D7.4 – Scenarios Beyond REWARDHeat: Energy, Environmental, Economic and Societal Impact Assessment

Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks

REWARDHeat

Project Title: Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks

Project Acronym: REWARDHeat

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1 Introduction

This report relates on the impacts of the REWARDHeat solutions developed, in terms of the energy, environmental, economic and societal aspects in the demonstrator networks and on a large scale in the urban or municipal DHC system surrounding. The assessment of impact scenarios builds on existing knowledge and approach within energy systems modelling and social cost benefit analysis.

The overall approach to the elaboration and assessment of impact scenarios is to see the REWARDHeat technologies and systems as part of a wider geographical and energy system context. Within this context they are upscaled from demo site level to a city-wide or municipality-wide level based on an evaluation of their expansion potential.

As the first step, performance indicators (KPIs) are defined that make it possible to capture, evaluate and compare the upscaled REWARDHeat solutions as part of the wider energy system. The KPIs are, therefore, defined at the energy system level. In the second step, the upscaled REWARDHeat technologies are assessed in the larger, future (urban/municipal) energy system they are situated in, by means of energy systems analysis using EnergyPLAN. For this, energy system scenarios are created. Third, the economic and societal impacts of the energy system scenarios are evaluated.

2 Key performance indicators

For the assessment of the impacts of the upscaled REWARDHeat technologies and systems, a set of KPIs has been defined. With the KPIs, the different impact scenarios can be compared. The KPIs are defined in alignment with the output categories of the scenario assessment tool (EnergyPLAN), and have been elaborated with the project partners. In the following paragraphs, the KPIs are defined on an overall level and then divided into the categories: energy system, environmental, economic and societal.

2.1 Definition of key performance indicators for the impact assessment

A KPI is a metric that demonstrates how effectively a project, or system achieves their objectives or how it performs. The nature of the objectives can be political, economic, social, technical, legal, and environmental. KPIs can help policymakers with decision making. Within the context of this report, the KPIs will show how the different technologies perform in a low and neutral DHC network. Different types of KPIs for a project or system can be defined, for example:

- Conditional (yes or no),
- Quantitative (e.g. kWh, €, MW, %, x/m^2 etc.),
- Qualitative (e.g. many, maybe, ++/0/--, etc.).

The focus in this task is on quantitative indicators since the performance of DHC systems can be measured relatively straightforward in this way. The discussion of the KPIs for each demo system is supplemented with qualitative considerations where relevant – for instance, in case of high uncertainty in a quantitative KPI, or in areas where it is difficult to define quantitative KPIs. Since low and neutral temperature DHC systems fulfil different goals (economic, environmental, societal) and differ, both, in type and technology, a set of different KPIs is defined to take these variations into account.

2.2 Energy and environmental indicators

Several types of indicators can be applied for the evaluation of an energy system. The focus in this task will primarily be on energy system KPIs that also capture the performance of low and neutral temperature DHC technologies, i.e., the following:

(1) Non-Renewable primary energy use:

Primary energy (PE) is the energy found in nature that has not been subjected to any human engineered conversion process. Primary energy can be non-renewable or renewable. Introducing low and neutral temperature DHC will have an impact on the consumption of fossil fuels in the surrounding energy system. This can be evident from reduced need of production at central DH/CHP plants or increased electricity consumption from power plants due to higher production from heat pumps in the low or neutral temperature DHC [1].

(2) Renewable primary energy use:

This indicator quantifies how much renewable energy can be introduced in connection to neutral temperature DHC networks as compared to a reference situation with conventional DHC. The indicator covers renewable thermal energy, in terms of solar thermal, biomass, geothermal as well as waste heat.

(3) Share of local waste heat / excess heat:

Low and neutral temperature DHC makes it possible to better integrate (low temperature) excess heat from industry and other sources, such as datacentres, transformer stations, supermarkets, wastewater treatment etc. Thus, this KPI quantifies the total share of excess heat in the DHC network – both, high and low temperature. This KPI is important as it also supports the reduction in fossil fuel consumption in the DHC network and might be object of regulation and policies, like subsidies.

(4) Losses:

This KPI quantifies network losses based on the difference between heating/cooling produced and consumed. In low and neutral temperature and DHC networks losses can generally be lower due to lower network temperatures. The change in network losses in the modelled scenarios is estimated based on information from the demo sites, and, on the estimates in Ref. [2]. wherever this information was not available from the demo sites.

(5) CO2 emissions:

The indicator uses CO_2 emission factors from fuels to calculate the overall emissions from the urban energy system with and without neutral temperature DHC technologies. In this way, it can be quantified if and where neutral temperature DHC contributes to CO_2 emission reductions in the system. The indicator of CO_2 emission is quantified for the entire energy system, in which the heating/cooling system is modelled as the main sector, but some components of the electricity system are included when directly linked to the heat production (such as the CHP, PV, etc).

(6) Air pollutions:

According to the World Health Organization (WHO) air pollution is one of the greatest environmental risks to health. By reducing air pollution levels, countries can reduce the burden of disease from stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma [3]. While for CO_2 it does not matter where they are emitted as they have global wide impact (climate change), for air pollutants it does matter, as they cause mainly local impacts (human health & ecological issues)[4].In DHC networks with lower shares of combustion-based energy, the amount air pollutants will typically be lower. Air pollutants, for example particulate matter (PM), sulphur oxide (SO_X), and nitrogen oxide (NO_X), mainly cause respiratory problems, but can also lead to cardiovascular diseases or premature death for people with heart or lung disease. In this KPI, the amount of air pollutants in tonnes as well as the accompanying shadow costs will be calculated.

2.3 Economic and Societal indicators

The annual total levelized costs and the job creation are selected as the economic and societal indicators.

(1) Annual total levelized costs of the DHC system

With this indicator, the overall costs of the DHC system can be assessed as it captures, both the costs of investing and upgrading the DHC system and other energy system investments, as well as the operational costs for DHC network during, e.g. one year of operation. One of the main costs for a DHC are (fossil) fuels that need to be bought. These fuels come mostly from outside the region, for example, biomass, gas or electricity bought from the national grid. Furthermore, investments, mainly for new technologies, can be expensive as well. However, it is also important to “follow the money”; buying foreign (fossil) fuels leads to transporting the money outside the region. While, if the money is invested in a (new) technology in the region, the money stays there and stimulates the local economy.

The cost indicator makes it possible to assess a DHC system at an overall level, if it will need higher investments (CAPEX) and relates this to maintain and operate costs (OPEX). Therefore, this KPI is an indirect indicator of revenues for investors and operators in the system. The indicator also serves as an input for calculating employment effects as part of the social cost benefit analysis.

(2) Job creation from investments in the DHC system

New work opportunities have a positive effect on a region and its economy. New jobs increase the revenues of the local economy within a region, which also contributes to reduction of unemployment rates and enhances and makes a region more attractive (especially if offering high-graded jobs).

Energy systems can provide several different types of jobs for a region and can be divided into temporary and permanent jobs, and direct and indirect jobs. Temporary jobs are jobs that are only provided for a certain period (e.g., construction), permanent jobs are jobs that will be there indefinite (e.g., network operator). Direct jobs are jobs that are directly linked to the energy system (like network operators), while indirect jobs are not directly linked to the DHC network (e.g., network pipe producer). In this KPI, the number of jobs created by investments in DHC networks are estimated for different scenarios of heating and cooling.

3 Methodology

The overall aim of the impact assessment is the modelling and analysing the impact of the REWARDHeat demonstration projects in energetic, environmental, economic and societal aspects. Due to the large variety of the demonstration projects in terms of geography, climate, size, resources and technologies the detailed steps of the impact analysis vary depending on the case. However, the overall approach to the impact analysis is similar for all cases and is described in the following. The variety of the demos lies in the types of technologies tested, data availability and their size and location within a district heating network (DHN) and within the various countries. This also means that the impacts are not easily comparable across the demo projects, and instead, the variety of impacts is compared in different scenarios within the wider demo DHNs.

The methodology for the scenarios and impact analysis is illustrated in Figure 1, where the general approach and context of the demos are defined as main inputs. These are then evaluated according to future upgrades and improvements within the demo and within the municipal/legal boundaries, with a focus on lower temperatures, renewable energy and waste heat use. The impact of these changes as well as aspects beyond the demo is compared by outputs of energy and environmental terms (e.g. energy supplies, emissions and renewable heat uses) and economic-societal aspects (e.g., job creations and total annual costs). Hence, in geographical aspects, the demo is part of the overall DHN within the city/municipality, which is therefore included in the analysis.

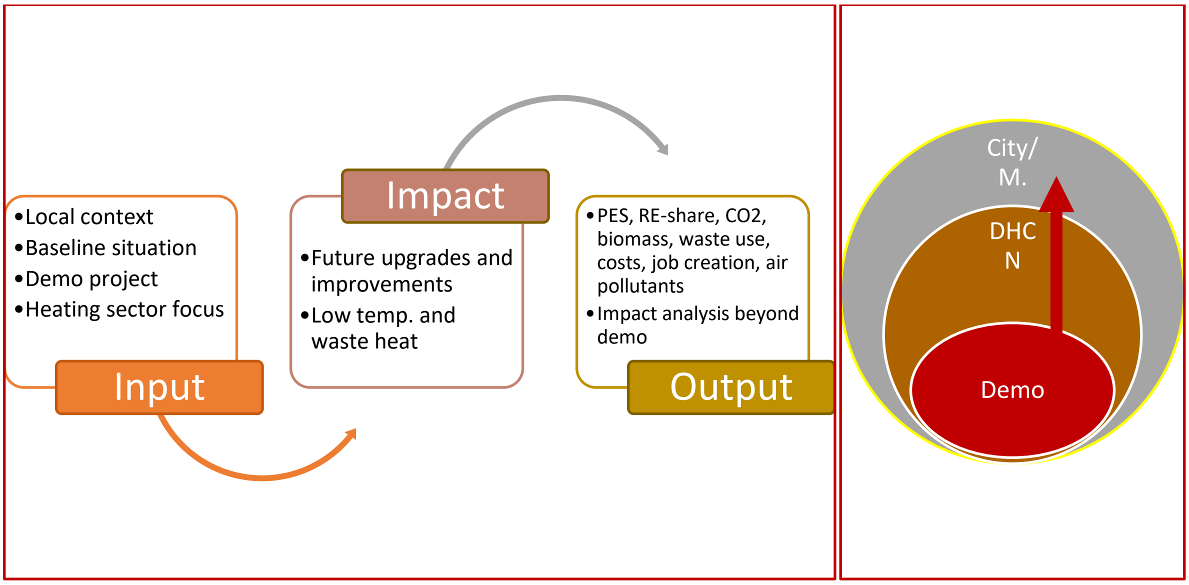

Figure 1: Overall methodology of the energy and eniromental impact analysis: The REWARDHeat demos are modelled as part of the local/municipal heating and cooling sector.

3.1 Scenarios setting

For each of the 7 demos in the REWARDHeat project, three scenarios are created, i.e., baseline 2020, future 2050 and 2050 100% REWARDHeat. Due to the different characteristics of the demonstrator networks in terms of size, pre-existing DH networks, climate etc., the impact scenarios are adapted to fit the local contexts and to adequately reflect the system impact of the demo networks and technologies.

The scenarios are focused on the heating sector, while the cooling sector is included only if it is part of the demo. Cooling is regarded as a sub-sector/addition to heating but excluded at most demos as it is not as well developed in district networks, nor is it the primary focus area of REWARDHeat. The other energy sectors such as the electricity, industry and transportation sector are excluded to facilitate that the REWARDHeat impacts can be identified directly. However, major expected impacts on e.g. the electricity sector in the modelled scenarios are discussed when relevant. The energy production and conversion technologies and related technical parameters such as capacity and efficiencies, especially for the heating sector, are described in the scenario. The geographical boundaries of the energy system created are set to municipality borders of the demos, in order to investigate the impacts of REWARDHeat project beyond the demo size.

The three scenarios designed are described below.

1) Baseline 2020 scenario

In this scenario, the current situation of the energy system of the municipality of each demo is modelled, representing the situation in 2020 with the latest available data (sometimes from 2018/19) as a baseline from both local demonstrator and regional/municipal data.

2) Future 2050 scenario

In this scenario, an estimation of energy system changes until 2050 is made with the focus on the implementation of 4th generation district heating (4GDH) for previously individually heated areas or transitioning to 4GDH for existing 3GDH areas. The related improvements are considered, including i) temperature reductions, network improvements, reduced network losses, and ii) exploration of local renewable and waste heat potentials for DHN.

The modelled system is delimitated from external changes to isolate and analyse the impacts of REWARDHeat measures, i.e., no changes in the housing stock and building energy consumption (except where explicitly stated in local strategies) are implemented, only expanding DH according to foreseen growth rates as part of REWARDHeat. In such way, the impacts of REWARDHeat can be shown in a clearer way, otherwise they are not distinguishable from the many other changes that may happen in the local energy system until 2050.

3) Future 2050 100%REWARDHeat scenario

This future scenario further develops the local DHN towards 100% renewable and waste heat recovery, building on the future 2050 scenario for comparison. In this scenario, the further decarbonization potential by upscaling the low-carbon technologies is investigated by utilizing the locally available resources and technologies, such as large-scale heat pumps, geothermal, thermal storage, and industrial waste/excess heat.

3.2 Methods of energy and environmental impact analysis

3.2.1 Energy system impact analysis based on EnergyPLAN

For the assessment of the impact scenarios, the energy system modelling tool EnergyPLAN is used. EnergyPLAN can simulate the demo cities' complete energy systems in terms of the heating, cooling, electricity, and transport sectors – yet, with a focus here on the heating sector as applicable in REWARDHeat project.

EnergyPLAN performs an hour-by-hour simulation of the defined energy system for one year and is an open access modelling tool [5]. EnergyPLAN has been widely used for national, regional and urban energy systems analysis making it a suitable tool for the task [6]. One advantage of the model is its fast calculation time (seconds) and the capability to capture the interaction and integration of technologies within the energy sectors, making it ideal for the analysis of energy systems with large shares of renewable and waste energy. As a simulation model, EnergyPLAN also fits the task of gradually upscaling the REWARDHeat solutions in the local energy systems. The tool requires a number of user-defined inputs making an initial data collection necessary as described above. In this task, primarily the heating sector are analysed, with partial analysis or discussion of the cooling and electricity sectors , as the demonstrator projects will have the largest impacts in these sectors. The demonstrator solutions are modelled as an integral part of the local energy system defined above to assess the energy and environmental impacts of their potential diffusion and upscaling until 2050. This allows a comparison of the present (2020 baseline) situation with the future scenarios of 2050.

In further detail, modelling energy systems and especially DHN with EnergyPLAN allows to integrate various technologies, options and aspects of production, conversion, storage and demands. Overall changes to future production or consumption technologies or patterns, or additional heat sources and fuels can be studied. This is done aiming at a technical optimization of the system through the software's technical simulation strategy, where renewable, waste energy and efficient technologies are simulated with priority over fossil-fuel based or inefficient ones. EnergyPLAN has the possibility (out of necessity) to integrate also electricity. This is based on the tool being developed in line with CHP plants, but is also of importance for electric boilers/heating systems or heat pumps. Hence, balances between sectors are important, such as when electricity or heat is used across sectors (CHP, electricity heating, waste heat, etc.) and thereby interferences within each network and across the system are visible.

The modelled demands and technologies in EnergyPLAN can furthermore be of various sizes, such as individual heating or small DHN to large-scale DHN with large CHP capacities. With CHP often at the centre of DHNs, these are in focus in the scenarios, besides relevant boilers, which are all defined by their efficiencies and their fuel types and shares; but also heat pumps and storages are key technologies, which EnergyPLAN is well equipped to simulate. Of further importance is the ability to simulate DHNs separately or aggregated. However, it is not possible to simulate sub-networks as part of larger ones, as might be the case in the REWARDHeat demos. Therefore, the macro perspective of the demo as part of the larger DHN is used.

As further applied in the scenarios of the demos, individual heating is added to present a full picture of the heating system within the local municipality or local administrative units (LAU) and to allow potential individual heat demands to be added to the DHN in the future scenarios. As mentioned, the cooling and electricity sectors are only represented to the extent that they significantly interact with the heating sector in the scenarios. EnergyPLAN models the cooling sector as a DH-independent technology and would present demands simply as additional loads. On the other hand, the electricity mix is dependent on a larger context than the local focus and is not further studied. The locally relevant electricity demands for heating, as well as potential influence of the cooling sector, is therefore only addressed in the qualitative impact analysis. And finally, while industrial waste heat plays an important role in the scenarios and can be utilized either directly or via heat pumps, the fuel demands behind industrial waste behind are excluded for further analysis [7].

Figure 2 shows the options and relations of the analysis of the energy system in EnergyPLAN, whether it is only the heating sector or a combination of several sectors, depending on the technologies available/relevant and the data provided. The output of the model includes the KPIs:

PES, RE share, and CO_2[1] emissions, as well as allows to extract the share of waste heat utilisation and individual heating unit operations.

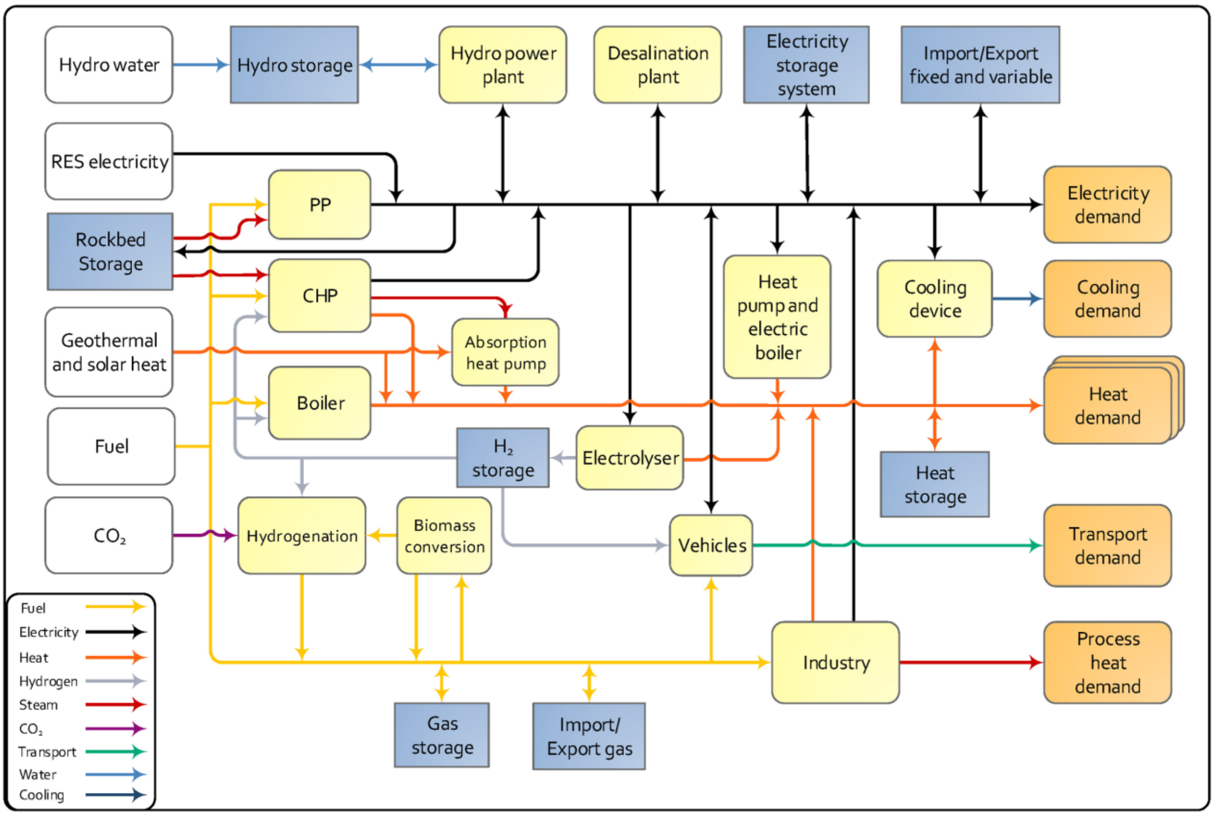

Figure 2: Graphic representation of the EnergyPLAN model with its simulation options, adjustable to the demo settings [6]

3.2.2 *Data collection for energy system models*

The data required for the impact analysis addresses the overall scenario design, as well as inputs to the changes in the 2050 scenarios. The data collection for the required input from the local energy systems was done by means of a data collection sheet that was filled in together with the demo sites and associated partners.This task is based on available data not only from common sources, but also on the data provided in previous tasks and deliverables in REWARDHeat. These include mainly the deliverables D5.7 [8], D6.2 [9] and D6.3 [10]. Hence, depending on the availability of data here, as well as inclusion of demo projects at the time of writing these reports, the approach for this task is adjusted – and the final selection and result is reflected in Section 4.

In case of missing or unavailable data, available data from similar cities in the same region or country data, e.g. from the Heat Roadmap Europe (HRE) [11] project, are used as supplement to complete the local scenarios. Furthermore, local statistics and energy reports are consulted. For the modelling and assessment of energy and environmental impacts of the scenarios, the following data is collected. This is further elaborated in the next sub-section as well as in the demo site presentations and discussions under each case.

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[1] while only CO_2 emissions are included in the EnergyPLAN analysis, other reductions of harmful emissions associated with the applied fuels can be expected, which are quantified outside the modelling tool based on the identified fuel consumptions.

Table 1: General approach to data collection and sources applied

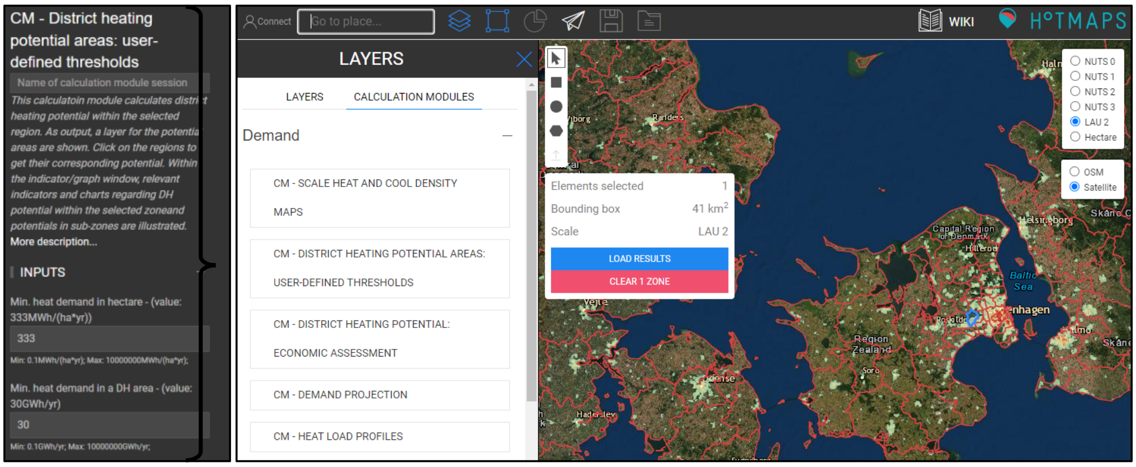
Data needed	Sources applied
Demo project data: technologies, capacities, efficiencies, potentials	REWARDHeat material [12–14] REWARDHeat partners
Heating demands at municipal level, incl. DH	HRE [11] Hotmaps [15]
Heating fuels, incl. DH	Literature review HRE [11]
Heating capacities and efficiencies, incl. DH	REWARDHeat partners, literature review, HRE [11], EnergyPLAN [6]
DH losses	EnergyPLAN [6], literature review
Heating/DH distributions	REWARDHeat partners, weather data, HRE [11]
CO_2 content of fuels	EnergyPLAN [6]
Additional relevant technologies, e.g. solar, storage, etc.	REWARDHeat partners
Costs	EnergyPLAN cost database [16]

Determination of heat demand

Heat demand is one of the most important data for the scenarios and the following energy system analysis. The local heat demand of each demo is identified by using multiple sources. The heat demand data collected from local partners is prioritized. In the case of unavailable data from partners, the Hotmaps tool is applied to help identify heat demand and DH potentials of the demos in the municipalities in which they are situated. Other datasets from HRE [11] statistics and local government documents also served as data sources for reference.

Hotmaps is an open-source online software developed during the Horizon 2020 Hotmaps Project (Grant Agreement number 723677). With the software, the LAUs are identified along with the municipal boundaries for which the scenario assessments are made. LAUs consist of municipalities or equivalent units in the 28 EU Member States and are selected for the assessment as they are: administrative for reasons such as the availability of data and policy implementation capacity; and appropriate for the implementation of local level typologies. [17]

The tool is applied to all the selected geographical settings of the demos, where total heat demand, potential heating demand, based on and including maximum heat densities, are extracted. Despite delimiting the impact analysis to the heating sector, it is also possible to extract cooling data to give an overview and add to the discussion in the impact analysis. Finally, where other, local data is deemed more suitable, Hotmaps is critically reviewed as its statistical approach and potential deviations from reality must be taken into consideration.


CM - District heating potential areas: user-defined thresholds

Name of calculation module session

This calculatoin module calculates district heating potential within the selected region. As output, a layer for the potential areas are shown. Click on the regions to get their corresponding potential. Within the indicator/graph window, relevant indicators and charts regarding DH potential within the selected zoneand potentials in sub-zones are illustrated.

More description...

INPUTS

Min. heat demand in hectare - (value: 333MWh/(ha*yr))

333

Min: 0.1MWh/(ha*yr); Max: 10000000MWh/(ha*yr);

Min. heat demand in a DH area - (value: 30GWh/yr)

30

Min: 0.1GWh/yr; Max: 10000000GWh/yr;

Elements selected: 1

Bounding box: 41 km²

Scale: LAU 2

Figure 3: Hotmaps tool interface showing LAUs and DH calculation potential module applied [17]

Assessment of low-temperature DH systems and benefits for future DHN

To illustrate the application of EnergyPLAN and the possibilities of scenario and impact analysis for the REWARDHeat impact analyses, the following presents the overall aim and supports the assessment with general data and an introduction to 4GDH. This is applied as point of departure for the demos' scenarios.

The magnitude of the benefits of the impact scenarios will to a large extent depend on which kinds of DH networks are deemed feasible in the various demonstrator towns until 2050. In the towns that have pre-existing DH networks, it has to be estimated to what extent these networks can be converted to low- and neutral temperature networks. Lower network temperatures can have various added system benefits – apart from a lower energy consumption. In the following, an approach for estimating these energy system benefits in the impact scenarios is described.

Aggregated production and supply of heat in the form of DH benefits the heating system and can support the transition to highly renewable energy systems. With one of the largest energy consumptions being in the building sector, DH addresses reductions by central production sites, which combine various technologies and distribute it to urban areas through water circulation. Especially, the integration of large heat-producing sites, such as power plants, waste incineration or industry can supply nearby homes with otherwise wasted heat. Moreover, large thermal storages can be added, as is the case in Denmark, where over 50% of all houses and heat demands are covered by DH. Connecting buildings in existing DH areas, in neighbour areas and establishing new DH networks with sufficient heat density can increase the total DH share in the heating sector. This can lead to significant reductions in fuel, CO_2 and costs. [18]

The transition to low-temperature (often referred to as 4th) DH improves the possibility to utilise further (low temperature) waste heat sources, such as from the upcoming production of electrofuels, biofuels or other sources that are not accessible through individual heating, like geothermal plants and low-temperature industrial waste heat (including supermarkets, electrical substations, metro stations etc.). However, DH entails network losses, which are typically in the range of 20-30% at an 80°C DH supply temperature. Reducing the DHN supply and return temperatures would not only reduce these losses, but also increase the options of excess heat utilisation and efficiencies of heat generation units. [19]

With reduced temperatures in especially supply, but also return pipes as part of transitioning from 3rd generation DH to 4th generation, both, production and storage technologies in the DH will be affected. Not only will generally *"lower supply temperatures translate into lower energy losses"* [20], but this is also *"expected to increase the COP of HPs and the thermal efficiency of CHP units including waste incineration"* [2]. A study of the city of Aalborg with a medium-size DH network shows that a typical 3rd generation DH network has temperature levels of around 80/45 degrees C of supply/return temperatures and a coefficient of performance (COP) of 2.9 of large, central heat pumps, while reduced temperatures to 55/25 degrees C can help increase the COP by 34% to 3.9. [21]

In Aalborg a reduction of losses from 27% to 19% for small-scale and 21% to 15% for large scale DH, respectively, can be achieved by network temperature reduction. This may be replicated in other DH networks with similar characteristics, like size and location. Results, hence, depend on soil temperatures and average forward and return temperatures for its current 3GDH and planned 4GDH, and not counting effects from energy savings in buildings. The utilizable waste heat from supermarkets increases in general by 60% in 4GDH compared to 3GDH and can be done according to a categorisation of supermarkets into three groups and resulting heat to be provided per year and store. The categories are assumed to provide 75, 100 and 150 MWh/year/store[2] for large, medium and small-scale supermarkets respectively. However, the use of waste heat sources still requires the use of HPs to increase the temperature of waste heat sources to match the forward temperature in the DH system, also for 4GDH temperatures, which are often available if the industry has cooling demands. Depending on the source and forward temperatures, the COP of the HP changes accordingly for 4GDH. The resulting overall heat demand in the DH network can be reduced by 14% due to the lower temperatures. [21]

Table 2: Impact assessment of transition from 3GDH to 4GDH, based on [21]

	3GDH – baseline	**4GDH – future**	**Difference – impact**
Temperatures	80-90/50-60	50-60/20-30	20-30°C
Losses	20-35%	12-27%	- 6-12% depending on existing losses
HP COP	2.5-3.5	3.5-4.5	+ 1-1.5
Waste incineration efficiency	80%	85-90%	+ 5-10%-p.
Boiler efficiency **CHP**	80-85%	82-90%	+ 2-5%-p.
Waste heat utilization share	Depends on local industry and resources	Depends on local industry and resources	+ 60% for supermarkets

Besides the benefits of 4GDH, a few things need to be considered. Problems that can occur include suitability of low temperatures for buildings and networks with high temperature demands during peak hours, such as buildings with low energy standards. Also, generally DH developments to go

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[2] Supermarket excess heat categories and Aalborg examples: 1 – large supermarkets, incl. Bilka, Føtex, Kvickly; 2 – medium supermarkets, incl. Meny, SuperBrugsen; 3 – small supermarkets, incl. Aldi, Fakta, Netto, Rema, Spar

hand in hand with building regulations and changes. Depending on the current existing DHN and the surrounding potentials, the figures above are only guiding – and the REWARDHeat energy scenarios are to be created within this context. Similarly relevant to the context, if 4GDH is planned and implemented in good time, additional capacity installations can be avoided, such as large capacities of wind turbines, heat pumps, CHP, additional transmission lines. Therefore, investments and expansions of DHN must always be seen in relation to each individual case. This can vary from adding certain buildings to expanding networks and differences between municipalities, taking into account existing technologies, future plans and potentials locally. While the following study tries to consider these aspects where possible, the results must be seen in the overall presented context of this methodology.

3.2.3 Environmental impact analysis

Air pollutants

In this report, the air pollutants are calculated based on the fuel outputs of EnergyPLAN. For each energy system models have been created in EnergyPLAN, as such the annual fuel consumptions from each category of heating technologies (e.g., CHP, boilers, waste incineration for DH systems; heat pumps and boilers for individual heating systems) can be obtained.

The selection of air pollutants are made by the inclusion in the database of the European Environment agency [22]. The emissions factor of different fuels and technologies are shown. The amount of pollutant emitted is calculated by formula below.

$$K_{XX} = \frac{\sum_i E_i * k_{XX,i}}{Q}$$

Where *XX* is the air pollutant assessed. K is the amount of the pollutant emitted by the system per energy produced in kg/kWh. E_i is the energy source “i” input in kWh and k_{XX} is the corresponding emission factor of pollutant *XX* of that energy source kg/kWh. Q is the total energy produced in kWh by the system.

Furthermore, as the impact of these pollutants is mainly locally, the electricity from the grid is not taken into account in this indicator, because the electricity from the grid is not generated locally. So, the impact of the pollutants emitted by the electricity generation is not assigned to the area that uses the electricity [23].

Shadow costs

Environmental prices are indices expressing the social cost of environmental emissions and other interventions in euros per kilo pollutant or similar units. They indicate the willingness-to-pay for preventing pollution and other unwanted impacts. It provides monetary values for emissions of over 2,500 substances. The prices are per kilo emission in Euros and differ per country and region. The most recent Environmental Prices can be found in our 2018 update of EU28 prices[24]..

Environmental prices are calculated numbers that represent the social damage caused by environmental pollution. Environmental prices reflect the welfare losses that occur if one extra kilogram of a substance ends up in the environment. Environmental prices can also be applied to non-material pollution, such as noise pollution. Environmental prices are used in analyses where financial quantities must be compared to environmental impacts. By expressing the environmental impacts in euros of damage, they can be weighed against each other compared with financial parameters such as in social cost/benefit analyses, social business cases and life cycle analyses.

With the rise of attention to the environment in the last decades, several institutes have tried to estimate this price on different environmental impacts. For emissions, these are shadow prices, which are measured in €/kg emitted pollution. In this report, the shadow prices developed by CE Delft [25] are used to assess the impact of the air pollutants. In Table 3, the different costs for the polluted emissions used in this study are displayed, retrieved from the CE Delft [25]. In 2023 an update of the Environmental Prices Handbook is published with actualisation of several parameters [26].

Table 3. Shadow costs of air pollutants in €/kg [25].

Pollutant	Lower scenario	Central scenario	Upper scenario
Hg	€ 27,344	€ 38,062	€ 59,202
Cd	€ 880.91	€ 1,279.42	€ 2,021.24
NMVOC	€ 1.78	€ 2.32	€ 3.48
PM10	€ 35.10	€ 49.23	€ 76.28
Zn	€ 2.48	€ 13.03	€ 34.88
PM2.5	€ 62.70	€ 87.76	€ 134.68
HCB	€ 156.75	€ 215.26	€ 333.38
NOx	€ 26.60	€ 38.31	€ 59.28
Benzo(a)pyrene	€ 9.23	€ 12.58	€ 19.54
Cu	€ 1.27	€ 4.64	€ 9.11
CO	€ 0.08	€ 0.11	€ 0.17
Cr	€ 0.17	€ 0.59	€ 1.13
SOx	€ 19.54	€ 27.49	€ 42.72
As	€ 776.04	€ 1,140.33	€ 1,421.82
Ni	€ 82.79	€ 146.82	€ 248.38
PCB	€ 0.00	€ 0.01	€ 0.02
Pb	€ 4,379.17	€ 6,521.84	€ 7,281.32
NH3	€ 21.75	€ 33.67	€ 53.87

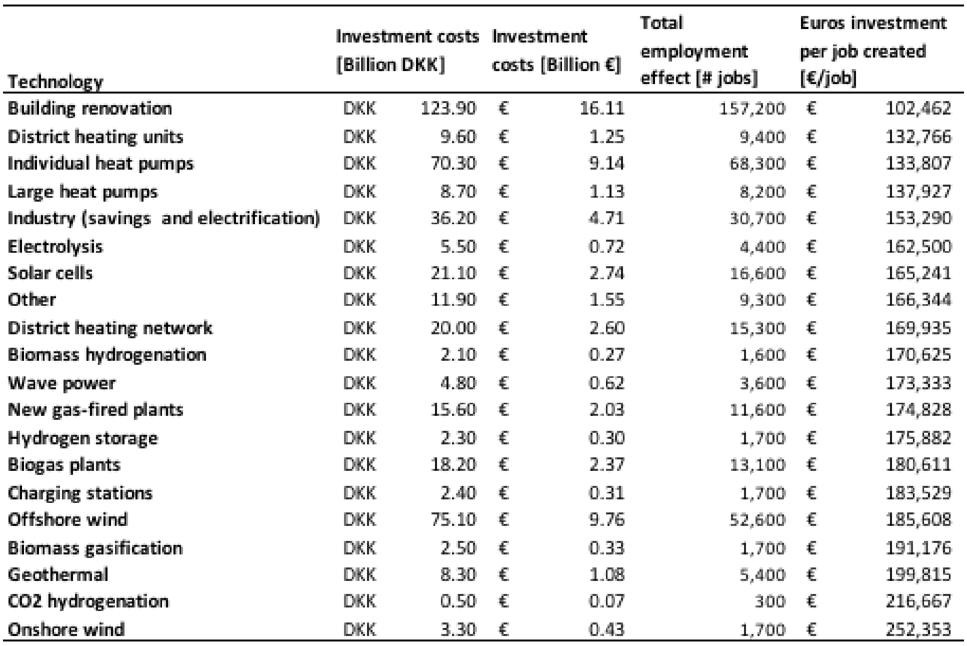
The table shows a lower, central, and upper scenarios. These scenarios are created because of the uncertainties of valuing the environmental impact of the pollutants. With these scenarios a range can be estimated where the actual result should be somewhere in between, but in the result section the central scenario will be used.

Because many of the prices and costs data are from previous years, there should be a correction for inflation. For the environmental shadow costs, CE Delft suggests to use the inflation rate of the consumer price index. For this we have taken the average consumer price index of 2021. The environmental shadow costs are from 2015, so, the inflation of the consumer price index in 2021 relative to 2015, which is determined at 110% [27].

3.3 Methods of economic and societal impact analysis

The social cost and benefit analysis (SCBA) is a method to support the decision-making of the national, provincial and municipal governments. Cost-benefit analyses are used for infrastructural projects, and also apply to, for example, area development projects, sustainable energy development and water and nature issues.

Table 4 Job creation of different energy technologies.



Technology	Investment costs [Billion DKK]		Investment costs [Billion €]		Total employment effect [# jobs]	Euros investment per job created [€/job]	
Building renovation	DKK	123.90	€	16.11	157,200	€	102,462
District heating units	DKK	9.60	€	1.25	9,400	€	132,766
Individual heat pumps	DKK	70.30	€	9.14	68,300	€	133,807
Large heat pumps	DKK	8.70	€	1.13	8,200	€	137,927
Industry (savings and electrification)	DKK	36.20	€	4.71	30,700	€	153,290
Electrolysis	DKK	5.50	€	0.72	4,400	€	162,500
Solar cells	DKK	21.10	€	2.74	16,600	€	165,241
Other	DKK	11.90	€	1.55	9,300	€	166,344
District heating network	DKK	20.00	€	2.60	15,300	€	169,935
Biomass hydrogenation	DKK	2.10	€	0.27	1,600	€	170,625
Wave power	DKK	4.80	€	0.62	3,600	€	173,333
New gas-fired plants	DKK	15.60	€	2.03	11,600	€	174,828
Hydrogen storage	DKK	2.30	€	0.30	1,700	€	175,882
Biogas plants	DKK	18.20	€	2.37	13,100	€	180,611
Charging stations	DKK	2.40	€	0.31	1,700	€	183,529
Offshore wind	DKK	75.10	€	9.76	52,600	€	185,608
Biomass gasification	DKK	2.50	€	0.33	1,700	€	191,176
Geothermal	DKK	8.30	€	1.08	5,400	€	199,815
CO2 hydrogenation	DKK	0.50	€	0.07	300	€	216,667
Onshore wind	DKK	3.30	€	0.43	1,700	€	252,353

3.3.1 Cost impact analysis

In this report, the costs structure will be assessed and how this changes in the different future EnergyPLAN scenarios, compared to the 2020 situation. Levelized annual costs are calculated for the cost impact analysis. For this the financial output of the EnergyPLAN model is used. Investment and O&M costs for the REWARDHeat technologies are obtained from the demo sites, whereas other costs are obtained from the latest, standard cost databases, such as the EnergyPLAN cost database [2] and the Danish Energy Agency's technology catalogue [3]. The differences in the cost structure between the two 2050 scenario, compared to the 2020 scenario will show if and how much the local economy is simulated.

3.3.2 Societal impact analysis

In this report, the new job creation is calculated using Danish Employment impact of climate response from The Danish Society of Engineers (IDA) [28]. In this document, the total investments in different technology sectors are linked to the corresponding number of jobs created. From these data the investment per job created can be calculated for the different sectors. From the total investment in the project and the cost data from the EnergyPLAN scenario's, an estimation can be made of the number of jobs created per technology. As Table 4 is showing, investments in District Heating and Heat Pumps result in a relatively large grow of employment.

4 Scenarios and impact analysis

In this chapter, the focus is on the scenarios and impact analysis of the demonstration projects in the REWARDHeat project. The demo cases will be introduced one by one, including the baseline situations, the long-term upgrade of the network as part of the future simulations, the long-term 100% REWARDHeat source-based future simulations and combined impact analysis discussions. The impact analysis will be discussed from two perspectives:

1. Energy and environmental impact analysis, and
2. Economic and societal impact analysis.

The aspects of impact analysis for the scenarios of each demo include:

1. Discussion of KPIs proposed in Section 2,
2. Interpolation of 2030 and 2040 results based on the results of the three scenarios,
3. Local contextual considerations, further steps and perspectives, such as the ones impacting the local demo/developments, e.g. industrial waste heat, new buildings, technologies, sectors, etc., and including the most significant expected developments in the electricity sector and (district) cooling in the discussions.

It should be noticed that the scenarios look at the heating sector in "isolation" to illustrate the impacts from the REWARDHeat projects only. To show the total future impacts of a full energy system decarbonization, a complete energy system analysis could be performed, as there will be cumulative effects from the electricity and transport sectors as well, but that is beyond the scope of this research.

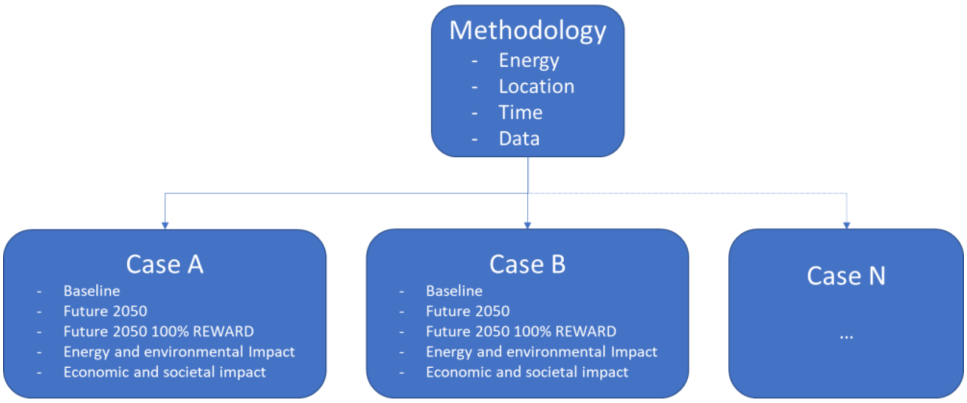


Figure 4: Approach for impact analysis for the demo cities and municipalities.

4.1 Demo cases scenarios

In the following sections, the demonstration cases are presented with the current baseline and future energy system scenarios, as modelled in EnergyPLAN and analysed afterwards. This follows the methodology presented in Section 3 with the geographical and temporary boundaries defined generally, unless otherwise stated.

The demo sites are presented within their corresponding municipalities, which are presented in the baseline scenarios, before the future scenarios address the implementation of the REWARDHeat demo projects in their foreseen growth rates. The overall discussion of the impact analysis concludes each demo chapter. Within each case, the REWARDHeat demos are presented, modelled and discussed with their impacts on the energy system by 2050. The interpolation of the intermediate steps from current (2020) to future (2050 and 2050 100% REWARDHeat) scenarios is presented next to the energy and environmental KPIs in the final steps.

To give an overview, Table 5 presents the demo sites with their total heat demand within their municipal borders (LAU), the maximal heat density that can be found within the area to indicate DH potentials, which are based on the Hotmaps data with the heat density threshold of 120 TJ/km^2. As can be seen, the DH potentials are on average 75% of the total heat demands with cities such as Milan reaching 96% or Albertslund reaching 80%. It must be noted that Albertslund states a DH coverage of over 90%, indicating potential delimitations in the tool's data and methodology compared to the actual DHNs'. The shares of potential DH out of the overall heat demand are also illustrated in Figure 5. Here, cooling is shown to follow heat demand (same methodology) and is significantly lower and therefore excluded from further analysis.

Table 5: Overview of demo sites, heat demands and potential DH demand at a minimum heat density of 120 TJ/km^2 [17]

LAU	Total heat demand in GWh/yr	Total cooling demand in GWh/yr	Max. Heat density in MWh/ha/yr	Potential DH demand (share) in GWh/yr
Albertslund	323	36	1322	258 (80%)
La Seyne-sur-Mer/Toulon	457	137	1155	297 (65%)
Topusko	8	3	220	8 (99%)
Helsingborg	1410	175	2086	793 (56%)
Mölndal	745	88	2099	463 (62%)
Heerlen (Brunssum)	261	48	986	205 (79%)
Milan (Balilla + Gadio area)	10367 (300-500)	3207	4856	10026 (96%) (285-475 (95%))

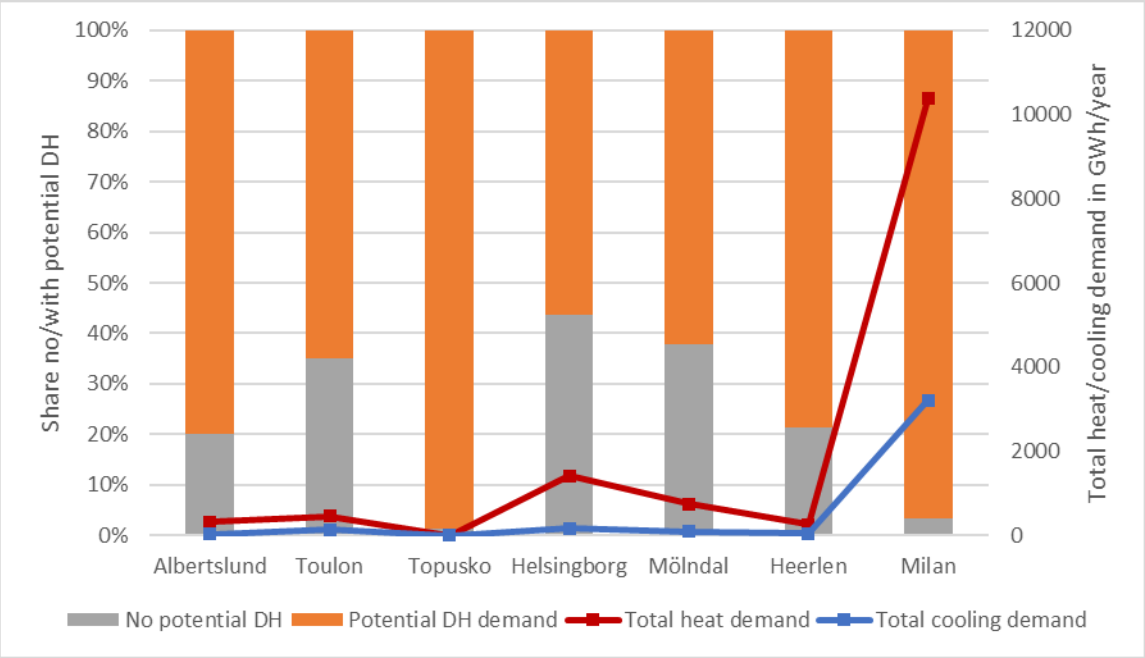


Figure 5: DH potentials and total heating/cooling demands

4.2 Albertslund

Albertslund is a local municipality of the Greater Copenhagen area with a population around 30,000, as shown in Figure 6. The municipality and its heat demand lie near the high heat densities of Copenhagen and Albertslund DHN is therefore connected to the Greater Copenhagen DHN. In the following, the baseline energy system scenario of the heating sector is presented with the local demonstration project as part of it before the foreseen growth and impact are analysed afterwards.

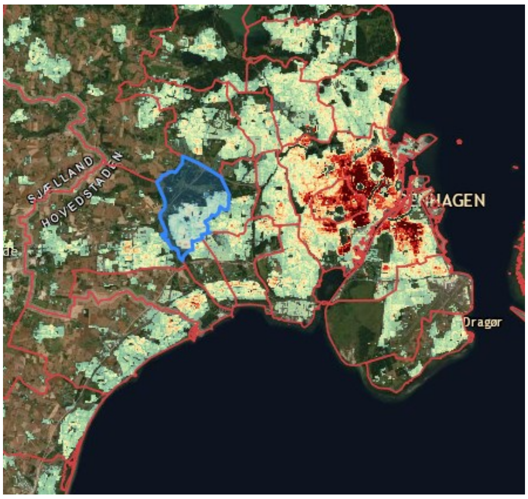


Figure 6: Albertslund local authority, location and heating potentials [17]

4.2.1 Baseline

In the 2020 baseline scenario, based on data from 2018/2019, the Albertslund DHN is mainly supplied by the Greater Copenhagen DHN through heat exchangers with a total capacity of around

100 MW, supplying 100-120 °C water via VEKS[3] – the common municipal district heating supplier for the 12 western suburban municipalities in Greater Copenhagen. District heating in the Copenhagen area is based on combined heat and power plants (CHP) with the following fuel shares [29]: 7% Natural gas, 10% Coal, and 82% 'Biomass' (31% Waste and biowaste and 51% Biomass)

Heat supplied from Greater Copenhagen transmissions network to Albertslund via three main connection substations (VEKS, RVP and HØB) using heat exchangers for 2018 amounted to 261.4 GWh [30]. For back-up, the local heat-only boilers in Albertslund support the DHN, supplying 2.6 GWh peak demand in 2019 [12]. The Albertslund boilers have a capacity of 145 MW with the following fuel distributions: 86% Gas, 8% Oil, and 6% Biomass.

Focusing on local waste heat exploitation in Albertslund, additional heat production from a local data centre amounts to 6.1 GWh in 2019 [12]. It supplies heat via a 350 kW_{th} heat pump and a baseline COP of 3. For the baseline and demonstration scenarios, the data centre is modelled to supply heat as output from industrial excess heat, which can be considered largely constant and is modelled accordingly in the scenarios. With the local boilers operating as back-up, they are modelled to supply the same amount of peak heating demands in both the baseline and future scenarios, limiting the import from the Greater Copenhagen DHN accordingly and allowing the scenarios to focus on the impacts from the REWARDHeat demo.

With the heat from the Greater Copenhagen DHN, the local boilers and the excess heat from the data centre, the total heat supplied for the baseline scenario is 270.1 GWh with the largest share in heating fuels being biomass [30]. Furthermore, at the consumption side, the total district heating demand (for commercial, households and public sectors) is listed as 179.2 GWh [29]. Hence, the overall network and heating losses amount to 33% for the baseline scenario of 2018/2019. The difference of the DH demand and the potential listed in Table 5 can be attributed to parts of Albertslund currently not connected to the DHN, despite its potential. These areas are currently supplied by natural gas, which explains the difference and amount to 7.2 GWh or around 3% of the total heat consumption in the municipality with 5.9 GWh from the national gas grid and approximately 100 houses (1.3 GWh) far away from the DHN [31].

Overall, in the heating system model of Albertslund DHN, the local boilers fill only the peak 0.96%, while the data centre supplies 2% DH and the remaining heat is modelled as heat delivered from the Greater Copenhagen DHN through its CHPs. The hourly heat supply (Figure 7) shows the main supply from biomass-heavy CHP with the peak demands supplied by the local boilers (mainly gas-based) and the data centre waste heat supplying a constant baseload of heat via heat pumps to the overall heating system. For the back-up boilers to supply 2.6 GWh, a maximum heat supply from the Copenhagen DHN of 55 MW is required. Finally, Figure 7 shows the approximate losses in relation to the heat production in the Albertslund DHN.

The REWARDHeat Albertslund demonstration site is located centrally within the municipal borders. The area is called **Porsager**, which has approximately 110 houses from the 1970s, and an annual heat consumption of 18 MWh each. Their total heat demand of 2 GWh represents around 1% of the Albertslund DHN demands and is part of the DHN supply and fuel distribution presented above.

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[3] VEKS, Vestegnens Kraftvarmeselskab I/S, is a transmission company supplying 20 local district heating companies with heat generated at Vestegnen, a suburban area west of Copenhagen.

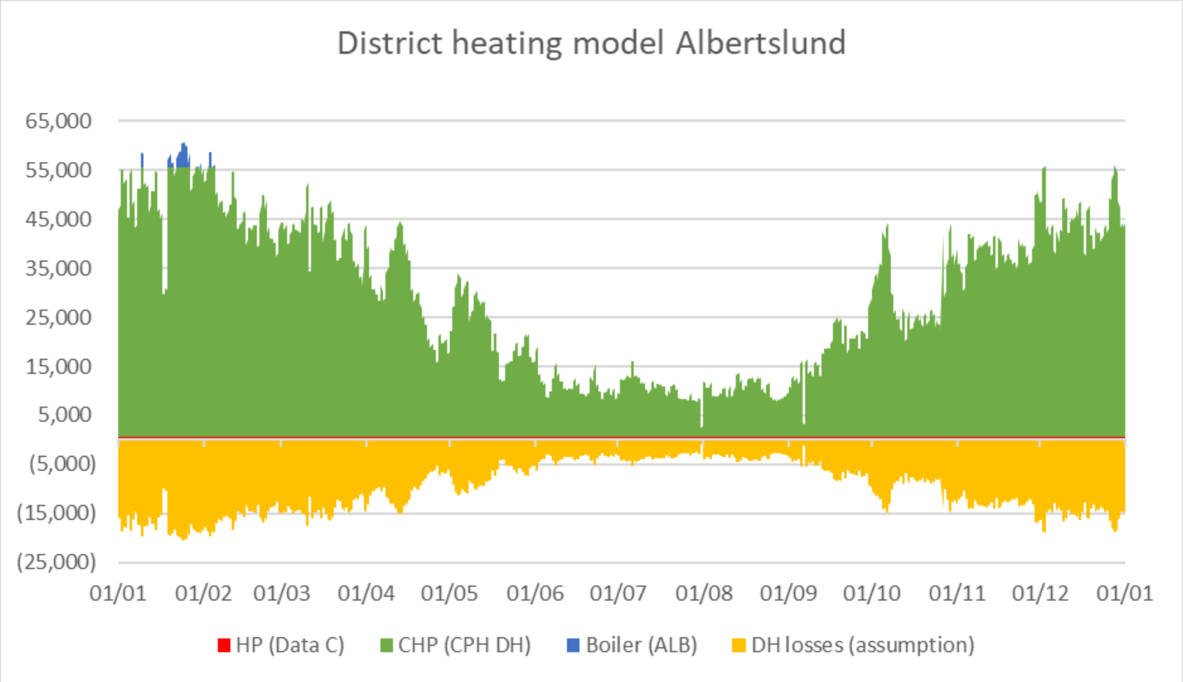

Figure 7: Hourly heat demand and related fuel distributions Albertslund

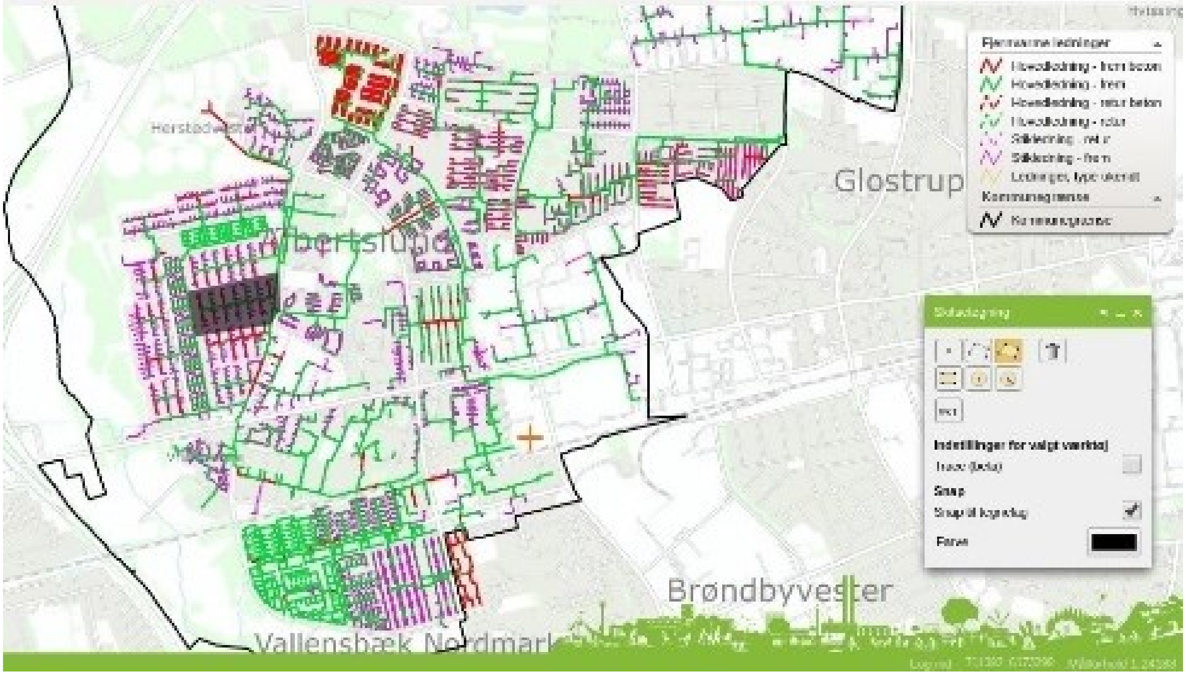

Figure 8: REWARDHeat demo in Albertslund

The objective of installing substations at the REWARDHeat Albertslund demo site is to allow reduced temperatures in the DHN to improve efficiencies and to allow further exploitation of local waste heat resources in the future. Hence, the demo being an integrated part of the energy system can have impacts beyond the local site.

4.2.2 Future 2050

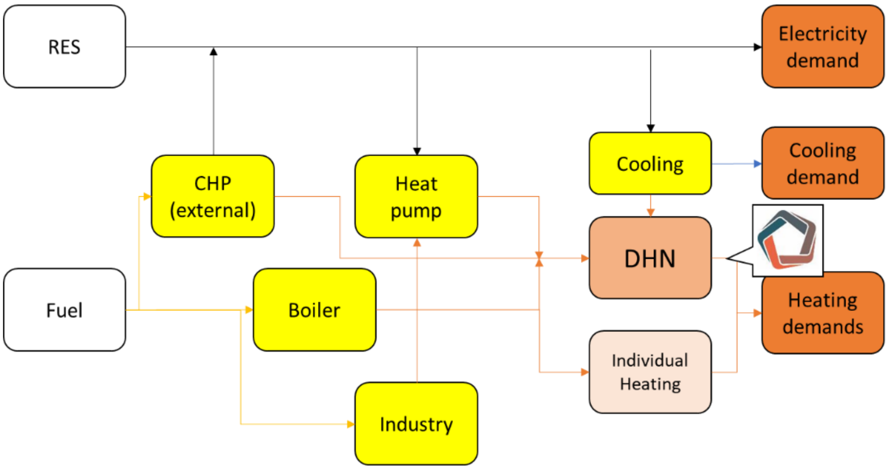

Figure 9: Energy system set-up of Albertslund in EnergyPLAN with REWARDHeat demo impact

Based on the above presented baseline scenario for Albertslund, various potentials and limitations can be identified for future energy system developments, influencing also the impact of the demonstration project at the local REWARDHeat site. The current temperatures of the Albertslund DHN are at around 85 degrees supply and 47 degrees return temperature [31], which implies there is a potential for overall temperature reduction in the grid. This would reduce the overall high current losses in the DHN, but furthermore, allows also for further deployment of low graded excess heat from supermarkets and industry. With a transition to 4GDH, similar benefits as in Section 3.2.2 can be expected, such as improvements in the heat supply technologies, resulting in overall lower production demand and use of resources, based on the interconnections of the heating system and the REWARDHeat demo within as shown also in Figure 9.

In line with the impact of the demo site on the development of the energy system towards 2050, the above-mentioned aspects and potentials of the Albertslund-Porsager REWARDHeat demo are applied to the macro-level of the DHN and extended to the entire network, not just the Porsager demo site. The impacts of the temperature reductions, as demonstrated through new shunt valves in the housing area of Porsager, as well as the consideration of supermarket waste heat exploitation are applied as follows.

Reducing the DHN supply/return temperatures from the baseline scenario temperature of 85/47 to 60/30 [31] is considered to entail the following impacts: The reduced temperature difference between DHN pipes and surrounding soil can lead to reduced grid losses of 6-8%-points [21], hence, 7%-points reduced losses are assumed, causing a reduction of heat production – or reduction of imported heat in the case of Albertslund. As studies of reducing temperatures in similar size DHN show, also the efficiencies of heat production units can increase by 2-5% for CHPs and boilers [21], while the COP of the heat pumps is expected to increase from 3 to 4.5 as stated by the operator of the heat pump installed at the data centre. While the improvements in losses and efficiencies mainly have an impact on the import of heat, also the local boilers and waste heat potentials are thereby considered to improve accordingly. The local boilers are further considered to produce a limited back-up capacity of 2.6 GWh (now at improved efficiencies), while the heat production of the heat pump increases directly from 6.1 to 9.2 GWh, solely based on the increased COP.

The reduced temperatures not only have an impact on the dedicated heat production sites, but also increases the potential of excess heat from industry that can be used in the future. Besides the two supermarkets specifically mentioned within the REWARDHeat project, there are other stores and industries applicable for potential excess heat utilisation, often resulting from internal cooling demands. Based on a study of those, an Albertslund district cooling survey mentions 21 GWh of excess heat [32]. (As [21] points out, the two mentioned supermarkets would have a combined excess heat potential of 0.15 GWh, hence, a small fraction of the overall heat potentials identified in the survey). This would increase the total amount of industrial waste heat to 30.15 GWh. In the 2050 energy scenario, this is modelled as industrial waste heat, and if heat pumps are used to deliver this heat, approximately 6.7 GWh electricity would be required.

The resulting impact of the local temperature reductions and waste heat exploitation would reduce the required import capacity from the Greater Copenhagen DHN from 55 to 46 MW, and thereby have an impact on the overall economy and fuel balance of Albertslund, as shown in Figure 10. The resulting shares for the Albertslund heat demand can be seen in Figure 10, where now 87% is supplied from the greater Copenhagen area with its CHP (same fuel mix modelled), 1.1% from local boilers and now 12% from electricity through heat pumps, which utilise the waste heat sources. The previously gas-supplied areas have not been changed as the impact is not directly foreseen within the REWARDHeat scope, but this is further discussed at the end of the impact analysis.

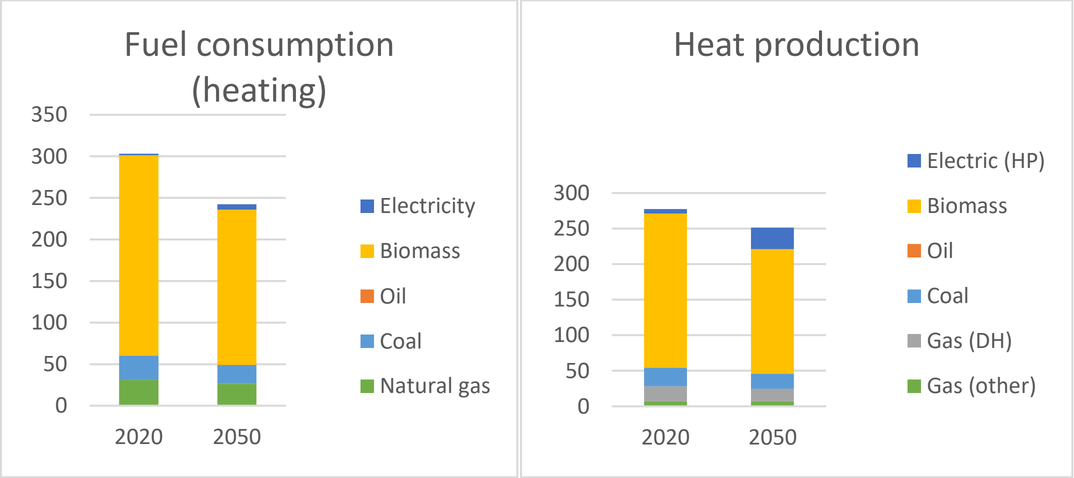

Figure 10: Albertslund fuel consumption and heat output by fuel for baseline (2020) and future demo impact (2050) scenarios

4.2.3 Future 2050 100% REWARDHeat

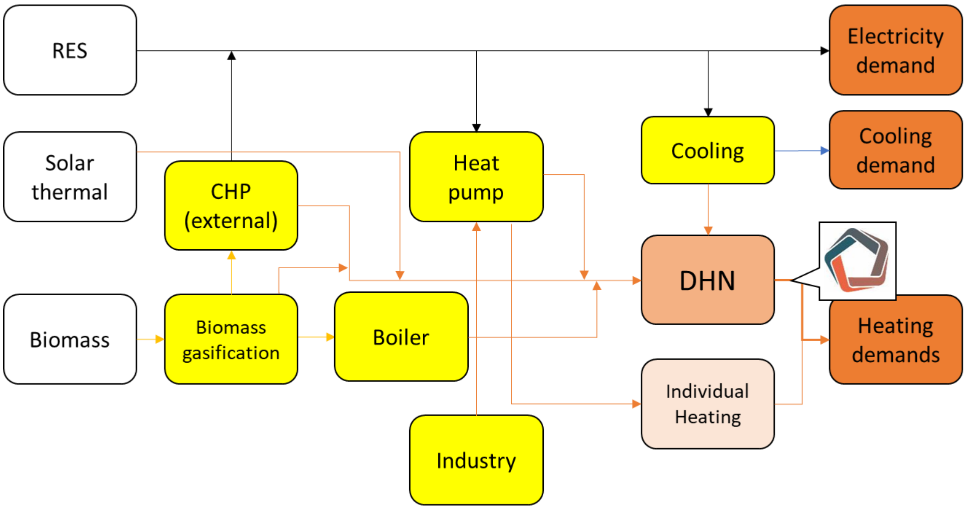

Figure 11: Energy system set-up of Albertslund in EnergyPLAN in 2050 100% REWARDHeat scenario

The future 100% REWARDHeat scenario is created based on the future 2050 scenario. In the individual heating system, it is assumed that all individual gas boilers will be replaced by individual heat pumps with COP 3.9, according to a previous study on future smart energy Denmark in 2045 [33].

Albertslund has a population of 30,000, corresponding to around 1.5% of the population of the Greater Copenhagen area (1.99 million). According to the previous study, Copenhagen Energy Vision 2050 [34], the total DH demand of Copenhagen is estimated to be 38.39 TWh/year in 2050. The DH demand of Albertslund is 179.14 GWh/year, or around 0.47% of the total heat demand in Copenhagen.

For the district heating system, all the PP, CHP and boilers are assumed to be turned into gas-fired units based on a biomass gasification plant. Condensing power plant and fuel boiler capacities in the scenarios are defined in such a way that they can meet the peak demand during a year plus 20% to account for potential unexpected fallouts of units (i.e., 76MW). This means that in the model a situation will never occur in which electricity has to be imported. The national biomass potential of Denmark is 240PJ per year (66.7TWh) [34]. The upper limit of biomass resources in Albertslund is set to 348 GWh/year according to the share of population in relation to the national number (~0.51%). In this case, 252 GWh biomass is used as input to the gasification plant (efficiency of gas output: 0.84, share of excess heat for DH: 0.1) to fulfil the gas needs of CHP, PP, and boilers.

Part of the heat production from gas boilers and CHP is substituted by large-scale heat pumps. The HPs are estimated to cover 35% of the DH production in Greater Copenhagen in 2050. Here we use the same share for HP production in the Albertslund system, which results in a HP capacity of 8 MW-e with a COP of 3.9 (efficiency based on [28]).

Apart from the above changes, solar thermal production is introduced in the 100%REWARDHeat scenario. The total solar thermal production in the centralised CHP areas of Copenhagen is expected to be 0.91 TWh/year in 2050 [34]. According to the share of local DH proportion compared to the entire Copenhagen area, Albertslund is assigned 4.28 GWh/year solar thermal (under the centralised CHP areas group3 in EnergyPLAN).

4.2.4 Energy and environmental impact analysis

The overall energy and environmental impacts, including the KPIs of REWARDHeat in Albertslund are presented in Table 6. As can be seen, fuels for heating represent only a share of the overall fuel consumption due to heating being supplied by combined heat and power units. Furthermore, these CHPs are located outside Albertslund municipality and have a high biomass share. This means that reducing the import of heat from Copenhagen is desirable for Albertslund, however, the biomass share in the Albertslund heating sector will decrease accordingly. The impacts of the REWARDHeat demo can be mostly seen in the reduced fuels and emissions in relation to the heat production and transmission (via reduced losses), but also with the foreseen growth of utilizing waste heat locally, which increases its share from 2 to 12% of the municipal heat demand in 2050.

Figure 12Figure 13 shows the fuel consumption and Figure 13 the heat production of Albertslund in 2020, 2050 and 2050 100% REWARDHeat scenario. As mentioned earlier, only the heating and cooling sectors are included in the energy system modelling for each municipality, while the electricity, transportation and industry sector are excluded. Compared to the 2050 scenario, in the 2050 100% REWARDHeat scenario, large-scale heat pumps are considered to play an important role, taking up a 33.9% share in total heat production and 34.9% in the DH system. The excess heat from biomass gasification production contributes to 45.5% excess heat production, while the rest is industrial waste heat.

Based on the data output from the 2020 and 2050/2050 100%REWARDHeat scenarios, the linear interpolation results of the non-RE PES and the share of RE% in 2030 and 2040 are displayed in Figure 14 and Figure 15. The results can serve as an indication for the local partners and of how the REWARDHeat impacts may develop from year to year.

Since the energy and environmental analysis focuses on the impacts of the REWARDHeat demo project and the local energy system of the heating sector, some aspects are left out of the analysis. As can be seen in Figure 12, the excess electricity produced from CHP needs to be exported - however this is because the other sectors are not included in the created EnergyPLAN model. Thus, the advantage of e.g. sector coupling is not considered here. On the one hand, this allows isolating the impacts of the demo from other changes in the system, but on the other hand, this approach might overlook synergies and trade-offs that may occur between energy sectors in a full energy system analysis.

The implementation of HPs in 2050 100% REWARDHeat scenario leads to growing electricity consumption. The electricity sector can see other changes and impacts beyond project boundaries. Apart from the scenario created in our model, in 2050, there are potential increases of wind turbine capacity and intra-day thermal storages – thermal storage typically increase system flexibility, especially in conjunction with intermittent industrial heat and/or variable heat pump production.

Table 6: Resulting annual fuels (for heating) and KPIs Albertslund

Albertslund								
	2020	2050	2050 100% REWARD	Diff.		Diff. 2050 100%REWARDHeat		
Fuels for heating								
Oil consumption (GWh)	0.23	0.22	0	-0.01	-4%	-0.2	-100%
Gas consumption (GWh)	28.96	25.32	0	-3.64	-13%	-29.0	-100%
Coal consumption (GWh)	26.41	21.37	0	-5.04	-19%	-26.4	-100%
Biomass consumption (GWh)	216.69	175.42	252	-41.27	-19%	35.3	16%
Electricity consumption (GWh)	0	0	23.73	0	-	23.7	-
KPIs							
Non-Renewable PES (GWh)	110.46	87.88	-0.29	-22.58	-20%	-110.8	-100%
Renewable PES (%)	81.40 %	81.00%	100.10%	0%-p.	0%	19%-p.	23%
CO2 emissions (kt)	30.65	24.22	-0.06	-6.43	-21%	-30.7	-100%
Share of local waste/excess heat in DHN	2.26%	12.34% a	22.66% b	10%-p.	446%	20%-p.	903%
Losses	33.0%	26.6%	26.6%	-6%-p.	-19%	-6%-p.	-19%
Notes: a Industrial excess heat b Excess heat from industries and the biomass gasification plant							

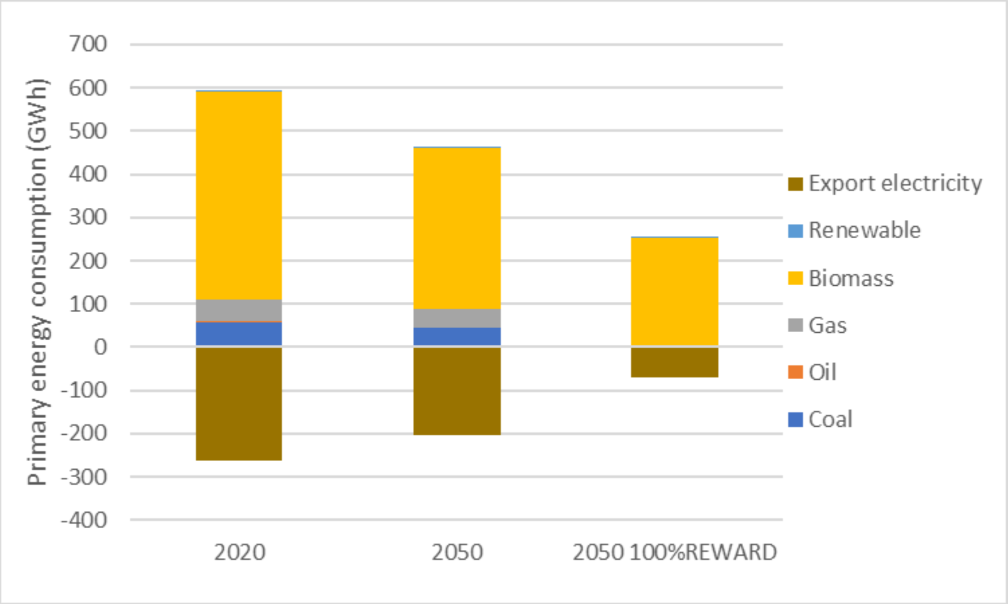

Figure 12: Albertslund fuel consumption for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

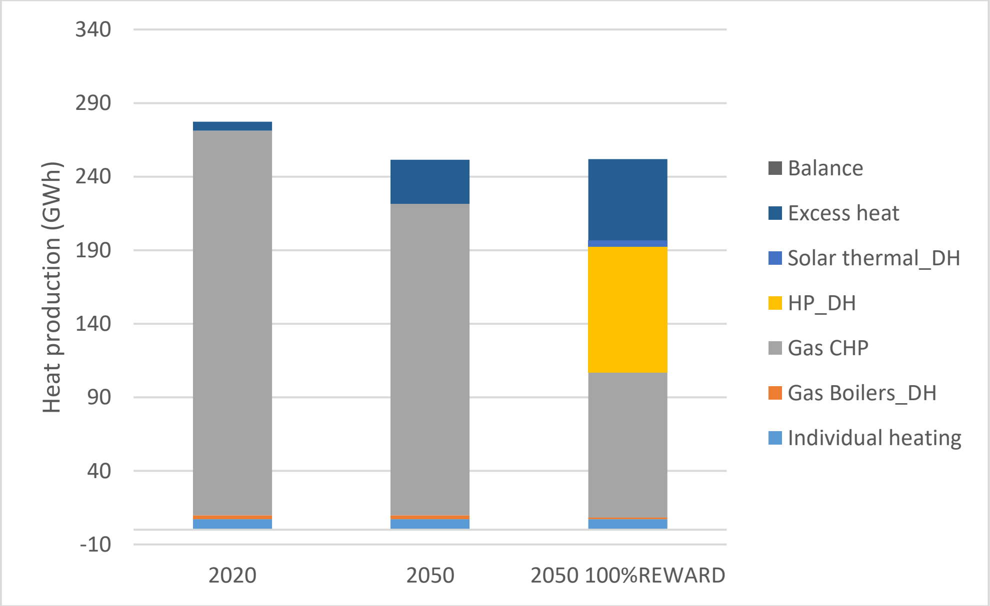

Figure 13: Albertslund heat production for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

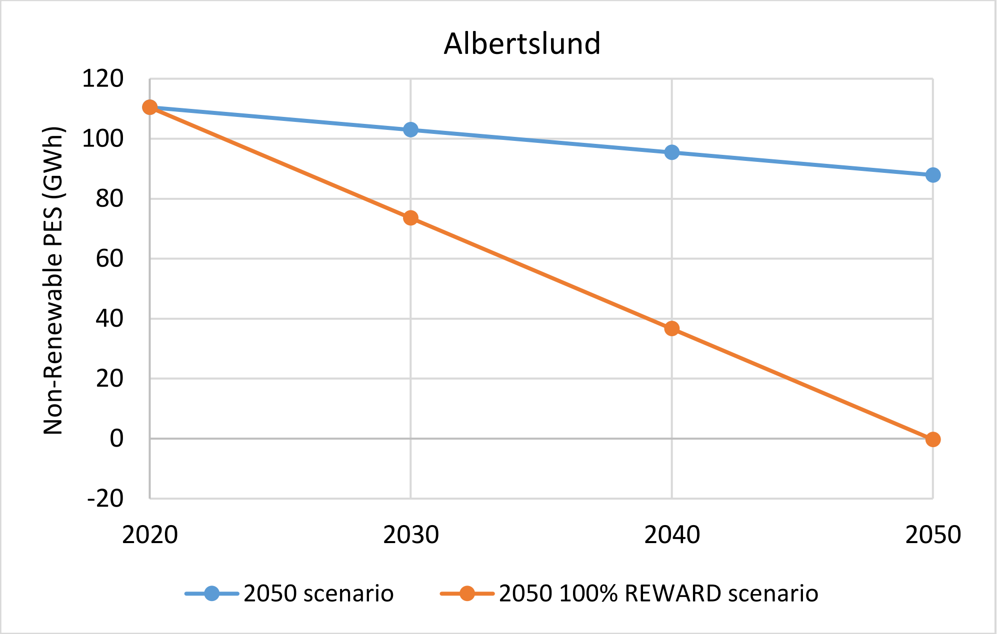

Figure 14: Result of linear interpolation of the non-renewable PES in Albertslund in 2030 and 2040.

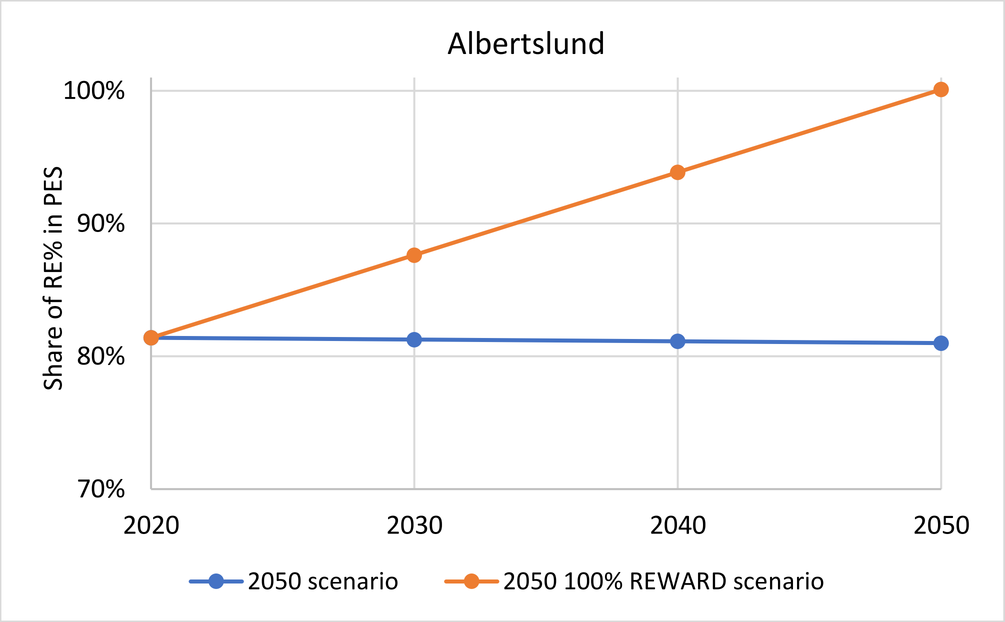

Figure 15: Result of linear interpolation of REshare in Albertslund in 2030 and 2040.

4.2.5 Economic and societal impact analysis

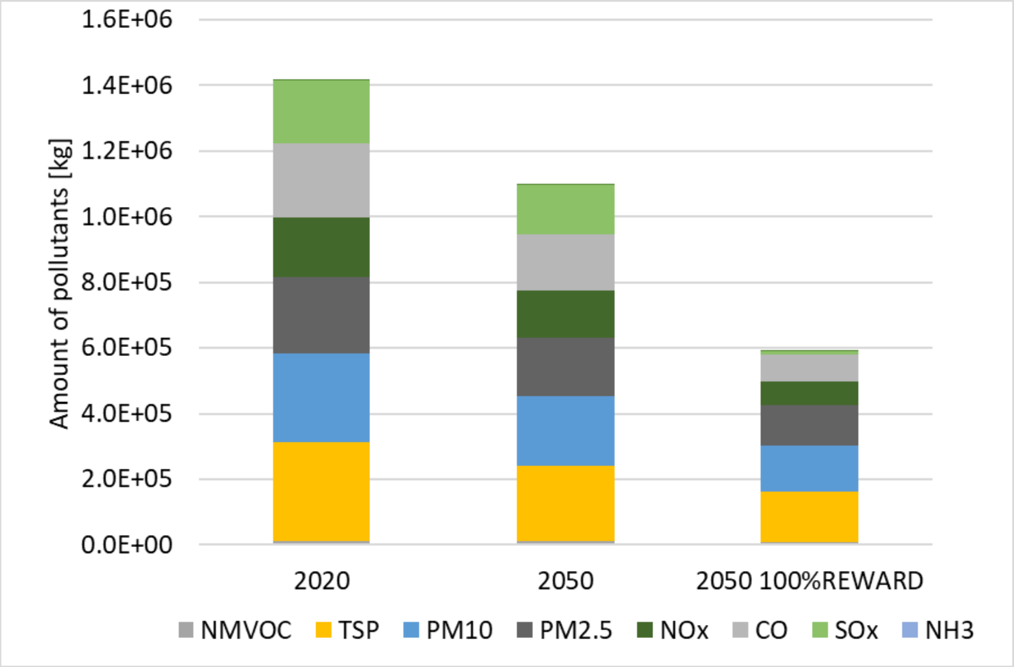

Figure 16: Amount of air pollutants in Albertslund for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

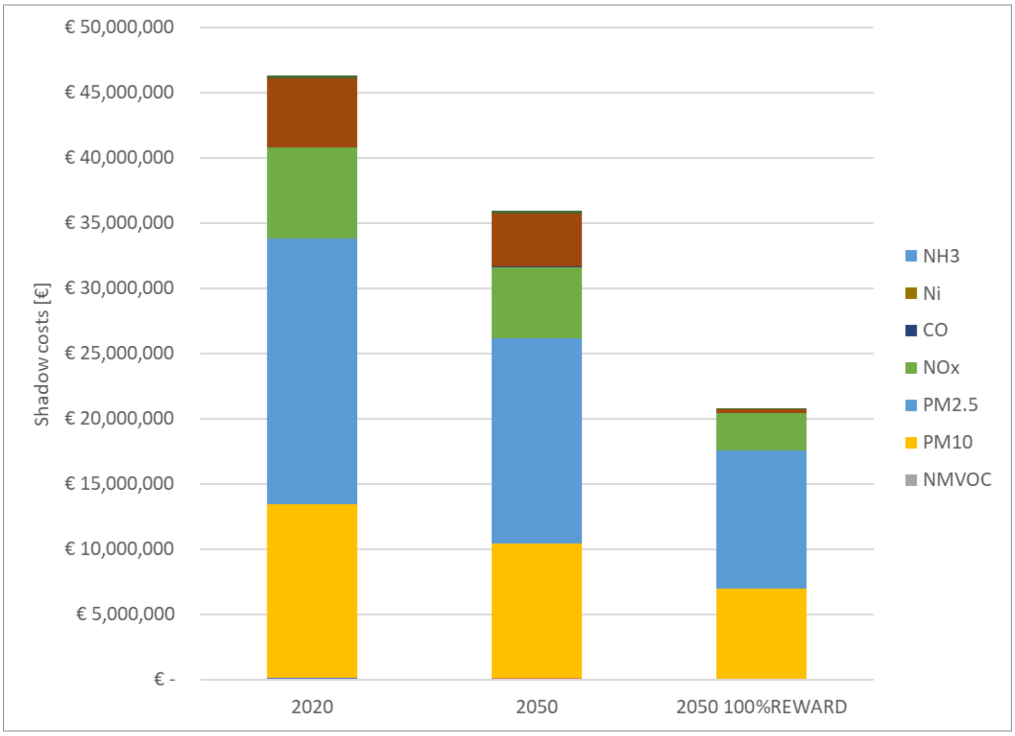

Figure 17 Shadow costs of air pollutantsin Albertslund for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

In the 2020 scenario, Albertslund uses a mix of biomass (± 80%), gas (± 10%), coal (± 10%), and small amounts of oil and renewables (>1%) (Figure 12). The heat production is almost entirely covered by

CHP (>95%). With these fuels and technology, the air pollutants emitted by the heating production are shown in Figure 16. The most common air pollutants are TSP, PM_{10}, $PM_{2.5}$, NO_X, CO, and SO_X. SO_X is mainly emitted due to the combustion of the coal. For the other pollutants, the combustion of the biomass is their main cause. Especially the particulate matter 2.5 and 10 have both high shadow costs as shown in Figure 17. They contribute for more than 70% of the total shadow costs. In this scenario, these emissions result in shadow costs of 0.25 € per kWh.

In the 2050 scenario, the fuel mix stays relatively the same, but in smaller amounts. This is also showed by the air pollution, of which the mix stays relatively similar, but the amount drops. This lower amount is the result that ± 15% of the heat production is now covered by excess heat. The reduction of emissions leads to shadow costs of 0.19 € per kWh.

In the 2050 100% renewable scenario, Albertslund uses almost only biomass and in lower amounts than before, due to the use of district heating heated with heat pumps. Coal is totally cancelled out, which result in almost no emission of SO_X. The rest of the emissions decreases with the similar reduction of the total use of biomass, which is almost half of the 2020 scenario. The shadow costs of the 100% renewable scenario decrease to 0.11 Euro per kWh.

The annual costs of Albertslund in the 2050 scenario, decreases with 25%. The two main reason are the decrease in Biomass costs and the Annual investment costs as shown in Figure 18. However, most new jobs created are still for new large power plants and CHP units (Figure 20).

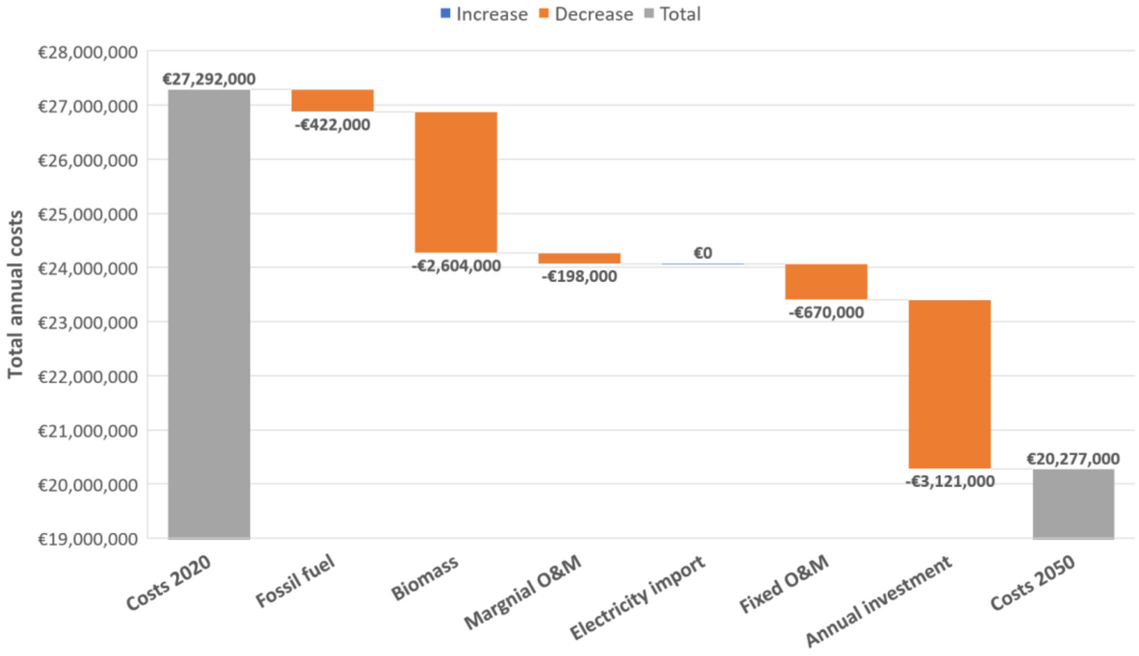

Figure 18 Total annual cost of the heating sector of Albertslund in 2050 scenario.

For the 2050 100%REWARDHeat scenario, the total annual costs decrease with 15% compared to the 2020 scenario (Figure 19). In this scenario, the biomass and fossil fuel costs cause a large drop in the costs, but the annual investment costs and the fixed O&M costs increases which results in a higher total cost than the 2050 scenario. The reason for this is that the newer technologies used in the 100% renewable scenario costs more than the conventional gas CHP from the 2050 scenario. However, if looking at the jobs created in the 100% scenario, because of the high investment costs, also much more jobs are created. Another note worth mentioned is that the fossil fuel and biomass costs are costs that are likely to be invested outside the region. While the fixed O&M and annual investment costs are likely to invested in the region. So, the money stays in the local economy.

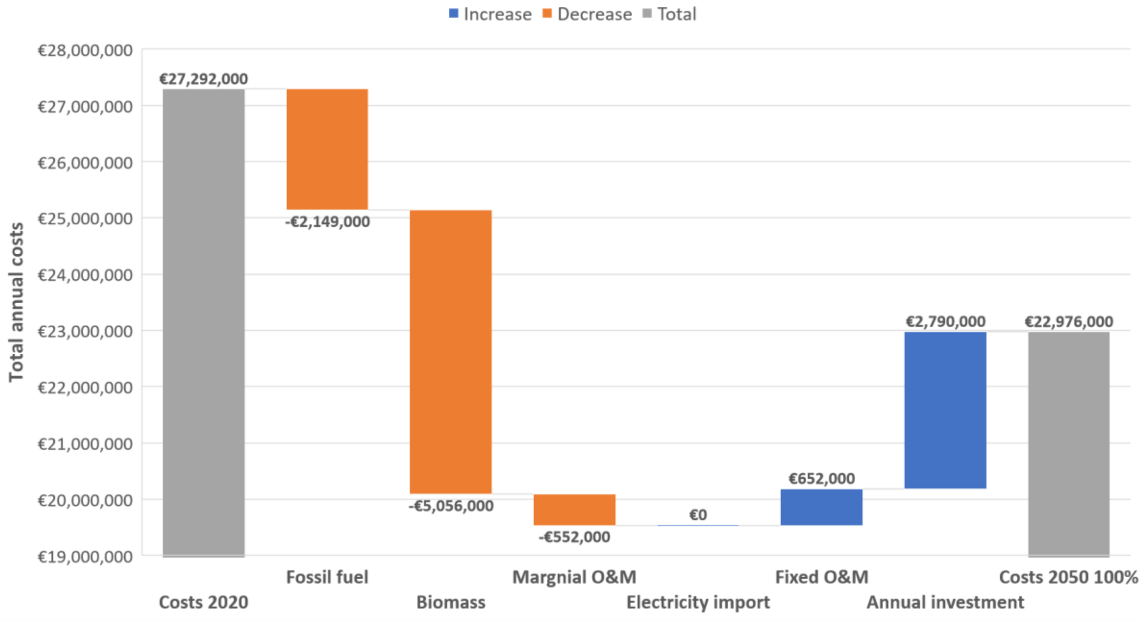

Figure 19 Total annual cost of the heating sector of Albertslund in 2050 100% REWARDHeat scenario.

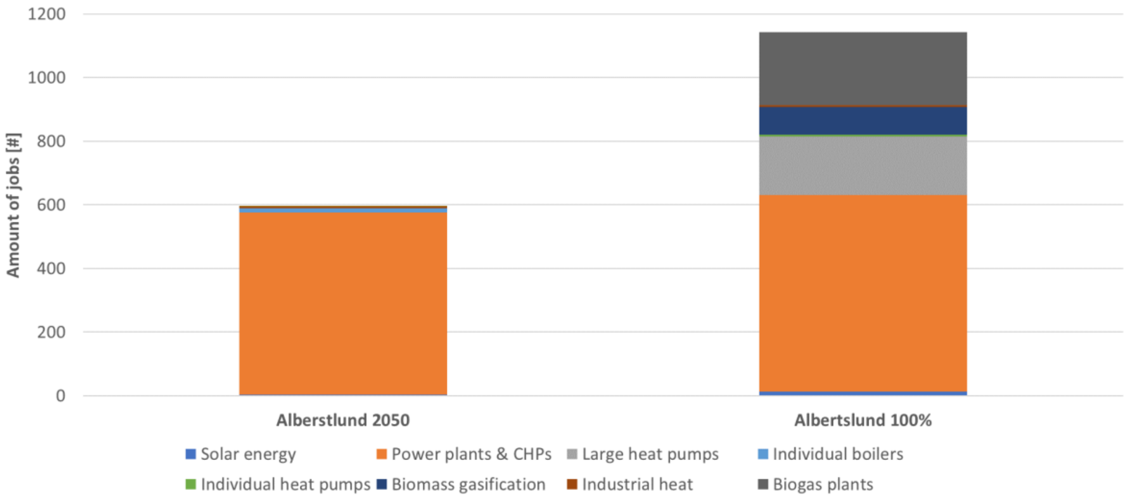

Figure 20 Amount of job creations in Albertslund in the 2050 and 2050 100% REWARDHeat scenario.

4.3 LSSM (Toulon)

La Seyne-sur-Mer (short LSSM) is part of the agglomeration of Toulon as a separate municipality within the region of Var and the province of Cote d'Azur. The local administrative unit and its boundaries for the following scenarios are presented in Figure 21.

Figure 21: LSSM local authority, location and heating potentials [17]

4.3.1 Baseline

The total heat demand of the local authority, or municipality of LSSM is 456.9 GWh/year [12]. Within this area, a waste incineration plant, the REWARDHeat demo and individual heating solutions can be found. The fuel consumption for heating is supplied as follows, based on statistics and local energy data [35]:

- 31.8% gas
- 35.7% electric
- 4.1% heat pumps
- 31.6% boilers
- 10.7% oil
- 18.0% biomass
- 3.8% DH
- 3.5% waste incineration
- 0.3% sea-water heat pump

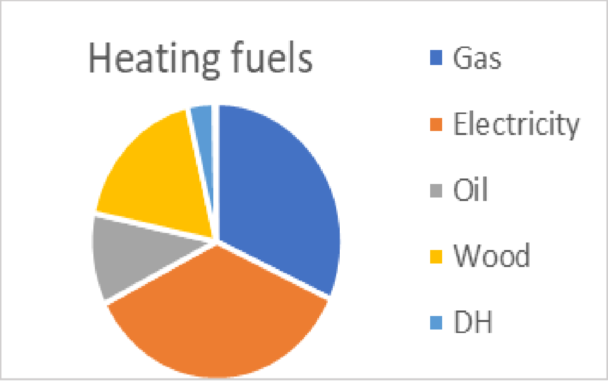

Figure 22: Share of the fuels in current heating system of LSSM

The overall share of DH in LSSM amounts to 4%, to which the waste incineration contributes the majority and the REWARDHeat demo site around 8%. These units are located a few km apart. The waste incineration plant has a capacity of 18 MW and produces 19.5 GWh at 18% losses (in 2020), covering 15.9 GWh of the annual demand in the municipality. 91% of this is consumed in the residential and the remainder in the tertiary sector [17].

The second local heating network of LSSM, where the REWARDHeat demo is located, currently only covers a small area at the harbour and is operated by Dalkia, together with EDF, consisting of an updated neutral-temperature DHN. The DHN exploits renewable energy from seawater, which is continuously available, and a connected sea-water heat pump of 4.8 MW electric capacity. At the demo site, natural gas is used for DHW production, which will potentially change to biogas in the future. The DH network has been operational since 2008 and is used for both DH and DC and operates at a temperature between 7-29°C according to the local partners. The temperature varies throughout the year depending on the seawater temperature and the balance between the heating and cooling loads. The REWARDHeat demo site in LSSM has a current heat consumption of 1.1 GWh (and 1.39 GWh/a cooling), hence, with an estimated grid loss of 15%, the production from the heat pump amounts to 1.3 GWh at a COP of 3.

The heat demand distribution for LSSM can be calculated with measurements of outside temperatures and shares for heating and hot water of 80 and 20% [21]. Given these heat demands for individual and district heating, including losses, Figure 23 summarizes the applied data for the scenarios. As indicated in the above production figures, the demo site constitutes only a small share in the overall heat demand.

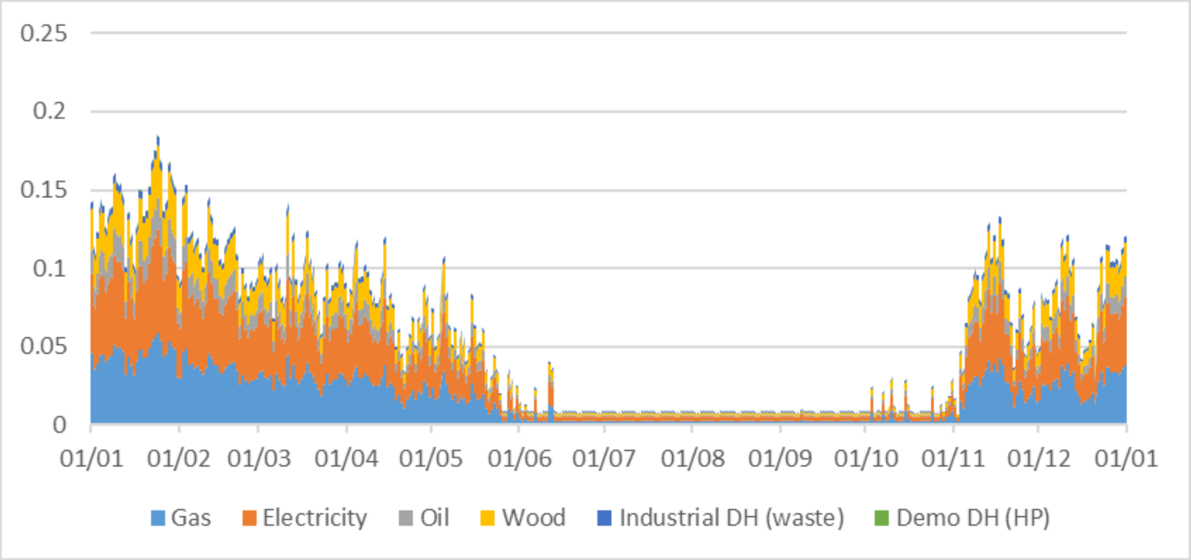

Figure 23: Hourly heat demand and related fuel distributions LSSM

Figure 24: Demo site of the REWARDHeat project in LSSM

The demo site of REWARDHeat in LSSM is situated in a central location with high heat demands in the vicinity and makes use of this potential by expanding the existing DHN section to additional consumers. With currently only 0.3% of the overall LSSM heat demand covered by the sea-water heat pump, besides the additional 3.5% of waste-based district heating, further expansions might be possible to make use of the high heat density in the surrounding area. The use of the available ambient heat in the sea water as well as the capacity of the heat pump, together with increased efficiency measures can result in positive energy and environmental impacts.

Note that the EnergyPLAN model is currently running and working for LSSM without the cooling sector due to the lack of detailed data.

4.3.2 Future 2050

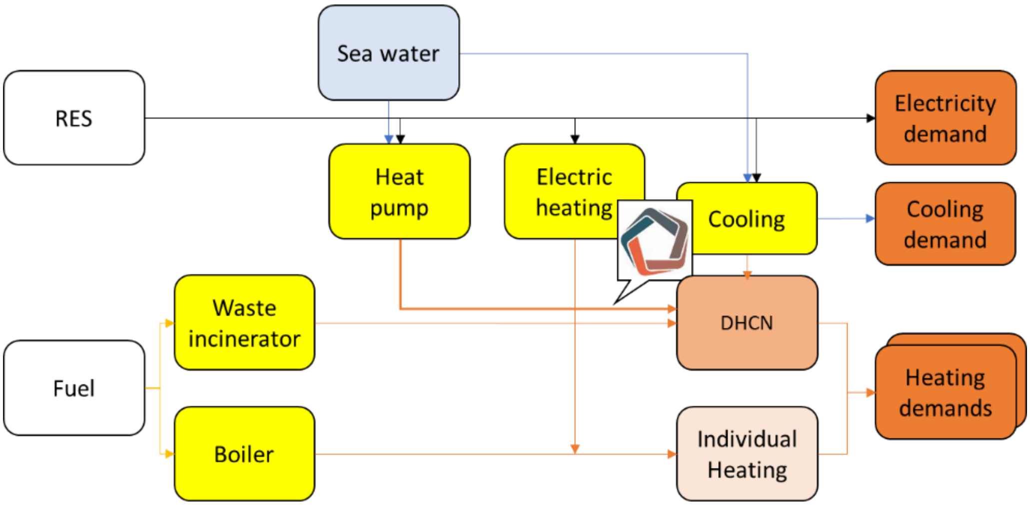

Figure 25: Energy system set-up of LSSM in EnergyPLAN with REWARDHeat demo impact

As part of REWARDHeat and besides the expansion of the DHN, the demo site in LSSM aims at the implementation of smart monitoring and control technologies and advances in demand site management. The objective of the demo DHN is to connect to both new and existing public, tertiary and residential buildings to further exploit the decentralised water-source heat pumps. This will replace the current use of natural gas for space heating, while electric and gas boilers for hot water will remain in place. Overall, it is foreseen that 6.5 GWh thermal energy can be exploited annually [36].

To evaluate the future scenarios with the foreseen growth, this potential of 6.5 GWh is explored, but furthermore upscaled to the whole municipality as part of the created energy system models. The potential future sites next to the REWARDHeat demo have an additional heat demand of 4.1 GWh already in the short term, while a total DH potential of around 70 GWh can be identified with the Hotmaps tool. Within the short term, already the expansion to the other 'islands' around the sea-water DHN could reduce the natural gas demand by 5 GWh annually, while electricity demand increases by 2 GWh (at a COP of 3 or 1.5 GWh at COP 4).

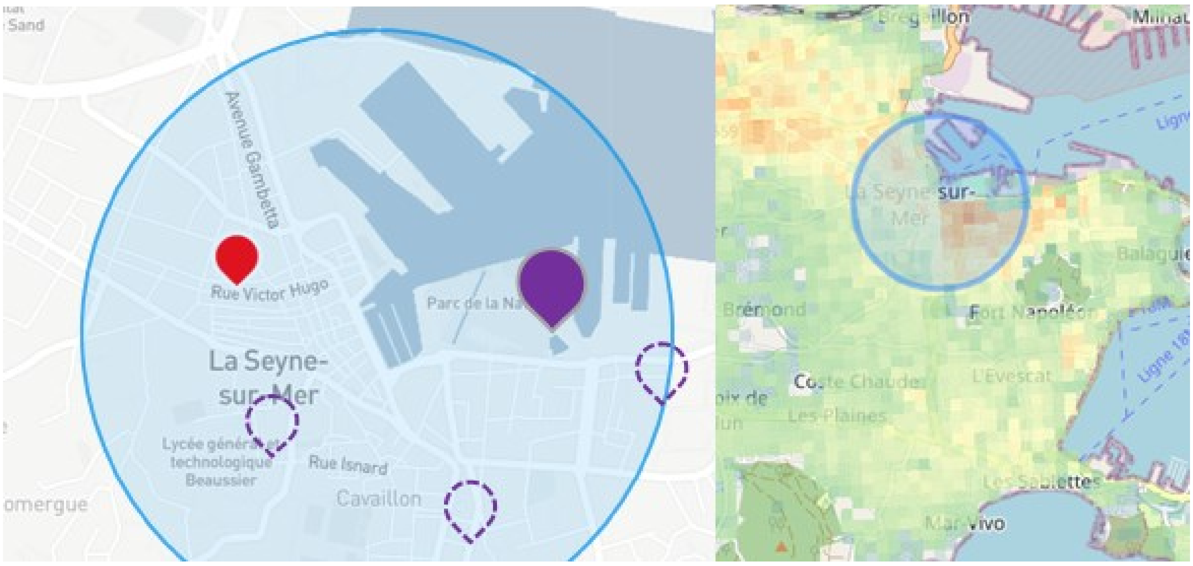

Figure 26: Location of the waste incineration unit LSSM [35] and heat demand industrial area (70 GWh) [15].*

In the long-term with the waste incineration DHN located nearby, an interconnection of both heating networks could be expected, where the total heat demand of 70 GWh – including the current and potential future island networks – could be covered by one large DHN. From the two individual smaller DHNs of 19.5 and 1.3 GWh, the additional demand for a combined and larger DHN amounts to 49 GWh. Even without connecting additional consumers, the waste incineration plant and the sea-water heat pump could supplement each other, and savings can be expected, where waste incineration heat can replace some load from the HP, which could free up additional connections in the long run – depending, of course, on the available waste input in the long term. This is in line and further enabled with the suggested improvements in the DHN, including the improved monitoring, performance and control of temperature, flow and DSM as foreseen within REWARDHeat and beyond. From this, additional improvements can be expected, like reduced network losses and higher efficiencies as previous studies show [37], which could enable an expansion of the DHN in the long run. For the future DH in LSSM, it is estimated that the network losses reduce from 18% and 15% for the waste-based and sea-water-based network respectively to reduced losses of 13.2%, and waste incineration and heat pump efficiencies increase by 5%-points and 1 COP respectively.

With the main impact coming from the replacement of gas with electricity for sea-water-based heating, the fuel consumption adjusts accordingly. Potentially, also oil, biomass or inefficient electric boilers might be replaced with more efficient DH.

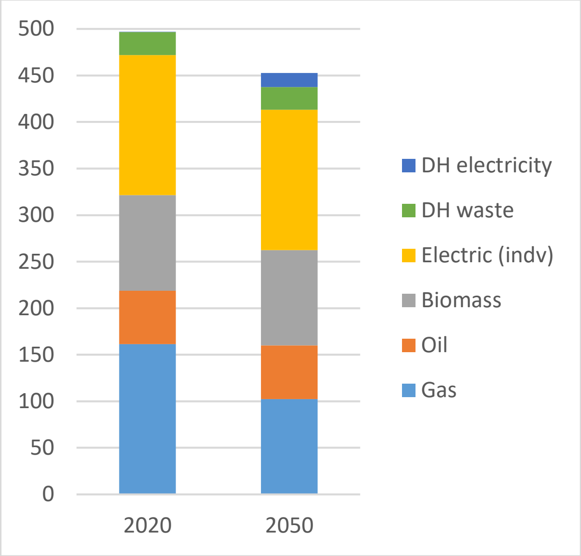

Figure 27: LSSM fuel consumption for heating for baseline (2020) and future demo impact (2050) scenarios

4.3.3 Future 2050 100% REWARDHeat

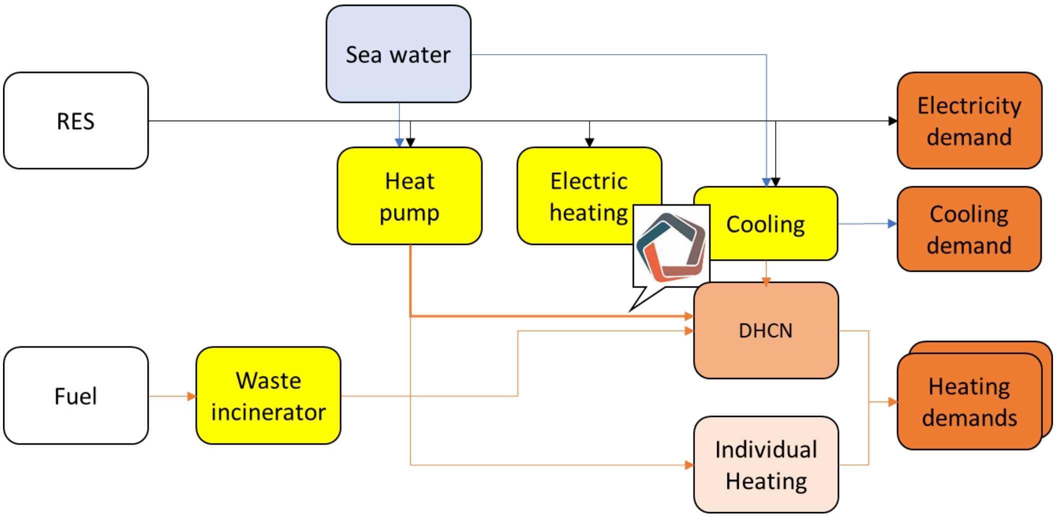

Figure 28: Energy system set-up of LSSM in EnergyPLAN in 2050 100% REWARDHeat scenario

In the future 100%REWARDHeat scenario, the major improvement is found in the individual heating system. The fuel boilers in the individual heating system are all expected to be substituted by individual heat pumps to reduce the oil, gas, and biomass consumption and the electricity consumption by replacing the relatively low-efficiency electric boilers. The individual HPs are considered primarily ground-source heat pumps, air-to-air heat pumps, and air-to-water heat pumps, with an average COP of 3.5, in accordance with the Heat Roadmap France study [38]. A total of 110 GWh electricity consumption is needed for individual HPs, which is modelled as imported electricity based on renewable energy sources to meet the electricity demand, as the electricity sector is not modelled in EnergyPLAN.

The utilisation of additional PV and storage solutions is not further considered in the REWARDHeat scope, but could be investigated in further analyses. In the analysed scenarios, the combination of the two DHNs can enable similar benefits such as reduced constrains on either technology/network.

4.3.4 Energy and environmental impact analysis

The results for the REWARDHeat demo as well as impacts of the foreseen growth at the macro level for the municipality of LSSM are presented in this section. While the baseline and demo heating system are presented above, various impacts beyond the direct demo boundaries can be considered. These are discussed below and cover KPI results and key takeaways, as well as implementation options and further discussions.

In accordance with the reduction in fossil fuel consumption, the renewable energy share increases and the air-borne emissions decrease. While the extent of the waste incineration is not considered to increase, the potential of sea-water-based heat via heat pumps could be further exploited, as is foreseen to take place also in the future scenario with 13% of the heat demand to be covered by sea-water heat pumps without major changes on the production side.

Figure 29 displays the fuel consumption and Figure 30 heat production structure of LSSM in 2020, 2050, and 2050 100% REWARDHeat scenarios. Figure 31 and Figure 32 show the results of the linear interpolation in 2030 and 2040 based on the data output of EnergyPLAN in 2020 and two 2050 scenarios. Compared to the 2020 baseline, the increased share of DH in 2050 (around 3 times that of 2020), reduced losses in the DH network as well the improvement in the efficiency of waste incineration and heat pumps result in 16.9% decline in primary energy consumption and 9.7% increase in electricity import. The 2050 100% REWARDHeat scenario achieves 100% renewable energy and zero CO_2 emissions. Compared to the future 2050 scenario, the 100% REWARDHeat scenario reduces primary energy consumption by around 90% and increases electricity consumption by 25%, which is due to the large implementation of the individual HPs, assuming that the electricity production and import are all based on RE.

Being out of the scope of the REWARDHeat project, the local PV potential could be explored further and deployed for LSSM to realize a 100% RE-based electricity system. Also, the utilization of decentralized PV panels combined with multiple storage solutions (e.g. battery electricity storage) could be considered by the local houseowners to reduce electricity consumption from the grid.

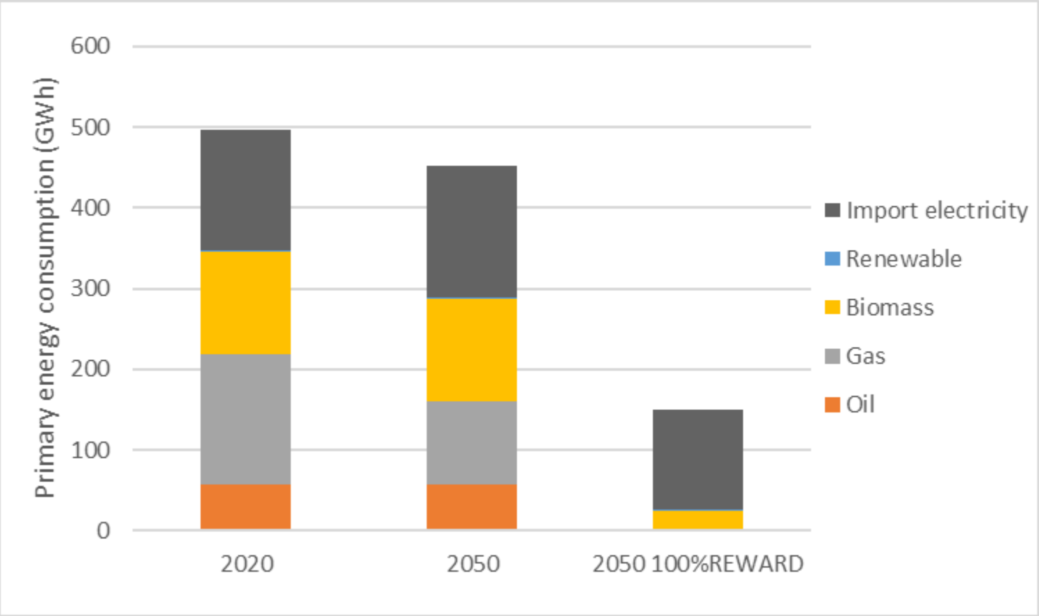

Figure 29: LSSM fuel consumption by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

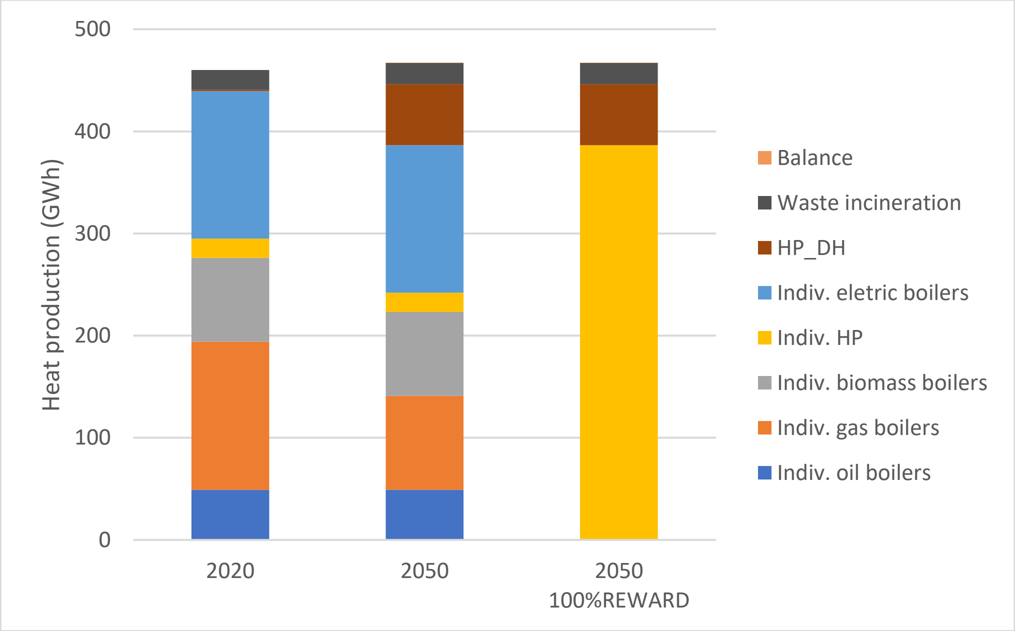

Figure 30: LSSM heat output by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

Table 7: Resulting annual fuels (for heating) and KPIs in LSSM

LSSM							
	2020	2050	2050 100%REWARDHeat	Diff.		Diff. 2050 100%REWARDHeat	
Fuels for heating							
Oil consumption (GWh)	57.52	57.52	0	0	0%	-57.5	-100%
Gas consumption (GWh)	161.4	102.5	0	-58.90	-36%	-161.4	-100%
Coal consumption (GWh)	0	0	0	0	-	0	-
Biomass consumption (GWh)	126.90	126.90	24.40	0	0%	-102.5	-81%
Electricity consumption (GWh) a	151.08	165.60	125.35	14.52	10%	-25.7	-17%
KPIs							
Non-Renewable PES (GWh) b	218.92	160.02	0	-58.9	-27%	-218.9	-100%
Renewable PES (%)	37.1%	44.6%	100%	8%-p.	20%	63%-p.	170%
CO2 emissions (kt)	48.27	36.25	0	-12.022	-25%	-48.3	-100%
Share of local waste/excess heat in DHN C	93.8%	25.7%	25.7%	-68%-p.	-73%	-68%-p.	-73%
Losses	15/18%	13.0%	13.0%	-2/5%-p.	13%-28%	-2/5%-p.	13%-28%
Notes: a From heat pumps in individual heating system and DH system c Mainly gas replacement in the individual heating system b Waste incineration + sea water 'excess' heat							

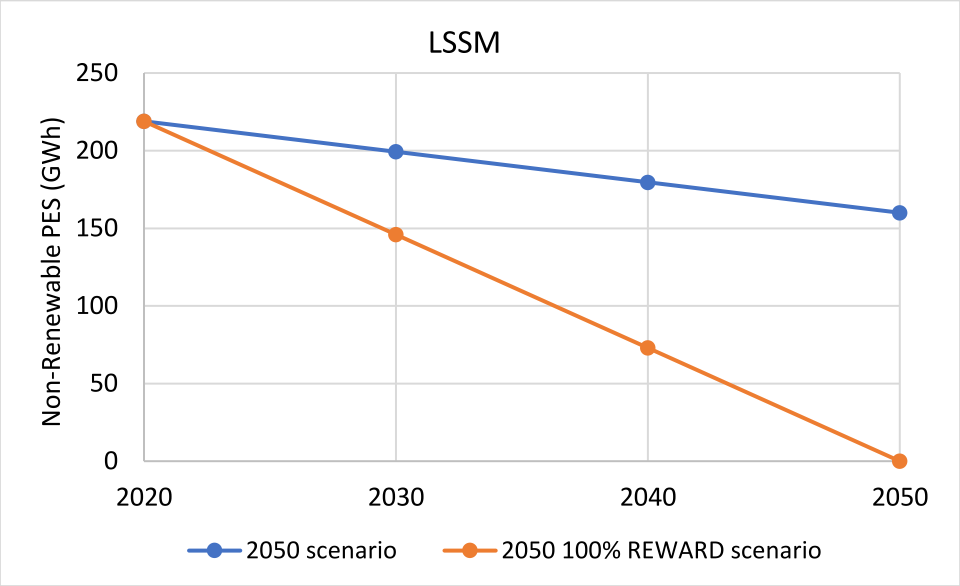

Figure 31: Result of linear interpolation of the non-renewable PES in LSSM in 2030 and 2040.

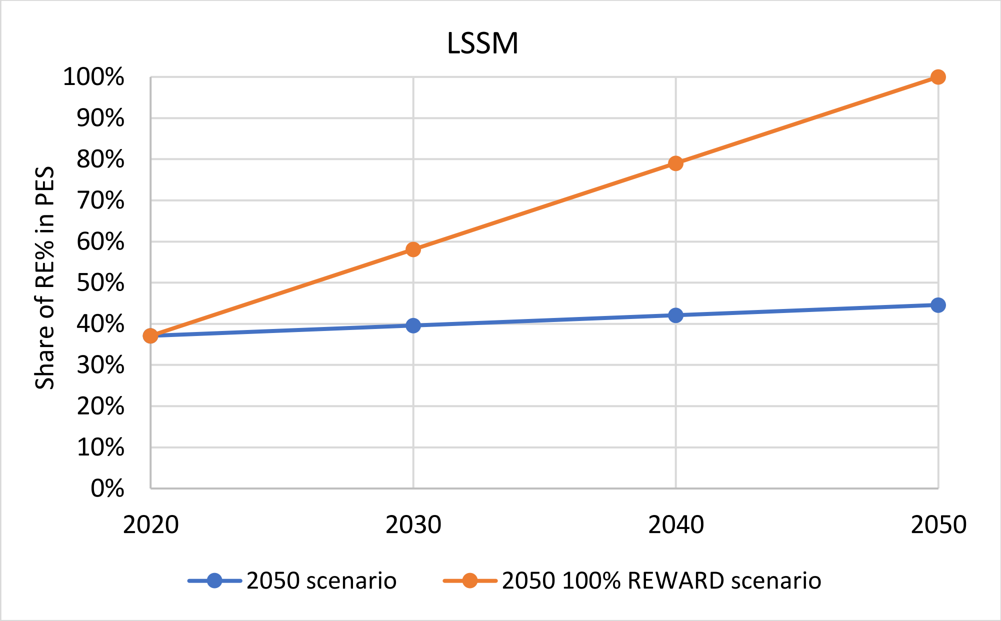

Figure 32: Result of linear interpolation of the REshare in LSSM in 2030 and 2040.

4.3.5 Economic and societal impact analysis

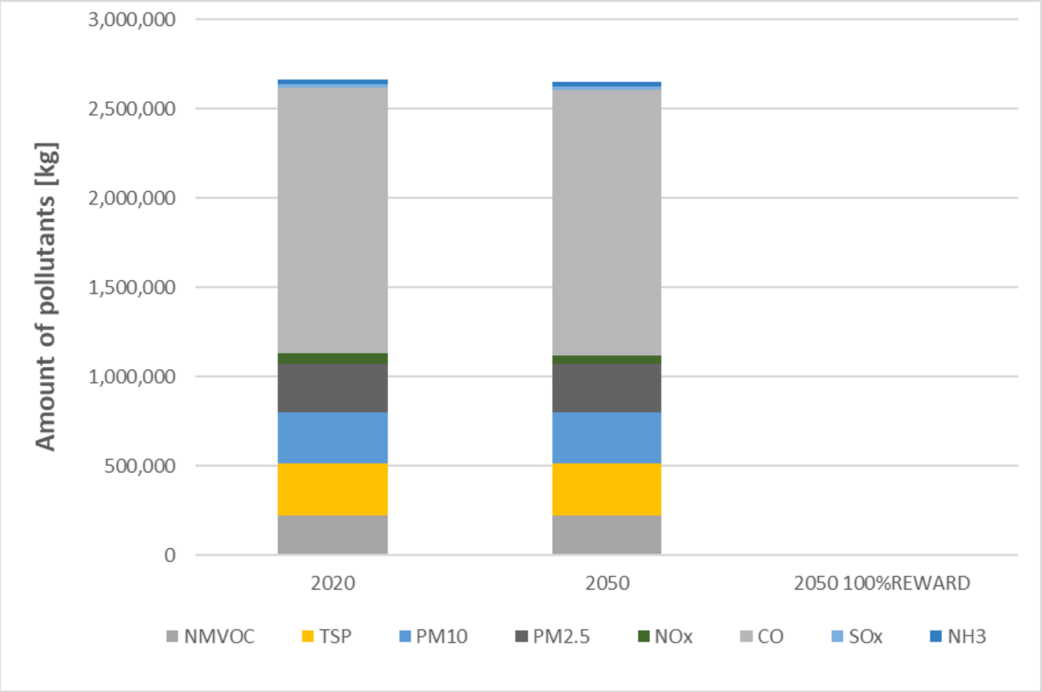

Figure 33 Amount of air pollutants in LSSM for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

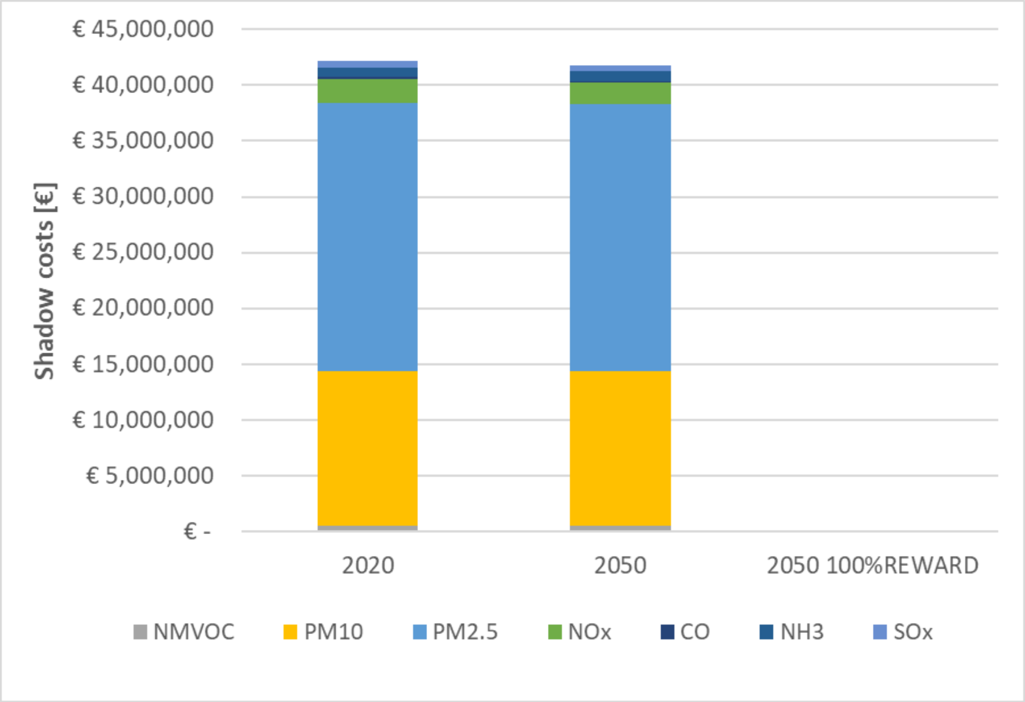

Figure 34 Shadow costs of air pollutants in LSSM for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

In 2020, LSSM has a diverse mix of different technologies to cover their heating demand (Figure 29, Figure 30), using biomass, oil, gas and electricity. However, as biomass emits the most air pollutants, especially in individual boilers, the biomass is responsible for 97% of all the pollutants. The emissions with the largest emissions are CO, TSP, $PM_{2.5}$, PM_{10} and NMVOC. The emissions result in a relative shadow cost of € 0.10 per kWh.

In the 2050 scenario, LSSM has almost the same primary energy and technology mix. Only a part of the individual gas boilers is replaced by district heating heated by heat pumps. However, as gas only account for ± 1.5% of the shadow costs. The shadow costs remain the same with € 0.10 per kWh.

In the 2050 100% renewable scenario, LSSM replaces almost all the technologies with individual heat pumps (± 85%). The other 15% is covered by district heating with heat pumps ±12% and waste incineration with biomass ±3%. Only this last fraction is emitting air pollutants. This results in relative shadow costs of € 0.00 per kWh.

In the 2050 scenario, the total annual costs decrease only with 3% compared to the 2020 scenario. Because of the replacement of the individual gas boilers by the district heating with heat pumps, the fossil fuel costs decrease with € 2.6 million. However, because this new technology uses a lot of electricity, the electricity costs increases with € 3.4 million. Because the fixed O&M and annual investment costs also decrease the total costs are lower. However, looking at the jobs created by the investments, still most are created for the individual boilers. As this sector still covers >85% of the heating demand. Only a small part is created for large, district heating heat pumps or small individual heat pumps.

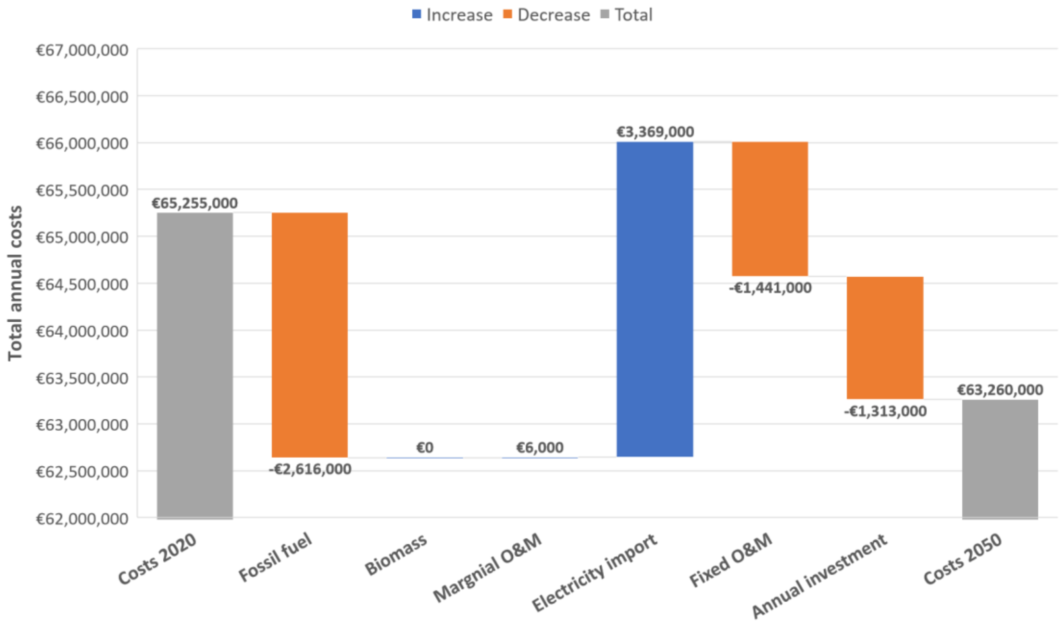

Figure 35 Total annual cost of the heating sector of LSSM in 2050 scenario.

In the 2050 100% renewable scenario, the total annual costs decrease with 40%. € 15 million of this is because of the reduction of fossil fuel and biomass. Instead of spending this money outside the region, it can be invested in the region, which will stimulate the local economy. In this scenario, opposite to the regular 2050 scenario, the electricity import will decline with € 6.0 million, instead of increase. This is probably a consequence of the replacement of the electric boilers. In this scenario, zero jobs are created for individual boilers, because this sector is cancelled out. But most jobs are created for individual heat pumps, as this now covers >85% of the heat production. However, the total jobs created are only 40% of the jobs of the 2050 regular scenario.

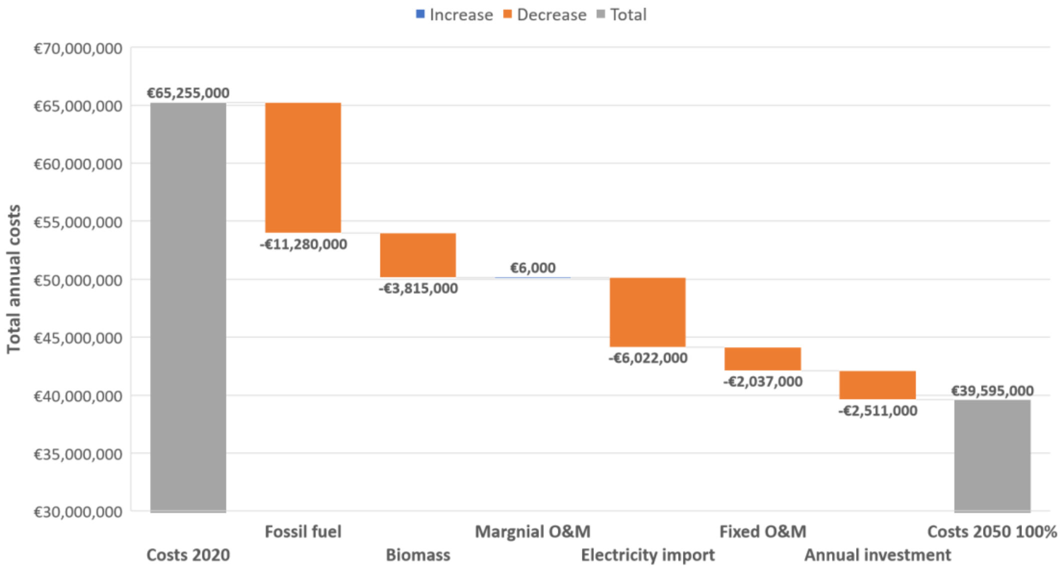

Figure 36 Total annual cost of the heating sector of LSSM in 2050 100% REWARDHeat scenario.

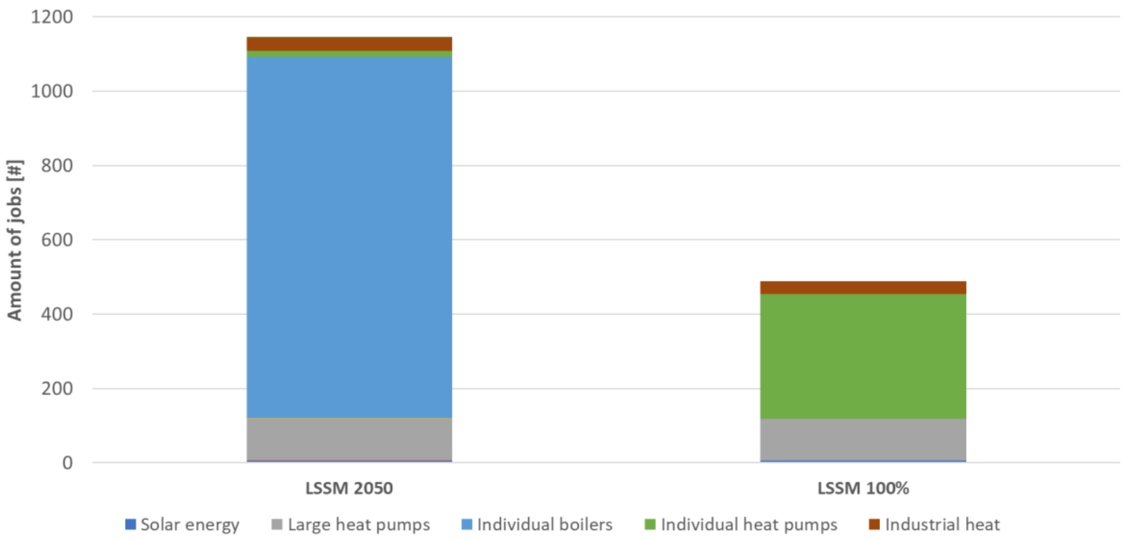

Figure 37 Amount of job creations in LSSM in the 2050 and 2050 100% REWARDHeat scenarios.

4.4 Topusko

Topusko is a municipality in Sisak-Moslavina County, located in central Croatia 70 km south of the capital city Zagreb. With a population of approximately 3,000 (1/3 of which in the town surrounding the demo), it is the smallest LAU in regard to heating demands. The scope of this demonstrator is the retrofit of an existing DHN with a focus on geothermal hot water supplying the local Spa. The local heating system supplies heat energy to private, business, and public sector facilities.

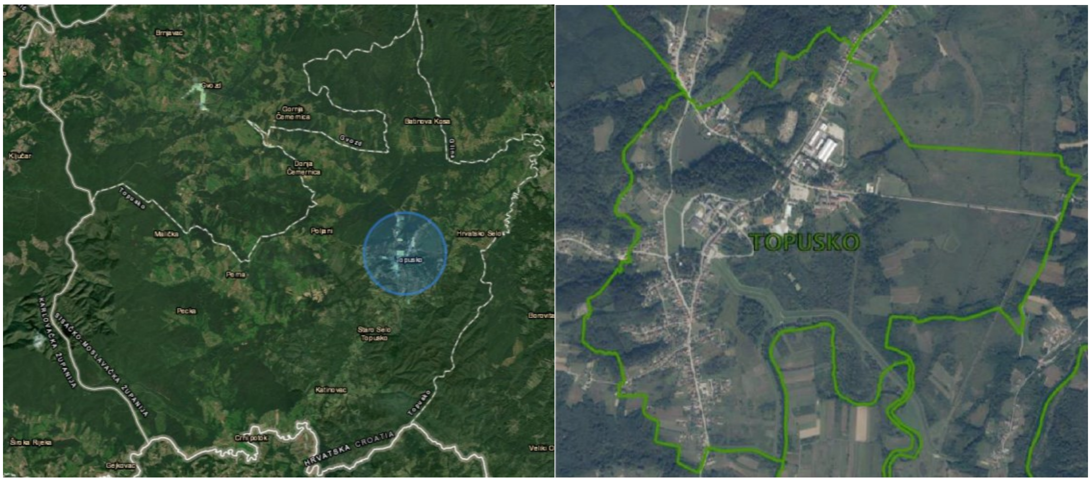

Figure 38: Location of Topusko local authority [17,39]

4.4.1 Baseline

The heat demand in the mainly rural LAU of Topusko amounts to 6.36 GWh annually [17]. Due to the low heat density in the area, the potential DH demand is low. Yet, the availability of geothermal hot springs is capable of supplying heat to the main consumer: the Health Spa; and with a connection to surrounding consumers, the geothermal hot water (GHW) based DHN supplies in total heat to 210 nearby private and public heating users.

The geothermal system in the municipality of Topusko consists of four geothermal wells, TEB-1, TEB-2, TEB-3 and TEB-4, distribution pipelines and a central heating station (CHS). Today, three of the four geothermal wells are in operation. The TEB-1 and TEB-3 wells supply heat to a smaller circle of external consumers in their vicinity. TEB-4, being the largest source of geothermal water, is connected by pipeline DN250 to the central heating station to enable the use of geothermal water for heating, DHW preparation and preparation of geothermal water for balneological and pool needs of the Spa complex, but also for heating to some private users. The CHS is responsible for the preparation of the heating medium, DHW, hot geothermal water and cooled geothermal water for the needs of the swimming pools and balneotherapy. The inner consumers of the DHN include Hotel Petrova Gora, Hotel Toplica, Movie theatre Lonia, Library, Mud baths, Outdoor swimming pools complex (during summer).The outer consumers include RC Church, Glinska 4, Glinska 8, Glinska 10, Dalekovod UP, Dalekovod S1, Dalekovod N2, Orthodox Church, Elementary school, High school, Kindergarten. The scope of the REWARDHeat project will only cover the geothermal well TEB-4 [40]. The following impact analysis beyond the demo considers all geothermal wells.

It is estimated that 30% of the population of Topusko Municipality currently use thermal energy for heating from geothermal water sources extracted from wells TEB-1, TEB-3 and TEB-4. According to the national official statistics of Croatia, the total heat delivered in the district heating sector of Topusko is 3.746 GWh in 2020, for the heated area of 22900 m^2 [41]. The energy lost in distribution is 10% according to D6.2 [9]. Projects that plan to expand the DHN are already initiated and are in the design phase [40]. Back-up heat sources are locally installed for consumers connected to TEB-3, via fuel oil boilers [40]. Most households have small privately-owned back-up boilers (oil boiler or biomass furnace), as an alternative to geothermal heating.

Outside of the geothermal network, most are stand-alone houses using biomass (wood) and occasionally fuel oil as a primary source of energy. The demand of individual heating is calculated by the total energy demand minus the district heating part, which is 2.99 GWh. Here, we apply the national data from [42] to the local area of Topusko, i.e., 51.2% oil and 48.8% biomass.

Figure 39 Current structure of DHN in Topusko

The focus of the REWARDHeat demo has been geothermal water as renewable energy source for heating. Cooling demand is not in the scope of the project. At some point of the project, a cooling application was considered in the form of an absorption chiller that would utilize low temperature waste heat, but was dismissed as technically challenging and economically not feasible.

4.4.2 Future 2050

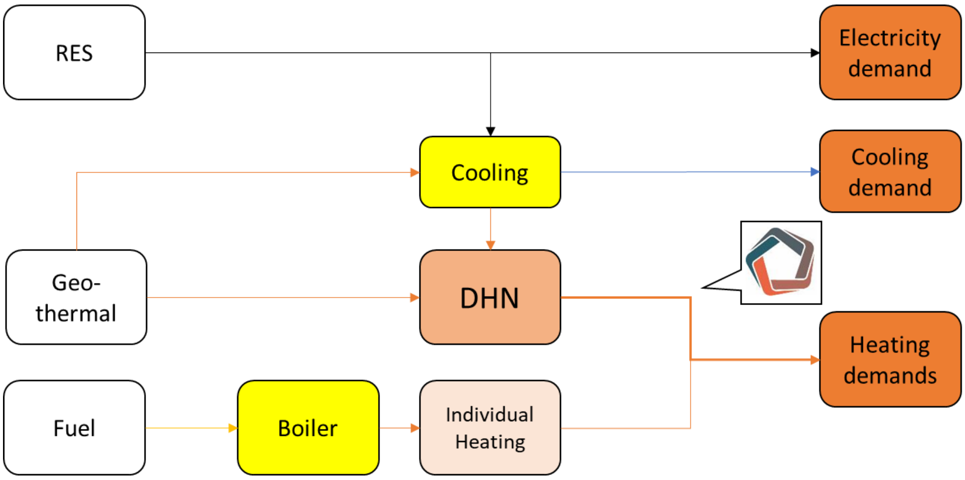

Figure 40: Energy system set-up of Topusko in EnergyPLAN with REWARDHeat demo impact

REWARDHeat project implementation at the demo site focuses on the geothermal network, renewal of the CHS, pipelines supplying energy from the geothermal source, monitoring and increasing efficiency of the geothermal network etc.. The CHS supplies some public and some private buildings with energy, corresponding only to a fraction of the town's heat demand. The main impact will be safer and more efficient use and supply of the geothermal water (fewer m^3

being pumped) as well as lower heating temperature regimes which will ultimately result in lower electricity consumption[40]

The details of the future plans are listed below:

- Lowering the supply heating temperature to 50 °C and return temperature to 40 °C
- Reduction of waste heat, cooling towers worktime and pollution from oil boilers.
- Utilization of waste heat from cooling towers in a low temperature heat pump facility driving district cooling system (cooling focus)

Part of the existing DHN that supplies internal consumers will be retrofitted by pipeline restoration, smart control, and a monitoring system by implementing smart monitoring and control hardware and software into the CHS, reducing the flow volume of geothermal water and amount of waste heat generated during exploitation.

Also, in the future, there is a plan to expand the use of geothermal hot water (GHW) and to connect as much as possible new consumers to a geothermal heat source, without backup heaters [40]. By building a new geothermal and hot water network, a large number of new users would be connected (as shown in the yellow network of Figure 41). Given the currently estimated pumping and the maximum possible estimated pumping of wells, there is a potential of 6.25 MW to connect new users to the geothermal hot water network. With the current 30% of users of the geothermal hot water network of the total population of the Municipality of Topusko, after the construction of the new geothermal and hot water network, it is estimated that 90% of the population would be consumers of the new network. [39]

Based on the above changes, the district heating demand is expected to increase by 5.72 GWh in 2050, while the individual heating demand will drop to 0.64 GWh (10% of the total heating demand). The individual heating systems are assumed to consist of oil boilers (51.6%) and biomass boilers (48.4%), which keep the same share as in the 2020 model.

Figure 41 Future expansion of DHN in Topusko (yellow area)

According to the rough estimation from the local partner, about 15% of energy can be saved in 2050 by implementing REWARDHeat solutions (compared to 2019). This will be determined by comparing geothermal water extraction in 2019 with the extraction of geothermal water in years to come. Also, a reduction in cooling tower working hours is expected when the lower temperature regimes are implemented. Another saving of energy can be achieved by connecting outer consumers to the return pipeline, but this is in the scope of other projects outside REWARDHeat.

4.4.3 Future 2050 100% REWARDHeat

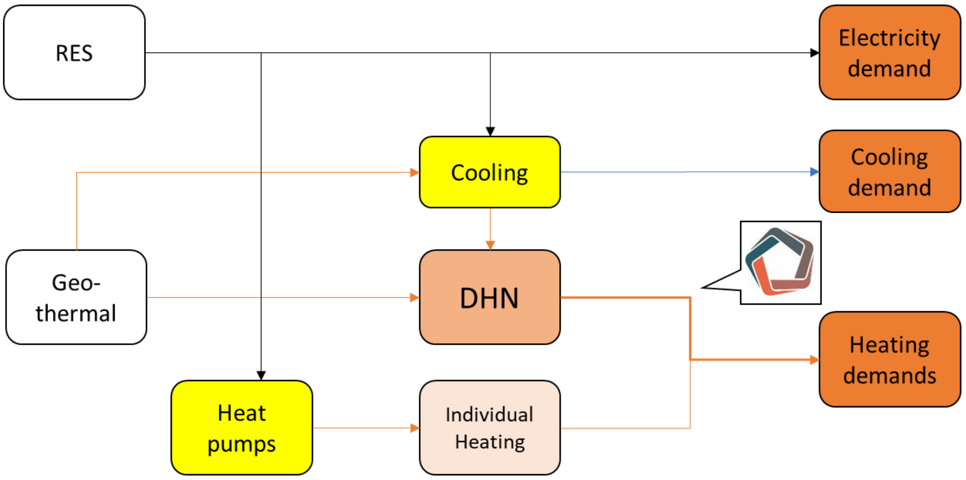

Figure 42: Energy system set-up of Topusko in EnergyPLAN in 2050 100% REWARDHeat scenario.

In the 100% REWARDHeat scenario, further decarbonization is achieved by replacing the remaining fuel boilers with individual heat pumps. According to a previous study on Croatia in the Stratego project, individual heat pumps are the most preferable individual heat solution based on a good balance between energy demand, emissions, and cost. These could be supplemented by small shares of individual solar thermal and biomass boilers [38]. Individual heat pumps may be too expensive in suburban areas, if the heat supply transfers from district heating to individual heating solutions. In the case of Topusko, it is assumed that all the biomass boilers and oil boilers will be replaced by individual heat pumps.

Note that even though the impact of energy efficiency improvement in the buildings is not quantified in this scenario, building renovation is still a prerequisite for the implementation of the future scenario.

4.4.4 Energy and environmental impact analysis

The energy-environmental impacts of and beyond the REWARDHeat project are summarized in this section. Figure 49 shows the structure of primary energy consumption and Figure 50 the structure of heat production in the 2020 baseline, 2050 demo impact and the 2050 100% REWARDHeat scenarios, while Table 8 shows the KPIs. The DH network expansion and the utilization of geothermal energy decreases the primary energy consumption significantly (-80%) in the heating sector of Topusko in 2050 compared to 2020. The fuel demand from the biomass and oil boilers in the individual heating sector is decreased to zero in the 2050 100% REWARDHeat scenario due to the replacement by the individual heat pumps. The CO_2 emissions from the heating sector are thereby reduced to zero. Here, it is assumed that in 2050 all grid electricity import is based on RE sources. The linear interpolations for 2030 and 2040 are displayed in Figure 45 and Figure 46. The increase of DH network and geothermal energy extraction can be implemented step by step in the years to come.

Different from other demos, Topusko is a very small rural LAU, yet with the highest potentials for geothermal energy. The expansion of the DH network and the connection of the new facilities should be implemented together with energy renovation measures in the buildings. This is because a large share of the current residential buildings in Topusko are rural houses with relatively low energy standards not suitable for the connection to DH. According to a previous study on the geothermal development in Topusko [39], after the energy renovation of existing facilities heated by geothermal water, the required heating power could be reduced by 40 to 60%.

The electricity sector is not considered in the EnergyPLAN model created for Topusko; however, further positive impact could be generated with the utilization of decentralised rooftop PV for the individual households which have fewer opportunities to connect to the geothermal-based DH network.

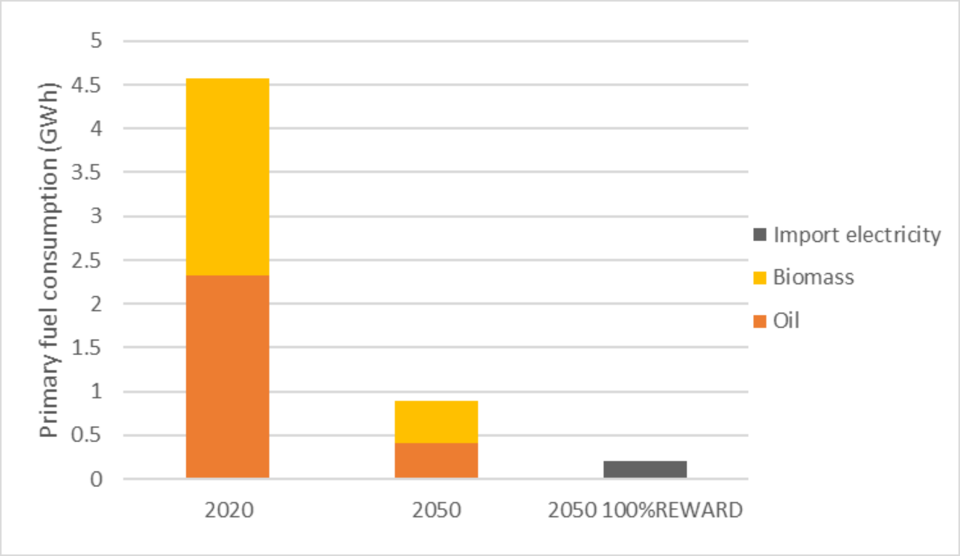

Figure 43: Topusko fuel consumption by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

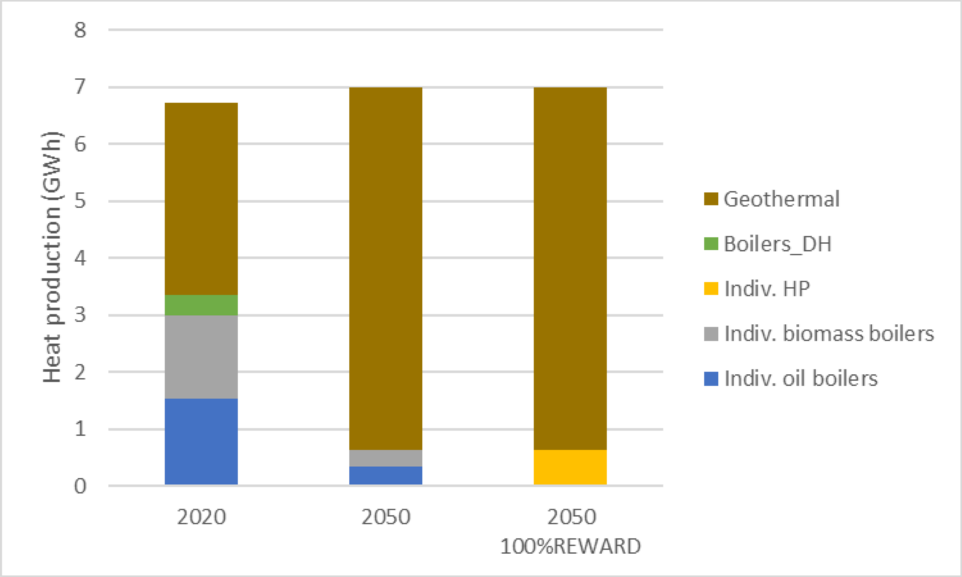

Figure 44: Topusko heat output by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

Table 8: Resulting annual fuels (for heating) and KPIs in Topusko

Topusko							
	2020	2050	2050 100%REWARDHeat	Diff.		Diff. 2050 100%REWARDHeat	
Fuels for heating							
Oil consumption (GWh)	2.32	0.41	0	-1.91	-82%	-2.3	-100%
Gas consumption (GWh)	0	0	0	0	-	0	-
Coal consumption (GWh)	0	0	0	0	-	0	-
Biomass consumption (GWh)	2.24	0.48	0	-1.76	-79%	-2.2	-100%
Electricity consumption (GWh)	0.00	0.00	0.21	0	-	0.21	-
KPIs							
Non-Renewable PES (GWh)	2.33	0.40	0 a	-1.93	-83%	-2.3	-100%
Renewable PES (%)	70.7%	94.3%	100%	24%-p.	33%	29%-p.	41%
CO2 emissions (kt)	0.62	0.11	0	-0.512	-83%	-0.6	-100%
Share of local waste/excess heat in DHN b	89.9%	100%	100%	10%-p.	11%	10%-p.	11%
Losses	10%	10%	10%	0%-p.	0%	0%-p.	0%

Notes:

a Only geothermal heat and electricity for heating sector. Assume that all the electricity is from RE sources
b All geothermal heat

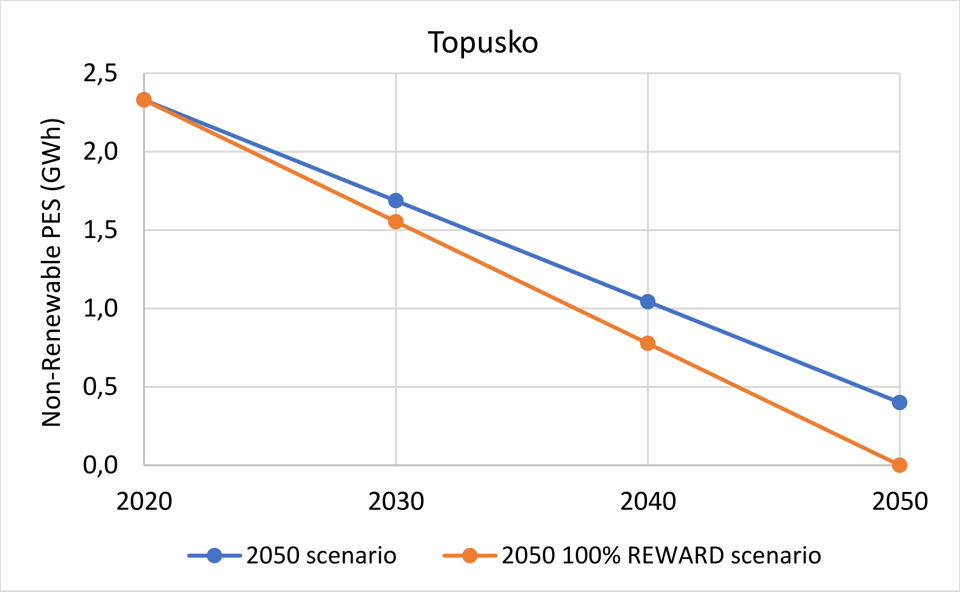

Figure 45: Result of linear interpolation of the non-renewable PES of Topusko in 2030 and 2040.

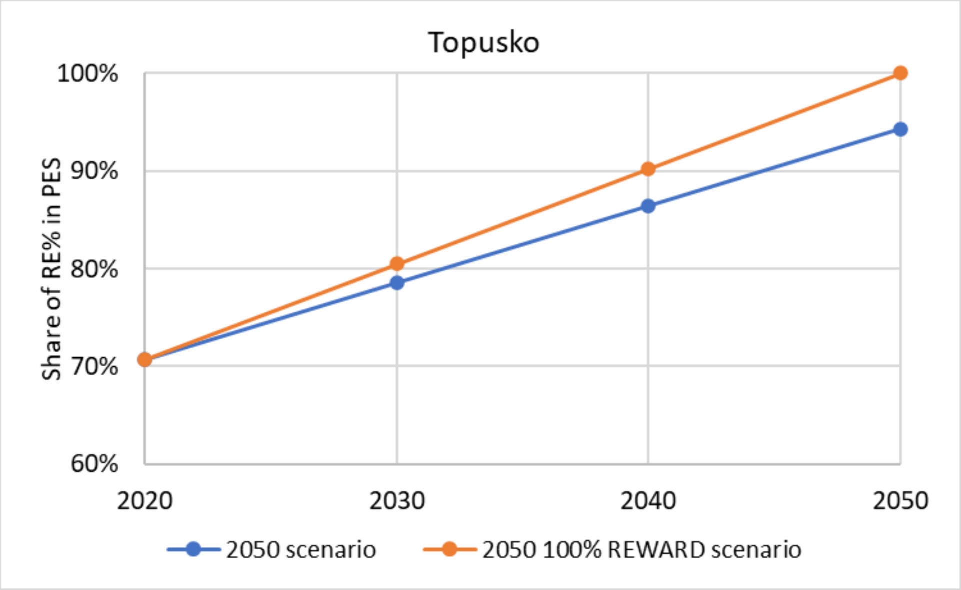

Figure 46: Result of linear interpolation of the share of RE% of Topusko in 2030 and 2040.

4.4.5 Economic and societal impact analysis

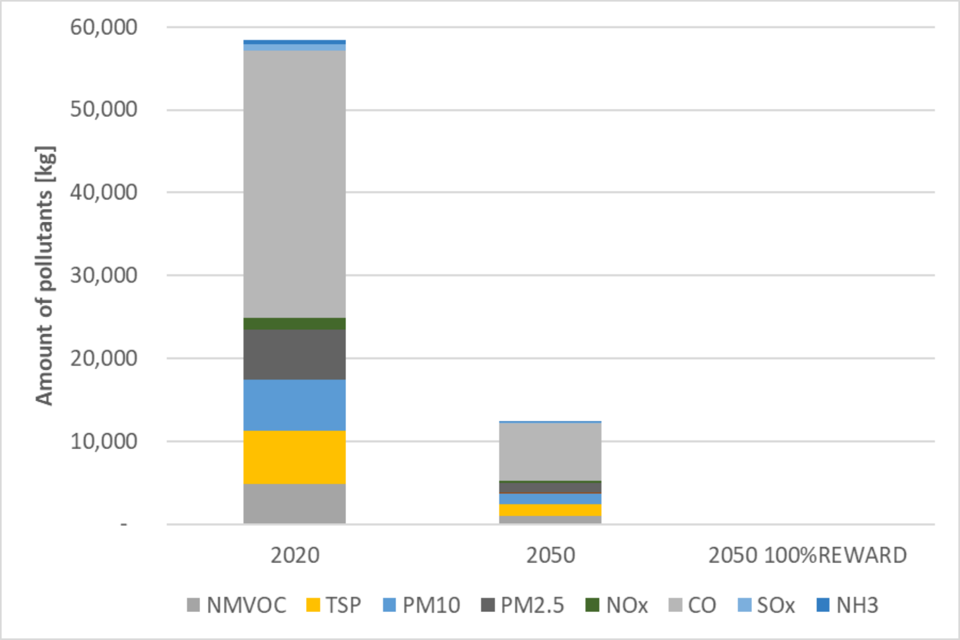

Figure 47 Amount of air pollutants in Topusko for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

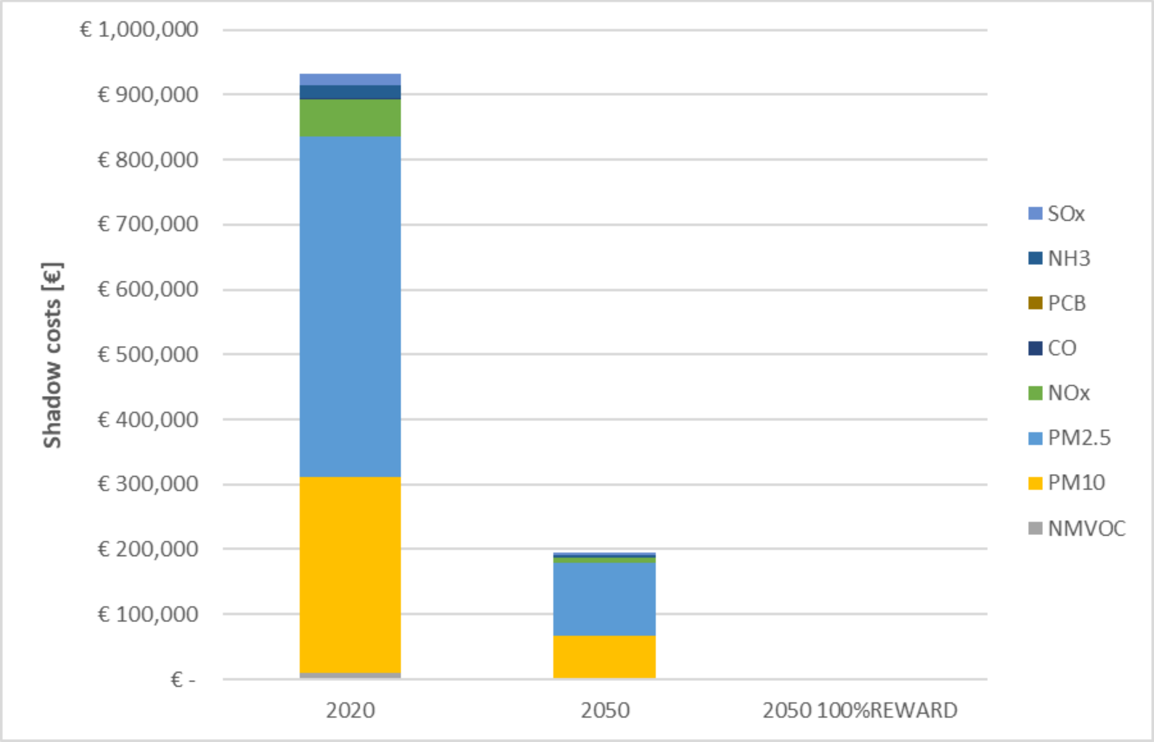

Figure 48 Shadow costs of air pollutants in Topusko for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

Topusko uses in 2020, a mix of different heating technologies; geothermal energy, district heating boilers fuelled by oil and individual boilers fuelled by biomass and oil (Figure 43 and Figure 44). The geothermal accounts for more than 50% of the heat demand. The individual boilers for 45%

and is split equally between oil fuelled and biomass fuelled. 5% is produced by the district heating boiler fuelled with oil. In Figure 47 the amount of air pollutants emitted are shown. The biomass is the main contributer of the $PM_{2.5}$, PM_{10}, TSP and NMVOC and NH_3. While the oil emits the most amount of the NO_X and SO_X. The relative shadow costs is € 0.15 per kWh.

In the 2050 scenario, the district heating boilers and partly the residential boilers are replaced by the geothermal energy. Only <10% is produced by the residential boilers, of which still is split equally between oil and biomass fuelled boilers. This results into a ± 5 times smaller amount of oil and biomass usage, and subsequently also in emissions (Figure 47). The relative shadow costs for this scenario are € 0.03 per kWh.

In the 2050 100% renewable scenario, all the individual boilers are replaced by individual heat pumps. This results in no air pollutant emissions at all. So, the shadow costs are € 0.00 per kWh.

In the 2050 scenario, the total annual costs decrease with 50%. This is for >98% caused by the reduction of fossil fuel and biomass, because of the expansion of the geothermal energy. This money stays in the region instead of investing it in fuels from outside the region. As Topusko is a small area, only a few jobs will be created, based on the investment costs; 8 jobs in the geothermal energy sector and 1 for the individual boilers.

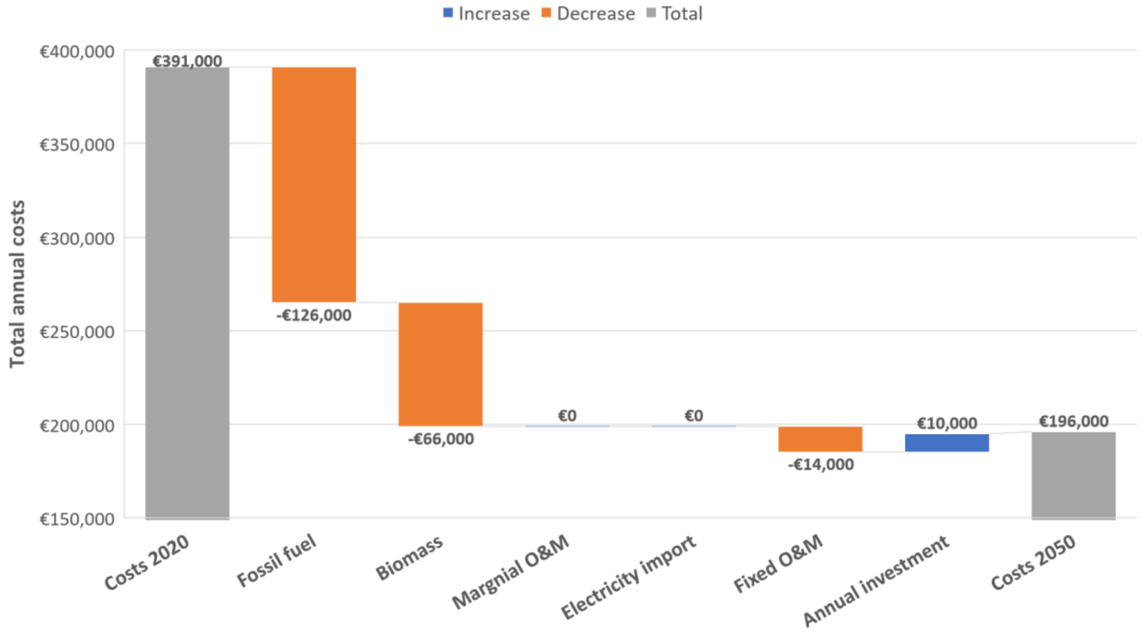

Figure 49 Total annual cost of the heating sector of Topusko in 2050 scenario.

In the 2050 100% renewable scenario, the total annual cost reduction is exactly the same as in the 2050 regular scenario. However, as all biomass and fossil fuel are cancelled out in this scenario, more money is reduced by this (and stays in the region). But, as the remaining biomass and fossil fuel in the 2050 regular scenario are replaced by individual heat pumps, more electricity need to be bought. This resulting in a net same reduction in total annual costs as the regular scenario. In this scenario, also 8 jobs are created for the geothermal energy and 0.5 job for individual heat pumps.

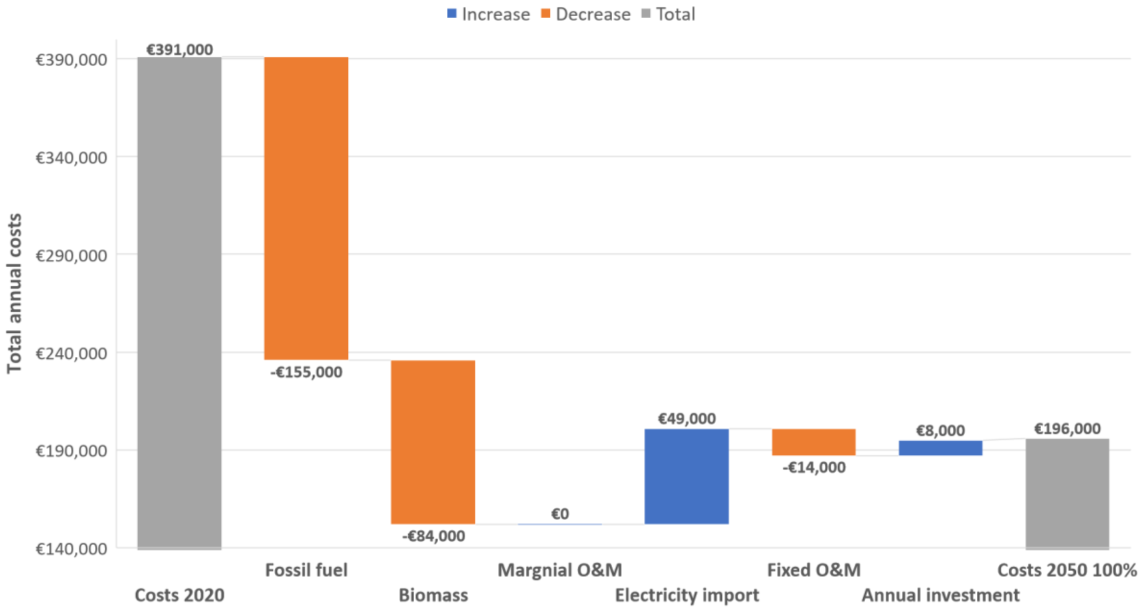

Figure 50 Total annual cost of the heating sector of Topusko in 2050 100% REWARDHeat scenario.

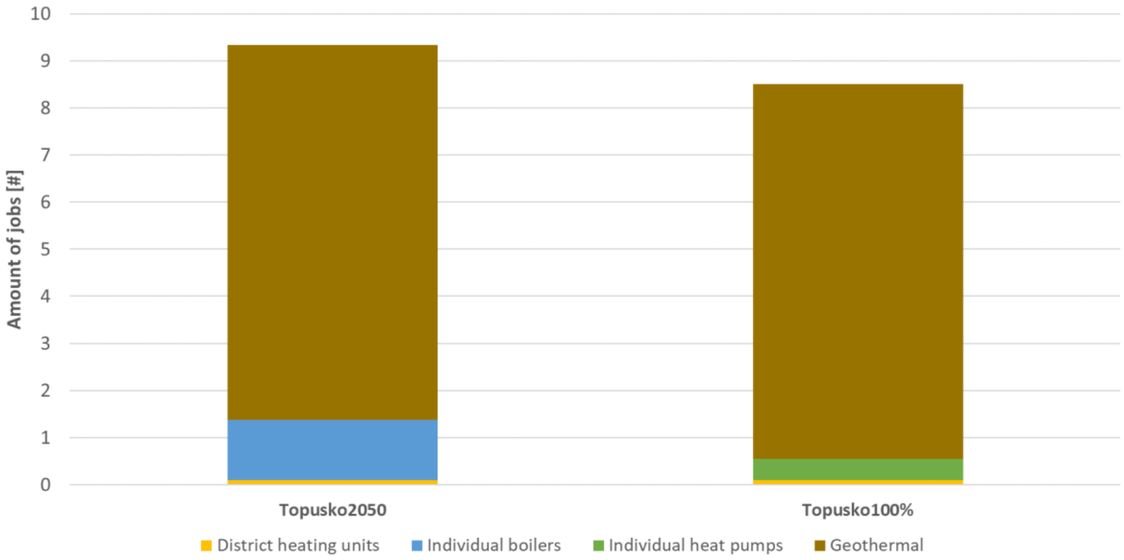

Figure 51 Amount of job creations in Topusko in the 2050 and 2050 100% REWARDH scenario

4.5 Helsingborg

Helsingborg and Mölndal demo sites in the south of Sweden are coordinated and set-up in a technically similar manner. Therefore, some similarities and overlaps between the approaches followed in the demos, as well as in their scenarios and impact analysis presented here, are apparent. On the one hand, the two systems show similar heating (and cooling) densities and DH potentials, on the other hand, the total heat demand and existing baseline set-ups and scenarios must be seen separately. Where future scenario considerations and discussions overlap again with common seasonal storage solutions, the final outcomes are presented individually. Mölndal is therefore presented separately, yet shorter, in the next section.

Helsingborg lies in the province of Scania and the municipality encompasses the area shown in Figure 53. The municipality of Helsingborg is the owner of Öresundkraft, the main producer of energy and heat delivered to the city through a district heating system, as well as it owns the local waste treatment company.

Figure 52: Locations of Helsingborg and Mölndal

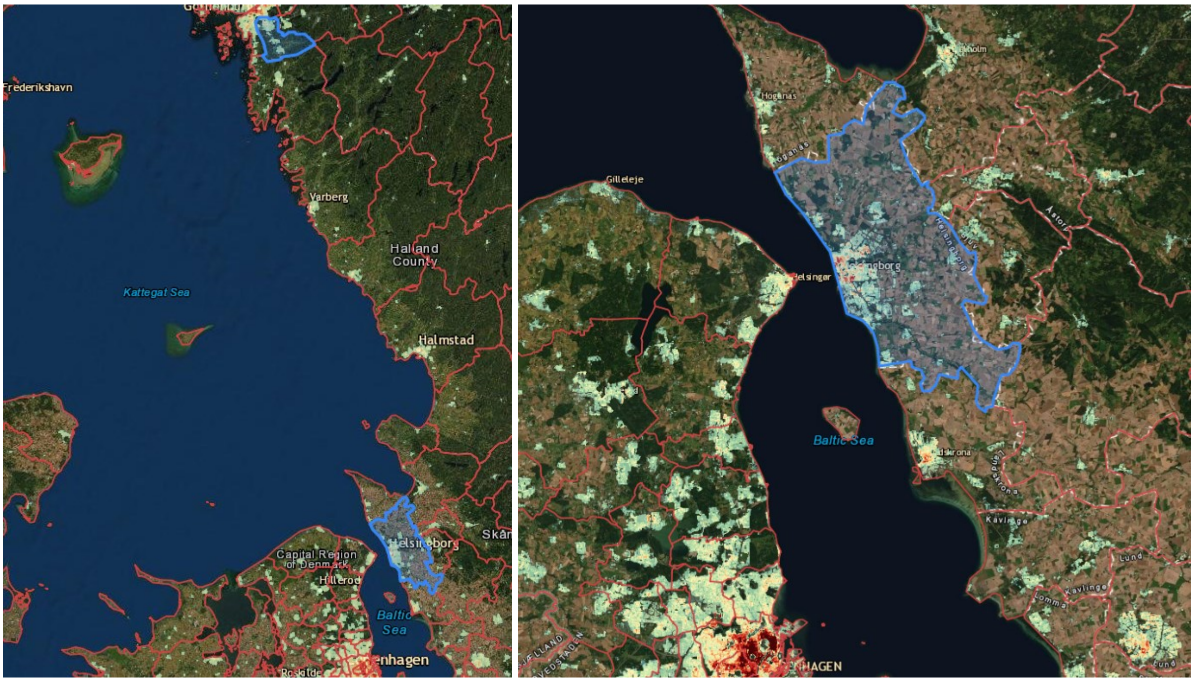

Figure 53: Helsingborg local authority, location and heating potentials (lower highlighted area on the left picture and close-up on the right) [43]

4.5.1 Baseline

The total heat demand of 1,410 GWh in the LAU [43] is to a large extent (around 60%) supplied by the DHN of Helsingborg. The heat sources for the DHN are split into three types: industrial waste heat, waste incineration (CHP) and biomass CHP. The industrial source is often referred to IPOS, the industry park of Sweden, which is managed by the Kemira group. IPOS supplies around 279 GWh, while another 63 GWh is supplied through industrial (waste water) excess heat and heat pumps operated by Öresundkraft. The remaining heat supply is also coming from Öresundkraft's two CHPs, supplying an additional combined 670 GWh through residual waste and wood pellets from forest residues. Both CHPs also produce electricity, but currently with a smaller share (20 and 33% of nominal capacities, influencing the final fuel balance) [44].

With both CHPs contributing to the same DHN, the heat and power productions are aggregated in the scenarios, and the fuel distribution in the DHN is as follows: 44% biomass, 23% waste CHP, 28% industrial heat and 6% waste heat from water treatment, hence, also considered industrial waste heat. Total produced district heating amounts to around 1 TWh annually [45], and the DHN losses amount to 17% (consistent of heat, water and measurement losses), meaning 58.8% of heating is attributed to district heating, close to the statistical Swedish average [46] and with 830 GWh slightly above the estimated values of Hotmaps (cf. 793 GWh). Within the urban area of Helsingborg, 90% of all buildings are connected to the DHN [45], but there are also many rural areas.

Besides the DHN, the individual heating within the local administrative area is divided further into electricity, biomass, oil and gas. In addition to the 58% for DH, buildings are heated 27% electrically, 12% with individual biomass boilers, 1% with oil and 1% with gas heaters [46]. Using the total heat demand identified in Hotmaps (apart from the DH demand), the following demands are simulated in EnergyPLAN for heating in the Helsingborg LAU: 830 GWh DH, 381 GWh el, 169 GWh bio, 14 GWh oil and also gas.

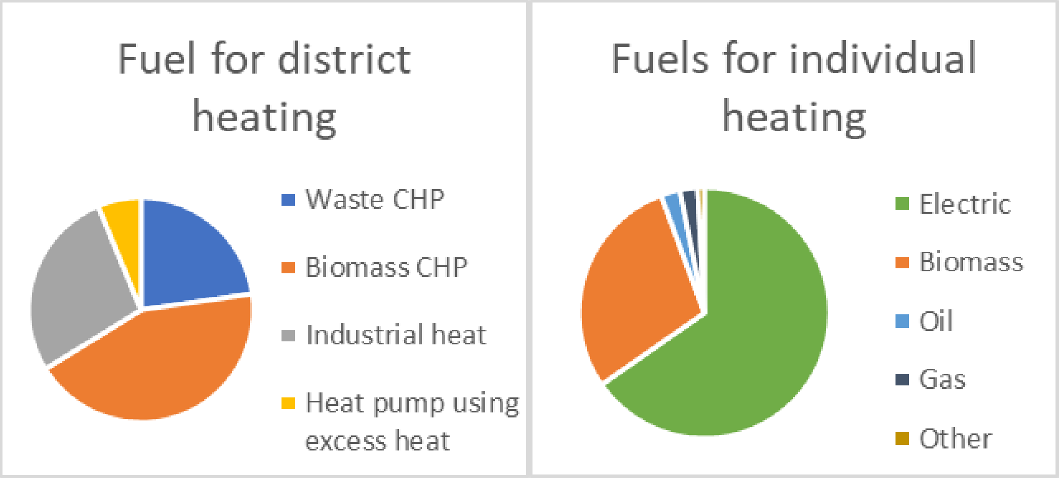

Figure 54 Fuel distributions of the DH system and individual heating system in Helsingborg.

The heat demand is distributed according to the HRE models for Sweden [47], where a difference is made for district and individual heat distribution. This difference is found mainly in the baseload due to grid losses in the DHN, especially in the summer months, where individual heat demand (statistically and thereby also here) only consists of domestic hot water demands. In the demo of the REWARDHeat project, the low summer heat demands are in focus due to the continuously available excess heat from industry, which cannot be utilized. According to Helsingborg partners, *"CHP and industry are currently wasting 150 GWh heat annually"* [45]. This makes it relevant to analyse alternative scenarios for how to integrate the otherwise wasted heat. In the EnergyPLAN model of the 2020 scenario, a total of 10.5 GWh heat is currently unutilised from waste heat, while the heat demand from CHP would be close to zero in the summer. While electricity prices and demands would impact the CHP operation, the following addresses only the balance of heat and further impacts, such as on the power sector, are addressed in the impact analysis section.

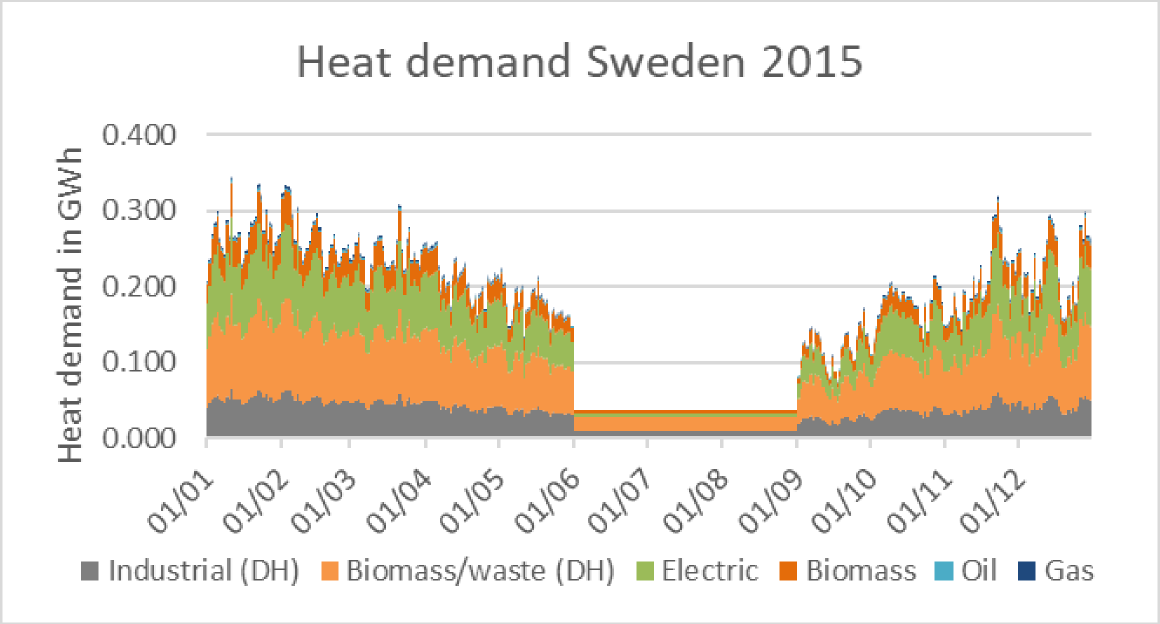

Figure 55: Applied Swedish heat distributions [1] and shares for Helsingborg

The Helsingborg demo site is integrated in and utilises heat from the existing DHN (see D6.2 [36]). It consists of a low-temperature sub-network that is (going to be) exploiting a borehole seasonal thermal energy storage system with a centralised heat pump. Overall, the demonstrator aims to install seasonal thermal energy storage, a centralised heat pump, PV-T and smart controls to exploit the cheapest heat sources between the DH and the borehole field. The demo site is a new residential housing area, which is often characterized by limited energy purchase allowance, related to new building regulations, neutral energy housing trends, integrated heat supply, etc.

The sub-network is to utilize PV-T to limit energy purchases from the DHN and the objective of the demo site is to explore the option of seasonal storage through existing boreholes; besides studying the low temperature effects and benefits from the smart controls. While the estimated energy uses of 0.1-0.3 GWh annually [36,45] at the demo site itself presents only a small fraction of the Helsingborg DHN demand, the borehole storages could contribute to the DHN also beyond by absorbing some of the industrial excess heat in the summer months.

4.5.2 Future 2050

As shown in Figure 56, seasonal thermal storage could be an advantage not just for the demo site but also the whole DHN, utilizing unused excess heat from the summer months in the winter. Similarly, explorations of the demo site, such as lower temperatures and better monitoring, are expected to be replicated in other areas, having an effect on the overall DHN in the future. Instead of an overall low-temperature DHN, this is envisioned to be mainly for sub-networks, similar to the electricity grid with high- and low-voltage areas [45].

Since the demo consists of a newly build sub-network system, it will supply space heating at 40 °C and DHW at 60 °C; while the main DHN operates at 85-110 °C. In the future model in EnergyPLAN of Helsingborg, therefore, generally lower temperatures in sub-networks can be considered, which could increase the efficiency of the existing technologies, as well as lowers losses in the DHN. This is supported by the demo's objective to implement smart control to optimise techno-economic exploitation of heat sources and to develop business models and an innovation platform. In line with this, the overall losses are expected to decrease (from 17%) to 15% (hence, required production being reduced from 1000 to 976.5 GWh) based on the assumption in [37]. This results in even more excess heat from the non-flexible heat producers, hence, the seasonal storage will become even more important for the future of Helsingborg DHN.

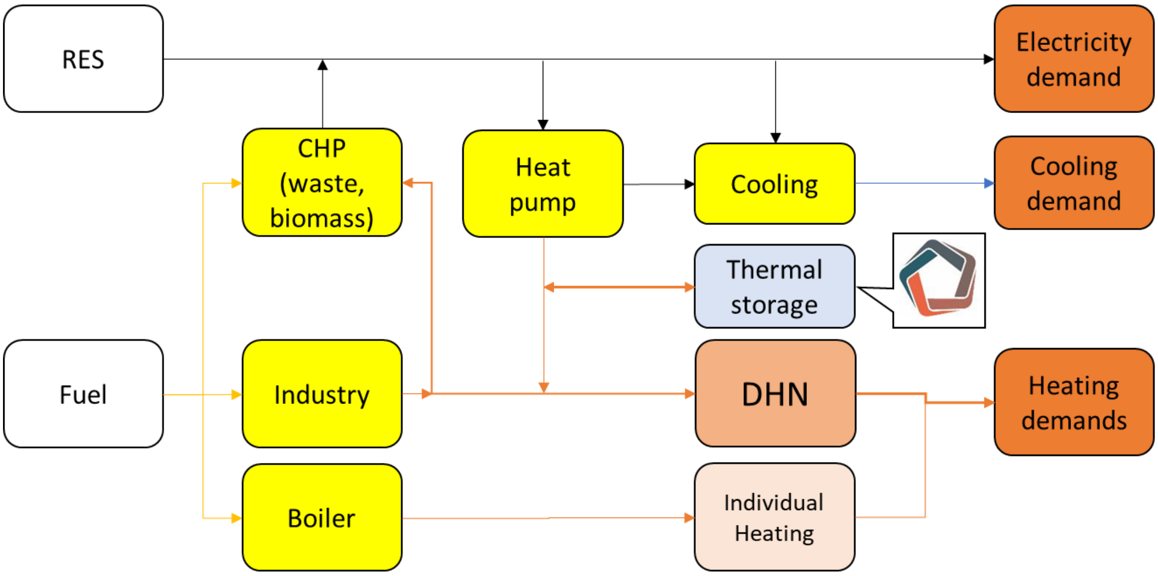

Figure 56: Energy system set-up of Helsingborg in EnergyPLAN with REWARDHeat demo impact

Therefore, decentralised thermal energy storage is added to utilise most of the excess heat. The storage capacity of boreholes is up to 300 GWh according to a simulation of the local partner in Helsingborg. With many options for small-scale boreholes around Helsingborg[4], the 300 MWh TES at the demo could be scaled up to exploit the full excess heat [45]. The result of constant industrial waste heat and additional storage of 14 GWh (in EnergyPLAN model, 13GWh input in solar thermal storage and 1GWh in thermal balancing) is shown in Figure 57, which results in lower heat production from the CHP in the autumn and winter. A SCOP 6 for borehole thermal storage systems is assumed, which leads to additional 2.08GWh electricity consumption.

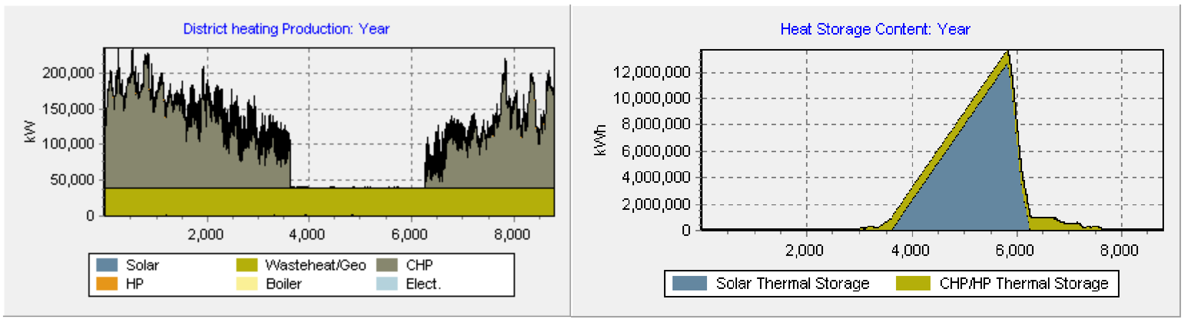

Figure 57: Heat supply and thermal storage potential for Helsingborg DHN

While the operation of the CHP in the model only aims to balance the heat demand and not the electricity demand, the final utilisation of the TES could vary. For example, the CHP is modelled to produce electricity only when there is a heat demand (or potential for storage), while the baseline

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[4] Of around 350 m depth, of which 700000 are already installed across the country

scenario and the individual electric heaters would require power from the grid or a power station elsewhere. However, to illustrate the impact of the demo and the TES, this approach is continued in the further analysis and results, while the impact is discussed in the following sub-section.

Additional technologies, which are added in the demo of Helsingborg include a HP system to supply baseload and a PV-T field of at least 245 panels. For the whole DHN, the impact of one HP and PV-T of two buildings is limited, but an upscale beyond the demo would show the potential of these additional technologies in the DHN of Helsingborg.

Additional HPs would align the CHP with both heat and electricity demands, if the HPs are used in the summer. The CHP fill the thermal storage in the summer, and also produces enough electricity for individual electrically heated houses and additional HP demands. With the added flexibility of the CHP due to the storage, current electricity demand issues can potentially be solved, where large consumers are currently limited supplied [45].

Before such HP is implemented and the optimal size estimated, additional solar thermal capacity is added to the DHN. While the PVT at the demo is intended to supply only the local houses, it nonetheless reduces the demands in the DHN and, therefore, 1 GWh solar is added. With limitation from the power sector, the 'PV part' with electricity production is not further addressed, but should be considered in further the impact analyses.

Finally, scaling up the small HP capacity from the demo to the whole DHN of Helsingborg, a total HP capacity of 500 kW with a COP of 4 is implemented (10.16 GWh-th/yr). The resulting heat production and storage shows the storage to be filled in the summer and supports the heating demands in the autumn and winter. Due to the solar and HP addition, the storage can support most of the winter (until end of March) before it is refilled.

4.5.3 Future 2050 100% REWARDHeat

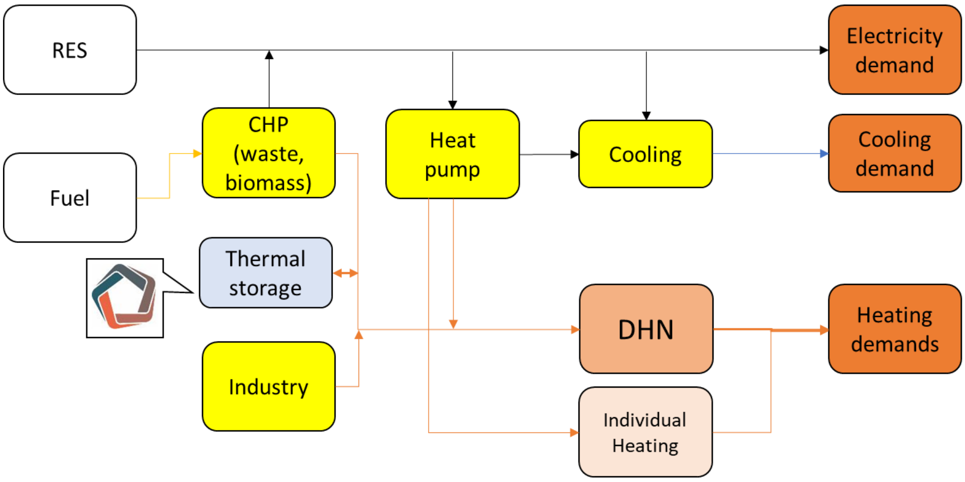

Figure 58: Energy system set-up of Helsingborg in EnergyPLAN in 2050 100% REWARDHeat scenario

In the 100% REWARDHeat scenario of Helsingborg, the major changes lie in the individual heating system and the fuel input of the power plant. All the individual fuel boilers (oil, gas and biomass) are turned into individual heat pumps with 3.5 COP according to Heat Roadmap Sweden[48]. The power plant will be transferred into purely biomass-based plant.

4.5.4 Energy and environmental impact analysis

Figure 59 and Figure 60 are showing the structure of energy consumption and heat production of Helsingborg for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios. Table 9 presents the KPIs and fuel consumption in Helsingborg, which show significant improvements in CO2 emissions and fossil fuels. This based on the heat pumps operation in the baseline when no heat from CHP is produced, compared to the future scenario where the CHP covers it through the addition of the storage enabling efficient CHP operation and the recovery of industrial excess heat. The electricity export is from the CHP during winter, spring and autumn, because the electricity sector is not modelled in the EnergyPLAN model. In fact, when other sectors especially the electricity sector are considered together in an integrated way, a more balanced local energy system is expected to be achieved.

Since the energy and environmental analysis focuses on the impacts of the REWARDHeat demo project and the local energy system of the heating sector in Helsingborg, some aspects are left out of the analysis. On the one hand, it allows to isolate the impacts of the demo from other changes in the system, but on the other hand, it might overlook interference or support of the changes when seen together. The following should be considered for discussion as part of the impact analysis:

First, the deployment of the planned and suggested technologies and expansion has to be done gradually with milestones for 2030, 2040 and finally reaching 2050 targets and potentials. This has to be in line with the natural development of buildings stock, as well as of the DHN expansion and improvements. Furthermore, this has to take into consideration other sectors influencing the heating system, such as the development of the industrial sector, which is very important for the Helsingborg DHN, but also electricity and potential new waste heat options and power-to-heat alternatives in the future. With a significant role of the cooling network in Helsingborg, also the alignment between cooling and heating networks can have an effect, as waste heat/cooling can be utilised in the respective systems. With the ambition for increased excess geothermal heat in the future, back-casting for 2040 and 2030 could be recommended to enable best-possible integration of seasonal thermal storage, etc. Figure 61 and Figure 62 show the linear interpolation the non-RE PE consumption and the share of RE of Helsingborg in 2030 and 2040.

Secondly, specifically for Helsingborg is the large influence of CHP on the DHN, while the demonstration project is comparably small. While an upscaling and expansion of similar technologies is expected and suggested, the final extent and impact can only be estimated. Of more influence is currently the CHP units, which are influenced not only by the heating market, but also electricity demands. While the model shows impacts of adding the demo technologies only to the heating system, the power sector could also have an impact. At the same time developments in general electricity demands, electricity especially for heating will play a larger role in the future. Similar to the interplay illustrated in the section above, this could cause changes in the final fuel savings and thermal storage utilisation. Also, the addition of solar thermal could influence the energy balance by interfering with heat production, which is considered a non-optimal alternative in regards to using waste heat in Helsingborg.

Finally, geographical impacts can be discussed, besides the local expansion of DHN and related industry, but also collaboration and influence from other DHN, as well as influence from regional and national levels. For example, the experience with new building regulations in DH-covered areas can be expected more in the future, making alternative approaches for those buildings more relevant. Also, the PV-T option could have different impacts in other DHN and in future scenarios. In the long term, reaching 2050 targets has to be done locally and internationally. A final future scenario, the DHN could also supply (waste) heat to the wells of individually heated buildings, which are not connected to the DHN, and could enable better utilisation of otherwise wasted heat further through new business model options.

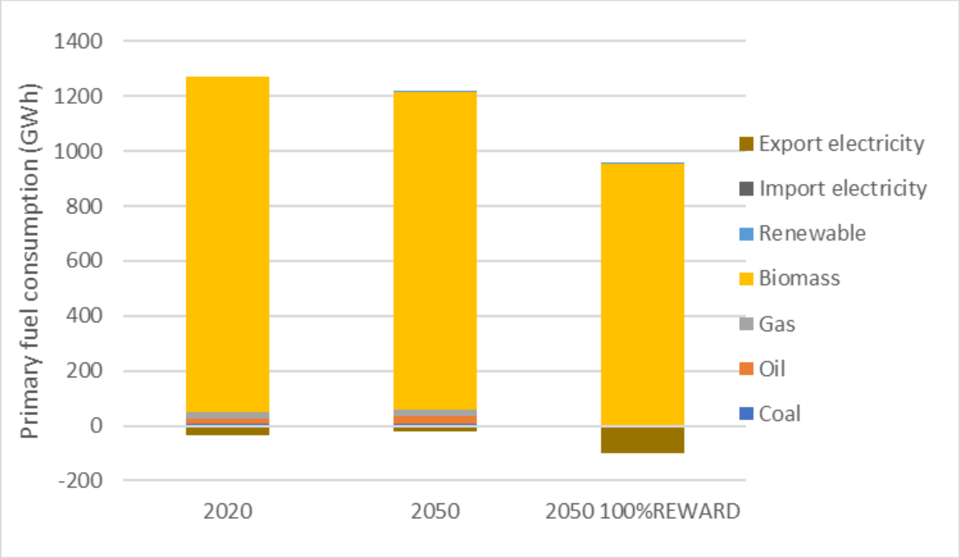

Figure 59: Helsingborg fuel consumption by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

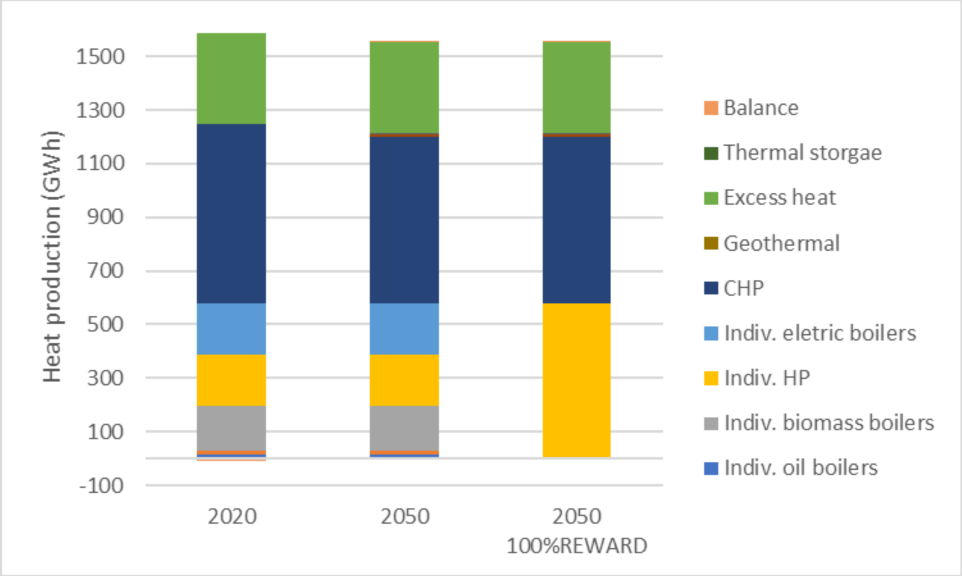

Figure 60: Helsingborg heat output by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

Table 9: Resulting annual fuels (for heating) and KPIs in Helsingborg

Helsingborg							
	2020	2050	2050 100%REWARDHeat	*Diff.*		*Diff. 2050 100%REWARD Heat*	
Fuels for heating							
Oil consumption (GWh)	16.50	16.50	0	*0*	*0%*	*-16.5*	*-100%*
Gas consumption (GWh)	15.60	15.60	0	*0*	*0%*	*-15.6*	*-100%*
Coal consumption (GWh)	0	0	0	*0*	*-*	*0*	*-*
Biomass consumption (GWh) [a]	879.76	833.65	620.78	*-46.11*	*-5%*	*-258.98*	*-29%*
Electricity consumption (GWh) [b]	254.00	247.65	168.23	*-6.35*	*-3%*	*-85.8*	*-34%*
KPIs							
Non-Renewable PES (GWh) [c]	48.24	57.05	0.00	*8.81*	*18%*	*-48.2*	*-100%*
Renewable PES (%)	96.2%	95.3%	100.0%	*-1%-p.*	*-1%*	*4%-p.*	*4%*
CO2 emissions (kt)	11.95	14.34	0	*2.385*	*20%*	*-12.0*	*-100%*
Share of local waste/excess heat in DHN	34.2%	35.0%	35.0%	*1%-p.*	*2%*	*1%-p.*	*2%*
Losses	17.0%	15.0%	15.0%	*-2%-p.*	*-12%*	*-2%-p.*	*-12%*

Notes:
a CHP 100% bio+waste
b mainly indv
c Electricity demand for HP from PP/CHP in summer

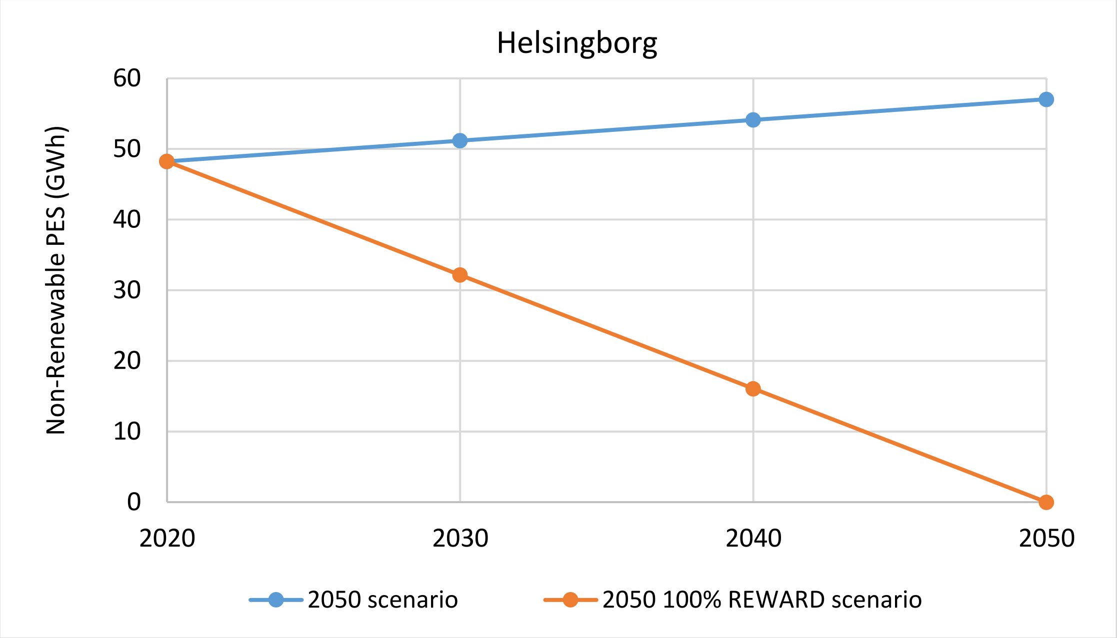

Figure 61: Result of linear interpolation of the non-renewable PES of Helsingborg in 2030 and 2040.

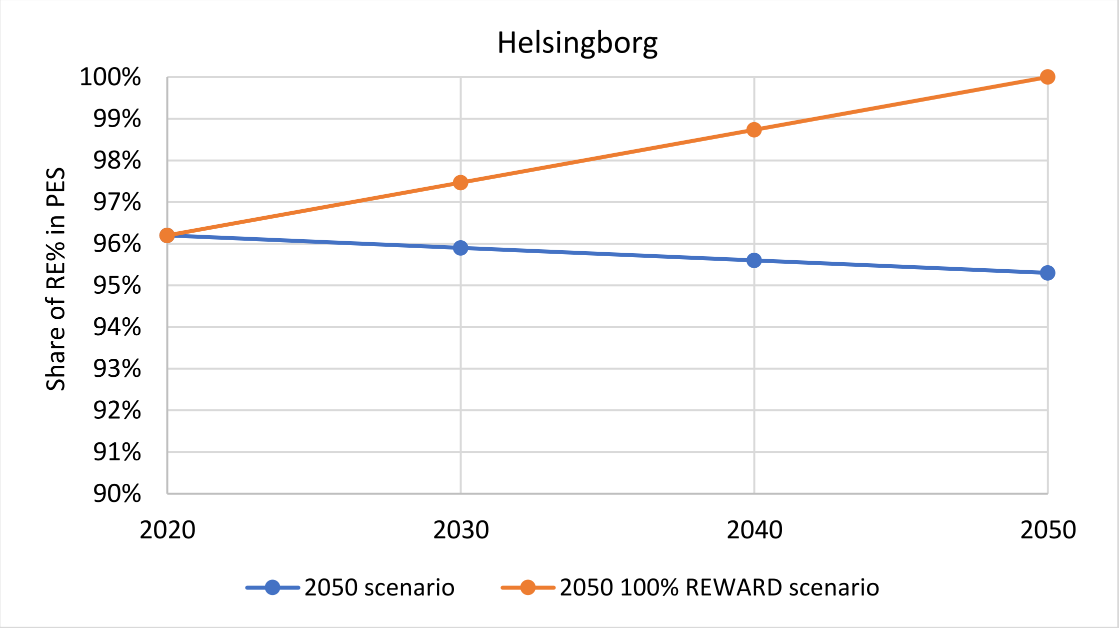

Figure 62: Result of linear interpolation of the share of RE% of Helsingborg in 2030 and 2040.

4.5.5 Economic and societal impact analysis

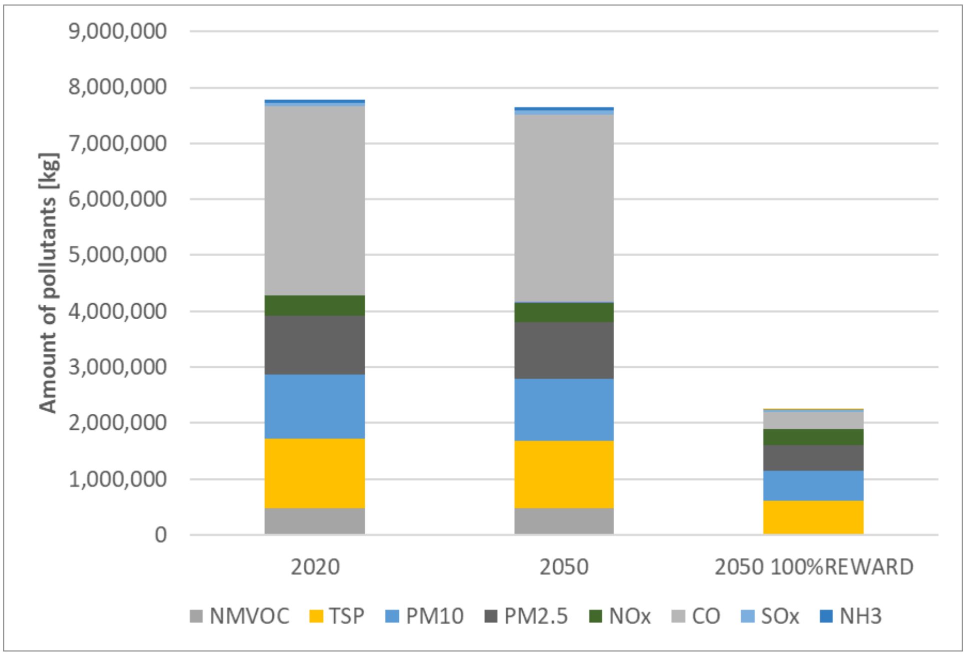

Figure 63 Amount of air pollutants in Helsingborg for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

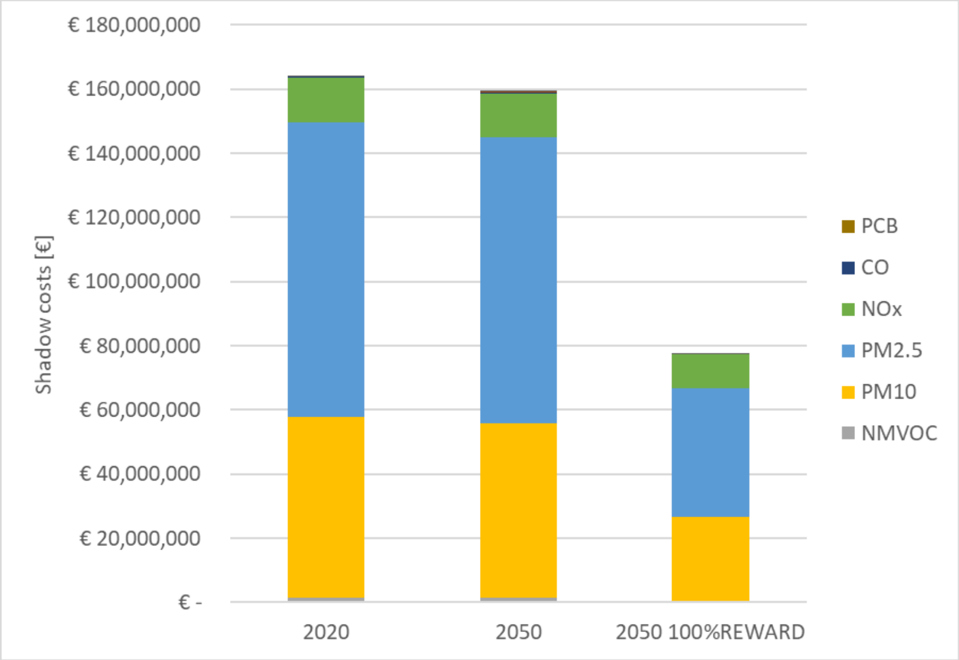

Figure 64 Shadow costs of air pollutantsin Helsingborg for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

Helsingborg uses in 2020 almost entirely biomass for their heating demand. As technologies, the largest part is covered by biomass fired CHP and a mix of excess heat, individual electrical boilers, individual biomass boilers and individual heat pumps. Especially the individual biomass boilers causing a lot air pollutions. CO is the most common pollutants by this type of technology, but also particulate matter 2.5 and 10, TSP, NMVOC and NO_X are emitted in significant amounts. However, CO has only very small shadow costs (€ 0.11 /kg, central scenario), so the shadow costs for Helsingborg are for 99% accounted by $PM_{2.5}$, PM_{10} and NO_X. In 2020, the shadow costs are € 0.12 per kWh.

In the 2050 scenario, no significant changes happen in the fuel mix or the technologies used. This results in an equal amount of emissions and shadow costs: € 0.12 per kWh.

However, in the 2050 100% renewable scenario, the individual boilers (biomass and oil) are replaced by individual heat pumps. This change results in a large reduction of emissions. For the particulate matters, TSP the emissions are only halve of the emissions from the other scenarios. For CO it reduces even with a magnitude larger than 10. The shadow costs for this scenario also decreases to € 0.06 per kWh.

In the 2050 scenario, the total annual costs reduce by 5% compared to the 2020 situation. This is mainly driven by a decrease in the fixed O&M and biomass costs. These are both caused by the decrease in CHP usage. The expenses of fossil fuel increase a little, as the usage of the powerplants will expand in 2050 compared to 2020. The jobs created in this scenario are ±40% for the individual boilers (± 1000 jobs) and ±40% for power plants and CHP. The other 20% is composed for individual heat pumps, industrial heat sector and district heating units.

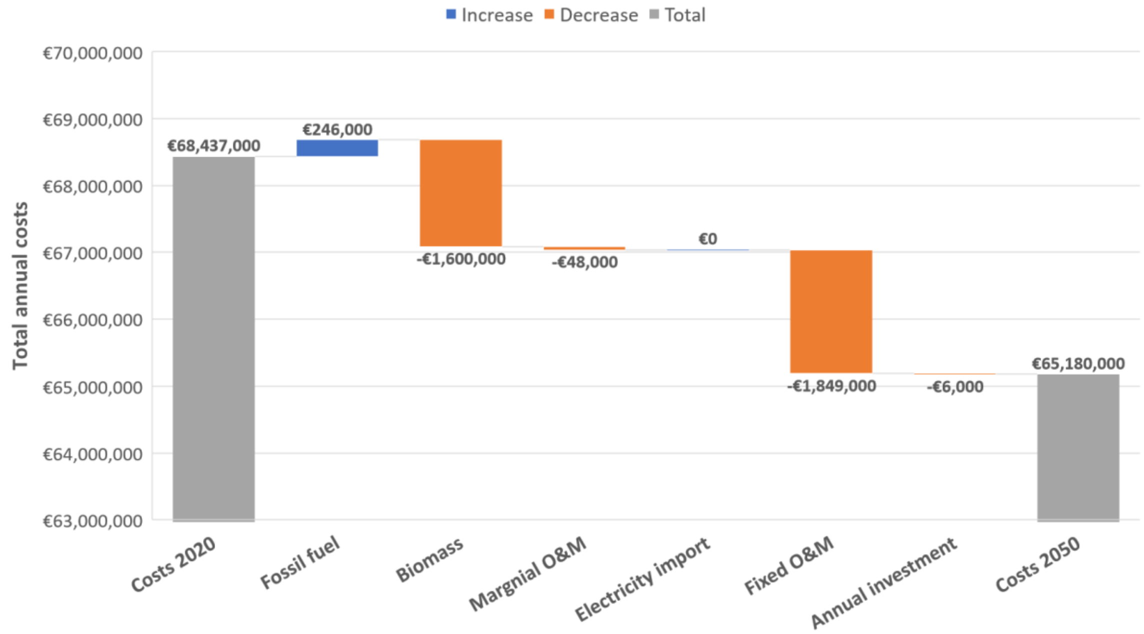

Figure 65 Total annual cost of the heating sector of Helsingborg in 2050 scenario.

In the 2050 100% renewable scenario, the total annual costs reduce with 25%. 55% of this cost reduction is because of the decline in biomass usage. All other costs expenses also decrease, except the electricity import. € 11.5 million will stay in the region as a consequence of the decline in fossil fuel and biomass. In this scenario, no jobs are created for the individual boilers, but more jobs are created for the individual heat pumps. The total jobs created will decrease with 30% compared to the regular 2050 scenario.

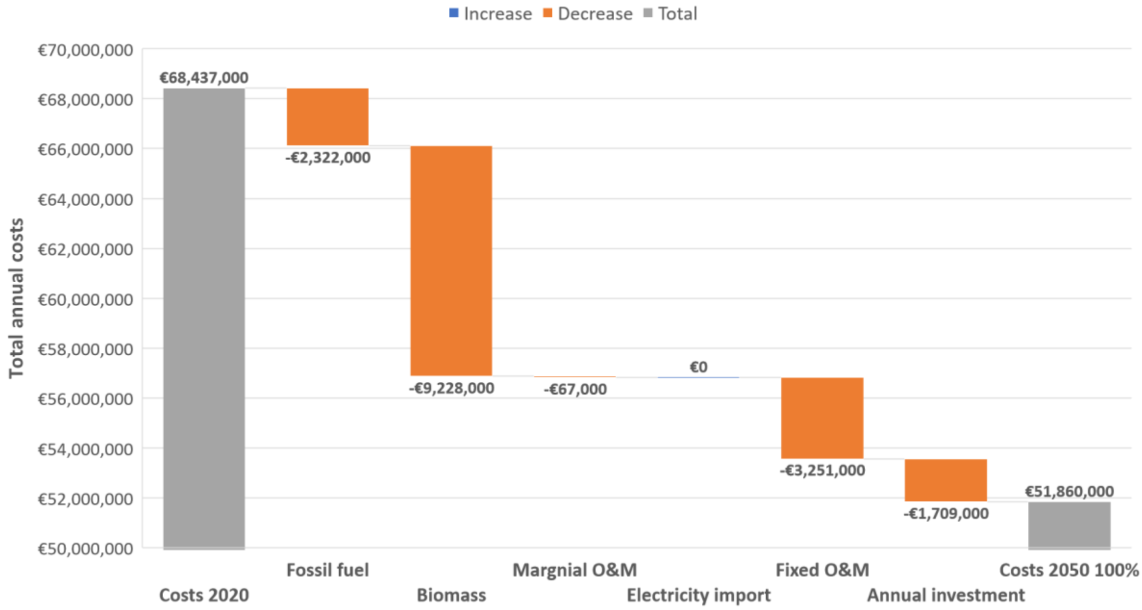

Figure 66 Total annual cost of the heating sector of Helsingborg in 2050 100% REWARDHeat scenario.

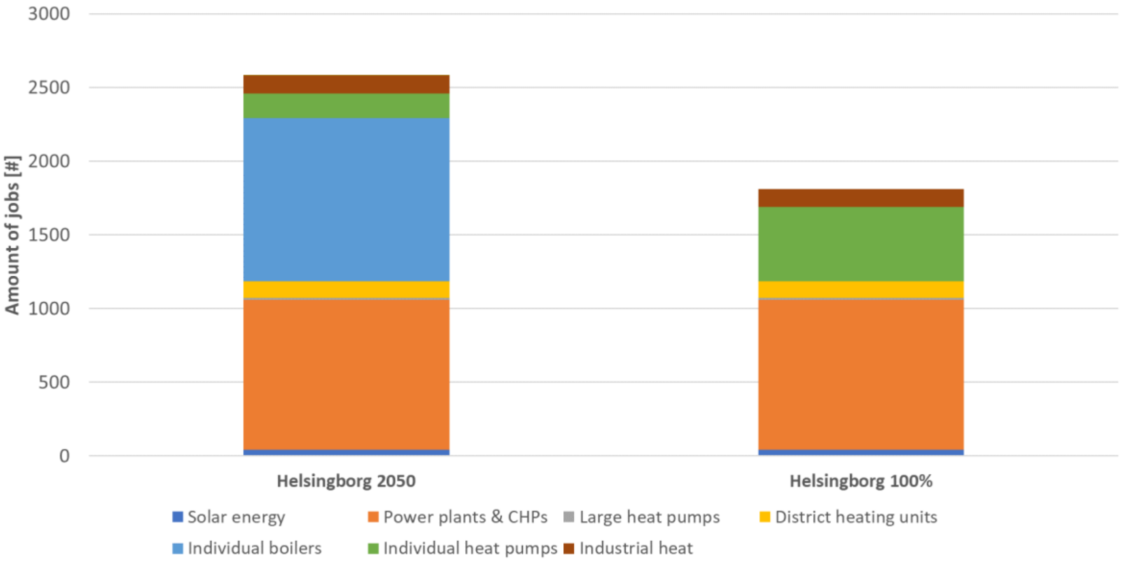

Figure 67 Amount of job creations in Helsingborg in the 2050 and 2050 100% REWARDHeat scenarios

4.6 Mölndal

Mölndal is a city district located in the southern area of Gothenburg in the Vestra Götaland. Figure 68 is outlining the border of the LAU.

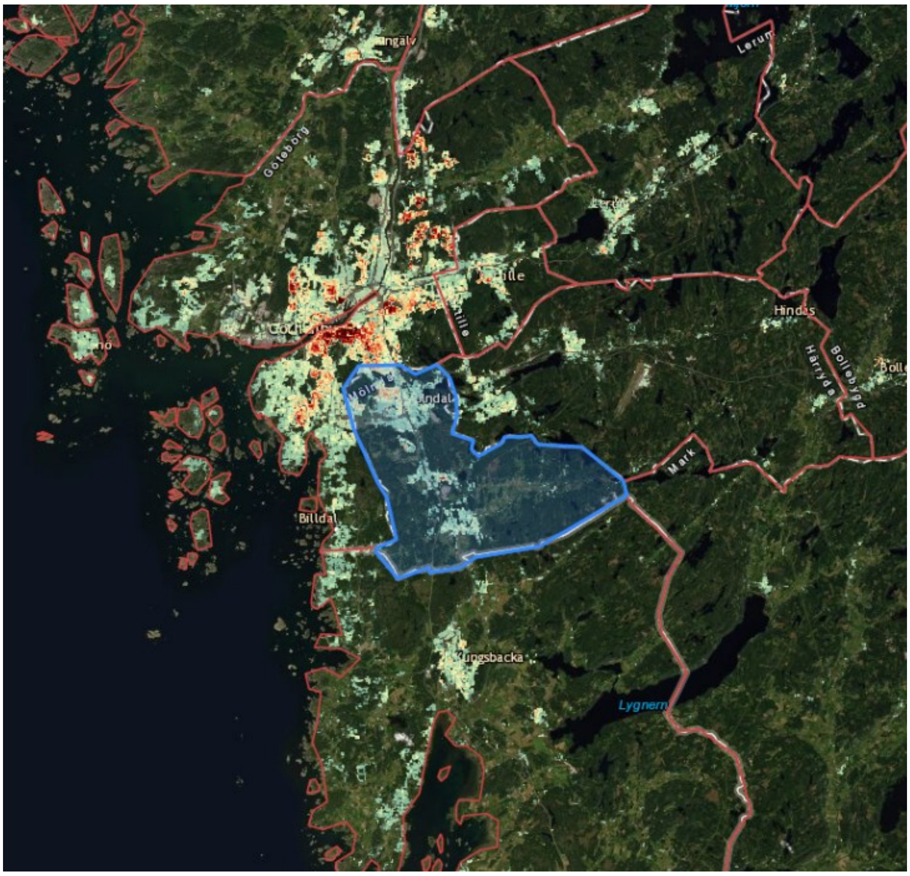

Figure 68: Mölndal local authority, location and heating potentials [17]

4.6.1 Baseline

The LAU in Hotmaps shows a total heat demand of 745 GWh and a DH potential of 463 GWh [17]. However, similar to the Swedish data for Helsingborg, a deviation from this data is found in the actual heating statistics of Vestra Götaland [49]. Here, a total DH production of 429 GWh and resulting DH consumption/demand of 274 GWh is listed. Being in close proximity to Gothenburg, a natural exchange of surplus heat can be found. While the 2017 statistics show an import to Mölndal from 23 GWh, a total of 138 GWh excess heat is exported from Mölndal, hence, the difference is considered part of the local Mölndal DH demand and the rest is excluded from the following. Therefore, even though the 138 GWh is locally produced, it is omitted from the scenarios due to not covering local demand.

Apart from the heat exchange and import from Gothenburg, the local heat production is based on boilers, heat pumps and flue gas condensation. The resulting DH consumption is 274 GWh and the production for the local consumption is (429-138+23=) 314 GWh, of which 291 GWh is from local boilers. These are fuelled mainly by biomass (95%), peat (4%, also considered biomass) and oil (<1%) at an average efficiency of 88%. Besides the import/export, 40 GWh/13% are losses [50]. The high biomass share is widely discussed in Mölndal: peat is considered biomass, while it may be considered fossil fuel in other places. The majority of biomass is from residual products from sawmills and forestry (bark, branches, etc) as well as construction/demolition industry [51].

The remaining heat demand in Mölndal district is individually covered with fuel consumptions of biomass (17.9 GWh), oil (9.4 GWh, of which 1.04 for households) and gas (6.6 GWh, only industrial). While the statistics only list fuel consumption, the electric heating share is calculated from Swedish statistics with 27% electricity-based heating [52], resulting in 130 GWh for Mölndal. The total heat demand of 432 GWh thereby consists of 63% DH, 30% electric, 4% biomass and 2% oil and gas each. Potential additional heating fuels, for example from fire stoves (12% biomass average [52]), might not be recorded, explaining the final deviation from the Hotmaps data.

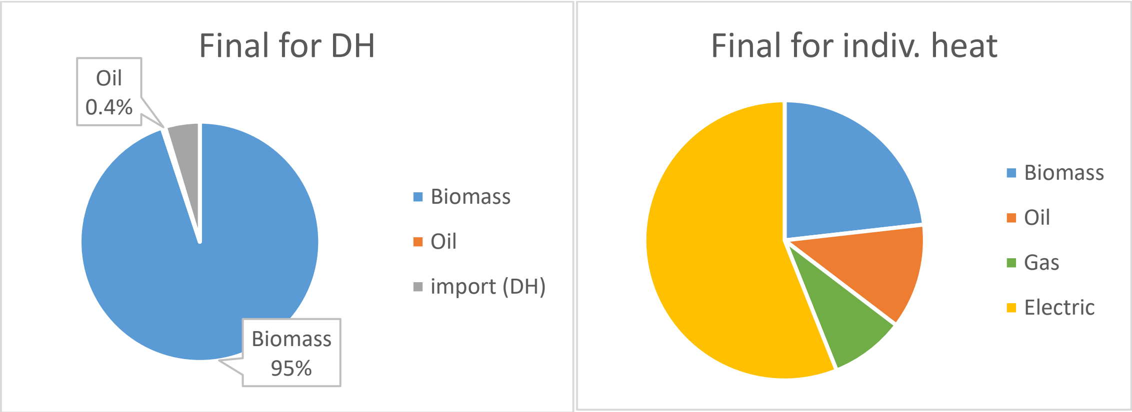

Figure 69 Fuel distribution of the DH system and individual heating system in Mölndal.

Regarding the scenarios, the distribution of heat consumption is based on Swedish statistics [53], as in Helsingborg, see overall distribution Figure 69. This results in a peak production of the DH boilers of 72.5 MW in the 2020 scenario (excluding export).

Figure 70: Piping to Boreholes in Energy Central at demo [14]

The REWARDHeat demo of Mölndal consists of a low-temperature district heating & cooling subnetwork which supplies thermal energy to a mix of existing and newly-built buildings with different uses. In particular, the involved building typologies comprise one historic building converted in a modern office, two existing office buildings, six newly-built (+1 existing) residential multi-family houses, and one new hotel. Here, the possibility of low temperature sub-network optimisation is explored, as well as exploitation of excess heat from geothermal wells with heat pumps, similar to the Helsingborg demo. In relation to the Mölndal DHN, the demo site uses around 77 MWh per year, which equals 0.003% of total DH supply [12].

4.6.2 Future 2050

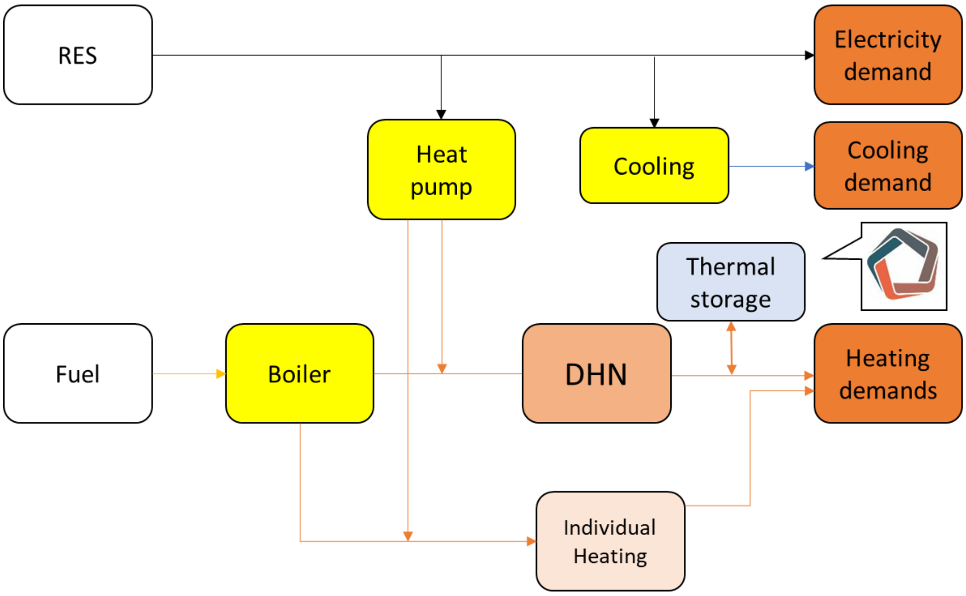

Figure 71: Energy system set-up of Mölndal in EnergyPLAN with REWARDHeat demo impact

Mölndal is assumed to be developing in similar directions as Helsingborg, though based on the local-specific demo and existing DHN. In comparison, Helsingborg's geothermal heat potentials are, however, considered to be higher due to the different ground conditions. The other difference is the overall lower temperatures in the DHN in Mölndal, with an average of 80 °C and resulting lower network losses. Based on the estimates for reduced-temperature DH [21], the losses are considered to improve further (from 13 to 10%), while boiler efficiency increases (from 88 to 90%), resulting in reduced heat production requirements.

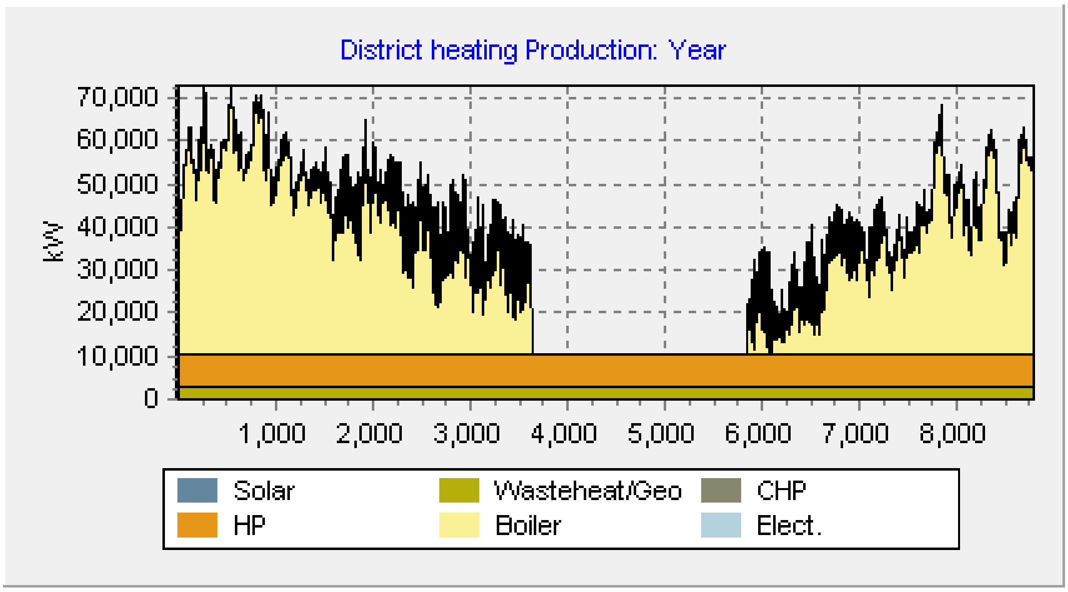

Figure 72: District heating production of Mölndal

With plans for the exploration and exploitation of geothermal heat at the demo, an up-scaled heat pump capacity of 500 kW is added for the overall DHN of the LAU. The future EnergyPLAN scenario of Mölndal shows this to support the heat production, yet not reach a level, where thermal storage becomes technically feasible. If the DH boilers were to be CHPs, the production related to electricity demand would potentially result in a thermal storage to become more feasible. In the current model, reduced fuel-based heat production is the consequence of additional HPs.

The demo in Mölndal thereby suggests that the exploitation of geothermal heat with heat pumps contributes positively to the DHN, while storage might result in further advantages, not yet included in the modelled scenario. While Helsingborg directly benefits from thermal storage due to the industrial and CHP heat, Mölndal DHN is less flexibility-needing system.

4.6.3 Future 2050 100% REWARDHeat

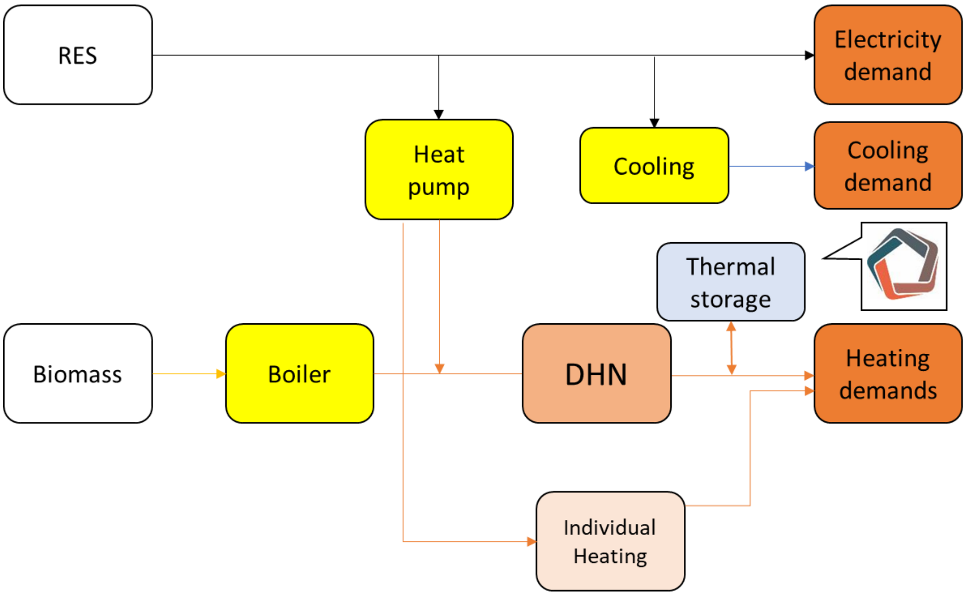

Figure 73: Energy system set-up of Mölndal in EnergyPLAN in 2050 100% REWARDHeat scenario

In the future 2050 100%REWARDHeat scenario, the boilers in district heating are fully based on biomass. And the boilers in the individual heating system are all converted to individual heat pumps according to the study of Heat Roadmap Sweden [48]. The excess heat is 23 GWh import from Gothenburg.

4.6.4 Energy and environmental impact analysis

While the baseline and demo heating system are presented above, various impacts beyond the direct demo ones can be considered. These are discussed below and cover KPI results and key takeaways, as well as further discussions.

Figure 74 and Figure 75 show the structure of energy consumption and the heat production of Mölndal in 2020, 2050 and 2050 100% REWARDHeat scenario. Figure 76 and Figure 77 show the results of the linear interpolation in 2030 and 2040 based on the data output of EnergyPLAN in 2020 and the two 2050 scenarios. Table 10 presents the KPIs and fuel consumption. Results indicate limited reductions in non-renewable fuels and CO_2 emissions when comparing the 2050 scenario to the 2020 baseline. The use of biomass for heating purpose decreases due to the increase of geothermal heat, which lead to an overall decrease of the renewable PES share as the geothermal heat is not counted as renewable PES. Yet, this can also be considered inevitable with a nearly 100% RE-based heating system created in 2050 100% REWARDHeat scenario with using fully biomass boilers in DH and heat pumps. Considering that Mölndal exports more excess heat to Gothenburg than the other way around, this is not considered in the 'local excess heat', while here only the heat from geothermal wells through HPs is included.

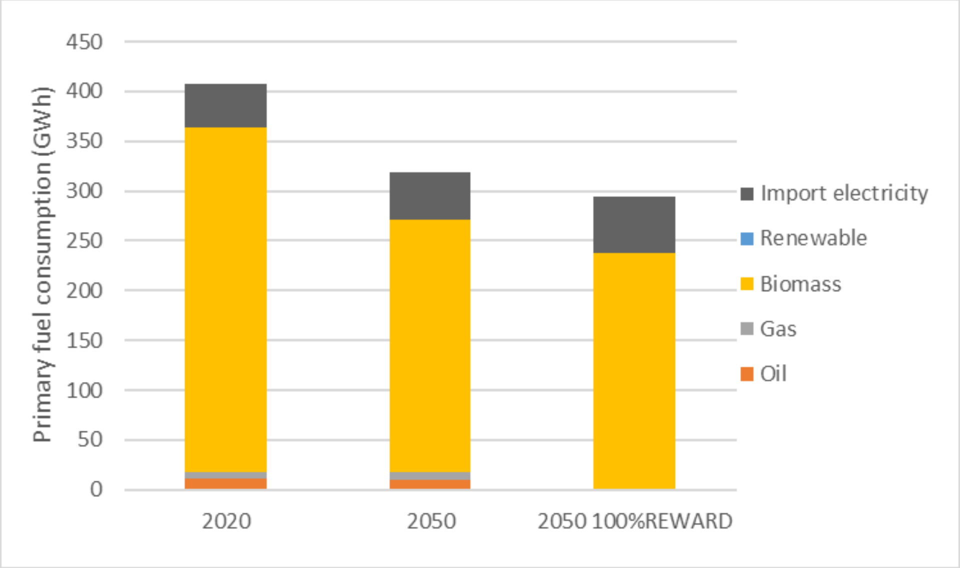

Figure 74: Mölndal fuel consumption by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

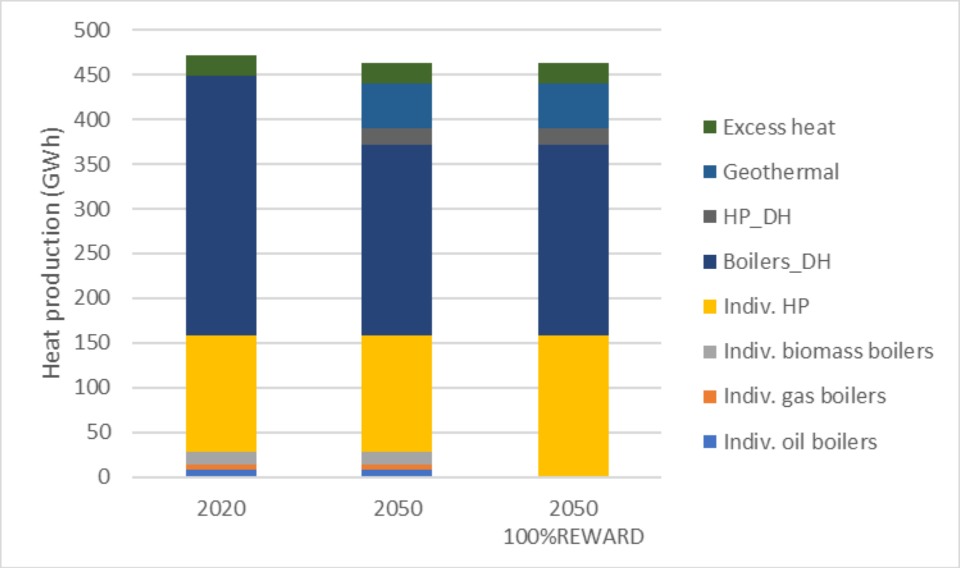

Figure 75: Mölndal heat output by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

The demo aims to exploit geothermal heat and electrify some heat production, which would replace fuel demands. Even though the model shows limited improvements for RE share and CO_2 emissions with the upscaled demo impact in the 2050 scenario, these may be considerably higher in a wider system perspective due to potential future biomass shortage and when considering other emissions from biomass, such as particle matter. Lager extent improvement can be achieved by introducing heat pumps in the individual heating systems based on renewable electricity.

The DHN configurations in Mölndal and Helsingborg shows differences for seemingly similar systems and regions. While thermal storage and geothermal heat are useful according to experience, the energy system perspective in our model suggests no direct need for storage in Mölndal, unless the heat production profile changes significantly.

Table 10: Resulting annual fuels (for heating) and KPIs in Mölndal

Mölndal								
	2020	2050	2050 100%REWARDHeat	*Diff.*		*Diff. 2050 100%REWARDHeat*		
Fuels for heating								
Oil consumption (GWh)	10.72	10.35	0	*-0.37*	*-3%*	*-10.7*	*-100%*
Gas consumption (GWh)	6.65	6.65	0	*0.00*	*0%*	*-6.7*	*-100%*
Coal consumption (GWh)	0	0	0	*0*	-	*0*	-
Biomass consumption (GWh)	346.93	254.36	237.37	*-92.57*	*-27%*	*-109.6*	*-32%*
Electricity consumption (GWh)	43.33	47.73	57.17	*4.4*	*10%*	*13.8*	*32%*
KPIs							
Non-Renewable PES (GWh)	17.37	16.99	0	*-0.38*	*-2%*	*-17.4*	*-100%*
Renewable PES (%)	95.2%	93.7%	100.0%	*-2%-p.*	*-2%*	*5%-p.*	*5%*
CO_2 emissions (kt) [a]	4.21	4.11	0	*-0.1*	*-2%*	*-4.2*	*-100%*
Share of local waste/excess heat in DHN [b]	0.0%	16.4%	16.4%	*16%-p.*	-	*16%-p.*	-
Losses	13.0%	10.0%	10.0%	*-3%-p.*	*-23%*	*-3%-p.*	*-23%*

Notes:

a only considering DH HP using geothermal heat in DHN

b Mainly from oil back-up boilers

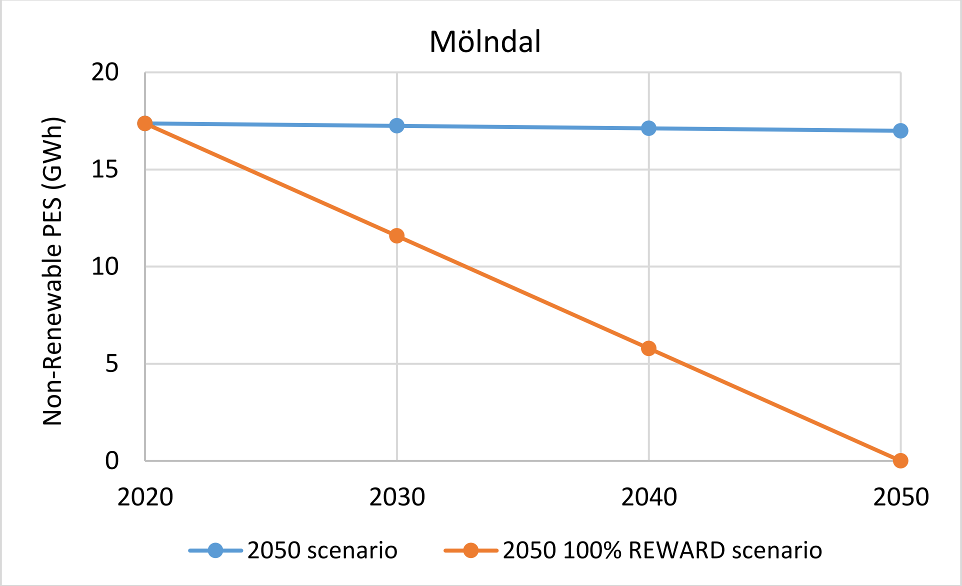

Figure 76: Result of linear interpolation of the non-renewable PES of Mölndal in 2030 and 2040.

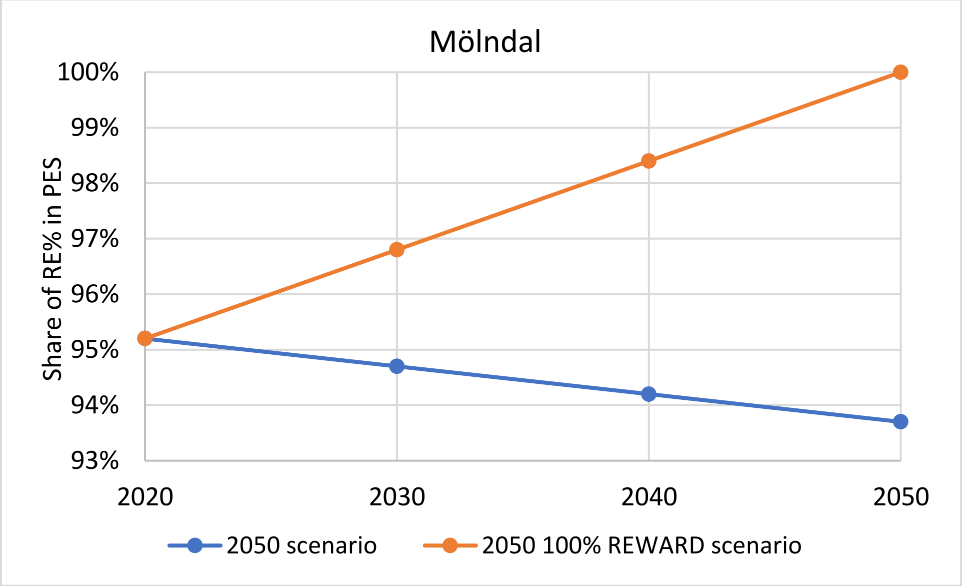

Figure 77: Result of linear interpolation of the share of RE% of Mölndal in 2030 and 2040.

4.6.5 Economic and societal impact analysis

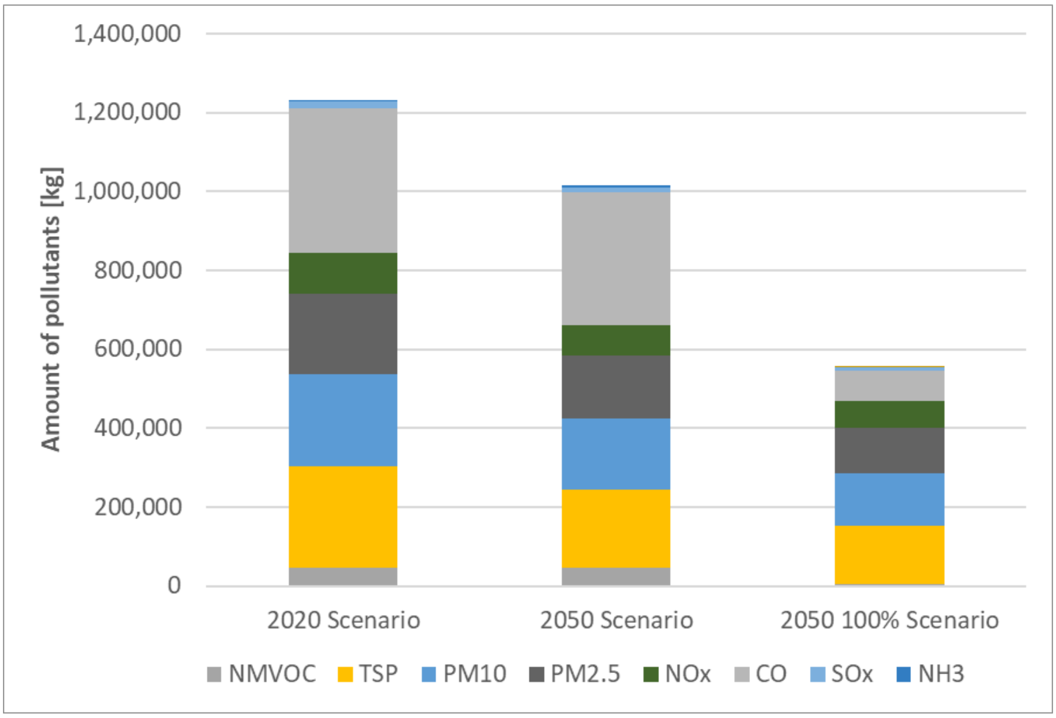

Figure 78 Amount of air pollutants in Mölndal for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

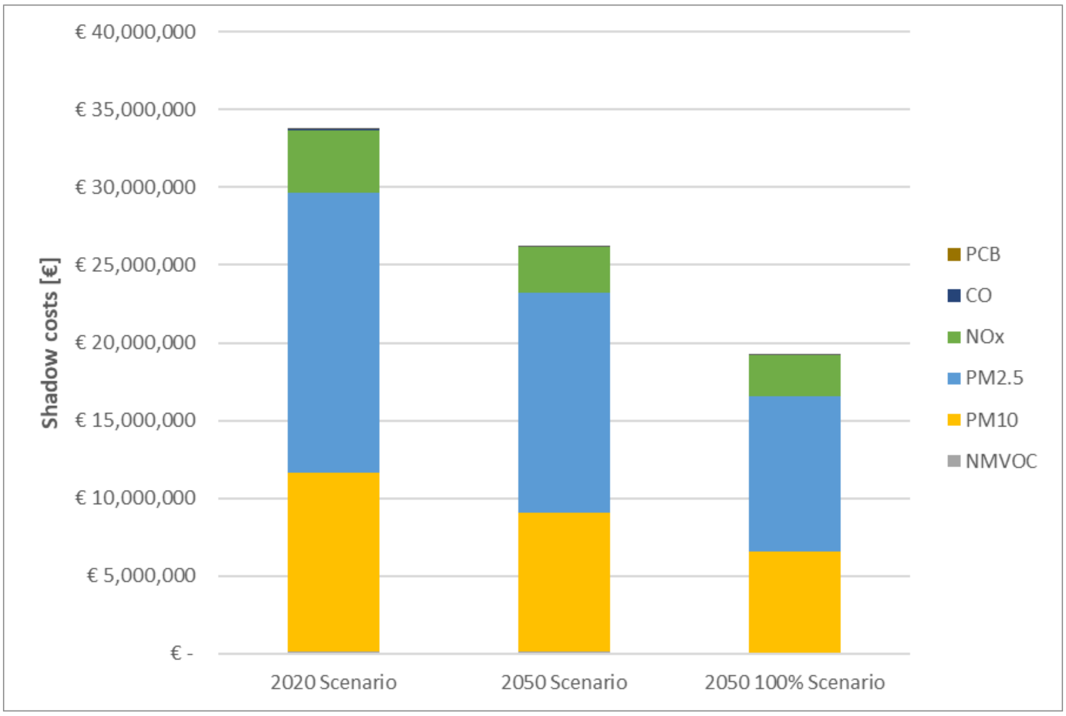

Figure 79 Shadow costs of air pollutants in Mölndal for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

In 2020, the heating demand of Mölndal is covered for a large amount by CHP fuelled with biomass (± 65%). Also, individual heat pumps are already covering ± 25% of the heat demand and excess heat ±

5%. In addition, a small amount (± 5%) is covered by the individual boilers fuelled with biomass, oil and gas. However, this 5% is responsible for more than 37% of all the emissions (especially CO and TSP), as individual boilers are more pollutant than large combustion techniques. With these emissions, the relative shadow costs are € 0.08 per kWh.

In the 2050 scenario, Mölndal, will have installed geothermal energy and district heating with heat pumps. This will reduce the usage of the CHP with ±25%, but not on the individual boilers. Therefore, CO and TSP stays almost the same, but the other emissions decrease according the reduction of the CHP. The shadow costs reduced to € 0.06 per kWh.

In the 2050 100% renewable scenario, the individual boilers are replaced by individual heat pumps. This replacement is 1/7 of primary energy reduction of the reduction of the 2020 scenario to the regular 2050 scenario, but has almost the same (95%) reduction in shadow costs. This because the individual boilers emit relatively the most amount of pollutants. The shadow costs for this scenario are € 0.05 per kWh.

In the 2050 scenario, the total annual costs only reduce with 1.3% compared to the 2020 situation. While the biomass costs reduce with € 2.2 million, the electricity import and annual investment costs combined raises with € 2.0 million. This is a result of the partly replacement of the biomass boiler fuelled district heating, with geothermal (high investment) combined with heat pumps (electricity usage) fuelled district heating. In this scenario, 43% of the jobs are created for the district heating boilers (power plants) (229 jobs), and 22% for the individual heat pump sector (113 jobs), 19% for the individual boiler sector (100 jobs) and 12% for the geothermal energy (63 jobs).

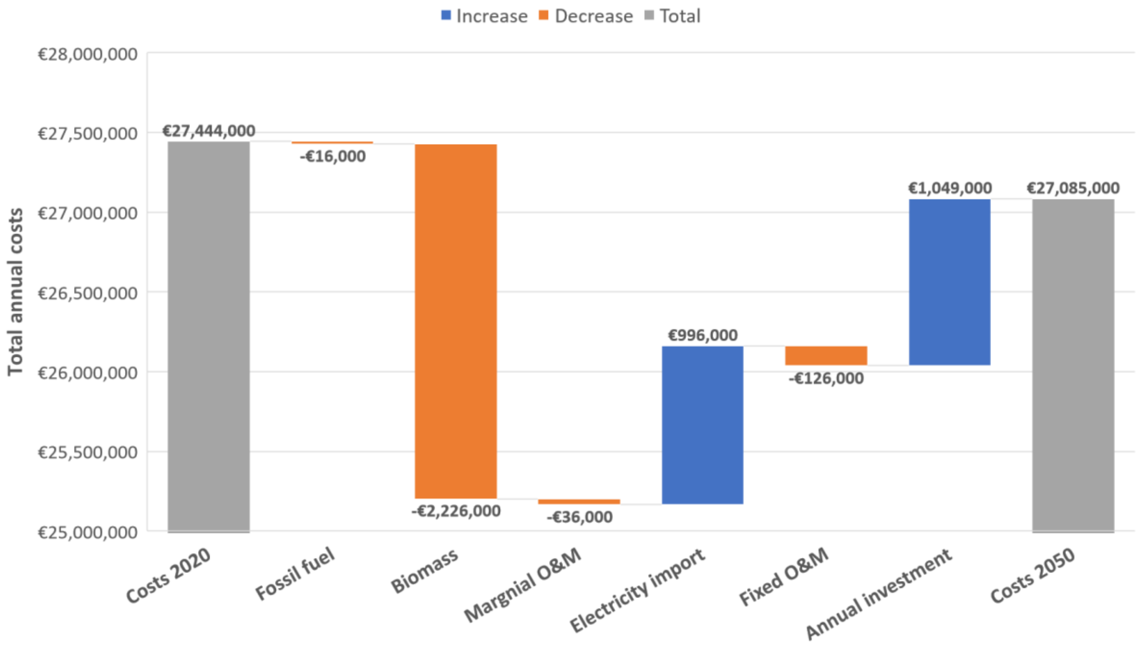

Figure 80 Total annual cost of the heating sector of Mölndal in 2050 scenario.

In the 2050 100% renewable scenario, the total annual costs also a decrease by 1.5% compared to the 2020 scenario. However, in this scenario there is a larger reduction of fossil fuel and biomass costs, the electricity import and annual investment costs have increased equally. This is due to the fact that the individual (fossil and biomass fuelled) boilers have been replaced by electric individual heat pumps. In the job creation this is also visible as a part of the jobs created in the regular 2050 scenario, are in the

100% renewable scenario created for the individual heat pump scenario. However, the total amount of jobs created decrease with ± 15%.

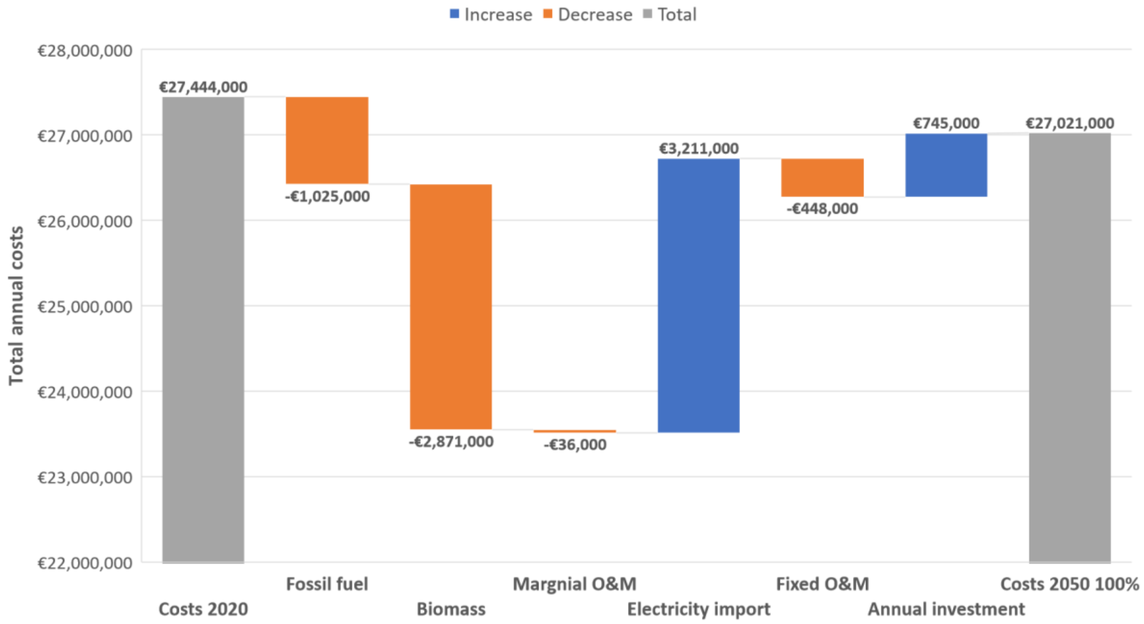

Figure 81 Total annual cost of the heating sector of Mölndal in 2050 100% REWARDHeat scenario.

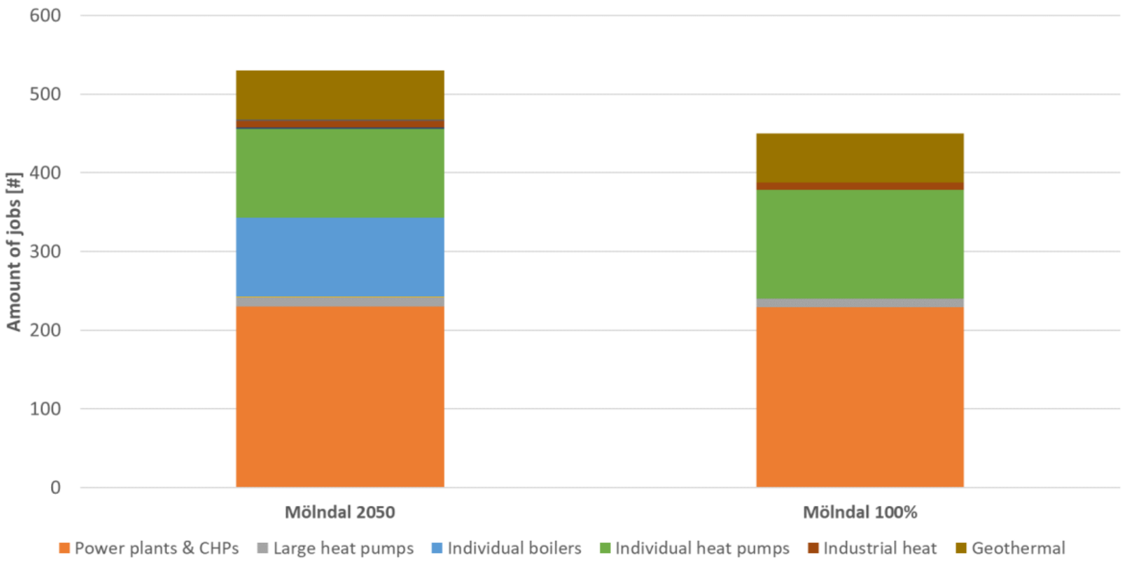

Figure 82 Amount of job creations in Mölndal in the 2050 and 2050 100% REWARDHeat scenarios

4.7 Heerlen (Brunssum)

Heerlen is a municipality and a town in the province of Limburg in the southeast of the Netherlands, between the North Belgium and the West of Germany. Heerlen owns a well-developed DHC network operating under neutral temperature conditions. Brunssum is a neighbouring town of Heerlen, which is currently regarded as a satellite system. Figure 83 outlines the border of the LAU of Brunssum, which is investigated here.

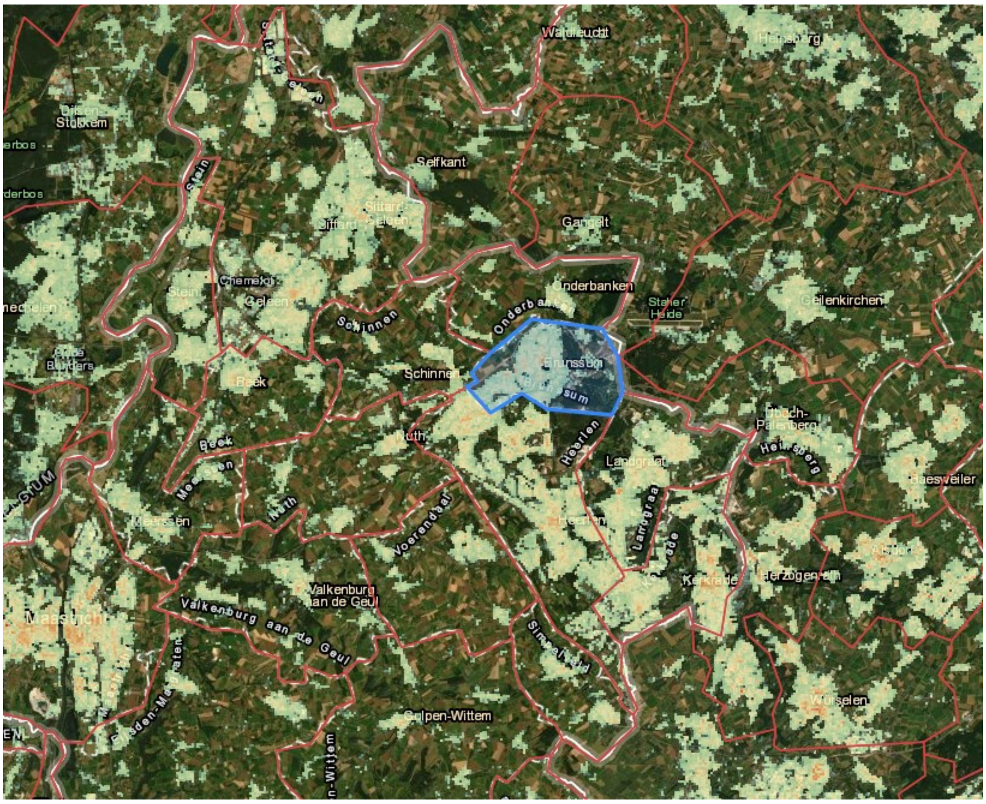

Figure 83 Brunssum local authority, location and heating potentials [5]

4.7.1 Baseline

In the 2020 baseline, the annual total heat demand of the LAU of Brunssum is 260.7 GWh based on Hotmaps [15]. According to the communication with the partners— Mijnwater, the individual heating demand accounts for 99% of the total heating demand, while the district heating demand accounts for 1%, which is 258.1 GWh and 2.6 GWh, respectively [54]. According to a feasibility study of Mijnwater, the cooling demand is about a quarter of the total heating demand, i.e., 65.2 GWh/year. It is assumed that the distribution between individual cooling and district cooling is the same as that in the heating system, thus the individual cooling demand is 64.5 GWh/year and the district cooling demand is 0.65 GWh/year.

The total energy consumption of housing and public buildings take up a share of 47% and 19% of the total energy consumption of the municipality of Brunssum in 2011 [55], in which natural gas and electricity are the two main energy carriers. Figure 84 shows the distribution of the housing stock by housing type in Brunssum. The detailed data for the heating solutions are not available. Here, the individual heating demands are assumed to be provided by gas boilers (92%) and electric heating solutions (8%, heat pumps and electric boilers). The share is calculated according to the national data of Netherlands from HRE4 [5].

The DHC demand is mainly provided by geothermal energy. The geothermal wells serve as the heat and cold sources as well as the thermal storage in Brunssum. The DH production from geothermal wells is 623.61 MWh/year, and the domestic hot water production is 260.5 MWh/year. A total of six heat pumps (capacity: 58kw, COP:4.8) of the type Alpha Innotec SWP 581 are installed for extracting geothermal energy. In 2020, the geothermal system was unbalanced as more heat was extracted than was put back in the return flow of the cold demand. The remaining DH demand in Brunssum is provided by two air-source heat pumps (capacity:117.2kw COP:3.25) of the type RHO EasyPACK-I TXAIQY 2115. A 5000 m3 thermal storage of 290MWh/year is installed in Brunssum as well.

Natural cooling from geothermal the well is employed for the cooling system of Brunssum. The cooling is done directly from the geothermal well with a cold production of 187.083 MWh/year. No heat pumps or chillers are involved, only transport pumps.

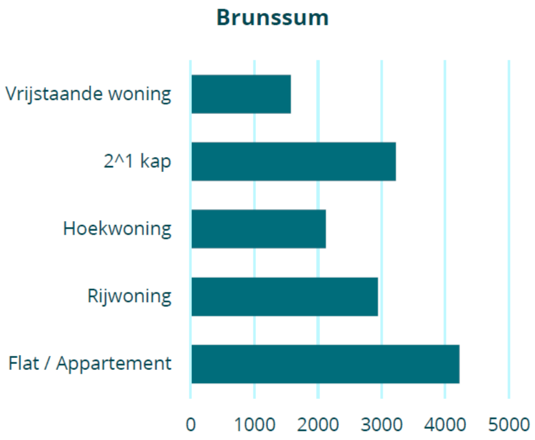

Figure 84 Distribution of housing stock by housing type in Brunssum [56]. (translation: Detached house, semi-detached houses, corner house, terraced house, flat/appartment)

4.7.2 Future 2050

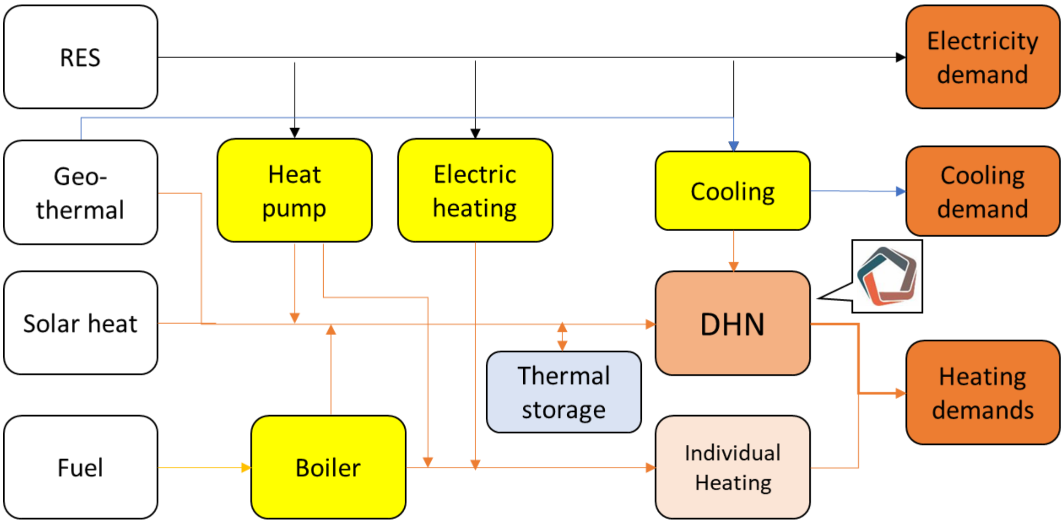

Figure 85: Energy system set-up of Brunssum in EnergyPLAN with REWARDHeat demo impact

According to [57], the heat demand in the Netherlands is assumed to decrease by 10% in 2050. Following this assumption, the annual heat demand of Brunssum would be 234.66 GWh in 2050, of which 50% will be supplied by DH, while the remaining demand will be covered by individual heating [54].

The municipality of Brunssum aims to be energy neutral by 2040 [55]. According to the local authority [56], Brunssum has committed to sustainable alternatives to natural gas. The solar thermal capacity of 2.576 MWh/year will be used to balance the geothermal energy source in 2050 [54]. The geothermal wells serve as heat sources as well as thermal storage for solar thermal. The heat provided by geothermal remains at the same level as in 2020. A hybrid solution of using heat pumps with central heating boilers running on natural gas will be adopted for the remaining heat demand, as an interim solution in the transition. The country data in Heat Roadmap Netherlands 2050 [58] are adopted to determine the share and the efficiency of the natural gas boilers (thermal capacity: 26500 KJ/s, thermal efficiency: 0.9) and heat pumps (electric capacity: 1850 kW, COP: 4).

For the individual heating systems, the share between natural gas boilers, heat pumps, and electric heating is assumed the same as in 2020. According to the local authority, the air-source heat pumps are used for individual heating, which can be potentially deployable in large parts of Brunssum [55].

Natural cooling provided by geothermal wells will supply all district cooling demand, while air-conditioning will be used for individual cooling.

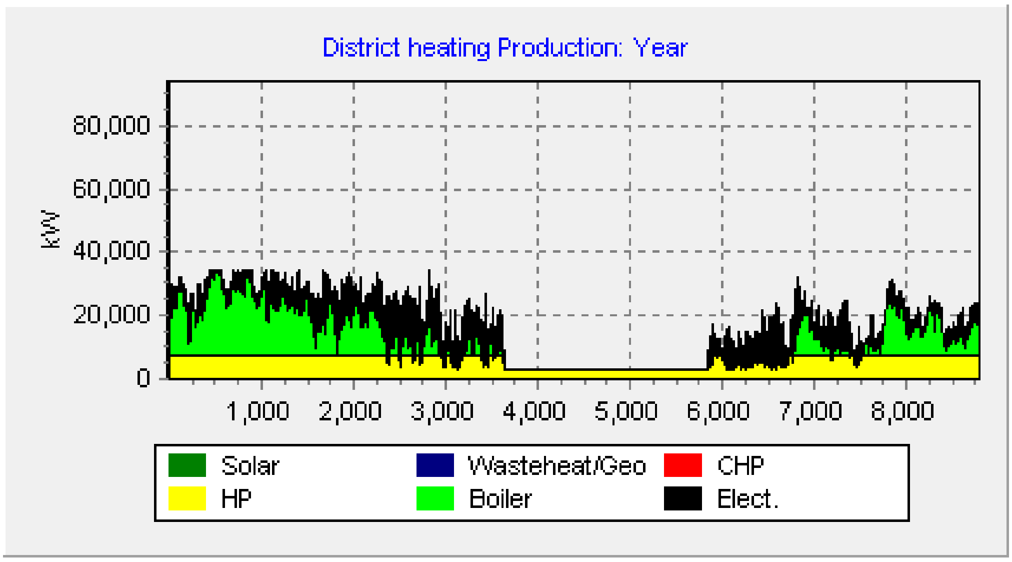

Figure 86 DH supply of Brunssum DHN during a year in the 2050 scenario

4.7.3 Future 100% REWARDHeat

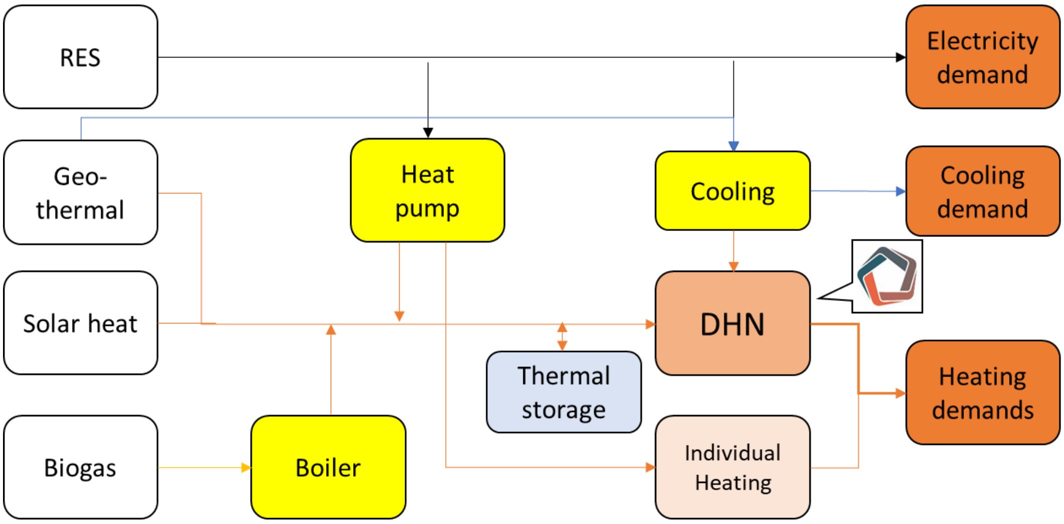

Figure 87: Energy system set-up of Brunssum in EnergyPLAN in 2050 100% REWARDHeat scenario

According to the local Heat Transition Vision (TVW) [56], Brunssum aims to abandon natural gas for heating systems before 2040. According to a spatial analysis in different sectors of Brunssum [55], the municipality appears to have a substantial potential for sustainable energy generation. Most of the potential is from solar energy and thermal energy storage.

In the 100% REWARDHeat scenario, the individual heating in Brunssum will be provided by individual air-source heat pumps, while the DH demand will be covered by heat pumps, green gas boilers, solar heat, geothermal energy, and thermal storage. Large-scale air-source heat pumps with a capacity of 6 MW-e are installed for DH, which produces heat of 105.8 GWh/year. The green gas here denotes biogas, hydrogen, etc. Considering the low efficiency and high expense of hydrogen heating, the potential of hydrogen heating is very limited or not available, thus not considered here. There is limited local potential for biomass, which is determined by the waste and residual flows present in Brunssum. The availability of biogas in Brunssum is 8.694 GWh/year, which concerns approximately 4.94 GWh/year from grass and green fodder crops, 1.94 GWh/year from GFT waste and 1.806 GWh/year from residual flows from agriculture [56]. The biogas needs to be upgraded to green gas until it has the same quality as natural gas before injected to the gas grid. The total capacity of the biogas boiler is 8500 kW.

The potential of solar collectors on roofs is 12.83 GWh. Here we assume that Brunssum will utilize its maximum solar thermal potential in the building sector. Along with the solar collectors, a solar thermal storage (150 MWh) is also installed. The total potential of geothermal energy is 149.7 GWh, including 100.2 GWh for housing, 19.86 GWh for public services, and 29.55 GWh for commercial services and industries. Thermal energy storage potential is 197 GWh. However, the location and the availability for utilizing geothermal and thermal storage in DH are unclear. Therefore, here the national geothermal consumption from the Heat Roadmap Netherlands is broken down to match the population of Brunssum (7.41 GWh).

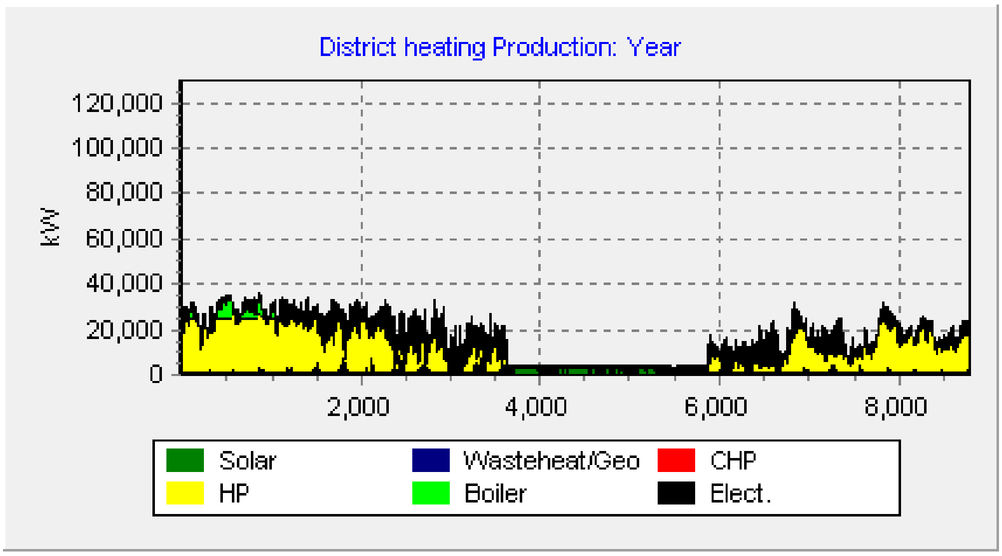

Figure 88 Heat supply for Brunssum DHN

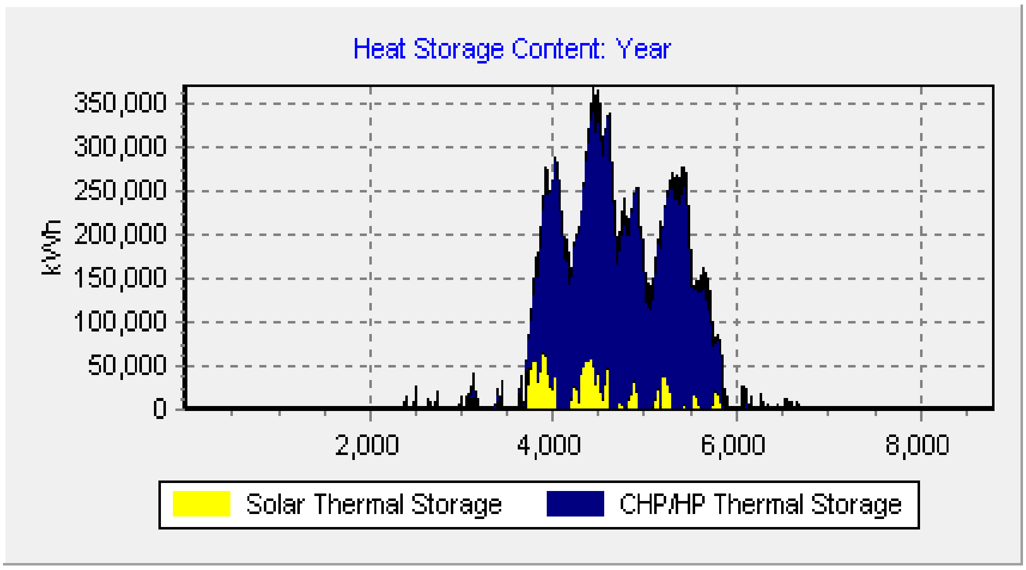

Figure 89 Thermal storage potential for Brunssum DHN

The comparison between 2020, 2050 and 2050 100% REWARDHeat scenarios are shown in Figure 90 and Figure 91. A certain share of natural gas boilers is substituted with the heat pumps in 2050 scenario, which brings downs the natural gas consumption and CO_2 emissions. Larger-scale heat pumps are implemented to realize 100% REWARDHeat, while a small share of boilers still exists driven by biogas. This leads to zero natural gas consumption and negative emissions.

4.7.4 Energy and environmental impact analysis

Different from the other demos of the REWARDHeat project, the heat sources in Brunssum are more diversified, including renewable sources such as solar thermal and, geothermal, the boilers as the baseload as well as the heat pumps to increase flexibility.

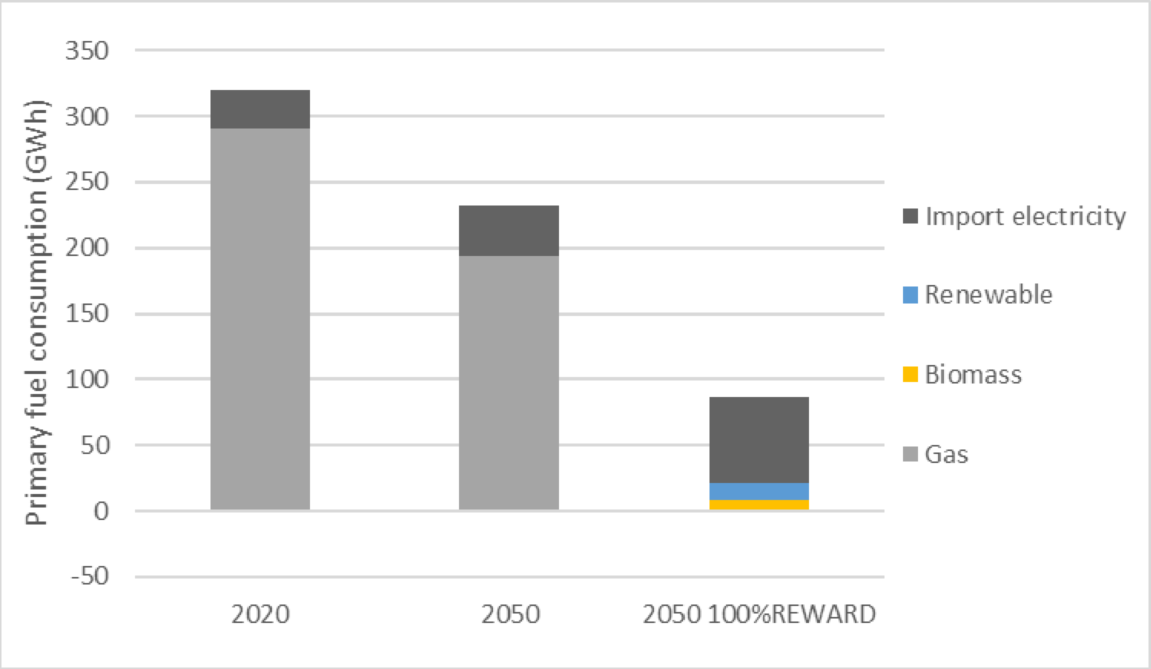

Figure 90: Brunssum fuel consumption by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

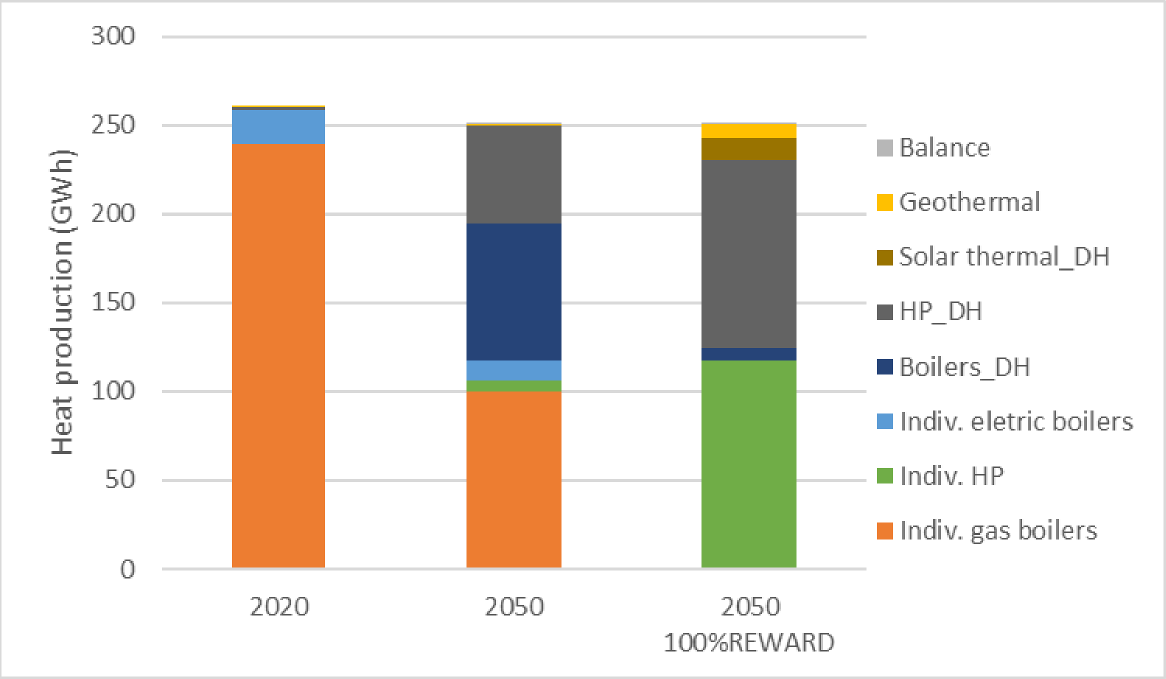

Figure 91: Brunssum heat output by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

Figure 90 and Figure 91 show the structure of energy consumption and the heat production of Brunssum in the 2020, 2050 and 2050 100% REWARDHeat scenarios. Figure 92 and Figure 93 show the results of the linear interpolation in 2030 and 2040 based on the data output of EnergyPLAN in 2020 and two 2050 scenarios. Table 11 presents the KPIs and fuel consumption. According to the modelling results, the primary energy and CO2 emissions improvement of Brunssum are also relatively higher compared to some of the other demos of the REWARDHeat project. Compared to the 2020 baseline, the 2050 scenario of Brunssum shows a 33.3% decrease in primary energy consumption and 32.4% electricity consumption increase at the same time, while the 2050 100% REWARDHeat scenario reaches a 92.9% decline in PE consumption and 119.9% increase in electricity consumption.

Table 11 Resulting annual fuels (for heating) and KPIs in Brunssum

Brunssum							
	2020	2050	2050 100%REWARDHeat	Diff. 2050		Diff. 2050 100%REWARDHeat	
Fuels for heating							
Oil consumption (GWh)	0	0	0	0	-	0	-
Gas consumption (GWh)	290.61	193.84	0	-96.77	-33%	-290.6[a]	-100%
Coal consumption (GWh)	0	0	0	0	-	0	-
Biomass consumption (GWh)	0	0	8.69	0	-	8.69	-
Electricity consumption (GWh)	19.53	26.46	57.09	6.93	35%	37.56 [a]	192%
KPIs							
Non-Renewable PES (GWh)	290.61	193.84	-1.02	-96.77	-33%	-291.6	-100%
Renewable PES (%)	0	0	1.05	0%-p.	-	105%-p. [b]	-
CO_2 emissions (kt)	59.32	39.57	-0.21 [c]	-19.753	-33%	-59.5	-100%
Share of local waste/excess heat in DHN	0%	0%	0%	0%-p.	-	0%-p.	-
Losses	12.0%	12.0%	12.0%	0%-p.	0%	0%-p.	0%

Notes:

[a] Using heat pumps to replace gas boilers in individual heating and DH

[b] From biomass, solar energy and geothermal

[c] Negative emissions due to net biogas import (biogas consumption in the heating system is less than the production)

Even though building renovation is not considered in the established EnergyPLAN model for Brunssum, further energy and environmental benefits could potentially be achieved with building-level energy efficiency improvement. According to [55], in 2040, the building renovation will lead to 23% energy savings for houses, and to 49% for public and commercial buildings, which will be the result of reducing the energy demand for space heating in particular by improving the thermal building envelope.

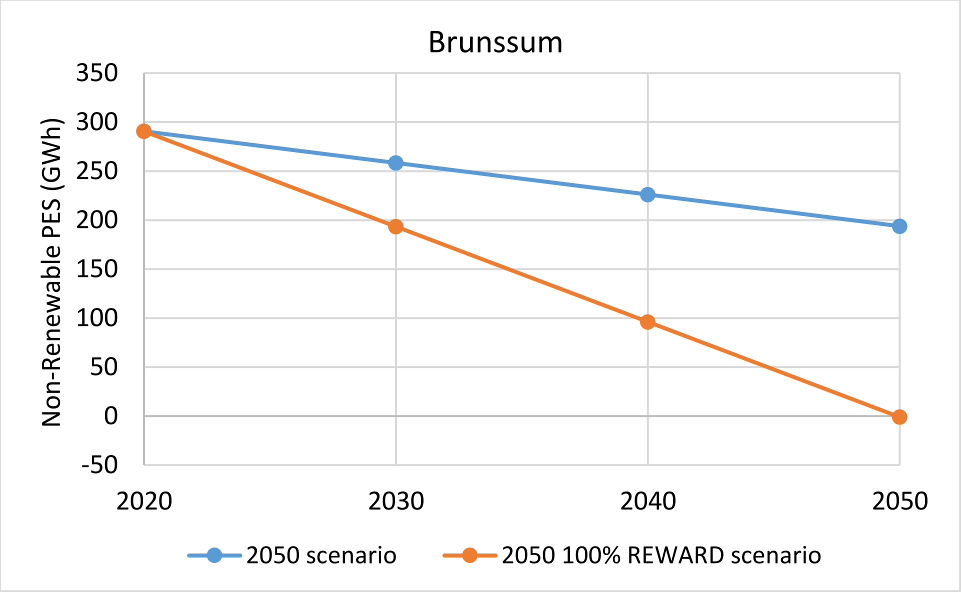

Figure 92: Result of linear interpolation of the non-renewable PES of Brunssum in 2030 and 2040.

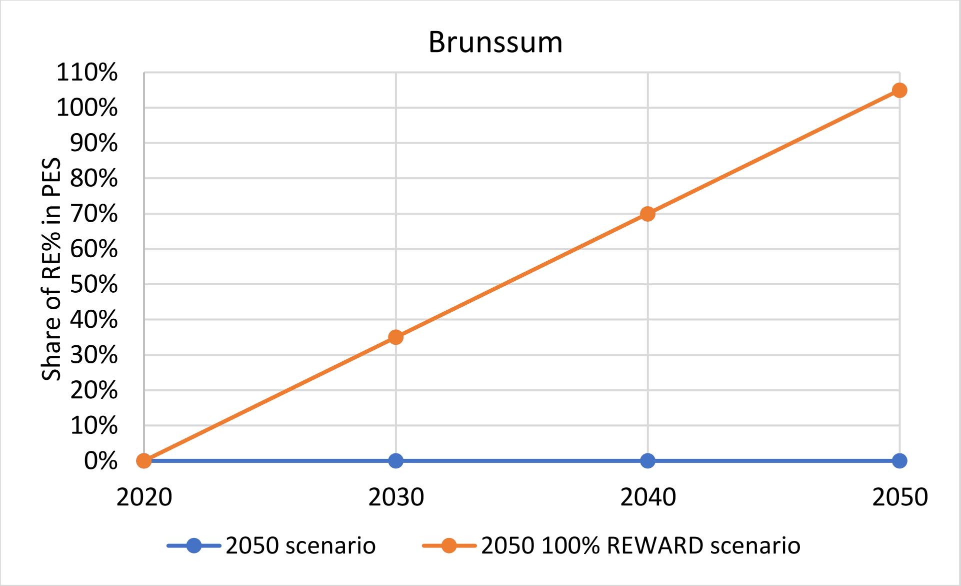

Figure 93: Result of linear interpolation of the share of RE% of Brunssum in 2030 and 2040.

4.7.5 Economic and societal impact analysis

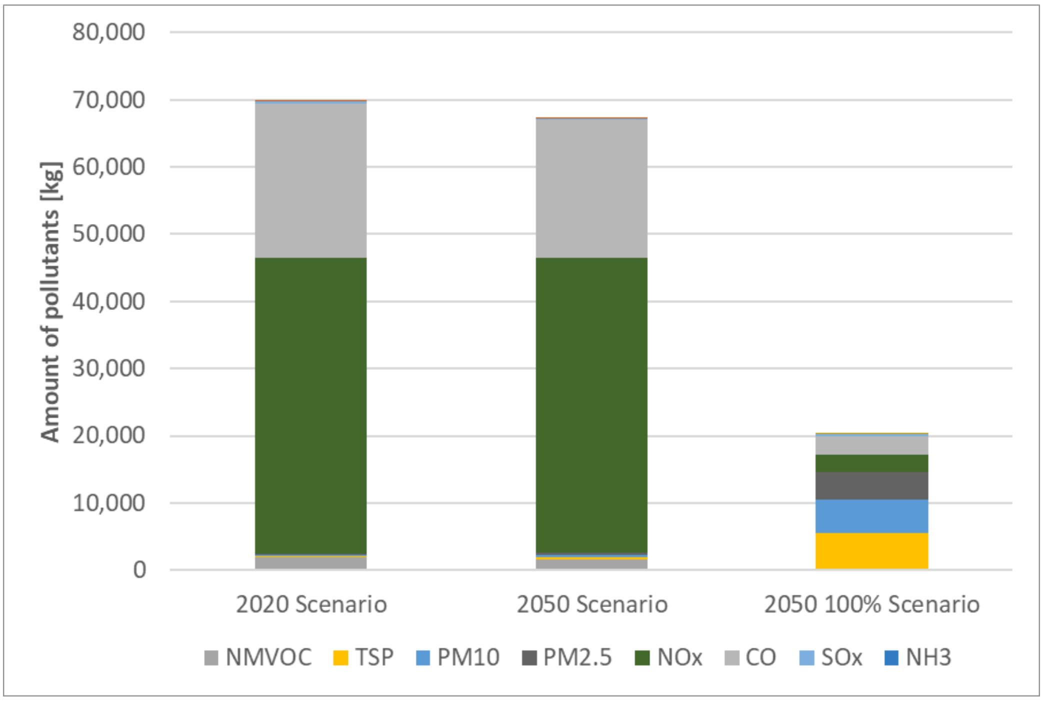

Figure 94 Amount of air pollutants in Brunssum for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

Figure 95 Shadow costs of air pollutants in Brunssum for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

In 2020, Brunssum uses almost solely individual gas boilers. This results in air pollution of NOX, CO and a small amount of NMVOC. The shadow costs of these pollutants are not very high, so, the relative shadow costs of the heating in Brunssum is € 0.01 per kWh.

In the 2050 scenario, only 40% of the heat production is covered by individual gas boilers. The largest addition in this scenario is the district heating with, heat pumps and gas boilers. The amount of gas needed decreases with ± 30%. However, because the district heating gas boilers emit more than residential boilers, the total pollution remains approximately the same, as well as the relative shadow costs of € 0.01 per kWh.

In the 2050 100% renewable scenario, Brunssum cancels out all the individual gas boilers. And replace them with individual heat pumps. The district heating gas boilers are also replaced by heat pumps and a small amount by biomass boilers. That is why compared to the first two scenarios, now the most emitted pollutants are TSP, PM2.5 and PM10. As PM2.5 and PM10 are relatively expensive, the shadow costs are still ± 40% of the previous scenarios, but results in € 0.003 per kWh.

In the 2050 scenario, the total annual costs decrease with 26% compared to the 2020 situation. This is reduction is driven by a decrease in fossil fuel, Fixed O&M and annual investment costs. This is due to the fact that in 2020 almost whole Brunssum was heated by individual gas boilers and in 2050 more than half of this production will be replaced by district heating fueled by heat pumps and boilers. Because of the usage of heat pumps, the electricity import increases in the 2050 scenario. However, still ± 80% of the jobs created are in the individual boiler sector, followed by ± 20% created for heat pumps.

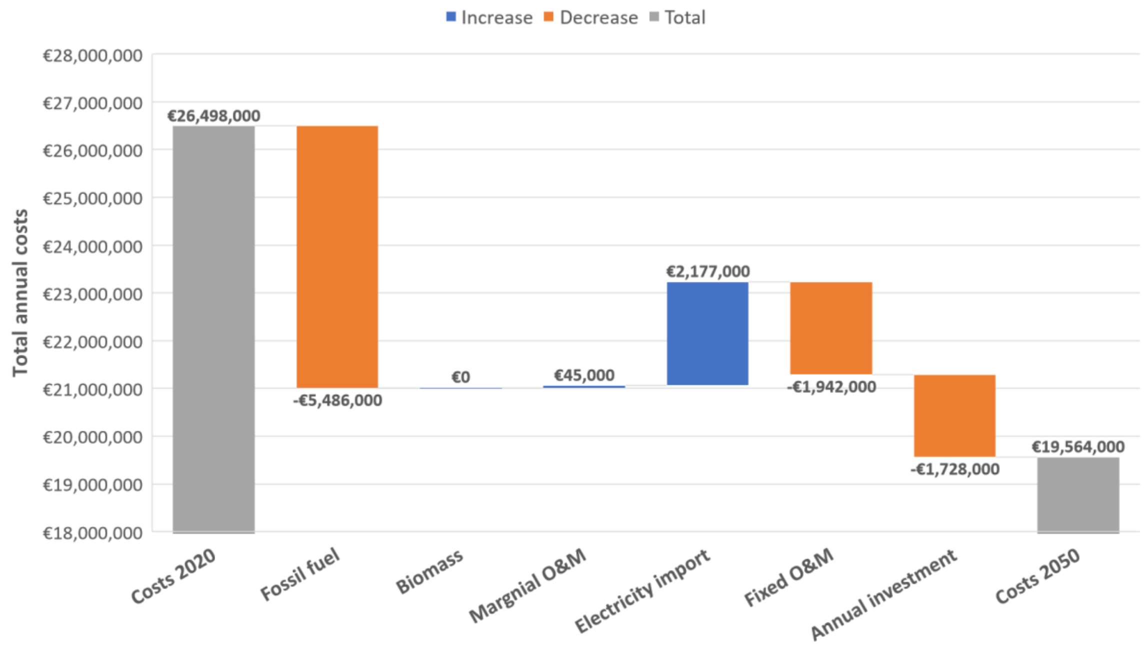

Figure 96 Total annual cost of the heating sector of Brunssum in 2050 scenario.

In the 2050 100% renewable scenario, the total annual costs also decrease with 26% compared to the 2020 situation. In this scenario, all biomass and fossil fuel costs are cancelled out. However, due to the transition to mainly individual and district heating heat pumps, a large amount of electricity needs to be imported. This entails a large increase in these costs, which reduces the costs savings. In this scenario, 13% (32 jobs) more jobs are created compared to the regular 2050 scenario. Furthermore, all of these jobs are in the renewable energy sector.

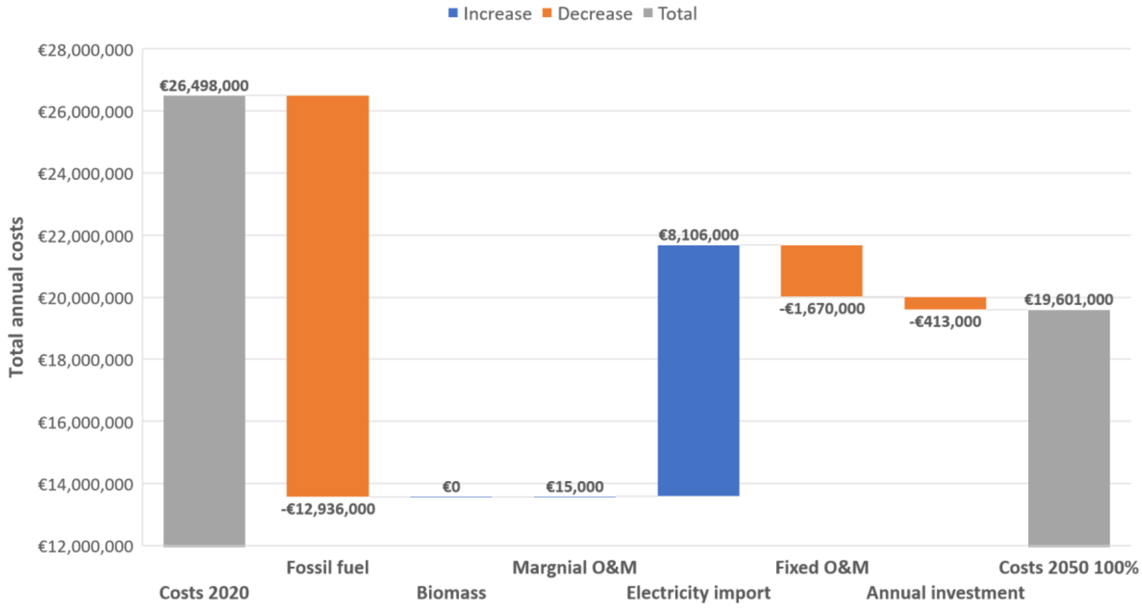

Figure 97 Total annual cost of the heating sector of Brunssum in 2050 100% REWARDHeat scenario.

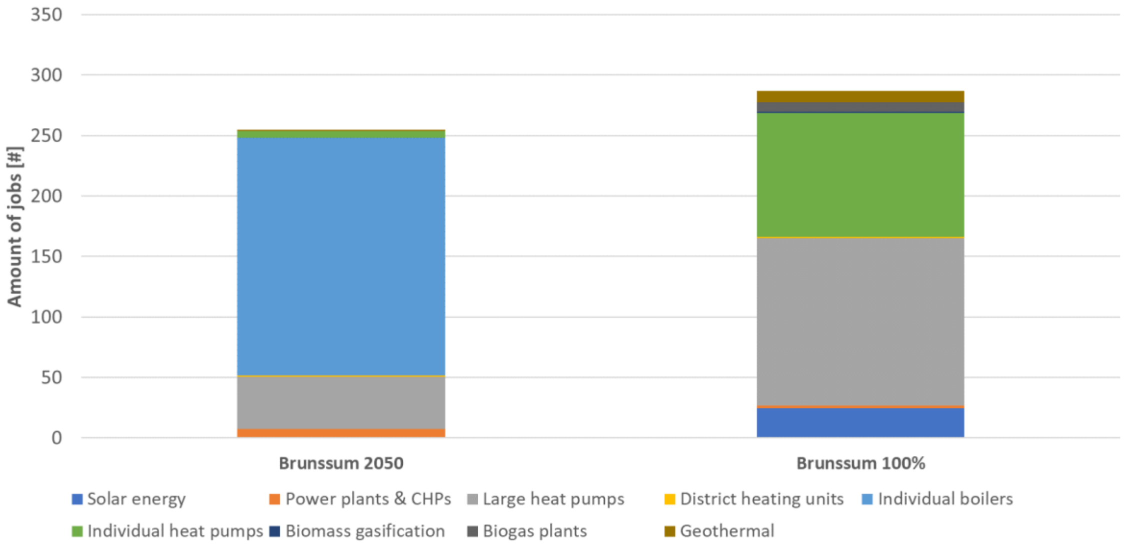

Figure 98 Amount of job creations in Brunssum in the 2050 and 2050 100% REWARDHeat scenarios

4.8 Milan

Milan is the capital of Lombardy, and Italy's second-largest city. The municipality and level for analysis are shown in Figure 99, consisting of 9 areas. Since the two demo sites at Balilla and Gadio fall within the same LAU, they are analysed together in the following.

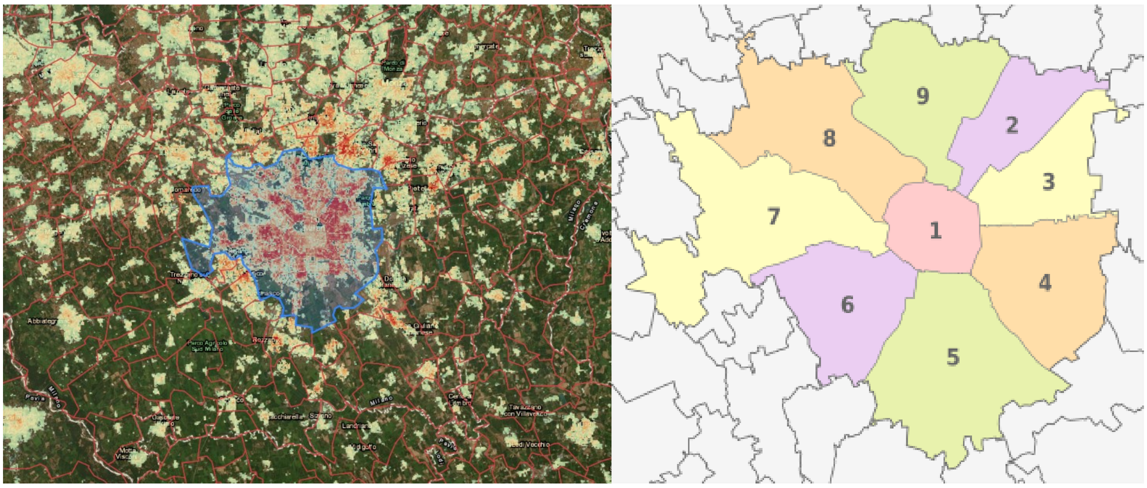

Figure 99: Milan local authority, location and heating potentials [17]

4.8.1 Baseline

The total annual heat demand of Milan municipality is 10,367 GWh, of which the demand in Balilla and Gadio areas is 300-500 GWh for each (areas of REWARDHeat demo). The total DH demand in Milan is around 810 GWh/yr according to the local partner A2A [59]. Thus, the individual heating demand is estimated to be 9557 GWh/yr.

The DH network of Milan consists of three main networks, i.e., North, East and West (88%), and other 8 small networks. Each DHN has its own network loss percentage. The heat demand of the centralized DH system with large CHP plants is around 719 GWh (gr.3 in EnergyPLAN), and the heat demand of the medium DH system with small CHP plants (gr.2) and decentralized DH (gr.1) without CPH is 10.7 GWh and 71.4 GWh respectively. The DH systems are supplied by gas boilers, gas CHP, waste incineration, heat pumps and industrial excess heat. The boilers are used for baseload and peak load. Apart from that, a certain share of the centralized thermal storage system is used to provide flexibility. In DH gr.3 of EnergyPLAN, there is 30.68 GWh/year unutilized surplus heat. The individual heating system in Milan consists of oil boilers (8.48%), gas boilers (76.15%), gas micro CHP (0.04%) and heat pumps (15.33%). The share of heating technologies in the individual heating system is shown in Figure 100 below.

Despite the cooling sector not being the focus of the demo in Milan, we still include the cooling demand in the model. The annual 0.6 GWh/year cooling demand is supplied by chillers with a COP of 4.9. The cooling system in 2050 and 100% REWARDHeat scenario is set the same as the 2020 scenario for a fair comparison among scenarios on the impact of the heating sector.

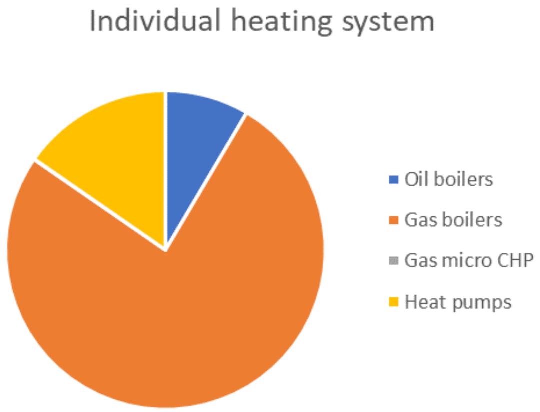

Figure 100: Share of different heating technologies in the individual heating system of Milan.

The REWARDHeat project in Milan targets two small-scale district heating and cooling networks as shown in Figure 101, which will operate at neutral temperature and will integrate RES and waste heat. The demonstrator aims to achieve the following goals:

- Installation of the network, and substations at building level
- Implementation of hardware/software for smart monitoring and control
- Develop business models adapted to the local context

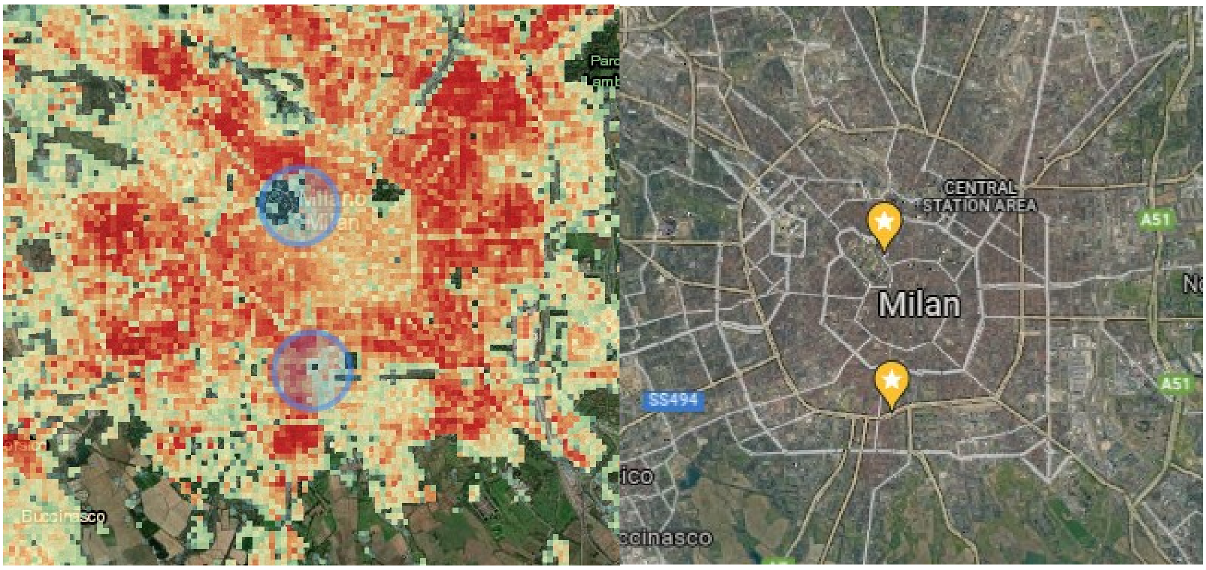

Figure 101: Areas of demo sites and surrounding heat demand (300 GWh/yr within clue circles; ~500 GWh if combined)

4.8.2 Future 2050

As mentioned, the REWARDHeat project focuses on two areas in Milan, Gadio and Balilla. The Gadio demo concerns a newly built neutral-temperature network in viale Gadio. The network will supply constant heat at 30-40°C for space heating purposes, from around 520 kW of excess heat produced from electrical power transformers in the Electric station Gadio. Preliminary estimations have provided total heating power of the network of around 0.4 MW, and a COP of 4.5. At the moment, the Municipal Aquarium that currently uses natural gas boilers is the only consumer that has confirmed their connection to the DHN. The scope of the project in Gadio demo is listed below:

- Installation of the network and substations, including insulated steel pipes, booster heat pumps and thermal energy storage at building level.
- Implementation of smart monitoring and control hardware and software.
- Investigation on business models adapted to the local context.

The Balilla demo focuses on a newly built neutral-temperature network that will exploit groundwater from existing wells as thermal source. There are 94 wells in total (~15ºC), heated up by a heat pump to 70/80 ℃. A heat pump will be installed in each of the substations, at building level. Current systems in the residential buildings will be removed, while they will be kept in the municipal centre and in the kindergarten, and connected in series with new heat pumps to be potentially used as backup systems. The main actions in this demo in the scope of the present project include:

- The installation of the network and the substations at building level for kindergarden, civic centre, residential building
- The implementation of smart monitoring and control hardware and software
- The investigation on business models adapted to local context.

In the future 2050 scenario, we apply the demo technologies to areas beyond the demo sites according to the governmental plan of Milan. The City Council of Milan approved the Air and Climate Plan (PAC), an action plan to become fully carbon neutral and a cycle-pedestrian city by 2050, in which 4GDH is to be promoted in Milan [60].

It is envisaged in the Sustainable Energy Action Plan (SEAP) that the DH potential of Milan is 1,152 GWh/year [61]. In the PIANO scenario, by 2030, heating oil will be eliminated and replaced with DH, gas (condensing boilers integrated with gas absorption heat pumps) and electric heat pumps for the existing buildings. With regard to new buildings, there will be 80% HPs (efficiency: 300%) and 18% natural gas and 2% DH. In the gas-based heat production, there will be 83% gas boilers (efficiency: 95%) and 17% gas HPs (efficiency 135%).

Based on the PIANO scenario of PAC, in the future 2050 scenario we adopt the number of 1,152 GWh for the DH demand in EnergyPLAN model (11.13% of total heat demand), while the individual heating demand decreases to 9,193 GWh (88.87%). In the individual heating system, heating oil will be eliminated and replaced with gas boilers (20%) and heat pumps (80%). In the DH system, the capacity and efficiency of the production facilities are kept with the same capacity as in the 2020 scenario. The results show that the heat supply in gr.3 will be balanced under the increased DH demand.

4.8.3 Future 100% REWARDHeat

In the future 100% REWARDHeat scenario, a deeper decarbonization for the heating sector of Milan is carried out compared to 2050 scenario. However, the 100% REWARDHeat scenario of Milan will be less ambitious compared to the scenarios created for the other 6 demos, which is because natural gas will still play a role in the DH system of Milan according to PAC, and in our model we follow the same trend.

In 2050 PLAN scenario of PAC, the civil sector will reduce energy consumption by 60% in 2050 compared to 2005, and the emissions of natural gas for heating use are reduced by up to 80%, most of which is due to building renovation. It is planned to increase the annual rate of deep renovation of buildings (to at least 3%) with simultaneous conversion of gas heating systems to electric HPs.

In the EnergyPLAN model, the major changes in the2050 100% REWARDHeat scenario will be the efficiency improvement and the replacement of heat production facilities. In the individual heating system, all gas boilers are substituted with heat pumps of COP 3 based on the assumption in the Heat Roadmap Italy study [62], which helps to reduce gas consumption by 1,949 GWh/year.

In the DH system, it is assumed that the renovation of buildings will bring at least 10% efficiency improvement of DH, which leads to lower network losses. The capacity of gas CHP, gas boilers and large-scale heat pumps in gr.3 are kept the same as in the 2020 baseline and 2050 scenario, but in the 100% REWARDHeat scenario the thermal efficiency of DH gas boilers is increased from 93% to 95% and the COP of heat pumps is increased from 2.67 to 3.0 [60]. In DH gr.2, new heat pumps (COP: 3) with 1 MW-e capacity are installed to reduce the gas consumption in boilers.

In that PCA, it is stated that natural gas will be partially replaced by renewable source-based gas (Power-to-Gas) in 2050, however, the specific amount/share of P2G-based gas in the total gas consumption is not clear and whether the gas will be locally produced or imported. Therefore, in the 100% REWARDHeat scenario, we do not investigate the detailed alternative solution for natural gas and, leave it open for further impact analysis.

4.8.4 Energy and environmental impact analysis

Figure 102and Figure 103 are showing the structure of energy consumption and the heat production of Milan in 2020, 2050 and 2050 100% REWARDHeat scenario. Figure 104 and Figure 105 show the results of the linear interpolation in 2030 and 2040 based on the data output of EnergyPLAN in 2020 and two 2050 scenarios. Table 12 presents the KPIs and fuel consumption.

Milan is the largest demo in the REWARDHeat project in terms of the heat demand. The results show the most significant improvement in energy and environmental indicators at the same time. The non-RE primary consumption achieves a 73% decline in the 2050 scenario and 93% in the 2050 100% REWARDHeat scenario assuming that all the electricity production is based on renewable energy sources. The CO_2 emissions decrease in the same order of magnitude. The most significant contribution to the improvement is derived from the individual heating system, with the substitution of individual fuel boilers with heat pumps .

Following the local governmental plan on the future energy system [61], the expansion of the DH network in Milan is limited (12% of the total heat demand) and (natural) gas continues to play a role in the 2050 energy system. A more ambitious expansion of DH would be expected to bring further benefits than the current modelling results, which should go hand in hand with building energy efficiency improvements.

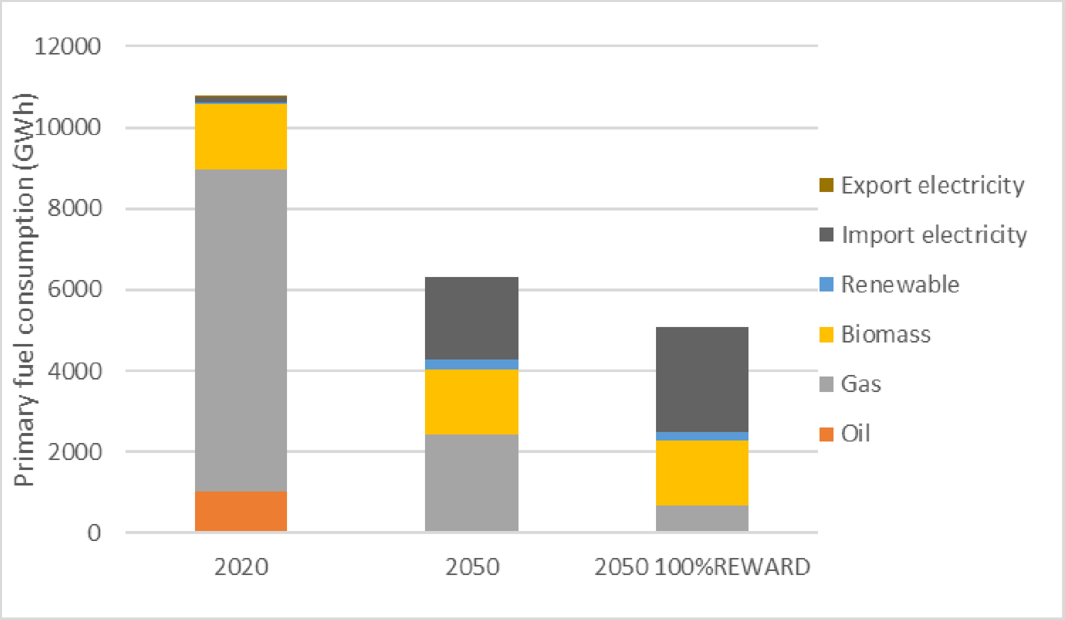

Figure 102: Milan fuel consumption by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

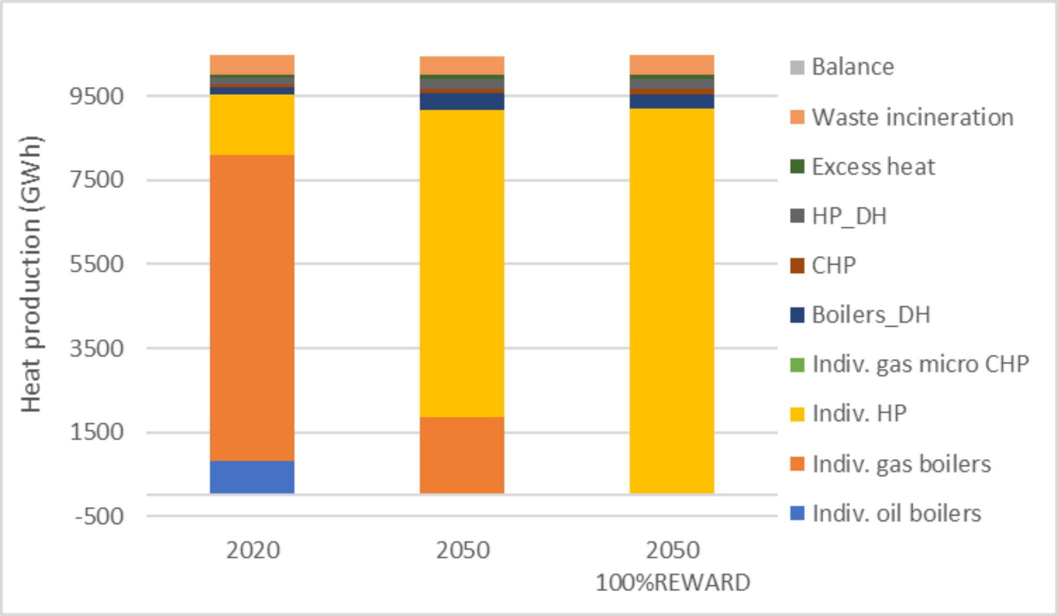

Figure 103: Milan heat output by type for baseline (2020), future demo impact (2050), and future 100%REWARDHeat scenarios.

Table 12 Resulting annual fuels for heating and KPIs in Milan

Milan							
	2020	2050	2050 100%REWARDHeat	Diff.		Diff. 2050 100%REWARD Heat	
Fuels for heating							
Oil consumption (GWh)	1013.54	0	0	-1013.54	-100%	-1013.5	-100%
Gas consumption (GWh)	7840.83	2234.7	480.18	-5606.13	-71%	-7360.7	-94%
Coal consumption (GWh)	0	0	0	0	-	0	-
Biomass consumption (GWh)	1617.38	1617.38	1617.38	0	0%	0	0%
Electricity consumption (GWh)	551.20	2530.21	3078.57	1979.01	359%	2527.37	459%
KPIs							
Non-Renewable PES (GWh)	8952.31	2419.61	664.91	-6532.7	-73%	-8287.4	-93%
Renewable PES (%)	0.16	0.43	0.74	28%-p.	178%	58%-p.	371%
CO_2 emissions (kt)	1890.47	493.89	135.72	-1396.6	-74%	-1754.7	-93%
Share of local waste/excess heat in DHN	0.61	0.43	0.43	-19%-p.	-30%	-18%-p.	-30%
Losses [a]	10%, 20%, 10%	10%, 20%, 10%	9%, 18%, 9%	0%-p.	0%	1%, 2%, 1%	10%
Notes: a respectively for DH system gr.1, gr.2 and gr.3							

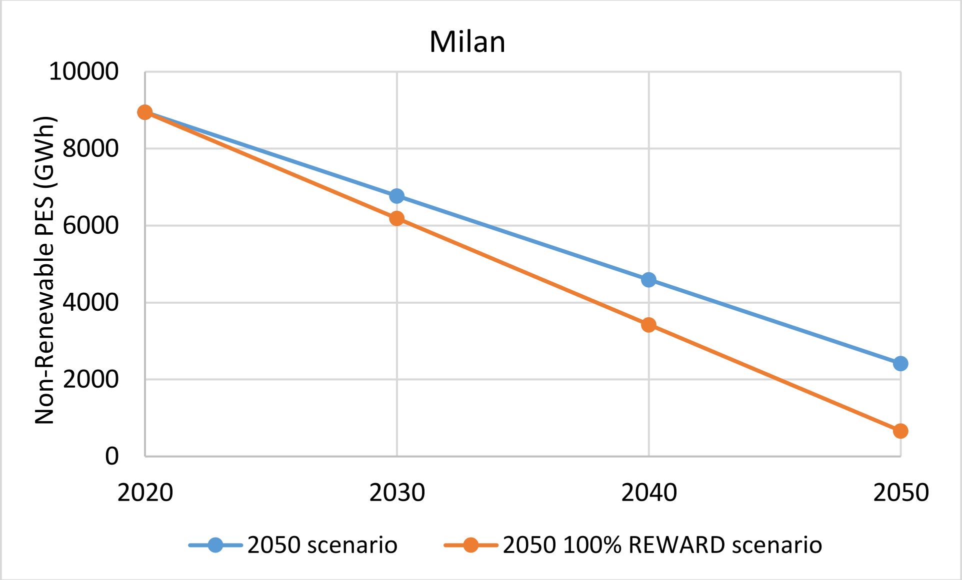

Figure 104: Result of linear interpolation of the non-renewable PES of Milan in 2030 and 2040.

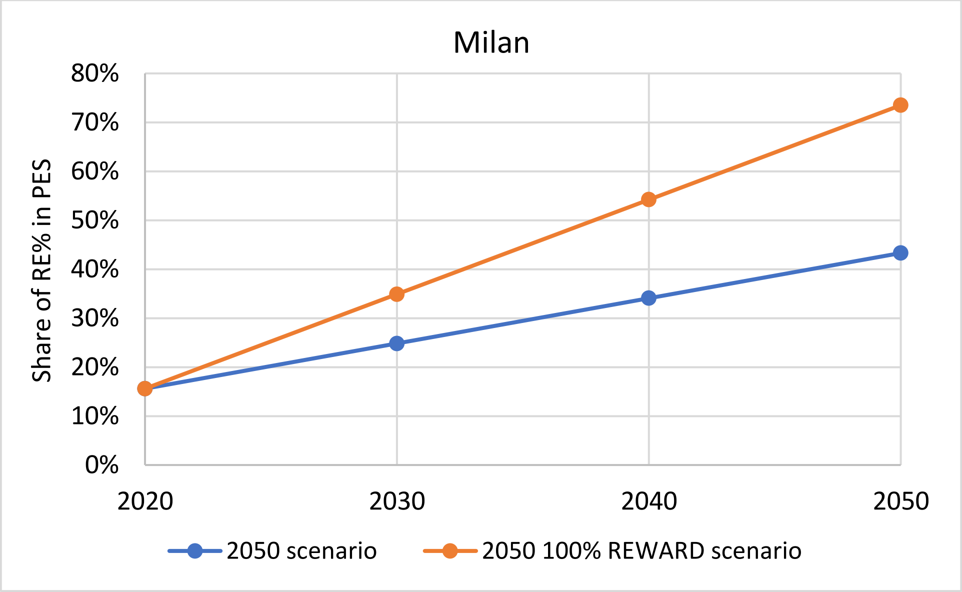

Figure 105: Result of linear interpolation of the share of RE% of Milan in 2030 and 2040.

4.8.5 Economic and societal impact analysis

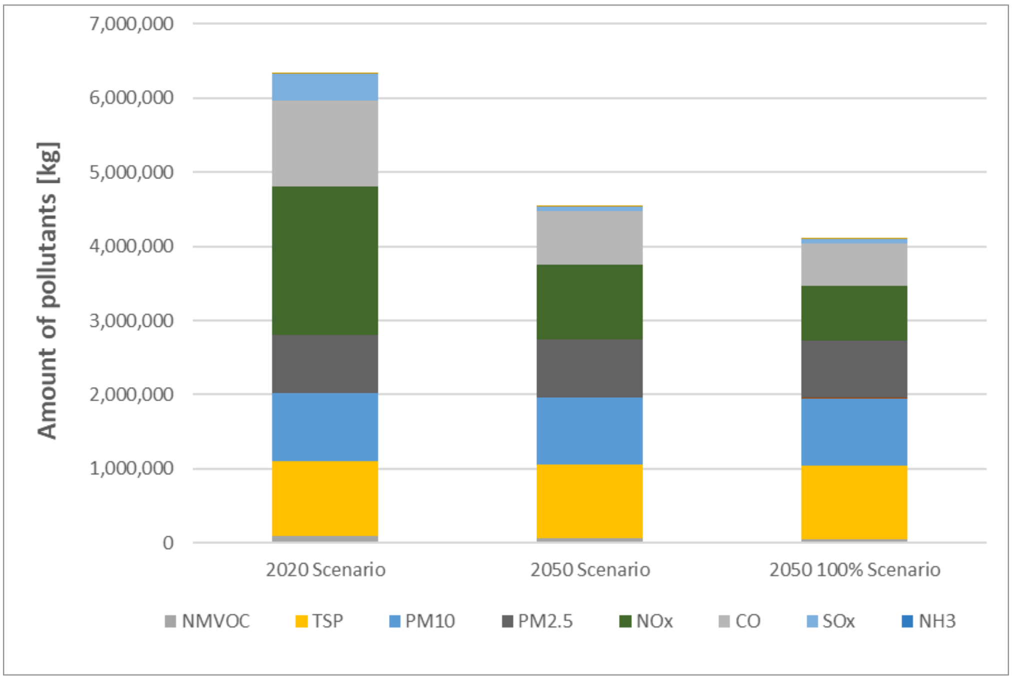

Figure 106 Amount of air pollutants in Milan for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

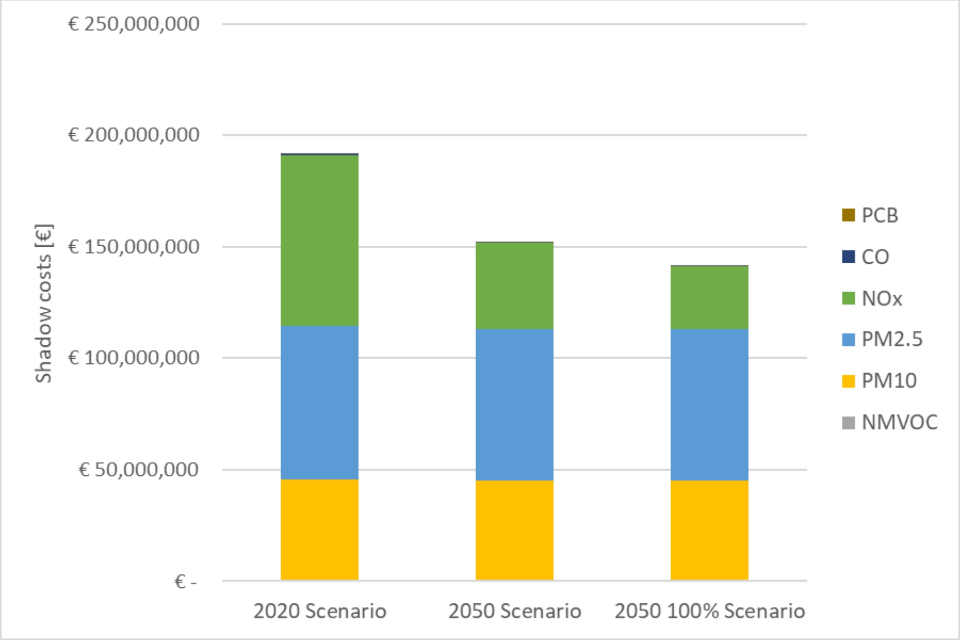

Figure 107 Shadow costs of air pollutants in Milan for baseline (2020), future demo impact (2050), and future 100% REWARDHeat scenarios.

In 2020, Milan covers their heating demand for 75% with individual gas boilers. Furthermore, the most used technologies are individual oil boilers, individual heat pumps and waste incineration (seen as Biomass). Most fuel used is therefore gas, oil and biomass. With these fuels the most emitted pollutants are NO_X and CO. Besides, $PM_{2.5}$, PM_{10} and TSP are emitted mostly by the biomass. The shadow costs are low, € 0.02 per kWh, because of the relatively clean gas usage and heat pumps.

In the 2050 scenario, a transition to 70% covered by individual heat pumps has been made. The individual oil boilers are cancelled out. Only ± 17.5% is covered by individual gas boilers. Because of the same amount of biomass used, the TSP, $PM_{2.5}$ and PM_{10} emission does not decrease significantly. The NO_X and CO pollutants do, and the shadow costs decrease to € 0.01 per kWh.

In the 2050 100% renewable scenario, the individual gas boilers are totally cancelled out and replaced by individual heat pumps. The amount of biomass used stays the same, which was already responsible for almost all the shadow costs. So, the shadow costs in the 100% renewable scenario does decrease only by 7%, compared to the regular 2050 scenario. Which is the reduction of NO_X and CO emitted by the gas boilers. The relative shadow costs are € 0.01 per kWh, the same as the regular 2050 scenario.

In the 2050 scenario, the total annual costs of Milan reduces with 27% compared to the 2020 situation. The main drivers for this reduction are the fossil fuel, fixed O&M and annual investment costs. The electricity import costs, on the other hand, have increased significantly, reducing even higher costs savings for the region. This transition from fossil fuel to electricity costs is caused by the replacement of a large part of the individual gas boilers by the individual heat pumps. However, in 2050 still the most jobs will be created for individual boilers (44% = 14,023 jobs). 25% of the new jobs are for the individual heat pump sector (6,388 jobs) and 7% for the geothermal energy (1,717 jobs).

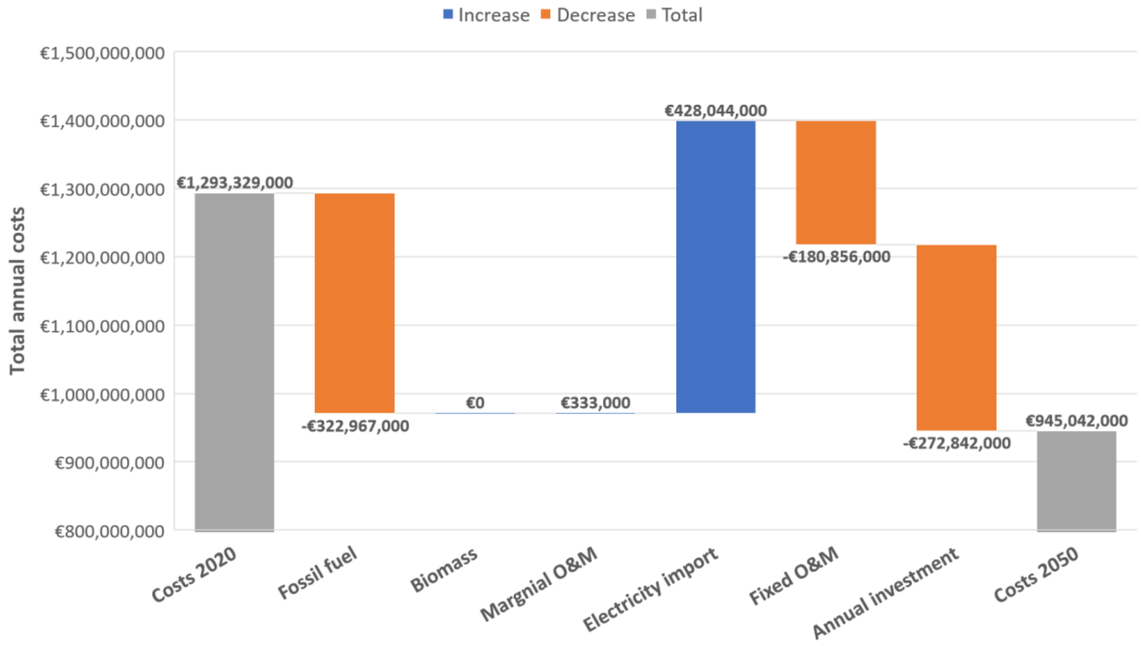

Figure 108 Total annual cost of the heating sector of Milan in 2050 scenario.

In the 2050 100% renewable sector, the total annual costs of Milan decreases with 32%. As now all the individual boilers are cancelled out, an even larger decrease in fossil fuel, fixed O&M and annual investment costs is realised, compared to the regular 2050 scenario. However, the electricity import costs increases, but not as hard as the previous mentioned cost savings. In the job creation, no jobs are now created for the individual boilers. And only a small part is replaced for the individual heat pump sector, causing a total decrease in jobs created of ± 50% (12,363 jobs).

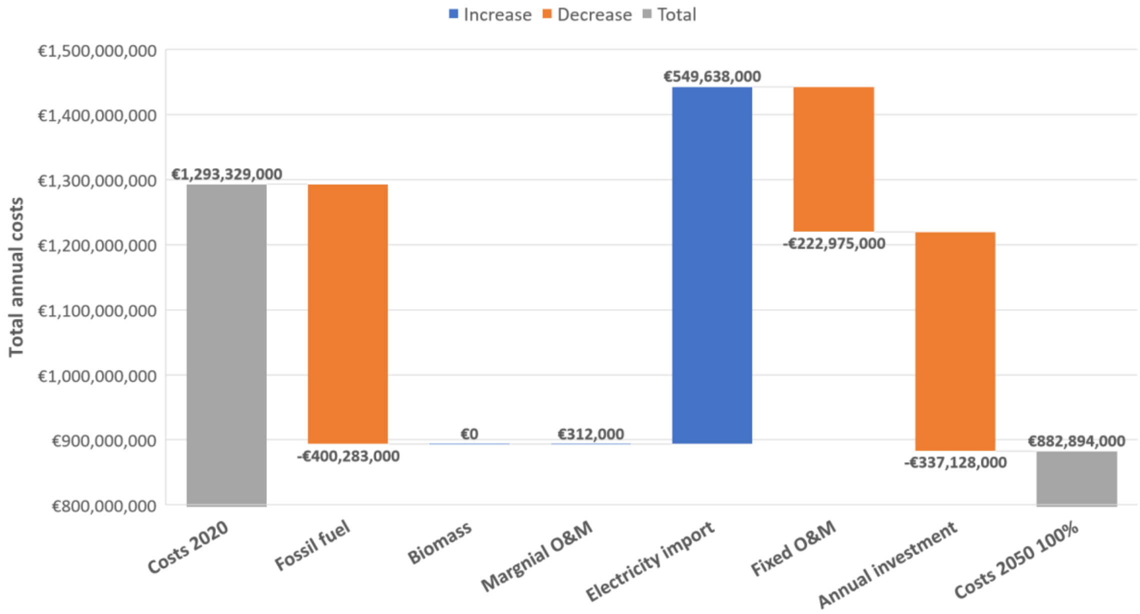

Figure 109 Total annual cost of the heating sector of Milan in 2050 100% REWARDHeat scenario.

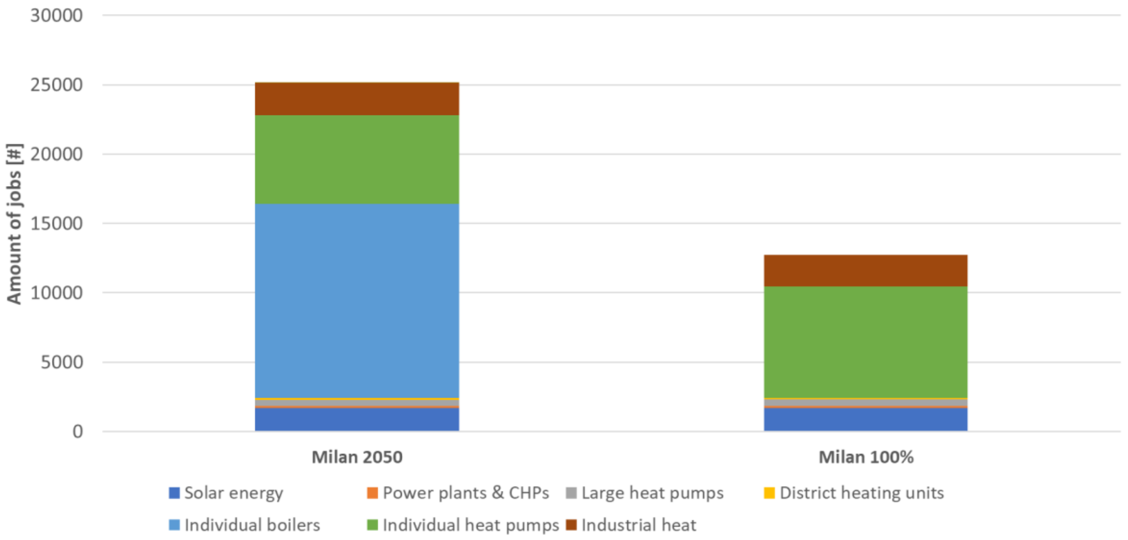

Figure 110 Amount of job creations in Milan in the 2050 and 2050 100% REWARDHeat scenarios

5 Conclusions

For the REWARDHeat project impact assessment and elaboration of impact scenarios beyond the project have been worked out to assess the impacts of the developed REWARDHeat solutions in terms of the energy, environmental, economic and societal aspects in the demonstrator networks and on a large scale in the urban or municipal DHC system surrounding. The assessment of impact scenarios was built on existing knowledge and approach within energy systems modelling and social cost benefit analysis. Three scenarios have been considered:

- Baseline 2020 scenario: the current situation of the energy system of the municipality of each demo, representing the situation in 2020 with the latest available data
- Future 2050 scenario: in this scenario an estimation of energy system changes until 2050 is made with the focus on the implementation of 4GDH (for previously individually heated areas) or transition to 4GDH (for existing 3GDH areas).
- Future 2050 100%REWARDHeat scenario: this future scenario further develops the local DHN towards 100% renewable and waste heat recovery, building on the Future 2050 scenario for comparison. In this scenario, the further decarbonization potential by upscaling the low-carbon technologies is investigated by utilizing the locally available resources and technologies, such as heat pumps, geothermal, thermal storage, and industrial excess heat.

A number of KPIs have been calculated for these scenario's showing the impact on energy, environmental, economic and societal aspects, as follows:

- Non-renewable primary energy use
- Renewable primary energy use
- Share of local waste heat/ excess heat
- Losses
- CO_2 emissions
- Air pollutions
- Annual total levelized costs of the DHC system
- Job creation from investments in the DHC system

For all demo sites The REWARDHeat solutions and future 100% REWARDHeat upscaling scenario show:

1. A substantial reduction of non-renewable energy use from 17-73 %, unless local biomass burning is replaced by DH, which may have a share of PE (Helsingborg, Mölndal), in the 100% REWARDHeat scenarios' non-renewable primary energy is phased out for 100 %.
2. As the reduction from non-renewables comes from lower distribution losses (due to lower network temperatures, higher efficiencies and deployment of green sources, the share of renewables is increasing from the REWARDHeat solutions.
3. The share of local waste/excess energy is increasing in many demos, mainly due to connecting these sources to the networks, but also due to lower network temperatures, allowing additional contributions from low graded sources.
4. A small reduction is found in network losses in many demo sites, mostly from lowering the network temperatures, most networks have already low losses in the current situation (<15-20%).

5. A major reduction is found in CO_2 emissions, mainly due to lower fossil fuel consumption, specifically in the 100% REWARDHeat scenarios, CO_2 is reduced to zero.
6. Air pollution is at first linked to biomass consumption and secondly to coal, oil and gas consumption. Specifically biomass has a large impact on the so called shadow costs, since it is applied on large scale in a number of demo sites and there are no plans to phase biomass out towards 2050.
7. None of the demo sites show an increase in the annual total levelized costs if REWARDHeat solutions get applied, some demos are more or less cost neutral, some show substantial cost reductions, meaning that by applying REWARDHeat solutions CO_2 savings and environmental gains can be achieved, without raising the energy bills for end consumers.
8. Most REWARDHeat solutions show a positive impact on local economies, either by creating new jobs and/or by reducing the spendings on fuels from outside the region. Some conventional technologies (like individual gas boilers) may have a higher need for local workforce, but for most cases the investments in local green infrastructure and forthcoming savings on imported energy will boost the local economy.

5.1 Appendix I. Overview of Impact analysis for all demosites

The results of energy, environmental, economic and societal impacts analysis are summarized in following graphs.

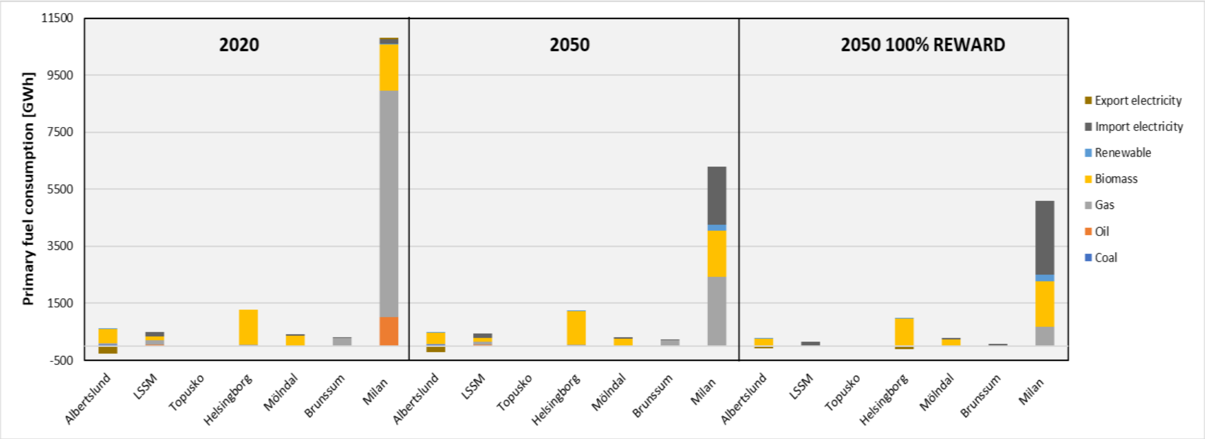

Figure 111 Summary of the structure of primary energy consumption in the 7 demos.

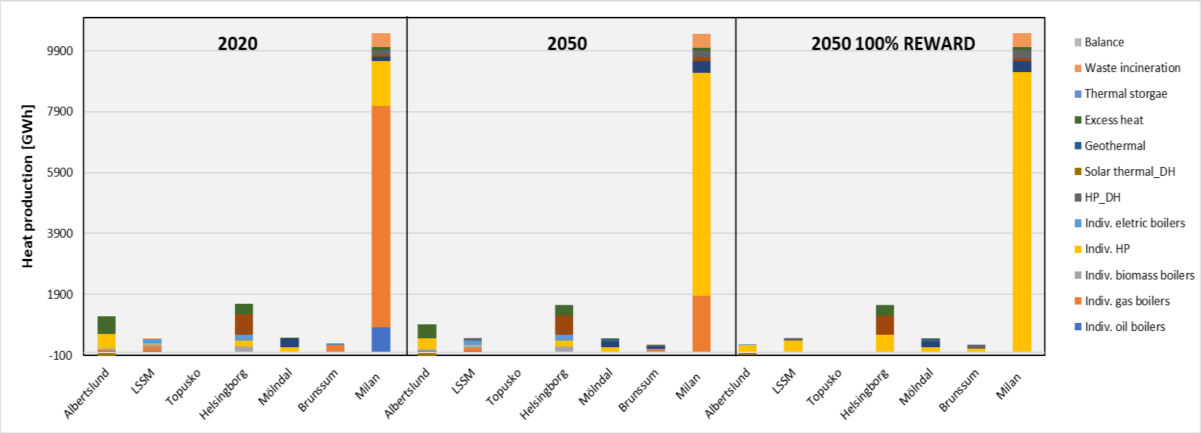

Figure 112 Summary of the structure of heat production in the 7 demos.

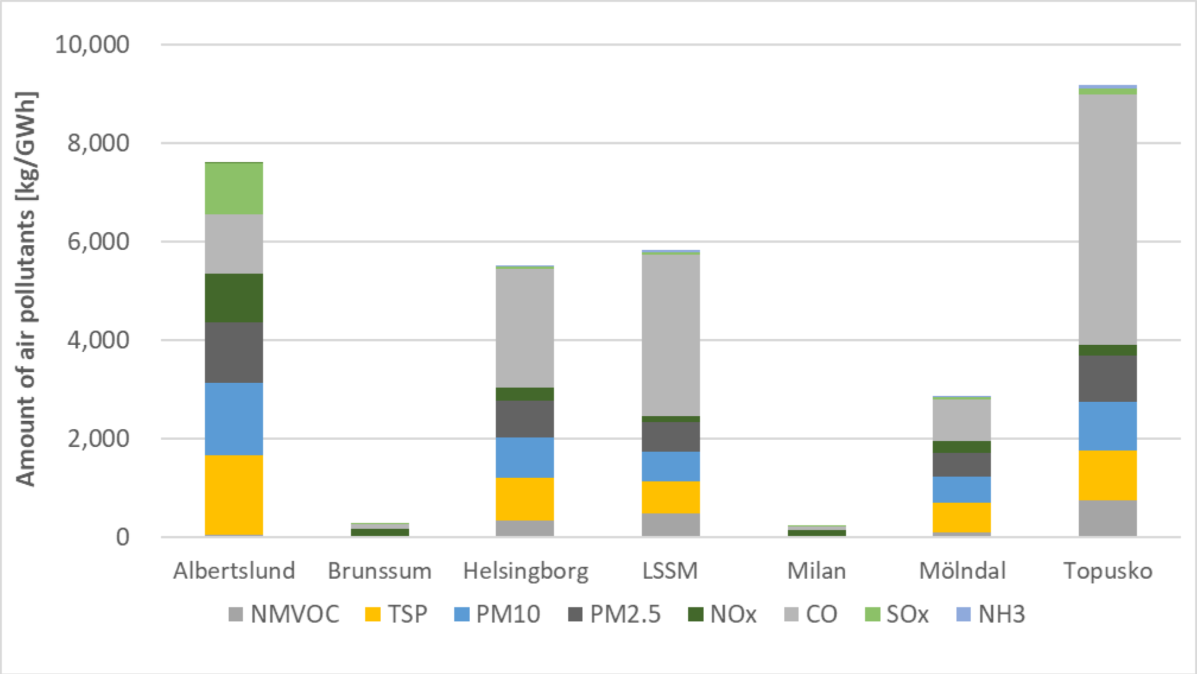

Figure 113 Summary of the amount of air pollutants in the 7 demos.

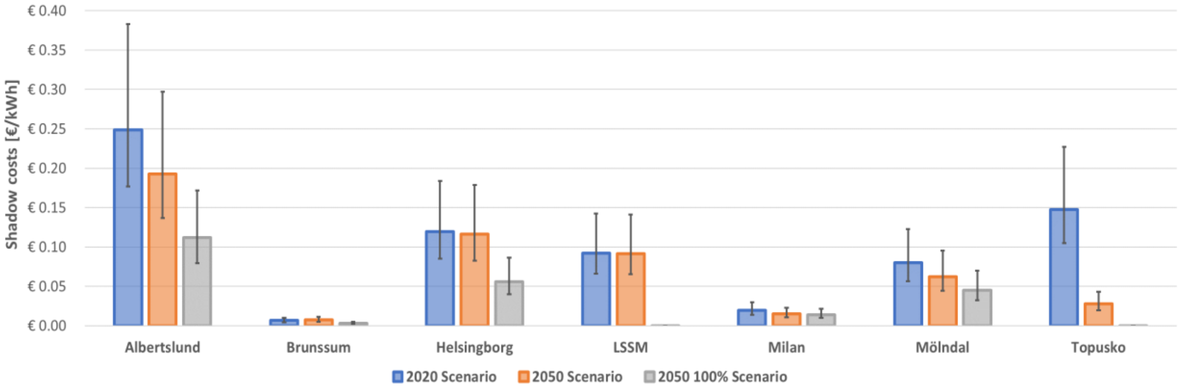

Figure 114 Summary of the shadow costs of air pollutants in the 7 demos.

The columns are the central scenario, the bottom of the black line is the lower scenario and the top of the black line is the upper scenario.

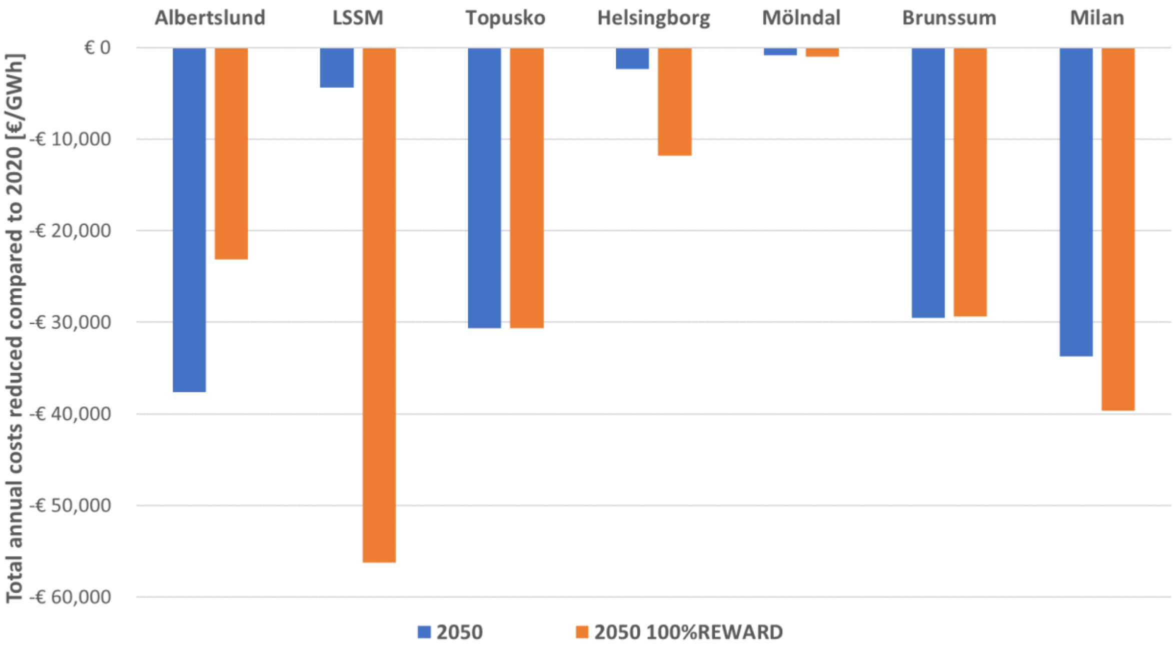

Figure 115 Summary of the total annual costs of the heating system compared to the baseline in the 7 demos.

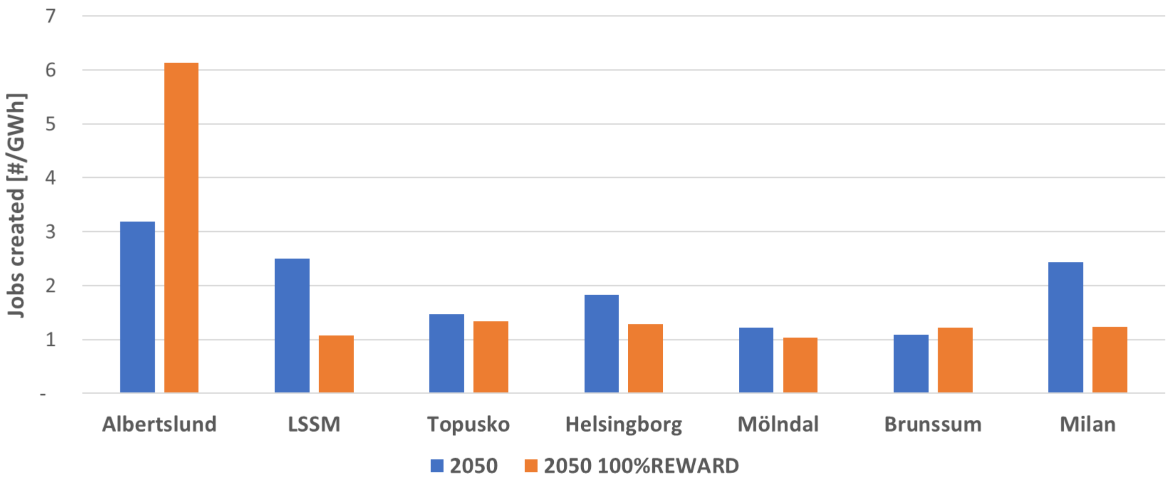

Figure 116 Summary of the amount of job creations in the 7 demos.

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