TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Materials and Environmental Technology

FEASIBILITY OF SOLAR COLLECTORS INTEGRATION TO DISTRICT HEATING NETWORKS IN ESTONIA

PÄIKESEKOLLEKTORITE ÜHENDAMISE KASULIKKUS KAUGKÜTTEVÕRKUTEGA EESTIS

MASTER THESIS

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Tallinn 2020

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Accepted for defence

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THESIS TASK

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Thesis main objectives:

1. Describe different consumers in terms of heating needs
2. Determine solar potential and solar resources in a specific location
3. Analyse the application of solar collectors in case of different consumers

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Solar power in district heating networks	
2.	Overview of district heating networks in Estonia	
3.	Methodology	
4.	Consumer description	
5.	Solar power potential and solar resources	
6.	Applying solar power in district heating networks in case of different CONSUMERS	
7.	Water thermal energy storage system	
8.	Economic feasibility of solar collectors' integration to district heating networks	

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CONTENTS

PREFACE

The proposition of the topic was made by Eduard Latõšov, Associate Professor and Programme Director (Energy Technology and Thermal Engineering) in Tallinn University of Technology, who is also the supervisor of this thesis.

I picked this topic, because of my personal interests. Most of the material used in this thesis was gained from online databases, learning conspectuses and the supervisor.

I wish to thank my supervisor, family, friends and colleagues. Their support was enormous, while writing this thesis.

Abstract: Integrating solar collectors to district heating networks could help to solve problems in the energy sector like increase the use of renewable energy resources, decrease the use of natural resources, decrease the amount of greenhouse gas emissions and reconstruct or build a district heating network. A methodology was introduced to determine the feasibility of that project. Firstly, the heating needs of three different consumers were determined to create different scenarios. Secondly, Hargreaves and Samani temperature-based model was used to determine solar resources in Estonia. Thirdly, solar collectors output power was calculated with different areas ranging from 500 – 25 000 m^2. Fourthly, the volume of the seasonal water thermal energy storage tanks was calculated in case the solar collectors production exceeded heat consumption. Lastly, the levelized cost of heat was calculated taking into account investment size for solar collectors, water thermal energy storage tank and other parameters and the results stayed in between 37.01 – 56.33 EUR/MWh. If government offers financial aids to cover half of the initial investment, the levelized cost of heat stayed between 20,7 – 31,5 EUR/MWh. This shows that solar collectors are competitive with other heat production technologies that have the levelized cost of heat between 18 – 65 EUR/MWh. Solar collectors are also competitive if we look at Estonia's district heating levelized cost of heat prices, that remain between 30,0 – 74,0 EUR/MWh.
Key words: district heating networks, solar collectors, solar power potential and resources, heating and ventilation, domestic hot water, heat losses, thermal energy storage, economic feasibility, levelized cost of heat, master thesis

INTRODUCTION

There are many goals in the energy sector in the world this century. The main goals are the following: fight climate change and reduce greenhouse gas emissions, increase the renewable energy consumption, achieve more energy savings, be ready for the possible consequences of climate warming, decrease the use of natural, limited energy resources. There are many technical solutions that can help to solve these problems and the contribution of every country should be equal and not depending on the location in the world. [1]

In this paper, solar collectors' integration to district heating networks is discussed. Integrating solar collectors to district heating networks helps to fight climate warming, reduce greenhouse gas emissions, increase the use of renewable energy resources and decrease the use of natural energy resources. So, integrating solar collectors to district heating networks helps to solve the main problems in the energy sector. Also, integrating solar collectors to district heating networks might help to replace amortized equipment used in district heating networks or make good adjustments in current district heating networks. Also, integrating solar collectors to district heating networks might be a feasible way technically and economically to reconstruct or build a district heating network.

The purpose of this work is to investigate the feasibility of solar collectors' integration to district heating networks in Estonia.

The following methods were used in this work. The principles of degree days to calculate consumers' heat consumption [2], determining solar resources and potential using Hargreaves and Samani temperature based model in this work mainly; calculating solar collectors production with a formula that include concepts like efficiency, global radiation on a horizontal surface and solar collectors area; calculating the volume of energy storage system with a concrete formula and finally, determining the levelized cost of heat with a certain formula.

The study is structured as follows. Chapter 1 describes the concept of district heating and evolvement of district heating over time. Chapter 2 provides an overview of district heating networks and heat sector in Estonia, heat consumption, prices of thermal energy. Chapter 3 gives the methodology how to evaluate the feasibility of solar collectors' integration to district heating networks. Chapter 4 gives the description of three different consumers in terms of heating needs, found by adding together temperature dependent heat consumption – heating and ventilation, temperature independent heat consumption – domestic hot water and heat losses. Chapter 5 determines solar power potential and solar resources using practical and estimation methods (Hargreaves and Samani temperature-based model used in this work mainly). Chapter 6 shows how solar collectors are applied with different areas in district heating networks in case of different consumers. Chapter 7 deals with finding the need for water thermal energy storage system in case the solar collectors production exceeds heat consumption and computing the volume of the seasonal water thermal energy storage tanks. Chapter 8 shows how to calculate the levelized cost of heat taking into account investment size for solar collectors, water thermal energy storage tank and other parameters. Also, a comparison is done to compare calculated costs with the costs of other heat production technologies.

1. SOLAR POWER IN DISTRICT HEATING NETWORKS

In this chapter, an overview about the usage of energy, district heating networks working principles, development of district heating networks and solar collectors' technologies in district heating networks have been given.

Europe consumes half of its' energy for heating and cooling purposes, most of this thermal energy is used in buildings and industry as shown in figure (Figure 1.1).

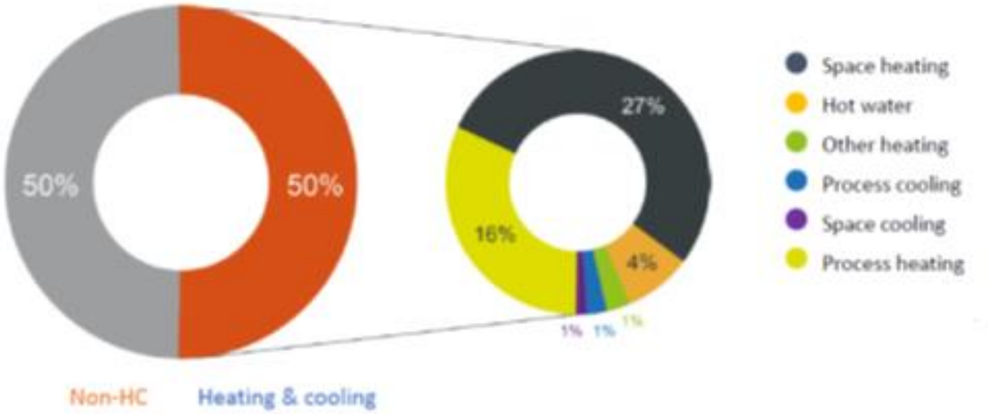

Figure 1.1. Share of energy consumption for heating and cooling [3]

A district heating system's main function is to supply customers with energy for heating and production of domestic warm water. In some cases, district heating also supplies low temperature industrial heat demands. District heating is suitable for residential as well as for commercial buildings. The use of district heating is rapidly spreading from traditional heating and domestic warm water preparation appliances to comfort cooling via absorption chillers and a wider range of domestic appliances. The main idea of using district heating for these purposes is to utilise surplus heat and to organize the heat production in a way that is more efficient than individual production. [4]

A district heating is composed of production, distribution and transmission and customer installations as seen in figure (Figure 1.2). All district heating system parts are interconnected. The system built for consumption – the radiators, the warm water system and the installed control system – sets the requirements for the connection system/substation, which again gives the dimensioning parameters for the distribution system and forward to the dimensioning of the production plant(s). [4]

Depending on the type of heat production plant the dimensioning criterions might be in reverse. The distribution, connection and consumption system parts are in principle simple construction systems. The secret is to do the right dimensioning, construction and controlling of the system. [4]

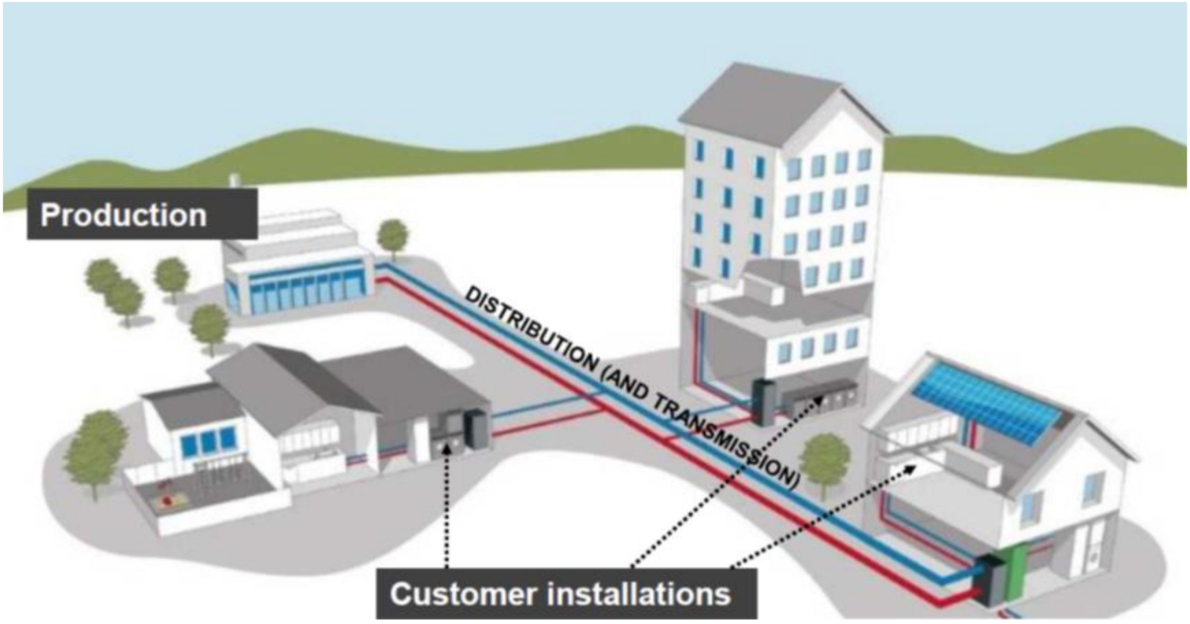

Figure 1.2. Principle scheme of district heating system [5]

When district heating was first used, mainly fossil fuels were used as the heating source. Nowadays, more and more different sources are being integrated to district heating. Integrating solar power into district heating has many benefits: it helps to lower the use of fossil fuels, save the environment by reducing carbon dioxide emissions, increase the use of renewable energy, fulfil different requirements of both national and international legislation, making district heating more efficient and so on.

The development of solar district heating in the last 140 years is shown in figure (Figure 1.3). The development can be divided into 4 generations by the units used in the district heating [4]:

1. Generation: steam storage; coal and waste plant; local district heating.
2. Generation: heat storage; CHP coal and oil plant; coal and waste plant; district heating.
3. Generation: large scale solar plant; biomass and CHP biomass; industry surplus; heat storage; CHP waste, coal and oil plant; gas, waste, oil and coal plant; district heating.
4. Generation: seasonal heat storage; large scale solar plant; geothermal plant; PV, wave, wind surplus, electricity; heat storage; industry surplus; CHP waste

incineration; low energy buildings; centralised heat pump; centralised district cooling plant; cold storage; CHP biomass, 2-way district heating, biomass conversion, future energy sources.

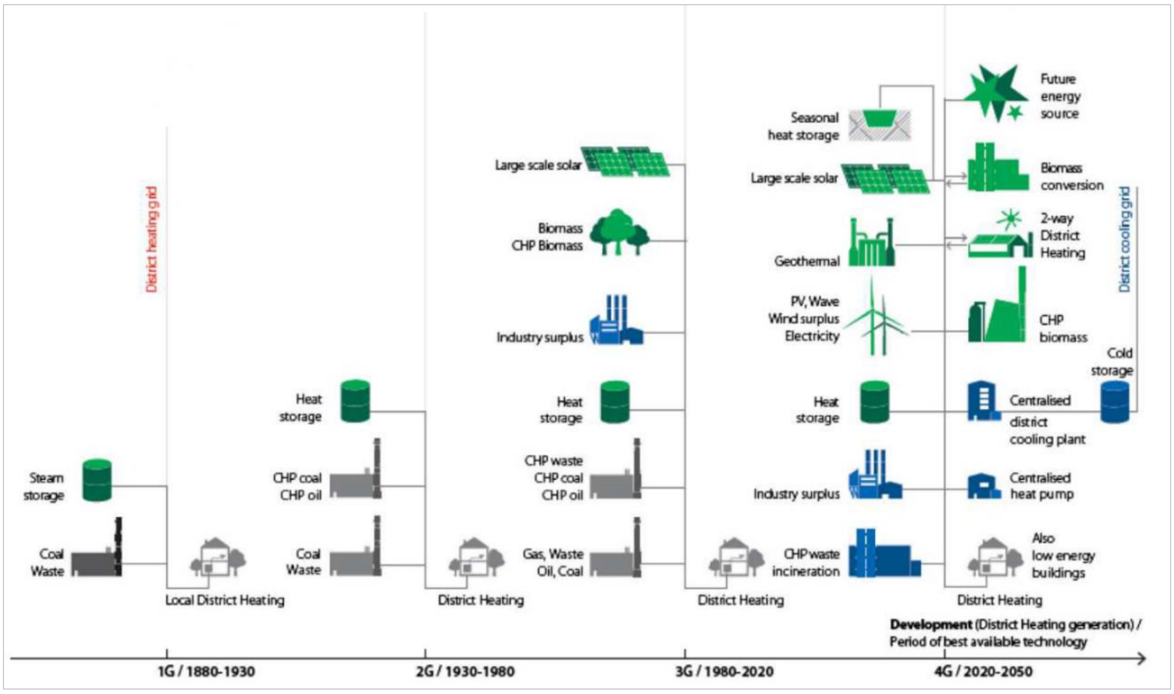

Figure 1.3. Development of district heating in the last 140 years [4]

There are many benefits of district heating by comparison with other heating options. These benefits are brought below [6]:

- District heating is suitable for all buildings in areas where DH networks are available irrespective of size or type.
- Equipment and maintenance
  - DH has minimal space requirements at the customer end with equipment of a compact size, which is simple to use, run and maintain;
  - With DH no maintenance is necessary for the customer, the DH utility can take care of energy and service 24 hours a day, typically without ever entering the house;
  - Buildings connected to DH have no need for fuel storage facilities, have no boiler or burner and do not require a chimney;
  - DH does not require a complementary or backup system;
  - The customers take no risks of fires, explosions or dangerous medias inside the house.
- Comfort
  - DH guaranties an unlimited amount of heating and domestic warm water 24/24;

    - Customers have no concern over fuel availability;
    - DH is easy to handle and works automatically.
- Costs
    - DH entails moderate investment costs and very low maintenance costs for the customer;
    - Prices of DH are competitive, predictable and steady, tariffs are public.
- Reliability and efficiency
    - DH is known as very reliable, because district heat is produced at multiple production facilities using a variety of fuels;
    - DH has a flexible and sustainable fuel mix and does not depend on a specific fuel;
    - DH substations have a long lifetime and a high efficiency.
- Environmental issues
    - DH is often based on the utilisation of surplus heat which would otherwise be lost (surplus heat from industry, cogeneration of heat and power etc.) and thereby avoids the use of fossil fuels and related emissions;
    - DH can use a wide variety of local energy sources and renewables (wood, waste, straw, municipal waste and sewage sludge etc.);
    - DH has low climate impact: low primary energy consumption and CO_2 emissions. DH reduces local pollutants as dust, fine particles, sulphur dioxide and nitrogen oxides by relocating exhausts from individual boilers to centralised chimneys. Due to economies of scale, far more effective pollution prevention and control measures can be implemented in central production facilities.

Solar water heating is one of the most widely used water heating system worldwide. The solar water heater can convert solar energy into concentrated heat efficiently, with advantages of mature technology based, low risk on global warming and low life cycle cost. The global capacity of solar water heating collector (Figure 1.4) has been increasing from less than 100 GW in 2004 to nearly 450 GW in 2015, and domestic hot water system is the most important market segment. The vast majority of global solar water heating capacity was installed in China. As shown in figure (Figure 1.4), in the year 2014, China accounted for 71% of the world installed capacity of solar water heating collectors. The next nine countries including the United States, Germany, Turkey, Brazil, Australia, India, Austria, Greece and Japan shared the rest 19%. [7]

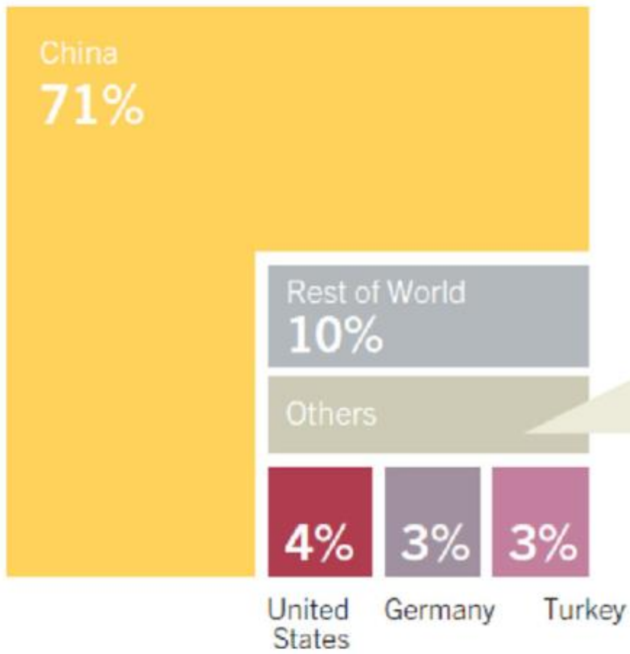

Figure 1.4. Shares of the solar water heating collectors' global capacity [7]

Usually, solar collectors are used in district heating networks when applying solar power in district heating networks and the principle diagram of a possible configuration for a solar district heating system is shown in figure (Figure 1.5). This kind of a configuration was used, when the feasibility of solar collectors' integration to district heating networks in Latvia was studied.

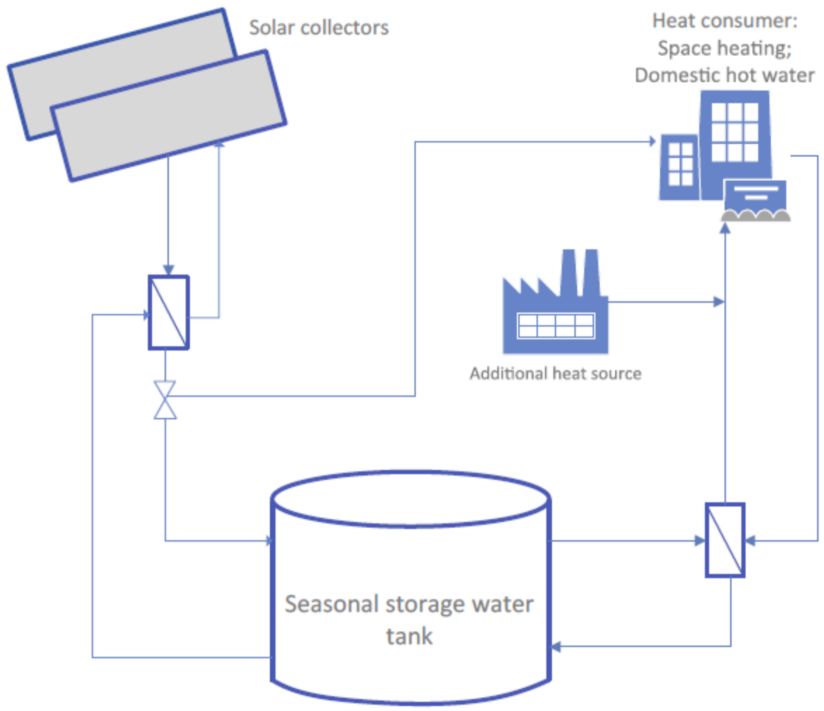

Figure 1.5. Principle diagram of a possible configuration for a solar district heating system [8]

In figure (Figure 1.6), we can see that 97% of existing solar district heating projects in European Union countries used flat plate collectors. [9]

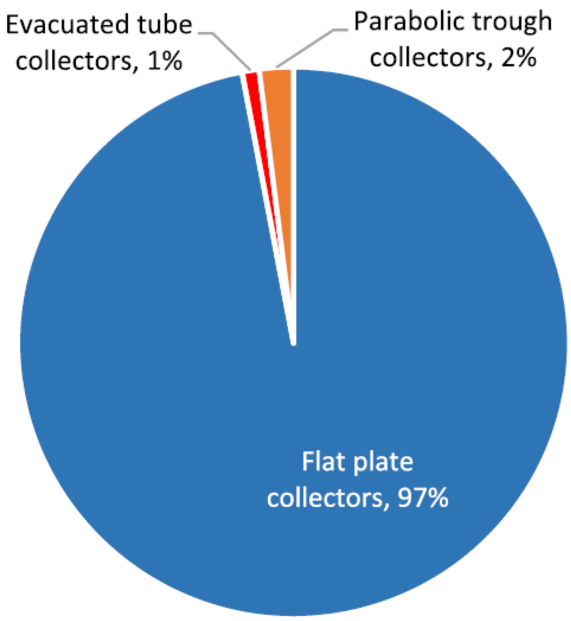

Figure 1.6. Solar collectors installed in district heating plants in existing 199 heating plants in Europe [9]

2. OVERVIEW OF DISTRICT HEATING NETWORKS IN ESTONIA

In this chapter, an overview about Estonia's district heating networks has been given. The following topics are covered: fuels used in district heating, installed solar collectors in Estonia, prices of thermal energy, different investments, problems and challenges in Estonia's district heating network.

District heating covers about 70% of the heat consumption in Estonia. In 2018, the total annual heat consumption of Estonia in district heating was 4.4 TWh. The total heat consumption was 6.3 TWh. The fuels used in district heating in 2018 are brought in figure (Figure 2.1). [10]

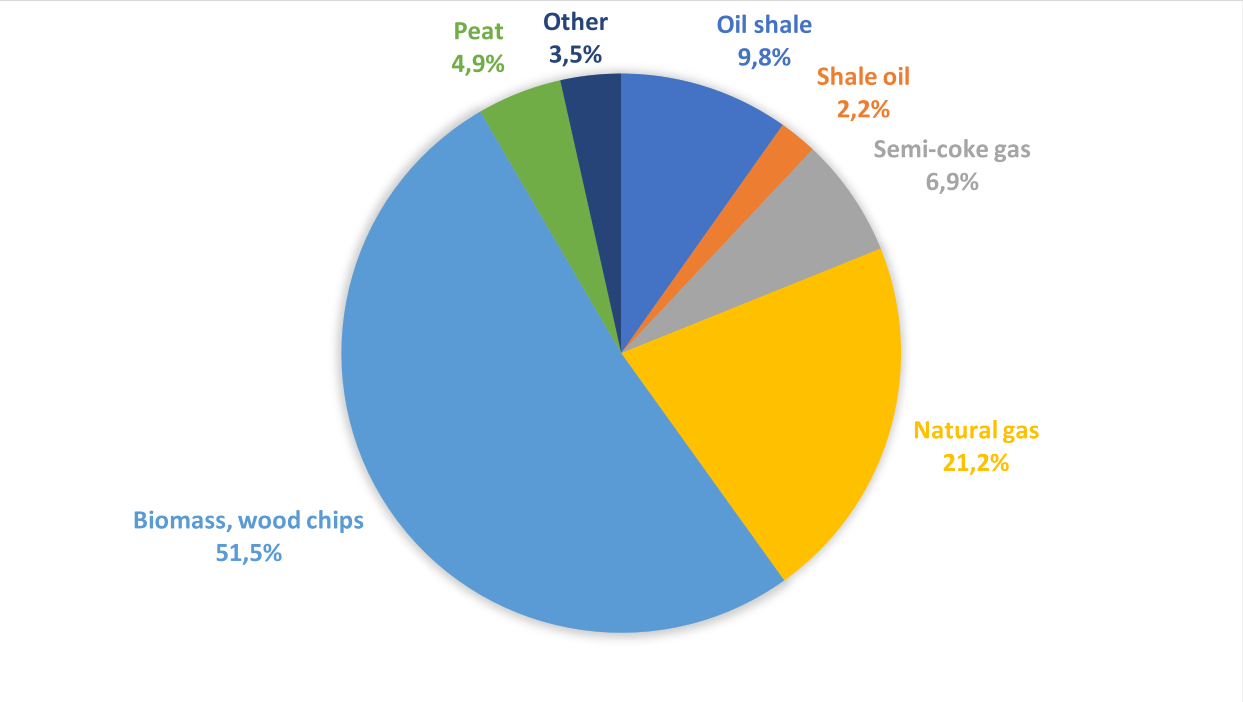

Figure 2.1. Fuels used in district heating [10]

It can be seen in figure (Figure 2.2), that in Estonia there are 6 kWh of installed solar collector power per 1000 inhabitants in general (not meaning integrated to solar district heating networks only), which is a pretty low number. But the number is pretty much the same in the near countries of Estonia like Latvia, Finland, Lithuania and Sweden as well. [8]

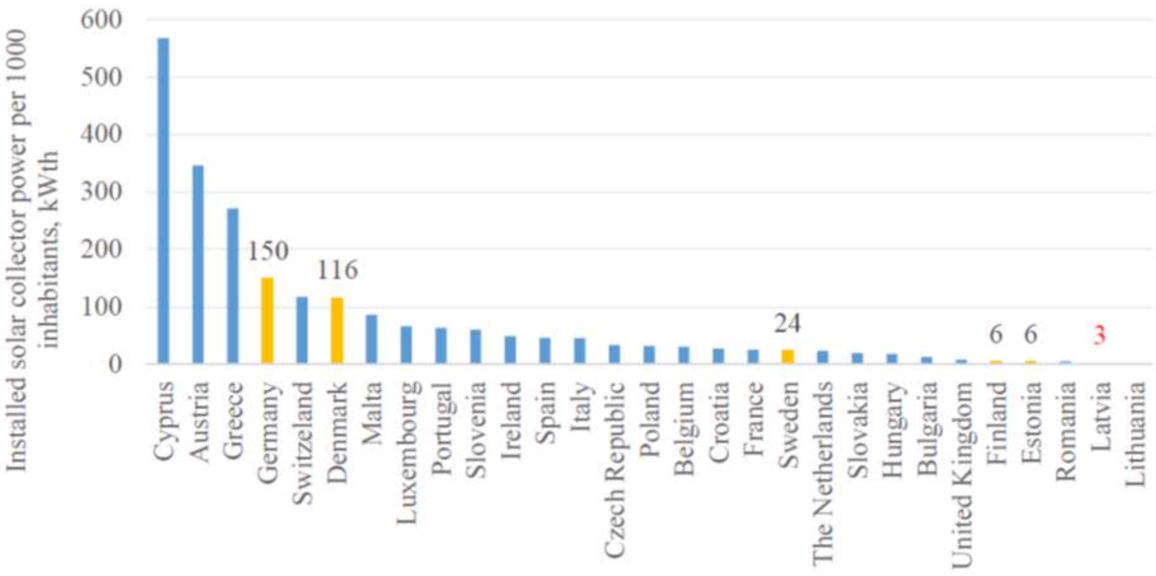

Figure 2.2. Installed solar collector power per 1000 inhabitants in Europe, 2015 [8]

There are 230 district heating network areas in Estonia. In November 2019, the prices of thermal energy for end users without value added tax, remained between 35.33 €/MWh (Narva) – 86.96 €/MWh (Harku). The average weighed price of thermal energy without value added tax, was 50.58 €/MWh, whereas the arithmetic mean value was 60.27 €/MWh. The prices of thermal energy for end-users in different districts are brought in figure (Figure 2.3). If the heat losses are 15%, the levelized cost of heat would be between 30,0 – 74,0 EUR/MWh in Estonia as we multiply the prices of thermal energy for end users with 0,85. [10, 11]

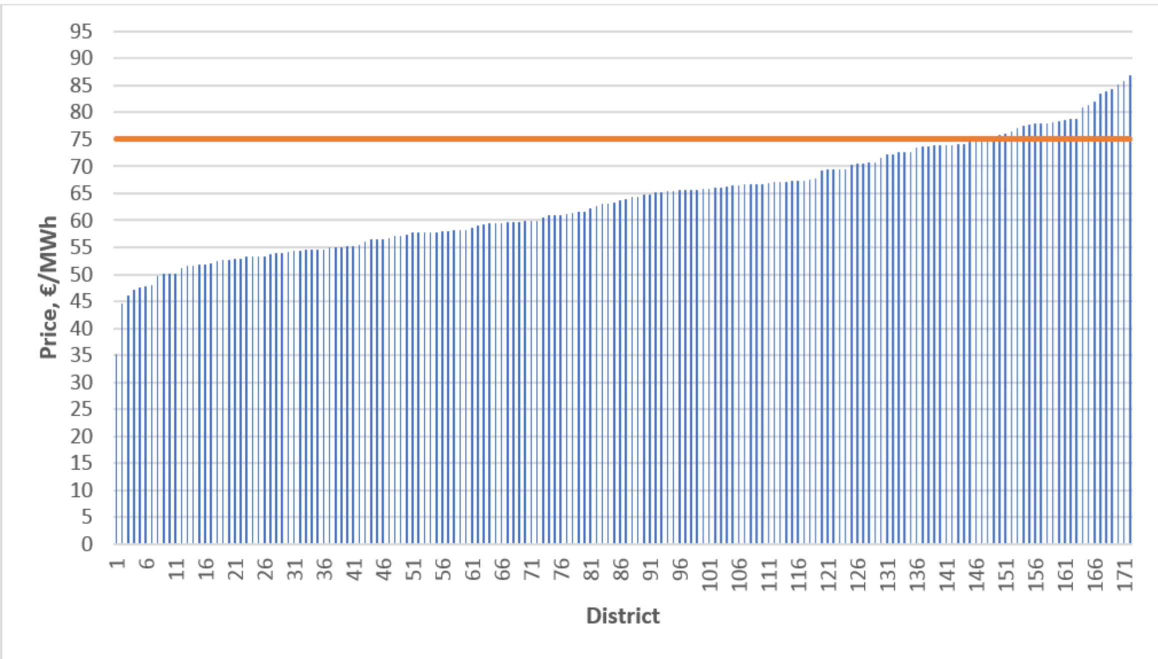

Figure 2.3. Prices of thermal energy in different districts [11]

It is estimated, that the reasonable thermal energy price is up to 75 €/MWh. After that price, it is economically feasible to apply alternative local sources of heat and it is definitely advisable to analyse the sustainability of the district and alternative approaches for heating before investments. From figure (Figure 2.3), it can be seen that there are 25 districts, where the thermal energy price exceeds 75 €/MWh. These districts are the following: Raasiku, Alu, Tabasalu, Kolga, Türisalu, Türi-Alliku, Luunja, Võnnu, Sõmeru, Päri, Rõngu, Käärdi, Kukruse, Viitina, Puurmani, Ilmatsalu, Rummu, Kaerepere, Nooda (Pärnu), Päinurme, Püssi, Abja-Paluoja Järve katlamaja, Rapla Võsa tn, Märja, Harku. [12, 11]

The high thermal energy price is mainly caused by using expensive fuels in boiler houses, like natural gas and shale oil, which prices are about 45 €/MWh. In comparison, the price of wood chips and peat have been estimated to be around 18 €/MWh. [12]

The main legislation, that covers Estonia's district heating and its' requirements are the following: District Heating Act, Competition Act and Emergency Act. [13]

Between 2014-2020, structural funds from European Union are invested into energetics in the scale of 232 million euros. About 102 million euros will be directed to achieve energy efficiency in buildings. As a result of that, the expenses for thermal energy will be reduced for consumers. Also, about 78 million euros are invested to produce and transmit thermal energy more efficiently. The goal is to reconstruct heating pipeage and go from district heating to local heating in districts that have no perspective. [10]

The main problems within the sector of district heating that also cause a higher price in district heating are the following [12]:

- Lack of motivation to find cheaper solutions for district heating and better inner quality. The price regulation of district heating does not motivate producers to find solutions, how to achieve lower district heating prices. The investments, that enable to reduce end-consumers thermal energy price, are not indicated in the companies' better economical results and all achievable effect is directed to the consumer.
- Unstable environment of regulation for encouraging long-period investment. The criteria of regulation is rigid and they change a lot.
- The sustainability of the district heating areas brought before, can be questionable to both for the companies and to Competition Authority.

At the same time, local authorities regularly do not have a sufficient heating management development plan to make a conclusion of the perspective of district heating area and its' sustainability. Because the sector of district heating has gained a lot of aid for investment, it is important by the government to exclude the situation, where aid is offered to a district heating area, which in the near future, is excluded by the low number of consumers. The district heating area can apply for aid only, if the local government has made a detailed and long-period heating management development plan, which parameters are tightly intertwined with the best practice and knowledge of the district heating company. Therefore, the local government takes responsibility in its' administrative field to develop a sustainable district heating area and also takes into account developing housing resources and affirming subdivision plans. In the same time, a possible investor gets an adequate overview of the intentions in heating management in an area and therefore is in a better position to make an investment decision. In the light of toughened criterions of effectiveness, it is needed to evaluate critically the possibilities of energy saving in a district heating area and develop the area according to it. [12]

Differences in fuel prices have motivated many heat producers to invest in changing boiler equipment. At the same time in the smaller areas, producers of heat are not able to make the required investments by their own resources and they rely on different subsidies. By the data of Environmental Investment Centre, between the period 2009-2012, about 84 projects were sponsored by the total value of 40 M€ within different structural aids and green investment schemes. Local governments have estimated the need of investment to be around 800 M€ to amortized district heating sector. [12]

In Estonia, many consumers search for alternatives to district heating because of the high price of thermal energy. But at the same time, when analysing the pros of local solutions and taking into account direct and indirect expenses, the transfer to local heat sources is not cheaper in longer perspective. Optimally built district heating networks with stable heating load are able to offer cheaper thermal energy price than the solutions of long-term local heating. By integrating local heating sources to district heating system, it is also possible to provide cheaper thermal energy price and increase ease of use. For example, in 2012 in Tabivere they did this and the thermal energy price is now 58 €/MWh. [12]

The examples brought are not the only ones. The need for investment in the sector is vast. Because of amortized producing equipment and heating pipeage, toughened requirements to effectiveness and lower volumes in consuming, it is important to motivate district heating companies to invest in the sector and let them be able to use the wide compensation mechanism. With this approach, both the consumers in the district heating network and also the district heating companies win. Over-dimensioned producing and keeping the transmission infrastructure in work is not effective and expensive, and in the long term, it becomes more expensive than the local heating solution. [12]

To awake investment interest, it has been proposed that the sufficient profit is tied to the lowering of consumer price. For example, the area using shale oil has the thermal energy price between 80-90 €/MWh. When building boiler houses working on biomass, the price would drop about 40% and more profit can be made. [12]

In addition, if the manufacturer can sell heat with a lower price than in the regulation, then the price does not have to be agreed with the Competition Authority. In that case, there is a post control and every consumer can make a complaint about the price formation made by the heating company and Competition Authority must make surveillance over it. [12]

3. METHODOLOGY

In this chapter, the methodology used in this work has been described, how to evaluate the feasibility of solar collectors' integration to district heating network.

When an overview of the district heating network has been given and there is a need to reconstruct a district heating area (for example, amortized district heating network, high fuel prices, high price of district heating, replace the usage of fossil fuels), look for better opportunities and consider other options, build a new district heating network, then in this work, a methodology has been proposed how to evaluate the feasibility of integrating solar collectors to district heating network.

The methodology is brought in appendices (Appendix 1). The methodology is divided into eight main processes and different content is described and analysed in detail in different chapters as shown below:

1. Determine the size of temperature dependent heat consumption – heating and ventilation for three different consumers. To do it, we need data about base temperature and outside temperature. Also, values of yearly temperature dependent heat consumption have been chosen to describe different consumers with different heating needs. This step is brought in chapter 4.
2. Determine the size of temperature independent heat consumption – domestic hot water for three different consumers. To do it, we need data about yearly temperature dependent heat consumption, which has been adjusted accordingly, data about the duration of heating network operation and data about the number of days in a specific month. This step is brought in chapter 4.
3. Determine the size of heat losses for three different consumers. To do it, we need data about yearly temperature dependent heat consumption, which has been adjusted, data about inlet and outlet temperature of heating network and data about the temperature of the environment where DH network is located. This step is brought in chapter 4.
4. Determine the size of total needed heating for three different consumers. To do it, we need to add together temperature dependent heat consumption – heating and ventilation, temperature independent heat consumption – domestic hot water and heat losses. This step is brought in chapter 4
5. Determining solar power potential and solar resources, calculating global horizontal radiation in a specific location with Hargreaves and Samani temperature-based model. To do it, we need data about extraterrestrial radiation, minimum and maximum temperature. This step is brought in chapter 5.

6. Calculating solar collectors' production in case of different solar collectors areas and applying solar power in district heating in case of different consumers and their heating needs. To do it, we need data about collectors' efficiency, collectors' intercept maximum efficiency, collectors' first and second order loss coefficient, collectors' fluid inlet temperature, daily average ambient air temperature, daily average global radiation on horizontal surface, solar collectors' area. This step is brought in chapter 6.

7. Determining the need of energy storage system and its' volume. Storage is needed if the solar collectors' production exceeds consumption and we need data about the total needed heating for storage to calculate the needed volume. This step can be found in chapter 7.

8. Economical evaluation, feasibility study, calculating levelized cost of heat values. To do it, we need data about the investment size of solar collectors and storage tanks, operation and maintenance expenditures in a specific year, auxiliary energy expenditures in a specific year, discount rate, solar production in a specific year. Levelized cost of heat values can be compared in case of different heat production technologies. This step is done in chapter 8.

4. CONSUMER DESCRIPTION

In this chapter, different consumers are described in terms of heat consumption.

In order to evaluate, how many solar collectors are needed to be installed, we need data about consumers and their total needed heat consumption. Total needed heat consumption can be divided into temperature dependent heat consumption – heating and ventilation, temperature independent heat consumption – domestic hot water and heat losses. In the following, these parameters are calculated step by step. Different heat consumption values are used to create different scenarios. This is because different consumers and locations can have different heat consumption values depending on their size, population and that all is needed to be taken into account.

At first, temperature dependent heat consumption values for heating and ventilation are calculated throughout the year for different consumer profiles as shown in figure (Figure 4.1). Heating and ventilation is a variable load. The different yearly temperature dependent heat consumption values for different consumers are given in table (Table 4.1). Those sizes cover majority of Estonia's small and intermediate scale district heating networks.

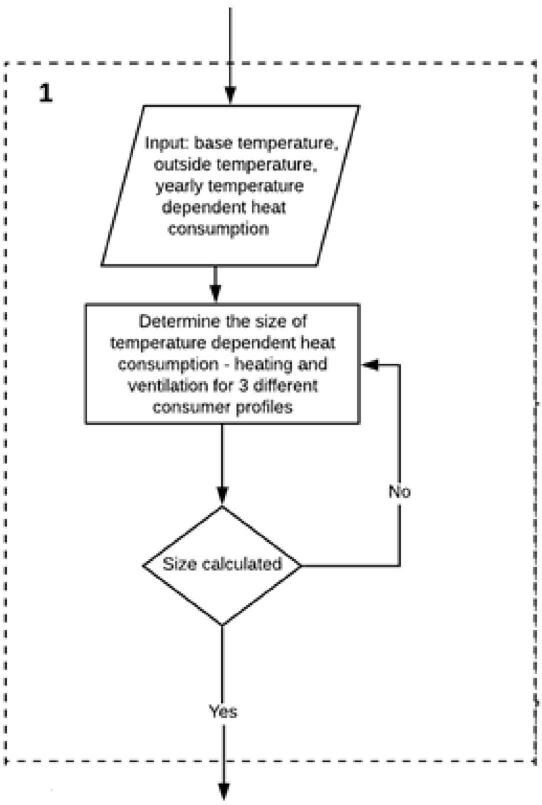

Figure 4.1. Process of calculating temperature dependent heat consumption values for heating and ventilation

Table 4.1. Consumer description in terms of yearly temperature dependent heat consumption

Heating and ventilation, temperature dependent heat consumption	**MWh**
Consumer 1	5000
Consumer 2	10000
Consumer 3	25000

At first, the sum between the difference of daily base temperature and outside temperature is calculated as shown in formula (4.1) and that way the results of degree days are gotten. The base temperature is the outdoor temperature that separates when the building needs heating from when it does not. In this work, the base temperature is given 17 degrees Celsius. The outside temperature is gained from the average temperature in Estonia in the year 2012.

$$S_{days} = \sum T_{base} - T_{out} \tag{4.1}$$

where T_{base} – base temperature, degrees Celsius,

T_{out} – daily outside temperature, degrees Celsius.

The difference between the daily base temperature and outside temperature is taken only, when the base temperature is greater than the daily outside temperature as shown in formula (4.2).

$$T_{base} < T_{out} => 0 \tag{4.2}$$

To get degree hours, we need to multiply degree days by 24 as shown in formula (4.3).

$$S_{hours} = 24 \cdot S_{days} \tag{4.3}$$

where S_{days} – degree days, degrees Celsius x day,

S_{hours} – degree hours, degrees Celsius x hours.

After that, we need to calculate a special factor as shown in formula (4.4)

$$F = \frac{Q}{S_{hours}} \tag{4.4}$$

where F – special factor for calculating power,

Q – heat consumption per year, MWh.

To get daily power, we need to use formula (4.5).

$$P_{daily} = (T_{base} - T_{out}) \cdot F \tag{4.5}$$

where P_{daily} – daily power, MW.

To get temperature dependent heat consumption values for heating and ventilation, we need to use formula (4.6).

$$Q_{daily} = 24 \cdot P \tag{4.6}$$

where Q_{daily} – daily heat consumption, MWh.

The results, values of monthly temperature dependent heat consumption for heating and ventilation for different consumers are brought in table (Table 4.2) and figure (Figure 4.2).

Table 4.2. The monthly values of monthly temperature dependent heat consumption for heating and ventilation for different consumers

Consumer	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Consumer 1, MWh	787	824	663	475	230	122	24	73	247	438	661	768
Consumer 2, MWh	1573	1647	1326	949	459	243	48	147	494	875	1322	1535
Consumer 3, MWh	3933	4118	3315	2373	1148	608	120	367	1235	2188	3305	3838

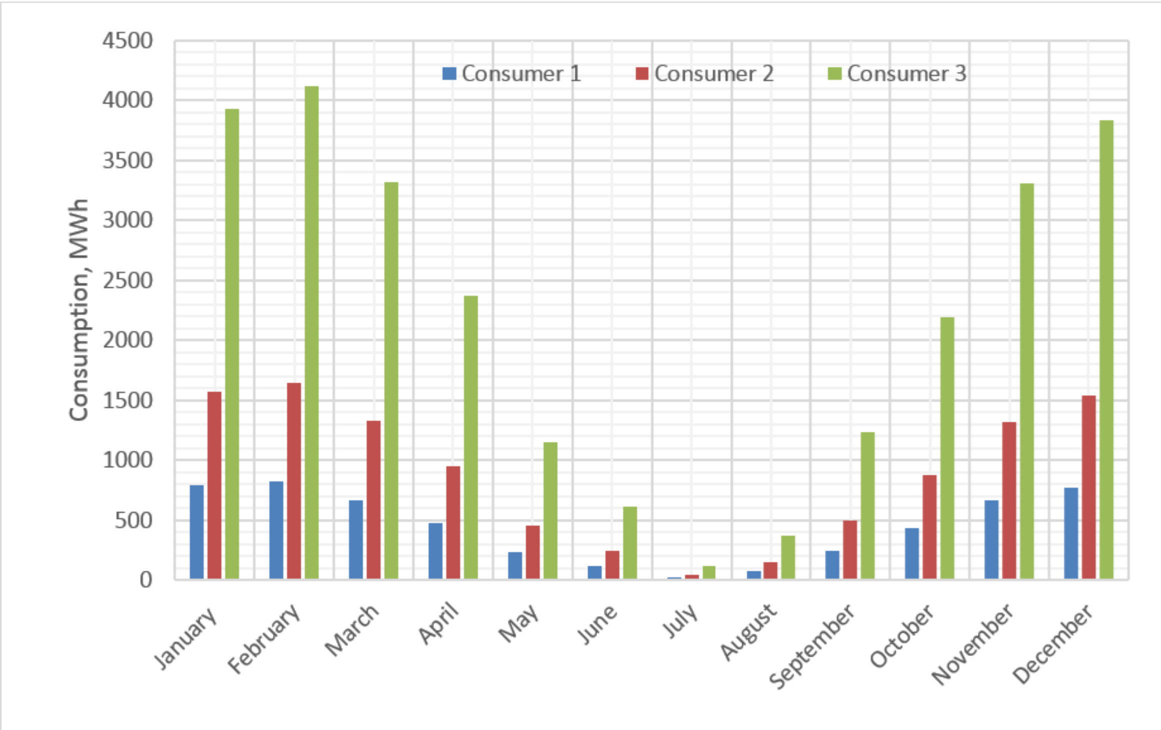

Figure 4.2. Monthly heating and ventilation for different consumers

In the next step, temperature independent heat consumption values for domestic hot water are calculated for different consumers as shown in figure (Figure 4.3). Domestic hot water is a fixed load throughout the year (daily average values are mainly constant). The yearly temperature independent heat consumption values for domestic hot water for different consumers are brought in table (Table 4.3). Also, values of duration of heating network operation are brought there (Table 4.3). The heat consumption values are gotten by multiplying temperature dependent heat consumption values by 0,15.

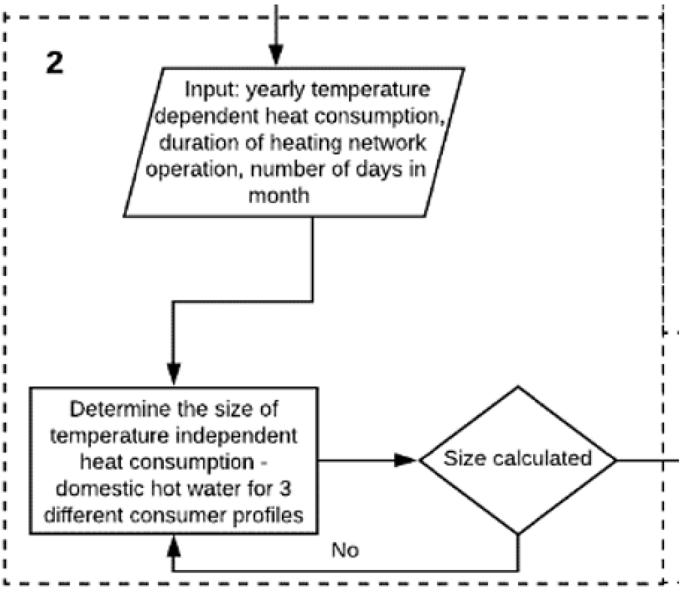

Figure 4.3. Process of calculating temperature independent heat consumption values for domestic hot water

Table 4.3. Consumer description in terms of domestic hot water, temperature independent heat consumption

Domestic hot water, temperature independent heat consumption	**MWh**
Consumer 1	750
Consumer 2	1500
Consumer 3	3750
Duration of heating network operation, days	366
Duration of heating network operation, hours	8784

To get the values of daily power, formula (4.7) is used.

$$P_{daily} = \frac{t}{Q} \quad (4.7)$$

where P_{daily} – daily power value, MW,

t – duration of heating network operation, hours,

Q – heat consumption per year, MWh.

To get monthly temperature independent heat consumption for domestic hot water, formula (4.8) is used.

$$Q_{month} = P_{daily} \cdot nr_{days} \quad (4.8)$$

where nr_{days} – number of days in a specific month,

Q_{month} - monthly heat consumption values, MWh.

The results of the calculations, the values of monthly temperature independent heat consumption for domestic hot water for different consumers are brought in table (Table 4.4) and figure (Figure 4.4).

Table 4.4. The monthly values of monthly temperature independent heat consumption for domestic hot water for different consumers

Consumer	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Consumer 1, MWh	64	59	64	61	64	61	64	64	61	64	61	64
Consumer 2, MWh	127	119	127	123	127	123	127	127	123	127	123	127
Consumer 3, MWh	318	297	318	307	318	307	318	318	307	318	307	318

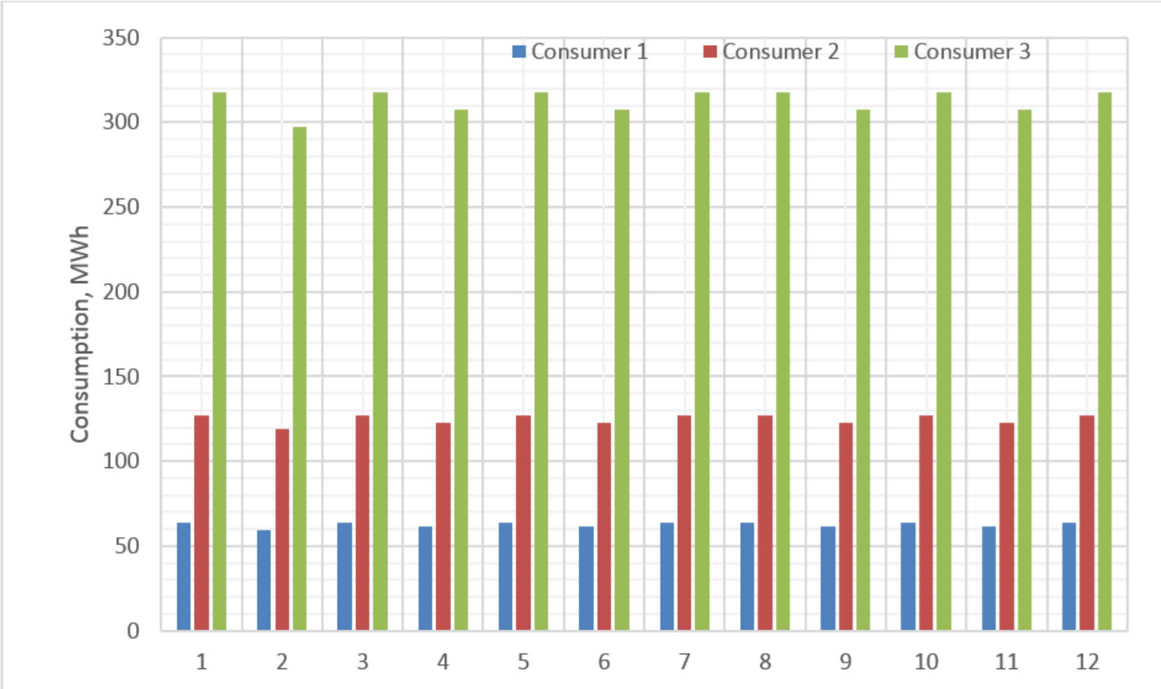

Figure 4.4. Monthly domestic hot water for different consumers

In the next step, the values of heat losses are calculated for different consumers as shown in figure (Figure 4.5).

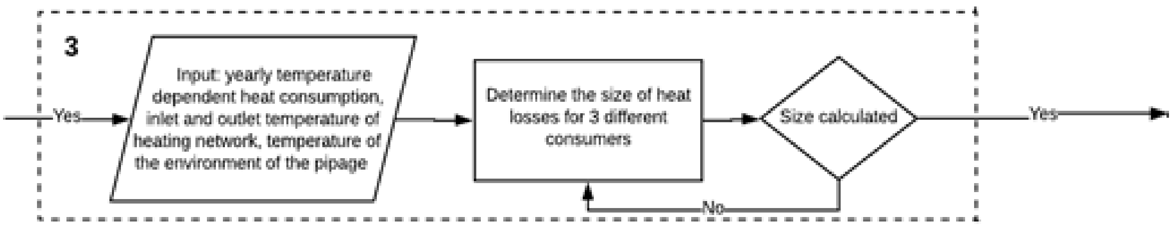

Figure 4.5. Process of calculating heat losses

The yearly heat consumption values are gotten by multiplying temperature dependent heat consumption values by 0,25 for different consumers. It is taken into account, that we are dealing with an older district heating network as with newer district heating networks, temperature dependent heat consumption values should be multiplied somewhere around by 0,15. To calculate heat losses, we need inlet and outlet temperature values of the heating network. These values depend on the outside temperature also. This value is summed up and divided by two to get an average value. Also, we need data about the temperature of the environment of the pipeage. In this work, this is taken 6 degrees Celsius, which suits for an underground pipeage. After that, the difference between the temperature of the environment and the average temperature value of the heating network is taken. To get degree days, the sum of that difference is taken as shown in formula (4.9). To get degree hours, the degree days are multiplied by 24. After that, a factor is gotten by dividing heat losses per year with degree hours. To get power, the factor value is multiplied with the daily values of the difference between the temperature of the environment and the average value of the heating network. To get the values of heat losses, the power is multiplied by 24. The monthly heat losses values are brought in table (Table 4.5) and figure (Figure 4.6) for different consumers.

$$S_{days} = \sum T_{network} - T_{out} \tag{4.9}$$

where $T_{network}$ – average temperature value of the heating network,

T_{out} – temperature of the environment, degrees Celsius.

Table 4.5. The monthly values of heat losses for different consumers

Consumer	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
Consumer 1, MWh	109	108	105	99	104	101	104	104	100	103	104	110	1250
Consumer 2, MWh	218	215	210	199	208	201	208	208	201	206	208	219	2500
Consumer 3, MWh	546	538	525	496	519	503	520	520	502	514	520	548	6250

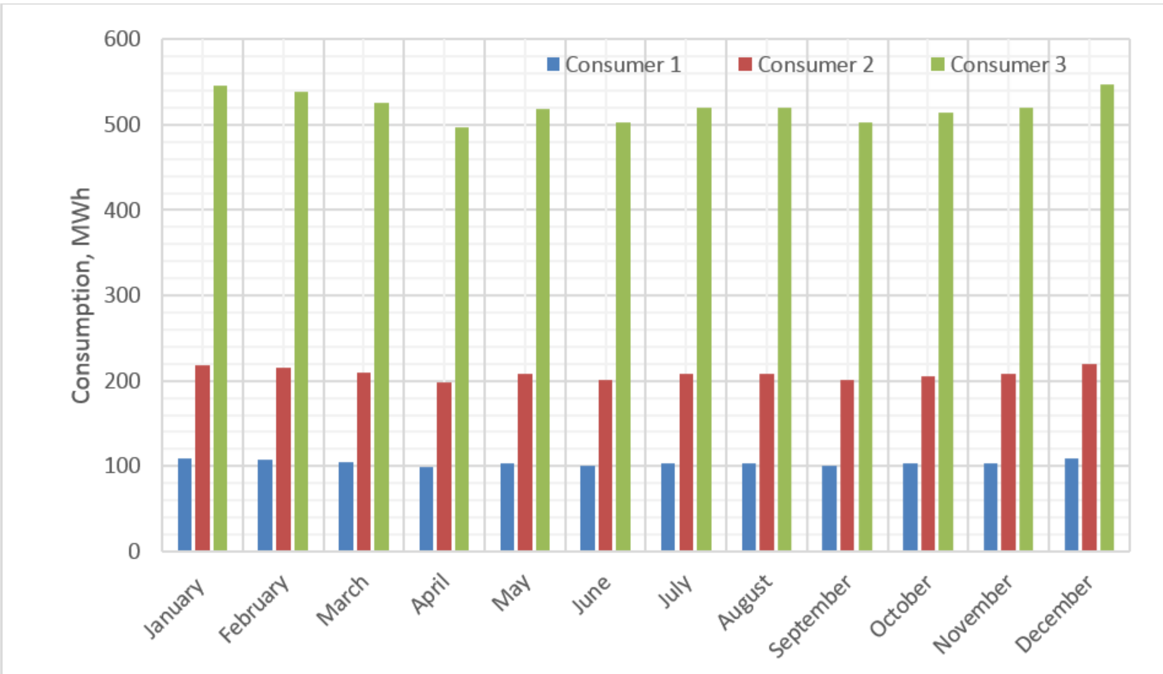

Figure 4.6. Monthly losses for different consumers

The last step is to get the whole monthly total needed heating for different consumers as seen in figure (Figure 4.7) by summing up the values of heating and ventilation, domestic hot water and monthly losses as seen in formula (4.10).

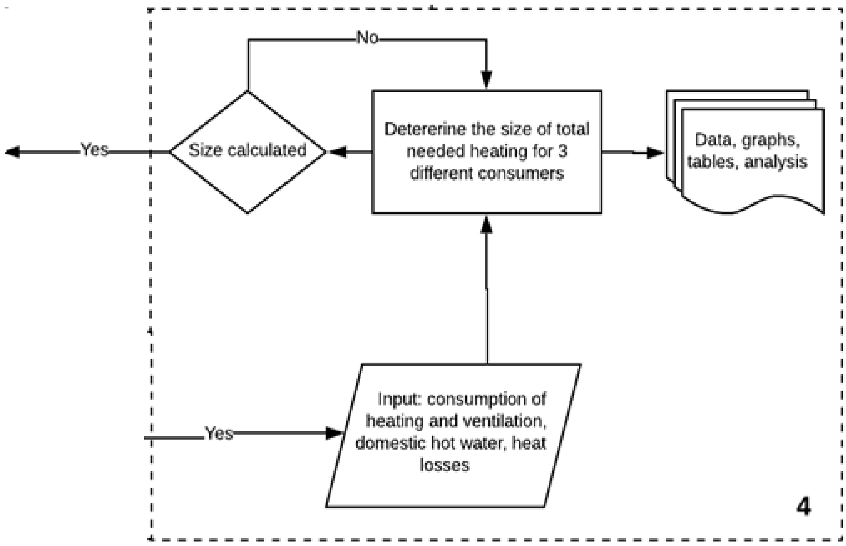

Figure 4.7. Process of calculating consumers' total heat needs

$$Q = Q_{heating\ and\ ventilation} + Q_{water} + Q_{losses} \quad (4.10)$$

where Q – monthly needed heating, MWh,

$Q_{heating\ and\ ventilation}$ – heat consumption of heating and ventilation, MWh,

Q_{water} – heat consumption values of domestic hot water, MWh,

Q_{losses} – heat consumption values of losses, MWh.

The results of the calculations, the values of monthly total needed heating for different consumers are brought in table (Table 4.6) and figure (Figure 4.8). The heat generation equipment must cover these values.

Table 4.6. Consumer description in terms of total needed heating

Consumer	1	2	3	4	5	6	7	8	9	10	11	12	Total
Consumer 1, MWh	959	991	832	635	397	284	191	241	409	604	826	941	7310
Consumer 2, MWh	1919	1981	1663	1271	794	567	383	482	818	1208	1653	1881	14619
Consumer 3, MWh	4796	4953	4158	3177	1985	1419	957	1204	2044	3020	4132	4703	36548

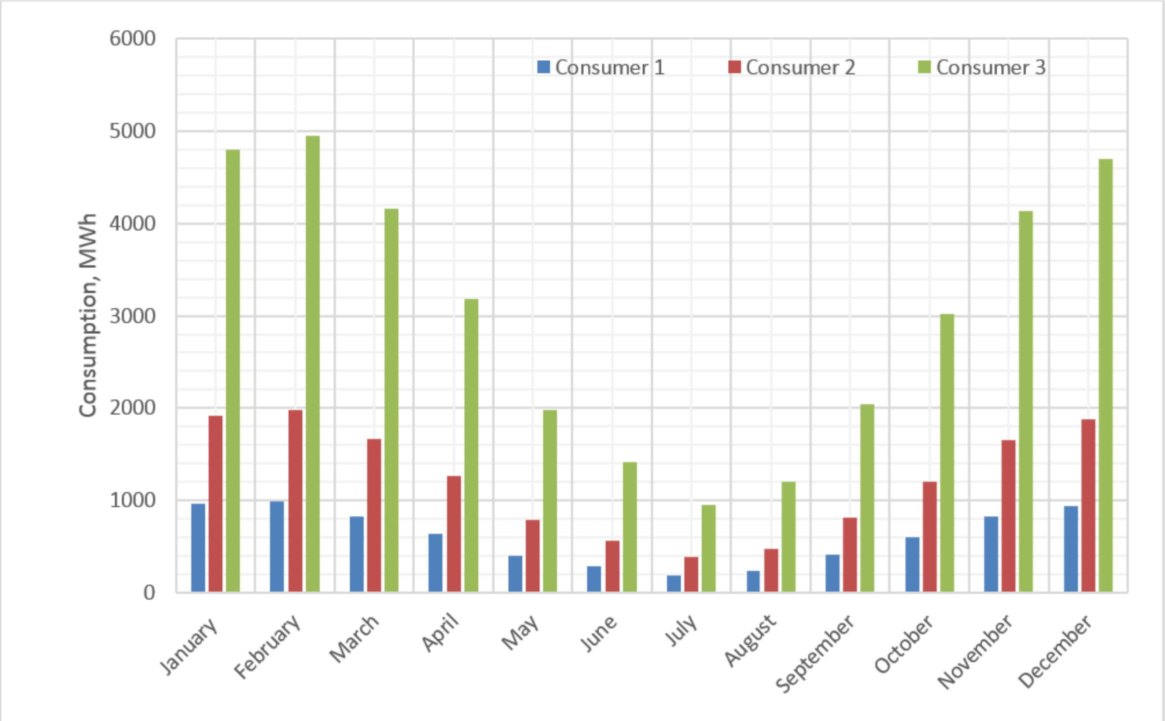

Figure 4.8. Monthly needed heating for different consumers

5. SOLAR POWER POTENTIAL AND SOLAR RESOURCES

In this chapter, the values of global horizontal irradiation are calculated to determine the solar power potential and solar resources of a location as shown in figure (Figure 5.1).

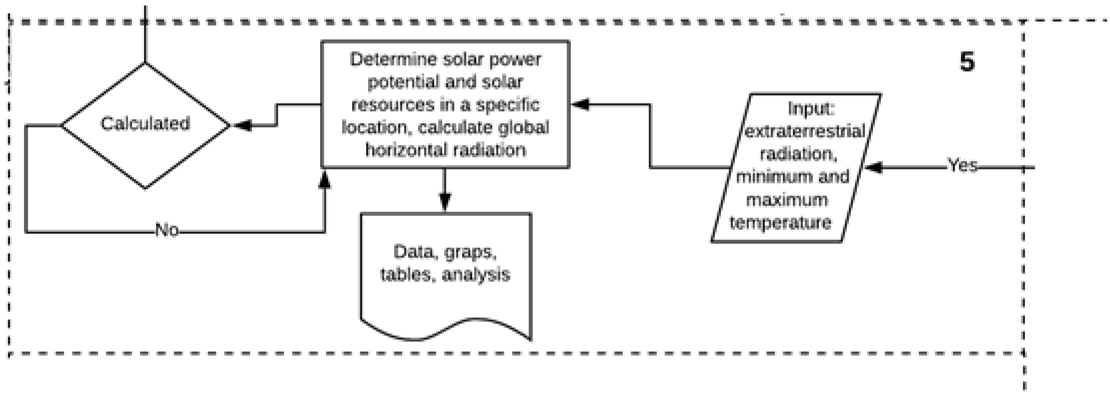

Figure 5.1. Process of calculating daily average global radiation on a horizontal surface to determine solar power potential and resources

When applying solar power into district heating networks, it is first needed to determine the solar resources available in the country.

In Estonia, the global horizontal irradiation is between 949-1095 kWh/m^2 as shown in figure (Figure 5.2). The higher values of global horizontal irradiation are at East Estonia, 1022-1095 kWh/m^2. Other places in Estonia have the values of global horizontal irradiation between 949-1022 kWh/m^2. [14]

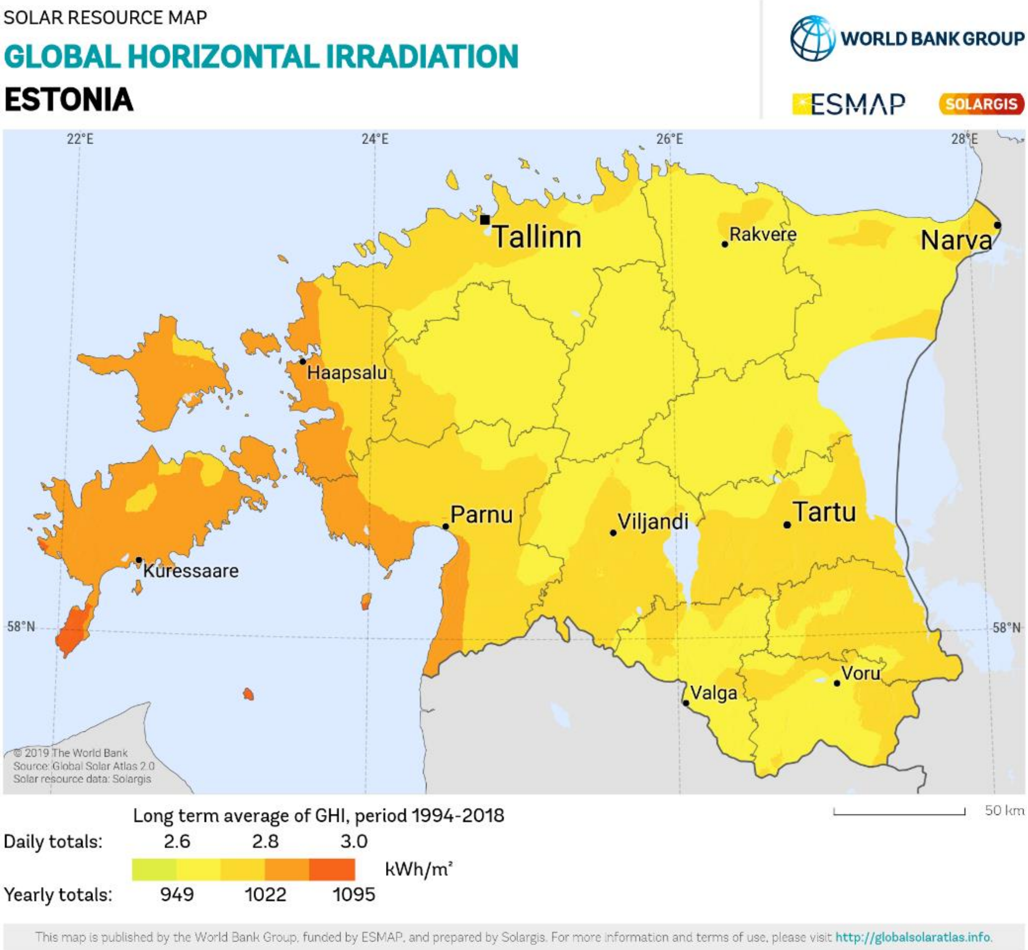

Figure 5.2. Global horizontal irradiation in Estonia [14]

If different global horizontal irradiation values are compared in the world by continents as shown in figure (Figure 5.3), it can be seen that Estonia has similar values of global horizontal irradiations as Europe, North Asia and northern part of North America. Other places have higher global horizontal irradiation values than the locations mentioned before. [14]

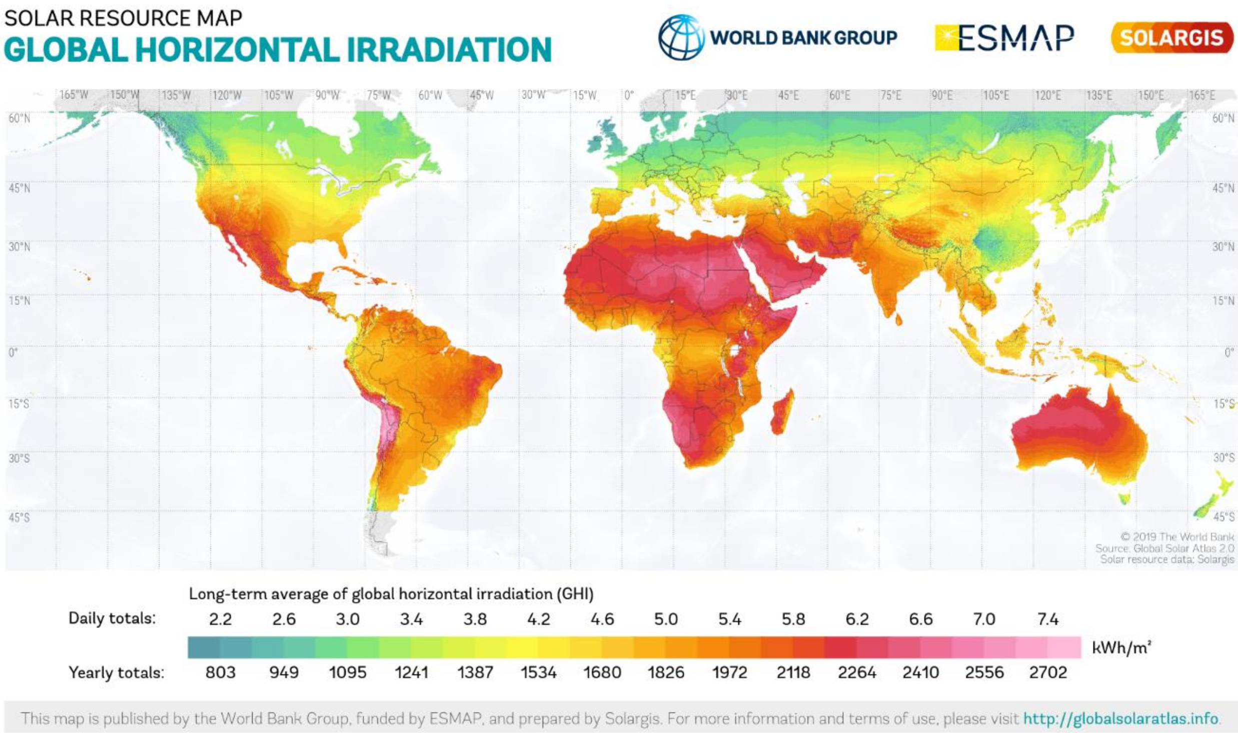

Figure 5.3. Global horizontal irradiation in the world [14]

When evaluating solar resources at a specific location, the best way to do it is to use special equipment to measure direct normal irradiance and diffuse horizontal irradiance. When this data is measured, we can compute global horizontal irradiance with formula (5.1). [15, 16]

$$GHI = DNI \cdot \cos\Theta + DHI \qquad (5.1)$$

where GHI – global horizontal irradiance (W/m^2),

DNI – direct normal irradiance (W/m^2),

DHI – diffuse horizontal irradiance (W/m^2),

ϴ – solar elevation angle (degrees).

Often, we do not have such equipment at a specific location and other means of data is necessary to obtain to evaluate solar resources. One way to do it is to use the Hargreaves and Samani temperature-based model as seen in formula (5.2), which takes into account temperature and extraterrestrial radiation. In the following work, this equation is used to calculate the solar collectors' production. This is done, because temperature data is almost always available at a specific location and the results of the measured values computed with formula (5.1) and the estimation made with formula (5.2) are very close. [17, 18]

$$H = H_0 \cdot K_r \cdot (T_{max} - T_{min})^{0,5} \qquad (5.2)$$

where H – daily average global radiation on a horizontal surface (W/m2),

H_0 – daily extraterrestrial radiation (W/m^2),

K_r – empirical coefficient, for coastal region 0,19 and for interior region 0,16,

T_{max} – maximum air temperature (degrees Celsius),

T_{min} – minimum air temperature (degrees Celsius).

Another estimation is done with Hargreaves and Samani modified model as seen in formula (5.3). That takes also humidity into account besides temperature and extraterrestrial radiation. [19, 18]

$$H = 0{,}338 \cdot H_0 \cdot (T_{max} - T_{min})^{0,3} \cdot \left(1{,}001 - \frac{RH}{100}\right)^{0,2} \qquad (5.3)$$

where H – daily average global radiation on a horizontal surface (W/m^2),

H_0 – daily extraterrestrial radiation (W/m^2),

T_{max} – maximum air temperature (degrees Celsius),

T_{min} – minimum air temperature (degrees Celsius),

RH – relative humidity (%).

The monthly and daily results of global radiation on a horizontal surface based on formulas (5.1, 5.2 and 5.3) are brought in table (Table 5.1) and figures (Figure 5.4 and Figure 5.5).

Table 5.1. Monthly global horizontal radiation

	Estimation 1, kWh/m²	**Estimation 2, kWh/m²**	**Measured, kWh/m²**
January	11,51	10,06	20,43
February	28,81	23,85	53,22
March	72,75	65,49	110,39
April	113,36	101,86	111,65
May	184,17	163,32	165,58
June	186,18	167,67	163,63
July	193,55	164,25	181,42
August	157,34	129,04	152,45
September	92,61	76,73	100,02
October	42,53	34,78	59,04
November	15,37	12,92	28,71
December	8,28	7,44	19,56
Total	1106,46	957,42	1166,09

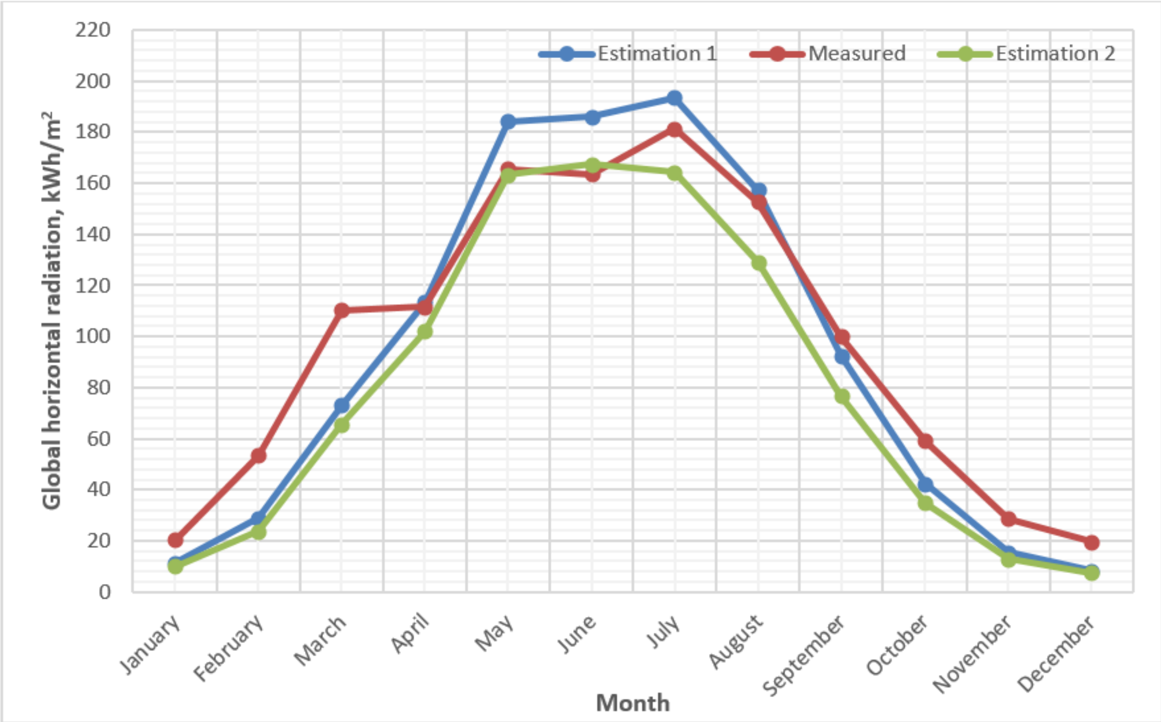

Figure 5.4. Monthly global horizontal radiation

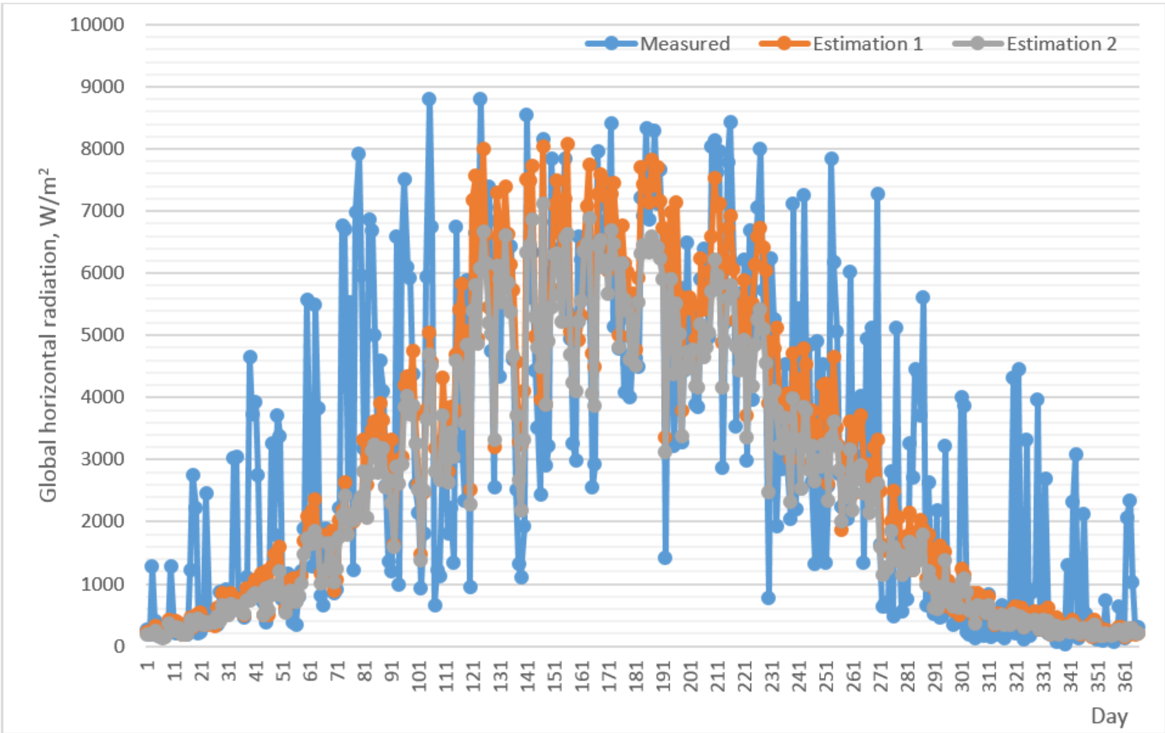

Figure 5.5. Daily global horizontal radiation

It can be concluded, that with estimation 1, 2 and measured monthly global horizontal radiation values, the results are closer together, while the daily values can vary a lot.

6. APPLYING SOLAR POWER IN DISTRICT HEATING NETWORKS IN CASE OF DIFFERENT CONSUMERS

In this chapter, it is shown how solar collectors with different areas are integrated into district heating networks in case of different heat consumption, different values of total needed heating. The solar collectors' production is calculated as seen in figure (Figure 6.1).

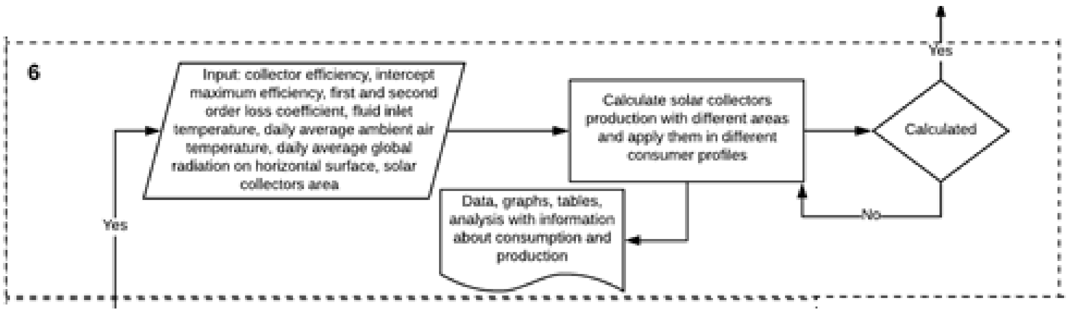

Figure 6.1. Process of calculating solar collectors' production

Now, we can begin to compute the solar output power. A popular solar collector is selected, see figures (Figure 6.2, Figure 6.3), and the necessary data is selected from the data sheet. The solar collector has the following components: vacuum tube; heat pipe, silicon cotton stopple and aluminium fin; manifold, insulation; tail stock; frame; stand. The efficiency is calculated with formula (6.1). [20]

$$\eta = \eta_0 - a_1 \cdot \frac{T_i - T_{out}}{H} - a_2 \cdot \frac{(T_i - T_{out})^2}{H} \quad (6.1)$$

where η – collector efficiency,

η_0 – intercept maximum efficiency,

a_1 – first order loss coefficient ($\frac{W}{m^2 \cdot K}$),

a_2 – second order loss coefficient ($\frac{W}{m^2 \cdot K^2}$),

T_i – fluid inlet temperature (degrees, Celsius),

T_a – daily average ambient air temperature (degrees Celsius),

H - daily average global radiation on a horizontal surface (W/m^2).

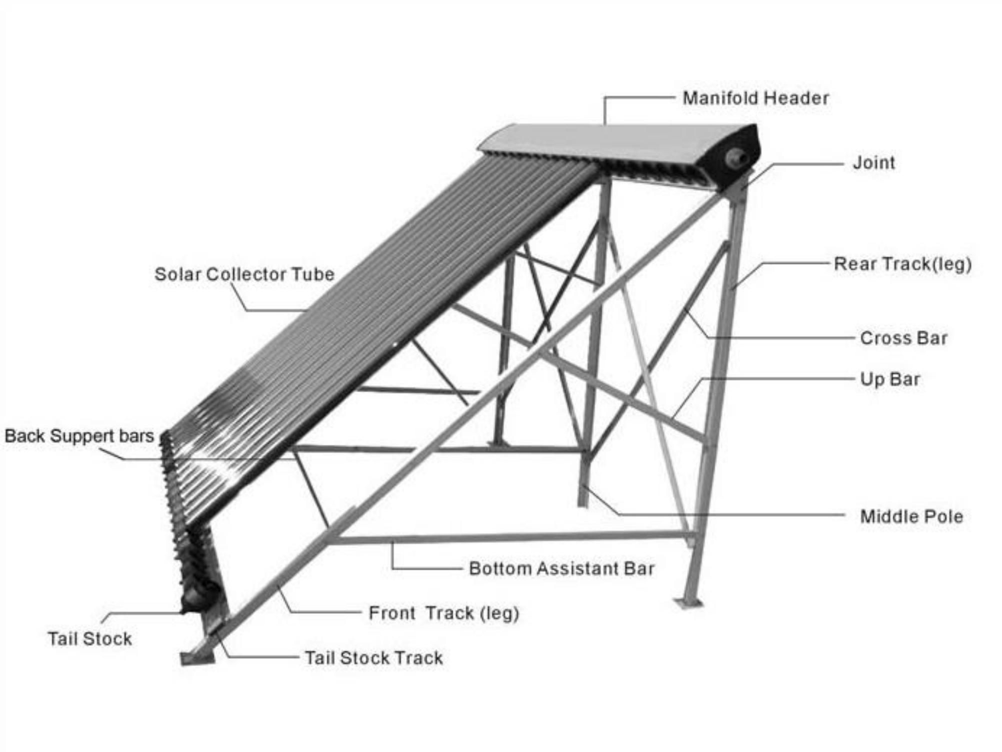

Figure 6.2. Sunrain solar heat pipe collector 1 [20]

Figure 6.3. Sunrain solar heat pipe collector 2 [20]

After getting the values of efficiency, the solar collectors output power with different areas are calculated with formula (6.2) and the results are brought in table (Table 6.1).

$$P_{out} = H \cdot \eta \cdot A \qquad (6.2)$$

where P_{out} – daily solar collectors output power (kW),

H – daily average global radiation on a horizontal surface, Hargreaves and Samani temperature-based model data was used (W/m^2),

η - collector efficiency,

A – solar collectors' area (m^2).

Table 6.1. Monthly and annual solar collectors heat production in MWh with different installed collector's areas

Area	**Heat production, MWh**												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
500 m^2	2	9	25	40	66	67	70	57	33	14	4	1	388
3000 m^2	13	52	149	240	398	403	420	340	196	84	23	7	2325
5000 m^2	22	86	249	400	663	672	700	566	327	141	38	11	3875
1000 m^2	4	17	50	80	133	134	140	113	65	28	8	2	775
10 000 m^2	45	172	497	801	1326	1344	1400	1132	654	281	77	22	7750
2500 m^2	11	43	124	200	331	336	350	283	163	70	19	5	1938
12 500 m^2	56	215	622	1001	1657	1679	1750	1416	817	352	96	27	9688
25 000 m^2	112	430	1244	2002	3314	3359	3499	2831	1635	703	192	55	19376

Three different scenarios are created for different consumers and solar collector output values. The values of total needed heating for three different consumers are brought in chapter (4). In the figures, the number behind the area marks the solar collectors' area in square meters. If the solar collectors output power is bigger than the whole needed heating, some kind of a thermal energy storage system is needed. A possible solution, water thermal energy storage system will be discussed in chapter (7). If the solar collectors output power stays lower than the whole needed heating throughout the year, there is no need for a thermal energy storage system. This also means less money is required for investments. If the solar collectors production does not cover the consumption in some days or months, other heat generation equipment is needed, which is not discussed in this work.

The first scenario, monthly and daily consumers' total heat needs (7310 MWh) and solar production (388, 2325 and 3875 MWh) are brought in figures (Figure 6.4, Figure 6.5).

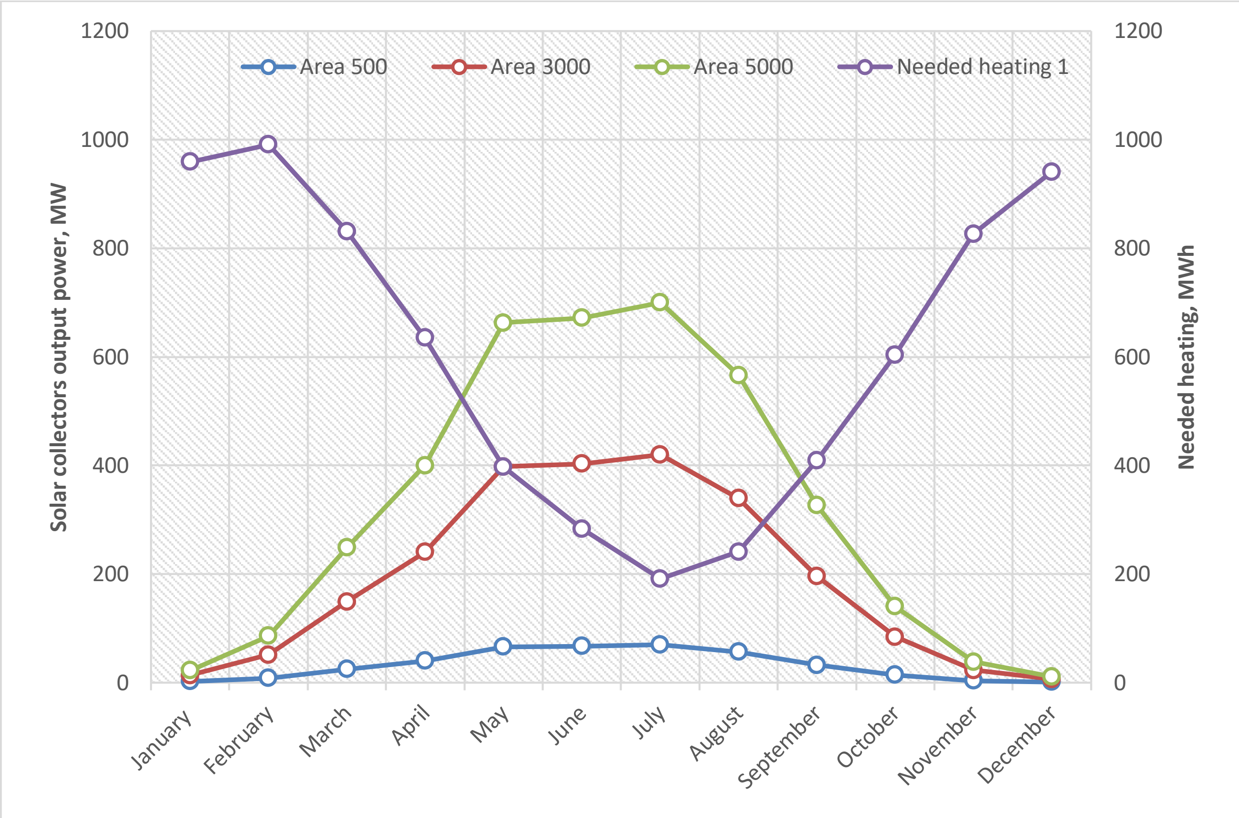

Figure 6.4. Scenario 1, consumer 1 and monthly solar collectors' production

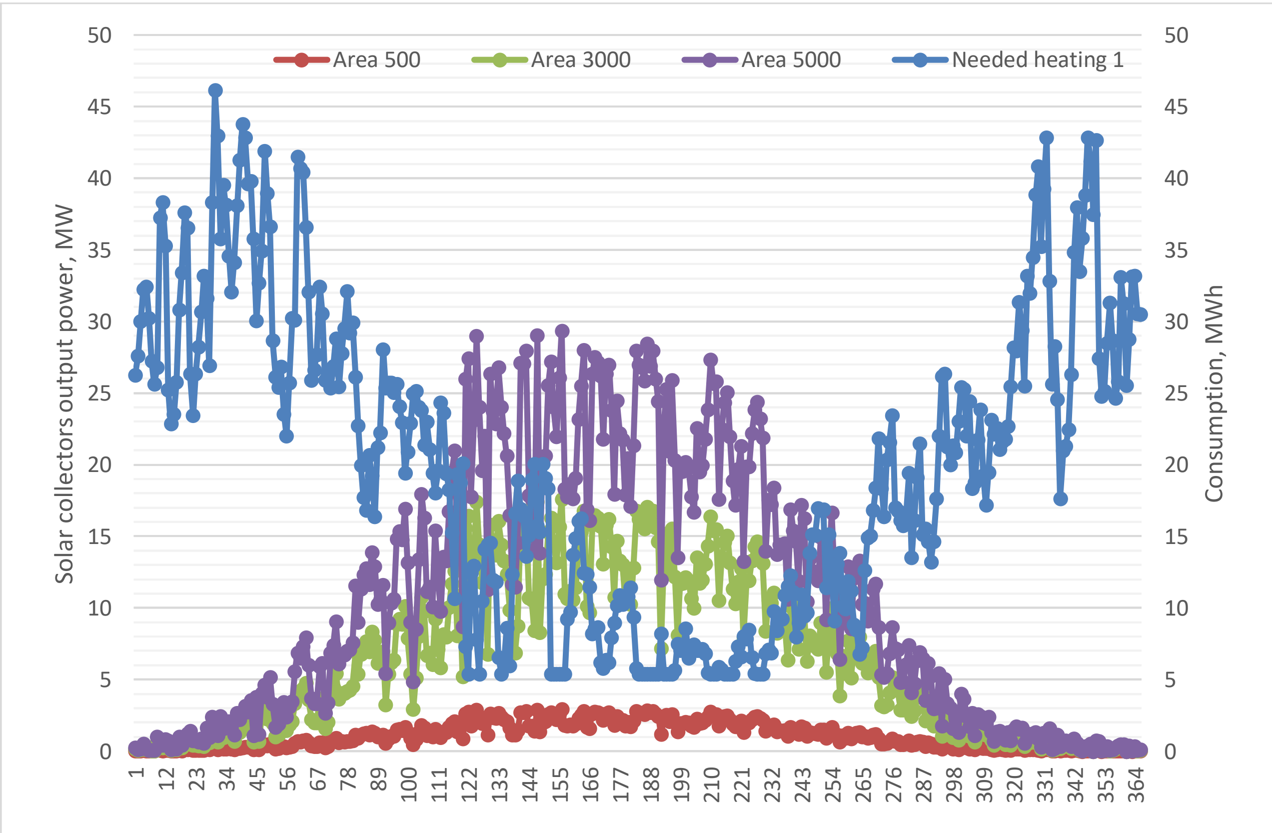

Figure 6.5. Scenario 1, consumer 1 and daily solar collectors' production

The second scenario, monthly and daily consumers' total heat needs (14 619 MWh) and solar production (775, 3875 and 7750 MWh) are brought in figures (Figure 6.6, Figure 6.7).

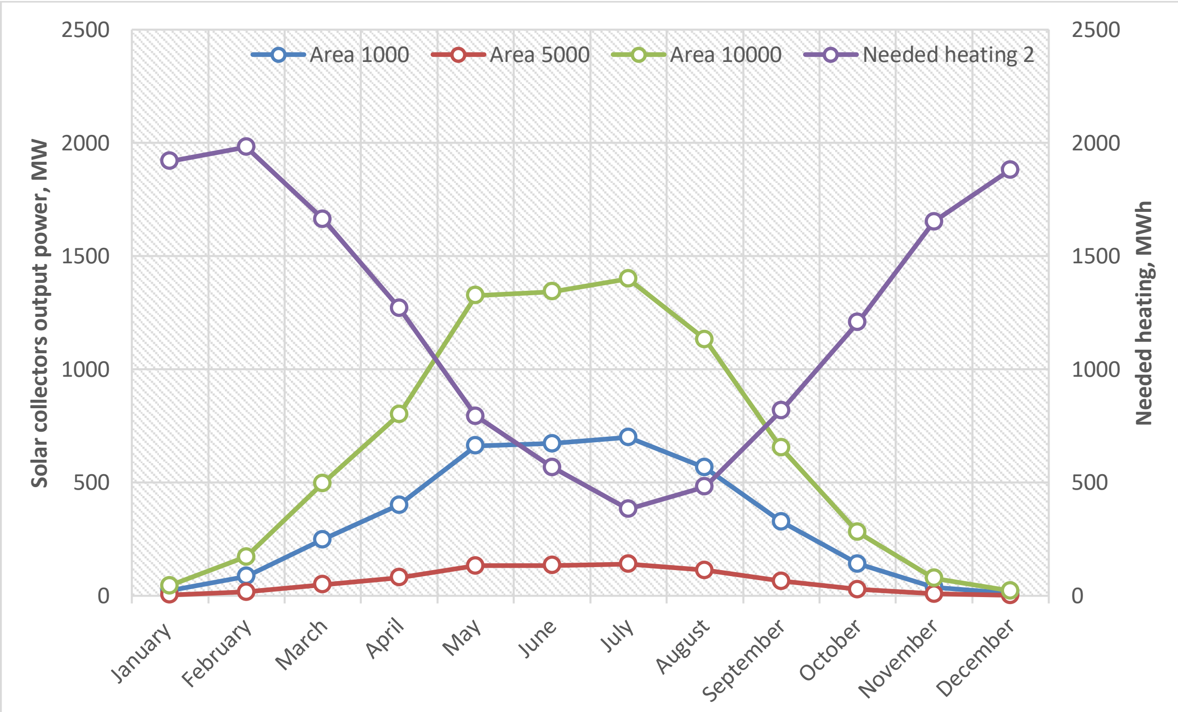

Figure 6.6. Scenario 2, consumer 2 and monthly solar collectors' production

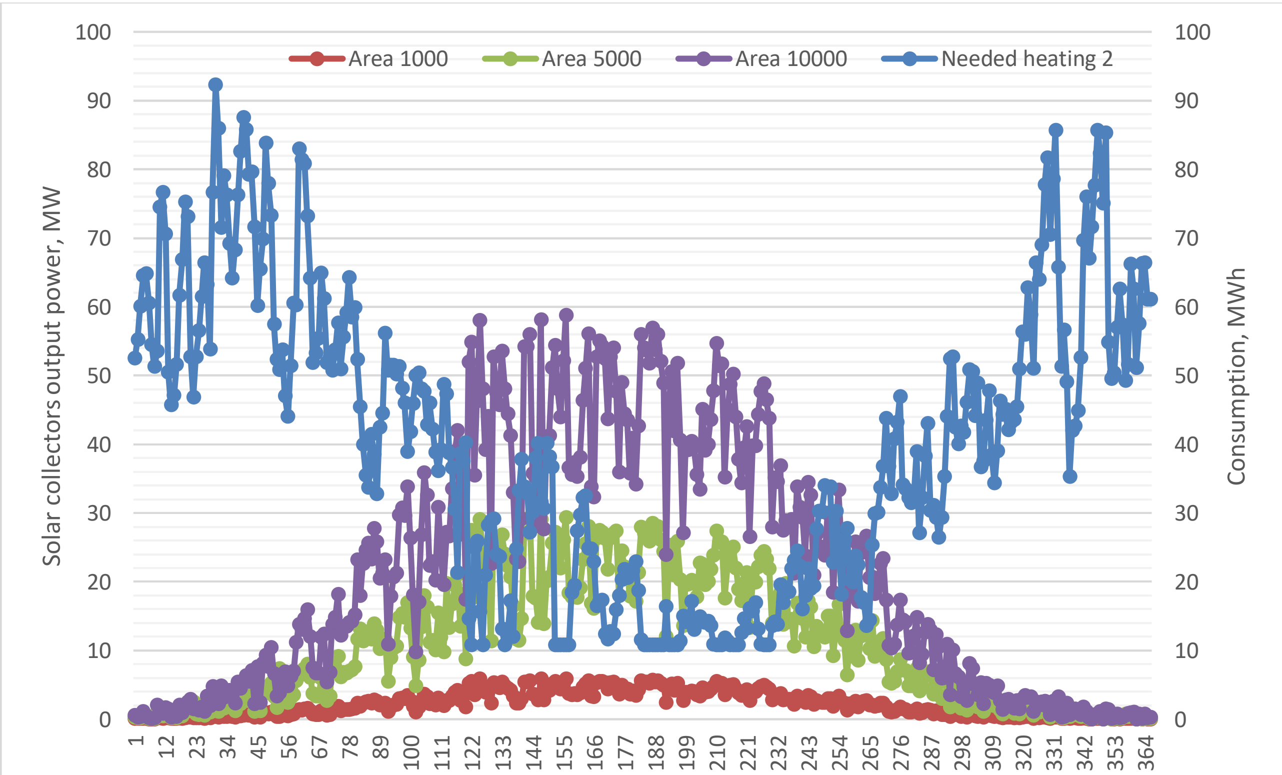

Figure 6.7. Scenario 2, consumer 2 and daily solar collectors' production

The third scenario, monthly and daily consumers' total heat needs (36 548 MWh) and solar production (1938, 9688 and 19 376 MWh) are brought in figures (Figure 6.8, Figure 6.9).

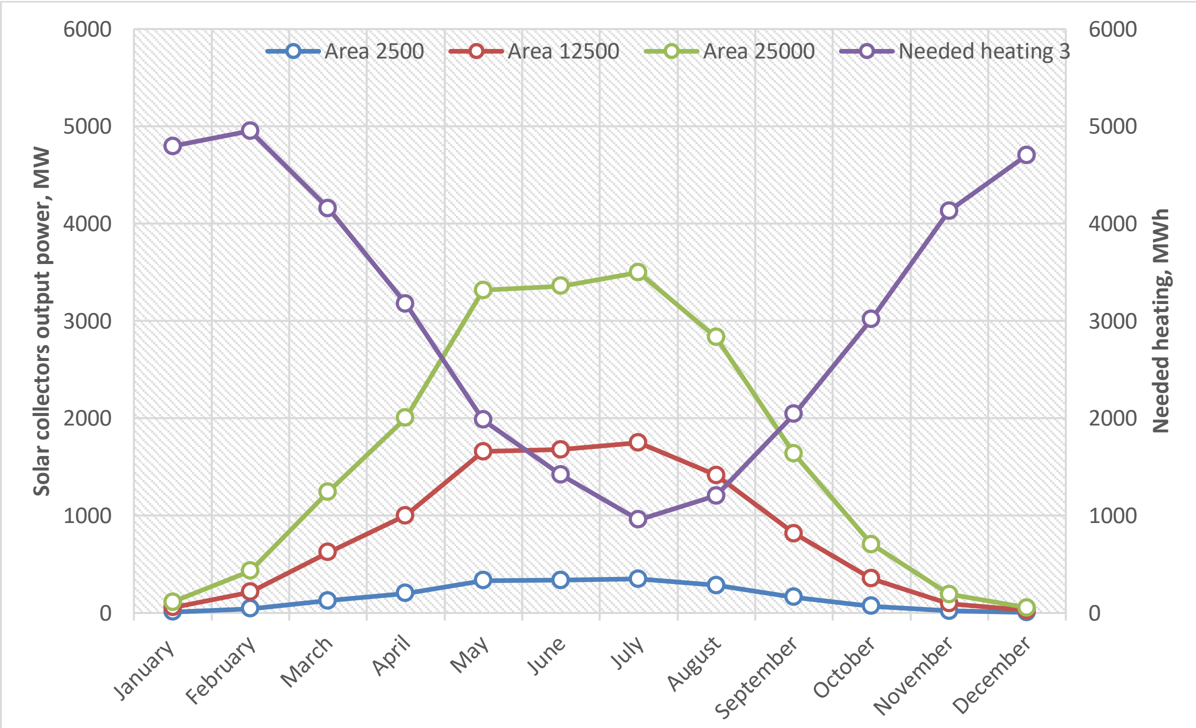

Figure 6.8. Scenario 3, consumer 3 and monthly solar collectors' production

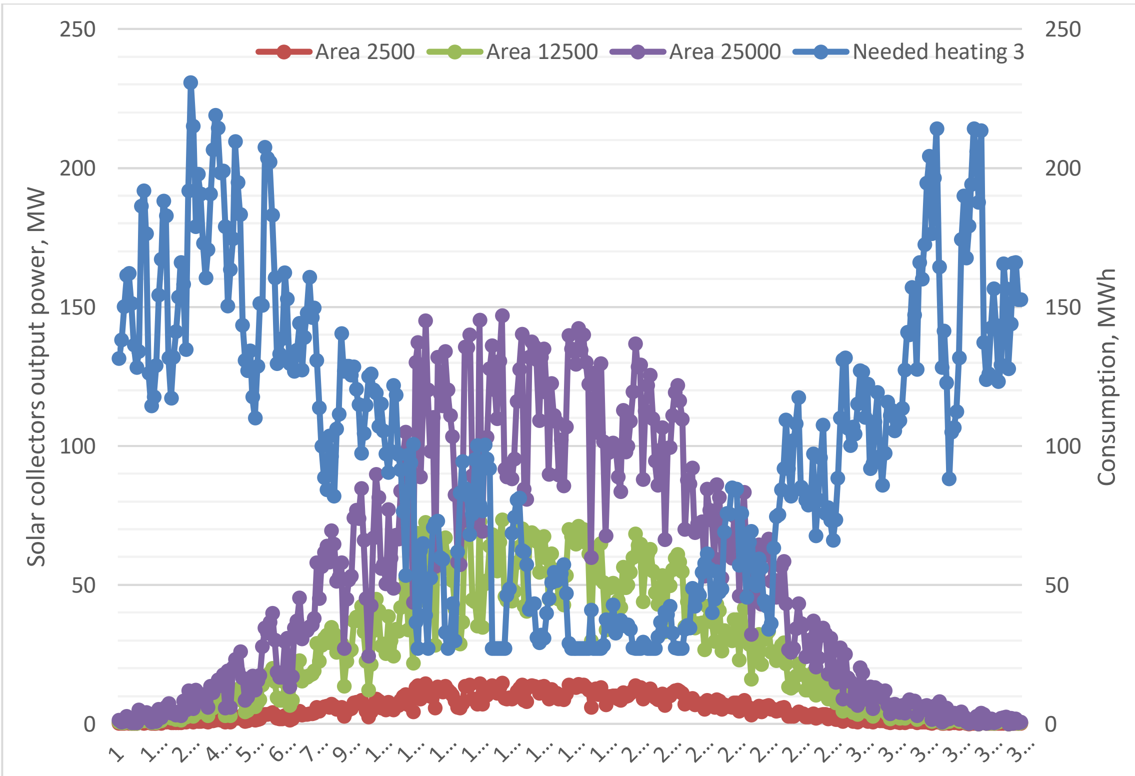

Figure 6.9. Scenario 3, consumer 3 and daily solar collectors' production

To get a better overview of the different consumers and solar collectors output power, relative numbers are used and the results are shown in figures (Figure 6.10, Figure 6.11). Relative numbers are gotten the following way: first we divide the monthly values of needed heating and solar collectors output power with the yearly needed heating; secondly, we find the highest value of the relative number, use it as a base and then divide all the relative numbers with that base.

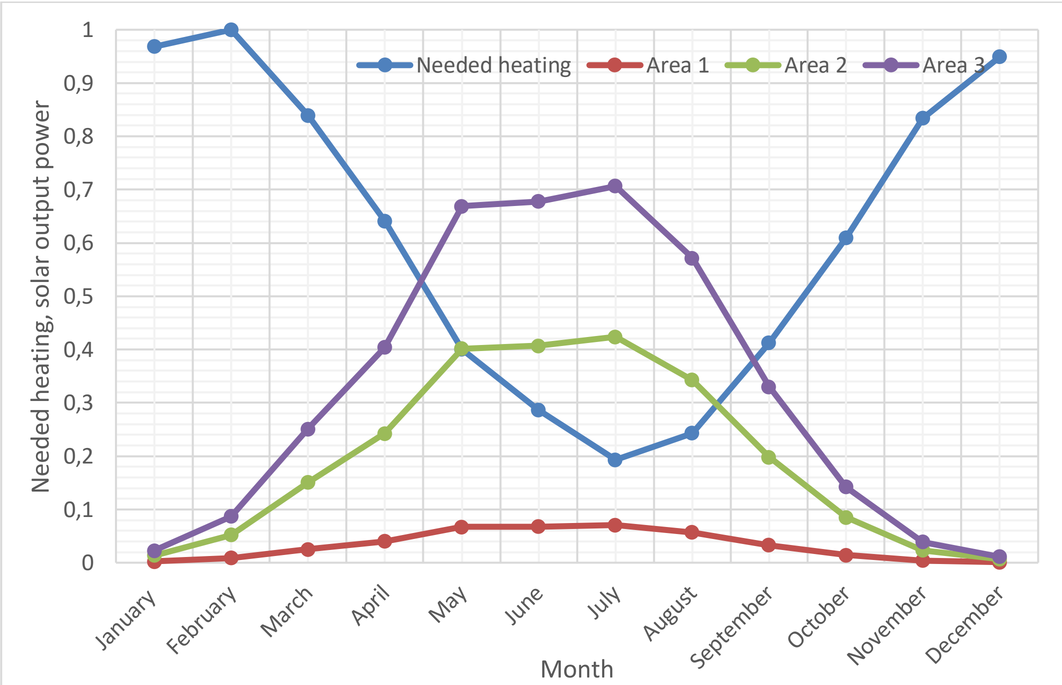

Figure 6.10. Monthly solar collectors' production and needed heating using index numbers'

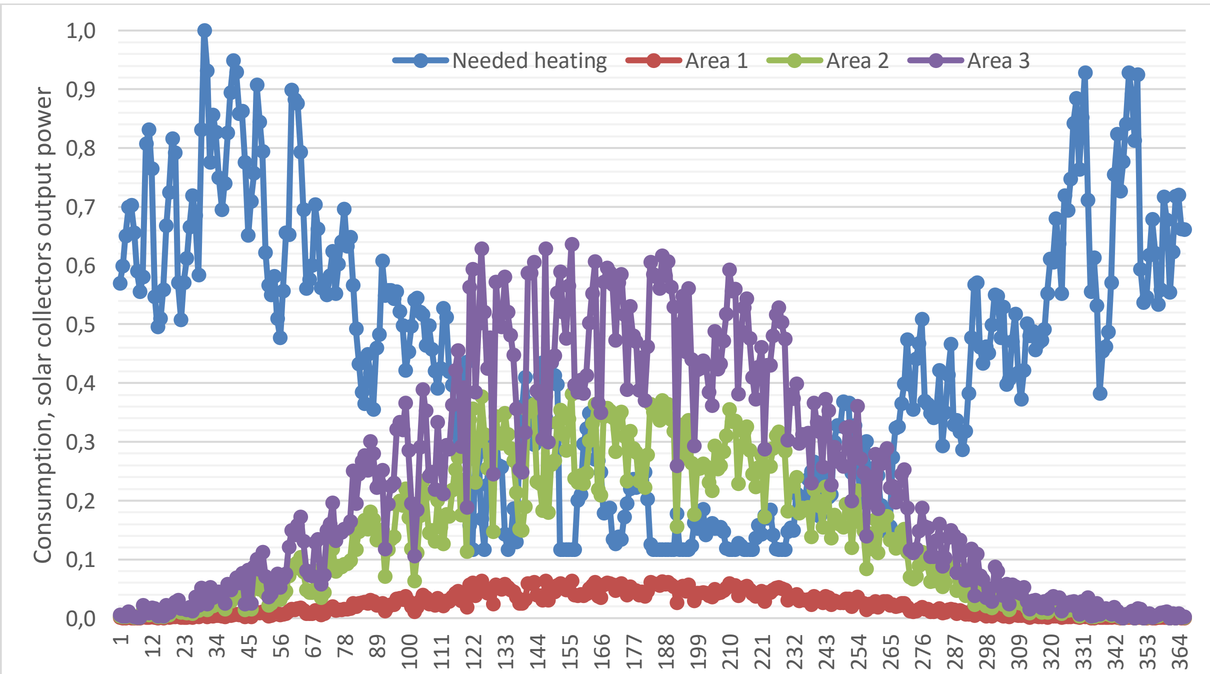

Figure 6.11. Daily solar collectors' production and needed heating using index numbers

It can be seen from the figures above, that monthly consumption and solar collectors' production does not vary a lot. The differences can be huge however, if we look at daily consumption and solar collectors' production. This means, that some kind of a short-term storage device is needed, for example a storage tank. In this work, this topic is not handled further, but must be taken into account, when installing solar collectors to district heating network in real situations.

7. WATER THERMAL ENERGY STORAGE SYSTEM

In this chapter, the need of a water thermal energy storage system has been discussed in case the solar collectors' production exceeds the heat consumption, total needed heating in a bigger proportion as shown in figure (Figure 7.1).

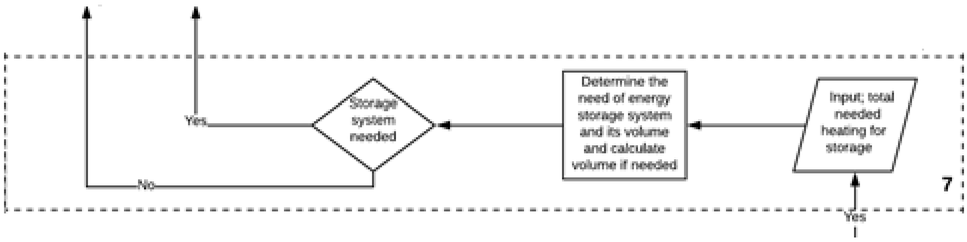

Figure 7.1. Process of calculating the need for water thermal energy storage tank

Like mentioned in the previous chapter, when the output power of the solar collectors exceeds the total needed heat demand in some months, there is a need to store the energy. This is illustrated in figure (Figure 7.2), where we can see that solar collectors with area 1 do not need any storage, while solar collectors with area 2 and 3 require energy storage that corresponds to the hatched area with marked colour. A water thermal energy storage system is used in this work.

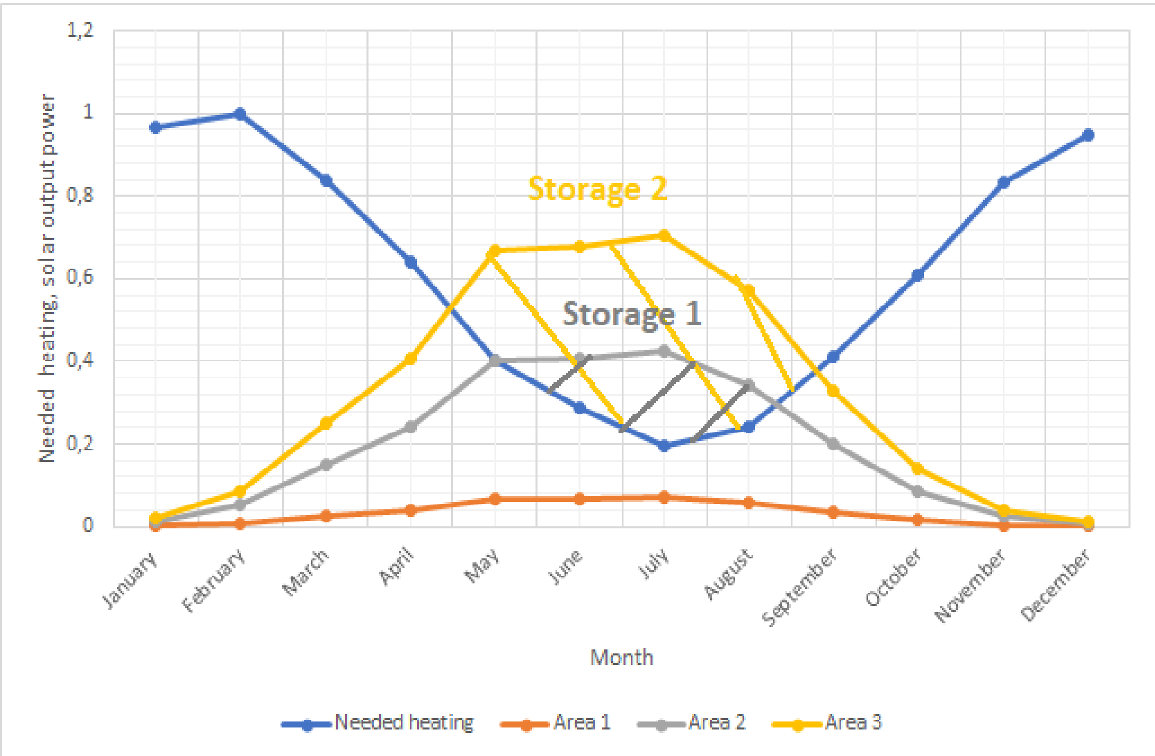

Figure 7.2. Need for storage in case of different solar collectors' areas

To calculate the exact energy needed to be stored in different scenarios brought in chapter (6), we need to do the following. From formula (7.1), it can be seen that we need to sum up the monthly differences between the solar collectors' production and total needed heating, total heat consumption.

$$Q_{storage} = \sum Q_{production} - Q_{consumption} \tag{7.1}$$

where $Q_{consumption}$- total needed heating, MWh,

$Q_{production}$- solar collectors production, MWh,

$Q_{storage}$- amount of energy needed to be stored, MWh.

This is done only if the monthly production is greater than consumption. If consumption exceeds production, the result is zero as shown in formula (7.2).

$$Q_{consumption} > Q_{production} => 0 \tag{7.2}$$

From figure (Figure 7.2), it can be seen, that we need to store energy in the summer time, when there is more sun and less heat consumption. So, the need to store energy is seasonal.

The exact results calculated with these formulas are brought in table (Table 7.1).
The next important thing is to calculate the volume of the seasonal water thermal energy storage tanks in different scenarios. This can be done by using formula (7.3). [8]

$$V = \frac{3{,}6 \cdot 10^6 \cdot Q_{storage}}{\rho \cdot c_p \cdot (T_{max} - T_{min}) \cdot \eta_T} \tag{7.3}$$

where $Q_{storage}$- total needed heating for storage, MWh,

ρ – water density, 997 kg/m^3,

c_p – specific heat of water, 4,187 kJ/kgK,

T_{max} – maximal temperature in water storage tank,

T_{min} – minimal temperature in water storage tank,

η_T- efficiency of water tank – taken 70% [8],

$T_{max} - T_{min}$ – this value is taken 50 K [8],

V – storage tank volume, m^3.

The results, the energy needed to be stored and the volumes of seasonal water thermal energy storage tanks needed in different scenarios, are brought in table (Table 7.1).

Table 7.1. The energy needed to be stored and the volumes of seasonal water thermal energy storage tanks needed in different scenarios

Scenario	**Excess heat to be stored, MWh**													**Volume, m³**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Yearly, MWh**	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0,2	119	2299	999	0	0	0	0	4488	11028
	0	0	0	0	266	388	509	325	0	0	0	0	1488	36661
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0,0	104	317	85	0	0	0	0	506	12469
	0	0	0	0	532	776	1017	651	0	0	0	0	2976	73321
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	261	793	211	0	0	0	0	1265	31173
	0	0	0	0	1330	1940	2543	1627	0	0	0	0	7439	183303

It can be seen from table (Table 7.1), that in different scenarios the yearly energy needed to be stored and the volumes of seasonal water thermal energy storage tanks can vary. Energy is mostly needed to be stored during summer months: May, June, July and August and as said previously, only if the solar collectors production exceeds consumption.

8. ECONOMIC FEASIBILITY OF SOLAR COLLECTORS INTEGRATION TO DISTRICT HEATING NETWORKS

In this chapter, the cost of solar collectors and water thermal energy storage system have been calculated. Also, levelized cost of energy has been calculated in case of integrating solar collectors to district heating networks. After that, a comparison is done to compare calculated costs with the costs of other heat production technologies in order to make the final decision whether or not to integrate solar collectors to district heating networks. This process is shown in figure (Figure 8.1).

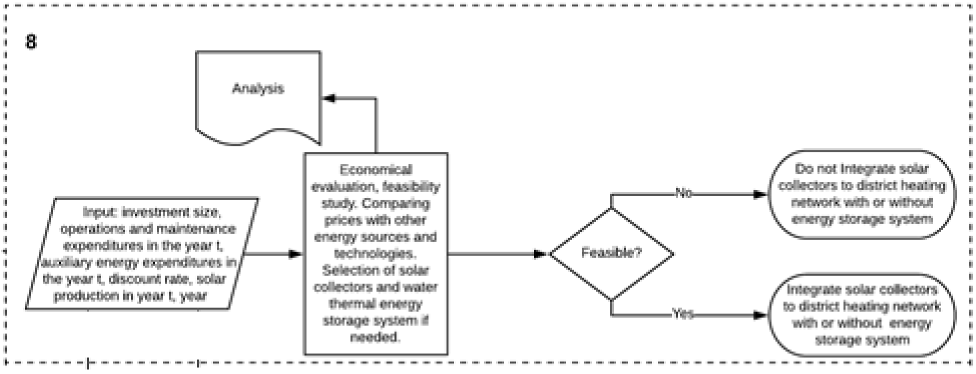

Figure 8.1. Process of evaluating project feasibility

When we install solar collectors with different areas and seasonal water thermal energy storage tanks, we need to evaluate the costs, the size of the investment. To do it, the following model is used as brought in figure (Figure 8.2). When we put the values of different solar collector areas and volumes of seasonal water thermal energy storage tanks into the functions brought in figure (Figure 8.2), we gain the data of solar collectors costs and storage tanks costs. The data about different solar collector areas and volumes of seasonal water thermal energy storage tanks are gained from tables (Table 6.1, Table 7.1). The results, solar collector and water thermal energy storage tank costs are brought in tables (Table 8.1, Table 8.2).

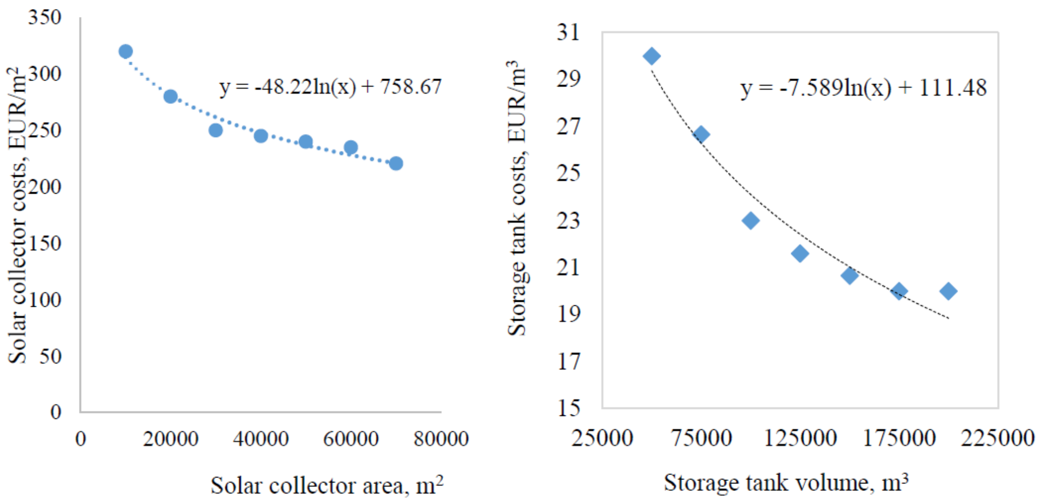

Figure 8.2. Evaluating the cost of solar collectors and storage tanks [8]

Table 8.1. Solar collectors' price

Scenario	Solar collector area size, m^2	Cost per m^2	Total cost, euros	Total cost, million euros
Scenario 1	500	459	229501	0,23
	3000	373	1117809	1,12
	5000	348	1739855	1,74
Scenario 2	1000	426	425578	0,43
	5000	348	1739855	1,74
	10000	315	3145474	3,15
Scenario 3	2500	381	953486	0,95
	12500	304	3797343	3,80
	25000	270	6759096	6,76

Table 8.2. Storage tank costs

Scenario	Storage tank volume, m^3	Cost per m^3	Total cost, euros	Total cost, million euros
Scenario 1	0	0	0	0,00
	11028	41	450401	0,45
	36661	32	1163010	1,16
Scenario 2	0	0	0	0,00
	12469	40	497625	0,50
	73321	26	1940329	1,94
Scenario 3	0	0	0	0,00
	31173	33	1027291	1,03
	183303	20	3576184	3,58

After getting the size of the initial investment, we can calculate the levelized cost of energy with formula (8.1). Also, the levelized cost of energy is calculated, when government covers half of the investment size with specials aids. The degradation of the solar collectors' system is taken 0,5% per year. Life time of the system is 25 years. It is clear that the whole district heating network with its' equipment needs to be operated and maintained continuously during the whole year and costs come with that. The operation and maintenance costs are 1% of the initial investment. The consumption of electricity for the auxiliary are considered equal to 1,5% of the solar production. The discount rate is 4% as suggested in the paper that the formula has been taken. The solar production in the first year is gotten from chapter (6). [21]

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Q_{sol,year,t}}{(1+r)^t}} \quad (8.1)$$

where I_t – investment size, EUR,

M_t – operations and maintenance expenditures in the year t, EUR,

F_t – auxiliary energy expenditures in the year t, EUR,

r – discount rate,

$Q_{sol,\ year,\ t}$ – solar production in year t, MWh,

t – year.

The levelized cost of heat values in different scenarios are brought in table (Table 8.3). It can be seen that the levelized cost of heat values are similar to those that are expected for solar collectors, in the range of 37 – 46 EUR/MWh [22].

Table 8.3. Levelized cost of heat values in different scenarios for solar collectors

Scenario	Solar collector area size, m²	Storage tank volume, m³	Levelized cost of heat, EUR/MWh	Levelized cost of heat with investment aids, EUR/MWh
Scenario 1	500	0	44,5	24,9
	3000	11028	50,7	28,4
	5000	366611	56,3	31,5
Scenario 2	1000	0	41,3	23,1
	5000	12469	43,4	24,3
	10000	73321	49,4	27,6
Scenario 3	2500	0	37,0	20,7
	12500	31173	37,5	21,0
	25000	183303	40,1	22,4

From table (Table 8.2), it can be seen, that the average levelized cost of heat is 44,5 EUR/MWh and with government aids, it is 24,9 EUR/MWh. The prices range from 37 – 56,3 EUR/MWh and between 20,7 – 31,5 EUR/MWh, if government support has been granted. It can be seen that the levelized cost of heat is very sensible to the investment size. The levelized cost of heat is lower if the consumption and the solar collectors production is bigger and the need to store energy is lower and vice versa.

To analyse the feasibility of solar collectors' integration to district heating network, we need to know the levelized cost of different heat production technologies that use different fuels. These levelized costs are brought in figure (Figure 8.3). Also, the prices of thermal energy are very compatible, if wood chips and peat are used as a fuel, the price is around 18 EUR/MWh [12]. It can be seen that solar collectors can compete with other technologies that have the levelized cost of heat between 18 – 65 EUR/MWh and it could be feasible to integrate solar collectors into district heating network. Solar collectors are also competitive if we look at Estonia's district heating levelized cost of heat prices, that remain between 30,0 – 74,0 EUR/MWh.

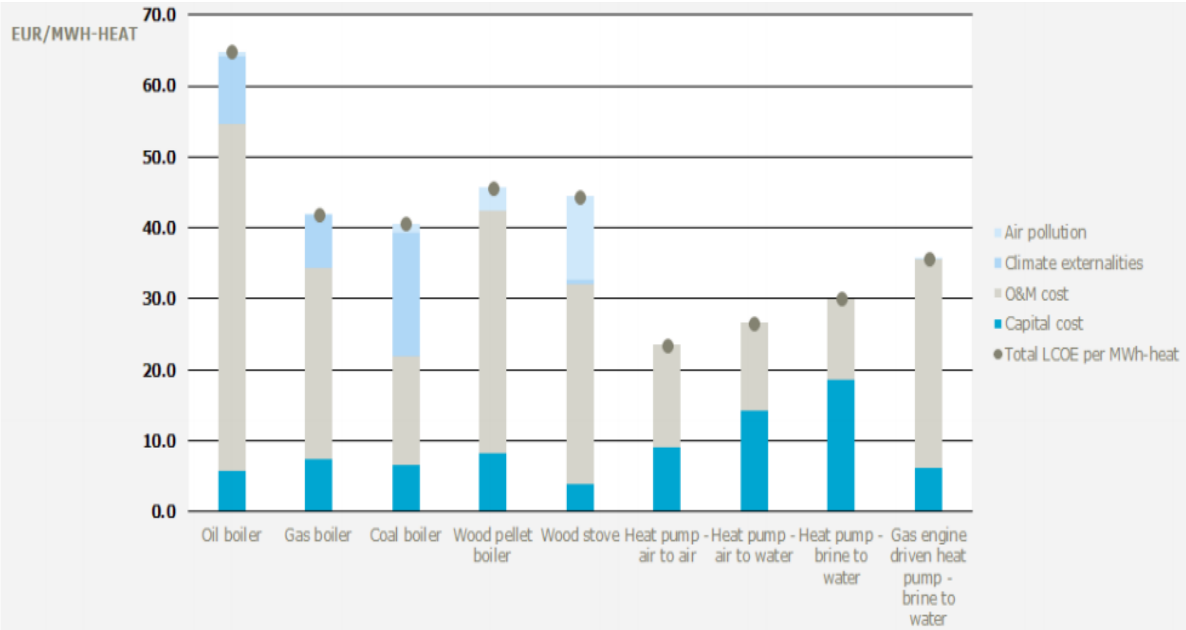

Figure 8.3. Levelized cost of different heat production technologies [23]

After analysing a district heating network area and deciding, that there is a need to reconstruct a district heating area (for example, amortized district heating network, high fuel prices, high price of district heating, replace the usage of fossil fuels), look for better opportunities and consider other options, we can then compute the levelized cost of heat, when integrating solar collectors to district heating and compare the levelized cost of heat with different heat production technologies. After the comparison has been made, we can then make the decision whether to integrate solar collectors and energy storage system if needed into district heating network.

SUMMARY

Integrating solar collectors to district heating networks could help to solve problems in the energy sector like increase the use of renewable energy resources, decrease the use of natural resources, decrease the amount of greenhouse gas emissions and reconstruct or build a district heating network. A methodology was introduced to determine the feasibility of that project.

In the beginning of this thesis, energy needs of the world were brought, the concept and the development of district heating and solar district heating were introduced, the benefits of district heating over other technologies were brought and the main types of solar collectors used in district heating were mentioned.

In the next step, an overview of Estonia's district heating network was brought. 70% of the heating needs are covered with district heating. In 2018, the total annual heat consumption of Estonia in district heating was 4,4 TWh. Also, it was shown that Estonia has installed very little amount of solar collectors in general (not only installed to district heating networks), there are 6 kWh of installed solar collector power per 1000 inhabitants. Prices of thermal energy were brought and also, an overview and analysis of the Estonia's heating sector was brought.

In the next part, a methodology was brought, which investigates the main part of this work, studying the feasibility of solar collectors' integration to district heating networks. It was divided into eight steps, each step has different inputs to calculate the values of necessary outputs. Also, it was shown, what documents are produced during these processes.

Firstly, the heating needs of three different consumers were determined to create different scenarios by adding together temperature dependent heat consumption – heating and ventilation, temperature independent heat consumption – domestic hot water and heat losses. The computed sizes of heat generation equipment were 7310, 14619 and 36 548 MWh. Those sizes cover majority of Estonia's small and intermediate scale district heating networks.

Secondly, three methods were brought, how to evaluate solar power potential and resources. In this work, Hargreaves and Saman'i temperature-based model was used to determine solar resources in Estonia and the yearly value was found 1106 kWh/m^2.

Thirdly, solar collectors output power was calculated with different areas ranging from 500 – 25 000 m^2 and the results were in the range of 388 – 19 376 MWh.

Fourthly, the volume of the seasonal water thermal energy storage tanks was calculated in case the solar collectors�###‘ production exceeded heat consumption and the results ranged from 11 028 – 183 302 m^2.

Lastly, the levelized cost of heat was calculated taking into account investment size for solar collectors, water thermal energy storage tank and other parameters and the results stayed in between 37,01 – 56,33 EUR/MWh. If government offers aids to cover half of the initial investment, the levelized cost of heat stays between 20,7 – 31,5 EUR/MWh.

The main result is that solar collectors’ integration to district heating networks is feasible, because they can compete with other heat production technologies. Levelized cost of heat for solar district heating stayed between 20,7 – 56,3 EUR/MWh. Other heat production technologies have levelized cost of heat between 18 – 65 EUR/MWh. Solar collectors are also competitive, if we look at Estonia’s district heating levelized cost of heat prices, that remain between 30,0 – 74,0 EUR/MWh.

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APPENDICES

Appendix 1. Methodology to evaluate the feasibility of integrating solar collectors to district heating network