In the last decades, large solar plants in DH systems have been established rapidly in Europe, especially in Germany, Austria, and Denmark. There are two successful cases of large solar systems in DH–the Drake Landing solar heating community in Canada and Danish solar plants in DH. The Drake Landing solar heating community is a well-known and good example, as this system can cover over 90% of space heat demand in a particular district. Nevertheless, that is the only large solar district heating system in Canada because natural gas boilers in Canada are more economically attractive. In the Danish case, it is different since the Danish government has an energy tax on natural gas. For Danish DH systems, solar thermal is a fully commercial solution, but still, in the planning process, cost-effectiveness must be analyzed. [64]

Globally, Denmark has the most large-scale solar-based DH systems [64]. As we can see in Fig.2.2., it had 124 large-scale solar district heating systems that covered about 1.6 million m^2 area in 2020. As before mentioned, Germany (43 systems) and Austria (19 systems) also have developed multiple systems but not as much as Denmark.

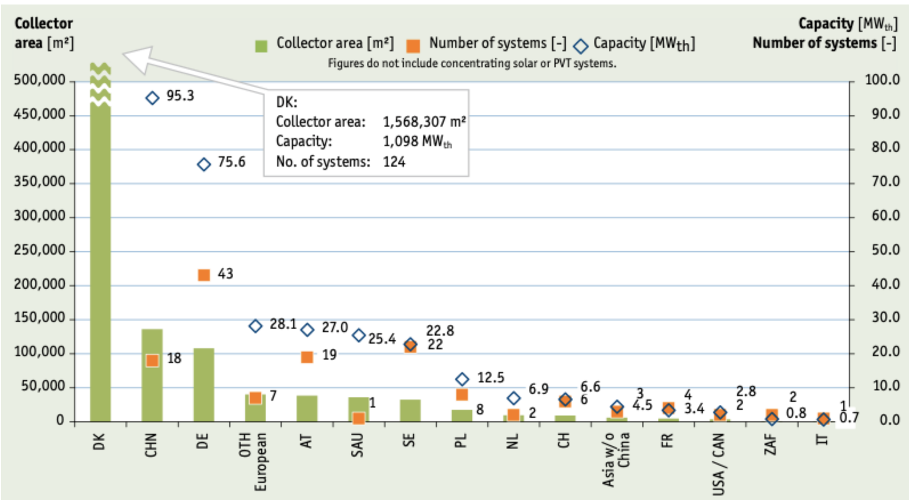

Fig.1.7. Large scale systems for solar district heating globally. Capacities and collector area installed and number of systems in 2020. [56]

Zhiyong Tian *et al*. summarized and analyzed the Danish experience with solar systems in DH. They came to four main conclusions [64]:

1. The key aspect to successful solar-based DH systems in Denmark was the low solar heat price since the heat price of electricity and natural gas boiler systems are high.

2. The end-users have the willingness to build solar district heating plants because mostly DH companies are owned by there communities. Also, the land is affordable, which makes it easier.

3. In Denmark, more than 64% of the heat demand of households is covered by DH systems. Because of this high need for DH systems services, the initial investment cost of solar heating plants are lower.

4. Denmark systems mainly use reliable solar collector components that have high efficiency and a long lifetime, so the consumers have gained great trust in the solar-based DH systems.

The authors recommend for other countries to learn from Denmark's experience. The most important is to gain trust between policymakers, companies, and end-users, carefully plan the systems and consider the price of solar heat and fossil-based energy systems. [64]

Solar thermal is a commercially mature technology that is already used in DH systems. Solar thermal plants are centralized (large-scale collector parks) or distributed (solar collectors located near the heat consumption point). Buildings with solar systems can provide electricity and domestic hot water for themself, and the excess can be given to the DH system. In another case, solar plants can be implemented into DH systems. One of the essential technical aspects of successful solar-based DH systems is seasonal heat storage.

Electricity use for heat energy production in district heating systems (use of heat pumps, electrical boilers, accumulation of heat energy)(wind energy)

Smart Energy Systems or Hybrid Energy Networks could be used to make energy systems more sustainable. The main idea of these systems is that energy systems (electricity, thermal, and gas) should be connected and coordinated to recognize synergies between them that can help reach an optimal solution for each sector and general energy system. It is found that electrification can help the district heating system to be more cost-effective and transition to renewable energy sources. Electrification of DH systems consists of two parts– direct electrification, for example, electric-driven heat pumps and electric boilers, and indirect electrification, for example, surplus heat from industrial operations that use electricity and excess heat from electricity generation. [66]

Direct electrification can be done by using power-to-heat technologies. In this section, we will look at three types of technologies–heat pumps, electric boilers, and heat accumulators. These can help DH systems to become carbon neutral because they can use energy from renewable sources, like wind energy, to generate heat.

Power-to-heat heat pumps supply flexible electricity needs and does not affect the overall efficiency of the system. CHP plants integrating large-scale heat pumps into their system can increase irregular renewable energy sources in the power supply by up to 40%. This technology has a lot of advantages, but one of the drawbacks is that they make the system more expensive because high investment costs are needed. Heat pump application in DH systems has been studied in the context of socio-economic potential analysis, feasibility study on its integration in DH system, technical analysis, policy issues, etc. Some studies suggest that in 4GDH, heat pumps are an essential element in the system. [67]

To better understand the costs of the system with heat pumps, Meng Yuan *et al*. conducted a techno-economic analysis of the system with heat pumps and industrial excess heat. The aim of this study was to understand the optimal shares of these two technologies in the heat generation mix in the context of 100% renewable smart energy systems. The DH system model in this study consists of all sectors of energy systems, including heat, electricity, industry, and transportation. For modeling, they used EnergyPLAN software. As a case study, Aalborg Municipality in Denmark was chosen. Results showed that the optimal solution for this DH system is a share of 20% heat pumps and 40% industrial excess heat. The rest energy, in this case, is provided by CHP, boilers, waste incineration, and excess heat from electrofuel conversion. The framework of this research can be used to determine the optimal solution for different cases also. [67]

Electric boilers in DH systems are power-to-heat plants with many benefits. For example, they have relatively low construction costs [68]. Electric boilers promote synergies between the power grid and DH system by using excess electricity to produce heat. Electric boilers can provide flexibly and cost-effectively negative secondary control power [68]. The heat storage electric boiler is an improved technology because it is an electric boiler and a storage heater in one [69]. The electrical load of this thermal device is not limited by the heat load demand since it has heat storage.

M. G. Nielsen *et al*. analyzed the economic value of heat pumps and electric boilers because these technologies have significant potential to improve flexibility in energy systems [70]. Both devices use electricity to generate heat. It is economically beneficial when certain events occur when the market price for electricity becomes close to zero, zero, or even negative. These events happen when fluctuating renewable power generation cannot be carefully accommodated to the grid or even generated amount overreaches the demand. Since the grids are getting more carbon neutral, the economic benefit of these technologies is getting greater. The authors used an operational strategy based on two-stage stochastic programming. Also, data from Copenhagen in 2013 was used in the analysis. Results showed that increasing the installed capacity of heat pumps and electrical boilers reduces the difference in performance. That is why advanced operational strategies should be used before implementing these devices in systems. Parameters like reduction in capacity, change in the coefficient of performance for the heat pump, and a decrease in power prices can save money between EUR 0.9 M and EUR

4.1 M per year. As expected, the biggest savings are when there are low electricity prices. Reviewed technologies will be most economically beneficial when electricity prices are low.

Heat accumulators are heat storages that we reviewed in section 1.2. The concept of thermal storage is that extra or low-cost energy is stored, and it is used when main plants cannot produce enough energy during peak hours, or the energy costs are too high [9]. The flexibility of the DH system can be increased by using thermal storage. For instance, during periods when electricity demand is low, excess fluctuating renewable energy like wind power is generated. This power can be used to heat water with heat pumps or electric boilers and then stored in thermal storage for peak hours when it is most needed [13].

J. Turunen *et al*. looked at the optimization of CHP plants in DH networks using heat accumulators [71]. Since power systems use more wind and solar energy, the utilization of CHP plants in DH systems is more challenging. Heat storage could solve this problem and minimize the operation costs of the DH system. The authors aimed to optimize an existing system with biomass fired CHP plant. For modeling the system, they used a mixed integer linear programming model. Results showed that it is possible to reduce operating costs of the CHP plant by 2.3% using short-term planning and optimization of heat accumulators. The challenging part still is heat load forecasting, that should be considered more.

Electrification of the DH system can be beneficial because during periods when electricity demand is low, excess fluctuating renewable energy like wind power is generated. Using wind power for heating not only can adapt surplus wind power and lower the rate of curtailed wind but also can reduce fossil resource consumption in DH systems, avoid waste of energy, and make systems more cost-efficient [69]. In the case of China, they are facing significant wind power curtailment because the power grid is not flexible enough and was not prepared for the integration of wind power. This problem could be solved by using excess electricity in heat pumps and electric boilers in DH systems [70], [72].

Jinda Wang *et al*. illustrated a typical district energy system (DES) that consists of district power and heat systems with an accent on clean-heating improvements and wind energy [72]. You can see the systematic representation in Fig.1.8. This study looked at the case of Chine, which is why fossil fuel is coal. Also, the electric grid is supplied with two kinds of CHP units, condensing power plants and wind turbines, because those are the main units in China. We can see that this system is improved with all technologies described above- heat pumps, electric boilers, and displacement storage accumulator (DSA). This system is different for every DH network since the technologies differ, but the idea and structure of the system stay the same.

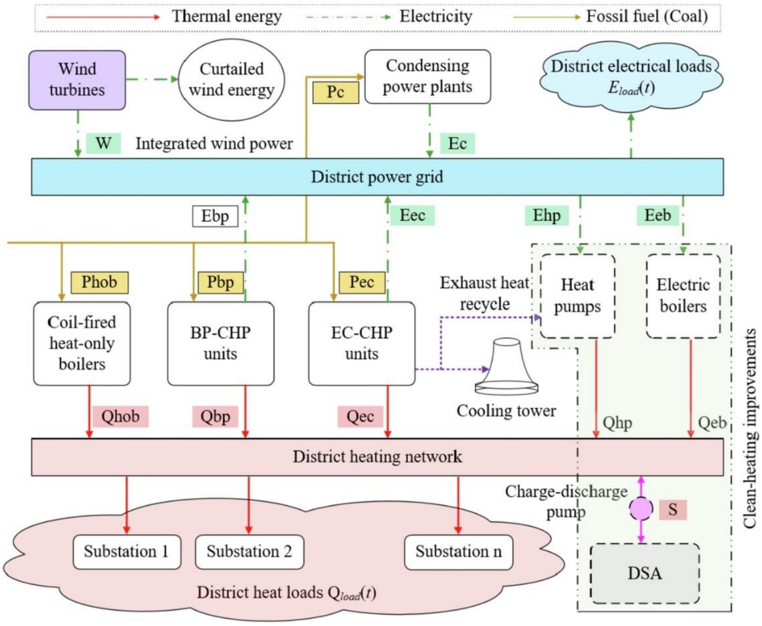

Fig.1.8. Schematic ilustration of a typical district energy system in China whith the clean-heating improvements [63]

Smart energy systems and power-to-heat technologies should be considered and implemented when decarbonizing our power grids. Electrification of the DH system can be beneficial because excess fluctuating renewable energy like wind power is generated during periods when electricity demand is low. Direct electrification of the DH system can be done by using power-to-heat technologies like heat pumps and electric boilers in combination with heat accumulators.

Bioenergy role in district heating systems today and in future (reduction of use of biomass)

Biomass is a raw material produced by photosynthesis like wood or energy crop. Its biggest benefits are less costly, lower GHG emissions compared to fossil fuels, and residues can be used. However, disadvantages of using biomass are a geographic restriction, if not locally accessible, then increased transportation expense, and pollution if burnt. Biomass is an attractive renewable energy source because of its easy usage, as the direct combustion of biomass instead of fossil fuels. [61]

Bioenergy is an option that allows significant decarbonization of the heating sector without major modifications to the system. The most used renewable energy resource in DH systems is biomass, but the majority of these systems are classified as 3GDH systems. CHP plants are the most efficient method to utilize biomass for energy production. But because the DH systems are being improved and are moving to lower supply temperatures (4GHD), biomass could be better used in biorefineries to produce transportation fuels, chemicals, and plastics. Therefore, DH should concentrate more on recovering waste heat from these industries. Also, the technical improvement of DH systems will lower system costs, so biomass usage in this sector most likely will decrease. However, it is not predicted to entirely not be used, but biomass is not a long-term answer for heating purposes. [61]

It is possible to implement 4GDH systems whit CHP plants and biomass. The efficiency of CHP in the 4GDH systems case would increase because the operating temperatures decrease heat losses. And, if the price of biomass is higher, it is more beneficial to install this system. Overall costs also would decrease because less biomass is needed. Logistical challenges and transportation costs make biomass more attractive for rural area DH systems than for urban areas. [61]

European countries established biomass heating systems before other countries in the world, so they have more mature technologies and policy systems. In 14 EU countries, bioenergy makes up more than 10% of final energy consumption. Latvia has the biggest share of biomass in the heating sector (33.21%). Then comes Finland, Sweden, Estonia, Denmark, and Lithuania, which has over 20% of bioenergy. Croatia, Austria, and Romania have over 15%. About 11% of bioenergy in heating has Portugal, Slovenia, Bulgaria, the Czech Republic, and Hungary. Bioenergy share in the heating sector differs because of the country's geographic location, climatic conditions, availability of natural resources, policies, technologies used, and environmental and sustainable development goals. [73]

Chenchen Song *et al*. divided 27 EU countries and UK into five zones by their utilization of biomass in the heating sector [64]. The distribution can be seen in Fig.1.9. The study considered four primary sources of biomass resources- woody biomass, stalk (remaining part of crops after they are harvested), residues from agricultural processing, municipal waste and wastewater, and animal manure [73].

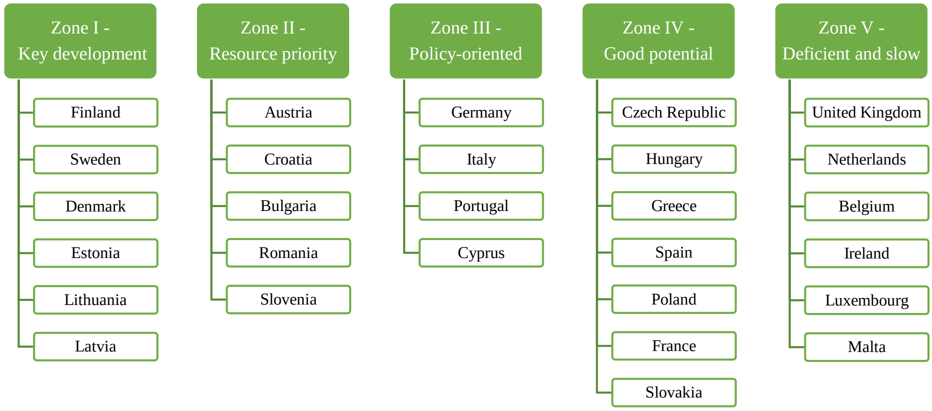

Fig.1.9. The distribution of 27 EU countries and UK into five zones by their utilization of biomass in the heating sector

Key development category (Zone I) countries have a leading position in the development of biomass heating, with a large amount of resources, mature technologies, and policy support. They have increased development efficiency. Countries in the resource priority category (Zone II) have benefits in terms of resources, a large number of resources, a good policy system, and a good status quo. Overall, they have a great opportunity for growth. Policy-oriented category (Zone III) countries are prioritizing policies for biomass heating utilization. These countries have a small amount of resources with poor scale and weak foundations. But thanks to a good policy foundation, the development of biomass for heating will be prioritized in the future. Countries with great potential for developing biomass heating are summarized in the good potential category (Zone IV). They have a good amount of resources, but their utilization of them is average. That could be because of ineffective policy, which does not give strong enough support. European climate goals implementation in policy could change the situation in the future. The last category is deficient and slow (Zone V). For countries in this zone, the level of development is the lowest. They have a limited amount of resources and undeveloped environmental policy in the biomass heating sector. They probably will have lower demand for biomass heating in the future. [73]

As we can see from this study [73], biomass is widely used in the EU heating sector. Bioenergy share in each country's heating sector varies because of many factors. In some countries like Belgium, biomass in the heating sector is not as much used, but that necessarily does not indicate the environmental impact of this country's heating sector because maybe other renewable recourses are more widely used. Also, this study did not look at the situation in DH systems but at the overall heating sector.

If we look specifically at the DH system, the biomass percentage slightly changes for each country. In Sweden's case, DH systems cover 60% of country building heat demand, from which more than two-thirds are generated using biomass and waste [74]. In the case of Latvia [75], a big part (76%) of the thermal energy for DH systems is generated in CHP. In 2020, 42% of produced heat in CHP was from wood chips and 6% from other renewable recourses (mainly biogas and different kinds of biomass). The rest (52%) was generated from natural gas. In Lithuania, 57% of heat demand is covered by DH systems. In 2017, DH systems in Lithuania generated 69% of heat using biofuel and waste [67]. DH systems in Denmark covered 56% of heat demand in 2019. CHPs powered by biomass supplied 29.8% of DH [77].

To summarize, biomass is a renewable resource that has easy usage in direct combustion, is relatively cheap, and does not require a significant modification of DH systems. It is used in many EU countries for heating purposes and could benefit from future 4GDH systems. But biomass could be better used in biorefineries to produce value-added products. Therefore, DH should concentrate more on using waste heat from these industries. Biomass is not a long-term answer for heating purposes, and most likely, its usage in DH systems will decrease.

2. 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 3rd generation DH systems to 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 that is 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 also 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 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.

2.1. 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 companies objectively, various sustainability indicators are covered and created 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. 2.1. The availability of statistical overviews for main DH operators is limited, therefore, it is necessary to combine different data sources. The reviews of environmental statistics (in particular, overview of air protection) coordinated by State limited Liability Company 'Latvian Environment, Geology and Meteorology Centre' are used to determine the fuel consumption for heat production [78]. The produced and consumed heat can be seen in applications from approvals of the heat energy tariff by the Public Utilities Commission (PUC) [79]. The power produced in CHP is obtained from the amounts paid within the framework of mandatory procurement (feed-in tariff) [80], but for the missing information annual reports of companies are used. Authors use the data set from 20 DH companies.

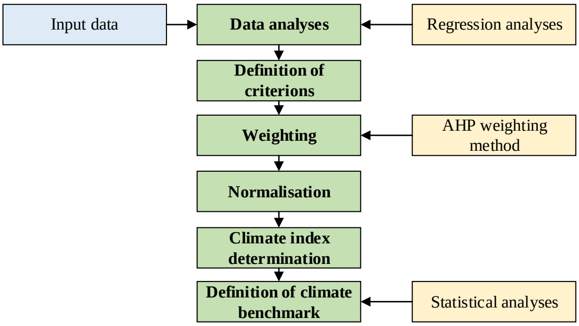

Fig. 2.1. Main steps and methods for determination of climate benchmark.

After the detailed data assessment, authors define the main criteria for further analyses. Seven different criteria are used (see Fig. 2.2.) for calculation of the Climate index in the particular case study. However, the criteria can be adjusted for country specific conditions. The criteria are grouped within three different categories to have a more comprehensive overview of DH system performance. Some of the selected criteria are interrelated, for example, the total CO_2 emissions and primary energy factor depend on heat losses and share of RES. However, each of chosen criteria show different aspects related to heat generation and transmission operation conditions. The further weighting step allows to take into account the interrelation by applying higher or lower weight score for particular criterion.

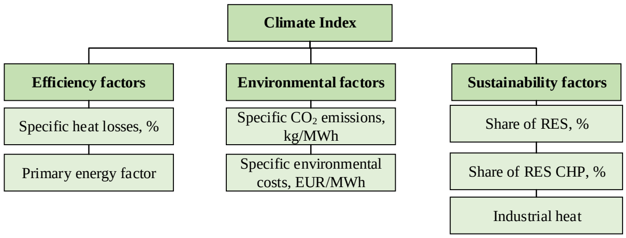

Fig. 2.2. Criteria merged within the Climate index

The analysed efficiency factors are the transmission heat losses from the heating network identified as a percentage of total produced heat and the primary energy factor. Primary energy factor (PEF) is an energy indicator used for quantifying the primary energy use of a plant defined according to (2.1).

$$\mathrm{PEF} = \frac{\sum_j E_j \cdot f_{p,j} - E_{CHP} \cdot f_{p,el}}{E_{del}}, \tag{2.1}$$

where

E_j the amount of the j_{th} primary energy consumed;

E_{CHP} the amount of electricity produced in the CHP if any is installed;

$f_{p,j}$ the primary energy factor related to an energy source;

$f_{p,el}$ the primary energy factor for the power plants;

E_{del} the amount of energy delivered to the consumers.

The used primary energy factors can be seen in Table 2.1. Those are determined as country specific values and highly depends on the national electricity mix. The assumptions can be subject to change for assessment in other countries.

Authors have identified two main environmental factors: the specific CO_2 emissions and the specific environmental costs associated with different external costs related to heat production. The environmental cost factors have been identified according to previous studies [81] (see Table 2.1).

In addition, sustainability criteria are used to evaluate the used energy production technologies and energy sources. Therefore, authors have 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. It should be noted, that the heat purchased from different energy production utilities is not perceived as heat from an industrial object. The heat from industrial enterprises could be attributed to industrial waste heat and other excess heat sources when such energy sources occur.

Table 2.1.

Main Assumptions for Calculation of Criteria

Primary energy factors	
Fossil fuels	1.1
Biogas	0.5
Biomass	0.2
Power from the grid	1.5
Environmental costs, EUR/MWh	
CHP Biomass	4.3
CHP Natural gas	11.7
CHP Coal	24.1
CHP Biogas	13.8
HOB Natural gas	17.9
HOB Biomass	11.2
CO_2 emission factors, kg/MWh	
Diesel fuel	267
Natural gas	202
Coal	354

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 is a pairwise comparison matrix, which reflects the relative importance of the criteria [82]. In this case, the evaluation was carried out by a group of experts, but a more comprehensive assessment could be provided by the involvement of various stakeholders in the weighting process. The obtained values of the criteria can be seen in Fig. 2.3. The highest priority has been determined for specific heat losses and the share of industrial heat.

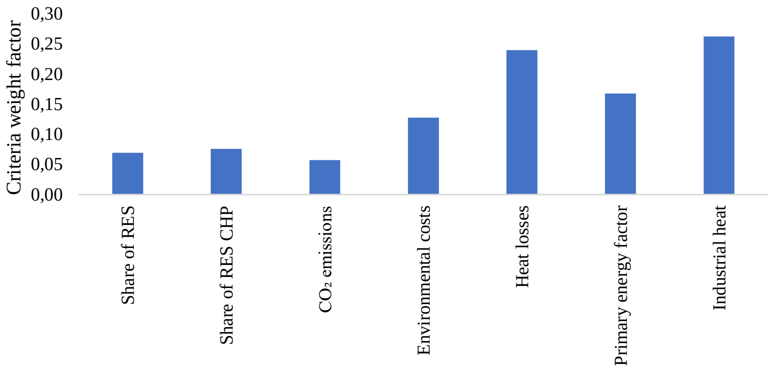

Fig. 2.3. Obtained weights for each criterion

The calculated criterion *j* has been normalized by using Weitendorf's linear normalization method [36]. Eq. (2.2) is used if the optimal indicator value needs to be maximized and Eq. (2.3) is used if the desirable indicator value is minimal.

$$b_{ij} = \frac{x_{ij} - min\, x_{ij}}{max\, x_{ij} - min\, x_{ij}} \tag{2.2}$$

$$b_{ij} = \frac{max\, x_{ij} - x_{ij}}{max\, x_{ij} - min\, x_{ij}} \tag{2.3}$$

The normalized and weighted values of the criteria are summed to obtain the Climate index for each DH operator.

2.2. Summarize and identify energy management indicators and influencing factors at the district heating company level

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

EnMS data collection of district heating company

Data collection stage, it is important to identify the data to be taken into account. District company – operation is divided into three parts; energy production, energy transmission and energy consumers.

First collect all of the data relating to the use of energy: consumption of energy resources: wood chips, natural gas, electricity, and other resources. All incoming flows must be fixed.

After that, need to collect data on produced units in the district heating company, that is the amount of heat produced. It is necessary to identify all data locations: remote data system, accounting data, and other accounting sources. The next step is to make sure that the data collected is needed to determine energy performance. After the required data collection, need to check are they representative: the measuring instruments have been verified, in the accounting data are no missing data and the remote reading system has not been data missing. The final step in data collection is to assess whether additional data are needed. If necessary, consider introducing a new measuring device or method. Data compilation steps summarized in Fig. 2.4.

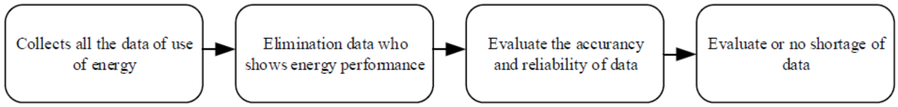

Fig. 2.4. EnMS data compilation principal scheme

Fig. 2.4. shows that the phases are following one after another in order to obtain data which can be further analysis in order to assess the company's energy efficiency in district heating company.

Energy performance indicators for district heating company

The next step in the selection of indicators is to verify that the indicator will change with changing circumstances, and define the factors affecting it. Has identified more than 180 different energy efficiency indicators both simple indicators and complex indicators. Choosing the appropriate EnPI should be established so that the company could objectively assess the energy performance [83].

The indicator selection process of the first stage is to evaluate which indicators are appropriate for district heating processes: heat production and transmission. District heating companies' main energy consumers have a boiler or CHP plant. The main electricity consumers are pumps, flue gas cleaning systems, hydraulic operations and etc.

EnPI should be every consumer's energy efficiency (each incoming flow compared to net unit). Energy efficiency indicator – boiler efficiency coefficient can be applied separately to each heat source and one type of fuel boiler total [84].

The next step in the selection of indicators is to verify that the indicator will change with changing circumstances, and define the factors affecting it. If the indicator does not change (direct relation) in a different size, then this is a simple indicator of a change in direct relation, it has formed a complex indicator.

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

- Identify all energy consumers;
- Define the major energy consumers;
- Determine the incoming resource flows;
- Determine the effectiveness of the heat source (each incoming flow compared to net output flow);
- Regression analyses to determine if there is correlation of the indicator with certain factors;
- Grouping of simple and complex indicators;
- Verify if the established indicators also perform operational indicator function;
- Selection of the necessary collection periods for each indicator (24 hours, a month or once per three, etc.).

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

2.3. Analysis of implementation energy management schemes benefits

To establish a reliable and functional data collection system by recording heat production and consumption data in the heating plant and in each building connected to the heating system. To be able to account produced and consumed energy, the installation of heat metering devices is mandatory. With this simple measure it is possible to achieve savings of up to 10 % [85].

The reduction of energy consumption in a building and the achievement of a certain amount of savings is possible, if centralized monitoring of a building's energy consumption per day, week, month and year is implemented in the municipality. An example of energy funding and a contractual relationship scheme for municipal building arrangement is illustrated in Figure 2.5.

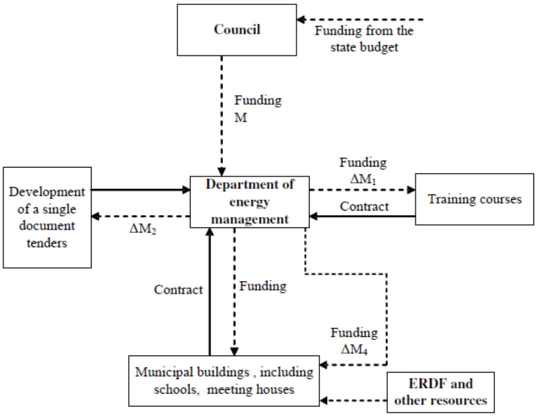

Fig. 2.5. Example of energy funding and contractual relationship scheme for municipal building arrangement [6]

As shown in Figure 2.5., one of the options is to establish a department of energy management. Initially it could employ only one person – the head of the department and gradually increase the number of people working for the department when the given financial scheme starts working. The person working for the energy management department would be responsible for managing operators of the heating plants and for managers of municipallyowned buildings (people who are doing day-to-day energy management in the building). The main tasks of the energy management department would be to plan and to reach energy savings and to report about the progress to the municipality or city council on a regular basis.

Monitoring and energy management expenses would be covered by the income from energy savings. The overall budget that a municipality is spending for energy (electricity, heat and/or fuel) will not change; however, it will also not require additional funds. This scheme will be beneficial in the long term (see Eq.2.4):

$$M = M_{cons} + \sum_{k=1}^{5} \Delta M \tag{2.4}$$

where:

ΔM - savings, €/year;
ΔM1 - establishment and maintenance of training course and system, €/year;
ΔM2 - stablishment (and update) of procurement system, €/year;
ΔM3 - maintenance of energy management department, €/year;
ΔM4 - co-financing for energy efficiency measures, €/year;
ΔM5 - expenses of energy management system, €/year;
M - total cost of energy at the moment, €/year;

M_{cons} - cost of consumed energy, €/year.

2.4. 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.

Methodology is applied to a medium-size district heating company with an installed capacity of about 30 MW. In the current system, 60 % of renewable energy is from renewable energy sources, 40 % from fossil fuel – natural gas. The goal is select RES technology to cover 30% and reduce fossil fuel use by up to 10 % and increase energy independence.

Table 2.2.

Tehnlogy distribution by load

	Current situation		**Planned situation**		**Alternative situation**	
Summer load	3 MW	Condensing gas boiler	Solar collectors 21 595 m^2 + accumulation tank 8000 m^3		Solar PV panels 5504 m^2 – heat pump COP 3	
Base load	7 MW + 1.68 MW	Woodchip boiler + flue gas condenser	7 MW + 1.68 MW	Woodchip boiler + flue gas condenser	7 MW + 1.68 MW	Woodchip boiler + flue gas condenser
Above the base load	3 MW	Same condensing gas boiler	3 MW + 0.5 MW	Woodchip boiler + flue gas condenser	3 MW	Woodchip boiler + flue gas condenser
Peak load	2·10 MW	Gas boiler	2·10 MW	Gas boiler	2·10 MW	Gas boiler

Have 3 potential variants: curren situation, solar collector system with accumulation tank in planned version and alternative heat pump with PV panels.

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.

The developed framework for choosing suitable RES technology for a district heating company is illustrated in Fig. 2.6.

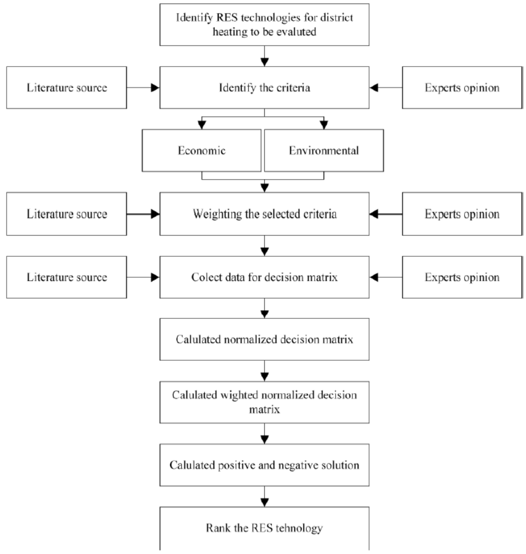

Fig. 2.6. Decision-making framework

To make the right decision needs to choose an indicator that objectively characterizes the situation. The first step to use MCDM is to select criteria. In literature and in the heat sector can find many different indicators that are used to compare technologies (see Fig.2.7.) [86], [87].

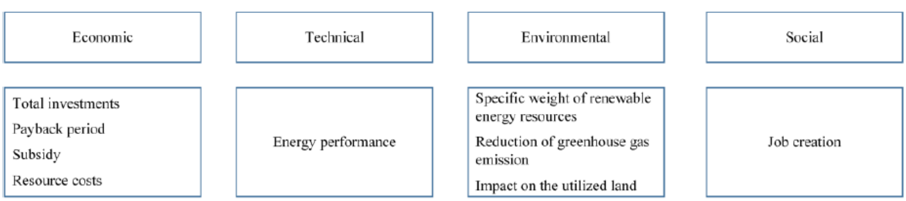

Fig.2.7. Indicators for Renewable Energy Heating Technologies

In this case study, the two most important aspects are environmental and economic due to the fact that the economic aspect has a direct impact on the heat tariff, and the company's goal is to deliver heat safely and at the lowest possible price. The environmental aspect is very important, because the companies operating in the energy sector that are in the ETS system in the 4th period from 2025 to 2030, CO_2 allowances will no longer be granted. During the transitional period, 30 % of the previous period will be calculated for companies that have previously had free allowances [88].

Energy technologies are evaluated according to four criteria. The indicators chosen are a 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 RES technology for DH, use the TOPSIS method is chosen. The TOPSIS procedure consists of five main steps: the development of the normalized decision matrix and the weighted normalized decision matrix, the calculation of the positive ideal and the negative ideal solution and the determination of the relative proximity to the ideal solution.

2.5. Evaluation of the implemented RES measures and supplementation of the energy management system indicators

When introducing new technology in a company, it is important to fit 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.

Case study

Analysed case study is a large-scale solar collector system installed in Latvia, Salaspils. The total active area of collectors is 21 672 m^2 with integrated thermal acumulation 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.

Have been installed total 1720 Arcon-Sunmark A/S HT-Heat Boost 35/10 solar collectors, size of each collector is 2 x 6.3 meters. The collector has high absorber efficiency ~83%. The solar system is operating with a temperature regime 45/63ºC, but in the thermal accumulation system the temperature can be raised to 85ºC.

Table 2.3.

Overview of main solar system parameters

Parameter	Value
Total active area	21 672m^2
Number of installed solar collectors	1720
Operational temperature regime of solar field	45/63°C
Volume of thermal storage tank	8000 m^3
Absorber efficiency	83%
Gross efficiency	77%
Heat loss coefficient, a1	2.27W/Km^2
Heat loss coefficient, a2	0.0181 W/Km^2

The operatin settings are also important for the solar yield evaluation. Operation is affected by two factors: the intensity of solar radiation and the set temperature.

The performance of solar collectors is determined according to the produced solar heat according to (2.5) [89]:

$$P_g = A_c \cdot [\eta_0 \cdot G - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2] \cdot f_p \cdot f_u \cdot f_o \qquad (2.5)$$

Where:

Pg - guaranteed performance (thermal power output),W;

Ac-collector area corresponding to the collector efficiency parameters, m2;

η0- optical efficiency;

a1,a2- heat loss coefficients W/(K·m²);

G-solar irradiance on collector plane W/m²;

Ta - ambient air temperature °C;

Tm- Mean temperature of solar collector fluid, °C;

fp -safety factor taking into account the pipe heat losses in the collector field and transmission lines;

fu -safety factor taking into account measurement uncertainty;

fo - safety factor for other parameters.

In the particular study the estimated pipe losses are 3%, therefore the used fp is 0.97. The value of fu is assumed to be 0.95 for the total measurement uncertainty estimated to be 5 %. The used safety factor for other parameters fu is assumed as 0.95 to take into account non-ideal flow distribution and unforeseen heat losses.

Mean temperature of solar collector fluid is calculated according (2.6) [89].

$$T_m = \frac{(T_{c,in} + T_{c,out})}{2} \qquad (2.6)$$

where Tc,in -hot side temperature (equal to collector outlet temperature) °C; Tc,out - cold side temperature (equal to collector inlet temperature), °C.

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

- Collector area;

- Collector optical efficiency;
- System losses;
- Ambient air temperature;
- DH return temperature – inlet temperature
- Collector outlet temperature.

The next step is to understand which factors in a particular system can be affected by the system operator and which can not. As this is the first project in the Baltic States the solar radiation is also analysed 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.

Solar system monitoring system and input data

The monitoring system is designed to ensure security and to be able to calculate the efficiency of solar collector field. Data reading points corresponds to solar district heating guideline showed in Fig. 2.7.

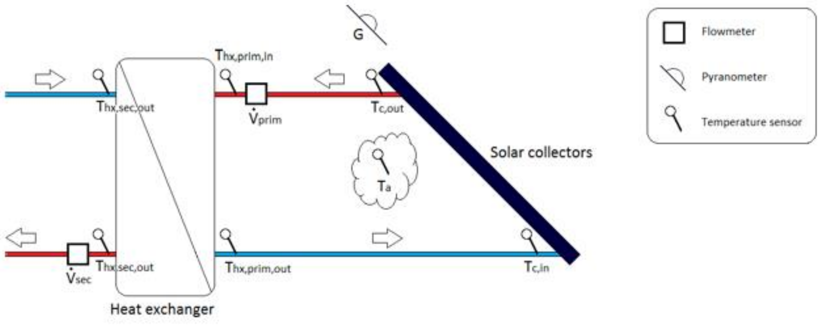

Fig. 2.7. Technical scheme of the measurement points [89]

The particular solar collector field in Salaspils is equipped with four solar radiation meters, which are installed in opposite quadrants of the collector field. Solar radiation meters are connected to circulation pumps, which increase or decrease the flow depending on the average measurement of the two radiation meters. The cloudy weather is the main reason why two measurements are compared. Radiation meters are located far enough away from each other and while a shadow from a cloud may have fallen on one of the radiation meters, at the same time other radiation meters are receiving a huge amount of solar radiation. Circulation pumps and flow are also connected and regulated by temperature meters, which display the temperature in the solar collector system.

The day's average radiation measurement is calculated using every measurement above 300 W/m2, because, experience shows that, at this value, it is possible to start thermal energy production and obtain useful temperature, all measurements which are under this value are not taken into account. During the night production stops. Radiation measurements are recorded automatically and shall be performed a minimum of once every two minutes or even more frequently. Up to 25 000 measurements are made during the 24 hours.

The produced thermal energy from solar collectors is also measured and recorded automatically, to evaluate the solar energy yield.

2.6. Optimization of energy management system 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. The data on first-year results allows to estimate and analyze the influencing factors of the large-scale solar collector field in the Baltic region, Latvia.

Statistical analyses and regression analyses method was used to obtain objective results because of availability of comprehensive monitoring data of solar field operation. The use of regression analyses clearly shows the influencing factors that should be optimized to reach higher efficiency of the solar field. The regression analyses is divided into three steps: the first part is data collection and compilation, the second part is the analysis of influencing factors, and the third part is multi-regression analyses. The statistical data analysis was performed by using Statgraphics 19-X64 software. The steps are summarized in the diagram (Figure 2.8.)

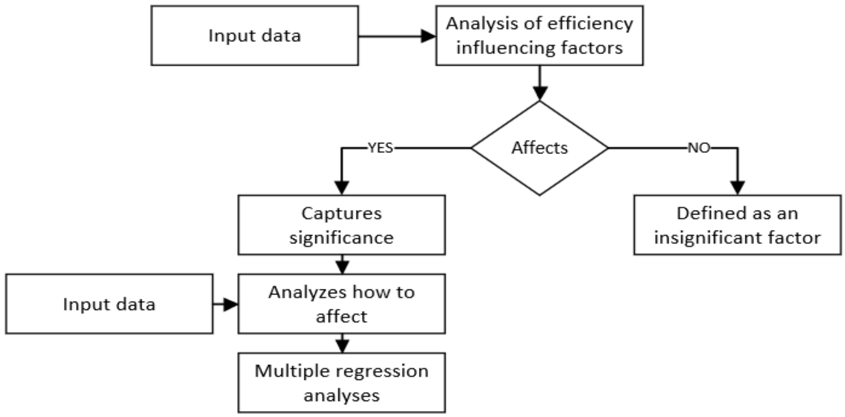

Figure 2.8. Algorithm of methodology

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 flow rate. These factors were chosen based on the analyzed results from previous studies of laboratory experiments and simulations.

Other factors such as wind speed and the effect of solar collector angle were not included in the detailed assessment because these factors cannot be directly influenced by the DH company, as the system is already operating. Furthermore, the solar collector field is stationary, not equipped with a tracking system, and the placing angle is fixed, since it was calculated according to the geographical location of Latvia. These last two mentioned factors should be considered if the solar collector field were at the design stage.

Case Study

This study continues the previous reserch about the solar collector field in a DH company in Salaspils, Latvia.

The heating plant consists of two wood chip boiler houses (7 MW + 1.68 MW flue gas condenser and 3MW + 0.5 MW flue gas condenser) and 3 gas boilers (capacity of 10, 10, and 3MW) for peak load coverage. The overall heat production scheme is shown in Figure 2.9.

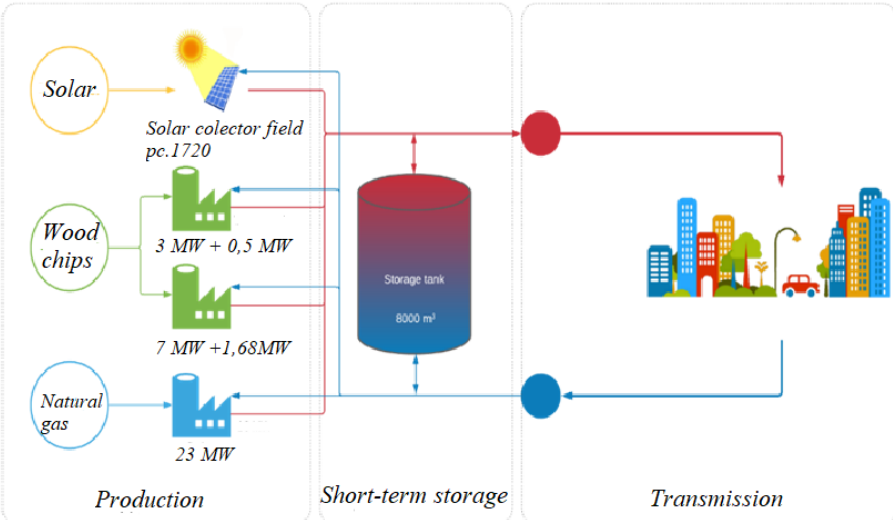

Figure 2.9. Case study scheme.

Weather Conditions in Latvia

The Baltic Sea surrounds Latvia; the border of Latvia is 1878 km long, with approximately 26.5% of which is a sea border. Consequently, there is a sea climate in a large part of Latvia, meaning the region experiences a smaller temperature amplitude throughout the year and more humid air. Based on information on the national meteorological database [90], the following climatic conditions were observed in Latvia:

Average ambient air temperature: 8.2 °C in 2019 and 8.8 °C in 2020;

Highest ambient air temperature: 33 °C in 2019 and 30.8 °C in 2020;

Lowest ambient air temperature: −23 °C in 2019 and −10.3 °C in 2020;

Approximately 120 days with rainfall annually.

Solar radiation intensity in Latvia is equal throughout the entire territory. However, it is most intense in the southern part of the country. The average annual solar radiation in Latvia is around 1000–1100 kWh/m2 per year, which means that the sun shines approximately 1700 to 1900 h per year. Figure 3. Comparison of monthly total solar radiation (a) and annual total solar radiation (b) in Riga from 2015 to 2020 [90].

The annual total solar radiance (Figure 3b) is an average of 1017 kWh/m2 in Riga. However, it differs from the yearly conditions. For example, the maximal annual total solar radiance was reached in 2018 (1074 kWh/m2), but the lowest value was in 2017 (966 kWh/m2).

Data Processing

In this study, the efficiency of solar collectors was analyzed during the active production season, i.e., April, May, June, July, and August in 2020. In this particular system, the solar field starts to produce a valuable amount of thermal energy when solar radiation reaches at least 300 W/m2. Consequently, to determine more precisely the effectiveness of solar collectors, the values from this mark were taken into account when calculating daily average solar radiation. When solar radiation is lower, the field of collectors is in the pre-heating phase, which is not considered. The time when solar radiation reaches 300 W/m2 is variable during the season. For example, on sunny days in April, it can be up to 9 h, while up to 11 h in July. The solar collector field is equipped with several heat meters. The data are transformed according to Equation (2.7) to make it possible to compare the data with observed solar radiation:

$$\mathrm{Pprod} = (\mathrm{Q}_{prod} \times 10^6)/(\mathrm{S} \times \mathrm{t}) \qquad (2.7)$$

Where:

P_{prod} - produced thermal energy by 1 m2 solar collectors of the specific day (W/m2);

Q_{prod} - total produced thermal energy with solar collectors of the specific day (MWh);

S -total active area of the solar collectors (m2);

t - time when solar radiation has reached at least 300 W/m2 (h).

In this study, solar collector field efficiency is calculated according to Equation (2.8).

$$\mathrm{E} = \mathrm{P}_{rad}/\mathrm{P}_{prod}\ 100\% \qquad (2.8)$$

Where:

E - efficiency of solar collectors (%)

P_{rad} -average solar radiation to 1 m2 of the surface of the specific day (W/m2)

Annual solar radiation is an absolute value that can be converted into thermal energy. Solar collector efficiency varies from approximately 17 to 77%. It is clear that solar collector efficiency and heat production depend on solar radiation, but solar radiation cannot be controlled, and thus this study further looks at how other DH operational parameters influence solar collector efficiency.

In the particular solar DH system, thermal energy production from solar energy is separated into two sides—primary and secondary. On the primary side, the heat carrier is circulated through solar collectors, from which it removes thermal energy. The primary and secondary side is connected through the heat exchanger. On the secondary side, heat is transferred to the accumulation tank, where thermal energy is stored until it is demanded.

The first analyzed parameter is the heat carrier flow in the primary side (primary flow). Specifically, we analyzed how the changes in primary flow impact solar collectors' efficiency. An increased flow rate reduces the amount of produced thermal energy, and vice versa. This parameter is increased under several conditions:

Solar energy production needs to be reduced due to thermal energy storage limitations. This mainly occurs when there is a significant amount of thermal energy in the accumulation tank and when weather forecasts expect high solar irradiation in the following days.

In early spring and late autumn, solar collectors cannot reach a temperature equal to the heating network supply temperature in the DH system. However, to remove the load from the other heat sources and not to use other energy resources unnecessarily, heat energy is removed from the solar collectors, and the heat carrier is heated as high as possible.

The flow has been reversed in two cases, namely (a) if the accumulation tank has to be cooled down in periods of high solar irradiation and low heat demand, and (b) when the ambient air temperature is low in the winter, and the solar collector field must be heated to prevent the system from freezing.

Another related parameter is the temperature difference between the return and supply temperatures on the primary side. Boilerhouse operators can manage the temperature of the heat carrier and can remove thermal energy from the primary side. One possibility of reducing or improving those parameters is by managing how much flow reaches the heat exchanger. The regulation strategy of the heat carrier's return temperature on the primary side is similar to the primary flow regulation described above.

The third analyzed parameter is the ambient air temperature. In Latvia, the daily average ambient air temperature can change even two or more times from day to day, so we considered this parameter important for further study.

Multiple Regression Analyses

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

3. RESULTS

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

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

Authors have 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 the capital city of Latvia, Riga to less than 1 GWh in smaller towns.

Table 3.1.shows the overview of normalized values of each criterion for analysed DH systems. The value 1 indicates the best ranked system, but the value 0 the lowest obtained value. As it can be seen, only two DH systems have purchased heat from industrial enterprises.

Table 3.1.

Normalised Values of Obtained Values of Criteria

DH location	RES	RES CHP	CO_2 emissions	Environmental costs	Heat losses	PEF	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
Brocēni	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

Fig. 3.1. 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 were the heat is produced by using a biomass CHP technology or the heat is purchased from industrial enterprises. The lowest Climate index values are for DH systems where natural gas is the main energy source for heat production.

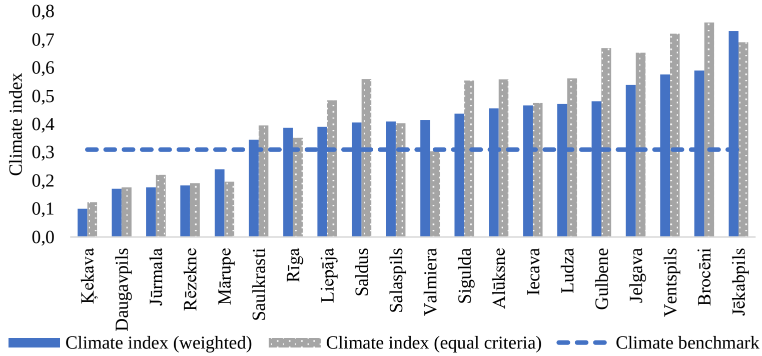

Fig. 3.1. Results of ranked Climate index values and obtained climate benchmark.

For the analyses, 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 progress.

The transition to RES has a significant impact on the heat tariff. The fuel cost share is much higher in the total heat tariff in cases when natural gas is used as the main energy source (see Fig. 3.2.).

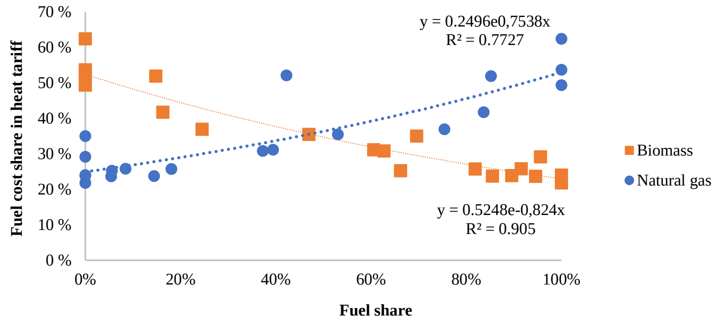

Fig. 3.2. Fuel cost share in heat tariff dependence on natural gas and biomass share in heat production

Fig. 3.2. shows a good correlation between the fuel cost share in heat tariff and total biomass and natural gas share in overall DH energy balance. When biomass is used as an energy source, the fuel cost share decreases and there is an increase in other costs. One of analysed DH systems is further from determined biomass trend line because of use of wood pellets, which is more expensive than other biomass energy sources.

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

3.2. Summarize and identify energy management indicators and influencing factors at the district heating 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 3.2 the most important energy efficiency indicators and influencing factors for DH company are summarized. [86, 91].

Table 3.2.

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 in DH company is specific fuel consumption or boiler efficiency coefficient. It is relatively easy to calculate 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 has 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.

. Ltd "Salaspils Siltums" woodchips boiler specific woodchips consumption depending on produced heat power collected in Fig. 3.3.

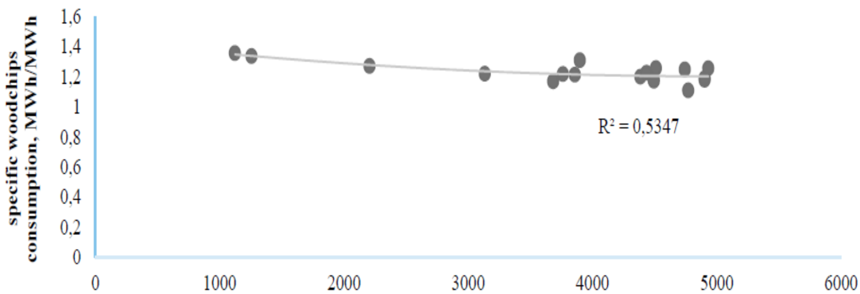

Fig. 3.3. Woodchips boiler specific woodchips consumption depending on produced heat power.

Specific woodchips consumption correlate on average with produced heat power (R2 = 0.53), can be explained by the fact that the quantity of fuel entered data monthly observed error. Because chips were stored outdoors sheds, and month-end surpluses read about. As well as the furnace supplied chips humidity varied, depending on the load and present still coming outdoor humidity, moisture in wood chips is determined upon arrival. Gas boiler efficiency coefficient depending on produced heat power collected in Fig. 3.4.

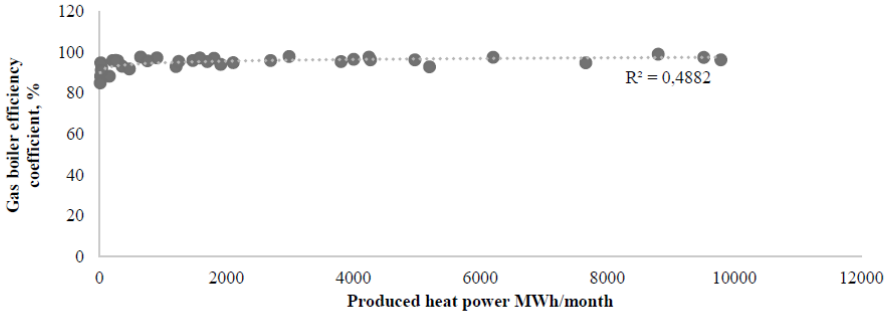

Fig. 3.4. Gas boiler efficiency coefficient depending on produced heat power

Between the gas boiler efficiency coefficient and the heat produced there is also average correlation (R2 = 0.488), an idealized version of that correlation does not exist, but at a smaller boiler capacity is less an efficiency, and to the power which is above 5 % is stabilizing, so also is the correlation [5]. Therefore, it is important to choose the boiler according to the heat load.

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 invest a small investment. Further, the measures that have a significant impact on consumption can get the most energy savings.

Measures, which do not require large investments, are employees and persons involved in training, behavioral changes (defined employee motivation), etc. The measures which are necessary for investments related to the new product change. Most of the identified measures which should be introduced in the company, does not require large investments. 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 every day control system and production process analyses;
- Create incentive measures for the control of the operator of work;
- Ensure regular training for 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.

3.3.Analysis of implementation energy management schemes benefits

When identifying the potential benefits of energy management, the specific situation and size of the organization should be considered. Be aware there is an exception or no existing system in the organization that can be supplemented, thus saving resources: time and money. In Latvia, the majority of shareholders in district heating companies are the municipality. This section explores ways to integrate energy management systems, including heat performance, through an existing system.

Application of energy management system according to ISO 50001 in the Saldus municipality. In accordance with the population, Saldus municipality is one of the ten biggest municipalities in Latvia. In January 2014 the number of inhabitants was around 27.2 thousand [92].

The size of the population is an important factor because it affects the number of employees that should be involved in providing energy services and this increases the complexity of the issue related to energy supply and use. To be able to introduce the energy management standard, the establishment of good information exchange and communication between the numerous local administrative units, is crucial.

When assessing the opportunity for introduction of the energy management standard in this particular municipality, the current function of the municipality in the energy sector should be taken into account. The Saldus municipality is an energy consumer, energy producer, and provider. Moreover, one of its functions is also the regulation of the heat energy tariff. All these mentioned roles should be considered when applying the ISO 50001 procedures.

The SEAP of Saldus municipality suggests that it is necessary to employ an energy manager. The energy manager will evaluate the existing system of data collection and availability and, based on this analysis, will develop a centralized data collection system where information from all involved organisations would be summarised.

Currently the collection of energy data is partially centralized and is done by the accountancy office of the municipality. However, the collected information is not assessed and analysed. The task of the energy manager would be to ensure that information is transparent and clear, that data are analysed and conclusions of the analysis are transferred into real energy savings. The energy manager should work closely together with the working group responsible for the implementation of SEAP activities (see Figure 3.5). According to the organisational model provided in Figure 3.5, representatives from local administrations are responsible for the collection and delivery of energy data concerning activities in their territory directly to the energy manager of the municipality.

In addition, companies that are owned or partially owned by the municipality are obliged to give information to the energy manager. These are utility companies with a housing management (SIA „Saldus namu pārvalde"), water and waste management (SIA "Saldus komunālserviss") and district heating provider (SIA "Saldus siltums") functions. The SEAP working group is under the direction of the Executive Director of the municipality.

Depending on the size of a municipality and the number of institutions that are involved, the complexity of the energy management structure is changing. In less populated municipalities, the proposed structure will be simpler. Besides organisational activities, the SEAP also includes technical activities that should be implemented to decrease CO_2 emissions. Some of the technical activities are linked to the implementation of standard ISO 50001. These include:

- Installation of heat metering devices in the local heating plants in villages;
- Installation of heat metering devices in buildings connected to the district heating systems;
- Establishing a registry for accounting the consumption of wood chips for heating;
- Paying attention and recording parameters related to the fuel quality;
- Solving the issue of the ownership of street lighting;
- Providing the training to employees about electricity energy saving;
- Replacing the indoor lighting systems with more efficient;
- Implementation of energy audits in buildings with the highest specific energy consumption.

In order to start adopting the ISO 50001 in Saldus municipality, the first step is the official decision by the council. Some good synergies can be expected between SEAP activities and standardisation procedure. The standardisation requires certain procedures in a given time frame.

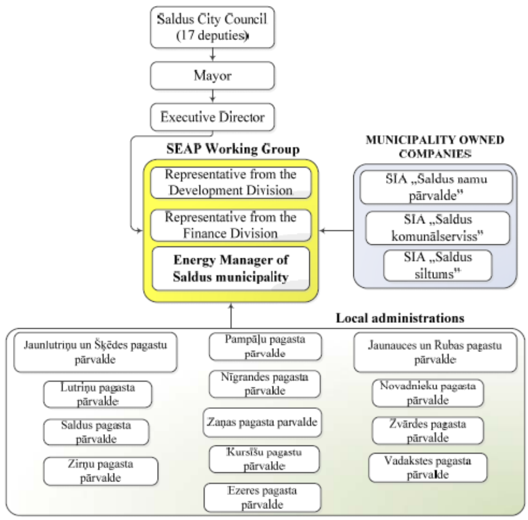

Fig. 3.5. Organizational structure proposed by the SEAP of Saldus municipality

Establishing strict communication procedures among all levels – management, local administrations, organisations and companies – in the first steps is essential. Other preparatory works that were suggested for Saldus municipality are: installation of heat metering devices and creation of database for centralized information storage.

The task of the energy manager will be to control data inputs, to analyses them and to prepare reports. This database/data analysis tool should also calculate energy indicators that should be further used for benchmarking purposes. The database should contain at least information about the number of inhabitants in each local territory, information about energy companies (heating plants, CHP plants), on a monthly basis – generated energy, consumed fuel, electricity consumption, heat consumption, number of buildings under the building management, change in the number of transport vehicles, fuel consumption, etc.

Establishing the procedures will also affect energy consumption and the decrease of CO_2 emissions could be achieved faster.

3.4. Selection of Renewable Energy Solution for District Heating 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 DH operator use a gas boiler in summer period and 2 alternative RES scenarios:

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

Resources cost to natural gas is average to medium district heating company per EUR to MWh, in Latvia natural gas price is to parts: consumption and distribution. In plan and alternative costs is taken 0, because energy resource is solar. In only actually situation is emitted greenhouse gas. In actually situation in 2018 50 % heat was produced using natural gas, second 50 % of heat is produced using renewable energy resources – from the woodchip boiler and from the flue gas condenser. In both alternatives, it is planned to refuse from fossil fuels, use only at peak loads (see in Table 3.3.). Both alternatives require extra land. In plan planned situation is necessary to prepare 6.5 ha of land to install solar collectors with 21 595 m^2 active square. An alternative to the solution is about the same area, but below it must be installed the active surface of the ground heat pump. The total investment is attributed to installed MW. In current situation no investments is 0, because all the equipment is existing. Both alternatives are designed to cover the summer load, with an average power of up to 3 MW. The planed system has a capacity of 12.3 MW, but is an 8000 m^3 accumulation tank, which accumulates heat for the period when there is no solar energy. But for the alternative, the installed capacity of the heat pump is 3 MW of heat produced. Since the energy source of the heat pump is from PV panels, in night mode electricity should be taken from the grid.

Resources costs, reduction of greenhouse gas emission, impact on the utilized land and total investments best solution is when valuable is minimum, but best solution specific weight of renewable energy resources in when valuable is maximum.

Table 3.3.

The Original Decision Making Matrix

	Resources costs	Reduction of greenhouse gas emission	Specific weight of renewable energy resources	Impact on the utilized land	Total investments
Current situation	35	0.2	50	0	0
Planed situation	0	0	90	2	375000
Alternative situation	0	0	90	3	613333
	min	min	max	min	min
Weights	0.25	0.23	0.2	0.14	0.18

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

Table 3.4.

Normalized Decision Matrix

	Resources costs	Reduction of greenhouse gas emission	Specific weight of renewable energy resources	Impact on the utilized land	Total investments
Current situation	0.00	0.00	0.37	0.95	0.93
Planed 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 indicators' weight, 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 for resources costs is slightly higher because 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. To make decision need put weight to normalized matrix (see in Table 3.5.)

Table 3.5.

Weighted Normalized Decision Matrix

	Resources costs	Reduction of greenhouse gas emission	Specific weight of renewable energy resources	Impact on the utilized land	Total investments
Current situation	0.000	0.000	0.073	0.133	0.168
Planed situation	0.177	0.163	0.132	0.044	0.065
Alternative situation	0.177	0.163	0.132	0.000	0.000

To identifying the ideal point calculated matrix, where ideal is 0 and the rest shows steps to ideal. The lower the value closer to ideal. The positive ideal solution for resource cost is in planed and alternative situation, because the solar energy cost is 0, but current situation is average natural gas prices. For reduction of greenhouse gas emission and specific weight of renewable energy resources also the same options as resources costs. Impact on the utilized land and total investments ideal solution is current situation, because don't need new investments and no more impact to land. Results are summarized in Table 3.6.

Table 3.6.

Positive Ideal Solution

	Resources costs	Reduction of greenhouse gas emission	Specific weight of renewable energy resources	Impact on the utilized land	Total investments
Current situation	0.177	0.163	0.059	0.000	0.000
Planed situation	0.000	0.000	0.000	0.089	0.103
Alternative situation	0.000	0.000	0.000	0.133	0.168

Reverse process to find ideal solution is find negative solution. The negative solution is the opposite ideal to resources costs, reduction of greenhouse gas emission and specific weight of renewable energy resources anti-idol solution is current situation. Results are summarized in Table 3.7.

Table 3.7.

Negative Ideal Solution

	Resources costs	Reduction of greenhouse gas emission	Specific weight of renewable energy resources	Impact on the utilized land	Total investments
Current situation	0.000	0.000	0.000	0.133	0.168
Planed situation	0.177	0.163	0.059	0.044	0.065
Alternative situation	0.177	0.163	0.059	0.000	0.000

The obtained TOPSIS result of this case study for the most suitable energy technology for a medium-size DH company is presented in Table 3.8. 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.

In this case study was evaluated current situation where nothing changes, in summer use gas boiler and 2 alternative situations, where use RES. This study presents a multicriteria decision – making to prioritize three situations.

Table 3.8.

TOPSIS Result of the Ideal/Anti-Idol Points and the Closeness Coefficients with Respect to the Tree Scenarios

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

A total of five indicators of decision-making covered economic and environmental aspects. The best option is the planned scenario where solar collectors and storage tanks will be installed (see in Fig.3.6.).

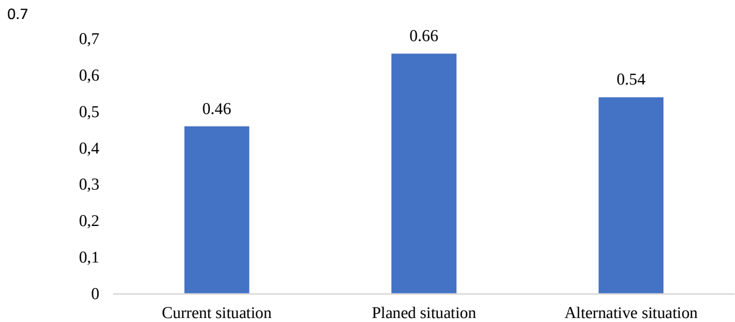

Fig. 3.6. The coefficients for 3 systems in case study.

3.4. Evaluation of the implemented RES measures and supplementation of the energy management system 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 are 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, whilst the total produced amount of thermal energy in Salaspils heating plant was about 58 GWh. The highest share of solar field production is observed in June, July and August when the solar energy share reached 46 – 49% compared to the total production. Although there are two wood chip boilers installed in Salaspils DH plant, it was concluded, that the best solution to cover the peaks demands in summer period is by using the natural gas boilers. Natural gas boilers can be started immediately without time-consuming boiler starting process, which would be if biomass boilers were used. Natural gas boilers in combination with solar collectors is used only in the summer months. Biomass boilers are continuing working in April and June as they are not sopped after the heating season. Therefore, total annual share of thermal energy produced with natural gas boilers was only 10%.

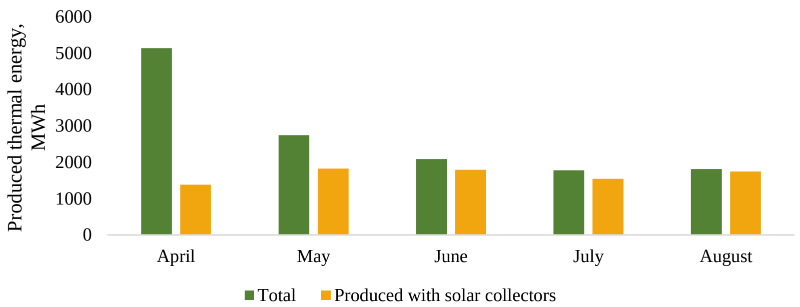

Fig.3.7. Share of thermal energy produced by solar collectors and total produced thermal energy in 2019

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 production by solar collectors is insufficient. In these moments, natural gas boilers are used for heat production which operation is more efficient than biomass 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 with the heat consumption. The opposite situation is in spring when 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. This method reflects the relationship between two factors, which means that when one value changes, the corresponding one also changes. The maximum value of correlation coefficients is 1.

The data presented have been collected throughout the sunny season, which in Latvia's case is from April until August. Fig.3.7. 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 [93]. 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 reducing produced thermal energy. But the highest correlation is 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 this correlation between 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.

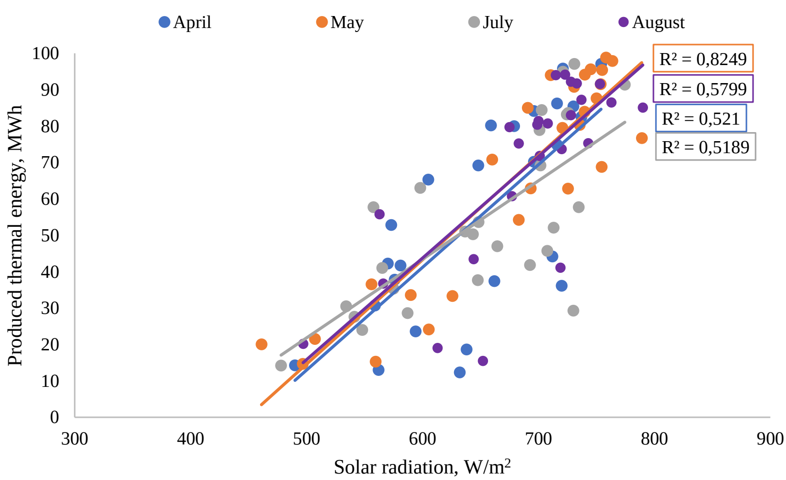

Fig. 3.8. Produced solar energy dependency of solar radiation

Fig.3.8. presents 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 is low and other conditions have higher impact on solar collector performance.

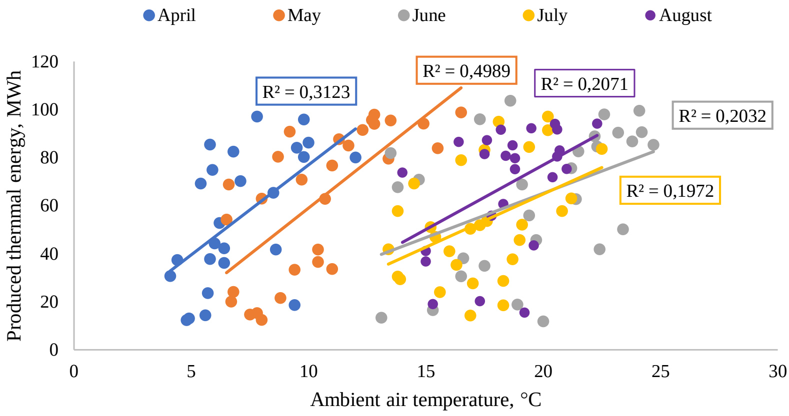

Fig. 3.9. Solar collector efficiency dependency of ambient air temperature

Another analysed impacting parameter that was examined in this study were flow and return temperature of heat carrier. Study showed that correlation between these parameters and 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 is very complicated. When the temperature difference changes several times a day, it is difficult to register and divide data on how much heat energy was produced with each specific temperature difference between supply and return temperatures.

Fig.3.9 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 presenter 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.

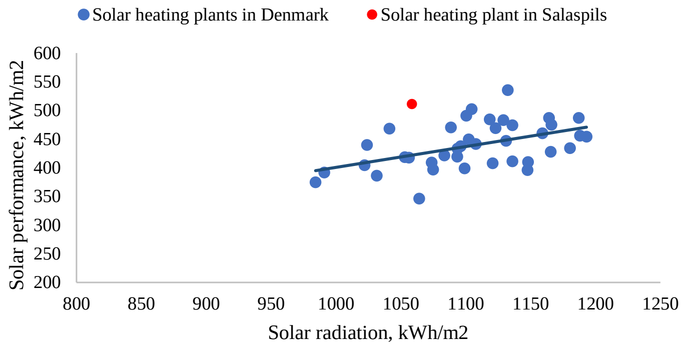

Fig.3.9. Comparison of solar heating plant performance demanding of solar radiation in Denmark (average data of 2012-2016) [94] and solar heating plant installed in Salaspils (2020)

The difference between the results could arise because solar heating plant in Salaspils is actively working 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 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 would have more storage, where to store the energy, or if the demand were higher. But the problem is that the weather can not 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, to better identify the effects of other factors, which impact efficiency less compared to solar radiation.

3.5.Optimization of energy management system in a district heating 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 Figure 2.6. It is therefore essential to investigate whether there is a potential for improvement.

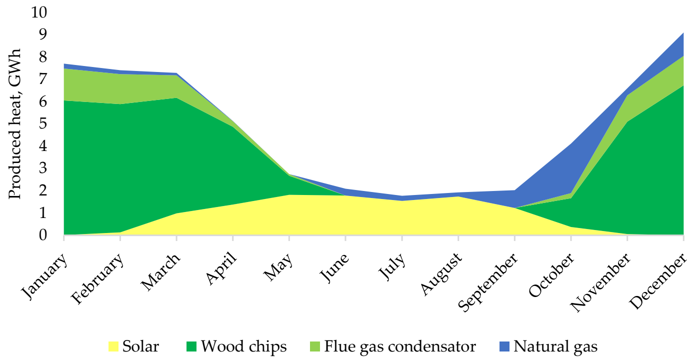

Figure 3.10. Produced heat by used fuel in 2020.

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 are 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 the efficiency. The obtained results of the regression analyses are summarized in Figure 3.11.

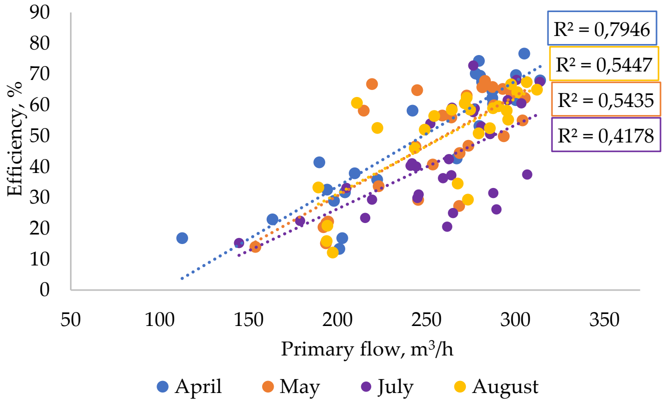

Figure 3.11. Correlation of heat carries primary flow rate and solar field efficiency.

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 analyzed 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, there is still space heating necessary. The efficiency is reduced when there are many sunny days and no demand is forecasted, and the storage tank is full. 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 analyses show 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 are shown in Figure 3.12.

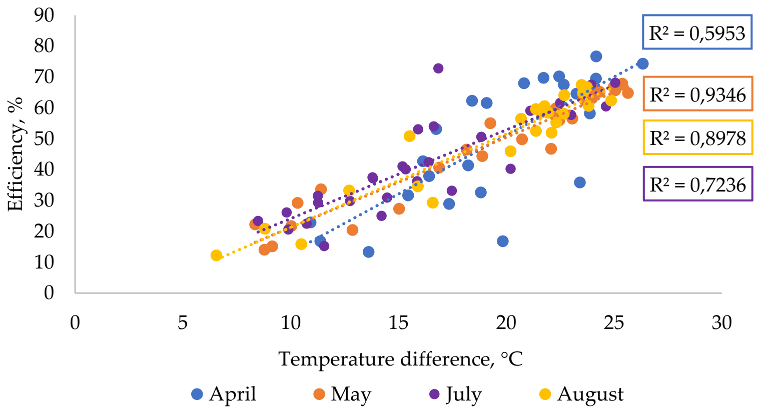

Figure 3.12. Solar collector efficiency dependency on temperature difference.

Results show that the higher the temperature difference, the higher 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 the spring, while qualitative regulation occurs in the summer. Results show that further optimization could be performed to choose the suitable heating network regulation mechanism by seeking the equilibrium between pumping costs, heat losses, and solar field efficiency.

The literature states that outdoor air temperature is an influencing factor [95] because it affects the flow rates and heat carrier temperatures. The average daily outdoor air temperature fluctuations were from + 1.7 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 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 is in May (R2 = 0.93) because the solar radiation was stable, and the settings of the solar field were not changed.

The third factor analyzed is the effect of ambient air temperature changes on the solar field efficiency (Figure 3.13.).

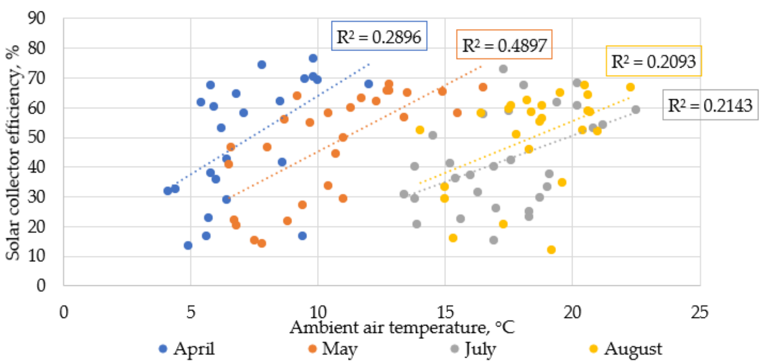

Figure 3.13. Solar collector efficiency dependency on ambient air temperature.

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 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 (R2 = 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 analyzed 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:

$$E = -31{,}617 + 0.135 \times w_1 + 2.32794 \times \Delta t + 0.091657\, t_a \qquad 3.1)$$

where w1 is primary flows, Δt is the temperature difference, and ta 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 solar field performance and forecast 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 Figure 3.14.

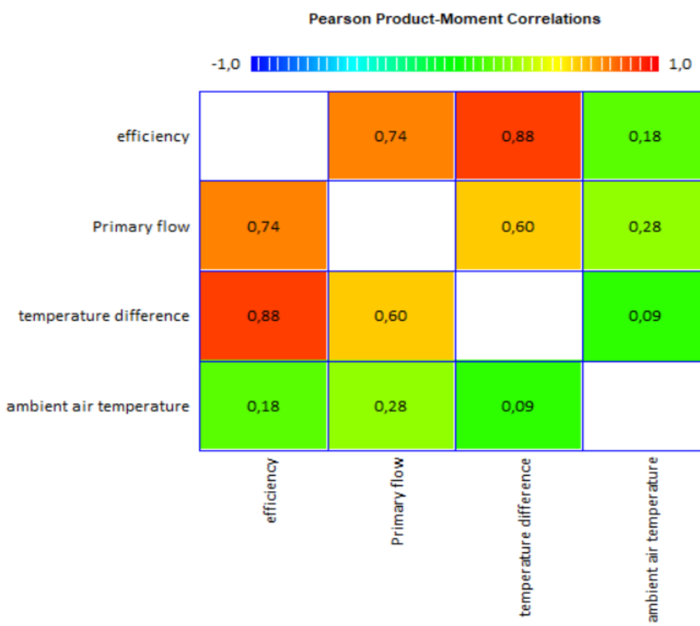

Figure 3.14. Correlation plot.

This table shows Pearson product–moment correlations between each pair of variables. These correlation coefficients range between −1 and + 1 and measures 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 efficiency and temperature difference, with a correlation coefficient of 0.88. The weakest correlation is between efficiency and ambient air temperature. However, ambient air temperature also affects the flow.

CONCLUSIONS

In the dissertation a methodology has been developed, which allows to plan, implement, evaluate, and optimise RES solutions into heat supply through the EnMS framework, which increases the company's energy efficiency and reduces its environmental impact. The energy management planning process have been applied at national, municipality and the 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 different 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 a Climate index could improve the competition among DH operators and promote moving toward more sustainable solutions. The determined Climate index could also be a criterion for the heat tariff calculation. DH companies with highest Climate index could be allowed to have a higher profit share, easier heat tariff approval process or obtain other benefits. The method is 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 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 to organisations, including municipalities. 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, a comprehensive guideline with step-by-step procedures and examples would be very useful. This guideline 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 work 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 work 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 demanding of several factors.

The results of the analysis show that the system's productivity is mainly demanded by solar radiation and the strongest correlation between these parameters is identifies in May. Solar collector performance is strongly affected by 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. 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 more 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, 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.

REFERENCES

[1] H.Lund , S.Werner , R. Wiltshire 4th Generation District heating (4GDH) Integration smart thermal grids into future suitable energy systems. Energy 2014:68:1–11. doi:10.1016/j.energy.2014.02.089

[2] Ministry of Environmental Protection and Regional Development. Latvian National Energy and Climate Plan 2020–2030.

[3] Data about district heating [Online]. [Accessed 15.03.2019]. Available: https://www.csb.gov.lv/lv/statistika/db

[4] Data for projects implemented by the EU [Online]. [Accessed 15.03.2019]. Available: www.esfondi.lv

[5] J.Joelsson , L.Gustavsson Swedish biomass strategies to reduce CO2 emission and oil use in an EU context. Energy 2012:43(1):448–468. doi:10.1016/j.energy.2012.03.050

[6] A.Rodzkin , S.Kundas , Y.Charnenak , B.Khroustalev , W.Wichtmann The Assessment of Cost of Biomass from Post-Mining Peaty Lands for Pellet Fabrication. Environmental and Climate Technologies 2018:22(1):118–131. doi:10.2478/rtuect-2018-0008

[7] P. A. Ostergaard, H.Lund A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Applied Energy 2011:88(2):479–487. doi:10.1016/j.apenergy.2010.03.018

[8] B.Morvaj, R.Evins, J.Carmeliet, Decarbonizing the electricity grid: the impact on urban energy systems, distribution grids and district heating potential. Applied Energy 2017:191:125–140. doi:10.1016/j.apenergy.2017.01.058 .

[9] European solar district heating system database [Online]. [Accessed 15.03.2019]. Available: http:// solar-district-heating.eu/ServicesTools/Plantdatabase.aspx

[10] I. Polikarpova and M. Rosa, "Energy reduction potential of the district heating company introducing energy management systems," Energy Procedia, vol. 128, pp. 66–71, Sep. 2017, doi: 10.1016/J.EGYPRO.2017.09.016.

[11] H. Averfalk and S. Werner, "Economic benefits of fourth generation district heating," Energy, vol. 193, p. 116727, Feb. 2020, doi: 10.1016/J.ENERGY.2019.116727.

[12] V. F. Sánchez and A. Garrido Marijuan, "Integrated model concept for district energy management optimisation platforms," Applied Thermal Engineering, vol. 196, p. 117233, Sep. 2021, doi: 10.1016/J.APPLTHERMALENG.2021.117233.

[13] H. G. Bergsteinsson, J. K. Møller, P. Nystrup, Ó. P. Pálsson, D. Guericke, and H. Madsen, "Heat load forecasting using adaptive temporal hierarchies," Applied Energy, vol. 292, p. 116872, Jun. 2021, doi: 10.1016/J.APENERGY.2021.116872.

[14] M. Gong, Y. Zhao, J. Sun, C. Han, G. Sun, and B. Yan, "Load forecasting of district heating system based on Informer," Energy, vol. 253, p. 124179, Aug. 2022, doi: 10.1016/J.ENERGY.2022.124179.

[15] N. Izadyar, H. Ghadamian, H. C. Ong, Z. moghadam, C. W. Tong, and S. Shamshirband, "Appraisal of the support vector machine to forecast residential heating demand for the District Heating System based on the monthly overall natural gas consumption," Energy, vol. 93, pp. 1558–1567, Dec. 2015, doi: 10.1016/J.ENERGY.2015.10.015.

[16] R. Wang, S. Lu, and Q. Li, “Multi-criteria comprehensive study on predictive algorithm of hourly heating energy consumption for residential buildings,” Sustainable Cities and Society, vol. 49, p. 101623, Aug. 2019, doi: 10.1016/J.SCS.2019.101623.

[17] E. Zeyen, V. Hagenmeyer, and T. Brown, “Mitigating heat demand peaks in buildings in a highly renewable European energy system,” Energy, vol. 231, p. 120784, Sep. 2021, doi: 10.1016/J.ENERGY.2021.120784.

[18] E. Guelpa and V. Verda, “Demand response and other demand side management techniques for district heating: A review,” Energy, vol. 219, p. 119440, Mar. 2021, doi: 10.1016/J.ENERGY.2020.119440.

[19] S. Selvakkumaran, L. Eriksson, J. Ottosson, K. Lygnerud, and I.-L. Svensson, “How are business models capturing flexibility in the District Energy (DE) grid?,” Energy Reports, vol. 7, no. September, pp. 263–272, 2021, doi: 10.1016/j.egyr.2021.08.146.

[20] H. Averfalk and S. Werner, “Economic benefits of fourth generation district heating,” Energy, vol. 193, p. 116727, 2020, doi: 10.1016/j.energy.2019.116727.

[21] G. Barone, A. Buonomano, C. Forzano, and A. Palombo, “A novel dynamic simulation model for the thermo-economic analysis and optimisation of district heating systems,” Energy Convers Manag, vol. v. 220, p. 2020 v.220, 2020, doi: 10.1016/j.enconman.2020.113052.

[22] Z. Ma, A. Knotzer, J. D. Billanes, and B. N. Jørgensen, “A literature review of energy flexibility in district heating with a survey of the stakeholders’ participation,” Renewable and Sustainable Energy Reviews, vol. 123, p. 109750, 2020, doi: https://doi.org/10.1016/j.rser.2020.109750.

[23] E. Guelpa, G. Mutani, V. Todeschi, and V. Verda, “Reduction of CO2 emissions in urban areas through optimal expansion of existing district heating networks,” Journal of Cleaner Production, vol. 204, pp. 117–129, 2018, doi: https://doi.org/10.1016/j.jclepro.2018.08.272.

[24] M. Noussan, “Performance indicators of District Heating Systems in Italy – Insights from a data analysis,” Applied Thermal Engineering, vol. 134, pp. 194–202, 2018, doi: https://doi.org/10.1016/j.applthermaleng.2018.01.125.

[25] H. Li, Q. Sun, Q. Zhang, and F. Wallin, “A review of the pricing mechanisms for district heating systems,” Renewable and Sustainable Energy Reviews, vol. 42, pp. 56–65, 2015, doi: 10.1016/j.rser.2014.10.003.

[26] A. Egüez, “District heating network ownership and prices: The case of an unregulated natural monopoly,” Utilities Policy, vol. 72, no. July, p. 101252, 2021, doi: 10.1016/j.jup.2021.101252.

[27] A. Hast, S. Syri, V. Lekavičius, and A. Galinis, “District heating in cities as a part of low-carbon energy system,” Energy, vol. 152, pp. 627–639, 2018, doi: https://doi.org/10.1016/j.energy.2018.03.156.

[28] Riigikogu, “District Heating Act,” 2017. https://www.riigiteataja.ee/en/eli/ee/520062017016/consolide/current

[29] M. Galindo Fernandez, A. Bacquet, S. Bensadi, P. Morisot, and A. Oger, Integrating renewable and waste heat and cold sources into district heating and cooling systems - Case studies analysis , replicable key success factors and potential policy implications. 2021. doi: 10.2760/111509.

[30] J. Patronen, E. Kaura, and C. Torvestad, Nordic heating and cooling : Nordic approach to EU's Heating and Cooling Strategy. Copenhagen: Nordisk Ministerråd, 2017. doi: 10.6027/TN2017-532.

[31] "Changes to the heat tariff scheme in Poland," no. December 2018, 2020.

[32] J. Songa, F. Wallina, H. Lia, and B. Karlssona, "Price models of district heating in Sweden," Energy Procedia, vol. 88, pp. 100–105, 2016, doi: 10.1016/j.egypro.2016.06.031.

[33] U. Sarma and G. Bazbauers, "Algorithm for calculation of district heating tariff benchmark," Energy Procedia, vol. 128, pp. 445–452, 2017, doi: https://doi.org/10.1016/j.egypro.2017.09.029.

[34] P. Bogetoft, "Incentive Efficient Production Frontiers: An Agency Perspective on DEA," Management Science, vol. 40, no. 8, pp. 959–968, 1994, doi: https://doi.org/10.1287/mnsc.40.8.959.

[35] G. A. Comnes, S. Stoft, N. Greene, and L. J. Hill, "Performance-Based Ratemaking for Electric Utilities: Review of Plans and Analysis of Economic and Resource- Planning Issues Volume I," LBNL, Berkeley, Nov. 1995.

[36] D. Magnusson, "Who brings the heat? – From municipal to diversified ownership in the Swedish district heating market post-liberalization," Energy Research & Social Science, vol. 22, pp. 198–209, 2016, doi: https://doi.org/10.1016/j.erss.2016.10.004.

[37] P. J. Agrell and P. Bogetoft, "Economic and environmental efficiencey of district heating plants," Energy Policy, vol. 33, no. 10, pp. 1351–1362, 2005, doi: 10.1016/j.enpol.2003.12.011.

[38] D. Toke and A. Fragaki, "Do liberalised electricity markets help or hinder CHP and district heating? The case of the UK," Energy Policy, vol. 36, no. 4, pp. 1448–1456, 2008, doi: https://doi.org/10.1016/j.enpol.2007.12.021.

[39] R. C. Marques, P. Simões, and J. S. Pires, "Performance Benchmarking in Utility Regulation: the Worldwide Experience," Polish Journal of Environmental Studies, vol. 20, no. 1, pp. 125–132, 2011.

[40] J. Munksgaard, L.-L. Pade, and P. Fristrup, "Efficiency gains in Danish district heating. Is there anything to learn from benchmarking?," Energy Policy, vol. 33, no. 15, pp. 1986–1997, 2005, doi: https://doi.org/10.1016/j.enpol.2004.03.019.

[41] I. Pakere et al., "Climate Index for District Heating System," Environmental and Climate Technologies, vol. 24, no. 1, pp. 406–418, 2020, doi: doi:10.2478/rtuect-2020-0024.

[42] J. Ziemele, G. Vigants, V. Vitolins, D. Blumberga, and I. Veidenbergs, "District Heating Systems Performance Analyses. Heat Energy Tariff," Environmental and Climate Technologies, vol. 13, no. 1, pp. 32–43, 2014, doi: doi:10.2478/rtuect-2014-0005.

[43] U. Sarma and G. Bazbauers, "District Heating Tariff Component Analysis for Tariff Benchmarking Model," Energy Procedia, vol. 113, pp. 104–110, 2017, doi: https://doi.org/10.1016/j.egypro.2017.04.029.

[44] T. Jamasb and M. Pollitt, "International benchmarking and regulation: an application to European electricity distribution utilities," Energy Policy, vol. 31, no. 15, pp. 1609–1622, 2003, doi: https://doi.org/10.1016/S0301-4215(02)00226-4.

[45] M. Åberg, L. Fälting, and A. Forssell, "Is Swedish district heating operating on an integrated market? – Differences in pricing, price convergence, and marketing strategy between

public and private district heating companies," Energy Policy, vol. 90, pp. 222–232, 2016, doi: https://doi.org/10.1016/j.enpol.2015.12.030.

[46] D. Connolly et al., "Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system," Energy Policy, vol. 65, pp. 475–489, 2014, doi: https://doi.org/10.1016/j.enpol.2013.10.035.

[47] A. Hast, S. Syri, V. Lekavičius, and A. Galinis, "District heating in cities as a part of low-carbon energy system," Energy, vol. 152, pp. 627–639, 2018, doi: 10.1016/j.energy.2018.03.156.

[48] V. Stennikov and A. Penkovskii, "The pricing methods on the monopoly district heating market," Energy Reports, vol. 6, pp. 187–193, 2020, doi: https://doi.org/10.1016/j.egyr.2019.11.061.

[49] A. Dalla Rosa and J. E. Christensen, "Low-energy district heating in energy-efficient building areas," Energy, vol. 36, no. 12, pp. 6890–6899, 2011, doi: https://doi.org/10.1016/j.energy.2011.10.001.

[50] D. Poputoaia and S. Bouzarovski, "Regulating district heating in Romania: Legislative challenges and energy efficiency barriers," Energy Policy, vol. 38, no. 7, pp. 3820–3829, 2010, doi: https://doi.org/10.1016/j.enpol.2010.03.002.

[51] J. Ziemele, I. Pakere, and D. Blumberga, "The future competitiveness of the non-Emissions Trading Scheme district heating systems in the Baltic States," Applied Energy, vol. 162, pp. 1579–1585, 2016, doi: https://doi.org/10.1016/j.apenergy.2015.05.043.

[52] S. Paiho and H. Saastamoinen, "How to develop district heating in Finland?," Energy Policy, vol. 122, pp. 668–676, 2018, doi: https://doi.org/10.1016/j.enpol.2018.08.025.

[53] U. Sarma and G. Bazbauers, "District Heating Regulation: Parameters for the Benchmarking Model," Energy Procedia, vol. 95, pp. 401–407, 2016, doi: https://doi.org/10.1016/j.egypro.2016.09.046.

[54] M. Badami, R. Gerboni, and A. Portoraro, "Determination and assessment of indices for the energy performance of district heating with cogeneration plants," Energy (Oxford), pp. 697–703, 2017, doi: DOI:101016/jenergy201703136.

[55] L. Grundahl, S. Nielsen, H. Lund, and B. Möller, "Comparison of district heating expansion potential based on consumer-economy or socio-economy," Energy, vol. 115, pp. 1771–1778, 2016, doi: https://doi.org/10.1016/j.energy.2016.05.094.

[56] S.-Y. Park, K.-S. Lee, and S.-H. Yoo, "Economies of scale in the Korean district heating system: A variable cost function approach," Energy Policy, vol. 88, pp. 197–203, 2016, doi: https://doi.org/10.1016/j.enpol.2015.10.026.

[57] European Commission, "An EU strategy on heating and cooling 2016," Journal of Chemical Information and Modeling, vol. 53, no. 9, pp. 1689–1699, 2016.

[58] D. F. Dominković, G. Stunjek, I. Blanco, H. Madsen, and G. Krajačić, "Technical, economic and environmental optimization of district heating expansion in an urban agglomeration," Energy, vol. 197, p. 117243, 2020, doi: https://doi.org/10.1016/j.energy.2020.117243.

[59] G. G. Alexandrov and A. S. Ginzburg, "Anthropogenic impact of Moscow district heating system on urban environment," Energy Procedia, vol. 149, pp. 161–169, 2018, doi: https://doi.org/10.1016/j.egypro.2018.08.180.

[60] J. Fitó, J. Ramousse, S. Hodencq, and F. Wurtz, "Energy, exergy, economic and exergoeconomic (4E) multicriteria analysis of an industrial waste heat valorization system through district heating," Sustainable Energy Technologies and Assessments, vol. 42, p. 100894, 2020, doi: https://doi.org/10.1016/j.seta.2020.100894.

[61] A. M. Jodeiri, M. J. Goldsworthy, S. Buffa, and M. Cozzini, "Role of sustainable heat sources in transition towards fourth generation district heating – A review," Renewable and Sustainable Energy Reviews, vol. 158, p. 112156, Apr. 2022, doi: 10.1016/J.RSER.2022.112156.

[62] A. Kumar, P. Baredar, and U. Qureshi, "Historical and recent development of photovoltaic thermal (PVT) technologies," Renewable and Sustainable Energy Reviews, vol. 42, pp. 1428–1436, Feb. 2015, doi: 10.1016/J.RSER.2014.11.044.

[63] A. Behzadi and A. Arabkoohsar, "Comparative performance assessment of a novel cogeneration solar-driven building energy system integrating with various district heating designs," Energy Conversion and Management, vol. 220, p. 113101, Sep. 2020, doi: 10.1016/J.ENCONMAN.2020.113101.

[64] Z. Tian et al., "Large-scale solar district heating plants in Danish smart thermal grid: Developments and recent trends," Energy Conversion and Management, vol. 189, pp. 67–80, Jun. 2019, doi: 10.1016/J.ENCONMAN.2019.03.071.

[65] W. Weiss and M. Spörk-Dür, "Solar Heat Worldwide 2021 version (Global Market Development and Trends in 2020 Detailed Market Figures 2019)," 2021.

[66] P. Sorknæs, "Hybrid energy networks and electrification of district heating under different energy system conditions," Energy Reports, vol. 7, pp. 222–236, Oct. 2021, doi: 10.1016/J.EGYR.2021.08.152.

[67] M. Yuan, J. Z. Thellufsen, P. Sorknæs, H. Lund, and Y. Liang, "District heating in 100% renewable energy systems: Combining industrial excess heat and heat pumps," Energy Conversion and Management, vol. 244, p. 114527, Sep. 2021, doi: 10.1016/J.ENCONMAN.2021.114527.

[68] D. Böttger, M. Götz, M. Theofilidi, and T. Bruckner, "Control power provision with power-to-heat plants in systems with high shares of renewable energy sources – An illustrative analysis for Germany based on the use of electric boilers in district heating grids," Energy, vol. 82, pp. 157–167, Mar. 2015, doi: 10.1016/J.ENERGY.2015.01.022.

[69] Z. Lei, G. Wang, T. Li, S. Cheng, J. Yang, and J. Cui, "Strategy analysis about the active curtailed wind accommodation of heat storage electric boiler heating," Energy Reports, vol. 7, pp. 65–71, Apr. 2021, doi: 10.1016/J.EGYR.2021.02.021.

[70] M. G. Nielsen, J. M. Morales, M. Zugno, T. E. Pedersen, and H. Madsen, "Economic valuation of heat pumps and electric boilers in the Danish energy system," Applied Energy, vol. 167, pp. 189–200, Apr. 2016, doi: 10.1016/J.APENERGY.2015.08.115.

[71] J. Turunen, Y. Majanne, and M. Vilkko, "Short-term Optimization of the Operation of the CHP District Heating Plant with Heat Accumulator," IFAC-PapersOnLine, vol. 53, no. 2, pp. 13236–13241, Jan. 2020, doi: 10.1016/J.IFACOL.2020.12.151.

[72] J. Wang, Z. Zhou, J. Zhao, J. Zheng, and Z. Guan, "Optimizing for clean-heating improvements in a district energy system with high penetration of wind power," Energy, vol. 175, pp. 1085–1099, May 2019, doi: 10.1016/J.ENERGY.2019.03.153.

[73] C. Song, J. He, and H. Zhang, "Comprehensive zoning of biomass energy heating in EU countries reference for China from European experience," Chinese Journal of Population, Resources and Environment, vol. 19, no. 4, pp. 321–329, Dec. 2021, doi: 10.1016/J.CJPRE.2022.01.005.

[74] K. Ericsson and S. Werner, "The introduction and expansion of biomass use in Swedish district heating systems," Biomass and Bioenergy, vol. 94, pp. 57–65, Nov. 2016, doi: 10.1016/J.BIOMBIOE.2016.08.011.

[75] S. A. Ozoliņa et al., "Can energy sector reach carbon neutrality with biomass limitations?," Energy, vol. 249, p. 123797, Jun. 2022, doi: 10.1016/J.ENERGY.2022.123797.

[76] R. Jonynas et al., "Renewables for district heating: The case of Lithuania," Energy, vol. 211, p. 119064, Nov. 2020, doi: 10.1016/J.ENERGY.2020.119064.

[77] K. Johansen and S. Werner, "Something is sustainable in the state of Denmark: A review of the Danish district heating sector," Renewable and Sustainable Energy Reviews, vol. 158, p. 112117, Apr. 2022, doi: 10.1016/J.RSER.2022.112117.

[78] Latvian Environment, Geology and Meteorology Centre database on environmental pollution [Online]. [Accessed 31.03.2020]. Available: https://www.meteo.lv/lapas/vide/parskatu-ievadisana/parskatu-ievadisana?id=1039&nid=376

[79] The Public Utilities Commission (PUC) or the Regulator. Approved energy tariffs [Online]. [Accessed 31.03.2020]. Available: https://www.sprk.gov.lv/index.php/content/iesniegtie-tarifu-projekti

[80] Ministry of Economics. Information on issued decisions on mandatory electricity procurement. [Online]. [Accessed 31.03.2020]. Available: https://em.gov.lv/lv/nozares_politika/atjaunojama_energija_un_koge neracija/informacija_par_izdotajiem_lemumiem_par_elektroenergijas_obligato_iepirkumu/

[81] S. Alberici, S. Boeve, P. Breevoort et.al. Subsidies and costs of EU energy. An interim report, 2014. [Online]. [Accessed 31.03.2020]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/EC OFYS%202014%20Subsidies%20and%20costs%20of%20EU%20energy_11_Nov.pdf

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

[83] IEA. Energy Efficiency Indicators: Fundamentals on Statistics; 2014. Available: https://www.iea.org/publications/freepublications/publication/IEA_EnergyEfficiencyIndicato rsFundamentalsonStatistics.pdf

[84] Phylipsen GJ. Energy Efficiency Indicators; 2010.

[85] D.Blumberga, A.Barisa, M.Rosa, I.Dzene, Energy planning guidelines of Vidzeme Planning Region, Report of the project "Wood Energy and Cleantech" 2012:17.

[86] Zihare L., Blumberga L. Market Opportunities for Cellulose Products From Combined Renewable Resources. Environmental and Climate Technologies 2017:19(1):33–38. doi:10.1515/rtuect-2017-0003

[87] Latosov E., Volkova A., Siirde A., Kurnitski J., Thalfeldt M. Methodological Approach to Determining the Effect of Parallel Energy Consumption on District Heating System. Environmental and Climate Technologies 2017:19(1):5–14. doi:10.1515/rtuect-2017-0001

[88] European Union Emissions Trading Scheme 4 [Online]. [Accessed 01.04.2019]. Available:http://www.varam.gov.lv/lat/darbibas_veidi/emisiju_tirdznieciba/emisiju_tirdzniecibu_periodi/?doc=25877

[89] SDH. Solar district heating guidelines. Graz: Steinhuber Infodesign, 2012.

[90] Latvian Environmental Geology and Meteorology Center. Meteorological database 2021. Available online: https://www.meteo.lv/ (accessed on 21 June 2021).

[91] H.Vigants, D.Blumberga, I.Veinbergs, Demand Side Management in Pellet Production: Internal and External Factors. Environmental and Climate Technologies 2014;14:30‑35.

[92] Sustainable Energy Action Plan of Saldus municipality 2014‑2020, Saldus municipality 2013:2‑66.

[93] M.Noussan, et al. Data Analysis of the Energy Performance of Large Scale Solar Collectors for District Heating. Energy Procedia 2017:134:61–68. https://doi.org/10.1016/j.egypro.2017.09.619

[94] S.Furbo , et al. Yearly thermal performances of solar heating plants in Denmark – Measured and calculated. Solar energy 2018:159:186–196. https://doi.org/10.1016/j.solener.2017.10.067

[95] L.Zhou, Y.Wanga, Q. Huang, Parametric analysis on the performance of flat plate collector with transparent insulation material.Energy 2019, 174, 534–542.

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Paper 5: Pakere I., Polikarpova I., Kakis R., Blumberga D. Optimizing Large-Scale Solar Field Efficiency: Latvia Case Study. (2021) *Energies,* 14 (14):1471.

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Application of ISO 50001 for implementation of sustainable energy action plans

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Abstract

The research paper focuses on the assessment of the application of the International Standard ISO 50001 by municipalities to facilitate the implementation of their sustainable energy action plans. Traditional energy management schemes are combined with provisions of the standard by applying measurable energy indicators. The methodology is tested on the Saldus municipality of Latvia. Discussions address crucial issues like availability of energy data, lack of measurable indicators in action plans and challenges in the application of standard procedures in the municipality.

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Keywords: energy planning; energy management; ISO 50001; energy indicators; sustainable energy action plans

1. Introduction

Currently municipalities face difficulties with the collection of historical energy consumption data. Mainly data collection is time consuming and data quality in some cases is low. It might be the case when, e.g. data are available only for one year or when the municipality can provide information only on partial energy consumptions of public buildings. Therefore it is necessary to create an argument on how to ensure energy data quality in order to select appropriate measures to reduce energy consumption and CO_2 emissions.

Hundreds of municipalities all over Europe have joined the Covenant of Mayors (CoM) initiative and developed Sustainable Energy Action Plans (SEAPs) that aim to cut CO_2 emissions by at least 20 % by 2020. Nineteen

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municipalities in Latvia have joined the initiative, and all of them have developed and locally approved SEAPs. However, the high number of signatories does not imply that the goals of the CoM will be achieved. Commitment is required by the local municipalities, along with the ability to find and apply available instruments to finance the required improvements [1]. This research study is focusing on how to increase the ability not only to finance, but also to organize the required actions by means of energy management that is strengthened with the adoption of the International Standard ISO 50001.

Another issue that is addressed in this study is related to the availability of reliable data in order to be able to monitor the performance of SEAP implementation by calculating the respective energy indicators.

2. Methodology of research

The methodology of the research uses traditional energy management schemes in combination with provisions of the ISO 50001. A new energy management system is proposed based on the procedures described in the standard and the main focus is set on the application of measurable energy indicators as suggested by Neves and Leal, 2010 [2].

Introduction of energy management systems helps to decrease costs for energy, to minimise impacts on environment, to improve indoor climate and working conditions, and to establish a positive public image of the municipality [3]. The main target of energy management is to improve the organisation and control of energy consumption. Energy management affects organisational activities and technical procedures as well as behavioural patterns to decrease the total energy consumption of the organisation.

2.1. Energy management schemes

Several energy management schemes and organisational models exist. The choice of appropriate schemes depends on the size of the municipality, existing organisational structure, present knowledge and capacity, and availability of human and financial resources [4, 5]. Further in this paper some typical organisational models of energy management schemes are provided – starting from one motivated person as an energy manager in a municipality to a division dedicated to deal with energy data collection, implementation of SEAP actions and monitoring of the results.

2.1.1. Implementation of a simple system of data collection and analysis

A commonly observed situation in rural municipalities is that energy production and consumption data is collected separately by different municipal offices and forwarded to the accounting office. Moreover, the information is not analysed. Often heat metering devices are installed neither in consumer buildings (both public and residential), nor in the heating plant. Records are limited only to information about the purchase of fuel, which is very often approximate. In this situation it is very crucial to establish a reliable and functional data collection system by recording heat production and consumption data in the heating plant and in each building connected to the heating system. To be able to account produced and consumed energy, the installation of heat metering devices is mandatory. With this simple measure it is possible to achieve savings of up to 10 % [6]. The four main stages of simplified energy management are:

System development (plan!): There are several options on how data should be collected and recorded. Data can be collected by the accounting office; however, it is more efficient to appoint one person who is responsible for energy management. This person should try developing a data collection system that would require minimal investment for collection of the maximum amount of relevant information.

Data collection (do!): The responsible person must have a clear idea and understanding about the information that is necessary to be collected. Installation of heat metering devices will assure collection of the actual energy consumption (kWh/month, week or day) of each building, but it is also important to collect information about fuel consumption, fuel quality, boiler efficiency, etc. Only a comprehensive set of information will allow for carrying out proper data analysis, drawing conclusions and planning necessary actions [4].

Data analysis (check!): The collected data should be processed and analysed. This will allow for avoiding situations where the efficiency of the boiler is reported unrealistically high (over 100 %) or is too low (below 50 %).

Collected data is to be mutually comparable and compared with historical data, and, if possible, with other buildings in other regions. This is called benchmarking [7].

Conclusions and change of action (act!): Depending on the data analysis, the responsible person can draw conclusions and plan the course of the action. With the analysis of energy consumption data, a municipality will be able to prioritise buildings, where energy efficiency measures should be implemented as a priority. In addition, accounting energy consumption of each building ensures that energy users pay for the energy amount that they consume. Cost for heating (heat tariff) in apartment buildings owned by a municipality is often set lower than the actual cost of heat production and transmission.

2.1.2. Implementation of centralized monitoring and energy management system

The reduction of energy consumption in a building and the achievement of a certain amount of savings is possible, if centralized monitoring of a building's energy consumption per day, week, month and year is implemented in the municipality. An example of energy funding and a contractual relationship scheme for municipal building arrangement is illustrated in Figure 1.

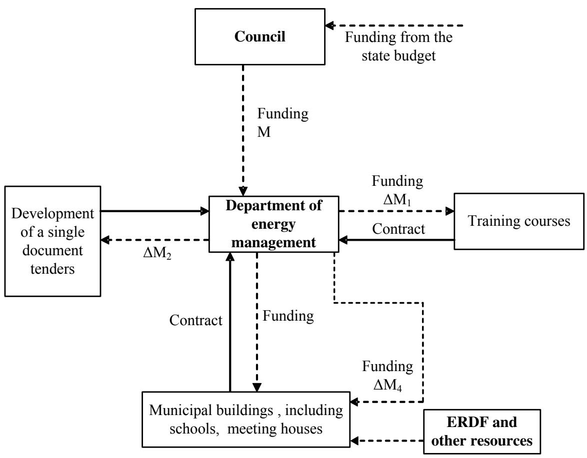

Fig. 1. Example of energy funding and contractual relationship scheme for municipal building arrangement [6]

As shown in Figure 1, one of the options is to establish a department of energy management. Initially it could employ only one person – the head of the department and gradually increase the number of people working for the department when the given financial scheme starts working. The person working for the energy management department would be responsible for managing operators of the heating plants and for managers of municipally-owned buildings (people who are doing day-to-day energy management in the building). The main tasks of the energy management department would be to plan and to reach energy savings and to report about the progress to the municipality or city council on a regular basis.

Monitoring and energy management expenses would be covered by the income from energy savings. The overall budget that a municipality is spending for energy (electricity, heat and/or fuel) will not change; however, it will also not require additional funds. This scheme will be beneficial in the long term (see Eq.1):

$$\mathrm{M} = \mathrm{M}_{\mathrm{cons}} + \sum_{\mathrm{k}=1}^{5} \Delta M \qquad (1)$$

where:
ΔM – savings, €/year;
ΔM_1 – establishment and maintenance of training course and system, €/year;
ΔM_2 – establishment (and update) of procurement system, €/year;
ΔM_3 – maintenance of energy management department, €/year;
ΔM_4 – co-financing for energy efficiency measures, €/year;
ΔM_5 – expenses of energy management system, €/year;
M – total cost of energy at the moment, €/year;
M_{cons} – cost of consumed energy, €/year.

2.2. International Standard ISO 50001

Before implementation of the ISO 50001 there were several attempts to develop a joint energy management system. In the beginning separate countries or regions developed national standards for their own use; however the general regulation on the international level was missing. Local governments have significant influence on energy management systems as they can either facilitate or hinder this process. Since 2000 a rapid development of national energy management standards can be observed [8, 9].

Introduced in June 2011, the ISO 50001 International Standard was developed to provide a unified framework for energy management. It specifies mandatory requirements for an energy management system such as an energy policy, energy objectives, targets and action plans on significant energy use [10]. So far the standard has been applied mostly in industrial sector organisations and companies [11]. Another International Standard on environmental management ISO 14001 has been used to improve the energy performance of organizations, companies and municipalities [12]. However, the focus of the latter standard is more on overall environmental performance, and less on energy issues. Therefore, in this study, authors are investigating the opportunity to apply ISO 50001 for municipal energy management schemes. Further a set of energy indicators that can be used by municipalities is provided and results in respect to ISO 50001 are analysed. Two examples of simple energy management schemes and their different organisational models in Ventspils and Liepāja municipalities are provided and described.

Results are concluded by the application of the developed methodology onto the Saldus municipality. The energy management system of this municipality is considered by assessing the implementation of their SEAP and by application of the selected energy indicators to be able to use procedures described in ISO 50001.

3. Results

3.1. Energy indicators

Energy indicators in local sustainable energy planning can be used both as an assessment and as an action-planning tool. Local authorities are using indicators mostly for diagnosis purposes, paying less attention to monitoring. Using indicators as decision criteria to choose the actions to be included in the action plan is not yet a common practice [2].

Poļikarpova I. [13] has provided eight important energy indicators that should be considered during the introduction of ISO 50001 procedures in municipality where SEAP is developed. These indicators are used to evaluate the energy efficiency performance of the municipality and can be used for benchmarking purposes – either among buildings or among administrative units of the municipality. An overview of the selected indicators is given in Table 1.

Table 1. Indicators for introduction of energy management standard in the municipality in connection with SEAPs

Indicator	Unit
Specific heat energy consumption	kWh/m^2 year
Specific electricity consumption	kWh/m^2 year
Energy consumption per inhabitant	MWh/inhabitant
Share of RES in total energy production	%
Share of renovated buildings in the total number of buildings	%
Share of the length of bicycle roads in the total length of the roads	%
Share of energy efficient lighting in the total number of lighting	%

3.2. Two alternative organisational models of energy management – case studies of municipalities in Latvia

This chapter gives example of two municipalities in Latvia - Ventspils and Liepāja - that have introduced slightly different simple energy management organisation systems. Both cities are among the seven largest cities of Latvia and are two central points of the western part of the country.

The governance of the Ventspils city is done by one main decision maker. In 2011 it was decided that training for public building managers and technical staff will be organised. The initiative came from the Ventspils city council and was mandatory for all public building managers. The training was provided by professional trainers in the field of energy efficiency, indoor climate and ventilation systems. Two training courses were organised – one in 2011, another in 2013. After the training, participants were required to take an examination. This requirement motivated trainees to put more effort in their studies and to achieve better results. After the trainings, building managers and technical staff were asked to apply their new knowledge to implement energy efficiency measures in their buildings. Keeping good micro-climate conditions in public buildings was a mandatory requirement. In parallel, an extensive monitoring programme of the energy performance of the buildings and indoor climate (CO_2 concentration, temperature) quality was initiated. Monitoring was performed by an external auditor who justified the achieved results of the building managers.

Another municipality – Liepāja started their energy management programme after development of SEAP. One group of the activities was related to setting up an energy data monitoring system and to introduce this system in the municipality. Liepāja municipality owns 65 public buildings and 56 of them were renovated during the last few years. An energy consumption monitoring system was applied for 54 buildings that are connected to the district heating system of the city. For these buildings the total annual heat consumption (MWh), specific heat consumption (kWh/m^2 year) and savings compared with the previous year (%) are calculated.

Since most of the buildings in Liepāja were renovated by targeted investment grants, certain levels of savings were mandatory. In order to achieve the planned energy savings, the municipality decided to start this energy management programme and appoint one person to work as an energy manager and assume responsibility for implementation of the required actions. All buildings were equipped with data loggers for temperature, moisture and CO_2 level measurements. Information from the data loggers are electronically sent to the energy manager who analyses it. Three trainings for building technicians were provided about proper operation of buildings after the renovation. Also a regulation of the city council about ensuring good micro-climate in the buildings was issued. The tool for data analysis was developed and is used by the energy manager.

In order to motivate building technicians and managers to achieve even greater energy savings, some part of the saved money is given back to the building. Up to 15 % of the savings budget can be used in addition to the regular salary of the staff. The remaining budget can be used for maintenance work, purchase of equipment or for financing further energy saving measures.

3.3. Application of energy management system according to ISO 50001 in the Saldus municipality

In accordance with the population, Saldus municipality is one of the ten biggest municipalities in Latvia. In January 2014 the number of inhabitants was around 27.2 thousand. The municipality is located in the south-western part of Latvia and consists of 16 territorial units – 15 rural territories and Saldus town. 43 % of the population lives in the town. The rural territories are administrated by 13 local administrations [14].

The size of the population is an important factor because it affects the number of employees that should be involved in providing energy services and this increases the complexity of the issue related to energy supply and use. To be able to introduce the energy management standard, the establishment of good information exchange and communication between the numerous local administrative units, is crucial.

When assessing the opportunity for introduction of the energy management standard in this particular municipality, the current function of the municipality in the energy sector should be taken into account. The Saldus municipality is an energy consumer, energy producer, and provider. Moreover, one of its functions is also the regulation of the heat energy tariff. All these mentioned roles should be considered when applying the ISO 50001 procedures.

The SEAP of Saldus municipality suggests that it is necessary to employ an energy manager. The energy manager will evaluate the existing system of data collection and availability and, based on this analysis, will develop a centralized data collection system where information from all involved organisations would be summarised. Currently the collection of energy data is partially centralized and is done by the accountancy office of the municipality. However, the collected information is not assessed and analysed. The task of the energy manager would be to ensure that information is transparent and clear, that data are analysed and conclusions of the analysis are transferred into real energy savings. The energy manager should work closely together with the working group responsible for the implementation of SEAP activities (see Figure 2). According to the organisational model provided in Figure 2, representatives from local administrations are responsible for the collection and delivery of energy data concerning activities in their territory directly to the energy manager of the municipality.

In addition, companies that are owned or partially owned by the municipality are obliged to give information to the energy manager. These are utility companies with a housing management (SIA „Saldus namu pārvalde”), water and waste management (SIA “Saldus komunālserviss”) and district heating provider (SIA “Saldus siltums”) functions. The SEAP working group is under the direction of the Executive Director of the municipality.

Depending on the size of a municipality and the number of institutions that are involved, the complexity of the energy management structure is changing. In less populated municipalities, the proposed structure will be simpler. Besides organisational activities, the SEAP also includes technical activities that should be implemented to decrease CO_2 emissions. Some of the technical activities are linked to the implementation of standard ISO 50001. These include:

- Installation of heat metering devices in the local heating plants in villages;
- Installation of heat metering devices in buildings connected to the district heating systems;
- Establishing a registry for accounting the consumption of wood logs for heating;
- Paying attention and recording parameters related to the fuel quality;
- Solving the issue of the ownership of street lighting;
- Providing the training to employees about electricity energy saving;
- Replacing the indoor lighting systems with more efficient;
- Implementation of energy audits in buildings with the highest specific energy consumption.

In order to start adopting the ISO 50001 in Saldus municipality, the first step is the official decision by the council. Some good synergies can be expected between SEAP activities and standardisation procedure. The standardisation requires certain procedures in a given time frame. Establishing the procedures will also affect energy consumption and the decrease of CO_2 emissions could be achieved faster.

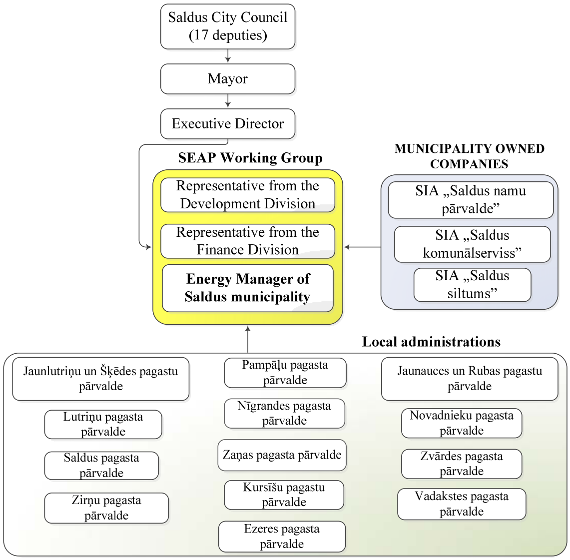

Fig. 2. Organizational structure proposed by the SEAP of Saldus municipality

Establishing strict communication procedures among all levels – management, local administrations, organisations and companies – in the first steps is essential. Other preparatory works that were suggested for Saldus municipality are: installation of heat metering devices and creation of database for centralized information storage. The task of the energy manager will be to control data inputs, to analyse them and to prepare reports. This database/data analysis tool should also calculate energy indicators that should be further used for benchmarking purposes. The database should contain at least information about the number of inhabitants in each local territory, information about energy companies (heating plants, CHP plants), on a monthly basis – generated energy, consumed fuel, electricity consumption, heat consumption, number of buildings under the building management, change in the number of transport vehicles, fuel consumption, etc.

4. Discussions

So far the international standard ISO 50001 has been applied by companies, however, the procedures are flexible and can be also successfully applied to organisations, including municipalities. Availability of energy data is crucial for planning the actions and also for monitoring their implementation. Lack of data can be solved through implementation of integrated data management procedures as part of an energy management system. Information should be further used for calculating measurable energy indicators.

A set of indicators that are appropriate for municipal energy system evaluation is available and tested on Saldus municipality. The system 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 energy management system at the municipal level. In the meantime it will also promote more efficient implementation of SEAP. To facilitate the implementation of energy management standard in municipalities, a comprehensive guideline with step-by-step procedures and examples would be very useful. This guideline 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.

5. Conclusions

SEAP is a good basis for implementation of ISO 50001 procedures in a municipality. This is because most of the information needed for energy management is already structured by the SEAP. Although good synergies between development of SEAPs and standardisation according ISO 50001 can be observed, it is only in case if activities of SEAPs are focused on the introduction/improvement of an energy management system in the municipality.

Acknowledgment

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References

[1] Christoforidis, G.C., Chatzisavvas, K.Ch., Lazarou, S., Parisses, C. Covenant of Mayors initiative – Public perception issues and barriers in Greece, *Energy Policy* 2013;60:643–655.
[2] Neves, A.R., Leal, V. Energy sustainability indicators for local energy planning: Review of current practices and derivation of a new framework, *Renewable and Sustainable Energy Reviews* 2010;14:2723–2735.
[3] Ates, S.A., Durakbasa, N.M. Evaluation of corporate energy management practices of energy intensive industries in Turkey, *Energy* 2012;45:81–91.
[4] Dzene, I., Rosa, M., Blumberga, D. How to select appropriate measures for reductions in negative environmental impact? Testing a screening method on a regional energy system. *Energy* 2011;36(4):1878–1883.
[5] Vigants, H., Blumberga, D., Veinbergs, I. Demand Side Management in Pellet Production: Internal and External Factors. *Environmental and Climate Technologies* 2014;14:30–35.
[6] Blumberga, D., Barisa, A., Rosa, M., Dzene, I., *Energy planning guidelines of Vidzeme Planning Region*, Report of the project "Wood Energy and Cleantech" 2012:17.
[7] Zahare, D., Rosa, M. Analysis of Energy Intensive Enterprises under EU Emission Trading System in Latvia. *Scientific Journal of Riga Technical University. Environmental and Climate Technologies* 2012;7(1):125–132.
[8] Mey, J., How can we facilitate the introduction of energy management systems (EnMS), *EGEE 2011 Summer study* 2011:759–766.
[9] Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), *Energy Management in Practice*, Germany 2012.
[10] ISO 50001:2011(E). *International standard, energy management systems – requirements with guidance for use*. International Organization for Standardization 2011.
[11] Gopalakrishnan, B., Ramamoorthy, K., Crowe, E., Chaudhari, S., Latif, H. A structured approach for facilitating the implementation of ISO 50001 standard in the manufacturing sector, *Sustainable Energy Technologies and Assessments* 2014;7:154–165.
[12] Lozano, M., Vallés J. An analysis of the implementation of an environmental management system in a local public administration, *Journal of Environmental Management* 2007;82: 495–511.
[13] Poļikarpova, I., Energy management systems (ISO 50001) application of local energy consumption reduction goals, *Bachelor Thesis, Riga Technical University, Institute of Energy Systems and Environment* 2014:61.
[14] Sustainable Energy Action Plan of Saldus municipality 2014–2020, Saldus municipality 2013:2–66.

ENERGY REDUCTION POTENTIAL OF THE DISTRICT HEATING COMPANY INTRODUCING ENERGY MANAGEMENT SYSTEMS

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Energy reduction potential of the district heating company introducing energy management systems

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Abstract

Research paper is focused on energy reduction in district heating company introducing energy management system. Methodology is tested on example of district heating company SIA "Salaspils Siltums" in Latvia.

Keywords: energy management; energy consumption reduce

1. Introduction

The European Parliament and the Council in order decrease climate change, issued of Directive 2012/27/EU, which provides that the state by 2020, the amount of CO_2 reduced by 20 %, increase energy efficiency by 20 %, increase renewable energy sources (hereinafter RES) in the comparison to 1990 [1].

District heating companies have one of the biggest potential for reducing energy consumption, improving efficiency and significantly reducing CO_2 emissions. Installing boilers with higher efficiency, isolating the heating pipes, etc., energy consumption will decrease significantly, as well as CO_2 emissions. Large energy efficiency projects require large investments, but there are a lot of activities, which do not require such huge investments.

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Energy management system (EnMS) is a one of the ways how to efficiently and controlled to reduce energy consumption in the organization. EnMS one of the main goal is control energy flow, identifying the place where need to make improvement. The introduction of energy management systems manufacturing company average energy consumption is reduced from 5 % to 15 %, depending on the company's energy level of quality [2].

This research study is focusing to prove, that energy management system in the district heating company is a suitable solution for energy saving.

2. Methodology of research

The methodology of the research is using traditional energy management system steps to determine possible to reduce energy consumption in the district heating company. EnMS can be adapted to different types of organizations – municipalities, office work, manufacturing companies, etc. EnMS main focus is set on to identify weak points in energy use and identify energy efficiency measures. To determine weak points in the organization of energy use is a necessary objective method of comparison − to select a precision energy efficiency indicator (EnPI).

2.1. EnMS data collection of district heating company

Data collection stage, it is important to identify the data to be taken into account. In determining the energy management system boundaries district heating company should take into account the specificity of the company – that the operation is divided into three parts; energy production, energy transmission and energy consumers.

Determine boundaries should take account of legislative requirements. Latvian legislative requirements (after Energy efficiencies law) states that the large electricity consumer company (in annual consumption of more than 500 MWh) EnMS cover 90 % of energy consumption, which means that the feasibility of all heat sources included. Medium large district heating company consumes approximately 1000 MWh.

District heating company defines how far analysed, will try to influence consumers, determined already by selecting the border, there are three scenarios:

- District heating company does not fully cover its consumers EnMS system, controlling the thermal efficiency;
- District heating company enterprise consumers include partially controlled house heat node status, increased monitoring of running back temperature (more than just a board in the compensation report if the return temperature is too high, to train administrators for house heating regulation and other related matters;
- Fully include consumers district heating company company EnMS, control building heat consumption, analyse, together with the house managers, the introduction of energy efficiency measures as appropriate.

Analyse limits may stop at certain boiler house, but you can analyze each boiler furnace equipment separately, setting limits for controlled flows.

Depending on the selected borders collects data. The basic framework for data collection throughout the spacious range EnMS is the same. Data collection started with all of the data relating to the use of energy, the collection in one place (in electronic form). The next step is data necessary for screening, this step has to be aware of the limits that are to introduce EnMS to be able to filter out the required data. After the required data collection, followed by a check whether they are representative, measuring instruments comply with the current rules, should be critically evaluated data sincerity. Data compilation is evaluated to the existing data analysis can be conducted to assess the efficiency of the company in case of shortage, make sure that the data can’t be obtained in some other way, or the other option must be installed in a new measuring devices. Data gathering basic steps summarized in Fig. 1.

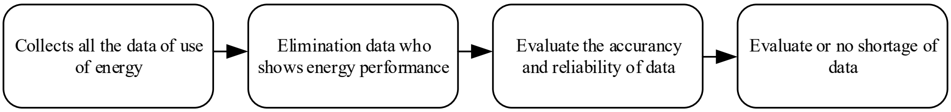

Fig. 1. EnMS data compilation principal scheme.

Fig. 1 shows that the phases are following one after another in order to obtain data which can be further analysis in order to assess the company's energy efficiency in district heating company.

2.2. Energy performance indicators for district heating company

Has identified more than 180 different energy efficiency indicators both simple indicators and complex indicators. Choosing the appropriate EnPI should be established so that the company could objectively assess the energy efficiency within certain limits [3].

Indicator selection process of the first stage of the main energy source, it inputs and outputs traffic definition and analysis. District heating company's main energy material input is fuel and electricity. Accordingly, the main energy consumers are easier to identify than other companies, they have a boiler or CHP plant. The main electricity consumers are circulating pumps, hydraulic operation, etc.

EnPI should be every consumer's energy efficiency (each incoming flow compared to net unit). DHS main business of energy efficiency indicator is the amount of fuel consumed in the production of heat energy. Energy efficiency indicator – boiler efficiency coefficient can be applied separately to each heat source and one type of fuel boilers total. EnPI should be every consumer's energy efficiency (each incoming flow compared to net unit) [4]. DHS main business of energy efficiency indicator is the amount of fuel consumed in the production of heat energy. Energy efficiency indicator – boiler efficiency coefficient can be applied separately to each heat source and one type of fuel boilers total. The next step in the selection of indicators is to verify that the indicator will change with changing circumstances, define the factors affecting. If the indicator does not change (direct relation) in a different size, then this is a simple indicator of a change in direct relation, it has formed a complex indicator.

In summary, in order to create a DHS company energy efficiency assessment system, which is based on the indicator method is carried out as follows the following basic steps, which may vary depending on the complexity and size of the organization:

- Identify all energy consumers;
- Define the major energy consumers;
- Determine the incoming resource flows;
- Define the useful and the rest of the output stream;
- Determine the effectiveness of the heat source (each incoming flow of net output flow);
- Determine the boundaries of what will happen comparison (each heat source, the same type of thermal springs, a boiler house, etc.);
- Determine whether the indicator is correlated with certain factors;
- Grouped simple and complex indicators;
- Verify that the established indicators also perform operational indicator function;
- Selected for each indicator, the necessary collection periods (24 hours a month, on a tree, etc.).

Creating indicator that objectively reflects the energy efficiency of the company, can be used as a tool to identify the places where you can make improvements and implement energy efficiency measures.

3. Results

One of the most important part in EnMS is data collection and analysis. The district heating plant material input that is monitoring – resource accounting, energy consumption and other parameters according to the situation. In Table 1 summarized the most important energy efficiency indicators and influencing factors [5, 6]. After this indicators companies can have analyzed energy efficiency.

Table 1. The most important energy efficiency indicators and influencing factors [5, 6].

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 EnPI in DHS company is Specific fuel consumption or boiler efficiency coefficient. Boiler who works to gas is relatively easy to calculate specific fuel consumption, because have gas meter and produced heat power meter, and this meter system are stable. But woodchips boiler, have more complicated, because difficult to determine the amount of the input woodchips, however a monthly basis data can be obtained reliable. Ltd “Salaspils Siltums” woodchips boiler specific woodchips consumption depending on produced heat power collected in Fig. 2.

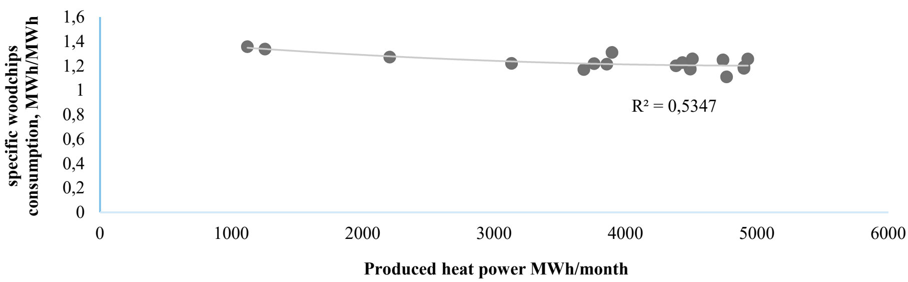

Fig. 2. Woodchips boiler specific woodchips consumption depending on produced heat power.

Specific woodchips consumption correlate on average with produced heat power ($R^2 = 0.53$), can be explained by the fact that the quantity of fuel entered data monthly observed error. Because chips were stored outdoors sheds, and month-end surpluses read about. As well as the furnace supplied chips humidity varied, depending on the load and present still coming outdoor humidity, moisture in wood chips is determined upon arrival. Gas boiler efficiency coefficient depending on produced heat power collected in Fig. 3.

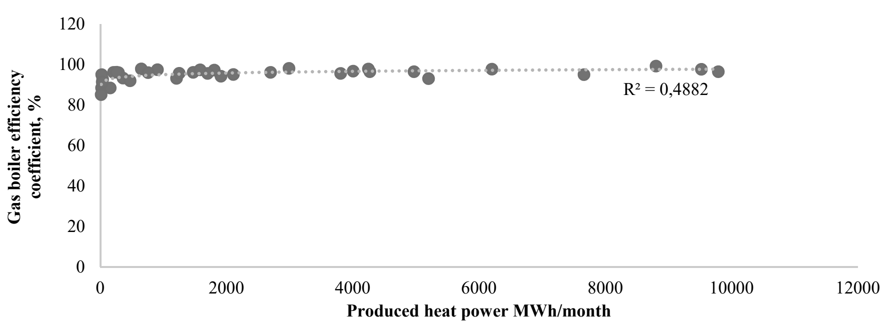

Fig. 3. Gas boiler efficiency coefficient depending on produced heat power.

Between the gas boiler efficiency coefficient and the heat produced there is also average correlation ($R^2 = 0.488$), an idealized version of that correlation does not exist, but at a smaller boiler capacity is less an efficiency, and to the power which is above 5 % is stabilizing, so also is the correlation [5]. Therefore, it is important to choose the boiler according to the heat load.

One of the EnMS analysis aims is find out the weak points in the company's energy consumption and identify energy efficiency measures. Introducing EnMS company and planning of activities and their order of priority, the significant energy consumers. DHS importance to the company, consumers are fired equipment – boilers and cogeneration. Businesses with more equipment, more energy flows are listed separately. There are two ways to take the steps to be energy-efficiency measures, the sequence:

- Start with the consumer, the consumer group, which recorded the highest energy consumption;
- Take the measures that are economically reasonable choice.

The first measures will be implemented with no need for investment, or invest a small investment, then the measures that have a significant impact on consumption and can get the most energy savings. Measures, which do not require large investments, are employees and persons involved in training, behavioral changes (defined employee motivation), etc. The measures which are necessary for investments related to the new product change.

Most of the identified measures which should be introduced in the company, does not require large investments. The identified measures should be introduced Ltd "Salaspils Siltums" in order to raise the efficiency of the production process:

- Implement operational indicators and procedures to ensure that every day should be controlled and analyzed production processes;
- Create incentive measures for the control of the operator of work;
- Regular boiler operator training courses;
- Train building administrators for heat knot adjustment;
- Boiler control system the optimal setting for regular check-ups;
- The introduction of energy efficiency measures identified Ltd. "Salaspils Siltums" on average per year could save about 4 % of its energy.

3. Conclusions

Successfully implemented energy management systems organization acted as a driving force for continuous energy efficiency improvements. Successful EnMS system is based on clearly defined organization's energy objectives and plan for the realization of a detailed energy analysis, which is based on the organization of the energy efficiency indicators table monitoring system, covers the procedure for the elimination of system failures and how is defining new organizational goals and objectives to ensure the system's sustainability.

To describe the organization's level of energy efficiency, energy efficiency indicators are used which are adapted to each organization individually. DHS energy efficiency indicators are generally complex indicators, because the value is dependent on both the external and internal factors. Work during the development of the indicators are divided into two groups – operational and statistical. Key indicators DHS company is boiler efficiency coefficient depending on the amount of heat produced, the outdoor air temperature, condenser efficiency coefficient depending on the return temperature and chips moisture, specific power consumption. EnMS is an important indicator of the share of renewable resources in the total amount of energy used.

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References

[1] VARAM. Vides politikas pamatnostadnu 2014–2020 gadam kopsavilkums; 2014.
[2] BSR. Energy Managment handbook; 2012.
[3] IEA. Energy Efficiency Indicators: Fundamentals on Statistics; 2014. Available: https://www.iea.org/publications/freepublications/publication/IEA_EnergyEfficiencyIndicatorsFundamentalsonStatistics.pdf
[4] Phylipsen GJ. Energy Efficiency Indicators; 2010.
[5] Valtere S, Koks N, Blumberga D. Vides vadiba un energoparvaldiba. Riga: RTU; 2014.
[6] Vigants G. Zema oglekla siltumapgades sistemas. Dissertation, Riga Technical university, 2011.

MULTI-CRITERIA ANALYSIS TO SELECT RENEWABLE ENERGY SOLUTION FOR DISTRICT HEATING SYSTEM

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Multi-Criteria Analysis to Select Renewable Energy Solution for District Heating System

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***Abstract* – The research paper is focused on how to choose the most suitable renewable energy solution using multi-criteria analysis for a district heating system. Making choices is based on indicators – economic, environmental and social. In this case, the study used five indicators: resources costs, totals investments, reduction of greenhouse gas emissions, specific weight of renewable energy resources and impact on utilized land. Three situations have been compared – current situation: gas boiler, planned: solar collectors 21 595 m^2 + accumulation tank 8000 m^3 and alternatives: solar PV panels 5504 m^2 – heat pump COP 3 are used in the estimation. The multi-criteria decision-making analysis shows that solar collectors 21 595 m^2 + accumulation tank 8000 m^3 are considered as the best alternative. The methodology is based on choosing a solution for a district heating company in Latvia.**

***Keywords* – Accumulation tank; alternatives; district heating; multi-criteria analysis; renewable energy; solar collectors; TOPSIS**

1. INTRODUCTION

District heating systems are beginning to change, going from 3rd generation heat sources to 4th generation heat sources. One of the most important aspects of this transition is integration of renewable energy sources (hereinafter RES). The main aim is to achieve a non-fossil district heat supply system, which will be a sustainable energy system [1]. Energy and climate policy is based on increasing renewable energy resources to reduce greenhouse gas emissions. To increase renewable energy sources to 54 % by 2030 in district heating in Latvia, is part of the objective in Latvia's National Energy and Climate Plan 2021–2030 [2].

To achieve the target, a large part of the responsibility is placed on medium and large heat producers. According to Regulation No. 736 of the Cabinet of Ministers, the average combustion plant is ≥ 1 MW ≤ 50. A large-scale heat producer is above 50 MW. The Regulation determines that from December 2018, all new boiler houses must comply with the stringent environmental requirements, and already installed boilers must comply to these same requirements from 2025.

Therefore, it would be far-sighted to replace incineration plants with 4 generations of equipment using solar, wind and recovered heat.

In Latvia there are 631 boiler houses and 175 combined heat and power plants (hereinafter CHP) which in total produced 7.15 TWh heat in 2017 according to central statistics data [3]. Every year Latvia's district heating companies develop and reduce fossil fuel use. Using EU

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funds 106 projects will be implemented to increase efficiency in heat sources, heat networks and move to renewable energy by 2020 [4].

In district heating systems (DHS), the most often used renewable energy sources (RES) include biomass [5], [6], wind [8], geothermal [7] and solar. In the last years, thermal solar energy [8] is used more and more in DHS. The largest thermal solar energy plants are in Denmark [10], and Latvia and Denmark have similar climate conditions.

In order to choose the most appropriate solution, there is need to conduct analyses of multiple criteria: economic, environmental and social. Multiple Criteria Decision Making (hereinafter MCDM) methods generally require the decision maker to evaluate alternatives with respect to decision criteria and also to assign importance weights to the criteria [11]–[13].

This research study is focusing on selecting the best RES energy technology solution to medium, local district heating systems in Latvia using the multi-criteria decision analysis method: TOPSIS. The TOPSIS and principle of TOPSIS (Technique for order performance by similarity to ideal solution) method is presented by Chen and Hwang.

2. METHODOLOGY OF RESEARCH

In this case study, the methodology is applied to an average district heating company with an installed capacity of about 30 MW. In the current system, 60 % of renewable energy is from renewable energy sources, 40 % from fossil fuel – natural gas. One goal is to increase energy independency and reduce fossil fuel use by up to 10 %.

TABLE 1. TECHNOLOGY DISTRIBUTION BY LOAD

	Current situation		**Planned situation**		**Alternative situation**	
Summer load	3 MW	Condensing gas boiler	Solar collectors 21 595 m^2 + accumulation tank 8000 m^3		Solar PV panels 5504 m^2 – heat pump COP 3	
Base load	7 MW + 1.68 MW	Woodchip boiler + flue gas condenser	7 MW + 1.68 MW	Woodchip boiler + flue gas condenser	7 MW + 1.68 MW	Woodchip boiler + flue gas condenser
Above the base load	3 MW	Same condensing gas boiler	3 MW + 0.5 MW	Woodchip boiler + flue gas condenser	3 MW	Woodchip boiler + flue gas condenser
Peak load	2·10 MW	Gas boiler	2·10 MW	Gas boiler	2·10 MW	Gas boiler

Multi-criteria analysis will select variations to the summer load – solar collector system with accumulation tank in planned version and alternative heat pump and solar cells.

The developed framework for choosing suitable RES technology for a district heating company is illustrated in Fig. 1.

To make the right decision one needs to choose an indicator that objectively characterizes the situation. The first step to use MCDM is to select criteria. Criteria can be classified into four aspects: technical, economic, environmental and social [14]. In literature and in the heat sector can find many different indicators that are used to compare technologies (see Fig. 2) [15], [16]. First those most used are collected, and after five heat industry specialists choose the most important ones. During the process of identifying the most valuable indicator, it was scaled to the particular situation. In this case study, the two most important aspects are economic and environmental due to the fact that the economic aspect has a direct impact on the heat tariff, and the company's goal is to deliver heat safely and at the lowest possible price. The environmental aspect is also very important, as the heat demand increase every year. For companies operating in the energy sector that are in the ETS system in the 4th period from 2020 to 2030, CO_2 allowances will no longer be granted. During the transitional period, 30 % of the previous period will be calculated for companies that have previously had free allowances [17]. It is therefore important to move to renewable energy in time.

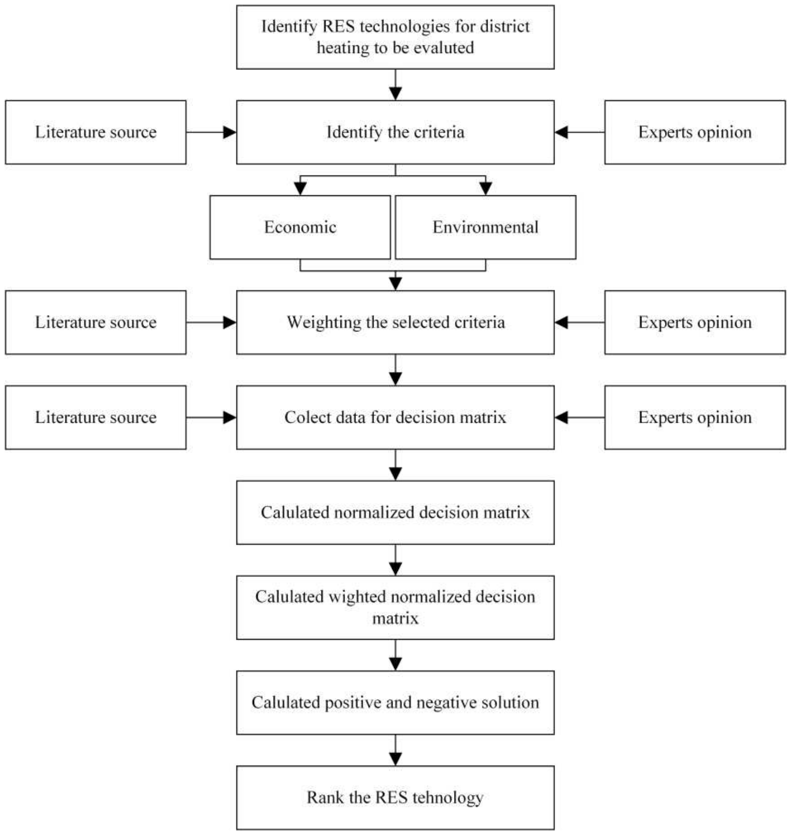

Fig. 1. Decision-making framework.

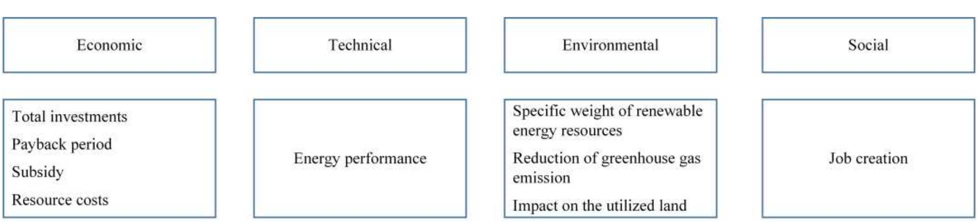

Fig. 2. Indicators for Renewable Energy Heating Technologies.

After summarizing indicators, TOPSIS is applied to make a decision. The procedure of TOPSIS consists of main five steps: normalized decision matrix, weighted normalized decision matrix, positive ideal and negative ideal solution, positive ideal and negative ideal solution and calculation of the relative closeness to the ideal solution.

The energy technology is evaluated with four criteria. The selected indicators are: total investments, resources costs, reduction of greenhouse gas emissions and impact on the utilized land. Experts selected the importance of the selected criteria from 0 to 5 by significance, 0 no influence – 5 extremely high influence:

- No influence: 0;
- Extremely low influence: 1;
- Moderately low influence: 2;
- Medium influence: 3;
- Moderately high influence: 4;
- Extremely high influence: 5.

Summarizing ratings were calculated weights. All chosen criteria weight in sum is equal to 1. Criteria weights for chosen indicators are as fallow:

- Total investments (ET): 0.18;
- Reduction of greenhouse gas emissions (ERG): 0.23;
- Resource costs (ER): 0.25;
- Impact on the utilized land (EI): 0.14;
- Specific weight of renewable energy resources (ES): 0.2.

Step one, in accordance with TOPSIS, is to calculate the normalized decision matrix. The normalized value r_{ij} is calculated as follows:

$$r_{ij} = \frac{\max \alpha_{ij} - \alpha_{ij}}{\max \alpha_{ij} - \min \alpha_{ij}}, \tag{1}$$

if max a_{ij} is preferable;

$$r_{ij} = \frac{\alpha_{ij} - \min \alpha_{ij}}{\max \alpha_{ij} - \min \alpha_{ij}}, \tag{2}$$

if min a_{ij} is preferable.

Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as follows:

$$v_{ij} = r_{ij} \cdot w_i \,. \tag{3}$$

The next step determines the ideal A^+ and negative ideal A^- solutions:

$$A^* = \{(\max_i v_{ij} \mid j \in C_b), (\min_i v_{ij} \mid j \in C_c)\} = \{v_j^* \mid j = 1, 2, \ldots, m\}, \tag{4}$$

$$A^- = \{(\min_i v_{ij} \mid j \in C_b), (\max_i v_{ij} \mid j \in C_c)\} = \{v_j^- \mid j = 1, 2, \ldots, m\}. \tag{5}$$

Calculate the separation measures using the m-dimensional Euclidean distance. The separation measures of each alternative from the positive ideal solution and the negative ideal solution, respectively, are as follows:

$$S^{+} = \sqrt{\sum_{j=1}^{n} (\nu_{ij} - \nu_{j}^{+})^2} \,, \tag{6}$$

where $i = 1, 2, \ldots, m$.

$$S^{-} = \sqrt{\sum_{j=1}^{n} (\nu_{ij} - \nu_{j}^{-})^2} \,. \tag{7}$$

The final step is to calculate the relative closeness to the ideal solution. The relative closeness of the alternative with respect to A^+ is defined as follows:

$$C_i^* = \frac{S_i^-}{(S_i^+ + S_i^-)} \,, \tag{8}$$

if C_i^* = 1, alternative is the ideal solution and if C_i^* = 0, alternative is the Negative-Ideal solution.

3. Results

In the original decision-making matrix in Table 3, all five indicators to all three scenarios are presented. The data in terms of current situation and planned situation are taken and calculated from company data. Data to alternative situation are taken from offers from companies. Resources cost to natural gas is average to medium district heating company per EUR to MWh, in Latvia natural gas price is split into two parts: consumption and distribution. In terms of the planned situation, alternative costs are considered to be 0, because the energy resource is the sun. Only in the actual situation are greenhouse gases emitted. In the actual situation in 2018, 50 % heat was produced using natural gas, second 50 % of heat is produced using renewable energy resources – from the woodchip boiler and from the flue gas condenser. In both alternatives, it is planned to refuse from the use of fossil fuels, and use them only at peak loads (see in Table 1). Both newer alternatives require extra land. In the planned situation is necessary to prepare 6.5 ha of land to install solar collectors with 21 595 m^2 active square. An alternative to the solution is about the same area, but below it must be installed the active surface of the ground heat pump. The total investment is attributed to the unit of installed MW. In the current situation, no investments is 0, because all the equipment is already present at the plant. Both alternatives are designed to cover the summer load, with an average power of up to 3 MW. The planned system has a capacity of 12.3 MW, but has an 8 000 m^3 accumulation tank, which accumulates heat for the period when there is no solar energy. But for the alternative, the installed capacity of the heat pump is 3 MW of heat produced. Since the energy source of the heat pump is from PV panels, during the night mode, electricity should be taken from the grid.

TABLE 4. ORIGINAL DECISION MAKING MATRIX

	Resource costs	Reduction of greenhouse gas emissions	Specific weight of renewable energy resources	Impact on utilized land	Total investments
Current situation	35	0.48	50	0	0
Planned situation	0	0	90	2	375 000
Alternative situation	0	0	90	3	613 333
	min	min	max	min	min
Weights	0.25	0.23	0.2	0.14	0.18

After normalizing the values, one obtains a matrix where values are from 0 to 1, after which it is easier to compare results, see Table 5.

TABLE 5. NORMALIZED DECISION MATRIX

	Resource costs	Reduction of greenhouse gas emissions	Specific weight of renewable energy resources	Impact on 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 an important part is indicator weight, which is determined by district heating experts. One criteria can be highly dominant, and can be equivalent. In this case study, all indicators, one can say, are equivalent. The most important indicator is resource cost, because the company gains more energy independence and changes in energy prices have less impact. The next important indicator is reduction of CO_2 emissions. Reducing greenhouse gases is an important part of choosing renewable energy sources. To make a decision, there is a need to put weight via a normalized matrix (see Table 6).

TABLE 6. WEIGHTED NORMALIZED DECISION MATRIX

	Resource costs	Reduction of greenhouse gas emissions	Specific weight of renewable energy resources	Impact on utilized land	Total investments
Current situation	0.000	0.000	0.073	0.133	0.168
Planned situation	0.177	0.163	0.132	0.044	0.065
Alternative situation	0.177	0.163	0.132	0.000	0.000

The point calculated matrix identifies the ideal, where the ideal is 0 and the rest shows in terms of steps to the ideal. The lower the value; the closer to the ideal. The positive ideal solution for resource cost is in the planned and alternative situation, because the solar energy cost is 0, but the current situation contains average natural gas prices. For reduction of greenhouse gas emissions and specific weight of renewable energy resources, the same options include resource costs. Impact on the utilized land and total investments ideal solution is current situation, because do not need new investments and no more impact to land. The results are summarized in Table 7.

TABLE 7. POSITIVE IDEAL SOLUTION

	Resource costs	Reduction of greenhouse gas emissions	Specific weight of renewable energy resources	Impact on utilized land	Total investments
Current situation	0.177	0.163	0.059	0.000	0.000
Planned situation	0.000	0.000	0.000	0.089	0.103
Alternative situation	0.000	0.000	0.000	0.133	0.168

The reverse process to the find ideal solution is to find the negative solution. The negative solution is the opposite ideal to resource costs, reduction of greenhouse gas emissions and specific weight of renewable energy resources anti-idol solution is current situation. The results are summarized in Table 8.

TABLE 8. NEGATIVE IDEAL SOLUTION

	Resource costs	Reduction of greenhouse gas emissions	Specific weight of renewable energy resources	Impact on utilized land	Total investments
Current situation	0.000	0.000	0.000	0.133	0.168
Planned situation	0.177	0.163	0.059	0.044	0.065
Alternative situation	0.177	0.163	0.059	0.000	0.000

The TOPSIS result of this case study, to choose the most suitable energy technology for medium district heating company, is presented in Table 9. Indicates that prior is planned alternative-solar collector with accumulation tank, second best is alternative heat pump with PV panels.

In this case study, the current situation was evaluated where nothing changes, in the summer a gas boiler is use and 2 alternative situations, where RES was used were considered. This study presents a multi-criteria decision making method to prioritize three situations.

TABLE 9. TOPSIS RESULT OF THE IDEAL/ANTI-IDOL POINTS AND THE CLOSENESS COEFFICIENTS WITH RESPECT TO THE TREE SCENARIOS

di^{+}	di^{-}	ci	Result rank
0.25	0.21	0.46	3.00
0.14	0.26	0.66	1.00
0.21	0.25	0.54	2.00

A total of five indicators for decision making cover economic and environmental aspects, however future studies should consider a wider range of aspects. The best option is the planned version where solar collectors and storage tanks will be installed (see Fig. 3).

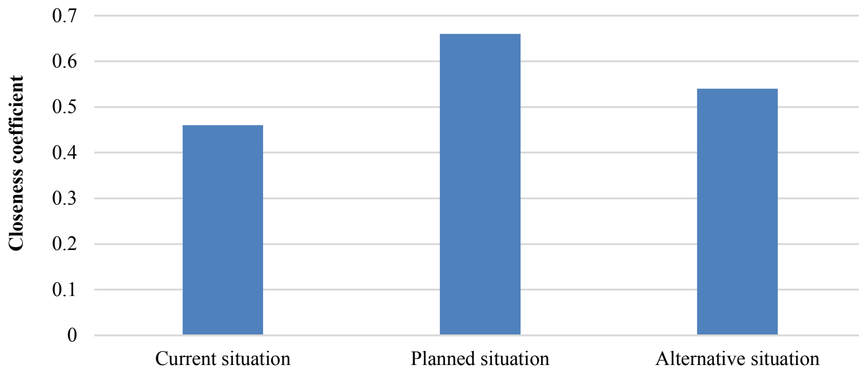

Fig. 3. The coefficients for 3 systems in case study.

4. Conclusions

After the multi-criteria analysis, the best option is the planned scenario where the solar collector field and the accumulation tank are installed. This alternative is better than heat pump with PV panels, because investment to installed MW is lower and impact to the land less. If the second alternative would be the accumulation tank and in there is no need to take electricity from the grid at night, then the result would be different. Because then, during the day you can produce more and accumulate heat that can be used at night. Although in the current situation there is no need for additional investment and land resources, the cost of resources and environmental impact make the current system less competitive.

However, the results are influenced by the choice of indicators, which also include subjectivity. More experts could be taken, but even the human factor would remain. In the future analysis, sensitivity analysis of the criteria weights can be used to clarify each criterion weight influences on the results.

Acknowledgement

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References

[1] Lund H., Werner S., Wiltshire R. 4th Generation District heating (4GDH) Integration smart thermal grids into future suitable energy systems. *Energy* 2014:68:1–11. doi:10.1016/j.energy.2014.02.089
[2] Ministry of Environmental Protection and Regional Development. Latvian National Energy and Climate Plan 2020–2030.
[3] Data for district heating [Online]. [Accessed 15.03.2019]. Available: https://www.csb.gov.lv/lv/statistika/db
[4] Data for projects implemented by the EU [Online]. [Accessed 15.03.2019]. Available: www.esfondi.lv
[5] Joelsson J., Gustavsson L. Swedish biomass strategies to reduce CO_2 emission and oil use in an EU context. Energy 2012:43(1):448–468. doi:10.1016/j.energy.2012.03.050
[6] Rodzkin A., Kundas S., Charnenak Y., Khroustalev B., Wichtmann W. The Assessment of Cost of Biomass from Post-Mining Peaty Lands for Pellet Fabrication. *Environmental and Climate Technologies* 2018:22(1):118–131. doi:10.2478/rtuect-2018-0008

[7] Ostergaard P. A., Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. *Applied Energy* 2011:88(2):479–487. doi:10.1016/j.apenergy.2010.03.018

[8] Morvaj B., Evins R., Carmeliet J. Decarbonizing the electricity grid: the impact on urban energy systems, distribution grids and district heating potential. *Applied Energy* 2017:191:125–140. doi:10.1016/j.apenergy.2017.01.058

[9] Mauthner F, Weiss W, Spork-Dür M. Solar heat worldwide. Markets and € contribution to the energy supply 2013. Institute for Sustainable Technologies, 2015.

[10] European solar district heating system database [Online]. [Accessed 15.03.2019]. Available: http:// solar-district-heating.eu/ServicesTools/Plantdatabase.aspx

[11] Asadabadi M. R. The stratified multi-criteria decision-making method. *Knowledge-Based Systems* 2018:162:115–123. doi:10.1016/j.knosys.2018.07.002

[12] Zaniolo C. Expressing and supporting efficiently greedy algorithms as locally stratified logic programs, 2015. [Online] Available: http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=303696FFBF56110B156D1950B9F394B4?doi=10.1.1.699.5302&rep=rep1&type=pdf

[13] Taha R. A., Daim T. Multi-criteria applications in renewable energy analysis, literature review. Research and technology management in the electricity industry. London: Springer-Verlag, 2013.

[14] Wang J.-J., Jing Y.-Y., Zhang C.-F., Zhao J.-H. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews* 2009:13(9):2263–2278. doi:10.1016/j.rser.2009.06.021

[15] Zihare L., Blumberga L. Market Opportunities for Cellulose Products From Combined Renewable Resources. *Environmental and Climate Technologies* 2017:19(1):33–38. doi:10.1515/rtuect-2017-0003

[16] Latosov E., Volkova A., Siirde A., Kurnitski J., Thalfeldt M. Methodological Approach to Determining the Effect of Parallel Energy Consumption on District Heating System. *Environmental and Climate Technologies* 2017:19(1):5–14. doi:10.1515/rtuect-2017-0001

[17] European Union Emissions Trading Scheme 4 [Online]. [Accessed 01.04.2019]. Available: http://www.varam.gov.lv/lat/darbibas_veidi/emisiju_tirdznieciba/emisiju_tirdzniecibu_periodi/?doc=25877

CLIMATE INDEX FOR DISTRICT HEATING SYSTEM

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Climate Index for District Heating System

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***Abstract* – District heating (DH) has been highlighted as an important part in future carbon neutral energy supply. However, the performance of different DH systems varies a lot and the existing regulations do not always motivate DH companies to move toward more sustainable heat production. Therefore, this article presents novel methodology for Climate index determination which can be further used for the comparison of DH systems. The Climate index includes seven different indicators which show DH system performance according to energy efficiency, sustainability and environmental impact dimensions. The methodology is applied for 20 different DH systems operating in Latvia. The results show that the performance of 5 natural gas-based DH systems is below the determined climate benchmark.**

***Keywords* – Benchmarking; district heating; energy efficiency; sustainable heat supply.**

1. INTRODUCTION

There are several aspects affecting the efficiency of the DH companies' heating generation and heat tariff [1]. One of most important is the district heating (DH) regulation mechanism. Limited or non-existing competition that is commonly seen in the natural monopolies of utilities, including the district heating production market, create additional challenges for the regulator when it comes to operational efficiency evaluation. The lack of competition does not incentivize DH producers to increase the productivity of their production processes and the integrity of tariff determination [2].

Compared to a strictly regulated DH market, in a fully liberalized DH environment, the tariff is determined based on the DH performance benchmarking parameters [1], [2]. It promotes an incentive-based regulation framework [3], [4]. While a strong debate over which of the DH regimes is the most convenient [5]–[8] is on-going, more and more studies focus on the examination of the effects and benefits of introducing benchmarks in DH market regulation for the operational efficiency evaluation [9], [10]. Benchmarking in a natural monopoly market structure is as useful as in a fully liberalized market since it allows to compare how the performance efficiency of DH production companies differ even though the same service is provided for the end-consumer [2].

A study by Marques *et al*. [11] concludes that the application of benchmarking for companies operating in the utilities and in a natural monopoly market structure has several advantages. It incentivizes companies to operate more efficiently and implement innovative solutions to increase technical efficiency which results in the optimization of operations and

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capital expenses, increased return on investment, and improved information transparency to the utility consumers and stakeholders [11].

The findings from previous studies conclude that DH providers and their systems differ considerably, therefore empirical regression analysis might not be sufficient to obtain valuable results [12]. Instead, the model should incorporate different explanatory parameters and relative indicator values that would rank each DH company with respect to its distance from the benchmark [12]. However, there is still no consensus among researches on the application of most appropriate benchmarking technique, since it has been found that the choice of the benchmarking methodological approach, including indicators and model boundaries influence the identified efficiency performance scores and ranking of the DH companies [13], [14].

There are studies that introduce benchmark-based models as tools to measure DH efficiency [9], [10]. A benchmark model includes a combination of different technical, structural, economic indicators such as fuel type and prices, regulations in force, heat load and system capacity, heat generation and transmission efficiency and others [15]. In addition, when evaluating economic and environmental efficiency of DH plants, governmental decision making, market structure, and managerial performance indicators are included [9].

Type of fuel consumed is a significant indicator that is incorporated in DH benchmark setting studies. The share of renewable energy resources (RES) used in DH systems measure the overall sustainability of the existing DH since it strongly affects the amount of greenhouse gas emissions produced [10]. Setting an appropriate benchmark allows to group DH companies not only with respect to their heat generation efficiency but by their achievement towards low-carbon system incorporation as well. Therefore, it allows to highlight those DH companies that reflect values below the determined benchmark. As a result, restructuration and system improvement activities might be suggested to move towards more sustainable low-carbon DH operation models [10]. In fact, environmental goals are found to be among the dominant long-term operational targets of DH producers [16] since more sustainable production is encouraged from the side of both the regulatory body and the consumer.

District heating plays a key role in achieving ambitious global climate change mitigation goals [17], [18], therefore it is necessary for the authorities to design instruments and introduce benchmarks that would monitor and stimulate DH providers to reduce their greenhouse gas emissions. Decarbonization of DH providers can be achieved by utilizing more efficient technologies or using less polluting energy sources, therefore moving closer towards fully implementing a renewable, sustainable, carbon-free DH system [19].

Energy efficiency is one of the most significant factors for both reduction of climate change and the DH tariff [20]–[22]. Energy efficiency in DH can be increased by adapting renewable energy resources [23] and by improving technological efficiency of heat generation and distribution networks [24]. Therefore, indicators measuring the performance of DH technical parameters should be incorporated within the DH evaluation benchmark-based models.

In terms of technological parameters, type of heat source (boiler houses or CHP) should be considered when analysing DH performance indicators [10]. Moreover, the technological condition of the boiler houses and CHP strongly affect the generated heat efficiency, therefore, DH benchmarking studies suggest to integrate variables that consider the investments made in the heat source reconstruction activities in the recent years of their operating activity [10]. In fact, it is especially important for the DH infrastructure performance assessment in Eastern Europe where lack of investments in the past indicate that future DH modernization strategies must be implemented for future DH sustainability [22].

The empirical findings by Noussan conclude that the performance and efficiency of DH providers is strongly dependent on the energy source, fuel mix, conversion technologies, as well as on the network losses in the system [25]. Moreover, when analysing technical indicators in more detail, temperature is responsible for a large amount of network losses that have occurred. In order to maximize the efficiency of the DH system, the network losses should be reduced to a minimum. Therefore, low heat supply and return temperature in the heat distribution chain is crucial to increase the energy efficiency of DH networks [26].

Other technology related opportunities are emphasized in a study by Paiho & Saastamoinen [8] as important factors for the long term development of DH system: the implementation of new production means, digitalization of operational processes and services. Diversification of the production means includes the utilization and implementation of solar, ground-source, surplus heat, geothermal energy, and other means that could potentially increase the long term energy efficiency and optimize costs for DH production companies [8].

A novel technological efficiency benchmarking parameter was introduced in the study by Sarma & Bazbauers, [1], which demonstrate that in order to enhance the technological development and advancement in the DH infrastructure, 'best available technology' (BAT) indicators could be used to set a benchmark that would serve as an instrument to monitor the achievements towards higher efficiency of DH companies [1]. By setting the efficiency requirements based on BAT indicators, DH companies could be stimulated and guided towards improving their efficiency [1]. BAT parameters for different DH elements could be used to construct the benchmark indices that would indicate how DH plant's energy efficiency deviates from the energy savings that BAT technologies can offer [27].

Another significant DH performance efficiency parameter is the amount of energy generated. If the total produced energy output increases, the DH system benefits from economies of scale [28] where the total costs per one unit of generated energy decreases [29] and therefore the system operates with higher economic efficiency and could provide a competitive heating tariff to the consumer. The cost optimization that the economies of scale bring to the DH system increases the overall efficiency and competitiveness of DH. Therefore, the mergers of DH companies and the overall expansion of DH business is suggested [30].

The main aim of this particular research is to present a novel methodology for Climate index determination which can be further used for the comparison of DH systems. The Climate index includes seven different indicators which show DH system performance according to energy efficiency, sustainability and environmental impact dimensions. The methodology is elaborated for Latvia, but it can be used in other countries, depending on the availability of data and national priorities in energy supply sector.

2. METHODOLOGY

The main steps for climate benchmark determination can be seen in Fig. 1. The availability of statistical overviews for main DH operators is limited, therefore, it is necessary to combine different data sources. The reviews of environmental statistics (in particular, overview of air protection) coordinated by State limited Liability Company 'Latvian Environment, Geology and Meteorology Centre' are used to determine the fuel consumption for heat production [31]. The produced and consumed heat can be seen in applications from approvals of the heat energy tariff by the Public Utilities Commission (PUC) [32]. The power produced in CHP is obtained from the amounts paid within the framework of mandatory procurement (feed-in tariff) [33], but for the missing information annual reports of companies are used. Authors use the data set from 20 DH companies.

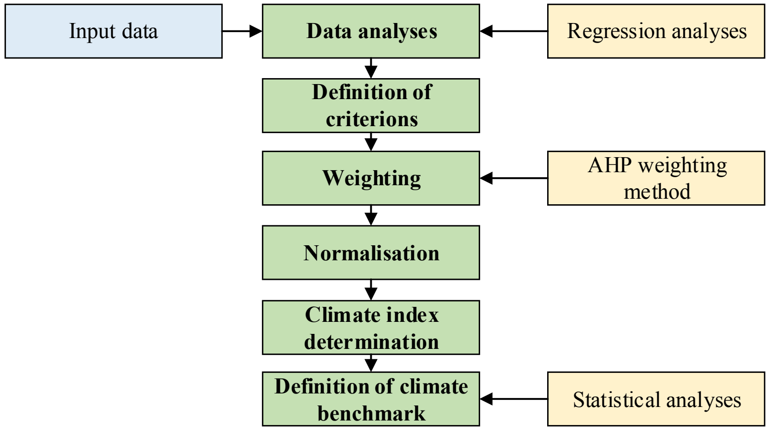

Fig. 1. Main steps and methods for determination of climate benchmark.

After the detailed data assessment, authors define the main criteria for further analyses. Seven different criteria are used (see Fig. 2) for calculation of the Climate index in the particular case study. However, the criteria can be adjusted for country specific conditions. The criteria are grouped within three different categories to have a more comprehensive overview of DH system performance. Some of the selected criteria are interrelated, for example, the total CO_2 emissions and primary energy factor depend on heat losses and share of RES. However, each of chosen criteria show different aspects related to heat generation and transmission operation conditions. The further weighting step allows to take into account the interrelation by applying higher or lower weight score for particular criterion.

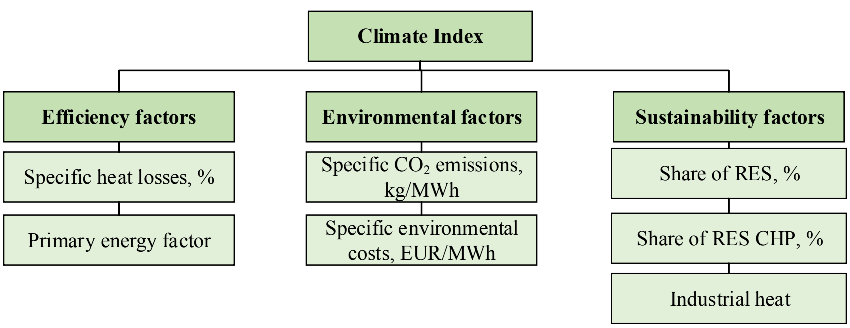

Fig. 2. Criteria merged within the Climate index.

The analysed efficiency factors are the transmission heat losses from the heating network identified as a percentage of total produced heat and the primary energy factor. Primary energy factor (PEF) is an energy indicator used for quantifying the primary energy use of a plant defined according to Eq. (1).

$$PEF = \frac{\sum_j E_j \cdot f_{\mathrm{p},j} - E_{\mathrm{CHP}} \cdot f_{\mathrm{p,el}}}{E_{\mathrm{del}}}, \tag{1}$$

where

E_j the amount of the *j-th* primary energy consumed;
E_{CHP} the amount of electricity produced in the CHP if any is installed;
$f_{\mathrm{p},j}$ the primary energy factor related to an energy source;
$f_{\mathrm{p,el}}$ the primary energy factor for the power plants;
E_{del} the amount of energy delivered to the consumers.

The used primary energy factors can be seen in Table 1. Those are determined as country specific values and highly depends on the national electricity mix. The assumptions can be subject to change for assessment in other countries.

Authors have identified two main environmental factors: the specific CO_2 emissions and the specific environmental costs associated with different external costs related to heat production. The environmental cost factors have been identified according to previous studies [34] (see Table 1).

In addition, sustainability criteria are used to evaluate the used energy production technologies and energy sources. Therefore, authors have 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. It should be noted, that the heat purchased from different energy production utilities is not perceived as heat from an industrial object. The heat from industrial enterprises could be attributed to industrial waste heat and other excess heat sources when such energy sources occur.

TABLE 1. MAIN ASSUMPTIONS FOR CALCULATION OF CRITERIA

Primary energy factors	
Fossil fuels	1.1
Biogas	0.5
Biomass	0.2
Power from the grid	1.5
Environmental costs, EUR/MWh	
CHP Biomass	4.3
CHP Natural gas	11.7
CHP Coal	24.1
CHP Biogas	13.8
HOB Natural gas	17.9
HOB Biomass	11.2
CO_2 emission factors, kg/MWh	
Diesel fuel	267
Natural gas	202
Coal	354

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 is a pairwise comparison matrix, which reflects the relative importance of the criteria [35]. In this case, the evaluation was carried out by a group of experts, but a more comprehensive assessment could be provided by the involvement of various stakeholders in the weighting process. The obtained values of the criteria can be seen in Fig. 3. The highest priority has been determined for specific heat losses and the share of industrial heat.

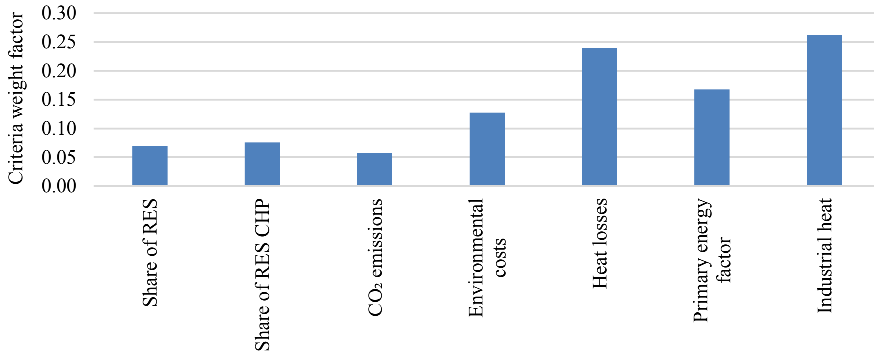

Fig. 3. Obtained weights for each criterion.

The calculated criterion *j* has been normalized by using Weitendorf's linear normalization method [36]. Eq. (2) is used if the optimal indicator value needs to be maximized and Eq. (3) is used if the desirable indicator value is minimal.

$$b_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{2}$$

$$b_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{3}$$

The normalized and weighted values of the criteria are summed to obtain the Climate index for each DH operator. Further, the authors use statistical analyses and the Pareto principle to determine the Climate benchmark for the particular set of DH operators.

3. Results

Authors have analysed the performance of 20 DH operators in 2017 according to the methodology described above. The analysed DH systems differ a lot. The produced amount of annual heat ranges from more than 500 GWh in the capital city of Latvia, Riga to less than 1 GWh in smaller towns. The heat is produced both in heat only boilers (HOB) and CHP by using different energy sources as showed in Fig. 4.

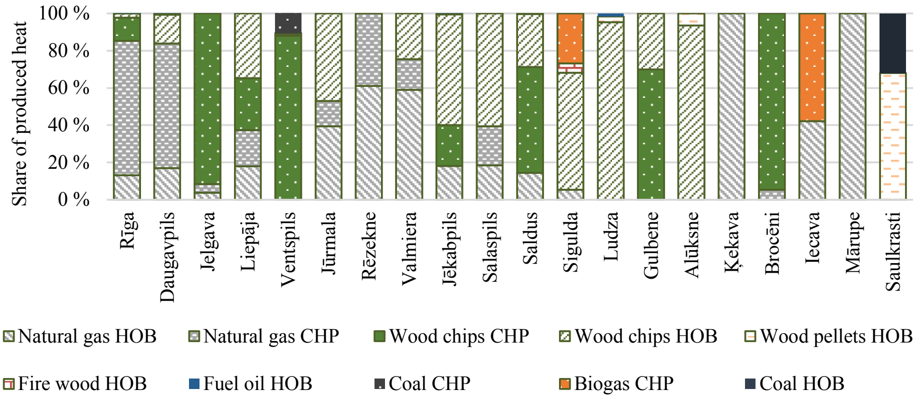

Fig. 4. Heat production technologies and energy sources used in analysed DH systems.

As can be seen in Fig. 4, there are DH systems that are already carbon neutral due to the use of biomass for heat production. However, the principles of sustainable development and biotechnology should be considered and the bio resource should be used efficiently. The heat production from biomass is not always the most sustainable solution.

The data analyses have been performed in order to determine the main impacting factors of the heat tariff. The regression analyses show an insufficient correlation between the determined criteria and final heat tariff which is in line with the conclusions of previous research [12]. The example of regression analyses for produced amount of heat and fuel costs is presented in Fig. 5. Even though the final heat tariff does not show a strong dependence of the total fuel costs (see Fig. 5), the fuel cost share is much higher in the total heat tariff in cases when natural gas is used as the main energy source (see Fig. 6).

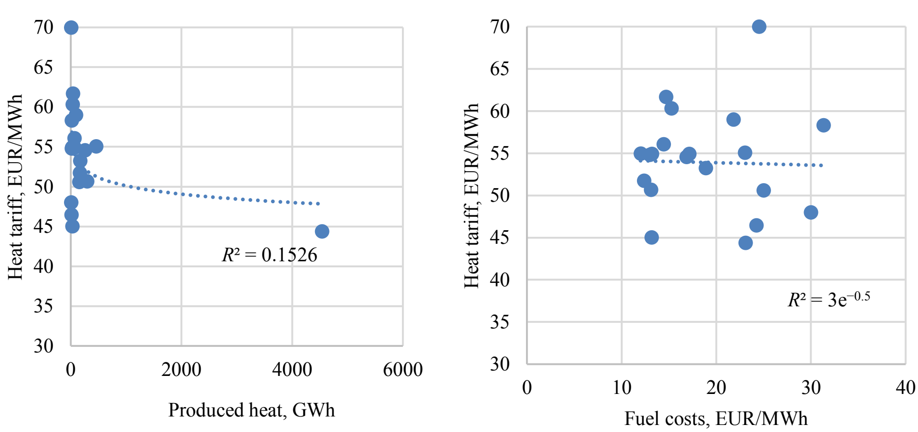

Fig. 5. Regression analyses results for different criteria.

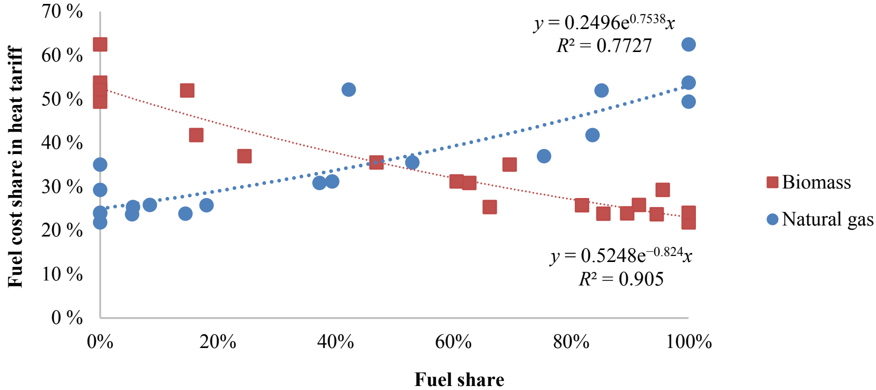

Fig. 6. Fuel cost share in heat tariff dependence on natural gas and biomass share in heat production.

Fig. 6 shows a good correlation between the fuel cost share in heat tariff and total biomass and natural gas share in overall DH energy balance. When biomass is used as an energy source, the fuel cost share decreases and there is an increase in other costs. One of analysed DH systems is further from determined biomass trend line because of use of wood pellets, which is more expensive than other biomass energy sources.

Table 2 shows the overview of normalized values of each criterion for analysed DH systems. The value 1 indicates the best ranked system, but the value 0 the lowest obtained value. As it can be seen, only two DH systems have purchased heat from industrial enterprises.

Fig. 7 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 were the heat is produced by using a biomass CHP technology or the heat is purchased from industrial enterprises. The lowest Climate index values are for DH systems where natural gas is the main energy source for heat production.

TABLE 2. NORMALISED VALUES OF OBTAINED VALUES OF CRITERIA

DH location	RES	RES CHP	CO_2 emissions	Environmental costs	Heat losses	PEF	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
Brocēni	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

For the particular analyses, 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. In order 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. Further methodology could be developed for the use of Climate index as one of criteria for heat tariff determination. Thus, the DH Companies with lowest Climate index values would be forced to move toward more sustainable heat production technologies.

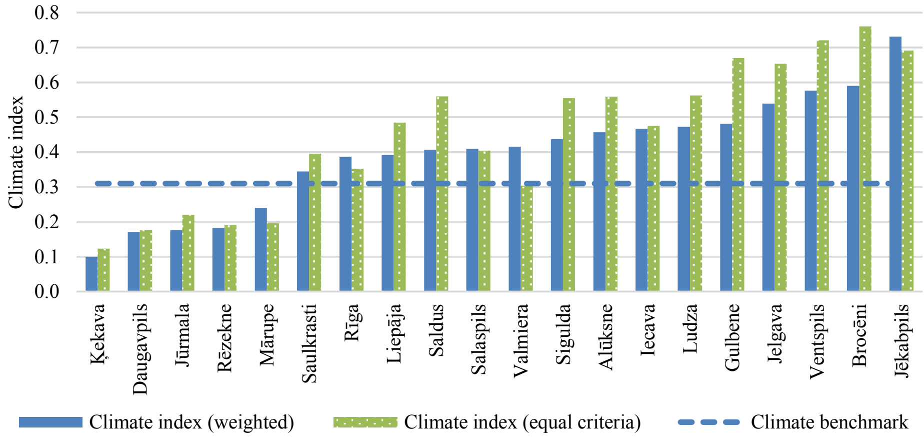

Fig. 7. Results of ranked Climate index values and obtained climate benchmark.

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

4. Conclusion

The Climate index has been introduced as a common indicator to evaluate the performance of DH system efficiency, environmental impact and sustainability. Seven different 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 criteria are prioritized and weighted according to the AHP method.

The method is applied for 20 different DH operators. The obtained Climate index values for 15 DH Companies are above the estimated benchmark for this particular study. Five DH systems were below the determined benchmark due to use of natural gas as the main energy source.

The use of a Climate index could improve the competition among DH operators and promote moving toward more sustainable solutions. The determined Climate index could be a criterion for the heat tariff calculation. DH Companies with highest Climate index could be allowed to have a higher profit share or easier heat tariff approval process.

The methodology can be adjusted and applied for different countries by including other criteria for evaluation. The national heat production objectives can be included through criteria weighting (e.g., lowering of transmission heat losses, integration of waste heat etc.).

Further analyses could include comparison of annual changes of Climate index values, as there are important improvements in DH system operation in recent years. Currently, the collection of necessary input data for Climate index calculations is time consuming. Therefore, the improvements in statistical data availability should be ensured in order to facilitate the calculation of the Climate index.

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References

[1] Sarma U., Bazbauers G. Algorithm for calculation of district heating tariff benchmark. *Energy Procedia* 2017:128:445–452. https://doi.org/10.1016/j.egypro.2017.09.029

[2] Munksgaard J., Pade L. L., Fristrup P. Efficiency gains in Danish district heating. Is there anything to learn from benchmarking? *Energy Policy* 2005:33(15):1986–1997. https://doi.org/10.1016/j.enpol.2004.03.019

[3] Comnes L. J., Stoft G.A., Greene S., Hill N. Performance-Based Ratemaking for Electric Utilities: Review of Plans and Analysis of Economic and Resource- Planning Issues Volume I. LBNL, Berkeley, 1995. [Online]. [Accessed 31.03.2020]. Available: https://emp.lbl.gov/publications/performance-based-ratemaking-electric

[4] Bogetoft P. Incentive Efficient Production Frontiers: An Agency Perspective on DEA. *Managing Science* 1994:40(8):959–968. https://doi.org/10.1287/mnsc.40.8.959

[5] Magnusson D. Who brings the heat? – From municipal to diversified ownership in the Swedish district heating market post-liberalization. *Energy Research & Social Science* 2016:22:198–209. https://doi.org/10.1016/j.erss.2016.10.004

[6] Toke D., Fragaki A. Do liberalised electricity markets help or hinder CHP and district heating? The case of the UK. *Energy Policy* 2008:36(4):1448–1456. https://doi.org/10.1016/j.enpol.2007.12.021

[7] Tsybina E., Moreno-Cruz J., Tereshin A. Liberalisation lowers primary energy efficiency: Evidence from twin power systems. *Energy* 2019:173:423–435. https://doi.org/10.1016/j.energy.2019.02.004

[8] Paiho S., Saastamoinen H. How to develop district heating in Finland? *Energy Policy* 2018:122:668–676. https://doi.org/10.1016/j.enpol.2018.08.025

[9] Agrell P. J., Bogetoft P. Economic and environmental efficiencey of district heating plants. *Energy Policy* 2005:33(10):1351–1362. https://doi.org/10.1016/j.enpol.2003.12.011

[10] Ziemele J., Vigants G., Vitolins V., Blumberga D., Veidenbergs I. District heating systems performance analyses. Heat energy tariff. *Environmental and Climate Technologies* 2014:13(1):32–43. https://doi.org/10.2478/rtuect-2014-0005

[11] Marques R. C., Simões P., Pires J. S. Performance benchmarking in utility regulation: The worldwide experience. *Polish Journal of Environmental Studies* 2011:20:125–132.

[12] Sarma U., Bazbauers G. District Heating Tariff Component Analysis for Tariff Benchmarking Model. *Energy Procedia* 2017:113:104–110. https://doi.org/10.1016/j.egypro.2017.04.029

[13] Jamasb T., Pollitt M. International benchmarking and regulation: An application to European electricity distribution utilities. *Energy Policy* 2003:31(15):1609–1622. https://doi.org/10.1016/S0301-4215(02)00226-4

[14] Hrovatin N., Zorić J. International Benchmarking of Electricity Tariffs. Enterp. Transit. Int. Conf. Proc. 2005:15:83–98. [Online]. [Accessed 31.03.2020]. Available: http://www.eskom.co.za/CustomerCare/MYPD3/Documents/International_Tariff_Benchmarking_Report_270512.pdf

[15] Sarma U., Bazbauers G. District Heating Regulation: Parameters for the Benchmarking Model. *Energy Procedia* 2016:95:401–407. https://doi.org/10.1016/j.egypro.2016.09.046

[16] Åberg M., Fälting L., Forssell A. Is Swedish district heating operating on an integrated market? - Differences in pricing, price convergence, and marketing strategy between public and private district heating companies. *Energy Policy* 2016:90:222–232. https://doi.org/10.1016/j.enpol.2015.12.030

[17] Connolly D. *et al.* Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. *Energy Policy* 2014:65:475–489. https://doi.org/10.1016/j.enpol.2013.10.035

[18] Büchele R., Kranzl L., Hummel M. What is the impact of the policy framework on the future of district heating in Eastern European countries? The case of Brasov. *Energy Strategy Reviews* 2018:19:72–75. https://doi.org/10.1016/j.esr.2017.12.003

[19] Hast A., Syri S., Lekavičius V., & Galinis A. District heating in cities as a part of low-carbon energy system. *Energy* 2018:152:627–639. https://doi.org/10.1016/j.energy.2018.03.156

[20] Difs K., Trygg L. Pricing district heating by marginal cost. *Energy Policy* 2009:37(2):606–616. https://doi.org/10.1016/j.enpol.2008.10.003

[21] Stennikov V., Penkovskii A. The pricing methods on the monopoly district heating market. *Energy Reports* 2020:6(S2):187–193. https://doi.org/10.1016/j.egyr.2019.11.061

[22] Poputoaia D., Bouzarovski S. Regulating district heating in Romania: Legislative challenges and energy efficiency barriers. *Energy Policy* 2010:38(7):3820–3829. https://doi.org/10.1016/j.enpol.2010.03.002

[23] Ristimäki M., Säynäjoki A., Heinonen J., Junnila S. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy* 2013:63:168–179. https://doi.org/10.1016/j.energy.2013.10.030

[24] Dalla Rosa A., Christensen J. E. Low-energy district heating in energy-efficient building areas. *Energy* 2011:36(12):6890–6899. https://doi.org/10.1016/j.energy.2011.10.001

[25] Noussan M. Performance indicators of District Heating Systems in Italy – Insights from a data analysis. *Applied Thermal Engineering* 2018:134:194–202. https://doi.org/10.1016/j.applthermaleng.2018.01.125

[26] Gong M., Werner S. An assessment of district heating research in China. *Renewable Energy* 2015:84:97–105. https://doi.org/10.1016/j.renene.2015.05.061

[27] Badami M., Gerboni R., A. Portoraro. Determination and assessment of indices for the energy performance of district heating with cogeneration plants. *Energy* 2017:127:697–703. https://doi.org/10.1016/j.energy.2017.03.136

[28] Grundahl L., Nielsen S., Lund H., Möller B. Comparison of district heating expansion potential based on consumer-economy or socio-economy. *Energy* 2016:115(P3):1771–1778. https://doi.org/10.1016/j.energy.2016.05.094

[29] Wang Z. Heat pumps with district heating for the UK's domestic heating: Individual versus district level. *Energy Procedia* 2018:149:354–362. https://doi.org/10.1016/j.egypro.2018.08.199

[30] Park S. Y., Lee K. S., Yoo S. H. Economies of scale in the Korean district heating system: A variable cost function approach. *Energy Policy* 2016:88:197–203. https://doi.org/10.1016/j.enpol.2015.10.026

[31] Latvian Environment, Geology and Meteorology Centre database on environmental pollution [Online]. [Accessed 31.03.2020]. Available: https://www.meteo.lv/lapas/vide/parskatu-ievadisana/parskatu-ievadisana?id=1039&nid=376

[32] The Public Utilities Commission (PUC) or the Regulator. Approved energy tariffs [Online]. [Accessed 31.03.2020]. Available: https://www.sprk.gov.lv/index.php/content/iesniegtie-tarifu-projekti

[33] Ministry of Economics. Information on issued decisions on mandatory electricity procurement. [Online]. [Accessed 31.03.2020]. Available: https://em.gov.lv/lv/nozares_politika/atjaunojama_energija_un_kogeneracija/informacija_par_izdotajiem_lemumiem_par_elektroenergijas_obligato_iepirkumu/

[34] Alberici S., Boeve S., Breevoort P. et.al. Subsidies and costs of EU energy. An interim report, 2014. [Online]. [Accessed 31.03.2020]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/ECOFYS%202014%20Subsidies%20and%20costs%20of%20EU%20energy_11_Nov.pdf

[35] Dynova L., Sevastjanov P., Tikhonenko A. A direct Interval Extension of TOPSIS Method. *Expert Systems with Applications* 2013:40(12):4841–4847. https://doi.org/10.1016/j.eswa.2013.02.022

[36] Turski F., Edmundas Z., Peldschus K. Multi-criteria Optimization System for Decision Making in Construction Design and Management. *Engineering Economics* 2009:1(61):7–17.

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OPTIMIZING LARGE-SCALE SOLAR FIELD EFFICIENCY: LATVIA CASE STUDY

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Optimizing Large-Scale Solar Field Efficiency: Latvia Case Study

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Abstract: Solar energy transformation technologies are increasingly being used worldwide in the district heating sector. In the Baltic states, only one district heating company has implemented a large-scale solar collector field into its thermal energy production system, which is analyzed within this research. In this study, we analyzed the first year operation of the solar field, solar collector efficiency, and several influencing factors, i.e., ambient air temperature, heat carrier flow, and the temperature difference between the supply and return heat carrier temperatures. The study includes collecting and compilation of the data, analyzing influencing factors, and data analysis using the statistical analysis method. In addition, the research presents a simplified multi-regression model based on the actual performance of a large-scale solar field, which allows for forecasting the efficiency of solar collectors by taking into account the main operational parameters of the DH system. The results show that solar energy covers around 90% of the summer heat load of a particular district heating system. However, they also show room for improvements in producing all the necessary heat in the summer using solar energy. The regression analyses show that the most significant correlation between all parameters examined was obtained in May, reaching R^2 = 0.9346 in solar field efficiency evaluation. This is due to several suitable conditions for solar energy production, i.e., placing solar collectors at an angle for them to be the most productive, having enough space in the storage tank, and the demand for thermal energy being still higher than in the summer months.

Keywords: large-scale solar collector field efficiency; solar district heating; solar collector field efficiency

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1. Introduction

In the energy sector, renewable energy sources have played an increasingly important role in recent years, including solar collectors. Since 1980, the price of solar collectors has fallen and has become more affordable. Moreover, the efficiency has increased significantly due to an improved control system, the availability of more energy-efficient pumps, and improvements to other components [1]. All district heating systems aim to have less impact on the environment as possible.

According to the latest data, in Europe, 70% of solar collector systems use flat collectors [2]. Improving the efficiency of solar collector systems requires laboratory and on-site testing. Several experimental case studies have examined the influencing factors for flat solar collectors' efficiency, namely solar radiation, temperature difference, and angle of the collector position. Maximum efficiency may be achieved under several fulfilled conditions, but it can also fall sharply after reaching it. Studies have also analyzed wind speed as another such influencing factor: The efficiency of a flat solar collector is reduced when wind velocity increases because the collector surface is cooled [3–5].

There are two types of solar district heating systems: standalone systems with storage and combined systems [6,7]. Before integrating a solar collector system into district heating (DH), it is crucial to consider the influencing factors to determine whether they are appropriate for the integration. For example, low return temperatures are essential when considering the 4th generation DH system [8]. The usual temperature regime in district heating networks is 90/60 °C, but typical low-temperature DH operates with heat supply temperatures of 40 to 60 °C [9].

The accumulation system is a crucial element in the solar collector system to produce more heat during peak hour when solar irradiation is highest [10]. An adjusted thermal storage tank allows the solar system to work effectively and can integrate the solar field into the overall DH systems.

2. Literature Review

Solar thermal technologies are becoming more and more popular solutions for DH. This observation is based on the fact that the maintenance costs are comparably low, loans for implementing such technologies are beneficial, and the technologies allow climate goals to be achieved and are sustainable [11]. The only costs incurred during operation are the electricity costs for circulation pumps that circulate the heat carrier. Other maintenance costs are related to the following:

- Glycol filler: Glycol impurity ensures that the heat carrier does not freeze during the low ambient air temperature. In most cases, the outdoor temperature at which the heat carrier can still work properly is −10 °C.
- Replacement of damaged equipment, for example, the temperature sensors or solar collector glass covers.

The abovementioned categories are the main reasons that can raise the annual maintenance costs, but those costs are still comparably low when considering other alternatives, for example, fossil fuel or biomass boilers. Moreover, the effectiveness of solar collectors is decreasing very slowly, i.e., only by a few percent per decade, and so the technology is sustainable and can be used for a long time.

There are few designs of the collectors which are chosen that demand temperature level requirements. For example, the most commonly used design in DH is flat plate collectors (FPC), but those are mainly used to produce heat with temperatures up to 80 °C. However, heat production with higher temperatures reduces the collectors' efficiency due to increased thermal losses [12]. Therefore, when higher temperatures are required, evacuated tube collectors (ETC) are mainly installed, but parabolic trough collectors (PTC) are used to reach even higher temperatures (70 to 150 °C) [11]. Recent publications have also explored how to use nanofluids to improve the field efficiency of solar collectors [13]. However, such solutions are not yet extensively used.

The latest trends show that large-scale solar collector fields have been installed during the last decade [11]. For example, the solar collector field installed in Silkeborg, Denmark, reaches 156,694 m^2. This tendency is becoming more popular because of the need to ensure renewable energy throughout the year. At the same time, it makes it necessary to integrate effective heat storage systems to store a significant amount of energy throughout the summer season, which can later be used in the autumn. Therefore, it is possible to avoid using other technologies, such as biomass or natural gas boilers. As a result, the higher solar fraction and share of emission-free technologies can be reached.

Most of the studies related to solar heating system optimization are simulation-based studies seeking optimal system design [12,13]. Several studies use technological design and operational data from one of the first large-scale solar DH systems at the Drake Landing Solar Community in Okotoks, Canada [14,15]. One such study was conducted by Saloux and Candanedo [16], who analyzed the potential improvements of this system and used model-based simulation to optimize the operation of circulation pumps and increase storage system efficiency.

Bava et al. [17] developed a simulation model to calculate flow distribution in a solar collector field. The obtained results were compared with the data from the solar collector field near Høje Taastrup, Denmark. The authors simulated the main hydraulic parameters (the pressure drop, flow rate, inlet, and outlet temperatures) to confirm whether uniform flow distribution in the solar field can be achieved. A further study from Bava and Furbo [18] investigated the effect of different improvement measures on the thermal performance of the Høje Taastrup solar DH field based on a TRNSYS–MATLAB simulation. The authors concluded that accurate inputs to the control strategy can increase the yearly solar yield by 3%. It is necessary to perform more accurate solar irradiance measures, while taking into consideration the temperature drop in heat exchangers and the efficiency drop due to the incidence angle modifications to improve the control strategy.

Tschopp et al. [19] presented an in-depth overview of large-scale solar DH systems in four countries (Denmark, China, Germany, and Austria), focusing on the DH market and different technological solutions. The authors investigated the operation of each country's best practice solar DH systems by analyzing monthly produced solar heat and efficiency. The study's main aim was to investigate the most appropriate business models and support policies, without focusing on the actual performance of the large-scale solar systems.

However, several researchers have investigated the actual operation of large-scale solar DH systems. Noussan et al. [20] performed the hourly data analyses of the performance of eight different solar fields in Denmark. The authors investigated the solar field efficiency on a monthly and hourly basis and found the linear relation between solar field efficiency and solar radiation. The authors concluded that further investigation is necessary to analyze different affecting parameters of solar field performance.

Furbo et al. [21] compared the measured and calculated performance of different solar fields in Denmark based on diverse weather conditions in six different regions. The authors investigated the solar fields' actual annual solar yield and calculated different efficiency rates (kWh/m^2) by assuming different mean solar collector fluid temperatures.

However, there is still a lack of studies that analyze the actual performance of large-scale solar fields integrated into the DH by considering the various conditions of the heating network.

3. Aim and Scope of the Study

The main aim of this particular article is to find the factors influencing a large-scale solar collector field and to find ways to improve its efficiency. The research focuses on the evaluation under Baltic climate conditions, which have not been analyzed previously. In addition, there is a lack of research based on actual operating conditions of solar fields, as most studies investigate the experimental systems. Therefore, the monitoring data analyses bring an added value to the evaluation of solar DH system performance. Previous studies have analyzed factors that influence the productivity of the solar collector field—for instance, solar radiation, heat carrier supply, return temperatures, and the ambient air temperature was examined in [19]. Since it is impossible to influence solar radiation, the main goal here is to approach which factors can be managed by the solar collector field operators and how this can be done, with the intention to optimize the solar heat production.

The data analyses show the main bottlenecks that should be considered in the solar DH system operational strategy. Furthermore, the obtained multi-regression equation allows for forecasting the solar field efficiency in a simplified manner, which is crucial in the preliminary investigation of the solar system integration. The multi-regression analysis has not been previously applied in the case of a large-scale solar DH system investigation.

The article consists of four main sections, i.e., literature review, methodology, results, and conclusions. First, Section 2 with the literature review presents the state-of-the-art for solar energy use and the main aspects of solar DH systems. It is followed by the methodology in Section 4, which describes the main steps of the research and has several subsections: case study, weather conditions in Latvia, data processing, and multiple regression analyses. Next, Section 5 shows the main results regarding booth data analyses and multiple regression analyses, and finally, the main findings are summarized in the Conclusions section in Section 6.

4. Methodology

This study examines and analyzes the influencing factors of the large-scale solar collector field in the Baltic region, Latvia. Different research methods have been used in previous evaluations related to the use of solar energy, for example, transient system simulations [12], multi-criteria analyses for decision-making [14], and system dynamics modeling [15]. However, the statistical analyses and regression analyses method was chosen here because accurate data on solar field operation are available. The use of regression analyses clearly shows the influencing factors that should be optimized in order to reach higher efficiency of the solar field.

The study is divided into 3 parts: the first part is data collection and compilation, the second part is the analysis of influencing factors, and the third part is multi-regression analyses. The statistical data analysis was performed by using Statgraphics 19-X64 software. The steps are summarized in the diagram (Figure 1).

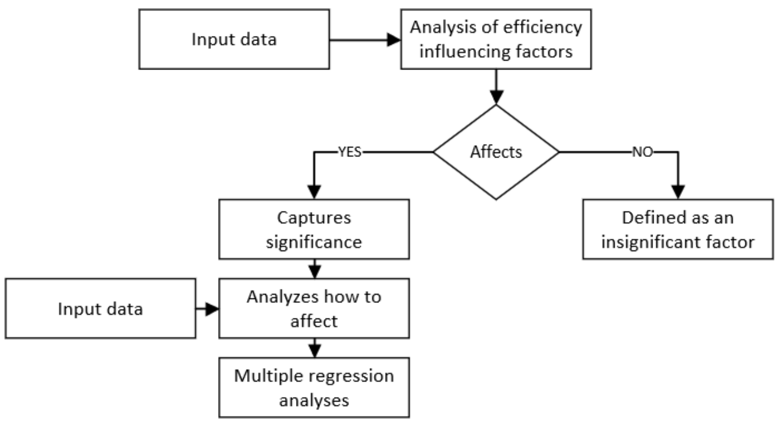


Figure 1. Algorithm of methodology.

In this research, 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 flow rate. These factors were chosen based on the analyzed results from previous studies of laboratory experiments and simulations. Other factors such as wind speed and the effect of solar collector angle were not included in the detailed assessment because these factors cannot be directly influenced by the DH company, as the system is already operating. Furthermore, the solar collector field is stationary, not equipped with a tracking system, and the placing angle is fixed, since it was calculated according to the geographical location of Latvia. These last two mentioned factors should be considered if the solar collector field were at the design stage.

4.1. Case Study

The study analyzed the solar collector field in a DH company in Salaspils, Latvia. The solar collector field with a storage tank was integrated into the existing system in the autumn of 2019. Therefore, the study analyzed the summer period of 2020.

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, 10, and 3 MW) for peak load coverage. The active area of the solar collector field is 21,672 m^2, and the total volume of the thermal energy storage tank is 8000 m^3. The overall heat production scheme is shown in Figure 2. The main technical parameters of the solar field and DH system is summarized in Table 1.

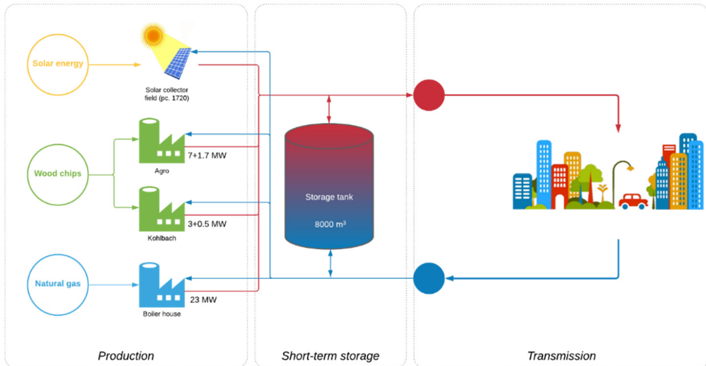


Figure 2. Case study scheme.

Table 1. Overview of main solar system parameters.

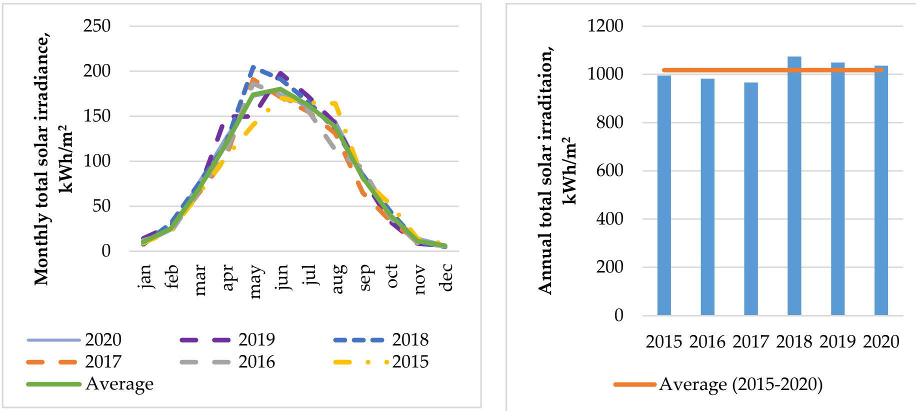
Parameter	Value
Heat network temperature regime	90/60 °C
Total active area of solar field	21,672 m^2
Number of installed solar collectors	1720
Collector brand	Arcon-Sunmark A/S HT-Heat Boost 35/10
Operational temperature regime of the solar field	45/63 °C
The volume of the thermal storage tank	8000 m^3
Absorber efficiency	83%
Gross efficiency	77%

4.2. Weather Conditions in Latvia

The Baltic Sea surrounds Latvia; the border of Latvia is 1878 km long, with approximately 26.5% of which is a sea border. Consequently, there is a sea climate in a large part of Latvia, meaning the region experiences a smaller temperature amplitude throughout the year and more humid air. Based on information on the national meteorological database [22], the following climatic conditions were observed in Latvia:

- Average ambient air temperature: 8.2 °C in 2019 and 8.8 °C in 2020;
- Highest ambient air temperature: 33 °C in 2019 and 30.8 °C in 2020;
- Lowest ambient air temperature: −23 °C in 2019 and −10.3 °C in 2020;
- Approximately 120 days with rainfall annually.

Several weather characteristics influence solar collector performance, such as solar radiation, the time when the sun shines, and the wind speed. Solar radiation intensity in Latvia is equal throughout the entire territory. However, it is most intense in the southern part of the country. The average annual solar radiation in Latvia is around 1000–1100 kWh/m^2 per year, which means that the sun shines approximately 1700 to 1900 h per year. Figure 3a shows the monthly total solar radiation distribution during the year. On average, the maximal solar monthly radiation is reached in May (173 kWh/m^2) and is minimal in December, i.e., only 7 kWh/m^2.



(**a**) (**b**)

Figure 3. Comparison of monthly total solar radiation (**a**) and annual total solar radiation (**b**) in Riga from 2015 to 2020 [22].

The annual total solar radiance (Figure 3b) is an average of 1017 kWh/m^2 in Riga. However, it differs from the yearly conditions. For example, the maximal annual total solar radiance was reached in 2018 (1074 kWh/m^2), but the lowest value was in 2017 (966 kWh/m^2).

The weather characteristics in Latvia cause considerable difficulties in planning the energy production rates and heat demand. The tendency of last few years shows that weather in Latvia is unpredictable. For example, in 2020, the highest ambient air temperature was 30.8 °C, but in 2021 the temperature has already reached 37 °C in some locations in Latvia; in 2020 the lowest ambient air temperature was −10.3 °C, but in 2021 it reached −31 °C. Therefore, the DH operators and heat producers should be ready for the different scenarios so that they can plan the necessary heat capacities, adapt to these temperature differences without putting equipment at risk, and prevent the damage caused by weather.

4.3. Data Processing

In this study, the efficiency of solar collectors was analyzed during the active production season, i.e., April, May, June, July, and August in 2020. In this particular system, the solar field starts to produce a valuable amount of thermal energy when solar radiation reaches at least 300 W/m^2. Consequently, to determine more precisely the effectiveness of solar collectors, the values from this mark were taken into account when calculating daily average solar radiation. When solar radiation is lower, the field of collectors is in the pre-heating phase, which is not considered. The time when solar radiation reaches 300 W/m^2 is variable during the season. For example, on sunny days in April, it can be up to 9 h, while up to 11 h in July. The solar collector field is equipped with several heat meters. The data are transformed according to Equation (1) to make it possible to compare the data with observed solar radiation:

$$P_{prod} = \left(Q_{prod} \times 10^6\right) / (S \times t) \quad (1)$$

where P_{prod} is the produced thermal energy by 1 m^2 solar collectors of the specific day (in W/m^2); Q_{prod} is the total produced thermal energy with solar collectors of the specific day (in MWh); S is the total active area of the solar collectors (in m^2); and t is the time when solar radiation has reached at least 300 W/m^2 (in h).

In this study, solar collector field efficiency is calculated according to Equation (2).

$$E = P_{rad}/P_{prod}\ 100\% \quad (2)$$

where E is the efficiency of solar collectors (in %) and P_{rad} is the average solar radiation to 1 m^2 of the surface of the specific day (in W/m^2).

Annual solar radiation is an absolute value that can be converted into thermal energy. Solar collector efficiency varies from approximately 17 to 77%. It is clear that solar collector efficiency and heat production depend on solar radiation, but solar radiation cannot be controlled, and thus this study further looks at how other DH operational parameters influence solar collector efficiency.

In the particular solar DH system, thermal energy production from solar energy is separated into two sides—primary and secondary. On the primary side, the heat carrier is circulated through solar collectors, from which it removes thermal energy. The primary and secondary side is connected through the heat exchanger. On the secondary side, heat is transferred to the accumulation tank, where thermal energy is stored until it is demanded.

The first analyzed parameter is the heat carrier flow in the primary side (primary flow). Specifically, we analyzed how the changes in primary flow impact solar collectors' efficiency. An increased flow rate reduces the amount of produced thermal energy, and vice versa. This parameter is increased under several conditions:

1. Solar energy production needs to be reduced due to thermal energy storage limitations. This mainly occurs when there is a significant amount of thermal energy in the accumulation tank and when weather forecasts expect high solar irradiation in the following days.
2. In early spring and late autumn, solar collectors cannot reach a temperature equal to the heating network supply temperature in the DH system. However, to remove the load from the other heat sources and not to use other energy resources unnecessarily, heat energy is removed from the solar collectors, and the heat carrier is heated as high as possible.
3. The flow has been reversed in two cases, namely (a) if the accumulation tank has to be cooled down in periods of high solar irradiation and low heat demand, and (b) when the ambient air temperature is low in the winter, and the solar collector field must be heated to prevent the system from freezing.

Another related parameter is the temperature difference between the return and supply temperatures on the primary side. Boilerhouse operators can manage the temperature of the heat carrier and can remove thermal energy from the primary side. One possibility of reducing or improving those parameters is by managing how much flow reaches the heat exchanger. The regulation strategy of the heat carrier's return temperature on the primary side is similar to the primary flow regulation described above.

The third analyzed parameter is the ambient air temperature. In Latvia, the daily average ambient air temperature can change even two or more times from day to day, so we considered this parameter important for further study.

4.4. Multiple Regression Analyses

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

5. Results

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 Figure 4. It is therefore essential to investigate whether there is room for improvement.

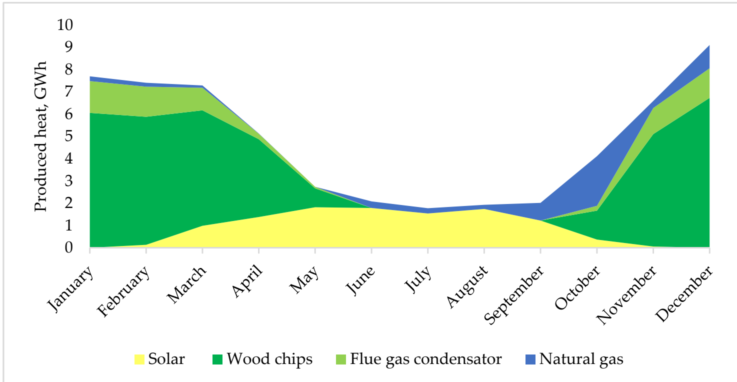


Figure 4. Produced heat by used fuel in 2020.

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 are evaluated separately. The considered factors were return temperature, flow rate, supply, and return temperature difference, and ambient temperature.

We first assessed how the primary flow changes the efficiency of the solar collector field. The obtained results show that the higher the flow, the higher the efficiency. The obtained results of the regression analyses are summarized in Figure 5.

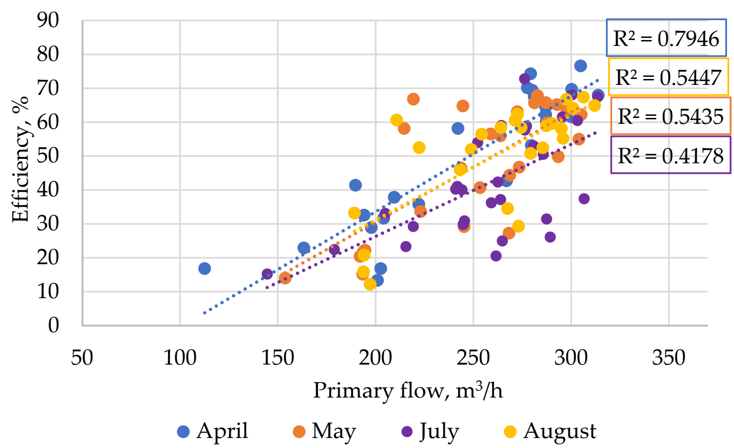


Figure 5. Correlation of heat carries primary flow rate and solar field efficiency.

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 analyzed 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, there is still space heating necessary. The efficiency is reduced when there are many sunny days and no demand is forecasted, and the storage tank is full. 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 analyses show that it was possible to reach higher solar efficiency with a lower flow rate in 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 are shown in Figure 6.

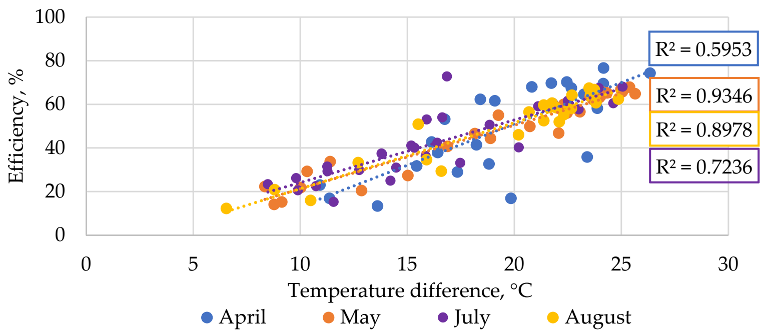


Figure 6. Solar collector efficiency dependency on temperature difference.

Results show that the higher the temperature difference, the higher 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, a lower dependence on the temperature difference was identified. This clearly shows that quantitative heating network regulation occurs in the spring, while qualitative regulation occurs in the summer. Results show that further optimization could be performed to choose the suitable heating network regulation mechanism by seeking the equilibrium between 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 to +12.1 °C. From the Figure 6. it can be seen 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 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 is in May (R^2 = 0.93) because the solar radiation was stable, and the settings of the solar field were not changed.

The third factor analyzed is the effect of ambient air temperature changes on the solar field efficiency (Figure 7).

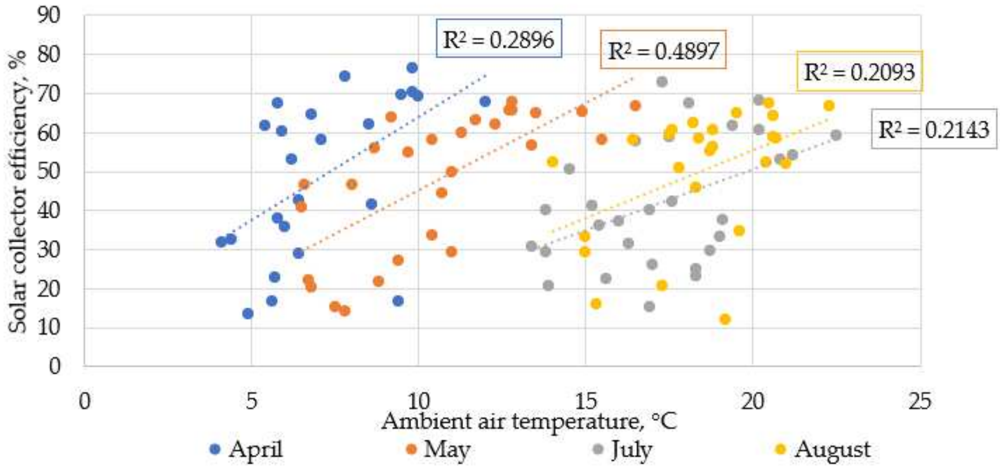


Figure 7. Solar collector efficiency dependency on ambient air temperature.

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 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 analyzed 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:

$$\mathrm{E} = -31,617 + 0.135 \times \mathrm{w}_1 + 2.32794 \times \Delta\mathrm{t} + 0.091657\ \mathrm{t}_\mathrm{a} \tag{3}$$

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 solar field performance and forecast 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 Figure 8.

This table shows Pearson product–moment correlations between each pair of variables. These correlation coefficients range between −1 and + 1 and measures 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 efficiency and temperature difference, with a correlation coefficient of 0.88. The weakest correlation is between efficiency and ambient air temperature. However, ambient air temperature also affects the flow.

Figure 8. Correlation plot.

6. Conclusions

The article presented an in-depth investigation of the operational data of the first large-scale solar collector field installed in the Baltic states. The solar collector efficiency dependence on primary heat carrier flow, the temperature difference between return and flow heat carrier temperatures, and the ambient air temperature were all analyzed.

The strongest correlation of solar collector efficiency was observed for the temperature difference between the return and flow temperatures of the heat carrier on the primary side. In addition, a significantly high regression coefficient was observed in May ($R^2 = 0.9346$). Therefore, the obtained data analyses show that it was possible to reach higher solar efficiency with a lower flow rate in some days, and further investigation could focus on optimizing primary flow to reduce the power consumption of the circulation pumps.

The obtained multi-regression equation shows the relationship between solar field efficiency and main DH operational parameters. Therefore, the obtained equation could be used in the simplified investigations to determine solar field efficiency by considering the affecting parameters of specific DH systems. It can also be used as an input in different optimization models in order to increase the solar field output under different conditions.

Given that the collector field was set up over 6.5 hectares, the solar radiation is not equal for every collector. This particular field has 4 solar radiation meters, which is sufficient for managing the collector field optimally. However, to increase efficiency, it would be necessary to equip the solar collector field with even more solar radiation meters to increase the average radiation value more appropriately to the situation. Thus, the flow rates would be better adjusted, and this would further increase the efficiency of the solar field.

The results show that a solar collector's field efficiency is significantly affected by the heat load due to operational parameters. The efficiency increases in the heating season but decreases if the DH system only provides hot water in the summer period. We found that there was a period in the summer when the overall efficiency could be increased by increasing thermal storage capacity. In the summer, demand was low, and the thermal energy storage tank was overloaded, which led to the need to cool the storage tank down by reversing the flows of the heat carrier at night. As follow up, there can be studies to further investigate the economic optimization of solar heat accumulation systems. Future studies can focus on the in-depth simulation of the thermal storage system to evaluate the possible improvements and the economic justification of the solar DH system.

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References

1. Schweiger, H.; Farinha Mendes, J.; Carvalho Ma, J.; Hennecke, K.; Krüger, D. Solar Heat for Industrial Processes. In *Advances in Solar Energy*; Routledge: London, UK, 2007; Volume 17, p. 45.
2. Weiss, W. Spörk-D Global market development and trends in 2019. *Sci. Technol. Built Environ.* **2019**, *24*, 819.
3. Singh, S.; Kumar, A.; Yadav, A. Experimental Investigation of Thermal Performance Evaluation of Solar Flat Plate Collector. *Mater. Today Proc.* **2020**, *24*, 1533–1540. [CrossRef]
4. Zhou, L.; Wanga, Y.; Huang, Q. Parametric analysis on the performance of flat plate collector with transparent insulation material. *Energy* **2019**, *174*, 534–542. [CrossRef]
5. Wojcicki, D.J. The application of the Typical Day Concept in flat plate solar collector models. *Renew. Sustain. Energy Rev.* **2015**, *49*, 968–974. [CrossRef]
6. Lund, H.; Werner, S.; Wiltshire, R.; Svendsen, S.; Thorsen, J.E.; Hvelplund, F.; Mathiesen, B.V. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. *Energy* **2014**, *68*, 1–11. [CrossRef]
7. Pauschingers, T. *Solar Thermal Energy for District Heating, Advanced District Heating and Cooling (DHC) Systems*; Woodhead Publishing Series in Energy: Amsterdam, The Netherlands, 2019.
8. Li, H.; Nord, N. Transition to the 4th generation district heating—Possibilities, bottlenecks, and challenges. *Energy Procedia* **2018**, *149*, 483–498. [CrossRef]
9. Schmidt, D.; Kallert, A. *Future Low Temperature District Heating Design Guidebook. Final report of IEA DHC Annex TS1 Low Temperature District Heating for Future Energy Systems*; International Energy Agency: Paris, France, 2017.
10. Soloha, R.; Pakere, I.; Blumberga, D. Solar energy use in district heating systems A case study in Latvia. *Energy* **2017**, *137*, 586–594. [CrossRef]
11. Said, Z.; Hachicha, A.A.; Aberoumand, S.; Yousef, B.A.A.; Sayed, E.T.; Bellos, E. Recent advances on nanofluids for low to medium temperature solar collectors: Energy, exergy, economic analysis and environmental impact. *Prog. Energy Combust. Sci.* **2021**, *84*, 100898. [CrossRef]

12. Maximov, S.A.; Mehmood, S.; Friedrich, D. Multi-objective optimisation of a solar district heating network with seasonal storage for conditions in cities of southern Chile. *Sustain. Cities Soc.* **2021**, *73*, 103087. [CrossRef]
13. Mäki, E.; Kannari, L.; Hannula, I.; Shemeikka, J. Decarbonization of a district heating system with a combination of solar heat and bioenergy: A techno-economic case study in the Northern European context. *Renew. Energy* **2021**, *175*, 1174–1199. [CrossRef]
14. Renaldi, R.; Friedrich, D. Techno-economic analysis of a solar district heating system with seasonal thermal storage in the UK. *Appl. Energy* **2019**, *236*, 388–400. [CrossRef]
15. Sibbitt, B.; McClenahan, D.; Djebbar, R.; Thornton, J.; Wong, B.; Carriere, J.; Kokko, J. The Performance of a High Solar Fraction Seasonal Storage District Heating System—Five Years of Operation. *Energy Procedia* **2012**, *30*, 856–865. [CrossRef]
16. Saloux, E.; Candanedo, J.A. Model-based predictive control to minimize primary energy use in a solar district heating system with seasonal thermal energy storage. *Appl. Energy* **2021**, *291*, 116840. [CrossRef]
17. Bava, F.; Dragsted, J.; Furbo, S. A numerical model to evaluate the flow distribution in a large solar collector field. *Sol. Energy* **2017**, *143*, 31–42. [CrossRef]
18. Bava, F.; Furbo, S. Impact of different improvement measures on the thermal performance of a solar collector field for district heating. *Energy* **2018**, *144*, 816–825. [CrossRef]
19. Tschopp, D.; Tian, Z.; Berberich, M.; Fan, J.; Perers, B.; Furbo, S. Large-scale solar thermal systems in leading countries: A review and comparative study of Denmark, China, Germany and Austria. *Appl. Energy* **2020**, *270*. [CrossRef]
20. Noussan, M.; Jarre, M.; Degiorgis, L.; Poggio, A. Data Analysis of the Energy Performance of Large Scale Solar Collectors for District Heating. *Energy Procedia* **2017**, *134*, 61–68. [CrossRef]
21. Furbo, S.; Dragsted, J.; Perers, B.; Andersen, E.; Bava, F.; Nielsenb, K.P. Yearly thermal performances of solar heating plants in Denmark—Measured and calculated. *Solar Energy* **2018**, *159*, 186–196. [CrossRef]
22. Latvian Environmental Geology and Meteorology Center. Meteorological database 2021. Available online: https://www.meteo.lv/ (accessed on 21 June 2021).

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Is It Possible to Obtain More Energy from Solar DH Field? Interpretation of Solar DH System Data

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***Abstract* – Europe has a course to zero emissions by 2050, with a strong emphasis on energy sector. Due to climatic conditions in Latvia, district heating (DH) plays an important role in the energy sector. One of the solutions to achieve the set goals in DH is to introduce emission-free technology. Therefore, the popularity of installation of large-scale solar collector plants continues to increase in DH in Europe. The first large-scale solar collector field in the Baltic States was installed in 2019. Solar collector active area is 21 672 m^2 with heat storage water tank 8000 m^3. The article shows the first operation results of this system and evaluates influencing factors. The results of the analysis show that system productivity is mainly demanded by solar radiation, and the strongest correlation between these parameters were established in May. The highest correlation between ambient air temperature and produced thermal energy is reached when ambient air temperature is between 7 °C to 15 °C and production process has not been externally regulated. The temperature difference between flow and return temperatures of the heat carrier affect solar collector performance minimally and strong correlation was not observed.**

***Keywords* – District heating; large scale solar collector field; regression analyses**

1. INTRODUCTION

A Green New Deal target is zero emission by 2050, as well as not to exceed global warming under 1.5 °C. One of the main steps in this resolution is to decarbonise the energy sector. The Green New Deal will promote decarbonisation of the economy in the energy sector and ensure longer investment periods [1].

In recent years, use of sustainable heat sources in district heating (DH) has been growing, heating network losses are reduced and digitalization is taking place to achieve the targets. A variety of sustainable energy sources are used in DH in the EU – solar energy, heat pumps, waste heat [2]. The system is moving to the 4th generation by implementing low potential heat sources, lowering network temperature, integrating smart grid technology, different storage technologies and promoting interaction with prosumers. When the operation of DH systems becomes more complex, it is important to plan long-term development of heat production, transmission and energy efficiency measures at the consumer's side [3], [4].

Solar energy is a high potential for use in district heating [5]–[7]. Solar collectors are emission-free technology and an appropriate solution to reduce CO_2 in the DH system. Implementation of solar collector systems is increasing, because it uses unlimited solar energy and have low maintenance costs [8]. Denmark is the world leader in the use of large-scale solar collectors in DH, where approximately 160 000 m^2 of solar collector active area have

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been installed [9]. In Denmark, 70 % of all large-scale solar collector are installed by Arcon-Sunmark. The high solar collectors' efficiency and long warranty decrease the payback time [10].

Climatic conditions are one of the main influencing factors in the operation of solar collectors [11], [12]. Yearly, the global radiation in Denmark is approximately 1000–1150 kWh/m^2, but total radiation on collector surfaces is around 1100–1200 kWh/m^2. The total radiation to the collector area is affected by the installation angle, which in Denmark is in average 30 to 40 degrees, depending on the goal – to get the maximum capacity in the summer or the maximum produced energy [13]. In Latvia, yearly global radiation is approximately 1000–1200 kWh/m^2 [14].

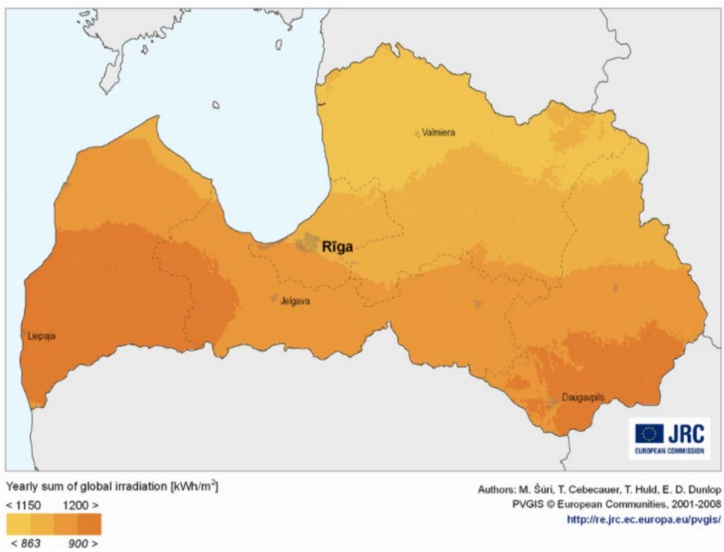

Fig 1. Global irradiation in Latvia [14].

As can be seen in Fig. 1, Latvia is divided into zones – in the north-west of Latvia radiation is higher. However, radiation levels in Denmark and Latvia can be considered equivalent.

The main aim of the article is to evaluate the performance of the first large scale solar system in Baltic States after one-year operation period by determining the potential solar yield under different impact factors.

2. METHODOLOGY

Several solar collector systems influencing factors and their importance have been evaluated in this research. Influencing indicators also show how effectively the overall system works.

2.1. Case Study

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

In total, 1720 Arcon-Sunmark A/S HT-Heat Boost 35/10 solar collectors have been installed, size of each collector is 2.0 × 6.3 meters. The collector has high absorber efficiency ~83 %. The solar system is operating with a temperature regime 45/63 ºC, but in the thermal accumulation system the temperature can be raised to 85 ºC, if necessary, which allows to increase the total amount of stored heat.

TABLE 1. OVERVIEW OF MAIN SOLAR SYSTEM PARAMETERS

Parameter	Value
Total active area	21 672 m^2
Number of installed solar collectors	1720
Operational temperature regime of solar field	45/63 °C
Volume of thermal storage tank	8000 m^3
Absorber efficiency	83 %
Gross efficiency	77 %
Heat loss coefficient, a_1	2.27 W/km^2
Heat loss coefficient, a_2	0.0181 W/km^2

The operating modes are also important for the solar yield evaluation. Operation is influenced by two factors: the intensity of solar radiation and the set temperature. When the solar irradiance is below 250 W/m^2, the solar field is preheated, but the heat production starts when the set temperature is reached. Production is divided into two stages – low temperature and high temperature. Low temperature production starts when the solar irradiance is from 250 W/m^2 to 650 W/m^2.When the solar irradiation is above 650 W/m^2, high temperature production starts. The overheating protection of solar field during high solar irradiation period is done in two different ways. The first option is to cool it through the collector field at night. The second option is to reduce efficiency by raising the inlet temperature in the collector field.

The performance of solar collectors is determined according to the produced solar heat according to Eq. (1) [15]:

$$P_{\mathrm{g}} = A_{\mathrm{c}} \cdot \left[\eta_0 \cdot G - a_1 \cdot (T_{\mathrm{m}} - T_{\mathrm{a}}) - a_2 \cdot (T_{\mathrm{m}} - T_{\mathrm{a}})^2 \cdot f_{\mathrm{p}} \cdot f_{\mathrm{u}} \cdot f_{\mathrm{o}} \right], \quad (1)$$

where

P_{g} Guaranteed performance (thermal power output), W;
A_{c} Collector area corresponding to the collector efficiency parameters, m^2;
η_0 Optical efficiency;
a_1, a_2 Heat loss coefficients W/(K·m^2);
G Solar irradiance on collector plane W/m^2;
T_{a} Ambient air temperature °C;
T_{m} Mean temperature of solar collector fluid, °C;
f_{p} Safety factor, considering the pipe heat losses in the collector field and transmission lines;
f_{u} Safety factor, considering measurement uncertainty;
f_{o} Safety factor for other parameters.

In the particular study the estimated pipe losses are 3 %, therefore the used fp is 0.97. The value of fu is assumed to be 0.95 for the total measurement uncertainty estimated to be 5 %.

The used safety factor for other parameters fu is assumed as 0.95, considering non-ideal flow distribution and unforeseen heat losses.

Mean temperature of solar collector fluid is calculated according to Eq. (2) [15].

$$T_{\mathrm{m}} = \frac{(T_{\mathrm{c,in}} + T_{\mathrm{c,out}})}{2}, \tag{2}$$

where

$T_{\mathrm{c,in}}$ Hot side temperature (equal to collector outlet temperature), °C;
$T_{\mathrm{c,out}}$ Cold side temperature (equal to collector inlet temperature), °C.

From the above equations it can be seen that the solar field performance is affected by the following factors:

- Collector area;
- Collector optical efficiency;
- System losses;
- Ambient air temperature;
- DH return temperature – inlet temperature;
- Collector outlet temperature.

The next step is to understand which factors in a particular system can be affected by the system operator and which cannot be changed. As this is the first project in the Baltic States the solar radiation is also analysed in order 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.

2.2. Solar System Monitoring System and Input Data

The monitoring system is designed to ensure security and to be able to calculate the efficiency of solar collector field. Data reading points corresponds to solar district heating guideline is shown in Fig. 2.

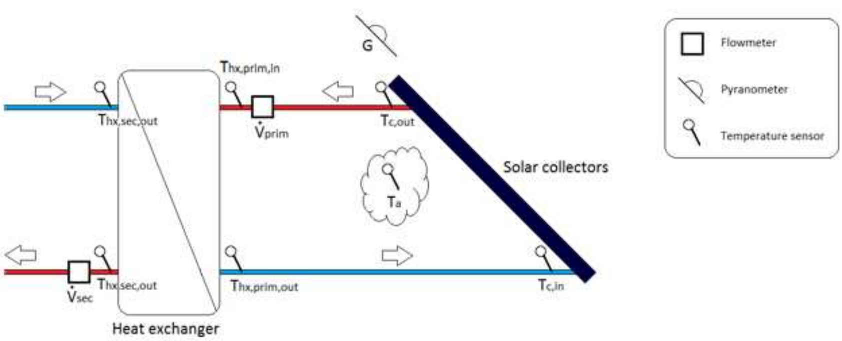

Fig. 2. Technical scheme of the measurement points [15].

The particular solar collector field in Salaspils is equipped with four solar radiation meters installed in opposite quadrants of the collector field. Solar radiation meters are connected to circulation pumps, which increases or decreases the flow depending on the average measurement of the two radiation meters. The cloudy weather is the main reasons why two measurements are compared. Radiation meters are located far enough away from each other and, while a shadow from a cloud may have been fallen on the one of the radiation meters, at the same time other radiation meters receive huge amount of solar radiation. Circulation pumps and flow is also connected and regulated from temperature meters, which displays the temperature in the solar collector system.

The days' average radiation measurement is calculated using every measurement above 300 W/m^2, because, as experience shows, at this value it is possible to start thermal energy production and obtain useful temperature, all measurements which are under this value are not taken into account. During the night production stops. Radiation measurements are recorded automatically and shall be performed as minimum once every two minutes or even more frequently. Up to 25 000 measurements are made at the 24-hour period.

The produced thermal energy from solar collectors is also measured and recorded automatically, in order to evaluate the solar energy yield.

3. RESULTS

In the first year since solar collectors are installed in 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 11 088 MWh, whilst the total produced amount of thermal energy in Salaspils heating plant were about 58 GWh. As it is shown in Fig. 3, the highest share of solar field production is observed in June, July and August, when the solar energy share reached 46–49 % comparing to the total production. Although there are two wood chip boilers installed in Salaspils DH plant, it was concluded, that the best solution to cover the peaks demands in summer period is by using the natural gas boilers. Natural gas boilers can be started immediately without the time-consuming boiler starting process, which would be the case if biomass boilers were used. Natural gas boilers in combination with solar collectors is used only in the summer months. Biomass boilers continue to operate in April and June, as they are not sopped after the heating season. Therefore, total annual share of thermal energy produced with natural gas boilers was only 10 %.

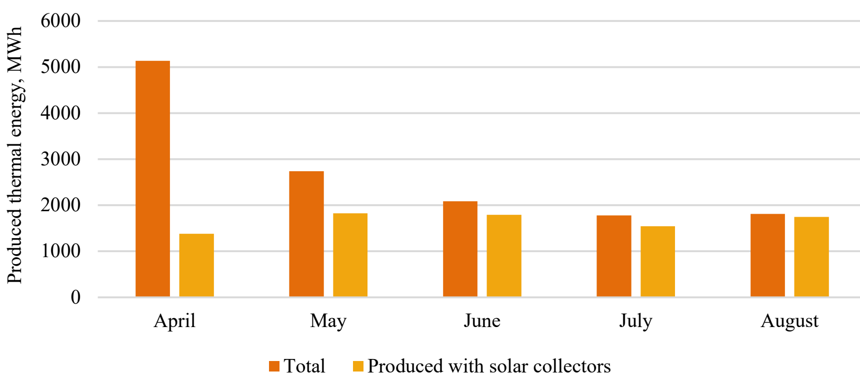

Fig. 3. Share of thermal energy produced by solar collectors and total produced thermal energy in 2019.

During the high solar radiation periods, when the sun reaches its highest intensity for several days, the installed 8 000 m^3 storage tank cannot accumulate all of the produced solar energy, and the overheating protection of solar field starts. However, there are also moments of low solar irradiation and cloudy weather for several days, in which all of stored heat is consumed and 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 boilers when switched on for a shorter time.

Another operational parameter that can be regulated by the operator is the solar field set point. 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 summer months the ambient air temperature and solar radiation is much higher than in spring. This results in higher solar thermal energy production, but the demand of thermal energy at 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 adjust it with the heat consumption. The opposite situation is observed in spring, when 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 regression analysis method by determining the correlation between different parameters. This method reflects the relationship between two factors, which means that when one value changes, the corresponding one also changes. The maximum value of correlation coefficients is one.

The data presented have been collected throughout the sunny season, which in Latvia's case is from April until August. Fig. 3 shows that solar radiation is the main impacting factor of produced solar thermal energy.

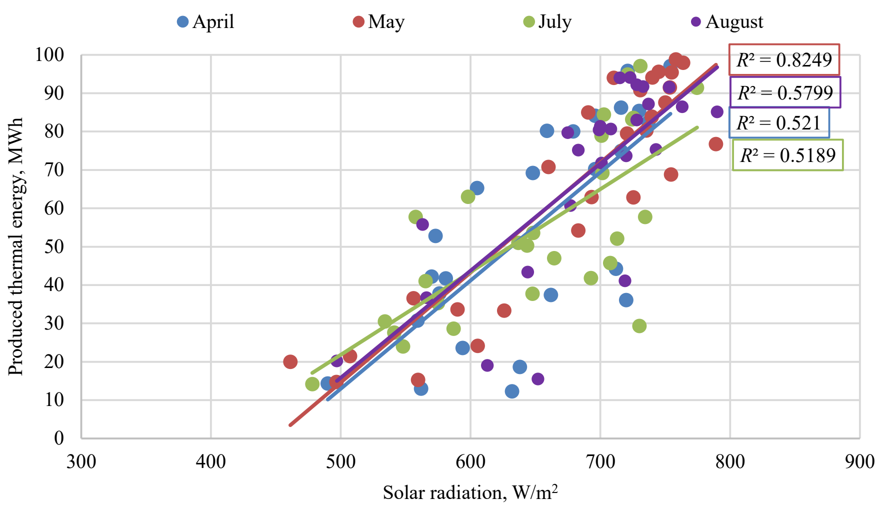

Fig. 4. Produced solar energy dependency of solar radiation.

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 [12]. The largest data distribution has been observed in July, which is due to the regulation of already mentioned set point. At high productivity over several days and insufficient heat demand, the set point was raised reducing produced thermal energy.

However, the highest correlation is 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 proves it. If this correlation between 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. 4 presents a 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. Average correlation between ambient air temperature and produced thermal energy is 0.2837, which means that the correlation is low and other conditions impact solar collector performance more.

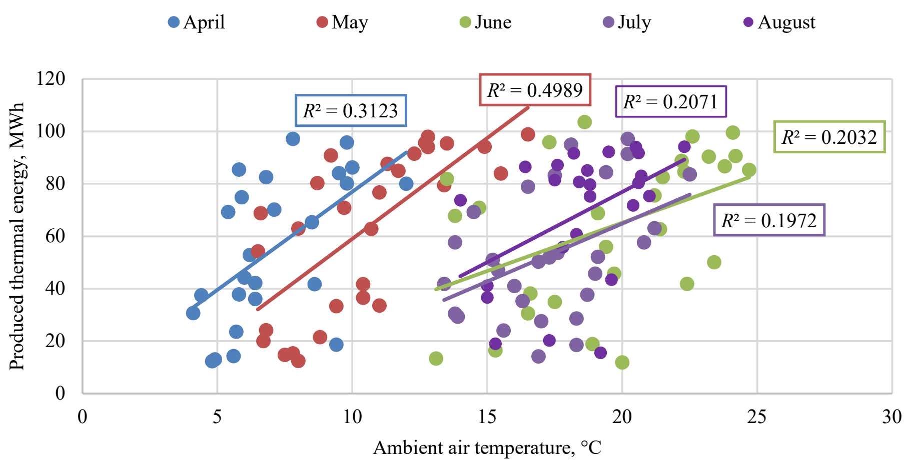

Fig. 5. Solar collector efficiency dependency of ambient air temperature.

Another analysed impacting parameters that were examined in this study were flow and return temperature of heat carrier. Study showed that correlation between these parameters and 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 is very complicated. When the temperature difference changes several times a day, it is difficult to register and divide data on how much heat energy was produced with each specific temperature difference between supply and return temperatures.

Fig. 5 shows the comparison of the performance about numerous solar heating plants in Denmark and the particular solar DH plant in Salaspils. All the heating plants included in this comparison are using the same solar collector technologies from Arcon-Sunmark A/S, HTHEATstore 35/10. The data was calculated as average solar performance and solar radiation results during the period from 2012 to 2016 presenter in [13]. It is clear that the Salaspils solar heating plant has achieved high solar yield. The specific solar performance (511 kWh/m^2) is high compared to other solar DH systems with similar average solar radiation.

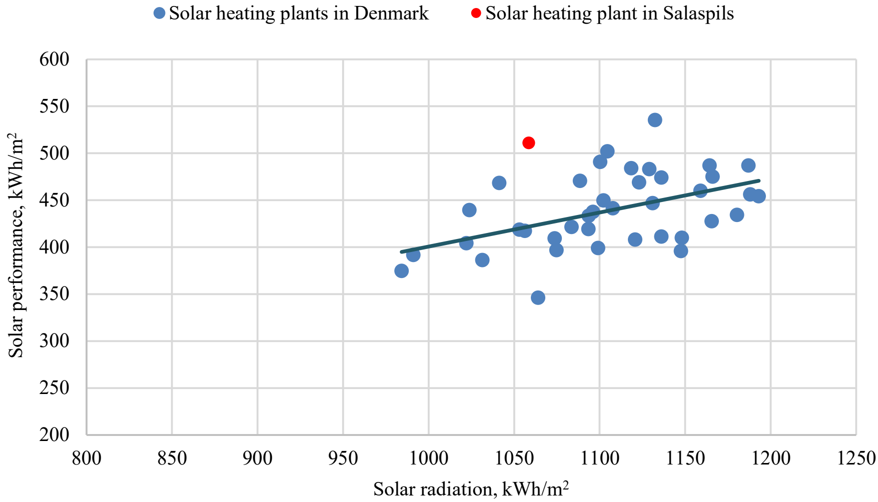

Fig. 6. Comparison of solar heating plant performance demanding of solar radiation in Denmark [13] and solar heating plant installed in Salaspils (2020).

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

Overall, the solar 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 more storage for 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. On the further research authors has planned to analyse the efficiency of solar collectors by excluding the influence of solar radiation, to better identify the effects of other factors, which dependency on the efficiency are significantly lower compared to solar radiation. One of the main tasks will be more detailed analysis of the set point by dividing several components – temperature limits and flow control, on the primary (solar collector) and secondary (rest of the system) sides of the system.

4. Conclusion

The article presents the operational data analysis of a first large-scale solar collector field in Latvia, connected to district heating network, and demanding of several factors.

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

Solar collectors installed in Salaspils are producing with the highest productivity at a time when it is most beneficial:

– Solar radiation is high and it would be possible to produce a large quantity of heat;
– Placement creates suitable conditions for efficient production;
– The temperature of ambient air is within such limits as the demand for heat has not yet fallen so low that the volume produced could not be realised.

The highest correlation between ambient air temperature and produced thermal energy is reached, when ambient air temperature is between 7 to 15 °C and production process has not been externally regulated. The temperature difference between flow and return temperatures of the heat carrier affect's solar collector performance minimally and strong correlation was not observed.

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References

[1] Mastinia R., Kallisa G., Hickelc J. A Green New Deal without growth? *Ecological Economics* 2021:179:106832. https://doi.org/10.1016/j.ecolecon.2020.106832

[2] Sayegh M. A., et al. Trends of European research and development in district heating technologies. *Renewable and Sustainable Energy Reviews* 2017:68(2):1183–1192. https://doi.org/10.1016/j.rser.2016.02.023

[3] Li Y., Rezgui Y., Zhu H. District heating and cooling optimization and enhancement – Towards integration of renewables, storage and smart grid. *Renewable and Sustainable Energy Reviews* 2017:72:281–294. https://doi.org/10.1016/j.rser.2017.01.061

[4] Lund H., et al. 4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems. *Energy* 2014:68:1–11. https://doi.org/10.1016/j.energy.2014.02.089

[5] Pelda J., Stelter F., Holler S. Potential of integrating industrial waste heat and solar thermal energy into district heating networks in German. *Energy* 2020:203:117812. https://doi.org/10.1016/j.energy.2020.117812

[6] Rezaie B., Rosen M. A. District heating and cooling: Review of technology and potential enhancements. *Applied Energy* 2012:93:2–10. https://doi.org/10.1016/j.apenergy.2011.04.020

[7] Lake A., Rezaie B., Beyerlein S. Review of district heating and cooling systems for a sustainable future. *Renewable and Sustanable Energy Reviews* 2017:67:417–425. https://doi.org/10.1016/j.rser.2016.09.061

[8] Carpaneto E., Lazzeroni P., Repetto M. Optimal integration of solar energy in a district heating network. *Renewable Energy* 2015:75:714–721. https://doi.org/10.1016/j.renene.2014.10.055

[9] Weiss W., Spörk-Dür M. Solar Heat Worldwide 2018 version (Global Market Development and Trends in 2017 Detailed Market Figures 2016). Graz: Steinhuber Infodesign, 2018.

[10] Tian Z., et al. Large-scale solar district heating plants in Danish smart thermal grid: Developments and recent trends. *Energy Conversion and Management* 2019:189:67–80. https://doi.org/10.1016/j.enconman.2019.03.071

[11] Adsten M., Perers B., Wackelgard E. The influence of climate and location on collector performance. *Renewable Energy* 2002:25(4):499–509. https://doi.org/10.1016/S0960-1481(01)00091-X

[12] Noussan M., et al. Data Analysis of the Energy Performance of Large Scale Solar Collectors for District Heating. *Energy Procedia* 2017:134:61–68. https://doi.org/10.1016/j.egypro.2017.09.619

[13] Furbo S., et al. Yearly thermal performances of solar heating plants in Denmark – Measured and calculated. *Solar energy* 2018:159:186–196. https://doi.org/10.1016/j.solener.2017.10.067

[14] The European Commission's science and knowledge service [Online]. [Accessed 21.01.2021]. Available: https://ec.europa.eu/jrc/en/pvgis

[15] SDH. Solar district heating guidelines. Graz: Steinhuber Infodesign, 2012.