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RIGA TECHNICAL UNIVERSITY

Armands Grāvelsiņš

COUPLING OF POWER AND HEATING SECTOR – OPPORTUNITY FOR HEATING SECTOR DEVELOPMENT

Summary of the Doctoral Thesis

RTU Press
Riga 2021

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

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Grāvelsiņš, A. Coupling of Power and Heating Sector – Opportunity for Heating Sector Development. Summary of the Doctoral Thesis. Riga: RTU Press, 2021. 42 p.

Published in accordance with the decision of the Institute of Energy Systems and Environment of 16th April 2021, Minutes No. 138.

This work has been supported by:

- Project "Flex4RES" funded by Nordic Energy Research Programme (No. 2156)
- Project "Assessment of Latvia's renewable energy supply-demand economic potential and policy recommendations" funded by National Research Programme (VPP) (No. VPP-EM-2018/AER_1_0001);
- Project "Development of heat supply and cooling systems in Latvia" funded by National Research Programme (VPP) (No. VPP-EM-EE-2018/1-0002);

Cover photo by Elīna Grāvelsiņa

https://doi.org/10.7250/9789934226632
ISBN 978-9934-22-663-2 (pdf)

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

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on August 26, 2021 at 14.00 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12 k-1 Azenes Street, Room 115.

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DECLARATION OF ACADEMIC INTEGRITY

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

Armands Grāvelsiņš ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction; 4 chapters; Conclusions; 75 figures; 12 tables; the total number of pages is 210. The Bibliography contains 157 titles.

CONTENTS

INTRODUCTION

Globally, nearly 80 % of produced energy comes from fossil fuels, which promotes climate change, water and air pollution, and natural resource depletion. Individual and district heating (DH) is responsible for part of these emissions when producing heat for building space heating and domestic hot water preparation [1]. Power production is also responsible for emissions. The European Union (EU) is aware that mitigating climate change is one of the main challenges to ensure the sustainable development of Europe, therefore EU officials have set ambitious targets for decarbonization, and are purposefully moving towards implementation of renewable energy [2].

Like all the other parts of energy system, also district heating is facing changes. In the last decade, increased attention from the researchers have been on the development of the 4th generation district heating system. The 4th generation district heating concept (4GDH) has been introduced by Lund et al. [3], and in last few years it has further developed. The researchers are starting to talk about ultra-low district heating or the 5th generation district heating concept. The main elements that characterize the 4th generation district heating system are renewable energy sources, low temperature level of heating carrier and consumers' energy efficiency (Fig. 1.).

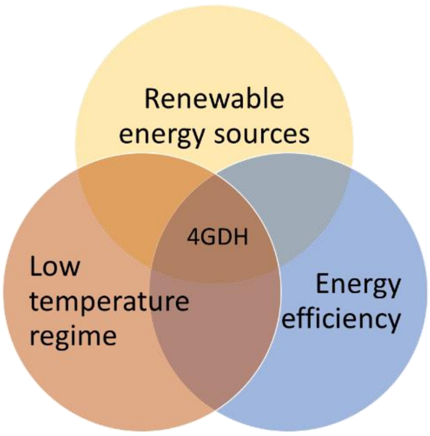

Fig. 1. Main elements of the 4th generation district heating.

One challenge that the decarbonization target presents for the power sector is the necessity for a high share of variable renewable energy (VRE), e.g. wind and solar technologies which have high level of uncertainty [4]. To reach a 100 % renewable power sector, flexibility measures should be implemented to address the issues with supply and demand balancing [5]. While the share of renewable energy is low, rapid changes in energy demand can be covered by the installed capacity of fossil-based technologies, but as the share of renewables increases, also the gap that should be covered increases, therefore presenting the issue of flexibility [6]. There is a limit to how much renewables can be introduced in the existing technological and institutional framework. There is no single value that corresponds to every country, because the existing systems differ in each country, but it is indicated that there are no technical barriers for integration of renewable energy up to 35 % [7]. There are several ways of increasing the capability of systems to adjust production to consumption: accumulate the power for periods when the demand increases, apply demand side management to align power consumption with power production and/or convert the power to different types of energy [8].

Sector coupling, especially between power and heat sector, could provide benefits to both systems. Power sector would be able to increase the production of renewable energy while not worrying about where to utilize power surplus, because power can be converted to the heat (i.e. P2H concept). Heating sector would be able to receive cheap renewable electricity from power surplus to utilize it in heat production via heat pumps, or if the electricity price is right, even electric boilers (Fig. 2).

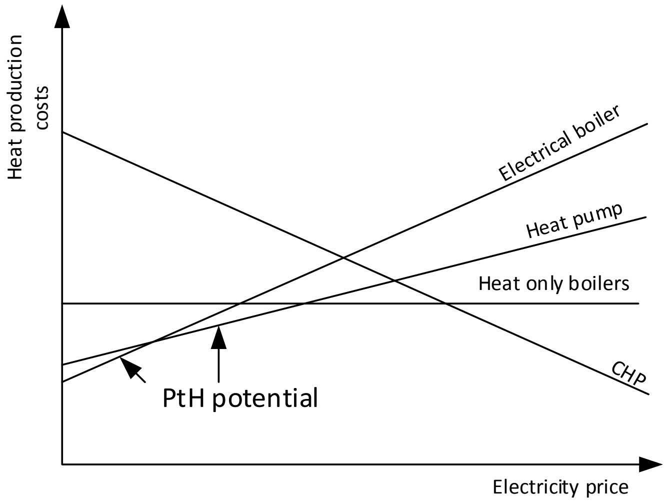

Fig. 2. Electricity price effect on heat production costs for different technologies [9].

Both sectors could be able to increase renewable energy share, thus participating in reaching the EU targets and moving towards carbon neutrality. Sector coupling of power and heat can be beneficial for both systems but is probably not enough to resolve power system flexibility issues on its own.

Research Topicality

Energy sector is one of the largest polluters in the world and also in Latvia. Combustion of fossil fuels in energy sector accounted for 65.5 % of total GHG emissions in Latvia in 2018. It includes both centralized and decentralized energy production, as well as transport sector.

At the end of 2019, the European Commission presented the Green Deal – a set of policy initiatives with the overarching goal to make European climate neutral by 2050. This means that all of the EU member states have to become climate neutral by 2050. To reach this goal, emission reduction is necessary in all sectors.

To decide on the transformation pathway for energy sector and make informed and sustainable decisions, tools that can help to answer how the energy system might develop in the future are necessary. Energy sector is a complex system with a lot of elements, non-linearities and feedbacks that humans cannot process, therefore mathematical simulation tools are necessary to assist policy makers in making long term policies that are economically justifiable, socially fair and sustainable.

Hypothesis

The hypothesis of the research is that the development of power sector and search for solutions for power system to be able to integrate high level of variable renewable energy can become as a contributing factor in heating sector electrification and increase in renewable energy share.

Aim and Objectives

The aim of the Thesis is to develop energy system simulation models for heating and power systems which can be used for local and national scale energy system modelling and can assess effects of different parameters and policy instruments. The model should be able to analyze the sector coupling influence on the system.

The main objectives are:

- to develop system a dynamics model structure for heating system development;
- to analyze the heating system at local and national scale;
- to assess the importance of power sector flexibility in the system development;
- to implement sector coupling elements in energy system;
- to analyze sector coupling as a flexibility increase measure for national scale and local systems.

Scientific Novelty

The Doctoral Thesis provides methodology on how to model and analyze power system flexibility and its development. Increase in power system flexibility is essential in order to integrate high level of variable renewable energy (solar, wind) in power system. The methodology offers to look at flexibility development as a stepwise process in which increase in use of variable renewable energy resources puts pressure on the existing power system, therefore seeking for new and innovative solutions to adapt the system to the new conditions.

The developed tools allow to evaluate energy systems at different scopes – local, regional, national. They allow to analyze different technologies and their potential. Short term and long term impact from policies can be evaluated.

Practical Significance

Energy efficiency and renewable energy goals set by the European Union are ambitious. Europe is set to reach carbon neutrality in 2050, but to transform energy sector in sustainable manner, each part of the energy sector should be analyzed separately as well as in combination in order to find the most feasible transformation option. The research has high practical significance, as it identifies and evaluates the technical and economic aspects of different technologies and evaluates the impact of sector coupling on heating and power systems.

The presented methodology and the obtained results can be used by policy makers to make informed decisions in new policies for energy sector development at national scale. It can be useful also for municipalities for regional planning, or district heating companies when deciding on technology replacement.

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Approbation of the Research Results at Scientific Conferences

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Thesis Structure

The Doctoral Thesis is based on seven thematically unified scientific articles that are presented, and the results have been approbated in various scientific conferences. All articles are accessible in international citation databases. The list of scientific articles used in the Doctoral Thesis can be seen in Table 1.

Table 1

Scientific Articles Used in the Doctoral Thesis

Methodology step	No	Publication title
1. Heating system development – national scale	1	System dynamics model analysis of pathway to 4th generation district heating in Latvia
	2	Linking energy efficiency policies toward 4th generation district heating system
2. Heating system development – local scale	3	Combining energy efficiency at source and at consumer to reach 4th generation district heating
3. Power system flexibility modelling	4	Modelling energy production flexibility: system dynamics approach
4. Sector coupling – national scale	5	Power sector flexibility through power-to-heat and power-to-gas application – system dynamics approach
5. Sector coupling – local scale	6	Solar power in district heating. P2H flexibility concept
6. Discussion on future power system modelling	7	Review of modelling energy transition pathways with application to energy system flexibility

The articles describe the methodology for heating and power system transformation towards carbon neutral system, with implementing sector coupling of heating and power systems. Articles examine both national scale and small-scale systems. The structure can be seen in Fig. 3.

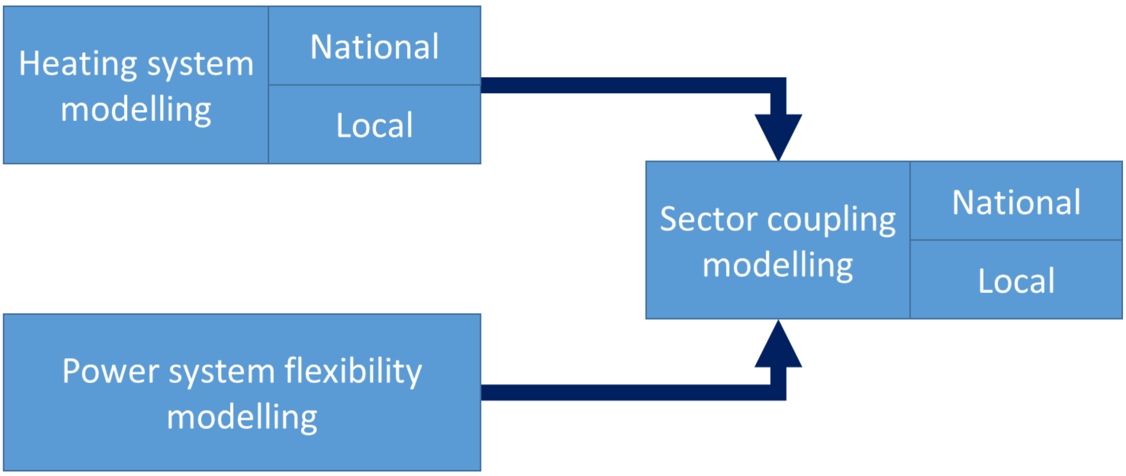

Fig. 3. Thesis structure.

This Thesis consists of introduction and five sections:

- Literature review,
- Research methodologies,
- Results,
- Discussion,
- Conclusions.

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

The first section of the work includes a literature review on topicality of energy system transformation, including the 4th generation district heating, sustainable power systems and flexibility issues related to them. The second section describes the research methods that are related to the research of sustainable development of district heating and power systems and sector coupling of both systems. The section of the results presents the development of heating systems, concept of power system flexibility limit increase, as well as the sector coupling effect on power and heating system development. The Discussion section reviews the future research steps for power sector transformation modelling, considering also flexibility related issues. Finally, conclusions are given at the end of the Thesis.

1. METHODOLOGY

Energy production from fossil fuels is one of the largest GHG emission sources. To determine how to transition towards carbon neutral energy sector, different aspects of energy sector and different policies need to be investigated. It is crucial to not only look at each part of energy system separately, but also look for cooperation opportunities. This methodology presents how the modelling of heating system can be done, how the power system and flexibility aspects can be modelled, as well as sector coupling is introduced. The modelling is done by applying system dynamics modelling method. The Thesis provides examples on how different levels of the system can be modelled by applying the same modelling method.

1.1. Heating System Modelling

1.1.1. Model of the National Level

The heating system modelled in this Thesis consists of two main parts – heat demand and heat supply (Fig. 1.1). For local and individual heating systems, heat consumer himself is responsible for obtaining enough fuel to ensure comfort temperature indoors throughout the year. Whereas, DH operators have to be aware of the demand from larger number of consumers, therefore information about demand is crucial to ensure that sufficient amount of heat energy is supplied to the consumers.

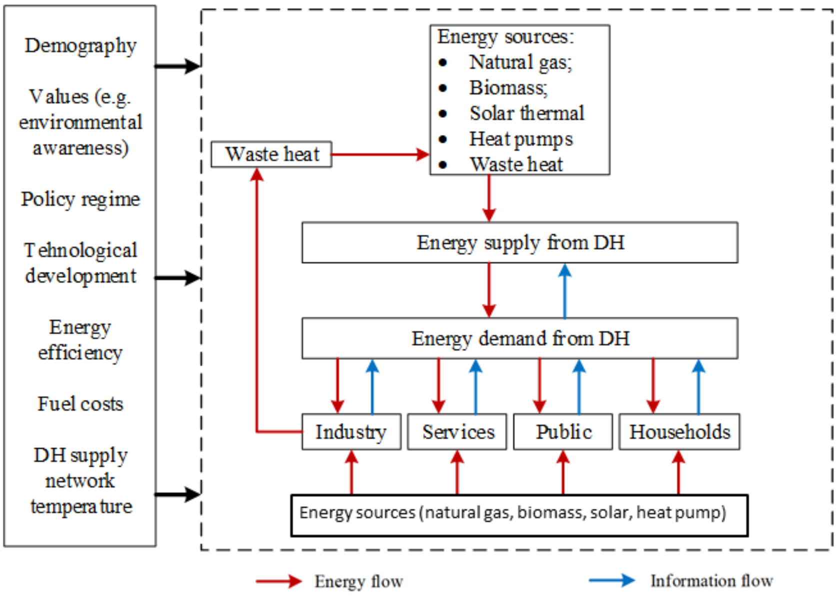

Fig. 1.1. Main blocks of the heating system.

Heat can be produced by using a variety of technologies and fuels, however, considering the European Union target of moving towards carbon neutrality, the demand for renewable technologies and fuels will increase and renewables will play more significant role in future energy system. Even more, waste heat recovery from industrial processes and utilization of this heat in district heating is one of the future priorities to ensure the efficient use of resources.

Development of the heating system model is performed in program "Powersim Studio 8".

Technology capacities are taken as the central elements of the model – natural gas boilers (GB) and biomass boilers (BB) as current renewable energy technology, as well as the currently not widely used but perspective solar collectors (SC) and heat pumps (HP).

The depreciation of technology depends on the service life of installed technologies. Installation of new capacities acts opposite to the depreciation. If there is shortage of energy production, when compared to the demand, new technologies are installed.

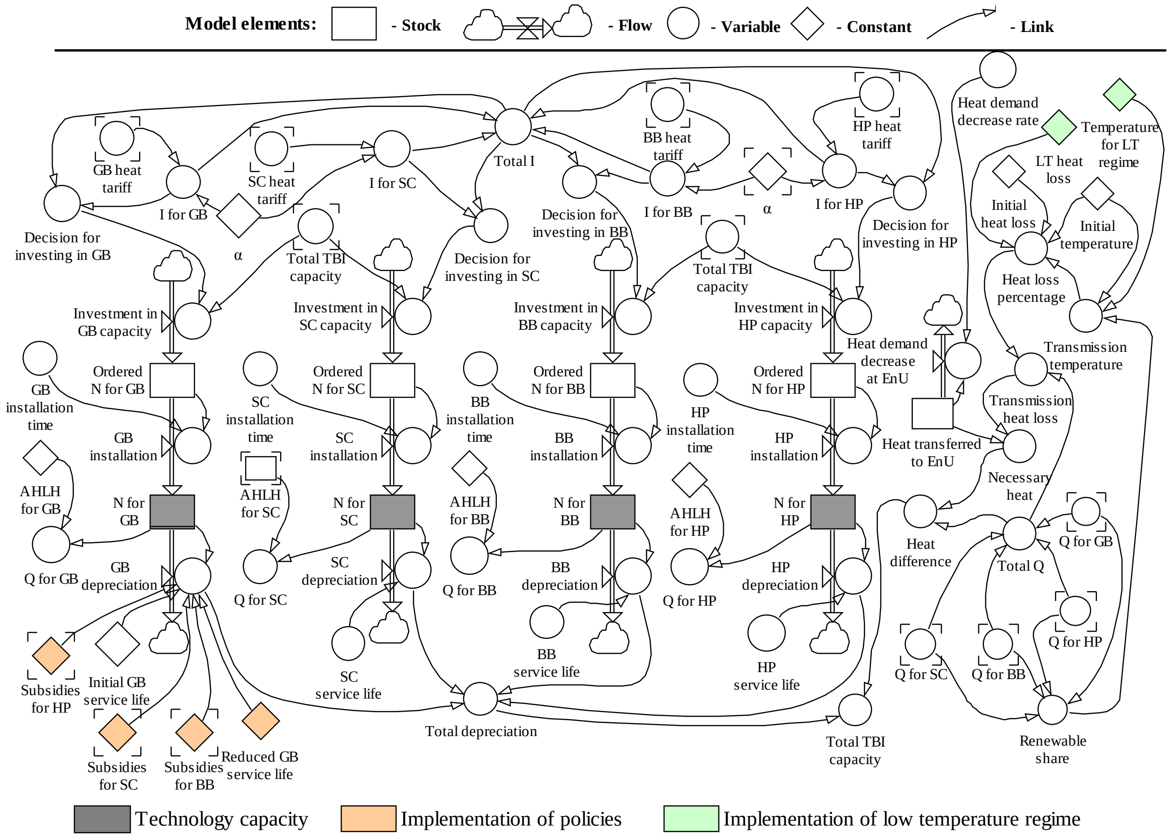

Fig. 1.2. Model for capacity substitution. GB – gas boiler, BB – biomass boiler, SC – solar collectors, HP – heat pumps, LT – low temperature, AHLH – adjusted heat load hours, EnU – the end users, TBI – to-be-installed capacity, I – technology investment share, Q – heat produced.

The amount of to-be-installed capacity for each technology is determined by the comparison of heat tariffs of individual technologies. Logit function is used in order to determine the technology to install:

$$I_1 = \frac{e^{-\alpha T_1}}{e^{-\alpha T_1} + e^{-\alpha T_2} + \ ... \ + e^{-\alpha T_n}}, \tag{1.1}$$

where $I_{1 \dots n}$ is investment decision in specific technology; $T_{1,\ 2}$ is heat tariff of the specific technology, EUR/MWh; and α is elasticity coefficient that describes the decision making nature of decision makers.

Based on the equation above, new technological capacities are being installed and a new energy balance is emerging. In case the installed capacities are sufficient to cover the energy demand and there is no energy shortage, new capacities are not installed, but the existing capacities are operated.

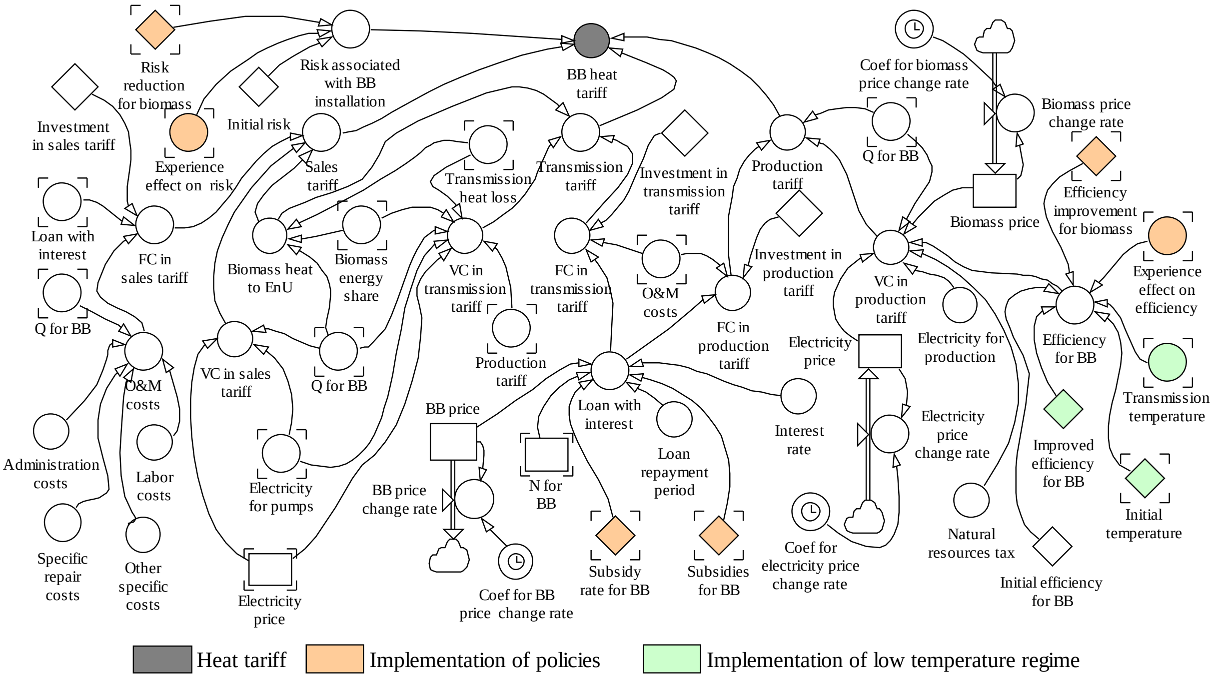

Fig. 1.3. A model of heat tariff for biomass boiler house. BB – biomass boiler; FC – fixed costs; VC – variable costs; O&M – operations and maintenance, EnU – the end users.

The model for calculation of the heat tariff is demonstrated in Fig. 1.3. The model of tariff calculation is formed based on the heat calculation methodology developed by the Public Utility Commission of Latvia [10]. The heat tariff is calculated individually for each type of technology. The heat tariff is formed of 3 parts – production tariff, transmission tariff and sales tariff. In addition to the production, transmission and sales tariffs, the total tariff includes a parameter called risk (inconvenience costs), which relates to the introduction of technologies.

1.1.2. Case Study of Local System

The research is based on the case study of DH area in Riga. For heat production two natural gas boilers with a capacity of 2.5 MW for base load are used; and additional 1 MW natural gas boiler is used to cover peak loads only. The heat from flue gas is recovered using the flue gas economizer. Heat is distributed using 115 °C supply and 70 °C return water temperature (115/70 temperature regime). Heat source has two type of consumers – apartment building area and industrial area (Fig. 1.4).

Thermal energy is used for heating both the building area (18 195 m^2) and industrial area (18 271 m^2). Hot water load is covered throughout the year only for the building area. The average amount of heat produced during the heating season is about 900 MWh per month; around 60 % of the produced heat is consumed by the building area and 40 % by the industrial area. The average amount of heat produced during the summer period is 116 MWh per month to cover the hot water load of the consumers.

Heat production is provided by one type of fuel – natural gas, which is not a sustainable solution. The normalized thermal energy consumption for heating is 6100 MWh per year. During the heating season, the transmission heat losses are as high as 110 MWh to 125 MWh, representing 12–14 % of total consumption, but in the summer, losses are on average 13 MWh to 16 MWh. Specific losses to the amount of heat supplied to the buildings during the summer period are 15–20 %.

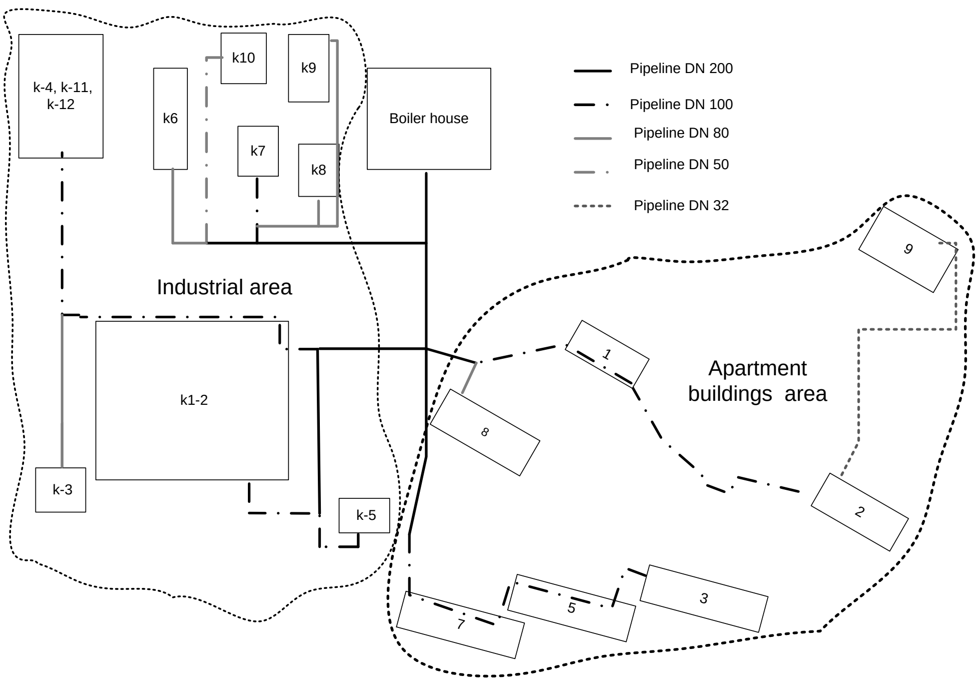

Fig. 1.4. Location of case study DH area.

The strategy for 4GDH foresees the introduction of renewable energy sources, such as solar energy with accumulation, heat pumps and biomass utilization, while also reducing heat energy consumption at the end-users through implementation of heat savings measures in buildings [3].

The case study introduces renewable energy sources and also considers the impact of implementation of energy savings measures at the end-users.

The efficiency characteristics for various scenarios, their cost range and project lifetimes are summarized in Table 1.1. The base scenario costs are not calculated, as it is based on the current state of existing buildings.

Table 1.1

Characteristics of Scenarios in the Model

Scenario	Building element	Resulting insulation thickness, mm	Resulting *U*-value, W/(m K)	Heat saving cost, EUR/m^2	Project lifetime
Base scenario (BSc)	Wall	–	1.07		
	Floor	–	0.82		
	Roof	–	0.42		
	Window	–	2.00		
	Ventilation	–	–		
	Industrial area		–		
Scenario 1 (Sc1)	Wall	150	0.19	70.1–85.5[a]	20
	Floor	100	0.22	15.2–18.7[a]	
	Roof	200	0.15	7.1–8.5[a]	
	Window	–	1.50	55.5–70.4[a]	
	Ventilation	–	–	–	
	Industrial area	–	–	–	
Scenario 2 (Sc2)	Wall	200	0.15	85.5–95.5[a]	20
	Floor	100	0.22	18.7–22.5[a]	
	Roof	300	0.11	8.5–12.2[a]	
	Window	–	1.10	70.4–94.9[a]	
	Ventilation	–	0.75**	25.5–40.0[b]	
	Industrial area		20.00*	87.0–142.0[c]	
Scenario 3 (Sc3)	Wall	400	0.08	100.0–180.0[a]	20
	Floor	100	0.22	18.7–22.5[a]	
	Roof	400	0.09	14.5–16.5[a]	
	Window	–	0.80	110.0–150.0[a]	
	Ventilation	–	0.75**	25.5–40.0[b]	
	Industrial area	–	40.00*	87.0–142.0[c]	

[a] heat saving cost per appropriate building element area (wall, floor, roof, windows, m^2);
[b] heat saving cost per heating area;
[c] heat saving cost per MWh;
* heat saving percentage;
** efficiency of heat recovery.

1.2. Modelling Power Sector Flexibility

Figure 1.5 illustrates possible structure of the model with main reinforcing and balancing loops which could be responsible for the system's behavior. As can be seen, decision on which type of technology to install depends on the total demand of energy, costs of production and production elasticity, which describes the level of impact the difference in production costs have on decision making. By comparing the unit costs of electricity production, it is decided how much power is produced from each type of technology. However, if RES-based power production approaches the flexibility limit for RES integration into power system, investments in new RES capacity cease. That can cause a gap between the total power production and the total demand, and this gap may be compensated by import or additional fossil-based capacity additions.

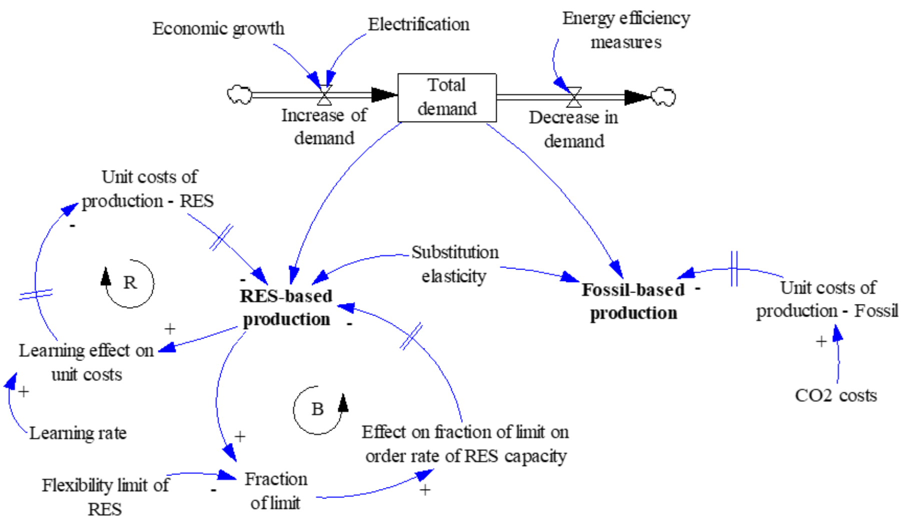

Fig. 1.5. Conceptual model structure; RES – renewable energy sources;
R – reinforcing loop; B – balancing loop.

The flexibility limit represents the current knowledge accumulated to integrate intermittent renewable energy sources into the existing system. As technologies develop and RES-based power production is approaching the flexibility limit of the existing system, the rate of RES integration slows down and the pressure to innovate and break these limits may become stronger. Motivation to innovate may result in partial reconfiguration of the existing regime, or the existing regime might get disrupted by a new regime in which a new flexibility level has been set. For this to happen, it often needs a political support and institutional changes.

1.2.1. Sector Coupling at National Level

Due to the different nature of conventional and VRE technologies, it is important to address the balancing issues that come from intermittent energy production by implementing the flexibility measures, whether those are at supply side or demand side. Due to the fact that district heating in Latvia has a high share of natural gas, it can be argued that power and heating sector coupling can be beneficial for both sectors. VRE energy increase in power sector can result in high uncertainty and, at times when demand is low but VRE energy production is high, surplus energy can be used in heat production. Not only that, but surplus energy can be used also in P2G applications. As Latvia has a very good gas infrastructure due to the fact that natural gas is the main energy source in power and heating sector, it means that for P2G development there is no necessity for new grid infrastructure, and the only barrier is the production technology installation. As there are a lot of gas technologies that are utilizing natural gas, there should be a large enough market for gas from P2G application. Of course, P2H and P2G development depends on ability to compete against current market players.

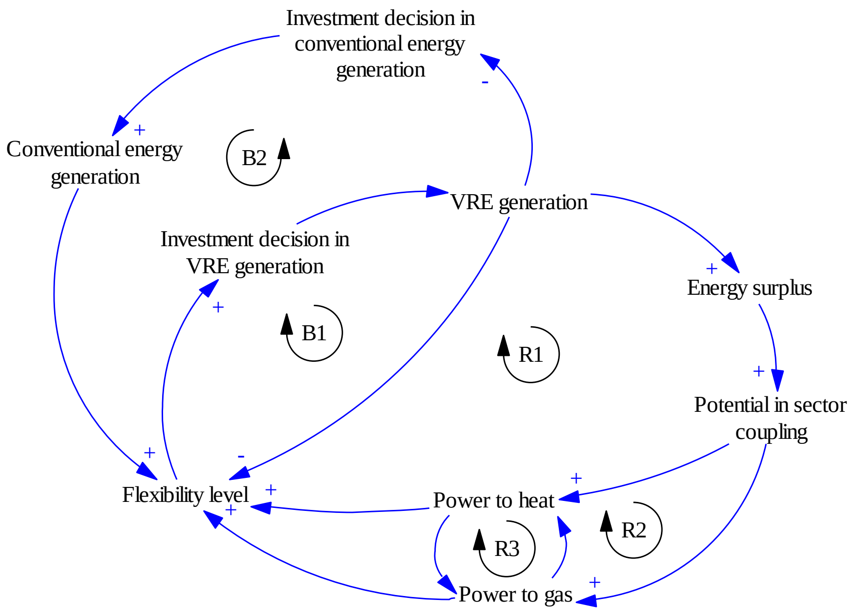

Fig. 1.6. Causal loop diagram.

As can be seen in Fig. 1.6, the causal loop diagram consists of five loops – three reinforcing loops (R1–R3) and two balancing loops (B1, B2). Reinforcing loops are responsible for growth of the system, while balancing loops are limiting the growth and keeping the system in balance.

The first and second reinforcing loops (R1 and R2) are responsible for the development of VRE sources and growth in their installed capacity. As VRE share increases, more common is the situation when electricity supply is not in balance with demand, therefore resulting in energy surplus, which cannot be absorbed by consumers. If cross-border transmission infrastructure is well developed, surplus energy can always be sold to the neighboring countries at low prices and it ensures a system flexibility, but in this research, it is assumed that cross-border transmission is not an option and energy surplus must be consumed within the country. In this research power sector flexibility is analyzed via sector coupling, e.g., power-to-heat and power-to-gas applications. The higher the power surplus, the more it can be used in power-to-heat and power-to-gas technologies, therefore resulting in an increased flexibility level of the system, which in turn allows to increase VRE share even more. The third reinforcing loop (R3) shows the competition between power-to-heat and power-to-gas applications. As energy surplus is limited in amount, also P2H and P2G capacities are limited, because it is assumed that P2H and P2G concepts are developed only by using renewable energy. The technology that proves to be more profitable, gains more of an advantage over the other technological solution.

The first balancing loop (B1) shows that VRE sources on their own cannot ensure the system flexibility, therefore the higher the share of VRE, the less flexible is the system, resulting in slower adoption rate of VRE. The second balancing loop (B2) shows how conventional power generation technologies are able to maintain the high share of energy production in the system. Conventional power generation technologies are those that ensure the power system flexibility at times when VRE technologies are unable to cover the energy demand due to weather conditions because they have a short start-up time and they can react fast to an increase in demand, therefore, if there is no other flexibility measure in place, the conventional generation technology capacity level will remain high.

The power model consists of six power production technologies, e.g., wind, solar PV, biogas, biomass, natural gas and hydro power, which interact with each other. The power system transformation depends on technology profitability – investment in technologies are calculated by using the Logit function, which favors technologies with lower tariffs.

The same basic principle is used also in modelling district heating technologies, e.g., natural gas, biomass, solar and heat pump, and also the decision making between P2H (heat pumps) and P2G (electrolyser + methanation reactor) technologies. There are also common interaction points between power and heating sectors (combined heat and power (CHP) plants), as well as between the heating sector and flexibility options (heat pumps). Gas from P2G application can be used in both the power and heating sector by replacing natural gas.

1.2.2. Sector Coupling for Local System

The aim of local system modelling is to evaluate whether it is reasonable to integrate a PV system into a DH company's system in order to cover part of the company's power self-consumption and convert the surplus solar energy into heat. In addition, the model makes it possible to compare different technologies that can be used to produce heat energy from surplus energy.

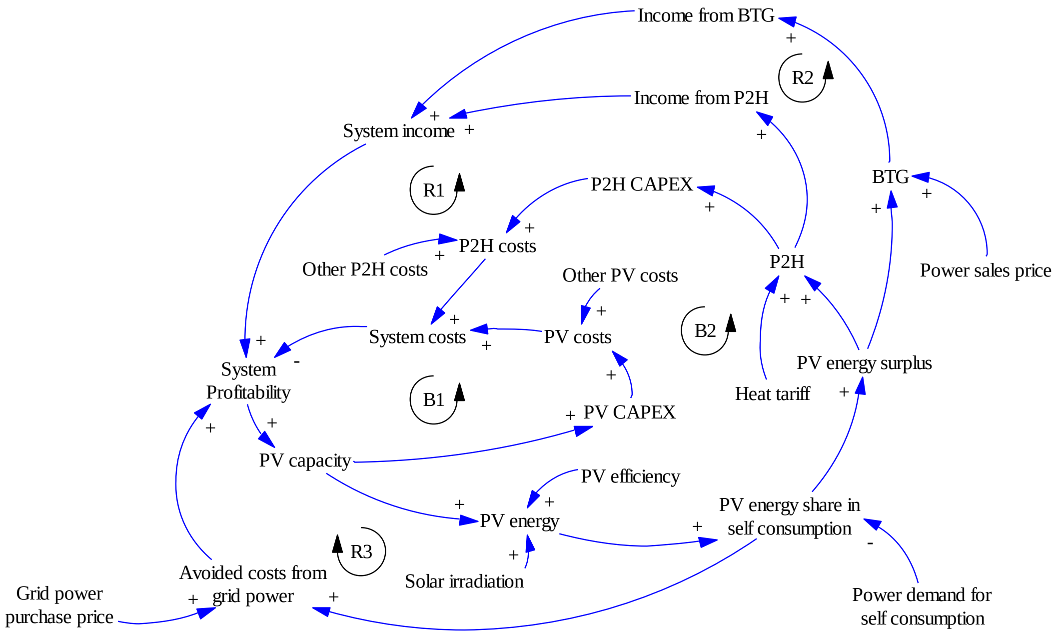

Fig. 1.7. Causal loop diagram for PV panel integration in a DH company.

The causal loop diagram describes mutual connections among the elements of the system.

The decision about additional PV panel area installation is based on economic considerations such as total revenue and costs of the installed PV system. If the operation is profitable, it is assumed that part of the profit will be redirected towards installation of new PV panels.

The surplus energy (PV power production minus the DH company's self-consumption) is transformed into heat or fed into the grid. The decision on whether to feed surplus power back into the grid or to use it in heat generation is based on economic considerations. The potential income from both options is compared, and the more profitable option is selected. If the heat tariff is higher, the surplus PV power is converted to heat taking into account the restrictions of heat demand and installed P2H technological capacity.

Table 1.2 shows the main input data for the baseline scenario and also includes the unit, the exact value and the source for each input parameter.

Table 1.2

Input Data for Baseline Scenario

Input parameter	**Unit**	**Value**	**Source**
Starting price for PV panels	EUR/m^2	180	[11]
PV panel price reduction	% per year	5	[11], [12]
PV commissioning time	years	1	[13]
Service life of PV	years	25	[13]
PV panel efficiency	%	16	[14]
Profit share in new PV	%	25	[12]
Solar irradiation	(kWh/m^2)/h	Hourly data	Meteorological database [15]
Electricity consumption	kWh	Hourly data	Data from DH company
Electricity needed for heat demand	kWh	Hourly data	Data from DH company
Heat tariff increase	%	2	Data from DH company
Heat tariff for end users	EUR/MWh	50	Data from DH company
HP COP	–	3	[16], [17]
Electricity price	EUR/MWh	Hourly data	Data from electricity market
HP price	EUR/kW	800	[16],[17]
Service life of HP equipment	years	20	[16]
HP capacity requirement	kWh/m^2	0.2	[16]
Investment payback time	years	10	Based on simulation time
Full electricity price	EUR/MWh	Hourly data	Average mark-up

2. RESULTS

2.1. Heating System Modelling

2.1.1. National Scale Development of Heating System

Four different scenarios were analyzed with the system dynamics model. The overview of scenarios can be seen in Table 2.1. The following scenarios were analyzed:

- Baseline scenario;
- Fossil fuel tax scenario;
- Renewable energy support scenario;
- Combined policy scenario.

Table 2.1

Comparison of Scenarios [18]

	Increase in excise duty, % per year	**Increase in CO_2 tax**	**Aid intensity for EE measures, %**	**Aid intensity for integrating RES into DHS, %**	**Aid intensity for integrating RES into individual SA, %**	**Aid intensity for the replacement of networks, %**
Baseline scenario	0	0 (after 2022)	0	0	0	0
Fossil tax scenario	8	up to the ETS quota price	30	0	0	0
Subsidy scenario	0	0 (after 2022)	30	40	20	40
Scenario for all policies	8	up to the ETS quota price	30	40	20	40

The total amount of funding and aid intensity are shown in Table 2.2. The model takes into consideration the funding available for the renovation of multi-apartment buildings for the 2016–2023 period. This funding is allocated in both the Baseline scenario and in all policy scenarios and is fully used, which also coincides with the functioning of the real system. Support for energy efficiency in buildings is granted in all scenarios, with the exception of the Baseline scenario.

Table 2.2

Amount of Support and Support Intensity up to 2030 [18]

	Sector	**Available funding, MEUR**	**Support intensity, %**
Energy efficiency of buildings	Commercial sector	300	30
	Public sector	100	30
	Multi-apartment buildings	1200	30
	Private buildings	100	30
Renewable resources	Households and public sector	267	20
	Industry	225	20
	DH	550	40
Transition to low-temperature DH system		60	40

The obtained results allow to analyze the long-term trends of heat generation in district and individual heating systems from various energy sources in the different policy scenarios.

The results of modelled heat demand trends in DH and individual heating are shown in Fig. 2.1. Due to energy efficiency measures the total thermal energy demand decreased by 2504 GWh in 2050 compared to Baseline. The DH heat demand decreases by 890 GWh in 2050 while individual heating demand falls by 1613 GWh in 2050. The heat produced is almost 8000 GWh per year in Baseline scenario, but the trend in the medium and long-term perspective shows that the heat produced within DH will decrease to 7000 GWh per year.

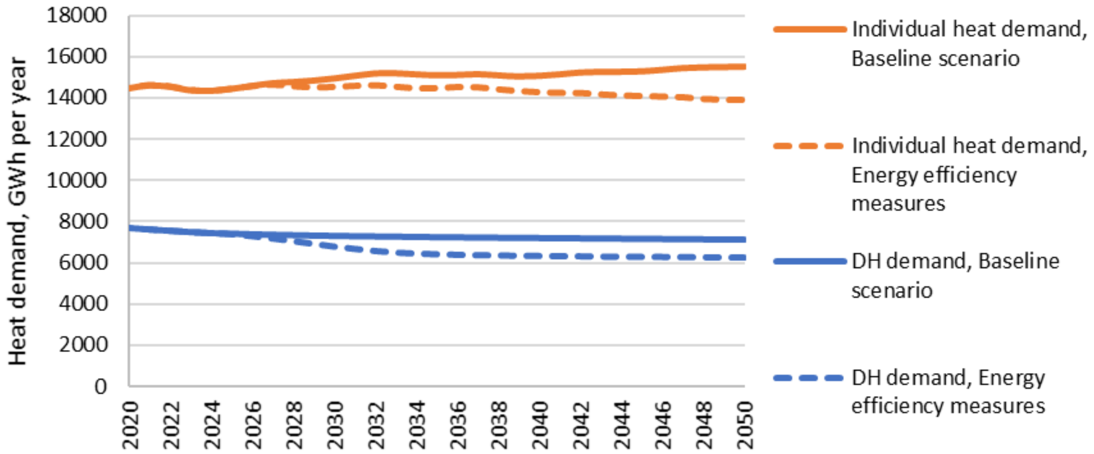

Fig. 2.1. DHS and individual heating demand forecast in the analysed scenarios.

The heat produced in individual heat supply differs from the DH. It can be observed that the reduction of fossil resource use in individual heat supply is not as significant as in the DH. The model assumes that the flexibility factor in decision-making when comparing technology costs is higher for DH than for individual heating technologies, so replacement is also slower and the observed economic benefits must be significantly higher than in DH.

In the Baseline scenario, the share of biomass in both district and individual heat supply is high, reflecting the current situation and existing political support. Due to bioeconomy principles the availability of high-quality biomass for heat production should decline due to production of higher added value products from the wood biomass, but the existing policy planning documents do not include the limitations for biomass use in energy sector.

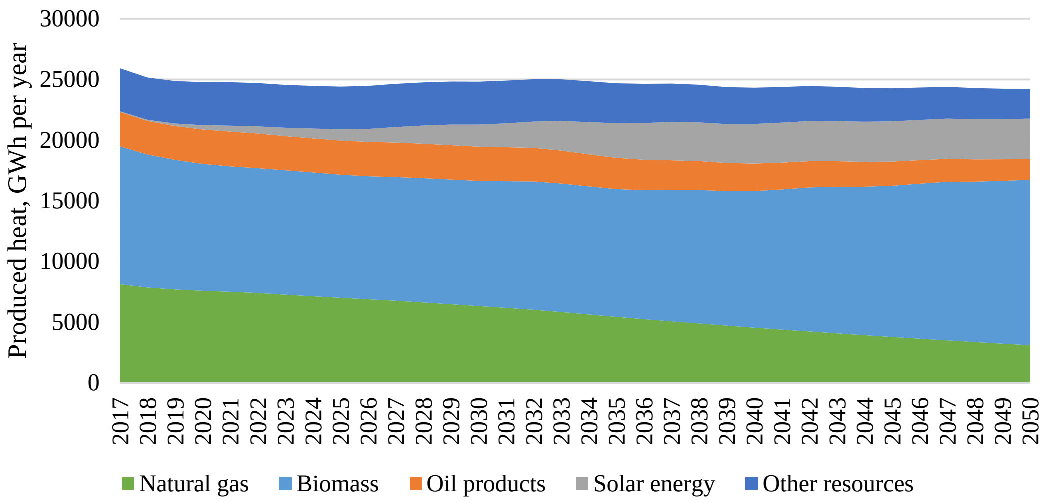

Fig. 2.2. Produced heat in national heat supply in Baseline scenario.

If policy instruments are adapted to the heat supply including support for energy efficiency measures and RES integration, then the production of district and individual heat is significantly different from the Baseline scenario, the results in Fig. 2.1 show that in the Combined policy scenario, the amount of heat produced in DH will decrease from 8500 GWh per year to 6000 GWh per year in 2050. The main energy resources in DH will be solar thermal energy and biomass. The Combined policy scenario envisages that heat production will also include the use of heat pump and waste heat, but their integration into the DH system is insignificant, as their potential should be more investigated. The use of fossil resources in this policy scenario decreases significantly, from ~5000 GWh per year to 230 GWh in 2050.

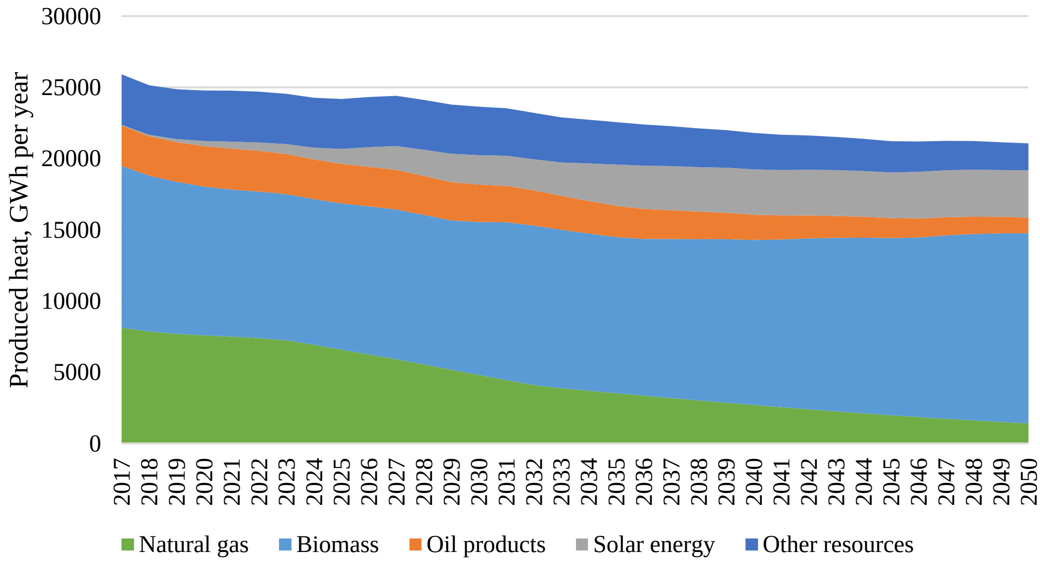

Fig. 2.3. Produced heat in national heat supply in Combined policy scenario.

By combining changes in tax policy and financial support in the form of subsidies, it is possible to achieve a significant reduction in fossil energy resource use in the national heat supply (Fig. 2.3). However, it is mainly based on the wider use of biomass. In order to effectively use the wood resources available in Latvia, additional regulation or long-term strategies in this area are needed.

The target set for the share of RES in the heat supply in Latvia in 2030 is 57.59 %, which is higher than the total share in final energy consumption (50 %). The achieved share of RES in district, individual and total national heat supply differs (Fig. 2.4). In the Baseline scenario, it can be seen that the share of RES in district and individual heating in current situation varies from 47 % to 55 %. The modelled results show that in the Baseline scenario the use of RES will increase and in 2030 will be close to 60 %. However, in the Combined policy scenario it is possible to achieve the share of RES up to 80 % in DH and 62 % in individual heat supply. The result for lower RES share growth in individual heating is a combination of various factors. There are higher specific capital costs for individual RES heating technologies. There is lower available financial support (subsidies) available compared to DH technologies, which is in line with the NECP for 2030.

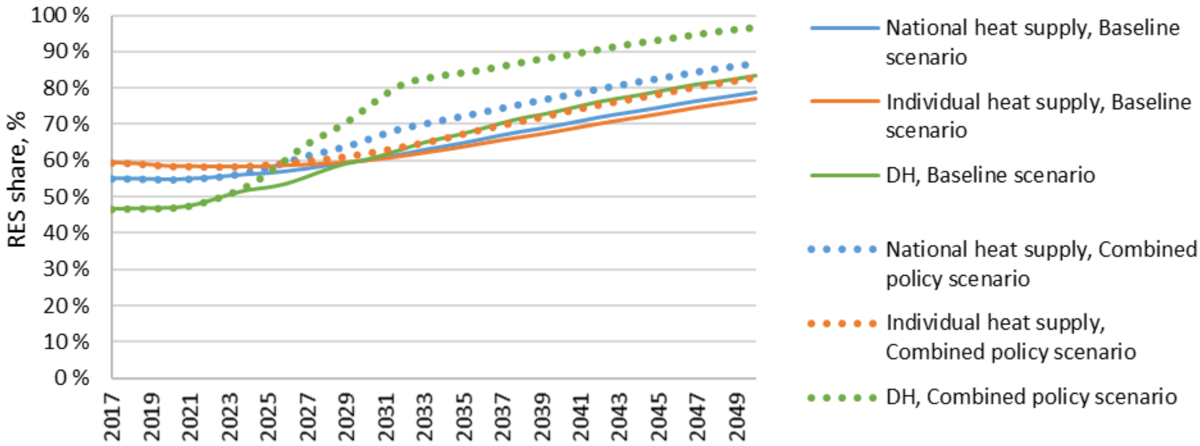

Fig. 2.4. Achieved share of RES in district, individual and national heat supply in Baseline and Combined policy scenarios.

One of the key indicators regarding the system energy efficiency is the amount of avoided GHG emissions resulting from increased share of RES and higher energy efficiency. In 2017, the total amount of emissions from heat supply was 2400 thousand tons.

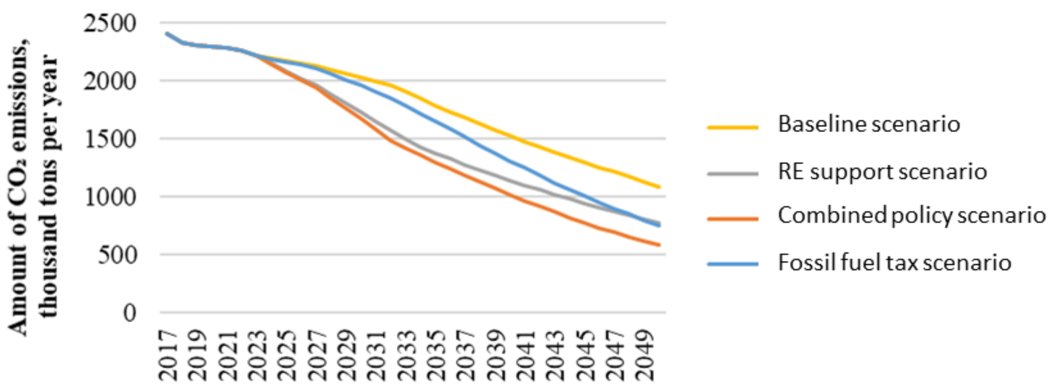

Fig. 2.5. The amount of CO2 emissions emitted in different scenarios in the total heat supply.

By implementing different support policies, it is possible to achieve important reduction of CO_2 emissions within the heat supply systems. As can be seen in Fig. 2.5, in the Combined policy scenario, it is possible to reduce the amount of emissions up to 579 thousand tons per year in 2050.

2.1.2. Case study of local system

The realization of various scenarios determines the energy efficiency levels in buildings and in the industrial area, which are characterized by specific heat energy consumption and building classes according to the “Regulations on the energy certification of buildings” [19] (Fig. 2.6).

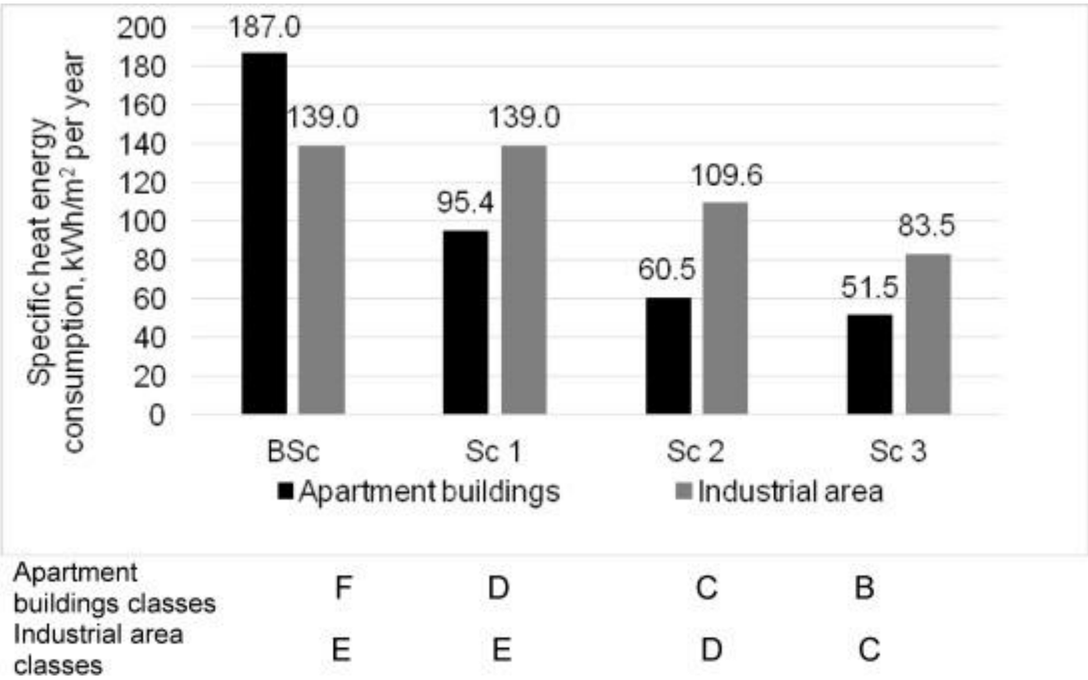

Fig. 2.6. Specific heat energy consumption by different scenarios and building.

It was also determined how the energy saving measures affect the introduction of low temperature regime and which scenario conditions allow to implement low temperature. Figure 2.7 shows the heat energy consumption compared to energy produced at the Baseline scenario. Only two of the examined scenarios (Sc2 and Sc3) could ensure a low temperature system without increasing electricity consumption for heat carrier pumping. In order to achieve this, the required installed heating capacity has to be reduced to 67 % benchmark from the Baseline scenario.

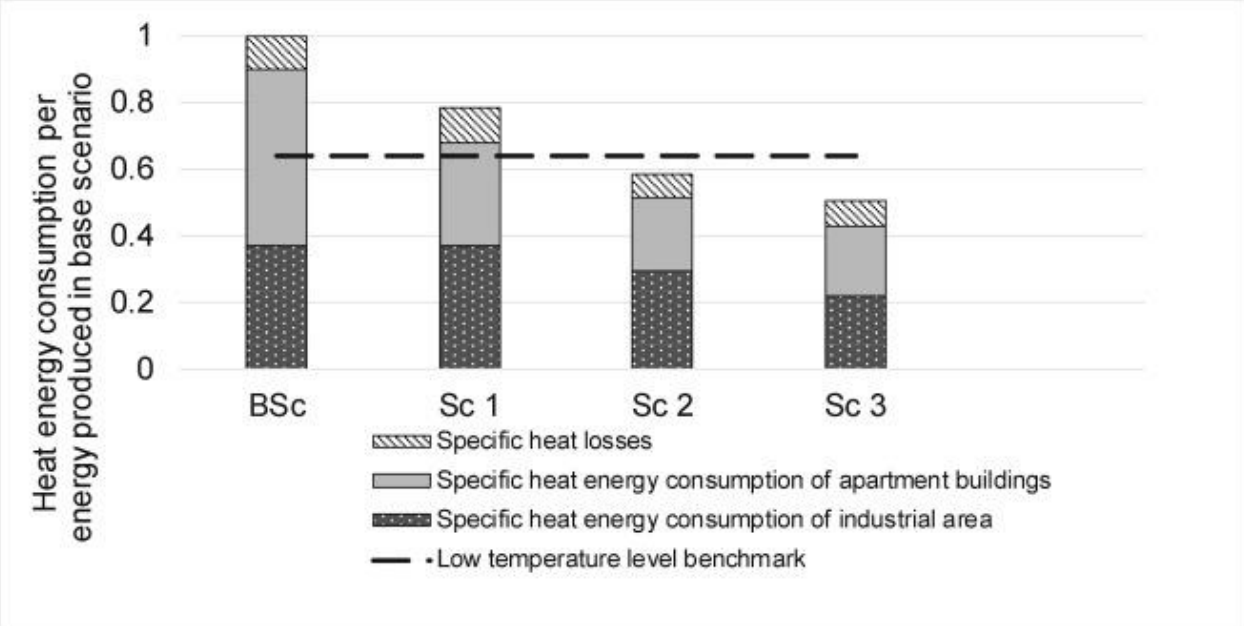

Fig. 2.7. Low temperature benchmarking evaluation by different scenarios.

The installed capacity for natural gas heating equipment in case study area is 3.6 MW. To increase the share of renewable energy, it is necessary to replace the fossil fuel based heating equipment with renewable energy technologies, e.g., biomass based and solar energy technologies (solar collectors with seasonal accumulation) as well as heat pump technologies.

By simulating, the heat source designs of all scenarios were created based on the share of technologies in 2050 (Fig. 2.8). The share of renewable energy sources (solar collectors with the accumulation and biomass) increases from 75 % in Scenario 1 to 93 % in Scenario 3, thus promoting the transition of the whole system towards a low carbon system.

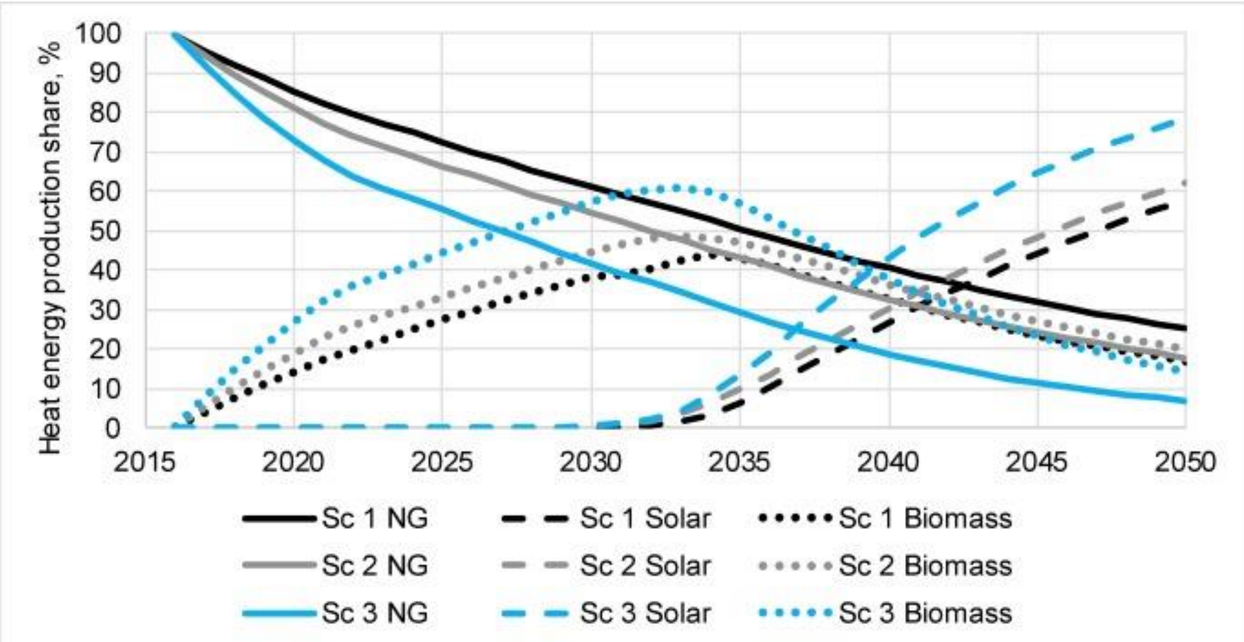

Fig. 2.8. The dynamics of heat energy production share for different scenarios.

The descriptions of the created technological solutions are provided in Table 6.

If energy saving measures are implemented, the necessary investments in the heat source in respect to the saved amount of heat would decrease 2.65 times (Sc1 against Sc3, Table 2.3).

Table 2.3

Heat Source Design

Parameters	Scenario 1	Scenario 2	Scenario 3
Heat energy share produced by NG, %	25.17	17.76	6.94
Heat energy share produced by solar collectors, %	57.67	62.02	78.39
Heat energy share produced by biomass %	16.98	19.83	14.16
Solar collectors area, m^2	7367	5120	5429
Heat storage volume, m^3	15 170	11 584	16 434
Specific investment by heat source, EUR/MWh_{saved}	1467.2	691.3	554.4
Specific investment by heat source, $EUR/MWh_{produced}$	406.3	497.4	550.1

The analysis of the investments in respect to the produced heat unit indicates that the investments are increasing; however, their relative increase (1.35) is lower in comparison with specific investment per saved energy. This is explained by the increase of the share of solar collectors with seasonal accumulation (Sc2 collector's flats 5120 m^2 but Sc3 – 5429 m^2) in the heating system and by the fact that their costs are decisive for the total investment.

2.2. Power Sector Flexibility

Figure 2.9 shows that unit costs for fossil-based electricity increase steadily because there were no feedback loops embedded in the model and growth is assumed to happen due to exogenous factors, while the changes in unit costs for RES-based electricity are regulated by the reinforcing and balancing loop.

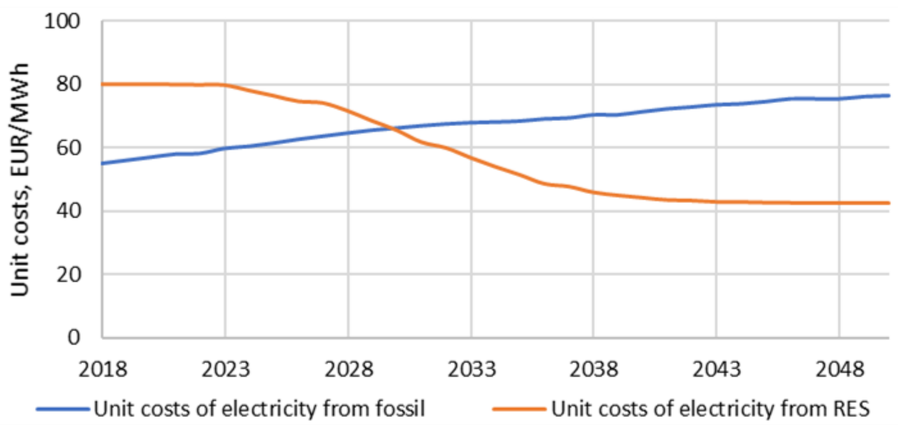

Fig. 2.9. Dynamics of unit costs of electricity production from fossil resources and RES.

The increasing rate of decline of unit costs for RES-based electricity production is due to learning effect. It can be seen in Fig. 2.10 that as more RES-based technologies replace fossil-based technologies, more capacity is installed and more knowledge is gained, resulting in further decrease of unit costs for RES-based power production (Fig. 2.9). The decline in unit costs of RES-based power production cannot continue forever because there is a limit for improvement of certain technology within the current level of knowledge. Therefore, when approaching the maximum level of technology penetration, less new capacities are installed and less improvements are gained leading to the decline of unit costs of production.

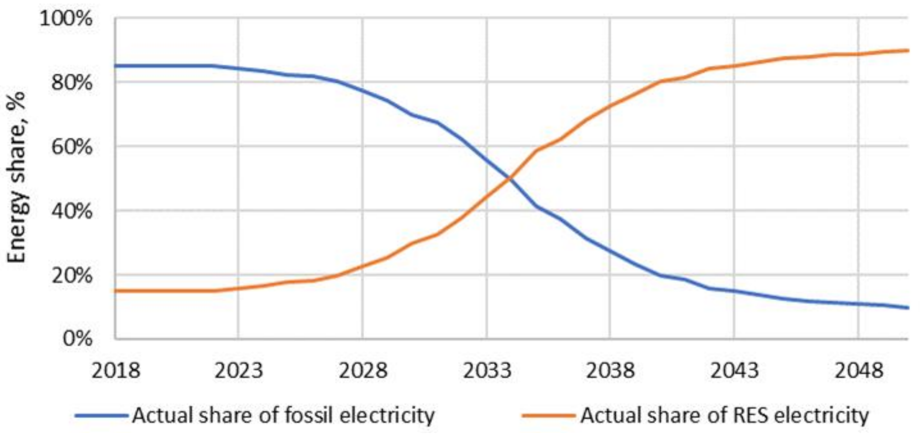

Fig. 2.10. Shares of fossil and RES-based power production.

Energy transition from fossil to renewable energy technologies happens gradually, not instantaneously, because the investment decisions of power companies have a delayed response to changes in the unit costs of technologies. In the model, this is considered by elasticity of substitution. Although the unit costs of power production for RES-based technologies become less than for fossil fuel-based technologies around year 2030 (Fig. 2.9), it takes several years before a share of RES-based power production overtakes a share of fossil- based power production.

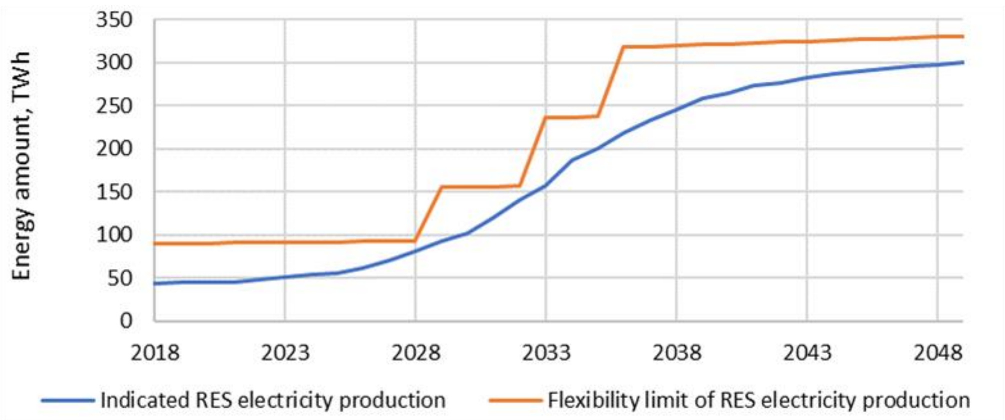

Fig. 2.11. Indicated RES electricity production depending on flexibility limits

Figure 2.11 illustrates the dynamics of RES-based power production depending on changes in flexibility limit. When the RES-based electricity production approaches flexibility limit, power companies become reluctant in investing in new RES capacities, and it is necessary to innovate in order to increase flexibility limit. Technological disruption due to innovation is modelled in the following way. When a certain threshold of the share of RES-based power production is reached (i.e. 80 % of the maximum allowed by flexibility constraints), disruption leads to new increased flexibility limit. The model also shows that if the threshold value is set higher, i.e. close to 100 % of the limit, it may become impossible to reach that threshold value (due to ceased investment in RES-based power production) and no disruption takes place. That leads to a situation when RES-based power production remains under the set flexibility limit and does not increase. This effect depends on the effect resulting from reaching a certain fraction of the flexibility limit on decisions to invest in new RES-based power production capacities.

2.2.1. Sector Coupling at National Level

In this research, four different scenarios were tested and compared. Scenario 1 describes the situation when no supporting policies are implemented, therefore system development happens based on market principles.

Table 2.4

Studied Scenarios

	Subsidies in capital costs		
	P2G	**P2H**	**Wind**
Scenario 1			
Scenario 2	70 %		
Scenario 3		30 %	
Scenario 4			30 %

In scenario 2, power-to-gas technology capital costs are subsidized in order to promote the development of power-to-gas. As Latvia is taken as a case study, P2G application was considered as a viable flexibility option due to a well-developed gas infrastructure.

Scenario 3 analyzes the impact that power-to-heat technology could have on power and heating sector development. In this scenario P2H technologies (heat pumps) receive 30 subsidies for capital costs.

In scenario 4, wind technologies (both on-shore and off-shore) receive capital cost subsidies in order to promote VRE development, and in the case of increased energy surplus, analyze whether it also promotes the development of P2H and P2G technologies.

After simulating Scenario 1, it can be seen that power sector development towards full decarbonization is very slow, and without additional incentives for renewable energy technologies, natural gas remains as one of the main power production technology (Fig. 2.12).

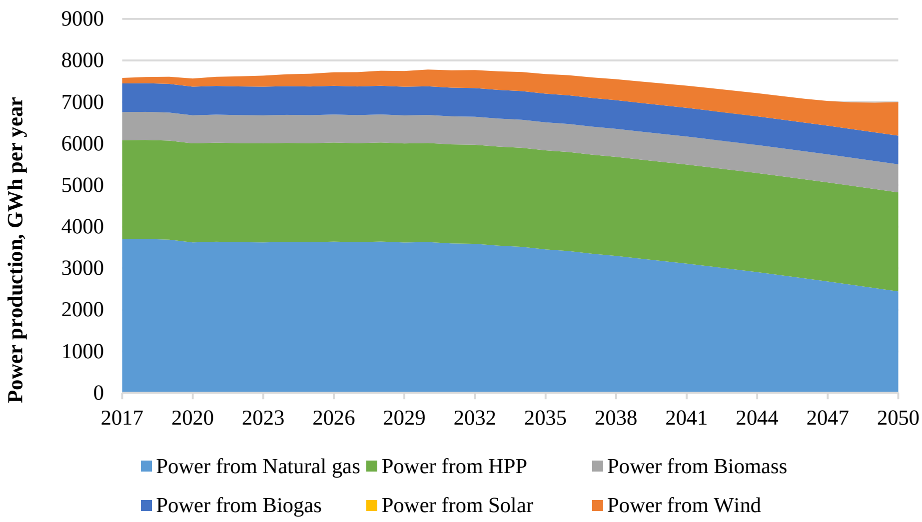

Fig. 2.12. Power production development (Scenario 1).

Although power produced by natural gas decreases by 34 %, it is not fully replaced by renewable energy, and the amount of renewable energy increases only by 17.4 % due to the fact that power demand has decreased in 2050. A large share of current power production comes from hydro power plants, and it was assumed that hydro power plants will not be demolished and will continue to produce at the same rate throughout simulation. HPPs are not considered VREs in this research. In this research only solar and wind technologies are categorized under VRE. It can be seen that wind technologies experienced the highest increase in capacity (+508.5 %), while solar technologies were unable to gain momentum. It should be noted that only centralized power production is considered in this research, therefore residential PVs and other decentralized production units are not modelled and will not be illustrated in total energy balance.

When comparing all four scenarios, it can be seen that the highest impact comes from subsidizing heat pump technologies (Fig. 2.13).

Scenario 1, in which no subsidies were granted, and scenario 2, in which subsidies for P2G technologies were granted, are practically the same when comparing VRE and natural gas share in 2050. This can be explained by the fact that although there is good gas infrastructure and 70 % of P2G capital costs were subsidized, still the total costs of production were too high to use P2G as a viable flexibility option. Only 7 % of power surplus was used in P2G application in Scenario 2. In other scenarios it was less than 1 %. Other incentives, like reduction of power grid costs, might be necessary to make it more competitive.

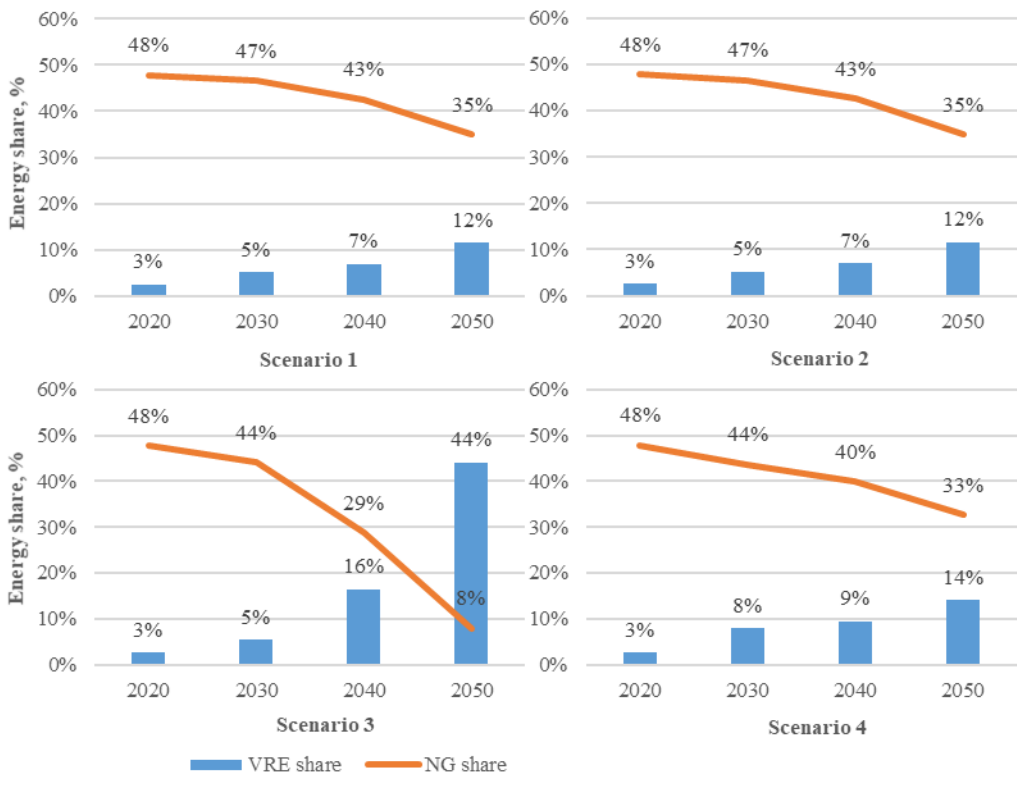

Fig. 2.13. Comparison of VRE and NG share in all scenarios.

It can be seen that also Scenario 4, in which wind generation technologies are subsidized, only 2 % improvement in VRE share can be observed. This might be due to the fact that large share of energy still comes from HPP, and to increase VRE share, it is necessary to decrease natural gas share, but 30 % subsidies are not enough.

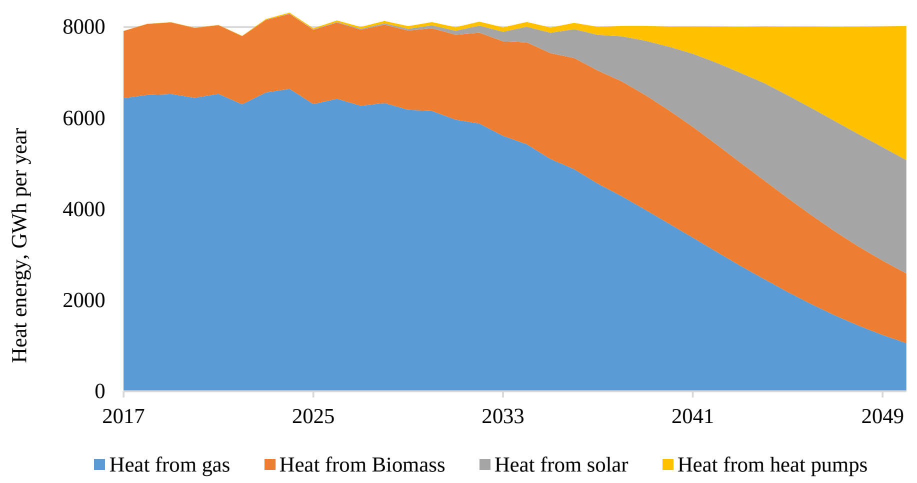

Fig. 2.14. Heat production development (Scenario 3).

Completely different results come from subsidizing P2H applications in district heating. Figure 2.14 shows that heat pumps (technology used in P2H application) are responsible for 37 % of total heat energy production in 2050 in Scenario 3, while natural gas production drops from 81 % to 13 % from total energy production. It should be underlined that P2H can develop only when there is enough surplus energy from VRE, and in Scenario 3, both wind and P2H technologies developed faster than in other scenarios. This can be explained by the fact that power and heat sector is connected via natural gas technologies that utilize CHP plants, and in order to replace natural gas in one sector, it should be at the same time replaced also in the other sector. As heat production is a priority for CHP plants, as they have to cover certain heat demand at their district, they cannot be shut down if there is no replacement in heat generation even if there is incentive to replace power generation capacity. Different situation is when there is incentive to replace heat generated by CHP, because power shortage from closing CHP plant in the short term can be replaced with power import, and it would be more cost effective than using CHP plant in condensing mode.

Subsidies in heat pump capital costs result in 44 % of VRE share in power production and 8 % natural gas share in power production in 2050 (Fig. 2.13). This is by far the best decarbonization scenario and also the best sector coupling scenario with highest flexibility.

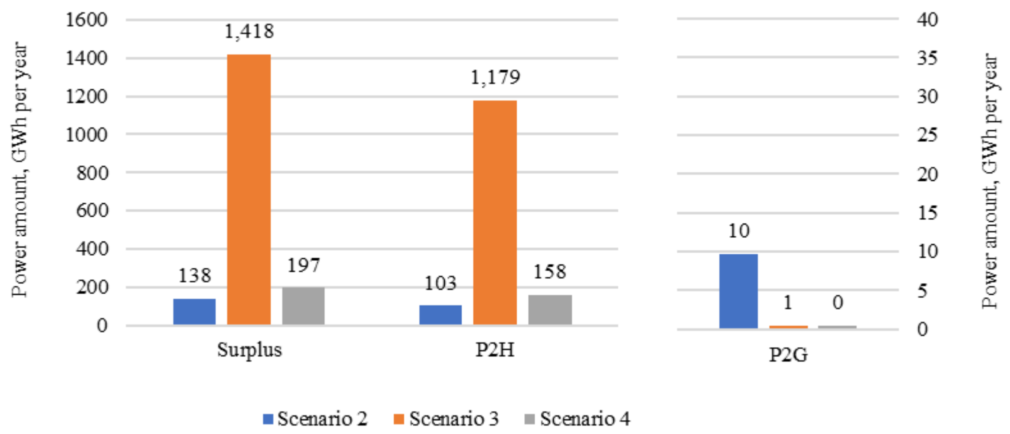

Fig. 2.15. Level of sector coupling in different scenarios.

Figure 2.15 shows the level of sector coupling. As described before, it can be seen that the largest energy surplus and P2H production amount is in Scenario 3, when heat pump capital costs are subsidized, followed by Scenario 4, when wind capital costs are subsidized. Unfortunately only in Scenario 2 there is noteworthy production of synthetic natural gas via P2G application, and even then it could not quite compete with P2H application and with natural gas price, and there is still a lot of research and technology development necessary to make it more competitive.

2.2.2. Sector Coupling for Local System

The developed SD model evaluates different solar power system configurations and policy instruments for renewable energy support. Table 2.5 summarizes the analyzed scenarios.

Scenarios 1, 2 and 5 represent the situation with different PV areas and without integrated HP for P2H concept. Solar power is only used for self-consumption coverage or sent BTG.

Scenarios 3, 4, 6 and 7 show the impact of different installed HP capacities for PV areas of 1000 m^2 and 500 m^2. The used values describe the part of the PV load that could be directly used for heat production via HP without covering self-consumption.

Scenarios 8 to 12 describe the situation with additional support for renewable technologies in the form of subsidies for investment in PV panels and HP. Scenarios 13 to 16 show the impact of increases in power and/or heat tariff as they directly impact the economic benefits of power conversion to heat.

Table 2.5

Overview of Analysed Scenarios

	Initial PV area	**HP capacity factor**	**PV subsidies**	**HP subsidies**	**Electricity price increase**	**Heat price increase**
	m^2	**–**	**%**	**%**	**%**	**%**
Baseline scenario	1000	0.1	0	0	0	0
Sc1	100	0	0	0	0	0
Sc2	1000	0	0	0	0	0
Sc3	1000	0.05	0	0	0	0
Sc4	1000	0.2	0	0	0	0
Sc5	500	0	0	0	0	0
Sc6	500	0.05	0	0	0	0
Sc7	500	0.1	0	0	0	0
Sc8	1000	0.1	20	0	0	0
Sc9	1000	0.1	40	0	0	0
Sc10	1000	0.1	0	20	0	0
Sc11	1000	0.1	0	40	0	0
Sc12	1000	0.1	40	40	0	0
Sc13	1000	0.1	0	0	20	0
Sc14	1000	0.1	0	0	50	0
Sc15	1000	0.1	0	0	0	20
Sc16	1000	0.1	0	0	0	50

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

Figure 2.16 shows the results of solar power production and utilization of surplus solar power. The solar fraction reaches around 20 % of total power consumption in the first year and drops to 13 % in the 7th year. Around 81 % of produced solar power is used directly for self-consumption; therefore, the remaining part is surplus power, which can be either transmitted BTG or converted to heat via HP when the electricity price is low.

The installed PV area within a 10-year period decreases from 1000 m^2 to 630 m^2 in 2026 because it is assumed that not all PV panels will last the whole lifetime predefined by manufacturer. If PV panels would prove to be economically beneficial, the company would be interested in investing in more PV panels, and the PV area would increase in the case when the investment rate is larger than the decommissioning rate.

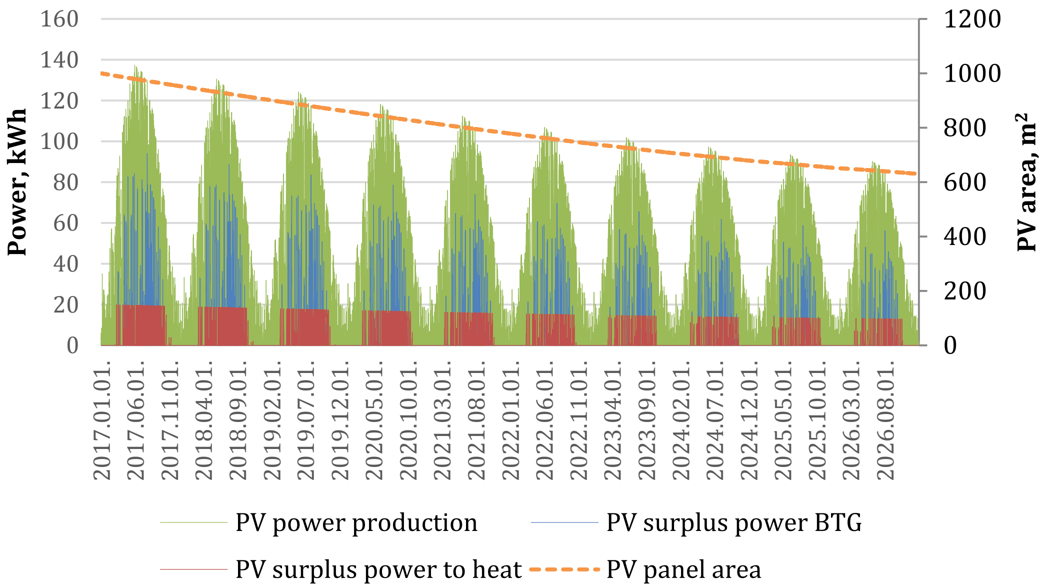

Fig. 2.16. Solar power production, surplus power utilization and changes of PV area in the Baseline scenario.

Around 47 % of surplus power is converted to heat and fed into the DH network, and the rest is transmitted to BTG. However, the use of power for heat production is strongly limited by the HP capacity. Part of the surplus power is sent to BTG due to insufficient HP capacity.

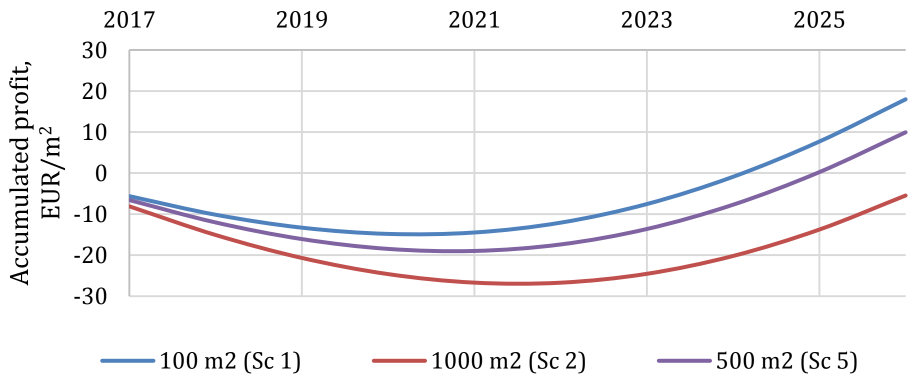

Fig. 2.17. Specific accumulated profit for scenarios without HP installation.

In order to compare the different scenarios with and without HP installation, the accumulated profit per m^2 of PV area is used as the main indicator. Figure 2.17 shows the result for different scenarios without use of HP when all the surplus power is sent to BTG (in case there is surplus power). The highest value is obtained for Scenario 1 with an installed solar panel area of 100 m^2. The total accumulated profit in year 2026 is 18 EUR/m^2. Figure 2.17 shows that Scenario 2 is not profitable during the analyzed period but PV installation of 500 m^2 results in 10 EUR/m^2 accumulated profit.

As indicated in Fig. 2.18, higher accumulated profit values are obtained for the Baseline scenario and Sc6 (PV 500 m^2 combined with HP). In addition, lower specific accumulated profit is evident in Sc4 and Sc7, in which case higher HP capacities are taken into account.

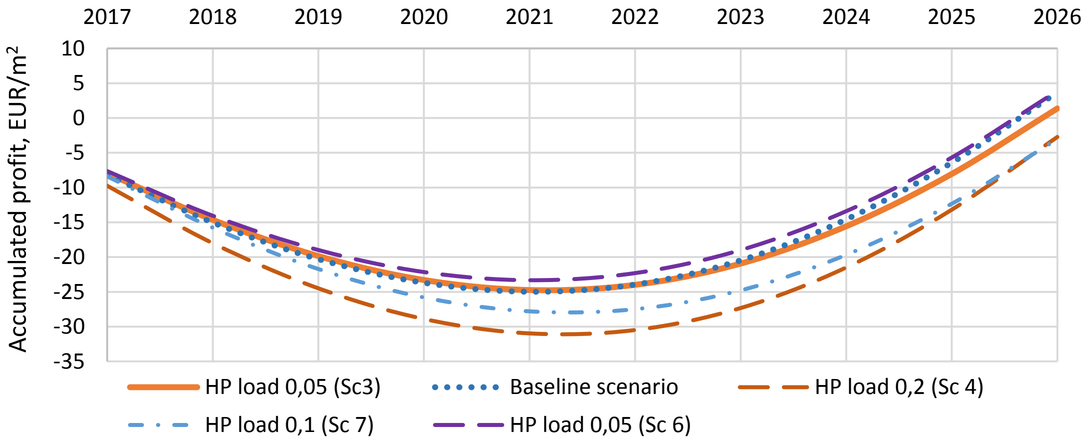

Fig. 2.18. Specific accumulated profit for scenarios with HP installation.

Several authors concluded that the P2H concept could be more beneficial with additional support policies or different tariff structures [9], [20], [21]. These analyses include scenarios with additional support in the form of subsidies both for the purchase and installation of PV panels and HP.

Figure 2.19 shows the accumulated profit per installed PV area for different grant policies. The obtained results are compared with the Baseline scenario. The subsidies for PV panel installations (20 % and 40 %) show higher accumulated profit increases compared with those that include the support for HP. The highest value of 88.25 EUR/m^2 is obtained for Sc12 when support is considered for both PV panels and HP. 40 % subsidies for PV panel installation only (Sc9) show profits reaching 78.26 EUR/m^2.

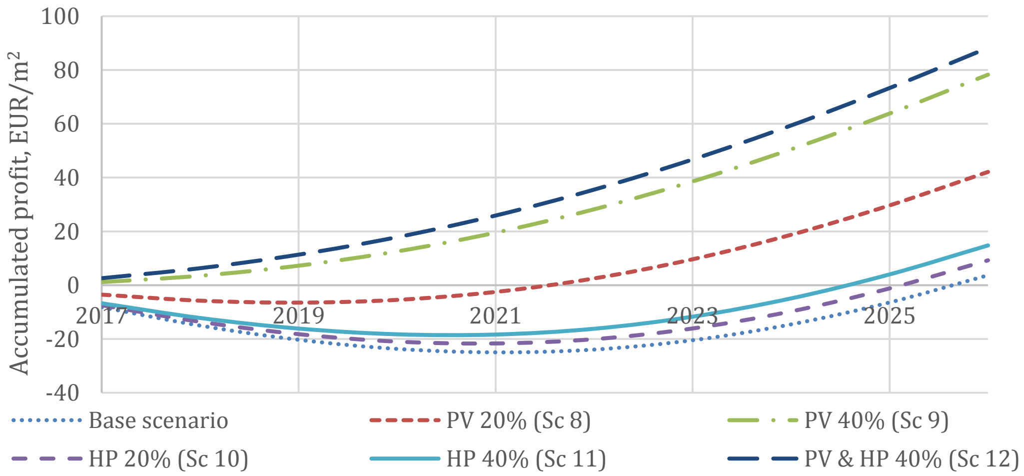

Fig. 2.19. Specific accumulated profit for different scenarios with support policies.

Figure 2.20 shows the impact that the increase in the price of heat and power have on the accumulated profit of PV system. If the price of heat increases by 20 %, the accumulated profit increases by 71 % in Sc15. However, an increase in the power price does not result in such a steady increase of accumulated profit.

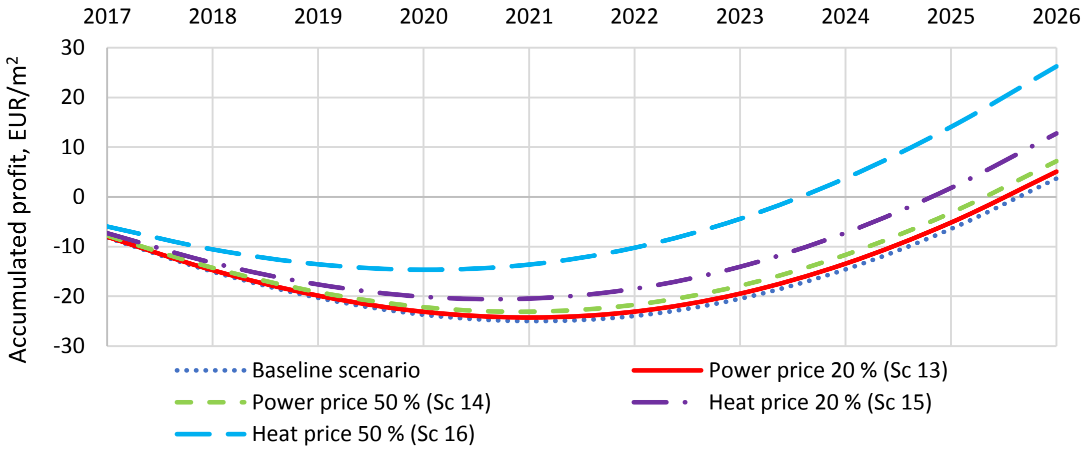

Fig. 2.20. Specific accumulated profit for different scenarios with increased power and heat tariffs.

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

CONCLUSIONS

Different heating system models are analyzed, and the results indicate that renewable energy integration in the system is not only possible but in the future it will be the economically most advantageous solution. It will happen mostly because of renewable technology development and decrease in capital costs, but also different policies aimed at reducing carbon footprint will play a role in heating system transformation.

While looking at the heating system separately from power sector, solar and biomass technologies prove to be most competitive with fossil-based technologies. Initial results suggest that with right support district heating system can easily reach high renewable energy penetration level, which can be seen in the Result section 2.1.1., while individual heating has slower transition rate. Individual heating might need additional policies to the ones tested in order to move towards carbon neutrality.

National scale heating system model predicts that RES share in individual heating can increase from initial value of 59 % in 2017 to 77 % in 2050 in base scenario and up to 83 % in scenario with policies specified in thesis. With selected policies RES share increase in district heating is even more significant. RES share in district heating increase from 47 % in 2017 to 83.5 % in 2050 in base scenario and up to 97 % in scenario with all policies selected. This means that both individual and district heating systems have high potential for RES utilization, but both existing and planned policy framework on which the analysis was based on are favoring district heating system. This results in lower RES share in individual heating.

Local scale district heating system model also shows high renewable energy potential. Initial transformation happens towards biomass utilization, but in 2050 system is dominated by solar collectors with seasonal accumulation. Renewable energy share in local system reaches over 92 % in 2050.

Power sector development towards renewables is inevitable due to the EU plan to reach carbon neutrality till the end of 2050. This means that integration of variable renewable energy sources is necessary, and this will completely transform power sector. Power sector will need to become more flexible in order to balance the supply and demand loads when high share of variable energy will dominate the system. Different flexibility measures will be necessary, like sector coupling.

Conceptual power system model showed the importance of power system flexibility increase on renewable energy integration. Technological disruption due to innovation is necessary to increase the flexibility limit. Existing flexibility limit is insufficient to support the high level of renewable energy in power system, without causing instability in the system. Pressure in the form of targeted policies should be put on the system in order to make renewable energy attractive and help to overcome the threshold after which the technological disruption happens.

Sector coupling can help the power sector to balance the system while transforming excess power at times of peak production in other energy forms – heat or gas, which can be stored much easier. This can be very beneficial to the district heating system, and renewable power can become as one of the main resources in heat production. The results in Sub-section

2.2.1. suggest that sector coupling can help to develop both systems. If there is high demand for renewable power at excess time, power sector is more likely to invest in variable renewable power capacity increase, while district heating companies are more likely to invest in heat pumps if there is excess power with lower price available in the system. National scale sector coupling model results indicate high potential of coupling between power and district heating systems. By granting support for heat pump technologies in district heating, it was possible to reach up to 37 % of heat generation from renewable power in district heating. Not only that. By increasing renewable power consumption in district heating, variable renewable energy share in power generation also increased up to 44 %, based on increased demand for variable renewable energy.

Local scale system indicates that coupling of power and heating system can be economically beneficial, however it is important to select the appropriate power and heat generation capacities. Solar PV capacity should be selected based on power consumption in company. If system is too large, payback time will increase. Same goes for heat pumps. Appropriate capacity should be chosen, based on forecasted power surplus. Larger heat pump capacities might ensure that all power surplus at peak generation periods is converted to heat, however rest of the time capacity is underloaded, resulting in longer payback period for heat pump technologies. For appropriately selected systems payback period is around seven to nine years, but with additional support system might become profitable already in its first year.

Both, national and local scale models show potential for renewable energy integration, therefore, indicating that not only large scale but also smaller systems are an economically feasible option for renewable energy.

Policy testing shows that certain policies, like support for renewable technologies, tax increase for fossil technologies, energy efficiency improvement at consumers and others, can stimulate renewable technology integration and opting out of using fossil resources, but the policies tested in the Thesis are insufficient to reach the carbon neutrality by 2050. Additional policies should be evaluated, especially for individual heating.

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