Flexi-Sync

Flexible energy system integration using
concept development, demonstration and replication

D2.3: ENERGY SYSTEM COST-OPTIMIZATION OF FLEXIBILITY POTENTIALS

VERSION 1.1

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Co-creating with partners that help to understand the needs of relevant stakeholders, we team up with intermediaries to provide an innovation eco-system supporting consortia for research, innovation, technical development, piloting and demonstration activities. These co-operations pave the way towards implementation in real-life environments and market introduction.

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SUMMARY

This Deliverable presents the results of Tasks 2.2 and Task 2.3 of Work Package (WP) 2 of the Flexi-Sync project. The project aims to identify how the untapped flexibility in district heating (DH) and district cooling (DC) systems can benefit the overall energy system by balancing the volatility caused by increased shares of variable Renewable Energy Sources (RES). Flexi-Sync includes partners from four European countries and has six demonstration sites in Germany (Berlin), Spain (Palma de Mallorca), Austria (Maria Laach auf Jauerling in the state of Lower Austria) and Sweden (Borås, Eskilstuna, Mölndal).

WP2 aims to estimate the cost-efficient flexibility potential of the DH systems available in the cities where the demo sites are located. For the demonstration sites of Eskilstuna and Lower Austria, the aims are addressed quantitatively. The method includes up-scaling the flexibility potential from demo-scale to city/region scale (Task 2.2) and dynamic energy system optimization modelling to assess cost–efficient flexibility potential of DH systems in the long-term (Task 2.3). For the rest of the demonstration sites, the aims are addressed qualitatively, by discussing the potential implications of the results from the modelled demonstration sites, the results from the other WPs and input from stakeholders. The flexibility types investigated in this WP include combined heat-and-power (CHP) plants, centralized and individual heat pumps (HPs), and thermal energy storages (TES), including TES in the DH network and in buildings (in both Eskilstuna and Lower Austria), and demand side management (DSM) (in Lower Austria, based on results from WP1).

For the city of Eskilstuna, the modeling results indicate that for all scenarios and availability of TES, the future heating sector will be dominated by heat pumps (HPs), both centralized (in the DH system) and individual. This implies that the city's heating sector becomes a net consumer of electricity and can help with the utilization of excess electricity from the power sector. The results also show that the already available and invested in TES solutions are actively used for storing heat between seasons and for decreasing the peak heat generation, i.e., flattening the heat generation curve. This results in lower system cost of heat supply and improved flexibility potential of the heating system.

For the region of Lower Austria, modeling results of both scenarios indicate that decarbonization of the heating sector is possible by 2040. In residential sector, building refurbishment will play an important role to reduce energy consumption as well as the expansion of the use of heat pumps (air and geothermal) together with the use DH. In service sector, DH increases its weight as predominant technology. During the transition, wood biomass becomes fundamental and air-source HPs play a relevant role. Finally, the use of wood biomass as well as air-source HP is high in the long-term and the role of CHP plants is predominant. There is an improvement in the use of DH to cover the winter peak. This is due to the better efficiency of future technologies but also to the use of DMS). The model does not invest in TES solutions connected to the DH systems at seasonal level. This can be explained on the one hand by low availability of variable sources (solar thermal) and on the other hand, by the already high utilization of other flexible systems such as CHP and HPs in DH.

ABBREVIATIONS

Acronym	Description
APL	Low-efficiency apartment
CHP	Combined heat-and-power plant
DC	District cooling
DH	District heating
DSM	Demand side management
ESM	Energy saving measures
GHG	Greenhouse gases
HDD	Heating degree days
HP	Heat pump
MILP	Mixed Integer Linear Programming
RES	Renewable Energy Sources
RHL	Low-efficiency single family house
SCB	Statistics Sweden
SMHI	Swedish Meteorological and Hydrological Institute
TES	Thermal energy storage
WP	Work Package

1 INTRODUCTION

The Flexi-Sync project aims to identify how the untapped flexibility in district heating and cooling systems can benefit the overall energy system by balancing the volatility caused by increased shares of variable Renewable Energy Sources (RES). Flexi-Sync includes partners from four European countries and has six demonstration sites (demo sites) in Germany, Spain, Austria and Sweden which will be briefly presented in Sections 3-4 and Annex C.

The project has five main goals, addressed in corresponding Work Packages (WPs):

1. Identification of the current flexibility potential in the six demo sites
2. Estimation of the cost-efficient flexibility potential in the local or regional energy system
3. Analysis of the adjustments needed to the cost-efficient solutions to be climate resilient
4. Implementation of the optimized flexibilities in the demo sites
5. Analysis of the business implications of increased flexibility and development of business model and market uptake analysis of the new service.

This deliverable D2.3 belongs to WP2. The goal of WP2 is to estimate the cost-efficient flexibility potential in the local or regional energy system (goal 2). There are three tasks to meet the goal. The first task, reported in D2.1 [1], defined future scenarios in line with ambitious climate targets as well as relevant to estimate the cost-efficient flexibility potential in the local or regional energy systems of the Flexi-Sync demonstration sites. The scenario framings have been further translated into input to the modelling assessments performed within WP2. The second Task 2.2 characterizes flexibility potentials for energy system assessment by upscaling the potentials obtained in the demonstration sites (D4.3 [2] and D4.4 [3]), whereas the third Task 2.3 identifies flexibility options and their utilization strategies, which would provide the most cost-efficient operation of the studied DH systems. The joint results of Tasks 2.2 and 2.3 are presented in this D2.3.

As summarized in Table 1, for the demonstration sites of Eskilstuna and Lower Austria, the aims are addressed quantitatively. The method includes up-scaling the flexibility potential from demo-scale to city/region scale (Task 2.2) and dynamic energy system optimization modelling to assess cost–efficient flexibility potential of DH systems in the long-term (Task 2.3). For the rest of the demonstration sites, the aims are addressed qualitatively, by discussing the potential implications of the results from the modelled demonstration sites, based on the results from the other WPs and stakeholder input.

Table 1: Overview of how the aims of Tasks 2.2. and 2.3 have been addressed for the different demonstration sites, and the sections of this report in which the findings are reported.

Demo site	Task 2.2	Task 2.3
Eskilstuna	Quantitatively; Section 2.1.2	Quantitatively; Section 2.2
Borås	Qualitatively; Discussion Section	Qualitatively; Section 4

Mölndal	Qualitatively; Discussion Section	Qualitatively; Section 4
Lower Austria	Quantitatively; Sections 3.1.1 and 3.1.3.3	Quantitatively; Section 3.2
Berlin	Qualitatively; Discussion Section	Qualitatively; Section 4
Palma de Mallorca	Qualitatively; Discussion Section	Qualitatively; Section 4

1.1 Background

The Paris Agreement reinforces targets to cut greenhouse gas (GHG) emissions with the increasing penetration of RES. Most of the RES growth is expected to be from volatile sources such as solar photovoltaics and wind power. With high penetration levels of volatile RES, additional and sometimes new kinds of flexibility measures are needed to balance the mismatches of supply and demand at different timescales [4].

There are several possible sources of flexibility in energy systems. Flexibility potentials of DH and DC systems are often suggested as one of the key principles to facilitate high levels of RES in the energy markets [4]. Flexibility in DH and DC systems can be provided by, but not limited to, combined heat-and-power (CHP) and HP technologies, power-to-heat and heat-to-power solutions, and TES technologies [5, 6, 7, 8]. TES technologies can be further disaggregated into centralized or decentralized heat storage units [9], thermal inertia of the connected buildings [10], as well as the heating/cooling network itself [11].

The usage of the heating/cooling network as TES is realized by using the mass of circulating water in the network to buffer heating (cooling) energy and, thereby smoothen the supply so as to meet the demand. The advantages of the network TES are that it requires minimal infrastructure investments (the network is already there) and the fact that some amount of storage capacity is available in any DH or DC system. However, network TES has its disadvantages. The buffering capacity of a network is limited, which means that the imbalance between the supply and demand variations is still significant even after the volume in the piping network is used at maximum capacity. Increased return temperature, which is a consequence of a storage cycle, would decrease efficiency of the generation units. Also, there is no standard method to estimate capacity of the network TES as well as there is no estimation of the threshold size of a network needed to enable storage [12].

Centralized and decentralized TES technologies can be divided into three types: 1) sensible heat storage, in which thermal energy is stored by heating or cooling a liquid or solid storage medium; 2) latent heat storage using phase-change materials; and 3) thermochemical storage using chemical reactions to store and release thermal energy [13]. The types of TES most applied in DH/DC systems are water-based sensible TES systems, owing to their low costs compared to latent or thermochemical TES systems. TES systems can also be classified as either centralized (e.g., a single standing borehole TES) or decentralized (e.g., a hot water tank installed in a household). Decentralized TES units are normally used for short-term, i.e., intra-day storage, while centralized TES units can be used to smoothen-out both short-term and long-term demand variations. In comparison to the network TES, centralized TES units can have much greater storage capacities and, hence, result in higher cost savings due to their utilization. However, investment costs of centralized TES systems are significant. The body of literature that investigates the utilization of centralized TES units in DH/DC systems is substantive [14, 9, 15, 16] and the overarching conclusion is that a TES can provide both economic and environmental benefits to the operation of DH/DC systems.

There are a few ways to store energy at the building side, e.g., individual water tanks, ceramic bricks, Phase Change Material heat batteries and others, but the one type that is currently available in all buildings but not yet utilized is storage in the thermal inertia (mass) of buildings, i.e., building TES. The principle of building TES operation is based on the temporal over-heating or under-heating of buildings and has been investigated in several studies [17, 18, 19]. In comparison to a centralized TES, which acts as a supply-side buffer and is under total control of a DH/DC system operator, building TES alters the heat load itself by smoothing its variations and may require the involvement of customers. Advantages of building TES are that it is available in any DH/DC system and that it requires lower investments than centralized TES units. The disadvantages include limited control and required involvement of the energy users.

Although the above-mentioned studies provide valuable insights on the varying aspects of the utilization of different types of storage technologies, there is a lack of studies that have compared the effects of these storage types on the operation of DH/DC systems (as in [20]). Moreover, most of the previous works investigated the effects of different TES types on the operation of DH/DC systems by applying them one at a time and thus, could not provide any insights on whether the investigated TES types are complementary or competing. The studies that investigated the effects of a centralized TES and building TES available in a system at the same time, reported complementary positive effects of these storage types on the cost and efficiency of the heat supply in DH systems [21, 22]. These are very promising results that should be further researched and validated from various angles and under different circumstances, as is attempted in the Flexi-Sync project in general and in this deliverable D2.3 in particular.

1.2 Report structure

The report consists of five sections, plus *Summary*, *Abbreviations*, *References* and three *Annexes*. The *Summary* and *Introduction* sections have briefly introduced the reader to the Flexi-Sync project and to this Deliverable D2.3.

The three following sections describe how the aims of WP2 have been met for the different demo sites. The results for the two demo sites that have been studied quantitatively, that is Eskilstuna (Sweden) and Lower Austria (Austria), the state where demo site Maria Laach am Jauerling is located, are presented in Sections 2 and 3. In Section 4, perspectives on the research questions from the other demo sites are included, based on results from other WPs and a qualitative analysis of the implications of the modelling results obtained for Eskilstuna and Lower Austria. These other demo sites are Borås and Mölndal in Sweden, Berlin (Germany) and Palma de Mallorca (Spain). All the main findings are summarized again in Section 5.

The *References* provide, in addition to the literature necessary to understand this report, other outputs of WP2 including conferences [23] [24] [25] and MSc thesis [26]. In the Annexes, the reader can find further information on the data collected, the scenarios, and other assumptions in the modelling, as well as additional information on the demosites of Borås and Mölndal (Sweden), Berlin (Germany) and Palma de Mallorca (Spain).

2 ESKILSTUNA

The city of Eskilstuna had 67 359 inhabitants in 2015, with a total population of 100 092 inhabitants in Eskilstuna municipality (2014). The total energy use of the Eskilstuna municipality was around 2 322 GWh in 2015 [27]. The energy system (including Housing & Premises, and DH) used around 66 % of the total energy supplied to the municipality. DH is the main supplier of heating in the city, and it accounts for about 65 % of the energy used for heating within the municipality. The city's annual demand for heating is around 700 GWh (differs between years), with more than 50 % of the delivered heat being used in multi-family buildings [28].

2.1 Method

The assessment of the cost-efficient flexibility potential in DH systems is performed in three steps, described in the consecutive subsections below. As the aim of this project is to investigate flexibility options (yellow marked in Figure 1), Task 2.2 has focused on upscaling the potentials for TES in buildings (as key flexibility solution to be investigated with ECCABS model) obtained in the demonstration sites. This upscaling has been done by implementing the equation obtained in the demo site (see section 2.1.2) to the energy demand for each of the buildings in the city derived with ECCABS model (see section 2.1.1).

In Task 2.3, these potentials for TES in buildings were incorporated, together with other existing and potential flexibility options (which are described further down), to the optimization model TIMES.

The developed and applied models are briefly explained below.

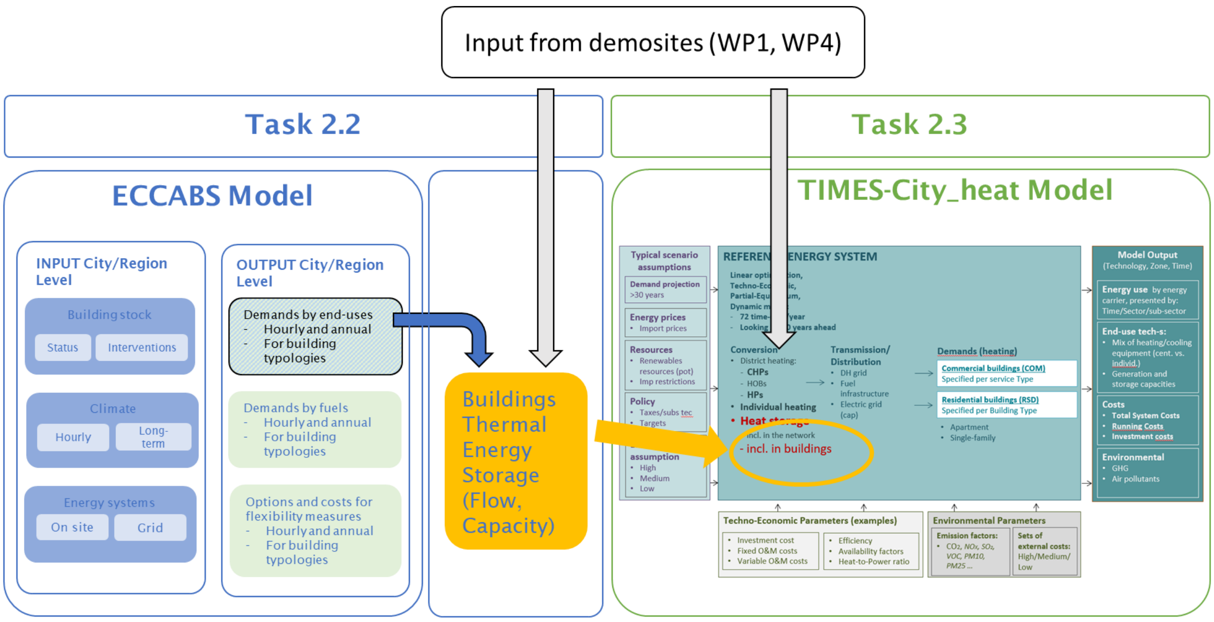

Figure 1: Description of the flow of the work between the models, from ECCABS model (Task 2.2) to TIMES model (Task 2.3) in this project.

2.1.1 ECCABS

The building-stock model ECCABS [29] [30], was initially developed to investigate reductions of energy use in Swedish residential buildings [31], and has been further developed to map opportunities (in terms of energy and GHG emissions) and costs for buildings' energy efficiency, and used to assess the transformation of Swedish residential buildings [32] (including urban applications [30]) and non-residential buildings [33], as well as the buildings of several European countries [34].

Figure 2 shows the model structure. Input data includes physical building data (e.g., heated floor area, window area, heat loss coefficients, ventilation); climate data (outdoor temperature); existing energy system (e.g., grid details); and further details to decide on scenarios and energy saving measures (ESMs) (e.g., constraints on cost, and human labour).

In the simulation module, the energy performance of the building stock is calculated together with the potential energy savings, associated CO_2 emissions and costs. The thermal mass of the building is considered at each time step (1 hour resolution) and the results are extended to the entire building stock in the city by means of weighting coefficients. This allows to calculate the buildings TES and is used as input in the TIMES-City model (see Figure 1).

In the optimization module, selected ESMs are implemented over a timeline following various technical and economical reasoning [14]. The output from optimization includes demands by end-uses and demands by fuels. However, this optimization module is not used in this project. Figure 2 shows (in blue) the parts of the model used in this project.

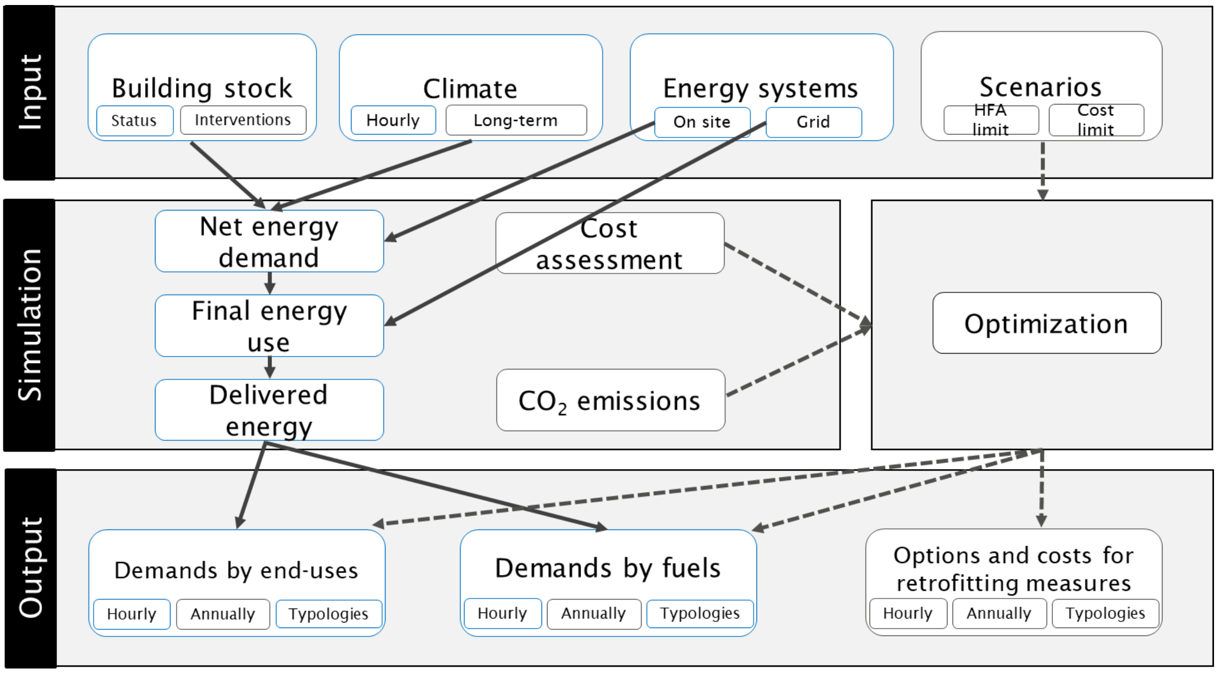

Figure 2: Structure and workflow of ECCABS Simulation Model. Adapted from [30] to show (with blue) the features of the model used in this work.

2.1.1.1 Data sources

Input data is collected, or calculated from, the data available at Statistics Sweden (SCB) [35] [36] and Swedish Energy Agency's [37] [38] database. Calculations were required when the data was not available at city level for Eskilstuna, but available at regional and national levels, as will be described in Section 2.1.1.3.

To represent the building stock of Eskilstuna in the model , archetype buildings are defined following a methodology thatconsists of three steps [39]: segmentation, quantification, and validation, which are described in corresponding subsections below.

2.1.1.2 Segmentation

The building stock is segmented according to:

- Use: single-, and multifamily buildings, following the different requirements of the building code (Boverkets's Building Regulations BBR 29 [40]) shown in Table 2, and the input requirements of TIMESCity_heat model (three categories of urban density, see Section 2.1.3),
- Building's size: ≤ 50 m², 50 - 90 m², 90 - 130 m², > 130 m², following the different requirements of the building code BBR 29 [40] shown in Table 2,
- Construction year: before 2005, 2006 - 2009 and 2010 - 2019. These categories are given by data availability, and changes in the building code, BBR 29 [40]. The data for the buildings that were constructed up to year 2006 is taken from another database, BETSI [41], as described and validated in [42] [43] [44] [29] [31].
- Main source for heating (DH, electrical, other). These categories are given by data availability, and requirements of the building code BBR 29 [40], and
- Ventilation system (Table 3).

In total, there is 142 different combinations of parameters.

Table 2: Energy performance and average heat transfer coefficient per house type/area, BBR 29 [40].

	Energy performance expressed as primary energy (EP_{pet}) [kWh / m² A_{temp} and year]	Average heat transfer coefficient (U_m)
Residential buildings		
Single-family houses > 130 m²	90	0.30
Single-family houses > 90-130 m²	95	0.30
Single-family houses > 50-90 m²	100	0.30
Single-family houses ≤ 50 m²	-	0.33
Multifamily buildings	75	0.40

Table 3: Types of ventilation systems.

	Specific fan power (SPF) [kW/(m³/s)]
Exhaust and supply air ventilation with heat recovery	1.5
Exhaust and supply air ventilation without heat recovery	1.1
Exhaust and supply air ventilation with heat recovery and cooling	1.6
Exhaust air ventilation with recycling	0.75
Exhaust air	0.5

Table 4: Resulting typologies used in the ECCABS model with their descriptions.

Typologies	Description
Type - 1	Single family buildings connected to district heating (DH)
Type - 2	Single family buildings heated with heat pump (HP)
Type - 3	Single family buildings heated with other sources (boilers, direct electricity, etc.)
Type - 4	Multifamily buildings less than 5 floors connected to DH
Type - 5	Multifamily buildings less than 5 floors heated with HP
Type - 6	Multifamily buildings less than 5 floors heated with other sources (boilers, direct electricity, etc.)
Type - 7	Multifamily buildings more than 5 floors connected to DH
Type - 8	Multifamily buildings more than 5 floors heated with HP
Type - 9	Multifamily buildings more than 5 floors heated with other sources (boilers, direct electricity, etc.)

2.1.1.3 Quantification

The frequency of each archetype in the stock is quantified by means of a weighting factor. To this end, the four segmentation categories above presented are calculated as shares and combined with the total number of dwellings for Eskilstuna taken from SCB [35] as presented in Equation 1.

$$W_{i,j,k,l} = ND_{Tot} \times P_{CY_i} \times P_{HS_j} \times P_{VS_k} \times P_{DS_l} \times P_{VS} \times P_{DS} \qquad \text{Equation 1}$$

Where,

$W_{i,j,k,l}$ is the weighting coefficient for each archetype

$\mathrm{ND_{Tot}}$ is the total number of dwellings

$\mathrm{P_{CY_i}}$ is the percentage of buildings per construction period i

P_{HS_j} is the percentage of buildings per heating system j

P_{VS_k} is the percentage of buildings per ventilation system k

P_{DS_l} is the percentage of buildings per dwelling size l

The shares for the different segmentation categories have been calculated from statistics from SCB and Swedish Energy Agency [37] [38] [45] [46] [47] [48] [49] [50] [51]. Some of the data are present on local level, while some statistics are on national level. For instance, the dwellings per size are presented for each municipality while the data regarding heating systems are presented on a national level. Assumptions have been made to scale national and municipal data, as follows:

- In TIMESCity_heat model, multifamily buildings are divided into small (below 5 floors) and big (above 5 floors). In statistics, multifamily houses are given by heated floor areas (in m^2). It was assumed that multifamily buildings > 3000 m^2 have more than 5 floors and the smaller buildings have less than 5 floors.
- Statistics for ventilation systems are only present for single family houses. The statistics for multifamily buildings have been assumed to be the same as for single family houses.
- Statistics of overall use of heating systems are presented on a national level, whereasthe use of heating systems differs depending on their geographical location. There are statistics on heating system for newly built dwellings, per region, which have been used to calculate an adjustment factor to reflect the regional use of heating system.

2.1.1.4 Validation

The model is validated by comparing with statistics the results for the number of dwellings, the heated floor areas, and the final energy use. The three parts of the validation are presented in corresponding tables below.

First, the number of dwellings calculated in the model is compared with statistics under the described categories in Table 5. The comparison shows that model have a 100 % match with statistics from SCB [35], as expected.

Second, the heated floor areas for single family houses and multifamily houses in the model are compared with available statistical data. In the case of Eskilstuna, the heated floor areas are not available in the statistics, and were calculated by dividing the final energy consumption for the city of Eskilstuna [52] by the average energy use for heating (in kWh/m2) in each temperature zone [53]. In Table 6 the difference with the statistics is shown for these categories under the "Match" column. For small houses, the difference is as low as 2 %, which is lower than statistical information. For the heated floor areas in multifamily buildings, the model result is 13 % lower than statistics. Both differences are considered acceptable since the heated floor areas per building type (explained in Section 2.1.1.2) are the averages determined by performance requirements in the building code BBR 29 [40].

Table 5: Comparison of model results for the number of dwellings in Eskilstuna with statistics.

Category	Number of dwellings ECCABS # dwellings	Statistics #dwellings	Match
Eskilstuna all dwellings	47 549	47 549	100 %
Single family houses	17 827	17 827	100 %
Multifamily buildings	29 722	29 722	100 %
Single family houses constructed between 2010 - 2019	236	236	100 %
Single family houses constructed between 2006 - 2009	1 227	1 227	100 %
Single family houses constructed before 2005	16 364	16 364	100 %
Multifamily buildings constructed between 2010 - 2019	1 566	1 566	100 %
Multifamily buildings constructed between 2006 - 2009	663	663	100 %
Multifamily buildings constructed before 2005	27 493	27 493	100 %

Table 6: Comparison of model results for the number of dwellings in Eskilstuna with statistics.

Category	Heated floor area ECCABS # Heated floor area (1 000 m²)	Statistics # Heated floor area (1 000 m²)	Match
Eskilstuna all dwellings	5 094	5 473	93 %
Single family houses	2 626	2 667	98 %
Multifamily buildings	2 469	2 845	87 %

The final energy use (model output) per building type and construction year category is compared tothe related data available in the SCB database for the city of Eskilstuna [54](Table 7). For single family houses, the final energy use is 22 % higher than the statistics. Since renovations are done for buildings constructed earlier and this results in lower heat demand, the difference is found reasonable. 100 % match is achieved for the multifamily buildings.

Table 7: Comparison of final energy use in Eskilstuna with statistics

Category	Final energy use ECCABS	Statistics	Match
	Final Energy Use (GWh/ year)	Final Energy Use (GWh/ year)	
Eskilstuna all buildingss	772	701	110 %
Single family houses	402	331	122 %
Multifamily buildings	370	370	100 %

2.1.2 Upscaling buildings' TES obtained in the demo site.

The potentials for TES in buildings obtained in the demo sites have been upscaled and characterized as required for TIMESCity_heat model i.e., maximum flow ($Flow_{Max}$) and maximum capacity ($Capacity_{Max}$), as follows:

$$Flow_{Max} = \sum_1^i (C_F \times \text{Energy signature}_i) \qquad \text{Equation 2}$$

$$Capacity_{Max} = \sum_1^i (C_c \times C_F \times \text{Energy signature}_i) \qquad \text{Equation 3}$$

Where

C_F is a constant

C_C is a constant

$\text{Energy signature}_i$ is the energy signature of the buildings utilized (kWh/°C)

The constants are based on previous research [50] [55] and have been verified during the demonstration work in Flexisync as well as in the parallel EU-project TEMPO (https://www.tempo-dhc.eu/). The maximum flow approximates the limitation of power in a building per hour. In modelling, power limitation usually is measured in [kW]. Instead, power limitations can be expressed in the unit [kW/°C] which should be interpreted as the power need for a building to keep the indoor temperature stable if the outdoor temperature decreases.

NODA (project partner of Flexi-Sync) Intelligent Systems have empirically found that 10 °C is a good approximation of this constant value (C_F) for buildings in general. This due to control system for a district heater have a maximum effect which is reached when the temperature difference reaches 10 °C. The theoretical maximum effect is reached at 12 °C temperature difference but measurements done on hundreds of real estates over time shows that in practices the effect from the control system is related to 10 °C difference. This measurement is highly dependent on the size of buildings which makes the measurement a bit blunt in the case of many different buildings, as in a city.

The energy signature can be calculated in different ways depending on the available data. For Eskilstuna, as already done in the literature [56], the energy signature has been calculated theoretically from output data from ECCABS model for each utilized building separately, as a linear regression where the hourly heat demand is expressed as a function of outdoor temperature, converting the [°C] to [kW]. For cases with limited data availability, the energy signature can be calculated in a more aggregated way for the entire built area modelled, for instance by multiplying the yearly heat use (kWh) by the share of heat use for space heating, then dividing by the number of yearly degree hours on the location (h).

The TES capacity approximates the maximum power which can be stored in a building. This can be expressed as [°Ch] where the hours simplify approximate how much energy that can be stored, compared with the power needs. NODA Intelligent Systems have simplified the TES capacity as described in Equation 3. Three control levels are used which differ in maximum control time; the proposed constant value (C_C) of 5 h is an average of the different levels of controlling [50] [55].

2.1.2.1 Comparison of climate data

In Equation 3, the *energy signature* for each building is calculated from their energy demand obtained with ECCABS model. The model uses climate data from Meteonorm, which is a calculated average of more than 30 years for the region [57]. Nevertheless, both constants (C_F, C_C) have been approximated empirically, therefore with the climate conditions in the demo sites, which have been measured in year 2020 by the Swedish Meteorological and Hydrological Institute (SMHI) and are different from the values of Meteonorm database. The potential implications of using different climate data in a same equation (in both Equations 2 and 3) are discussed in right below.

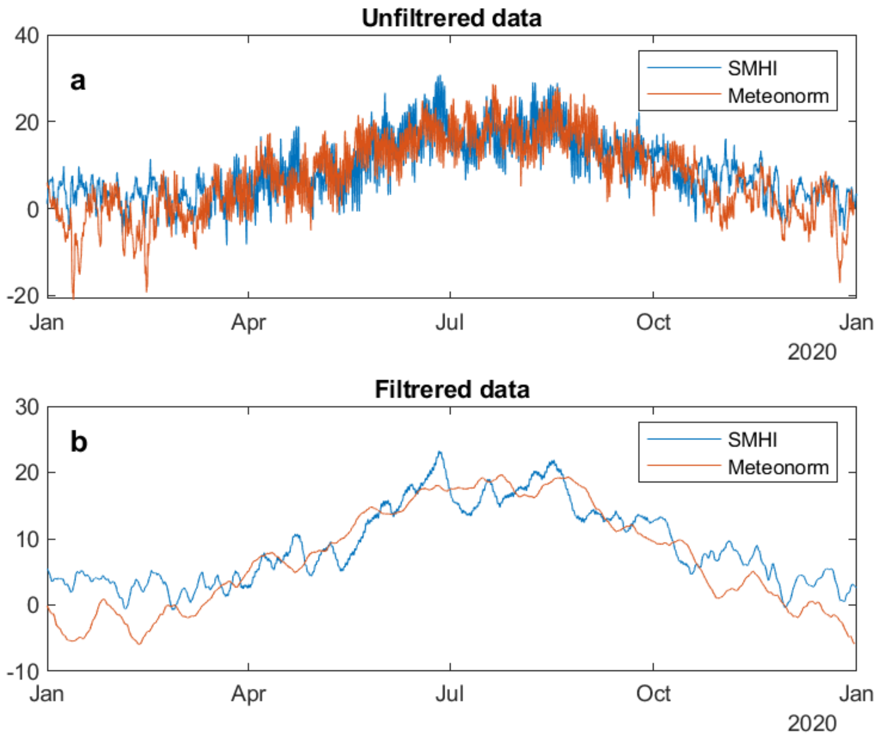

Figure 3: Comparison between data from SMHI and Meteonom. Data from SMHI is from the region near Eskilstuna from 2020 and the Meteonorm data is average calculated over 25 years for the same region.

The hourly outdoor temperatures of both data sets, i.e., the Meteonorm weather model and statistics for 2020 from SMHI for the region near Eskilstuna, are compared in Figure 3a. Figure 3b shows the same data with a moving average filter to reduce the noise of the temperature data. The data from the two different sources show a similar pattern and generally follow the same trend. In the beginning (Jan-Feb) and end (Dec) of the year, there is a difference between the lines, explained by that the SMHI data only includes averaged data, whereas winter in year 2020 was warmer than the average.

2.1.3 TIMESCity_heat model

The cost-efficient flexibility potential in DH systems at a local (city) level is in this work studied with the help of a well-established TIMES (The Integrated MARKAL-EFOM System) model generator [58, 59]. TIMES is a technology rich, bottom-up model generator, which uses linear-programming to produce a least-cost energy system, optimized according to several user constraints over a pre-defined time horizon, usually a few decades. The studied energy system is represented by different processes that are connected by flows of commodities. Each process (such as e.g., an energy conversion technology – HP) is described by its input and output commodities, efficiency, availability, lifetime, and costs. Each commodity (such as e.g., a fuel - biomass) is described by its availability, extraction or import cost and environmental impacts.

Once a model has been set-up in TIMES, i.e., model structure, input data, constraints, scenarios have been put in place, the model solves its objective function. Most commonly, an objective function of a model is to minimize the total system cost, i.e., the sum of the running and investment costs, of the modelled energy system while assuring that the energy system meets the energy service demands over a time horizon. Models developed in TIMES assume perfect foresight, which is to say that all investment decisions are made in each investment period with full knowledge of future events. The results expected from a model run are: 1) the optimal mix of technologies available and running in each modelled period; 2) the fuels used for in the used technologies; 3) emissions from the operation of the energy system, and others.

For the purposes of the Flexi-Sync project, a TIMES model, which spans the heating sector of a given city, was developed by IVL, and applied to Eskilstuna and it will hereafter be referred to as the TIMESCity_heat model. The objective function of the TIMESCity_heat model is to minimize the cost of meeting the total heating demand of the city. The total heating demand consists of the space heating and hot water demands from the city's residential and non-residential buildings stocks. The supply side includes both centralized (in DH) and decentralized (individual), heating technologies. The DH network is also represented in the model but in a simplified way – only in terms of energy flows (in MWh), while disregarding physical parameters such as, water volumes and temperatures, or pressure drops in the network. A schematic representation of the TIMESCity_heat model can be seen in the Figure 4.

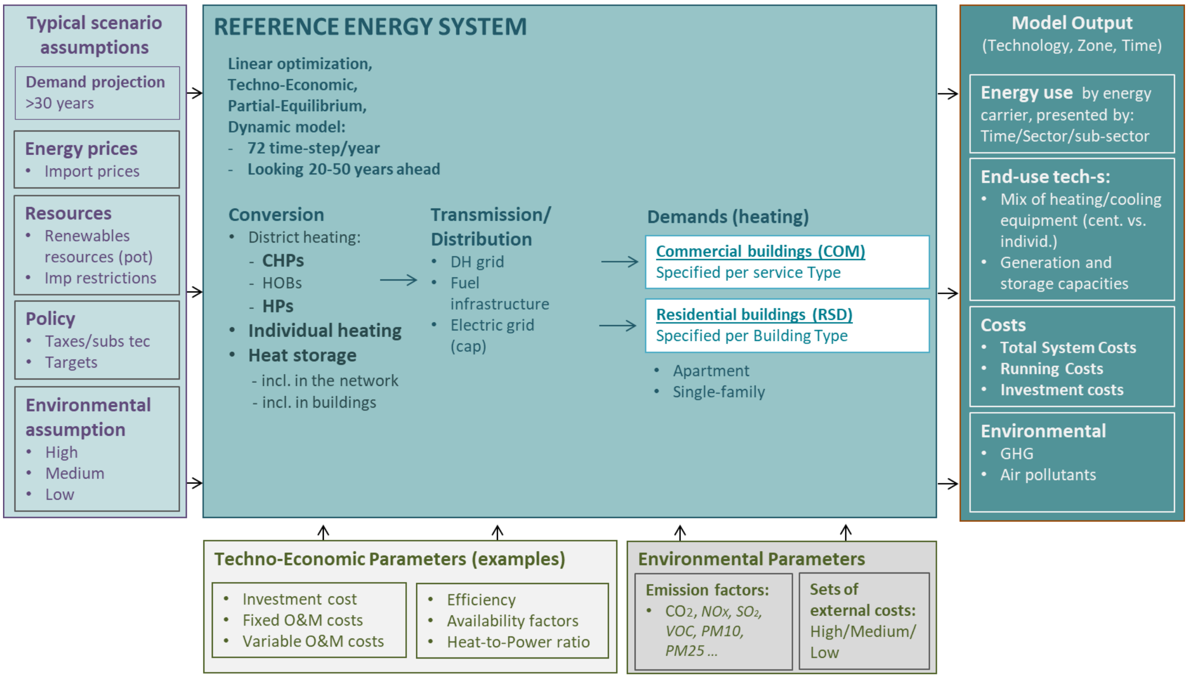

Figure 4: Schematics of the developed TIMESCity_heat model.

The TIMESCity_heat model has a time horizon of several decades, i.e., covers the period between the base year (2018) and the year 2050 (with 5-year step). In the base year, centralized and decentralized heating technologies included in the model reflect the existing generation units and the fuel mix of the modelled city. Under the modelled period, existing generation capacities will gradually be phased out and replaced by new technologies as a result of the model optimization. The existing DH network will also be updated/expanded in the future because of the model optimization. Each model year is divided in 72 time-slices, representing combinations of 12 months, workday and weekend, day/night/peak time (12 * 2 * 3 = 72), as shown in Figure 5.

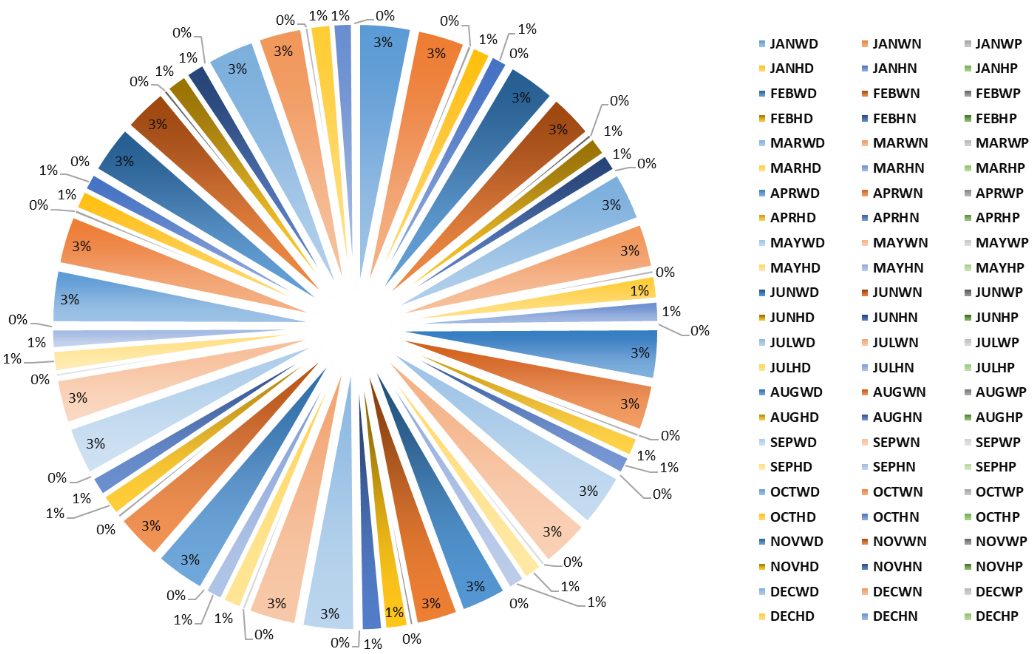

Figure 5: Breakdown of time-slices in TIMESCity_heat model.

Projections for future heat demand (including implementation of efficiency measures in buildings) are provided as inputs to the model, as described in section 2.1.2.3 below. As indicated earlier, the analysis is limited to heating supply and demand of the city, although electricity generation and consumption is considered when it is generated in CHP plants or consumed by electric boilers or HPs. The electricity system as well as international markets for fuels are treated exogenously. A discount rate of 5 % is used in the model.

2.1.3.1 Case study: Eskilstuna

In the TIMESCity_heat model, the DH system of Eskilstuna in the base year 2018 comprises a biomass-fired CHP plant, biomass-fired heat only boiler (HOB), four bio-oil-fired HOBs, and four oil-fired boilers normally used as a reserve capacity. Both the CHP and the biomass-fired HOB have flue gas condensation, which increases the efficiency of the plants. The total heat generation capacity available in the DH system of Eskilstuna is 465 MW. There is a centralized TES connected to the network with the capacity of 900 MWh. Supply/return temperatures of the DH network are 75 – 100 / 40 - 50 °C. DH network length: 33 km. Yearly losses in the DH network are assumed at 10 %.

2.1.3.2 Input data and assumptions

The heat generation technologies included in the modelling can be divided into i) existing investments, and ii) potential new investments. Each of these categories includes centralized heat generation units – units that supply heat to the DH network, and individual heat generation units installed at the building side. The assumed in the model technical parameters of the existing centralized heat generation units were checked with the project partner - Eskilstuna Energi och Miljö. The technical parameters of the existing individual heat generation units were assumed to be the same as in the TIMES-City model, developed and applied in the ERA-NET SureCity project [60]. The techno-economic parameters assumed for the centralized and individual heat generation technologies available in the model as investment options were extracted from the Danish Technology Catalogue [61].

The total yearly heating demand (both space heating and domestic hot water) in the city of Eskilstuna was assumed to be around 1 400 GWh in the base year (2018) [28, 27]. In this work, the heat demand of the city is assumed to remain the same in the future up to the year 2050. This can be explained by the fact that the potential increase in the heating demand due to expanding building stock will be compensated (reduced) to a similar degree by implementation of energy saving measures in the existing stock. The assumption is also motivated by that the effects of changed heating demand on the heating supply of the city are not the focus of this project, as will be commented in Section 4.

The total yearly heating demand is divided in the model by the heat source, i.e., generation technology, and by the end use: space heating and hot water demand. The shares of the heating demand supplied by DH and by other technologies in the base year were assumed based on the information available from the Eskilstuna municipality [28].

In the TIMESCity_heat model, the balance between heat supply and demand is kept not only at the yearly level, but also at the sub-annual level, i.e., in each time-slice. The aggregated hourly heat demand profile from the DH substations of the city of Eskilstuna in the year 2018 was obtained from WP4 and used as a basis for estimating space heating and domestic hot water demands in each time-slice. The approach used to separate space heating demand profile from the hot water demand profile using a single profile from the DH substations has been described in the literature [62]. The space heating demand and hot water demand profiles (fractions of the total demand) used in this work are presented in the Annex A, Figure A.27.

The hourly electricity price profiles and the CO_2 emission factors for electricity consumption/generation in the price area of Sweden used in this project (see Appendix A) were obtained from the NordPool wholesale electricity market *[63]* and Balmorel modelling performed by EA Energy Analysis A/S *[64]*. The assumed fuel and CO_2 prices used as inputs in the SURECIty_heat model were extracted from the TIMES model developed and applied in the Nordic Clean Energy Scenarios (NCES) (https://cleanenergyscenarios.nordicenergy.org/).

Existing TES technologies in the DH system of Eskilstuna are a hot water tank and TES in the DH network. TESs in multi- and single-family houses are already present in the city but require investments in, at least, smart-metering devices and hence, are classified as investment TES options. All the TES technologies considered in this work, together with their parameters, are listed in the Table 8. The technical parameters of the TESs in the DH network were calculated by project partner LTU, whereas for the buildings TES, the maximum capacities and flows were calculated separately for multifamily buildings and single-family houses as described in Section 2.1.2 (ECCABS model, Task 2.2).

Table 8: Assumed techno-economic parameters of the investigated TES options.

		Existing TES		**Investment TES options**					
	Unit	TES in DH network	Existing water tank	TES in multi-family houses	TES in single-family houses	Large water tank	Cavern TES	Pit TES	Borehole TES
Cycle efficiency (inflow/outflow)	%	100	98	100	100	98	98	70	98
Daily losses	%/day	24	0.19	14	22	0.19	0.07	0.14	0.12
Maximum inflow/outflow	MW	13*	60	20**	32**	-		-	
Maximum capacity	MWh	30*	900	102**	160**	-	-	-	-
Lifetime	Yr	-	40	-	-	40	40	20	40
Investment cost	kEUR/TJ	-	-	15.6***	23.5***	823	500	161	53
Fixed O&M cost	kEUR/TJ	-	-	-	-	2.4		0.8	-

* Considering temperature difference in the supply water pipe of 5K,
** Calculated in Task 2.2, see sections 2.1.1 and 2.1.2
*** Values are in kEUR/MW and are calculated based on the estimated number of substations and the data and approach presented by Romanchenko et al. [20].

2.1.3.3 Scenarios

Four scenarios are investigated in this work using the TIMESCity_heat model. All the scenarios share the same Carbon Neutral Nordic (CNN) central storyline (also described in D2.1 [1]) and are only different regarding the availability of TES (both centralized and decentralized) in the studied DH system, as explained below.

The CNN storyline has been developed in the NCES project. The CNN storyline seeks the lowest-cost pathway to carbon neutrality for the Nordic countries by 2050, considering national plans, strategies, and targets. According to this storyline, the green transition is driven by high CO_2 prices equal to those applied in the Sustainable Development scenario of the IEA's World Energy Outlook 2020. The storyline is also characterized by high deployment rates of RES, limited biomass imports to the Nordic countries, significant demand for power-to-XX technologies and increased export of electricity from the Nordic Countries (more details: https://cleanenergyscenarios.nordicenergy.org/). The impact of the CNN storyline on the modelling performed with the TIMESCity_heat model is this work is via the assumed electricity price profiles, CO_2 emission factors associated with electricity consumption, fuel prices and price of CO_2 (further details in Section 2.1.3.2).

The four scenarios investigated in this work with the TIMESCity_heat model are:

1) "No_TES" – none of the TES options are included in the model (no TES in the city),

2) "Exist_TES" – existing TES options are included in the model,

3) "New_TES" – existing TES options are excluded from the model (assumed to be unavailable), but the model can invest in new storage capacities,

4) "All_TES" – both types of TES, i.e., existing and new investment options, are available in the model.

Note that there are two TES options already available in the city of Eskilstuna: i) a large water tank connected to the DH system, and ii) the DH network itself. Hence, the "No_TES" and "New_TES" scenarios are not realistic. However, having these scenarios is deemed necessary to study the effects of TES on the heating supply of the city and on the interplay between the DH system and the electric power system. In other words, to investigate the benefits of having a TES in the DH system, the operation of the system without a TES should be compared to the operation of the system with TES available.

2.2 Results

2.2.1 Connection between the heating and electric power sectors

The results of the modelling show that the heating sector of the city of Eskilstuna will be dominated by electricity consuming technologies, i.e., HPs, starting as early as the year 2040. Figure 6 shows the total heat generation mix of the city between the base year 2018 and year 2050 obtained from the modelling in the "No_TES" scenario (scenario without any TES unit). The available in the DH system biomass-fired CHP plant is retired between the years 2035 and 2040 and stops heat generation. To replace the retired capacity, the model invests in an air-based HP that becomes the main heat generation unit in the DH system of Eskilstuna. One of the reasons for this shift from the CHP plant-dominated to the HP-dominated DH system is the assumed decrease in the electricity price in the future years (see Figure A.28), which makes CHP plants less profitable and HPs more profitable to run. Also, an expected increase in the COP value of the analysed HPs is another major factor.

Figure 6 also shows that slightly less than one third of the heating demand of Eskilstuna in the year 2050 will be covered by individual heating technologies. These are, again, air-based HPs and biomass-fired heat only boilers. The reasons for the utilization of individual HPs are like the ones discussed for the centralized HPs above. The main reason behind the investments in the biomass-fired boilers is the limit in the transmission capacity of the DH network. The model does not invest in the expansion of the DH network, i.e., the capacity of the network remains at the current level (the amount of heat delivered by the DH network does not change with time). This indicates that considering both investment and running costs over the investigated time horizon it is cheaper to supply one third of the city's heating demand by individual heating technologies than to invest in expansion of the DH network.

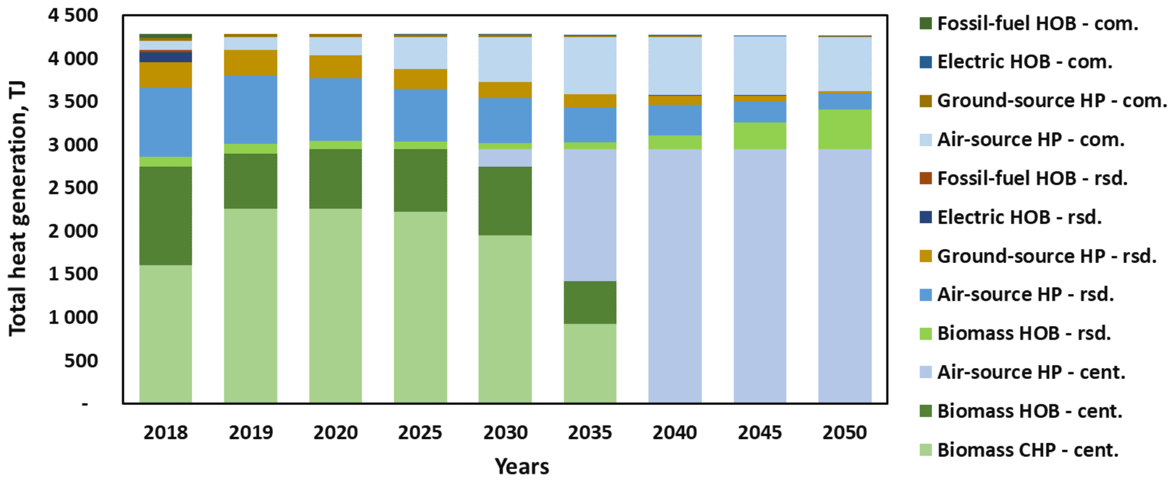

Figure 6: The total heat generation mix of the city of Eskilstuna between the base year 2018 and year 2050, as obtained from the modelling in the "No_TES" scenario. "cent.", centralized (in DH); "rsd.", individual residential heat generation technologies; and "com.", individual commercial heat generation technologies.

The modelling results for the "Exist_TES", "New_TES", and "All_TES" scenarios show similar results of the development of the heat generation mix of Eskilstuna - dominance of HPs by the year 2050, as in the "No_TES" scenario. This indicates that the availability of a TES does not affect the generation mix of the heating sector of the city to a significant extent.

Our results show that the heating sector of Eskilstuna shifts from being a net electricity generator to a major electricity consumer (see Figure 7). The cost-optimal operation of the DH system of Eskilstuna in year 2019, results in almost 1 000 TJ of generated electricity by the available CHP plant. At the same time, total electricity consumption for heating is around 400 TJ. Starting year 2040, the electricity consumption for heating exceeds 1 000 TJ while there is no more electricity generation. This implies that the city's heating sector becomes a net consumer of electricity and can use the cheap, excess electricity in the power sector. However, such a shift in the direction of electricity flows creates a significant challenge for the local power distribution grid. Also, reliance only on electricity consuming technologies in the city's heating sector limits its potential to provide flexibility services to the electric power sector – retirement of the CHP plant eliminates the possibility to generate electricity during the periods of high electricity prices.

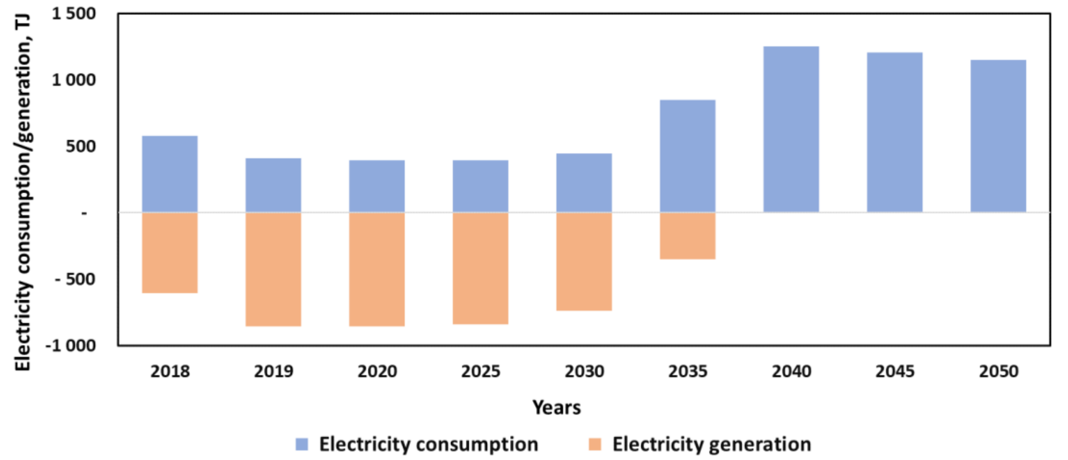

Figure 7: The electricity generation-consumption balance of the heating sector of Eskilstuna, as obtained from the modelling in the "No_TES" scenario and shown for the years 2018 - 2050.

The modelling results indicate that the effect of a TES being available in the DH system on the overall electricity consumption/generation balance of the city is minor (comparing results of the "Exist_TES", "New_TES", "All_TES" scenarios to the "No_TES" scenarios). Yet, electricity consumption noticeably increases in the "New_TES" and "ALL_TES" scenarios. This is due to greater levels of heat generation by HPs with the objective to store heat between seasons.

The tight connection between the heating and electricity sectors is highlighted in Figure 8. The modelling results show that the variations in the applied electricity price profile are significant enough to affect the operation of the heat generation units in the investigated heating sector of Eskilstuna: the air-based HPs generate heat during the periods of lower electricity prices, while the biomass-fired CHP plant is dispatched to generate heat during the periods with higher electricity price. It can also be noted that during the periods of greater heat demand, i.e., the month of October in the figure (and other winter months), the impact of varying electricity prices is not evident, because both the HP and CHP technologies generate heat at their rated capacities.

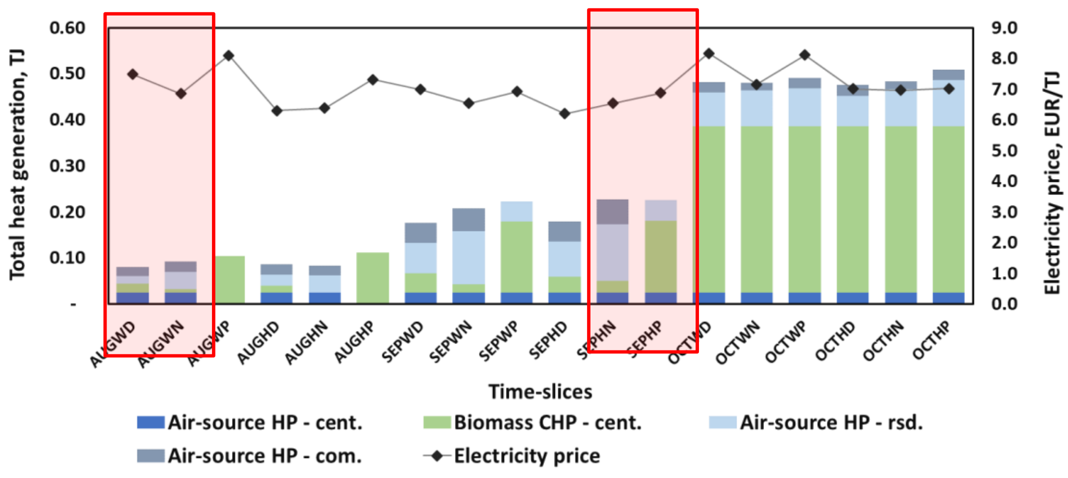

Figure 8: The total heat generation mix of the city of Eskilstuna, as obtained from the modelling in the "No_TES" scenario and presented for several time-slices (the values are in TJ/hour). Notations "AUG", "SEP", and "OCT" stand for August, September and October, respectively. "W" and "H" stand for workday and weekend, respectively. "D", "N", "P", stand for day, night, and peak, respectively.

2.2.2 Cost-efficient flexibility (thermal storage) potential

The modelling results show that the changes to the heat supply strategy of the city in the presence of a TES lead to reduced costs of heating. Table 9 shows the total system cost of heat supply in the city over the modelled time horizon: 2018 - 2050. It can be noted that the total cost of heat supply is reduced by 0.5 % in the "Exist_TES" and "New_TES" scenarios and by 1 % in the "All_TES" scenarios, as compared to the "No_TES" scenario. This indicates that despite the investment cost required to invest in TES, the cost is paid off by reduced operational expenses of heat generation.

Table 9: The total system cost (over the time horizon) as well as total energy and power capacity of the TESs (in the year 2050) in the city of Eskilstuna, as obtained from the modelling for the 4 investigated scenarios.

	Total energy capacity of the TESs in 2050, MWh	Total power capacity of the TESs in 2050, MW	Total system cost, MUR
"No_TES" scenario	-	-	842.6
"Exist_TES" scenario	930	73	838.5
"New_TES" scenario	197 046	130	838.4
"All_TES" scenario	200 930	188	834.6

The results show that significant effect on the operation of the centralized heat generation units occurs in the "New_TES" and "All_TES" scenarios. This is because of the significant investment in a seasonal borehole TES of around 200 GWh of energy and 100 MW power capacity. The effect of the seasonal TES can be seen in Figure 9, which presents so-called duration curves of heat generation, i.e., heat generated in each of the time-slices placed in descending order. The generation of heat during the periods of highest heat demand is significantly reduced in the "New_TES" and "All_TES" scenarios, as compared to the "No_TES" and "Exist_TES" scenarios. Whereas, between the time-slices 30 and 50 in the figure, the heat generation in the last two scenarios is obviously greater than in the first two. This indicates that the heat generated during the periods of lower demand is stored in the seasonal TES and then released from the TES during the periods of peak demand.

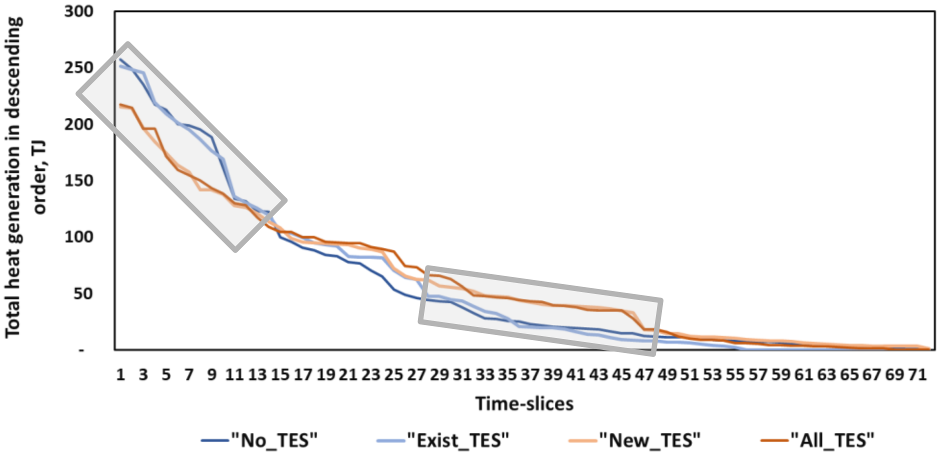

Figure 9: Total heat generation in descending order, for the different scenarios modelled.

It can also be added that the model invests in the building TES, specifically in TES in multi-family houses, in the "New_TES" scenario. From this, we can conclude that in the absence of the existing TES options (hot water tank and the network TES), investment in the building TES becomes cost-effective. At the same time, the model does not invest in the TES in single-family houses, indicating that their storage capabilities are less attractive for storing heat. That is, investment cot in the single/family houses TES is greater than in the multi/family houses TES. Also, losses from the former TES are greater than in the latter.

3 LOWER AUSTRIA

The demo Maria Laach is in the region of Lower Austria. With a land area of 19 186 ics and a population of 1 612 million inhabitants, Lower Austria is the country's largest state and the second one most populated after the federal state of Vienna [65].

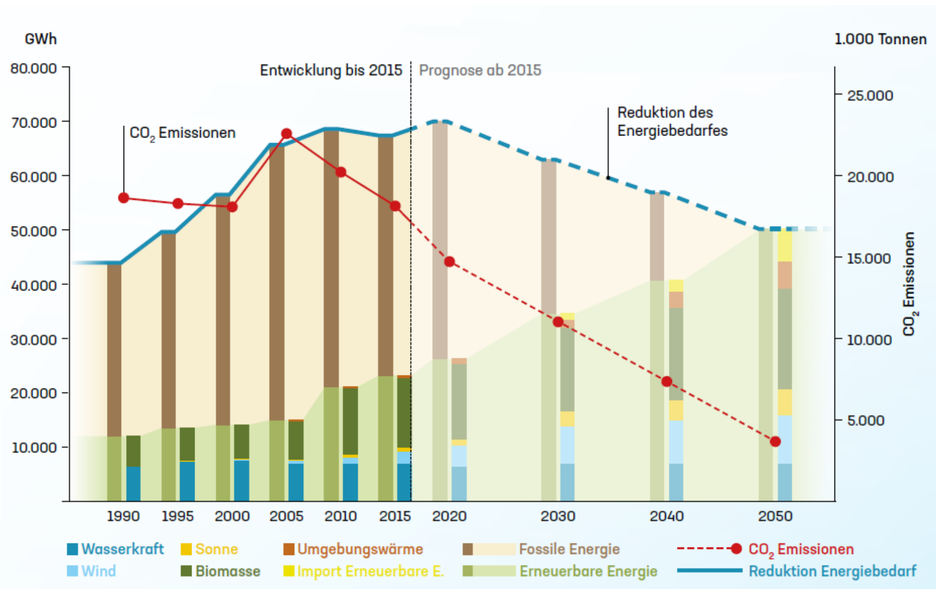

Figure 10: Lower Austrian vision for energy transformation [59].

Figure 10 shows the Lower Austria vision of the future energy transformation. The goal of Lower Austria is to replace gasoline, diesel, heating oil, natural gas and coal with renewable electricity, heat and fuels from hydropower, biomass, wind, ambient heat, as well as solar heat and electricity. The largest expansion of renewable energy is to take place in wind power and solar power (photovoltaics, PV). Wind energy is to be doubled and P) sevenfold by 2030. An increase of a third is planned for biomass. A slight expansion of hydropower as well as geothermal and solar heating also contribute to the fact that renewable energy production is to be increased from just under 28 TWh today to 37 TWh by 2030 and over 45 TWh by 2050 [66].

In the heating sector, fossil fuels, including natural gas, are gradually being reduced. The existing heaters that use liquid and solid fossil fuels are planned to be banned in 2040 [67]. This change will be accompanied by promoting a switch to sustainable heating systems such as HPs, biomass, and DH. Wood and other biomass (e.g., pellets) are only available to a limited extent, so the greatest increase in the heat sector is to be expected in the case of HPs [66]. In addition, biogas, and synthetic gasses[1] will be promoted to replace natural gas to take advance of the current gas grid infrastructure to support the decarbonization of the gas sector [67].

In parallel, the implementation of the Directive 2012/27/EU will allow low-energy buildings tol become the standard for new and refurbished buildings, reducing future heat demand [67].

3.1 Method

The methodology integrates three modelling approaches to i) assess the impacts of flexibility measures in Maria Laach am Jauerling on the electricity markets from WP1 (blue box), ii) project future electricity price in Austria (green box) and finally iii) project developments of the heating sector for the residential and service buildings in Lower Austria (red box) (Figure 11). The models will be presented in corresponding subsections below. Data collection and assessment of the status of Lower Austria relate to Task 2.2 while the implementation of the HLA-Times model as well as the linking of this model with the other models is performed in Task 2.3.

[1] Synthetic gas refers to a fuel gas mixture consisting of hydrogen, carbon monoxide and carbon dioxide.

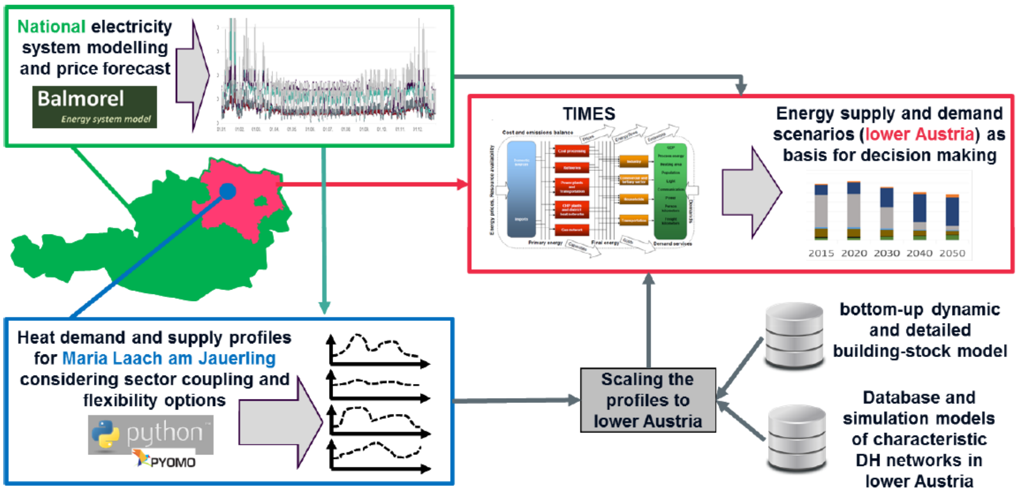

Figure 11: Overall methodology for Austrian study case.

The models are combined to evaluate future development scenarios for the heating sector (residential and services) in Lower Austria, in the following steps:

1. Deployment of the overall structure of the heating sector with energy system model TIMES-MARKAL
2. Integration of the future electricity prices from Balmorel model
3. Integration of the flexible measures evaluated in Maria Laach am Jauerling from the MILP optimization model
4. Creation of a techno-economic of database for the residential, service and DH sector
5. Calibration of the base year and future demand heat projections
6. Implementation of the of the energy and technological constrains
7. Scenario implementation for future decarbonization and energy transition to assess the scalability of the flexible measures
8. Scenario evaluation.

3.1.1 (MILP) optimization model

The first energy model assesses the impact of Demand Side Management (DSM) as a flexibility measure for the demo site Maria Laach am Jauerling (see also DSM in Appendix B2). This assessment is done with the use of a Mixed Integer Linear Programming (MILP) optimization model. For the implementation, the PYOMO optimization framework is used in conjunction with the IBM CPLEX solver to determine the economic potential of both a CHP and a HP, delivering thermal power to flexible buildings and participating in the day ahead and balancing electricity market.

3.1.2 Balmorel

The second energy model estimates future electricity prices in Austria. For this purpose, BALMOREL power system model is applied. It is an open-source modelling tool that minimizes the total investment and operational costs of the system. It considers the balance of supply and demand of electricity, possible investment in new generation and transmission capacity, power plant and transmission line capacity restrictions and efficiencies, as well as limits of hydro reservoirs and other storage systems [68].

The average price grows between 2017 and 2030 from 34.27 €/MWh to 43.02 €/MWh (Appendix B2). This is mainly due to the higher investment in renewables and the future increase of the price of natural gas, which is used as back-up when RES are not able to cover the electricity demand.

Electricity prices from 2017 and 2030 are converted by time slices to be implemented in HLA-Times (Appendix B2). Figure B.40 shows electricity prices by different time-slices in 2017, 2030 and 2050. According to the projection, electricity prices will grow beyond 2030 to an average of 55.63 €/MWh in 2050. Nevertheless, the increase of the prices will not be homogenous in all the time slices. While a reduction of electricity prices in the day-slice can be estimated, a continuous increase is taking place in the night-slice.

3.1.3 TIMES Heating Lower Austria (HLA)

The third energy system model assesses the impact of the flexible measures in the heat sector of Lower Austria, which aims for scaling up measures considered for Austrian demo site. This model is developed with TIMES energy system modelling tool, which is a technology rich, bottom-up model generator. The model uses linear-programming to produce a least-cost energy system, optimized, over medium to long-term time horizons. It encompasses all the steps from primary resources through the chain of processes that transform, transport, distribute and convert energy into the supply of energy services demanded by energy consumers [69] .

As in any TIMES model, the equilibrium is driven by the maximization of the discounted present value of total surplus, representing the sum of surplus of producers and consumers, which acts as a proxy for welfare in each region of the model [69].

The HLA-Times model considers both the energy supply and demand sides of the energy system as depicted in Figure 12.

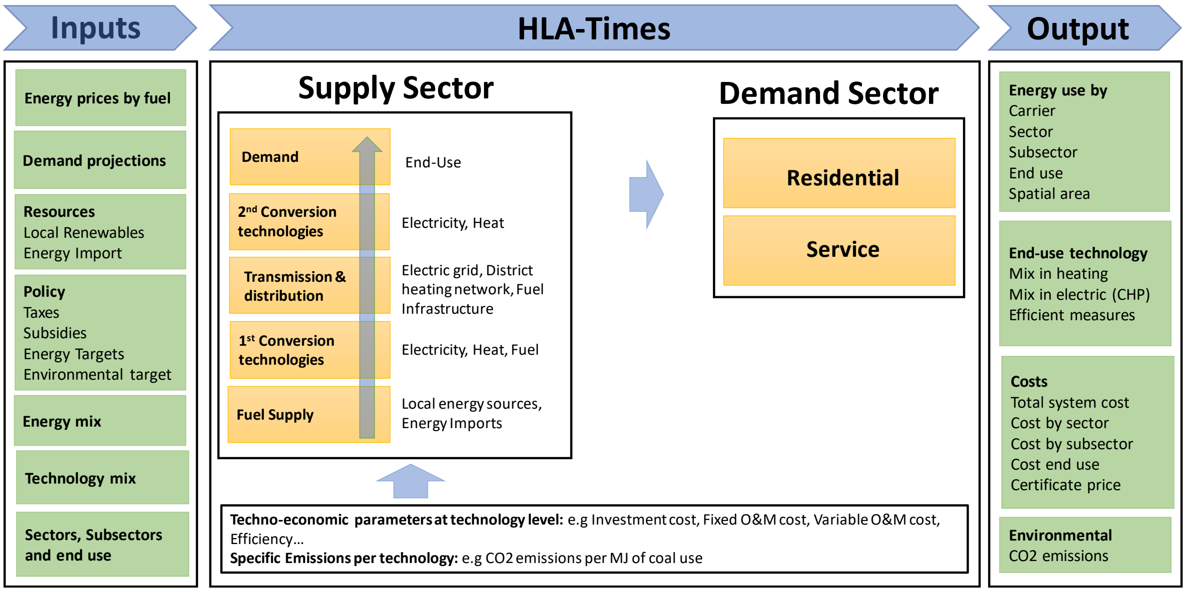

Figure 12: Overview of the HLA-Times model.

HLA-Times model considers the following demand sectors separately:

- Residential buildings (RSD) disaggregated into two building typologies according to single house (Residential Houses-RH) or multiapartment (AP). Each typology is split in four classes depending on the energy performance of the building envelope: very high efficiency, high efficiency, standard efficiency, and low efficiency.
- Service sector (SERV) considers only one category.

In addition, the model considers the following energy sectors:

- Energy supply (SUP) that covers the supply of RES within the region, as well as the energy imports from outside the region, namely, electricity, natural gas, liquid petroleum gas, gasoline, diesel, coal, fuel oil, biomass, and municipal waste. It also includes the possibility of exporting electricity generated within the region.
- Heat generation (HEAT), which includes all possible generation plants for DH within the region´s boundaries and disaggregated by heat only and combined heat and power (CHP).

HLA-Times energy model requires as input a set of some specific data exogenously:

- Energy demand for final end-use energy services. HLA-Times energy model considers two end-use services for RSD and SERV sectors: Space heating (SH) and domestic hot water (DHW).
- Techno-environmental-economic characteristics of existing and future energy technologies at building level and DH level.
- Existing and future energy sources and potentials including endogenous energy sources potential, imports limits and costs.
- Policy assumptions and constraints such as GHG mitigation targets, potential for building retrofit or expansion of DH. These are scenario specific and are connected to the policy portfolio to be assessed and analysed.

3.1.3.1 Case study: Spatial and temporal resolution

Lower Austria accounts 573 municipalities, from which the most relevant are Sankt Pölten and Wiener Neustadt with 55 878 and 46 456 Inhabitants [70]. The municipalities are included in the models as two spatial zones: Urban (population higher than 10 000 inhabitants) and Rural (Appendix B2).

As for the temporal resolutions, the HLA-Times model represents Lower Austria from the selected 2017 (base year) till 2050 in five-year time steps (base year, 2020, 2025, 2030, 2035, 2040, 2045, 2050). Figure 13 shows the allocation of the time-slices in fraction of the year for HLA-Times Model. Each year is divided in 12 time-slices that represent an average day (D), night (N) and peak (P) demand for every one of the four seasons: Spring (R), Summer (S), Fall (F) and Winter (W).

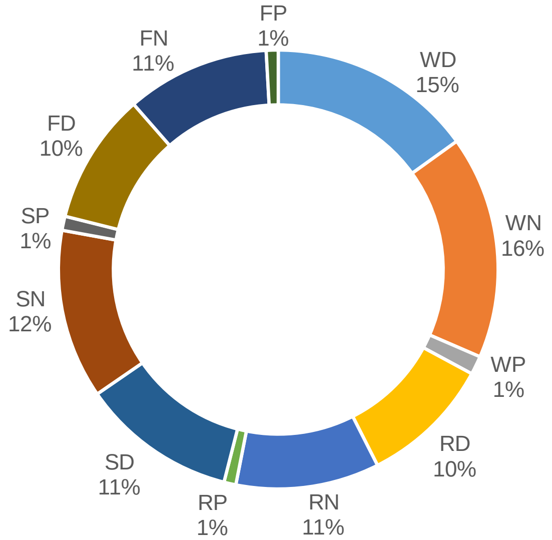

Figure 13: Breakdown of time-slices in HLA-Times Model. RD: Spring Day, RN: Spring Night, RP: Spring Peak, SD: Summer Day, SN: Summer Night, SP: Summer Peak, FD: Fall Day, FN: Fall Night, FP: Fall Peak, WD: Winter Day, WN: Winter Night, WP: Winter Peak.

3.1.3.2 Input data and assumptions

HLA-Times energy model requires following exogenously inputs: heat demand projections by sectors (residential and service), building typology (apartment building or single building) and final end-use energy services (space heating and domestic hot water). The assumptions for these inputs are shown in Appendix B1.

Fuel prices are based on the JRC-EU-TIMES model for Austria [71]. All prices and costs are at constant prices in euros 2017. Therefore, the impact of inflation is not considered along the simulated period (up to 2050) or another unexpected events that may affect fuel prices or technology costs. The future electricity prices are estimated (2030) by Balmorel energy model, as described in section 3.1.2 . The model considers national targets by 2030 based on the Austrian National Climate and Energy Plan (NECP) [72]. Electricity prices are calculated as constant in 2017 and for the year 2030, and then extrapolated for the remaining periods (i.e., for 2050). CO_2 emission prices are assumed to increase in the future, due to the structure of EU ETS [73]. Accordingly, CO_2 prices increase from 7.8 €/ t CO_2 in 2017 to 34.2 €/ tCO_2 in 2030, and up to 200 €/ tCO_2 in 2050. Further details on the prices for fuels, electricity and CO_2 emissions are given in Appendix B2.

3.1.3.3 Scenarios

Two scenarios are explored for the heating sector in Lower Austria: 100 % Renewable scenario (100% RES) and Maximized Flexibility (MF) scenario. Both scenarios follow the vision for the local development [1]:

- high decarbonization of the heating sector
- high integration and collaboration between political administration and companies
- high penetration of DH with a predominant use of RES, mainly biomass.
- DH networks are "smart"; they include energy storages and DSM. In year 2050, DSM is implemented in the 25 % of buildings in the case of 100 % RES scenario while in the 45 % of buildings in the case of MF Scenario.

Figure 10 describes the main parameters of 100 % RES and MF scenarios. The fundamental difference between both scenarios is that the 100 % RES explores the transformation of the heating sector in Lower Austria due to the increase of use of RES, mainly biomass, as well as the expansion of DH. MF scenario, on the other hand, goes further in exploring the expansion of additional innovative solutions such as heat pumps, DSM, thermal storages or use of biogas in CHP plants.

The flexibility measures that contribute to the decarbonization of heating sector in Lower Austria include sector coupling via HPs and CHP plants and other flexibility options such as TESs for DH and demand-side management (DSM). Two main TESs are considered: Pit TES and large-scale water tanks for DH.

Table 10: 100 % RES and MF scenario

	100 % RES	MF
GHG emissions	▪ Low GHG Emission	▪ Low GHG Emission
Energy demand side	▪ Economic value creation decouples from final energy demand. ▪ Annual building renovation rate is 0.6 %/a up to 2050	▪ Economic value creation decouples from final energy demand. ▪ ***High penetration of flexibility measures.*** ▪ Annual building renovation rate is 0.6 %/a up to 2050
Energy conversion	▪ CO_2 neutral society by 2040. ▪ Policy support for energy efficiency improvements and use of green technologies. ▪ High relevance of DH with a predominant use of biomass.	▪ CO_2 neutral society by 2040. ▪ Policy support for energy efficiency improvements and use of green technologies. ▪ High relevance of DH with additional fuels like biogas apart from biomass. ▪ ***DH incorporates innovative solutions such as biogas, heat pumps and other flexibility options (thermal storages and DSM)***
Fossil fuel supply	▪ Clear reduction of fossil fuel supply. ▪ High acceptance of biomass renewables technologies ▪ Medium acceptance for non-biomass fuels	▪ Clear reduction of fossil fuel supply. ▪ High acceptance of biomass renewables technologies ▪ ***High*** acceptance for non-biomass such as biogas and heat pumps. ▪ ***Flexibility options are fully accepted.***

The techno-economic characteristics of these measures considered in the simulation (e.g., efficiency, costs, availability factor, lifetime) are presented in Appendix B2 for the years 2017, 2030 and 2050.

The DSM measures are implemented in the HLA-Times energy modelling by modifying the share of the heating load in the time slices. Figure 14 shows the capacity load ratio by time slices in case that DSM is implemented or not in the residential sector. The capacity load ratio is defined as the ratio between the maximum[2] capacity need to cover the heat demand in each time slice. In case of WP, capacity ratio is highest when non-DSM is applied.

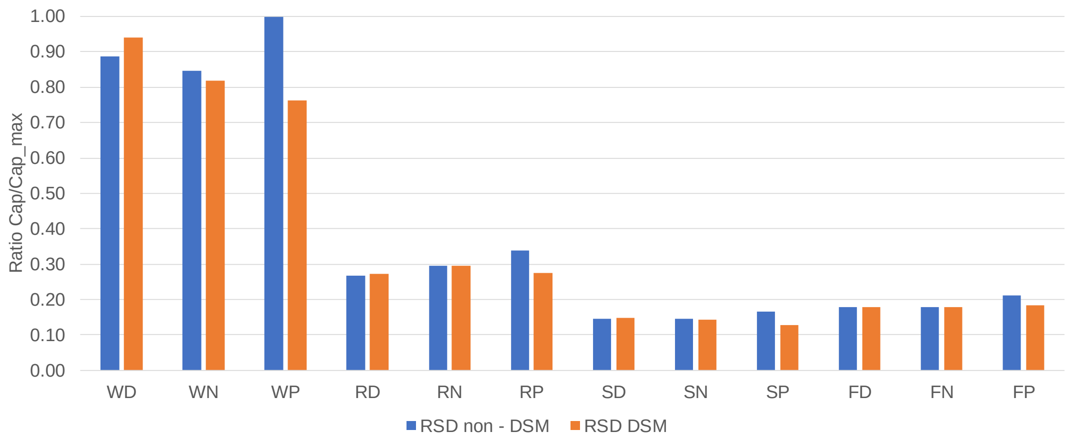

Figure 14: Capacity load ratio by time slices without DSM (non-DSM-Demand) and with DSM (DSM-Demand) for the residential sector. RD: Spring Day, RN: Spring Night, RP: Spring Peak, SD: Summer Day, SN: Summer Night, SP: Summer Peak, FD: Fall Day, FN: Fall Night, FP: Fall Peak, WD: Winter Day, WN: Winter Night, WP: Winter Peak, RSD non-DSM: Residential building without DSM system, RSD DSM: Residential building with DSM.

Figure 15 presents capacity load ratio by time slices without DSM and with DSM. As in the residential sector, the maximum capacity peak load for the service sector is in case of WP in the non-DSM case.

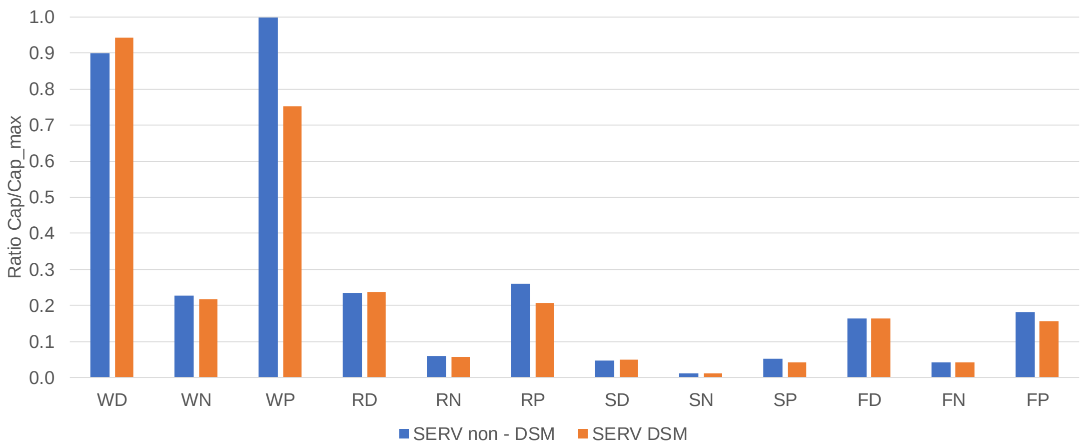

Figure 15: Capacity load ratio by time slices without DSM (non-DSM-Demand) and with DSM (DSM-Demand) for the service sector. RD: Spring Day, RN: Spring Night, RP: Spring Peak, SD: Summer Day, SN: Summer Night, SP: Summer Peak, FD: Fall Day, FN: Fall Night, FP: Fall Peak, WD: Winter Day, WN: Winter Night, WP: Winter Peak, RSD non-DSM: Residential building without DSM system, RSD DSM: Residential building with DSM.

3.2 Results

The results from the simulation for the 100 % RES Scenario and MF Scenarios show that in general the sector coupling (biomass CHP and air-source heat pumps) will play a decisive role for the decarbonisation of the heating system in Lower Austria. These are also in line with state level goals (see section 3).

In following the results are presented in terms of energy consumption for analysed sectors (residential, service and DH) in more detail. In addition, for the DH sector, heat and electricity generation are addressed.

3.2.1 Residential sector

For the 100 % RES and MF scenario, the use of fossil fuel in the residential sector ends in 2040 and building refurbishment plays an important role to reduce energy consumption. To cover the future heat demand, the relevance of heat pumps (air and geothermal-AHT and GEO) together with DH increases in both scenarios. However, the use of heat pumps is in MF Scenario higher.

Figure 16 shows the projection of fuel consumption and heat demand of the residential sector in urban zones for both scenarios. In both scenarios, heat demand is reduced representing around 6.9 PJ (1 917 GWh) in 2050. In this year, building refurbishment (SAV) plays an important role, which a contribute to reduce the heat demand in around 1.8 PJ (500 GWh). The value related to the insulation (SAV) represents the energy savings due to this measure and how the overall heat demand is reduced by this measure.

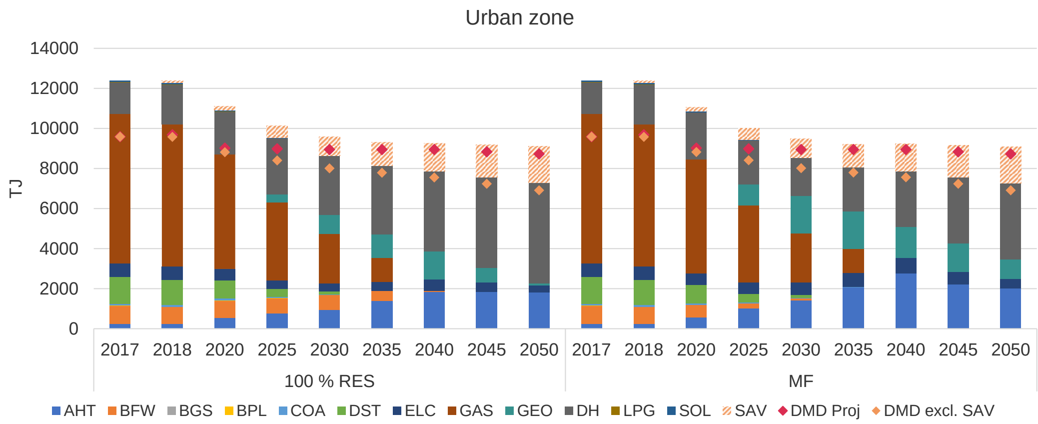

Figure 16: Projection of fuel consumption and heat demand projection in urban zone and residential sector up to 2050 in 100 % RES and MF Scenarios. AHT: Ambient heat, BFW: Biofuel wood, BGS: Biogas, BPL: Bio-pellets, COA: Coal, DST: Diesel/Fuel-oil, ELC: Electricity, GAS: Natural gas, GEO: Geothermal heat, DH: District heating, LPG: Liquid petroleum gas, SOL_ Solar thermal, SAV: Saving due to insulation, DMD – Proj: Heat demand projection, DMD excl. SAV: Heat demand projection discounting heat saving due to insulation.

In 2050, for 100 % RES Scenario total fuel consumption is 7.2 PJ (2000 GWh) where DH and air-source heat pumps (AHT) are the main technologies covering 69 % and 30 % of the fuel consumption. Although, geothermal heat pump (GEO) is important technology for the transition, for example it generates 1.4 PJ (389 GWh) and shares 20 % in 2040, its relevance decreases along the time and is marginal in 2050.

In 2050, for MF Scenario total fuel consumption is 7.3 PJ (2 028 GWh) where district heating (DH) and air-source heat pumps (AHT) are the main technologies covering 52 % and 33 % of the heat demand. Geothermal heat pumps have certain relevance in 2050 differing on this point with 100 % RES scenario.

Figure 17 shows the projection of fuel consumption and heat demand of the residential sector in rural zones for both scenarios. In both scenarios, heat demand is reduced representing 18.4 PJ (5 111 GWh) in 2050. As the same way that urban zone, building refurbishment as an energy efficiency measure takes an important role which a contribute to reduce the heat demand in around 4.8 PJ (1 333 GWh) in 2050.

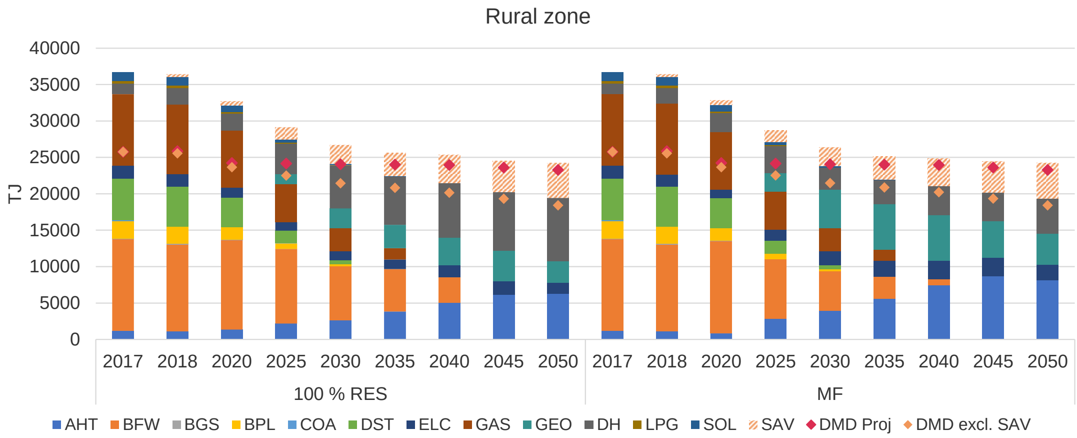

Figure 17: Projection of fuel consumption and heat demand projection in urban zone and residential sector up to 2050 in 100 % RES and MF Scenarios. AHT: Ambient heat, BFW: Biofuel wood, BGS: Biogas, BPL: Bio-pellets, COA: Coal, DST: Diesel/Fuel-oil, ELC: Electricity, GAS: Natural gas, GEO: Geothermal heat, DH: District heating, LPG: Liquid petroleum gas, SOL_ Solar thermal, SAV: Saving due to insulation, DMD – Proj: Heat demand projection, DMD excl. SAV: Heat demand projection discounting heat saving due to insulation.

In the 100 % RES scenario, in 2050 the total fuel consumption is 19.4 PJ (5 389 GWh), and DH and air-source heat pumps are the main technologies covering 45 % and 38 % of the heat demand. Compared to the urban zones, geothermal heat pump plays an important role being the third relevant technology covering the remaining 17 % of the heat demand. Wood biomass is replaced by heat pumps and DH along the time; however, this fuel plays an important role in the next 20 years still representing 16 % of fuel need in 2040.

In the MF scenario, in 2050 the total fuel consumption is 19.3 PJ (5 361 GWh) where DH, air-source heat pumps and geothermal heat pumps are the main technologies covering 25 %, 51 % and 24 % respectively of the fuel needs. In addition, both heat pumps (air and geothermal) cover a higher proportion of the fuel need, 75 % compared with in the urban zones where it accounts for 48 %.

3.2.2 Service sector

For the 100 % RES and MF scenarios, the use of fossil fuel in the service sector ends in 2035 and 2040 respectively. In both scenarios, DH as well as wood biomass became fundamental along the time, in parallel for the 100 % RES scenario air-source heat pumps play a relevant role during the intermediate years.

Figure 18 shows the projection of fuel consumption and heat demand of the service sector in urban zones in both scenarios. In both scenarios, heat demand is reduced and represents 2.3 PJ (639 GWh) in 2050.

In 2050 for 100 % RES scenario, total fuel consumption is 2.4 PJ (667 GWh), where the prevalence of DH increases by covering a share of 85 % with 2.1 PJ (583 GWh). The remaining heat demand is covered by wood biomass. Although, air-source heat pump is an important technology for the intermediated years, for example it generates 0.4 PJ (111 GWh) and shares 16 % of the heat production in 2035, its relevance decreases afterwards being replaced by the expansion of the wood biomass.

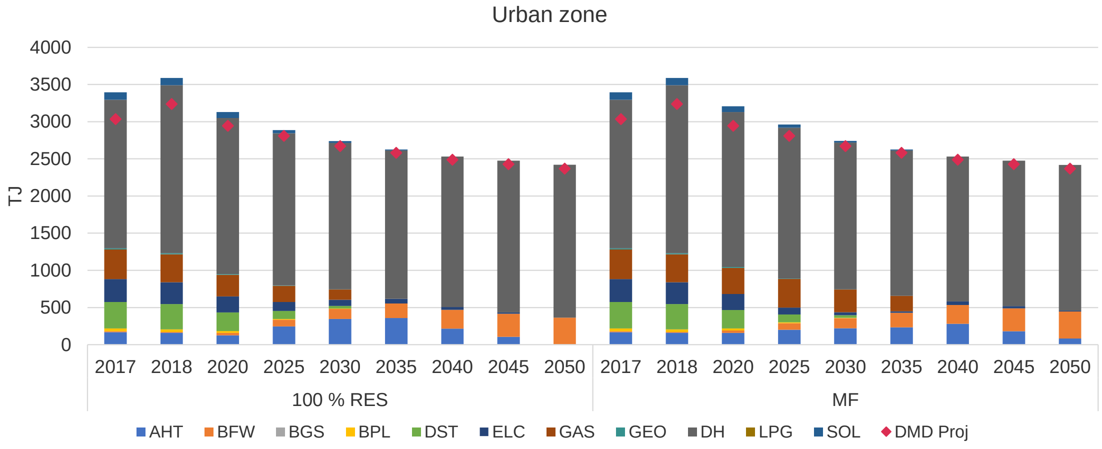

Figure 18: Projection of fuel consumption and heat demand projection in urban zone up and service sector to 2050 in the 100 % RES and MF Scenarios. AHT: Ambient heat, BFW: Biofuel wood, BGS: Biogas, BPL: Bio-pellets, DST: Diesel/Fuel-oil, ELC: Electricity, GAS: Natural gas, GEO: Geothermal heat, DH: District heating, LPG: Liquid petroleum gas, SOL_ Solar thermal, SAV: Saving due to insulation, DMD – Proj: Heat demand projection.

In the MF scenario, in 2050 total fuel consumption is like 100 % RES scenario accounting for 2.4 PJ (667 GWh) where the prevalence of DH increase sharing 81 % and 1.9 PJ (528 GWh). The remaining heat demand is covered mainly by wood biomass. Air-source heat pumps have certain contribution to the intermediated years, for example it represents 0.3 PJ (83 GWh) of fuel demand and shares 13 % of fuel needs in 2040. Its relevance decreases along the time having a minor contribution of 97 PJ (27 TWh), which represents 3 % of the total, in 2050.

Figure 19 shows the projection of fuel consumption and heat demand of the service sector in rural zones in both scenarios. In this case, heat demand is reduced representing 4.6 PJ (1 278 GWh) in 2050. In both scenarios, the intermediate years in rural zones are like urban zones.

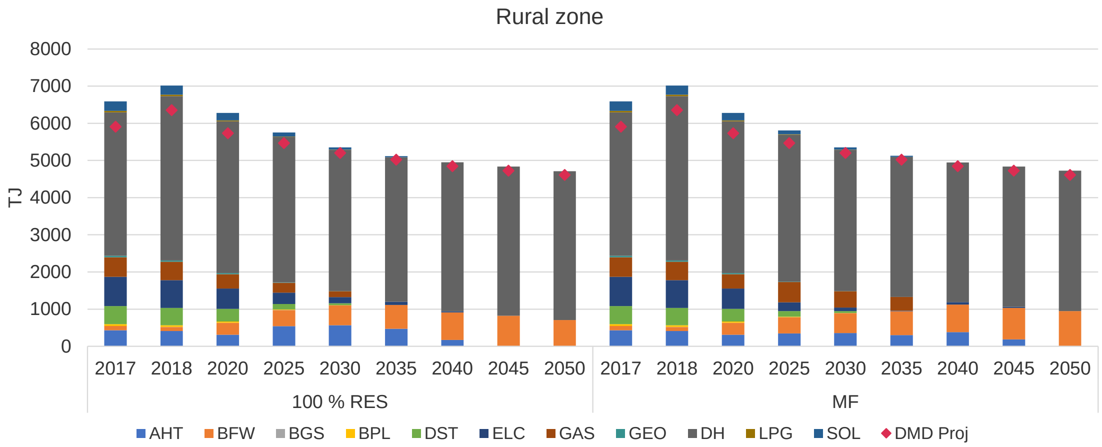

Figure 19: Projection of fuel consumption and heat demand projection in rural zone up and service sector to 2050 in the 100 % RES and MF Scenarios. AHT: Ambient heat, BFW: Biofuel wood, BGS: Biogas, BPL: Bio-pellets, DST: Diesel/Fuel-oil, ELC: Electricity, GAS: Natural gas, GEO: Geothermal heat, DH: District heating, LPG: Liquid petroleum gas, SOL_ Solar thermal, SAV: Saving due to insulation, DMD – Proj: Heat demand projection.

In the 100 % RES scenario, in 2050, total fuel consumption is 4.7 PJ (1 305 GWh) and the prevalence of DH increase sharing 85 % of the total with 4.0 PJ (1 111 GWh). The remaining heat demand is covered by wood biomass. In the same way air-source heat pump is an important technology for the intermediated years, generating 0.7 PJ (194 GWh) and a 14 % share of the heat production in 2030, its relevance decreases along the time being replaced by the expansion of the use of wood biomass.

In 2050 for the MF scenario, total fuel consumption is similar 100 % RES scenario, accounting 4.7 PJ (1 305 GWh) and DH increases up to 80 % of the total heat demand. The remaining heat demand is covered by wood biomass. In this case, there is not a minor contribution of air-source heat pumps in 2050 as it is the case for urban zones.

3.2.3 District heating sector

The fuel consumption by the DH sector is presented for the 100 % RES and MF scenarios. In both scenarios, the use of biomass (wood and pellets) and heat pumps play a fundamental role in the long-term perspective and for the future decarbonization of the system. For the 100 % RES and MF scenarios, the use of fossil fuels in the DH sector ends in 2040. In both scenarios, the use of wood biomass as well as air-source heat pumps are high in the long-term. In the 100 % RES scenario, there is also a minor use of solar thermal. In addition, for this scenario the use of pellets is relevant in the intermediated years, i.e., by 2035, while this is biogas for the MF scenario.

Figure 20 shows the projection of fuel consumption of the DH sector in urban zones for both scenarios.

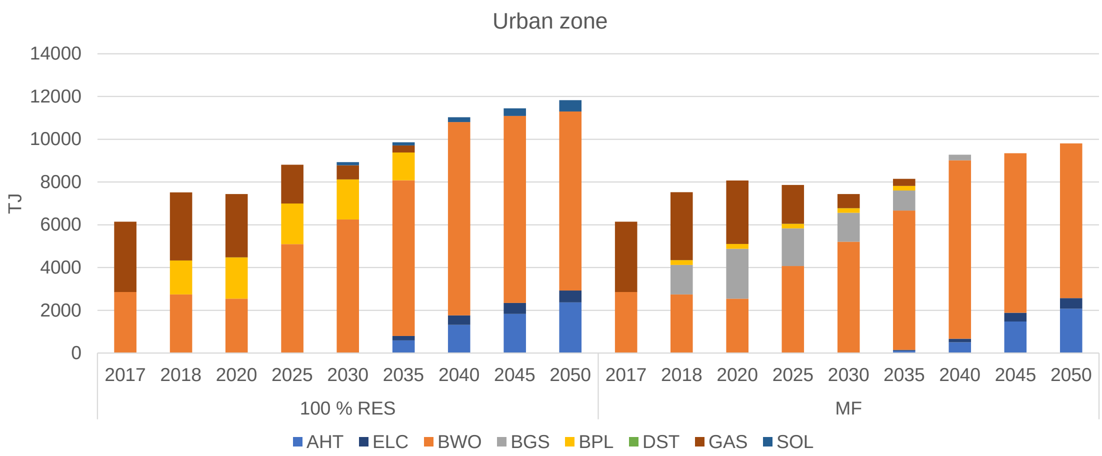

Figure 20: Projection of fuel consumption of the DH in urban zones up to 2050 in the 100 % RES and MF Scenarios. AHT: Ambient heat, ELC: Electricity, BWO: Biofuel wood, BGS: Biogas, BPL: Bio-pellets, DST: Diesel/Fuel-oil, GAS: Natural gas, SOL: Solar Thermal.

In the 100 % RES scenario, fuel consumption increases and represents 11.8 PJ (3 278 GWh) in 2050. In this year, wood biomass (BWO) and air-source heat pumps (AHT) are the main technologies covering 71 % and 25 % of the heat demand and the remaining part is covered by solar thermal. Due to the improvement of CHP share and its relevance for DH, wood biomass is dominating along the time up to 2050. The use of pellets (BPL) appears to be relevant for the intermediated years (up to 2035).

In the MF scenario, fuel consumption increases as well, but less than in the 100 % RES scenario, accounting 9.8 PJ (2 722 GWh) in 2050. In this year, wood biomass is also the main fuel covering 74 % of fuel demand and the remaining part is covered by air-source heat pumps. In this scenario, biogas (BGS) is also relevant during the intermediate year-up to 2035, where biogas CHP plants appear to be competitive.

Figure 21 shows the projection of fuel consumption of the DH sector in rural zones for both scenarios.

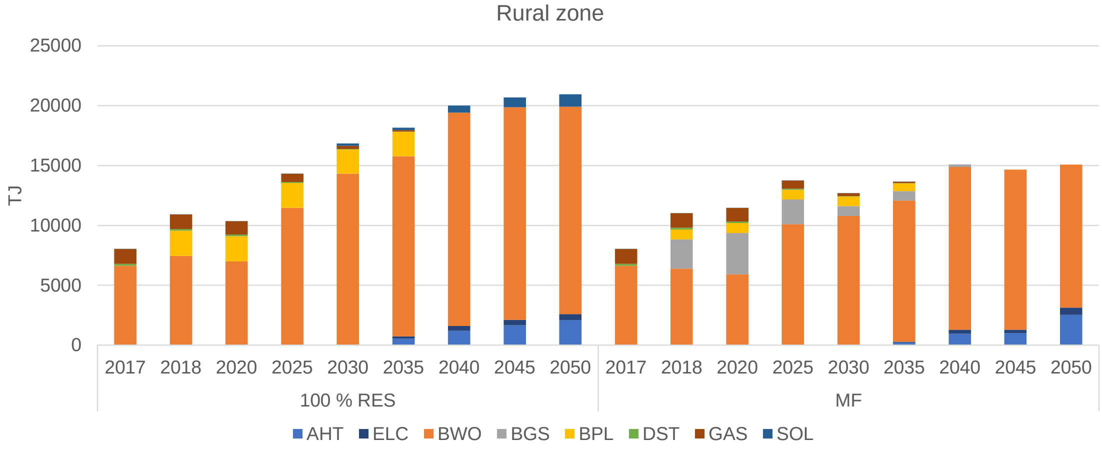

Figure 21: Projection of fuel consumption of the DH sector in rural zones up to 2050 in the 100 % RES and MF Scenarios. HT: Ambient heat, ELC: Electricity, BWO: Biofuel wood, BGS: Biogas, BPL: Bio-pellets, DST: Diesel/Fuel-oil, GAS: Natural gas, SOL: Solar Thermal.

In the 100 % RES scenario, fuel consumption increases compared to 2017 representing 20.9 PJ (5 805 GWh) in 2050. In this year, wood biomass (BWO) and air-source heat pumps (AHT) are the main technologies covering 83 % and 12 % of the heat demand while the remaining part is covered by solar thermal. Pellets fuelled CHPs play an important role in the intermediated years. In the MF scenario, fuel consumption increases representing 15.0 PJ (4 167 GWh) in 2050. In this year, wood biomass is the main fuel covering 79 % and remaining part is covered by heat pumps. As like the urban zones, in rural zones biogas also plays a relevant role in the intermediated years. However, the improvement of the CHP plants driven by wood biomass allows to this technology to be dominant in the long-term.

The projection of heat generation in the DH sector in urban zones for both scenarios is presented in Figure 22.

In the 100 % RES scenario, heat generation increases representing 8.5 PJ (2 361 GWh) in 2050. In this year, wood fuelled CHP plants (CHP_BWO) and air-source heat pumps (HP_AHT) are the main technologies covering 60 % and 34 % respectively of the heat demand, while the remaining part is solar thermal DH (DH_SOL). During the period, there is a large increase of the use of CHP plants in detriment of heat-only plants. In 2017, CHP plants generated 17 % of the heat and in 2050 this grows to 60 %. CHP plants fuelled with pellets is an important technology during intermediated years up to 2035.

In the MF scenario, heat generation increases to 6.9 PJ (1 917 GWh) in 2050. In this year, wood fuelled CHP plants is the main heat generation technology contributing with 63 % of the total supplied heat. The remaining heat is covered by air-source heat pumps. As like 100 % RES scenario, in MF scenario there is also a high increase of the use of CHP plants in detriment of heat only plants. in 2017, CHP plants generates 17 % of the heat, while in 2050 this grows to 63 %. CHP plants fuelled by biogas is an important technology during intermediated years.

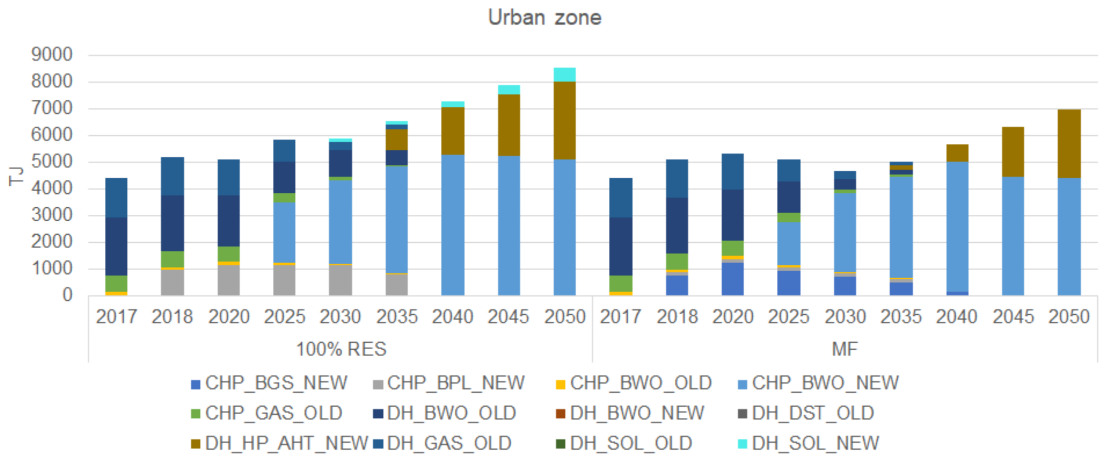

Figure 22: Projection of heat generation in urban zones by DH plants up to 2050 in the 100 % RES and MF scenarios. CHP_BGS_NEW: New CHP biogas plant, CHP_BPL_NEW: New CHP biofuel pellet plant, CHP_BWO_OLD: Old CHP biofuel biomass plant, CHP_BWO_NEW: New CHP biofuel biomass plant, CHP_GAS_OLD: Old CHP biofuel natural gas plant, DH_BWO_OLD: Old only Heat biofuel biomass plant, DH_BWO_NEW: New only Heat biofuel biomass plant, DH_DST_OLD: Old only Heat diesel-fuel oil plant, DH_HP_AHT_NEW: New only Heat plant driven with air-source heat pump, DH_GAS_OLD: Old only Heat natural gas plant, DH_SOL_OLD: Old only Heat thermal solar plant, DH_SOL_NEW: New only Heat thermal solar plant.

Figure 23 shows the heat generation projection in the DH sector in rural zones for both scenarios.

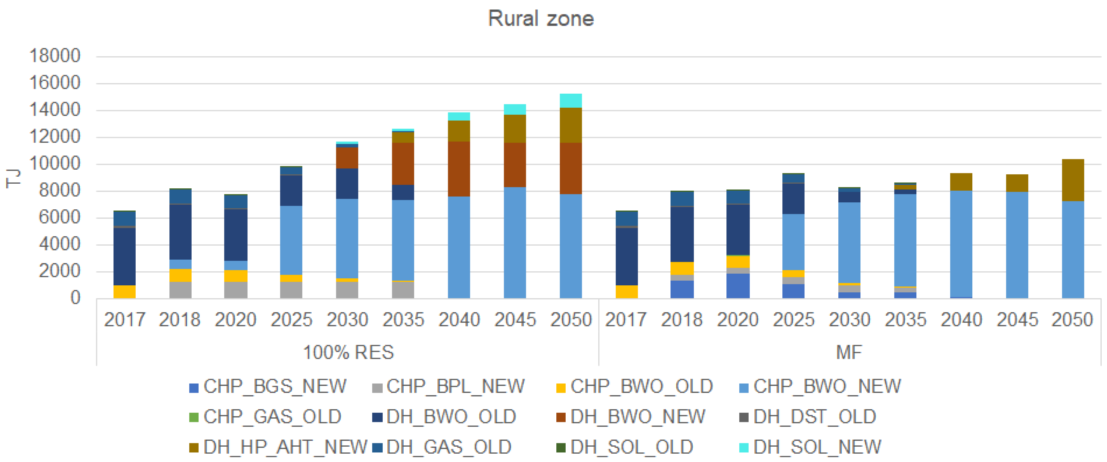

Figure 23: Projection of heat generation in rural zone by DH plants up to 2050 in the 100 % RES and MF scenarios. CHP_BGS_NEW: New CHP biogas plant, CHP_BPL_NEW: New CHP biofuel pellet plant, CHP_BWO_OLD: Old CHP biofuel biomass plant, CHP_BWO_NEW: New CHP biofuel biomass plant, CHP_GAS_OLD: Old CHP biofuel natural gas plant, DH_BWO_OLD: Old only Heat biofuel biomass plant, DH_BWO_NEW: New only Heat biofuel biomass plant, DH_DST_OLD: Old only Heat diesel-fuel oil plant, DH_HP_AHT_NEW: New only Heat plant driven with air-source heat pump, DH_GAS_OLD: Old only Heat natural gas plant, DH_SOL_OLD: Old only Heat thermal solar plant, DH_SOL_NEW: New only Heat thermal solar plant.

In the 100 % Scenario, heat generation increases to 15.2 PJ (4 222 GWh) in 2050. In 2050, wood fuelled CHP and heat-only plants and air-source heat pumps are the main technologies covering 51 %, 25 % and 17 % respectively of the heat demand while the remaining part is covered by new solar DH. As in the urban areas, there is a high increase of the use of CHP plants in detriment of heat-only plants. In base year 2017, CHP plants generated 15 % of the heat while in 2050 this grows to 51 %. Also, CHP plants fuelled with pellets is an important technology during intermediated years.

In the MF scenario heat generation also increases to 10.3 PJ (2 861 GWh) in 2050. Wood fuelled CHP plants play the main role, supplying 70 % of the heat, and the remaining part is from air-source heat. There is a high increase of the use of CHP plants in detriment of heat-only plants. In 2017, CHP plants generated 15 % of the heat and in 2050 this grows to 70 %. Also, CHP plants fuelled with biogas is an important technology during intermediated years.

As for DH electricity generation, in both scenarios, CHP plants have a high growth in the long-term and CHP biofuel biomass (pellets and wood) plants are the dominant. Figure 24 shows the projection of electricity generation of CHP plants connected to the DH sector in urban zones for both scenarios. CHP plants become more relevant in the mid- to long-term due to the reduced investment costs of these technologies, the expected future increase of the electricity prices as well as the increase of the electricity demand e.g., because of increase of the use of heat pumps in single household buildings.

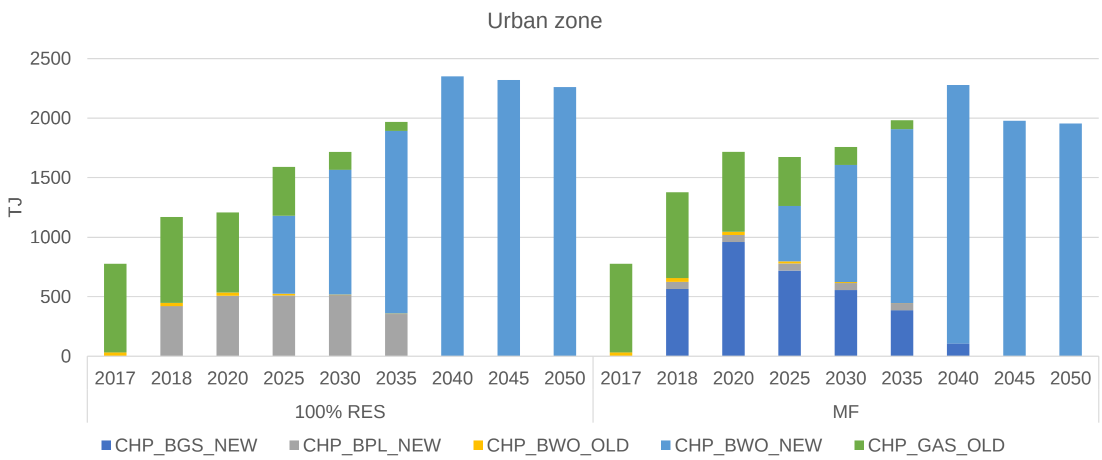

Figure 24: Projection of electricity generation in urban zone by CHP plant types up to 2050 in the 100 % RES and MF scenarios. CHP_BGS_NEW: New CHP biogas plant, CHP_BPL_NEW: New CHP biofuel pellet plant, CHP_BWO_OLD: Old CHP biofuel biomass plant, CHP_BWO_NEW: New CHP biofuel biomass plant, CHP_GAS_OLD: Old CHP biofuel natural gas plant.

Electricity generation increases for the 100 % RES and MF scenarios to 2.3 PJ (639 GWh) and 1.9 PJ (528 GWh) in 2050 respectively. Replacing the old CHP plants, mainly fuelled by natural gas, by wood-fuelled CHP plants. Up to the intermediated years pellets CHP plants in 100 % RES scenario and the biogas CHP plants in the MF scenario take part in the decarbonisation of the DH system, however in the long-term, they are also replaced by wood biomass CHP. This is also the case for the rural zones (see Figure 25).

Figure 25 shows the projection of electricity generation of CHP plants connected to the DH sector in rural zones for both scenarios. Rural zones perform in a similar way as rural zones.

Electricity generation increases for the 100 % RES scenario and the MF scenario to 3.4 PJ (944 GWh) and 3.2 PJ (889 GWh) respectively in 2050. In both scenarios there is a replacement of the old CHP plants, mainly driven by wood biomass, by new wood fuelled CHP plants.

Heating energy systems are designed to cover **heat peak loads**. In the future flexibility measures, including DSM are also expected to be key elements for contribution of peak loads. This is especially relevant for DH systems as it can reduce the installed capacity. In HLA-Times model, winter peak (WP) is the most critical time slice where maximum DH capacity is used to meet the heat demand in a short time of the year (3.1.3.1).

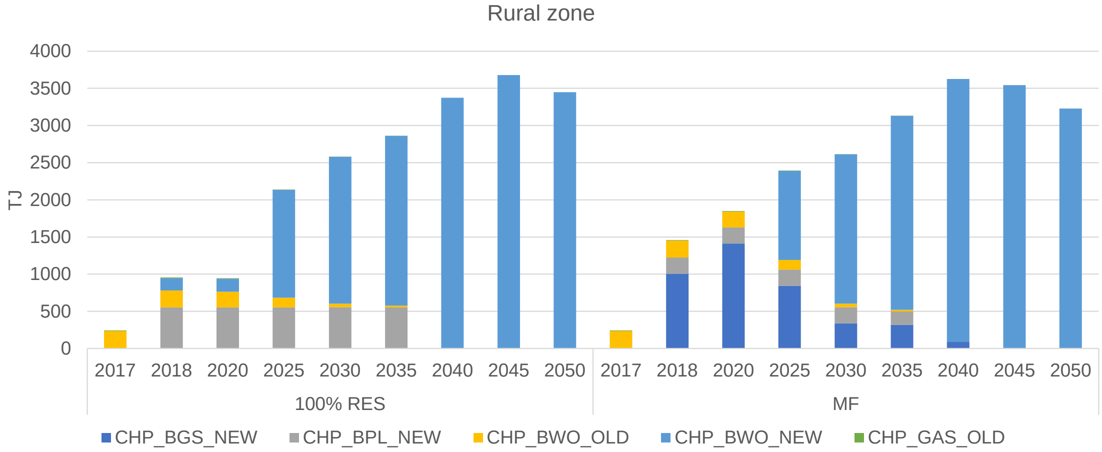

Figure 25: Projection of electricity generation in rural zones by CHP plant types up to 2050 in the 100 % RES and MF scenarios. CHP_BGS_NEW: New CHP biogas plant, CHP_BPL_NEW: New CHP biofuel pellet plant, CHP_BWO_OLD: Old CHP biofuel biomass plant, CHP_BWO_NEW: New CHP biofuel biomass plant, CHP_GAS_OLD: Old CHP biofuel natural gas plant.

Figure 26 compares the relation between heat generation and installed capacity in 2017 and 2050 for both scenarios. The values are normalized taking the base year as reference to make them comparable. In both scenarios, compared to 2017, there is an improvement of the DH use in 2050 being able to cover WP times with the reduced installed capacity. This is due to estimated efficiency improvement of future technologies, but also contribution of DSM to reduce the WP peaks. This is especially relevant in the MF scenario with high acceptance of DSM as a flexibility measure.

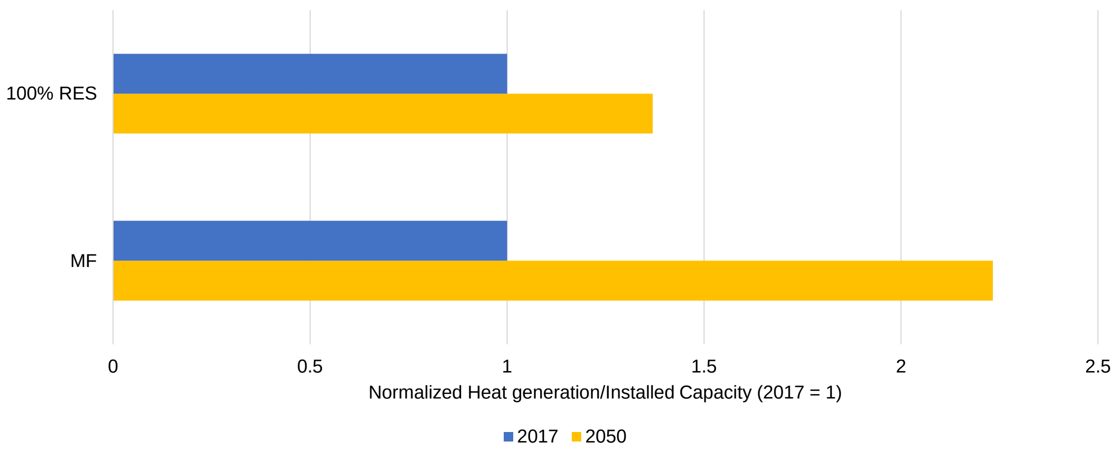

Figure 26: Winter Peak performance in the 100 % RES and MF scenarios.

In all, the model invests in additional DH systems in urban as well as in rural zones. **Fel! Hittar inte referenskälla.** Table 11 summarizes the total heat and electricity generation from different technologies in the district heating sector. Both simulated scenarios imply the significant role of flexible technologies such as CHP and HP. Biomass CHP (mainly wood biomass) as well as air sourced HPs are expected to be main options for the DH in the long-term by 2050. The use of pellet and biogas in CHPs can be expected during the transition years i.e., by 2035. In both scenarios there is an improvement in the use of DH being able to cover the winter peak with the less installed capacity in 2050 compared to in 2017. This is due to the better performance of future technologies with better efficiencies but also the use of DSM to reduce the winter peaks. DSM is especially relevant in the MF scenario, where this flexibility measure estimated to have a higher acceptance.

In the model, Pit TES and large-scale water tanks are considered as seasonal thermal storages in district heating systems. However, the model doesn't invest in these technologies. This can be explained one the one hand by low availability of variable sources (solar thermal) in the district heating system, and on the other hand by the already high utilization of other flexible technologies such as CHP and HP.

Table 11: Cost-efficient heat and electricity generation for Lower Austrian district heating system from flexible technologies (CHP and HP) as well as Heat only boilers (in GWh).

GWh		2017	2030		2050	
		100 % RES	100 % RES	MF	100 % RES	MF
Biogas CHP	**HEAT**	0	0	317	0	0
	ELC	0	0	248	0	0
Pellets CHP	**HEAT**	0	667	174	0	0
	ELC	0	296	77	0	0
Wood Biomass CHP	**HEAT**	310	2 584	2 558	3 568	3 238
	ELC	74	855	847	1 586	1 439
Natural Gas CHP	**HEAT**	177	35	35	0	0
	ELC	210	42	42	0	0
Air-source HP	**HEAT**	0	0	0	1 534	1 583
Wood Biomass HOB	HEAT	1 774	1 352	337	1 072	0
Diesel HOB	HEAT	41	8	8	0	0
Natural Gas HOB	HEAT	707	141	141	0	0
Solar thermal	HEAT	1	99	0	437	0
Total generation (heat and electricity) in DH sector		***3 294***	***6 080***	***4 785***	***8 197***	***6 260***
Total heat from flexible technologies (CHP & HP)		***487***	***3 286***	***3 084***	***5 102***	***4 821***
Total electricity from flexible technologies (CHP)		***284***	***1 194***	***1 214***	***1 586***	***1 439***

4 DISCUSSION

In this WP, the analysis of economic viability of the investigated flexibility potentials in DH systems is performed using optimization models. As is the case for any modelling, the results obtained in this work depend on the assumed input data. The assumed electricity prices, changes in heating demand, and investment costs in technology and infrastructure, among others, have significant effect on the presented results.

Different fuel and electricity price assumptions are one of the main reasons why the modelling results for Eskilstuna and Maria Laach differ from each other. In addition, taxation and subsidiary structures applied to businesses (DH) and households contribute to the observed differences in the results. In the case of Eskilstuna, the electricity prices were extracted from the Balmorel modelling for the so-called CNN storyline, which are lower in the years 2030 and 2050 than in the real prices in year 2018. This is one of the main reasons why the model heavily invested in HPs (both centralized and decentralised) Although an in depth analysis on future energy prices is beyond the scope of this report, lower future prices are typically due to high shares of renewables-. Additional model runs with assumed electricity prices higher than the prices in 2018 could have resulted in (re)investments in biomass-fired CHP plants (biomass prices are also assumed relatively low in the future years). The predominance of investments in HPs can also be due to the assumptions on investment costs, variable and fixed operation costs, fuel prices, taxes, and subsidies.

In general, strong dependency on the electricity consuming technologies in the heating sector, i.e., HPs (as is shown for Eskilstuna) and electric boilers, will lead to the lock-in effect of the entire sector to one technology type and hence jeopardize the security of supply and increase the pressure on the electric power sector. And yet, country- and continental-scale energy models often show that the electricity prices can get lower in the future, naturally leading to significant investments in HPs. This discrepancy between the 1) recently observed high electricity prices and the common belief of experts working in the field (at least in Sweden) that future DH system should contain CHP plants and be able to support the electric power sector, and 2) the modelling results pointing towards high shares of HPs, should be addressed in detail in future research.

In the case of Austria, electricity prices were extracted from the national power system model by using Balmorel modelling tool. The simulated storyline is based on the national electricity targets, namely 100 % renewable electricity supply by 2030 (generation and consumption balanced). Contrary to lower electricity prices expected for Sweden, electricity prices are expected to increase in Austria by 37 % by 2030 and 62 % by 2050 in comparison to 2017-level, that constitutes the base year of the Austrian case. Furthermore, the future electricity demand is expected to increase in Austria. Together with increased electricity prices, this leads to a model specific result on significant growth of the CHP plants in the mid- to long-term. The massive use of CHP plants in both scenarios (100 % RES and MF) results in greater electricity generation from green fuels allowing to support also the decarbonization of the electricity sector, which is expected to be driven mainly by wood biomass by 2050.

Changes in the heating demand. The heating demands of the investigated demo sites (e.g., Eskilstuna) may increase or decrease in the future. Decrease in demand is expected due to implementation of heat saving measures. Increase in demand is expected due to the growth of the cities. Using the SureCity_heat model, several additional model runs were performed with the heating demand decreasing and increasing in the future. The results show that greater or lower heating demand will certainly impact the amount of generated heat and the size of the installed heat generation/storage capacities, but the generation mix and the overall composition of the heating sector of Eskilstuna remains like the cases with constant heating demand in the future.

Investment cost in technology and infrastructure. In the case of Eskilstuna, the model does not invest in expansion of the DH network capacity (all 4 scenarios). Instead, the model (re)invests in individual heat generation units. This result can clearly change if the investment costs were different. In this work, we have assumed the cost of DH network expansion applicable to heat density areas of 120-300 TJ/km^2. With the costs estimated for areas with higher heat densities (lower costs), the result could have been different – expansion of the DH network. The same result could have been observed if the investment or running costs of the individual heating technologies went up. A short conclusion can be made here that a deeper analysis with more model runs is required to make more robust conclusions on the future development and hence, flexibility potential of DH systems.

Modelling approach and model structure. In addition to the arguments related to input data discussed above, the very structures and specifics of the applied optimization models have significant impacts on the obtained results. E.g., the model applied to Eskilstuna represents a given modelled year using 72 time-slices, while for the case of Maria-Laach the number of time slices is 12. Also, the approach to model flexibility in buildings is different: i) in the case of Eskilstuna, the potential of buildings to serve as a TES is expressed as a maximum total capacity that can be optimised by the optimization model, ii) in the case of Maria-Laach, the flexible heat demand of the buildings was precalculated and provided to the optimization model a number of different heat demand profiles (with and without activated flexibility). Furthermore, while Eskilstuna model refers to a city concentrated model (around 100 thousand population), Lower Austria Model refers to a large region with around 1.6 million population also with different density characteristics, by the urban and rural zones, which need to be illustrated separately in the model. Finally, the scenarios studied by the two applied models are different, which is due to agreements of the partners with the national funding bodies and generally slightly different focuses of the models.

The other four cities, which host the demo-sites: Borås, Mölndal, Berlin and Palma, were not modelled using the developed energy system optimization models but can still be discussed here based on the insights from the Eskilstuna and Maria Laach modelling. The

DH systems of Borås and Mölndal are in Sweden and hence, share several conditions and circumstances with the DH system of Eskilstuna, e.g., taxation schemes, fuel and electricity supply contracts and price. Currently, the DH systems of Borås and Mölndal are dominated by CHP plants – most of the heat comes from cogeneration. This already indicates strong connections of the heating sectors of these two cities to the electric power sector. As in the case of Eskilstuna, the DH systems of Borås and Eskilstuna will likely have to choose between keeping or reinvesting in their CHP capacities or to heavily invest in HPs, if electricity prices in Sweden are in the future lower, as in the projections used in the modelling. Regarding the TES capacities, the DH system of Borås already has a TES tank of significant capacity that is being used for redundancy and for providing flexibility to the system. Hence, the economic viability of investments in the building TES is not evident and requires further research. In the case of Mölndal, there are no significant storage capacities available now and an in-depth study on the role of different sizes and types of TES to provide energy system flexibility is recommended.

For both demo-sites of Palma and Berlin, it is evident the heating systems are, and likely will be, tightly connected to the electric power sector – either via HPs or via CHP plants. The demo-site in Palma includes a CHP plant that produces electricity, DH and DC, and utilizes the DH network as a TES. The demo site does therefore already have a high utilization rate of the available flexibility both in terms of supporting the heat generation and in terms of the heat to electricity synergy. As for the demo-site in Berlin, all projected developments of the DH system show in Annex C point towards the high utilization rate of waste heat sources, large scale air-source based HPs and HOBs running on biomass and some share of natural gas. Those projections indicate that the heating sector of Berlin will be mainly electricity consuming (HPs) and not electricity generating (CHP plants). In any case, before any long-term decisions for the development of the DH systems of either Palma or Berlin are made, we recommend energy system optimization modelling of the potential future alternative developments.

5 CONCLUSIONS

The modelling results for the city of Eskilstuna indicate that irrespectively of the applied climate scenario or the availability of TES, the future heating sector of Eskilstuna will be dominated by HPs, both centralized (in the DH system) and individual. This implies that the city's heating sector becomes a net consumer of electricity and can help with the utilization of excess electricity in the power sector. However, reliance only on electricity consuming technologies in the city's heating sector limits its potential to provide flexibility services to the electric power sector – retirement of the CHP plant eliminates the possibility to generate electricity during the periods of high electricity prices. Moreover, recently observed high electricity prices and the overall business consensus (at least in Sweden) that future DH system should contain CHP plants and be able to support the electric power sector contradict the modelling results. This leads towards the conclusion that further research activities, which will bridge the scientific, modelling, governmental and corporate perspectives on the development of the heating sectors of different countries are of high importance.

The results of the modelling also show that the already available and invested in TES solutions are actively used in the future for storing heat between seasons and for decreasing the peak heat generation, i.e., flattening the heat generation curve. This results in lower system cost of heat supply and improved flexibility potential of the heating system. In addition, operation of heat pumps together with TES units in DH systems will greatly benefit the electric power sector by providing reliable flexibility service.

The decarbonization of the heating sector in Lower Austria in 2040 is possible in both analysed scenarios- (i.e. 100% Renewable, Maximized Flexibility) being the use of fossil fuel marginal already in 2035. The use of fossil fuel in the residential sector ends in 2040, where demand reduction through building refurbishment plays an important role together with the expansion of the heat pumps (air and geothermal) and the DH. In the service sector, DH increases its weight as predominant technology. Wood biomass became fundamental for the transition, followed by air-source heat pumps. These results are linked to the assumed techno-economic parameters of the technologies, energy prices and CO_2 prices. These assumptions try to follow the most plausible expected situation in the mid-to-long term perspective. Therefore, they do not reflect the current increases in prices and technology investment costs as result of unexpected events.

In DH sector, in both scenarios, the use of wood biomass together with air-source heat pumps is high in the long-term and the role of CHP plants increases. During the intermediate years, the use of pellet CHP plants appear to be relevant in 100 % RES scenario, whereas the same is biogas CHP plants in the MF scenario. The massive use of CHP plants multiplicate the electricity generation. Finally, in both scenarios there is an improvement in the use of DH being able to cover the winter peaks. It is expected that this will be accompanied with better performance of future technologies due efficiency increase as well as expansion of DSM utilization to reduce the winter peaks.

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ANNEX A – INPUT DATA TO THE TIMESCITY_HEAT MODEL ESKILSTUNA

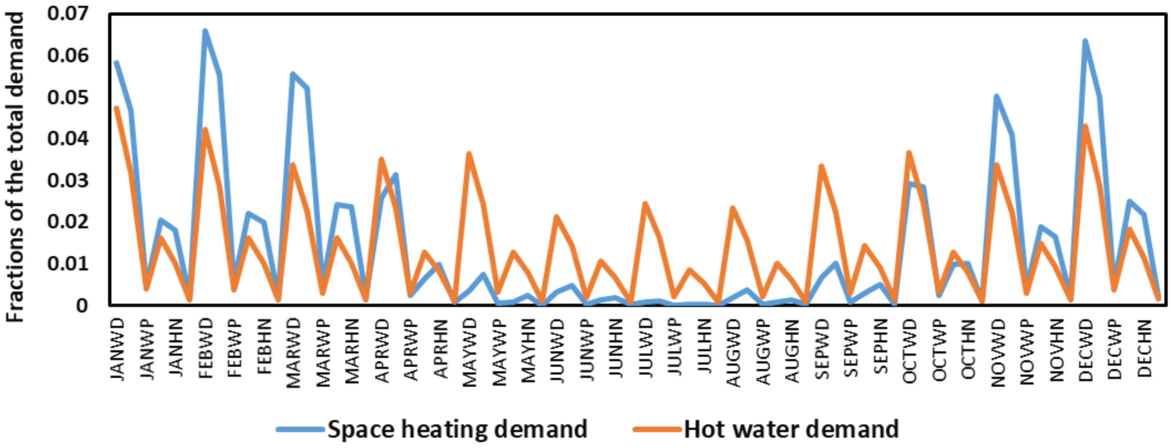

Figure A.27: The fractions of the assumed total space heating and hot water demands in the SURECity_heat model.

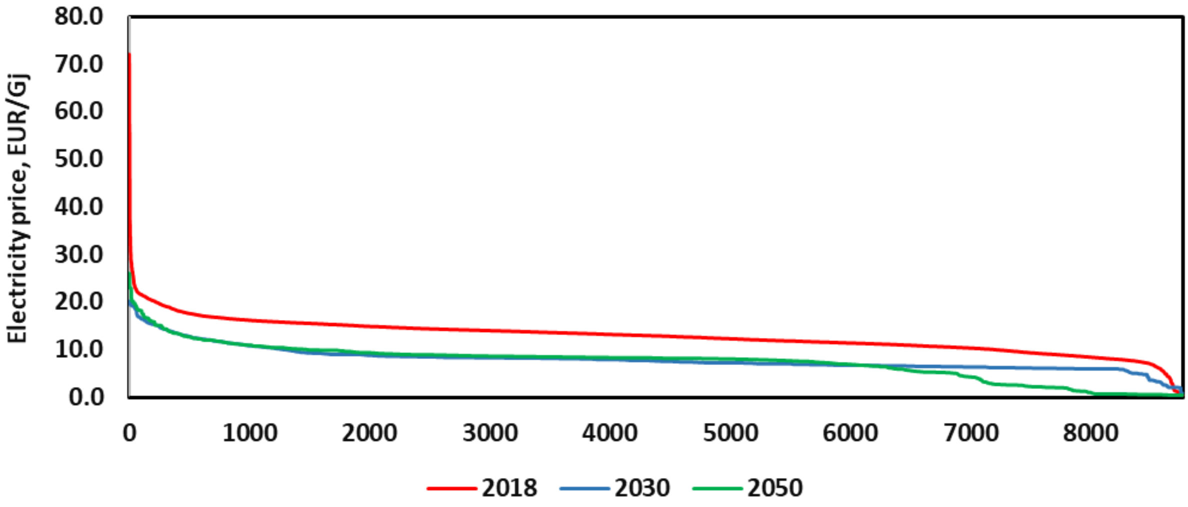

Figure A.28: The electricity price duration curves, as obtained from the Nordpool wholesale electricity market (Year 2018) and Balmorel modelling (Years 2030 and 2050) for the price area of Sweden, used as inputs to the TIMESCity_heat model applied in this work.

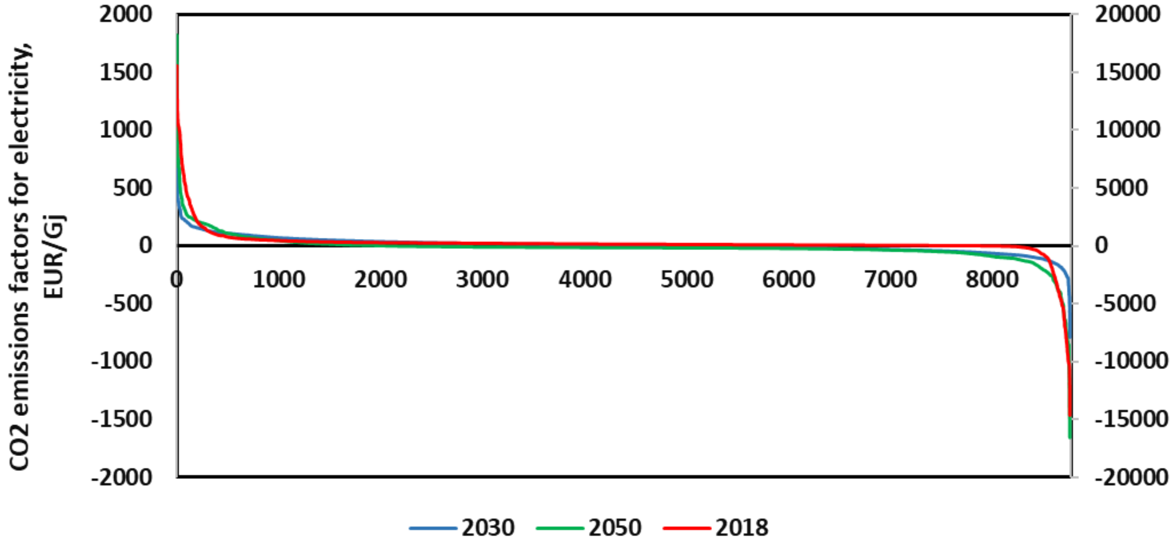

Figure A.29: The duration curves of the CO_2 emissions factors of the electricity consumption/generation, as obtained from the Balmorel modelling, used as inputs to the TIMESCity_heat model applied in this work. Note: the values for the Year 2018 are on the secondary axis (to provide a better visual comparison to the values for the Years 2030 and 2050).

ANNEX B – LOWER AUSTRIA

B1 Baseline year 2017

This section presents the status in the base year (2017) of the heating sector in Lower Austria for the residential and service sectors and district heating sector.

Residential sector demand

Figure B.30 shows the estimated heat demand for residential sector by end uses and by zones. The overall heat demand is around 35.3 PJ (9 805 GWh) where rural zone represents the main part with around 73 %. In terms of type of building the heat demand is concentrated in single houses with around 29.1 PJ (8 083 GWh), where low-efficiency single family houses (RHL) (i.e., with low energy performance) demand 75 % of total heat. Finally, space heating (SH) shares are around 85 % of the total heat demand by end-use.

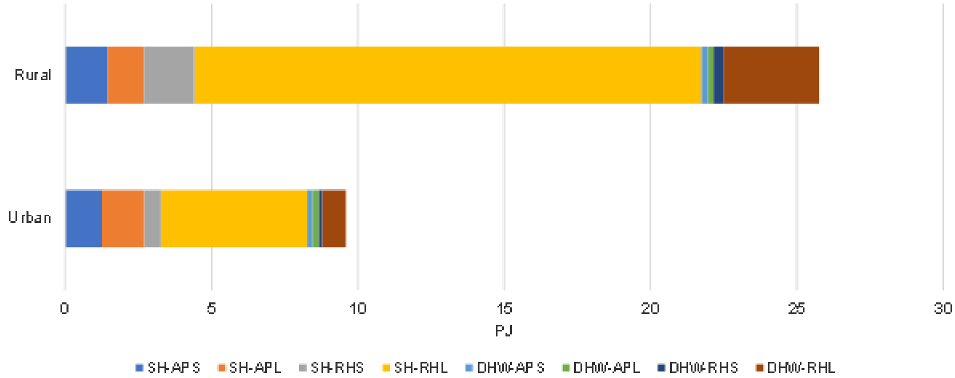

Figure B.30: Heat demand by zones, type of buildings and end uses in residential sector. SH-APS: Space heating in Apartment buildings with standard insulation efficiency, SH-APL: Space heating in Apartment buildings with low insulation efficiency. SH-RHS: Space heating in single houses with standard insulation efficiency, SH-RHL: Space heating in single houses with low insulation efficiency, DHW-APS: Domestic hot water in Apartment buildings with standard insulation efficiency, DHW-APL: Domestic hot water in Apartment buildings with low insulation efficiency. DHW-RHS: Domestic hot water in single houses with standard insulation efficiency, DHW-RHL: Domestic hot water in single houses with low insulation efficiency.

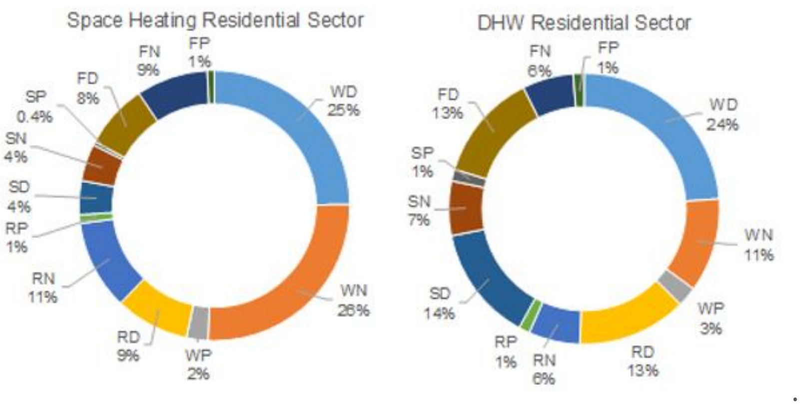

Figure B.31: Heat demand by time slice for space heating and DHW in residential sector. RD: Spring Day, RN: Spring Night, RP: Spring Peak, SD: Summer Day, SN: Summer Night, SP: Summer Peak, FD: Fall Day, FN: Fall Night, FP: Fall Peak, WD: Winter Day, WN: Winter Night, WP: Winter Peak.

Figure B.31 shows the allocation of time-slices in fractions of the year of the heat demand by end uses (space heating (SH) and domestic hot water (DHW)). In this case, it is assumed that this allocation does not differ by the building type. Notice that, although, Winter Peak time has a low energy share with around 0.5 PJ (139 GWh) of the total head demand, this time-slide represents the highest use of the installed capacity due to short duration in the year

Heat demand is covered by a wide range of technologies. These technologies consume different types of fuels, which can be renewables or conventional, such as ambient heat in the heat pumps or natural gas in the gas boilers. Figure B.32a shows fuel consumption by zones and end uses in the base year. In overall terms, natural gas (GAS) is the main energy source with around 17.3 PJ (4 805 GWh), followed by biomass -wood (BFW) and pellets (BPL)- with 13.5 PJ (3 750 GWh) and diesel (DST) with 7.1 PJ (1 972 GWh). These fuels contributed to around 79 % of the total fuel consumption. Nevertheless, fuel consumption differs greatly by zones. While natural gas contributes to 60 % of the total fuel consumption in urban zones, this proportion drops to 27 % in rural zones. In rural zones biomass consumption is the main fuel with around 41 % of the total.

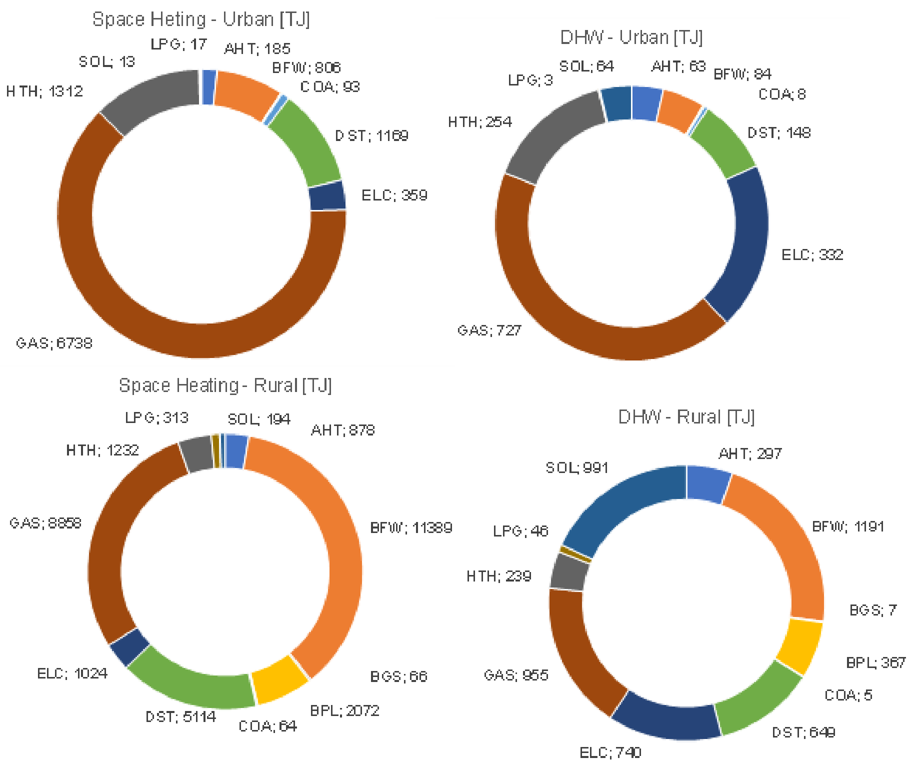

Figure B.32a: Base year fuel mix to cover the heat demand by zones and end uses in residential sector. LPG: Liquid petroleum gas, SOL_ Solar thermal, AHT: Ambient heat, BFW: Biofuel wood, BGS: Biogas, BPL: Bio-pellets, COA: Coal, DST: Diesel/Fuel-oil, ELC: Electricity, GAS: Natural gas, HTH: District heating

Finally, direct CO_2 emission in the residential sector is estimated around 1 684 kilotons of CO_2 where around 65 % correspond rural zones [1]. The overall CO_2 intensity is around 47.6 tons of CO_2/TJ (13.2 tons of CO_2/GWh), nevertheless there are high difference by zones. Urban zones have a higher CO_2 intensity with around 61.9 tons of CO_2/TJ (17.2 tons of CO_2/GWh), while it drops to 42.4 tons of CO_2/TJ (11.8 tons of CO_2/GWh) in the rural zones.

Service sector demand

Figure B.33 shows the estimated heat demand for service sector by end use and by zone. The overall heat demand is around 8.9 PJ (2 472 GWh) where rural zone represents the main part with around 66 % of this total. Finally, space heating shares around 72 % of the total heat demand by end-use.

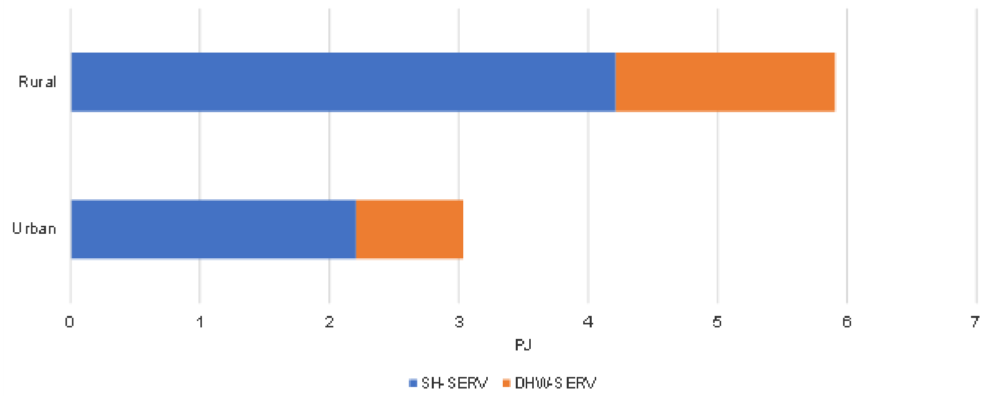

Figure B.33: Base year heat demand by zones, type of buildings and end-uses of service sector. SH-SERV: Space heating in service sector, DHW-SERV: Domestic hot water in service sector.

Figure B.34 shows the share of heat demand by time-slices in case of end uses (space heating, domestic hot water) in the base year. Notice that, although, WP has a low energy share of the total heat demand with round 0.12 PJ (33 GWh), this time-slide represents the highest use of the installed capacity due to its low duration in the year.

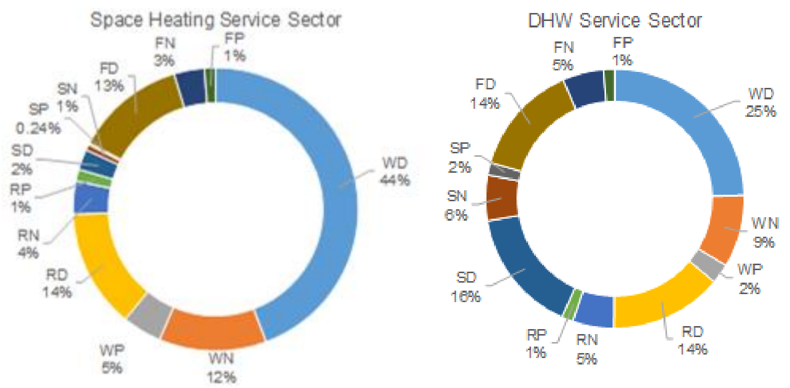

Figure B.34: Base year heat demand by time slices for space heating and DHW (domestic hot water) of service sector. RD: Spring Day, RN: Spring Night, RP: Spring Peak, SD: Summer Day, SN: Summer Night, SP: Summer Peak, FD: Fall Day, FN: Fall Night, FP: Fall Peak, WD: Winter Day, WN: Winter Night, WP: Winter Peak.

Figure B.35 shows fuel consumption by zones and end uses in the base year for service sector. In total, district heating with around 5.8 PJ (1 611 GWh) is the main energy source, followed by electricity (for appliances, electric boilers, and heat pumps) with 1.1 PJ (305 GWh) and natural gas with 0.9 PJ (250 GWh). These fuels share around 79 % of the total fuel consumption.

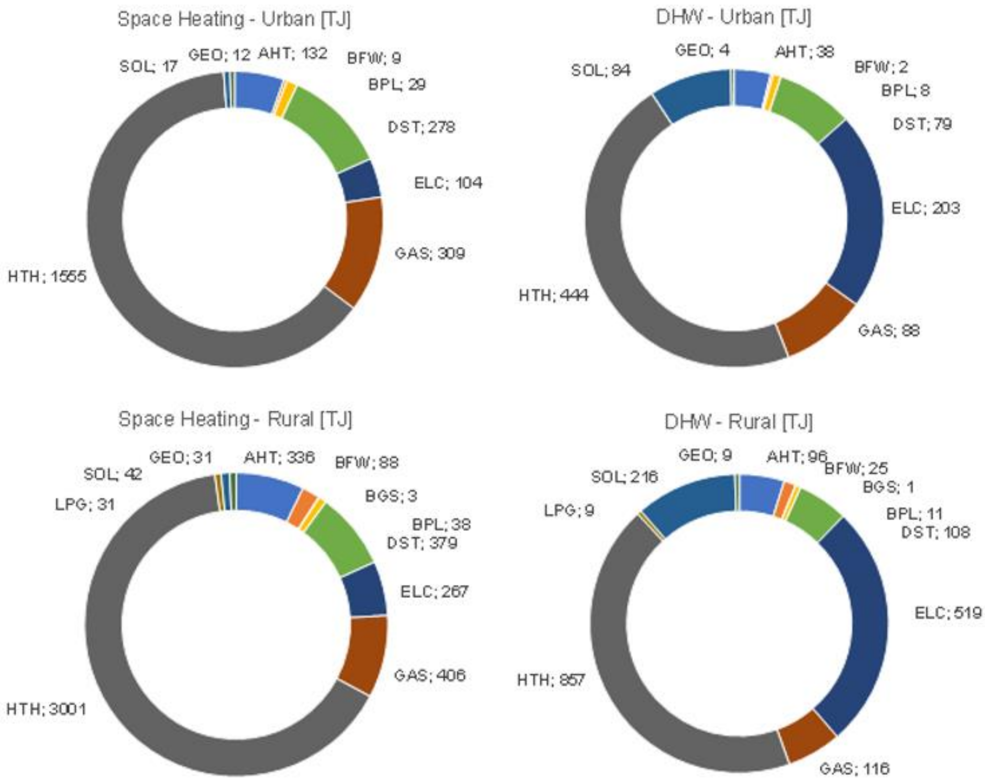

Figure B.35: Fuel mix to cover the heat demand by zone and end-use in the service sector. LPG: Liquid petroleum gas, SOL_ Solar thermal, AHT: Ambient heat, BFW: Biofuel wood, BGS: Biogas, BPL: Bio-pellets, COA: Coal, DST: Diesel/Fuel-oil, ELC: Electricity, GAS: Natural gas, DH: District heating, GEO: Geothermal heat.

Finally, direct CO_2 emission in the service sector is estimated around 124 kilotons of CO_2 where around 75 % correspond rural zones. The overall CO_2 intensity is around 14 tons of CO_2/TJ (3.9 tons of CO_2/GWh), nevertheless there are large differences between zones. Urban zones have a higher CO_2 intensity with around 17 tons of CO_2/TJ (4.7 tons of CO_2/GWh) whereas this drops to 12 tons of CO_2/TJ (3.3 tons of CO_2/GWh) in rural zones.

District heating sector

Figure B.36 shows the heat and electricity generation by CHP and heat only plants for urban and rural zones. Total heat and electricity production is 11.8 PJ (3 278 GWh), of which total heat production is 10.8 PJ (3 000 GWh) where heat only plants are the main type of technology generating 9.1 PJ (2 528 GWh) which contribute to 84 % of the total heat production.

Biomass and natural gas are the main fuels for heat production being biomass the most relevant fuel. Biomass generates 7.5 PJ (2 083 GWh) of heat and represents around 70 % of the total. Meanwhile natural gas produces 3.1 PJ (861 GWh) of heat sharing 29 % of the total. There is a marginal use of fuel oil and solar thermal covering 1.4 % and 0.02 % of the heat generation.

CHP generates around 17 % and 15 % of the heat from district heating in urban and rural zones respectively. In terms of electricity production, in urban zones CHP plants generates around 0.8 PJ (222 GWh) of electricity. This represents 12 % of the overall energy generation (heat and electricity) is connected to the district heating. This value drops to 4 % in rural zones with a total electricity generation of 0.2 PJ (55 GWh).

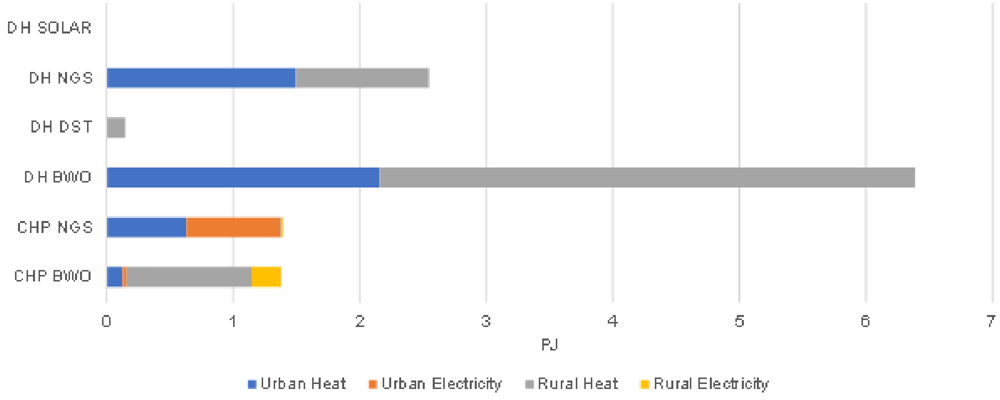

Figure B.36: Heat and Electricity generation by CHP and heat only plants and zone. DH Solar: Solar thermal heat plant, DH NGS: Natural gas heat plant, DH DST: Diesel/Fuel-Oil heat plant, DH BWO: Wood biofuel heat plant, CHP NGS: Natural gas combine heat and power plant, CHP BWO: Wood biofuel combine heat and power.

Figure B.37 shows the fuel consumption by CHP, heat only plants and zones. Biomass with around 8.8 PJ (2 444 GWh) is the main energy source, followed by natural gas with 5.6 PJ (1 555 GWh) sharing around 38 % the total fuel consumption.

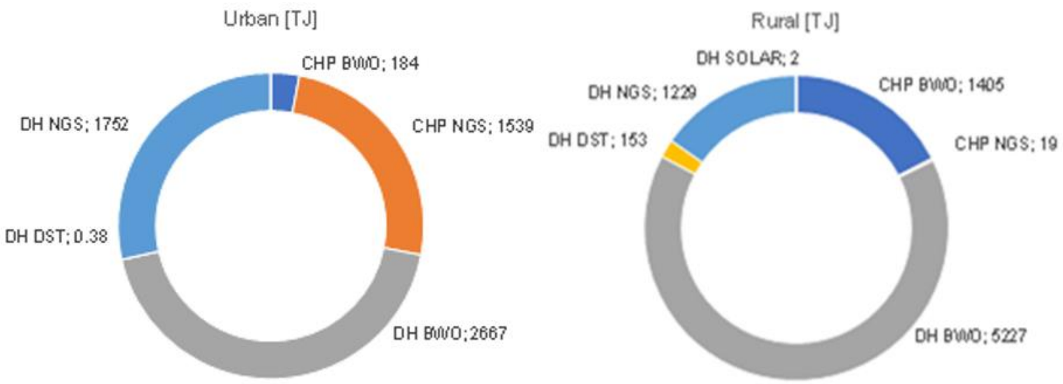

Figure B.37: Fuel consumption by CHP and heat only plants in urban and rural zone. DH Solar: Solar thermal heat plant, DH NGS: Natural gas heat plant, DH DST: Diesel/Fuel-Oil heat plant, DH BWO: Wood biofuel heat plant, CHP NGS: Natural gas combine heat and power plant, CHP BWO: Wood biofuel combine heat and power.

Finally, CO_2 emission in district heating sector is estimated to around 306 kilotons of CO_2 where around 70 % correspond urban zones. This is because these zones concentrate most of CHP and heat plans fuelled by natural gas. In fact, practically all CO_2 emissions in urban zones are caused using natural gas, sharing almost 100 %. The CO_2 emissions from use fuel-oil (diesel) are marginal. In rural zones CO_2 emissions from natural gas is still predominant with 88 % of the total emissions. In this zone the use of diesel is much more import than in urban zones being responsible of 12 % of total CO_2 emissions.

Finally, the overall CO_2 intensity is around 26 tons of CO_2/TJ (7.2 tons of CO_2/GWh) including heat and electricity production from CHP. Urban zones have an overall higher CO_2 intensity with around 41 tons of CO_2/TJ (11.4 tons of CO_2/GWh), while it drops to 14 tons of CO_2/TJ (3.9 tons of CO_2/GWh) in rural zones.

B2 Input data

Fuel prices

Current and future **fuel prices** adopted in the HLA-Times energy model are presented in Figure B.38. and based on [71] at constant prices in euros 2017.

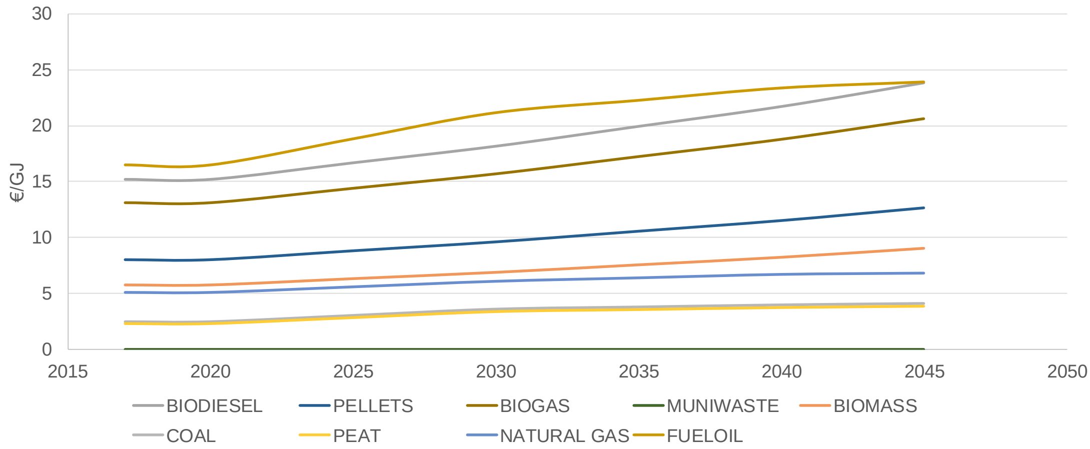

Figure B.38: Fuel prices forecast (based on [71]).

The electricity prices are shown in Figure B.39 for the base year (2017) and 2030. Electricity prices for 2017 are actual prices [74], whereas the prices for 2030 are calculated by using Balmorel modelling tool. Electricity prices are modelled just up to 2030 as the NECP are fix until this year. As the electricity prices are very depending on subsidies and energy policy, it is not clear the energy policy in 2050 except some targets.

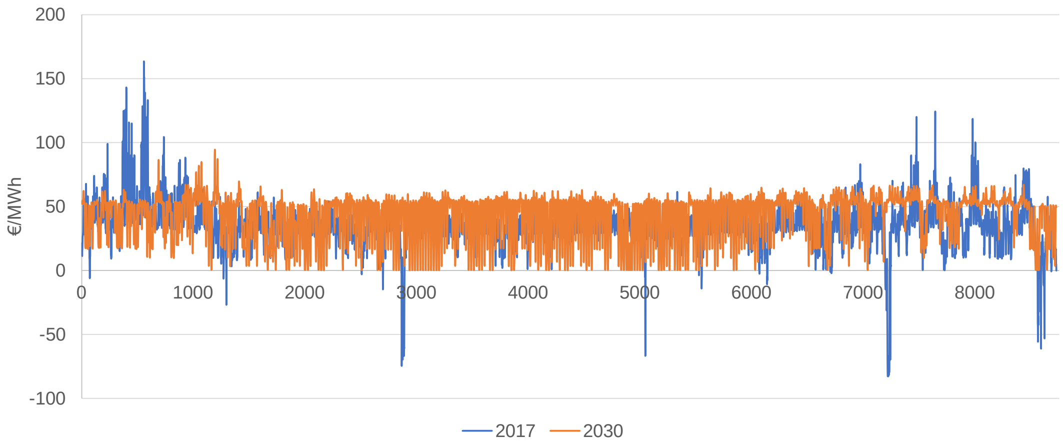

Figure B.39: Electricity prices for base year (2017) actual data [74] and 2030 from Balmorel.

Electricity prices for the other years are estimated by interpolation and extrapolation between these values. Electricity prices from 2017 and 2030 are converted by time slices to be implemented in HLA-Times. Figure B.40 shows electricity prices by different time-slices in 2017, 2030 and 2050.

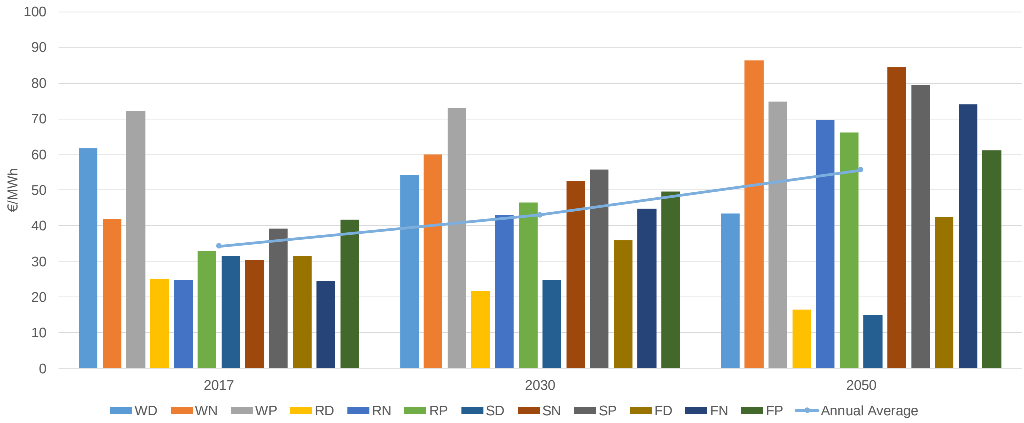

Figure B.40: Electricity prices in the HLA-Times model at time slice level. RD: Spring Day, RN: Spring Night, RP: Spring Peak, SD: Summer Day, SN: Summer Night, SP: Summer Peak, FD: Fall Day, FN: Fall Night, FP: Fall Peak, WD: Winter Day, WN: Winter Night, WP: Winter Peak.

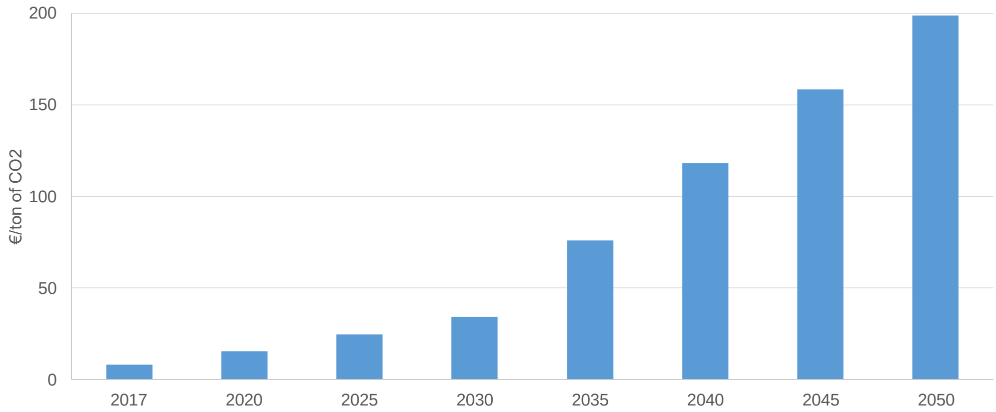

Figure B.41: CO_2 emissions prices forecast [74].

Population

Figure B.42 shows the population distribution by size of city in Lower Austria [70]. This region is characterized by a higher number of small cities with a relative low population. In this sense, urban zones account for 26 cities with a total population of around 480 000 inhabitants. This accounts approx. 28 % of the total population and 5 % of the total municipalities.

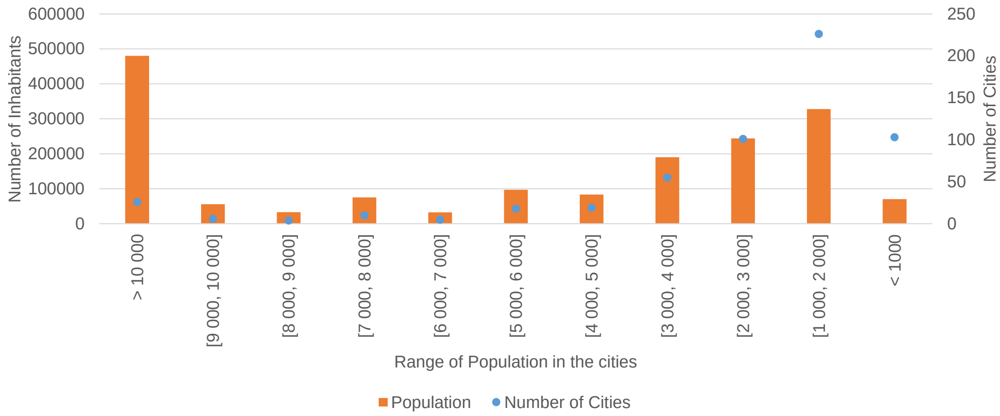

Figure B.42: Distribution of the population in Lower Austria.

Demand projections

Figure B.43 shows the heat demand projection for space heating by building typology and zone. These values are normalized by taking the base year (2017 = 100) as reference. In this projection, the future increase of space heating demand due to the expansion of the buildings is partially compensated by the reduction of the heating degree days (HDD). This effect is more relevant especially in case of the low-efficiency- apartment (APL) and -single houses (RHL), where a demand reduction for space heating can be expected.

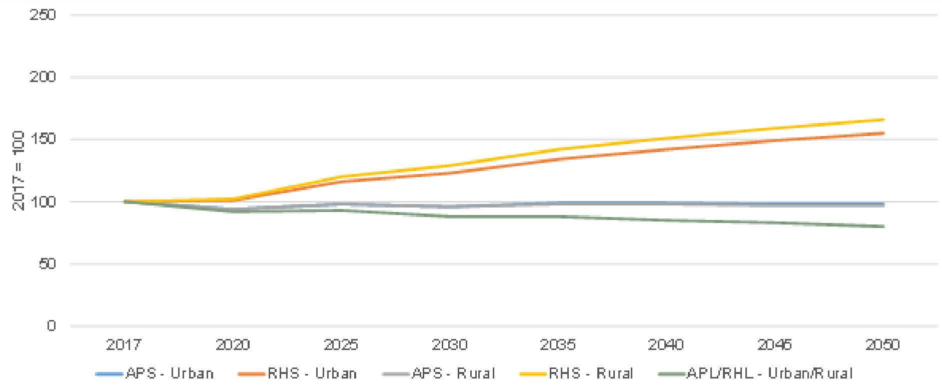

Figure B.43: Heat demand forecast for space heating for the residential sector. APS-Urban: Apartment with standard insulation in urban zones, RHS – Urban: Single houses with standard insulation in urban zones, APS-Rural: Apartment with standard insulation in rural zones, RHS – Rural: Single houses with standard insulation in rural zones, APL/RHL - Urban/Rural: Apartment and Single houses with low insulation in urban and rural zones.

Figure B.44 shows the heat demand projection for domestic hot water by building typology and zone. These values are normalized by taking the base year (2017=100) as reference. Standard single-family houses will have the highest relative increase due the high future expansion of this buildings.

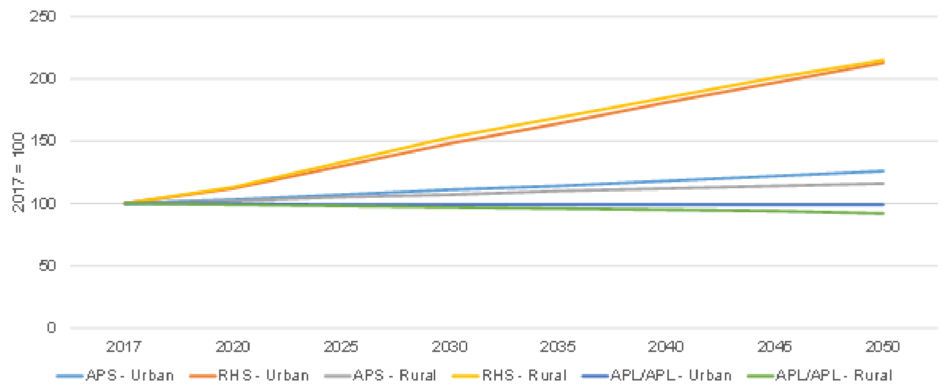

Figure B.44: Heat demand forecast for domestic hot water for the residential sector. APS-Urban: Apartment with standard insulation in urban zones, RHS – Urban: Single houses with standard insulation in urban zones, APS-Rural: Apartment with standard insulation in rural zones, RHS – Rural: Single houses with standard insulation in rural zones, APL/RHL - Urban/Rural: Apartment and Single houses with low insulation in urban and rural zones.

Figure B.45 shows the heat demand projection in the service sector. These values are normalized by taking the base year (2017=100) as reference. The projections are based on the evolution of the energy intensity, defined by the ratio between heat demand and gross value added (GVA). It is expected that energy intensity will be similar for urban and rural zones, and it will be reduced in future due to higher monetary growth compared to heat demand as well as increase of the energy efficiency of buildings.

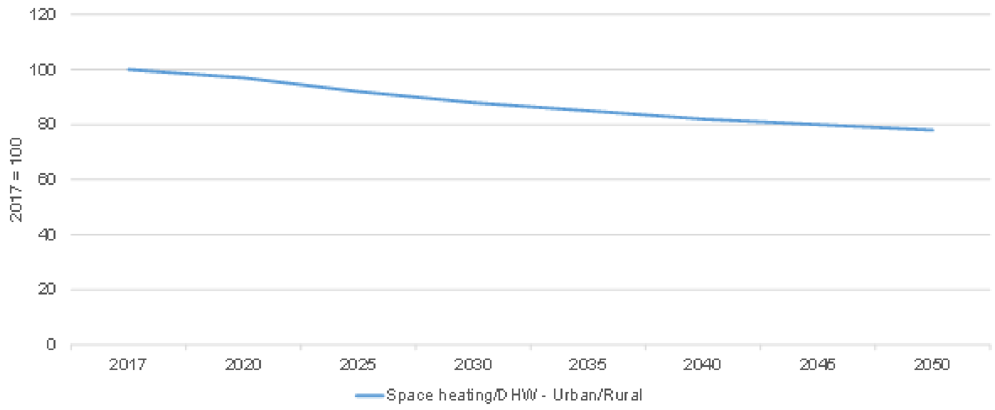

Figure B.45: Demand projection for space heating and domestic hot water for service sector. Space heating/DHW - Urban/Rural: Space heating and domestic hot water in urban and rural zones of service sector.

Flexibility measures

Table B.12: Technology characteristics of HPs technologies for 2017, 2030 and 2050. HP, Heat Pump; DH, District Heating; COP, Coefficient of Operative Performance (based on [75] , [76], [77]).

	COP [-]	Inv. Costs [€/kW]	Fixed O&M Costs [€/kW]	Av. Factor [-]	Economic Lifetime [Year]
Small air-air HP for buildings					
2017	3.20	238	3.2	0.9	20
2030	3.34	227	3.2	0.9	25
2050	3.93	222	3.2	0.9	25
Large air-air HP for buildings					
2017	3.84	130	2.2	0.9	20
2030	4.00	124	2.2	0.9	25
2050	4.72	121	2.2	0.9	25
Small ground HP for buildings					
2017	5.00	1 430	1.6	0.9	25
2030	5.21	1 366	1.6	0.9	30
2050	6.14	1 355	1.6	0.9	30
Large ground HP for buildings					
2017	6.00	1 001	1.1	0.9	25
2030	6.26	956	1.1	0.9	30
2050	7.37	935	1.1	0.9	30
Large air-source HP for DH					
2017	3.50	694	13.9	0.87	20
2030	3.80	663	13.3	0.87	205
2050	5.20	578	11.6	0.87	25

For **HPs**, Table B.12 presents the techno-economic characteristics considered in the simulation in terms of Coefficient of Performance (COP), costs, availability factor and lifetime for the years 2017, 2030 and 2050 (All the cost are at constant prices in euro 2017) [75] , [76], [77].

For CHPs, Table B.13 presents the techno-economic characteristics considered in the simulation in terms of efficiency, costs, CHP ratio (relation between heat and electricity production), availability factor and lifetime for the years 2017, 2030 and 2050 [75] , [76], [77].

Table B.13: Technology characteristics of CHP technologies for 2017, 2030 and 2050 (based on [75] , [76], [77]).

	Efficiency [-]	CHP Ratio [-]	Inv. Costs [€/kW]	Fixed O&M Costs [€/kW]	Availability Factor [-]	Economic Lifetime [Year]
CHP Wood Biomass						
2017	0.81	4.20	1 600	20	0.85	20
2030	0.85	3.00	1 511	16	0.85	25
2050	0.88	2.25	1 333	12	0.85	30
CHP Gasifier Biomass						
2017	0.81	3.50	1 514	31	0.78	20
2030	0.86	3.50	1 457	28	0.78	25
2050	0.90	3.50	1 343	25	0.78	30
CHP Biogas Upgraded						
2017	0.92	2.27	499	4	0.73	25
2030	0.95	2.27	566	4	0.73	30
2050	0.98	2.27	501	4	0.73	30
CHP Diesel						
2017	0.78	2.25	884	4	0.81	25
2030	0.80	2.25	844	4	0.81	30
2050	0.81	2.25	804	3	0.81	35
CHP Waste						
2017	0.53	2.00	3 600	101	0.82	20
2030	0.54	2.00	3 450	95	0.82	25
2050	0.57	2.00	3 350	90	0.82	30
CHP Natural Gas						
2017	0.88	1.83	540	5	0.77	30
2030	0.91	1.83	491	5	0.77	35
2050	0.94	1.83	442	4	0.77	35

Two main **TESs** are considered in scenarios: Pit TES and large-scale water tanks for DH (All the cost are in constant euro 2017) [75] , [76], [77].

Table B.14: Technology characteristics of thermal energy storages for 2017, 2030 and 2050 based on [75] , [76], [77].

	Efficiency [-]	Investment Costs [€/kWh]	Fixed O&M Costs [€/kWh]	Availability Factor [-]	Economic Lifetime [Year]
Pit Thermal Energy Storage					
2017	0.7	0.58	0.01	0.9	40
2030	0.7	0.54	0.01	0.9	40
2050	0.7	0.46	0.01	0.9	50
Large-Scale Water Tanks					
2017	0.98	3.00	0.06	0.9	30
2030	0.98	3.00	0.06	0.9	35
2050	0.98	3.00	0.06	0.9	40

Demand Side Management (DSM)

Heating energy systems are designed to satisfy heat peak load, this makes that DSM one of the key elements for future energy grids. This energy control is implanted at customer side allowing to reduce the peak load. This is done switching part of the heat load during peak period to other periods reducing the fluctuations during heating peaks and valleys.

Figure B.46 shows the estimated heat load profiles for buildings in Maria Laach am Jauerling when a DSM system control is implemented or not. As it was mentioned, the total energy consumption in both cases is 228 MWh, nevertheless, the peak load with DSM is 1 644 kW compared to the 2 211 kW without DSM, this represents a reduction of 26 % of the heating peak.

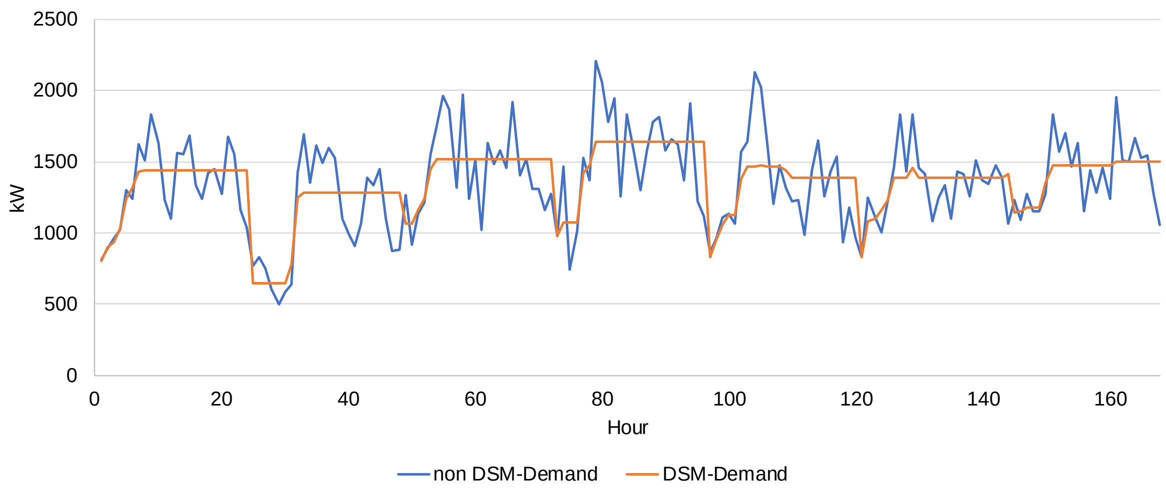

Figure B.46: Heat load profile for buildings without DSM (non-DSM-Demand) and with DSM (DSM-Demand) for Maria Laach am Jauerling during the first week of January.

ANNEX C – OTHER DEMOSITES

C1 Borås (Sweden)

This demo site is in the city of Borås, in the southwest of Sweden. Here the municipal company Borås Energi och Miljö AB (BEM) is delivering both DH and cooling to the citizens of Borås. BEM, together with Willhem, Utilifeed and NODA, form the Borås demo site in the Flexi-Sync project. Willhem is a housing company with approximately 26 000 rental apartments in 13 of the major cities in Sweden and one of the largest customers of BEM.

The base load units producing DH in Borås today are two waste-fired CHP boilers, delivering roughly one third of the total annual heat demand of approximately 600 GWh. The remaining part of the heat demand is mainly produced at KVV Sobacken, a biomass-fired CHP boiler established in 2019 and located about 10 km south of the city centre. When the heat demand is temporary high, there are additional heat only boilers utilizing pellets and bio-oil as fuel.

Figure C.47: The biomass-fired CHP boiler KVV Sobacken (120 MW).

BEM joined the project mainly to investigate how the flexibility of heat customers, with multiple heat sources installed in their buildings, can lower the total costs for both DH provider and heat customers and at the same time reduce the environmental impact. Together with housing company Willhem and energy service providers Utilifeed and NODA, they have investigated how a co-optimization of the supply side (marginal production of DH) and demand side (the shifting of heat pump and DH for heating in buildings) can be obtained. The buildings selected as part of the demo site are two multi-family residential buildings in Borås equipped with both DH supplied by BEM and a local ground source heat pump. These buildings were selected because they can shift between the two heat sources, which in turn can be used to provide demand side flexibility to the energy system.

The goal is that the Flexi-Sync project will be able to show that a more flexible operation of the buildings' heating alternatives can create both economic and environmental values. An additional strength with the Flexi-Sync project is that there are several different DH companies, with different production systems, involved in the project. The operational strategy found in Borås might not be the same as for the other demo sites, which will show the importance of finding the right boundary conditions for each specific co-optimization case.

Within the Flexi-Sync project, the project partner Utilifeed has developed an optimization tool for supply and demand side flexibility and BEM has assisted with the integration of Borås demo site with the software. NODA and Willhem have installed indoor climate sensors and a control system in two of Willhem's residential buildings. In the beginning of 2022 tests were carried out to see how the flexibility of the buildings' heating alternatives could be utilized.

During the test period the optimization tool was able to estimate and suggest how the heating of the two buildings could be optimized. Signals from the optimization tool was successfully sent to the NODA control system in the two residential buildings, but unfortunately the ground source heat pumps did not react to the signals.

C2 Mölndal (Sweden)

Mölndal Energi AB is a municipal-owned energy company that develops and offers affordable and sustainable energy solutions to customers in both Mölndal and the rest of Sweden. The company owns and operates district heating (DH) and cooling network (DC) with over 2300 customers. The production is based on 100 % renewable energy and includes a large, combined heat and power plant, 80 MW. The DHN is connected to the much larger Gothenburg network and the heat is traded daily. The sister organisation Mölndal Elnät AB owns and operates the local electricity network in the Mölndal.

Mölndal joined the project as a start of the development of demand side management systems in district heating and cooling to minimize primary energy demand as well as minimising production costs. Another aspect is security of supply and the possibility to distribute the energy in case of a major incident in the production or distribution.

Within the Flexi-Sync project, the project partner Utilifeed has developed an optimization tool for supply and demand side flexibility and BEM has assisted with the integration of the demo site with the software. NODA and Willhem have installed a control system in three residential buildings. In the beginning of 2022 tests were successfully carried out to see how the flexibility of the buildings' heating alternatives could be utilized.

C3 Berlin (Germany)

The demonstrator is in the eastern Berlin district of Biesdorf. The "Grüne Aue" residential complex comprises 113 residential units with a total of 11 400 square meters.

Figure C.48: Visualization of the "Grüne Aue" plant in Berlin Biesdorf (cksa.de).

Here, a wastewater HP was custom-made as part of a decentralized heat supply system for the newly built complex which adds up to a particularly sustainable energy supply solution. The overall energy system contains a heat pump, heat only boiler and a CHP.

Figure C.49: Exemplary illustration of the demo site in Berlin.

The “Grüne Aue” district is supplied with heat by a total of three generation plants: In addition to the wastewater heat pump, a combined CHP and a condensing boiler are used in the heating center. The annual heat requirement is 740 megawatt hours. The environmental energy for the heat pumps comes from heat exchanger plates in a wastewater sewer. Here, 58 modules with a total length of 60 meters and an extraction capacity of 80 kW are installed.

As part of the preliminary planning, a flow of 22 l/s was determined as the dry weather flow in the sewer, with a sewer diameter of 600 mm.

Figure C.50: Map of the demo site in Berlin.

A condensing boiler covers the heat demand at peak times. The heat is distributed via a local heating network with a route length of one kilometer. The system combination is supplemented by remotely readable heat meters that enable fully automated meter reading. In addition, the maximum local power generation by PV modules is recorded via a cooperation with Leaftech. The electricity generated on site can be used directly as domestic electricity, to operate the heat pump, charge the e-cars and more, depending on demand.

C3.1 Methodology

C3.1.1 Tool

The tool used to calculate the investigated scenarios is built in Excel and it can carry out hourly based energy balance in Stationary manner. This means, that hourly values are used with maximum resolution and depending on the application, either a lump sum method or correlations existing on trend lines and regression curves are used for the modeling. The calculation tool consists of different modules that enables step-by-step calculation.

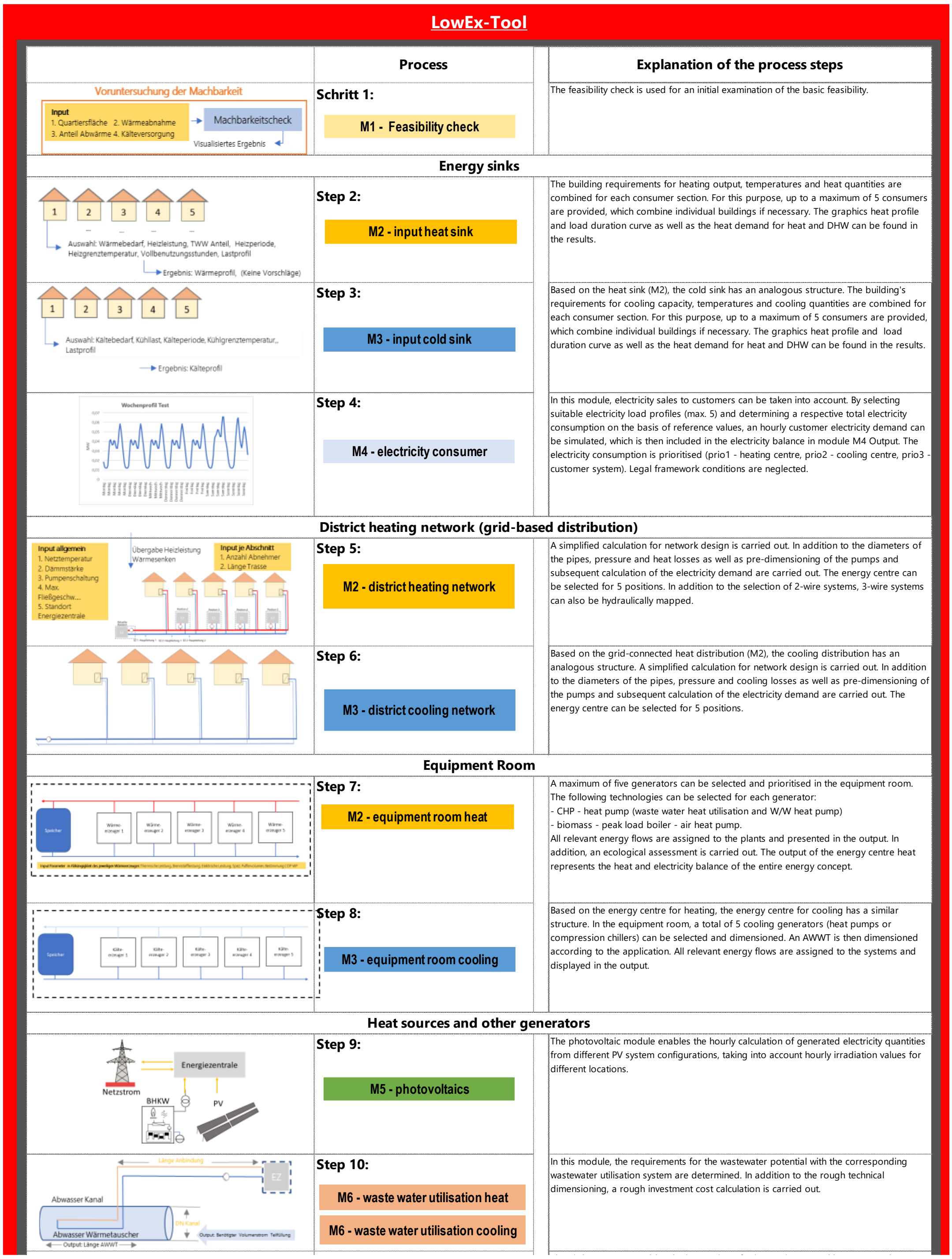

Figure C.51: LowEx Tool start page.

The calculation tool is structured in such a way that the heat sinks are defined at the beginning, the network-connected distribution is then designed and based on this, a generator concept with the corresponding environmental heat sources is designed. This procedure is carried out equivalently for the provision of heat and cooling (if provided).

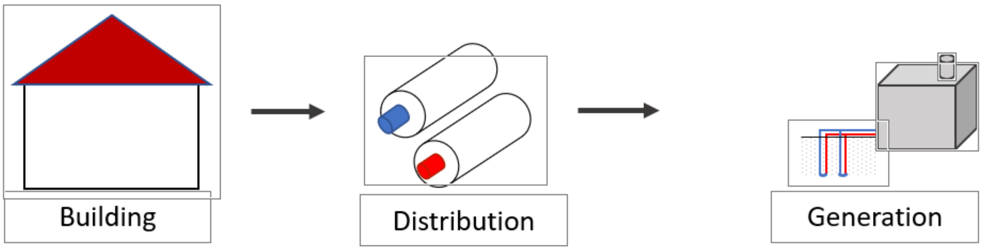

Figure C.52: Structure of the calculation tool.

In the step-by-step processing of the modules, a distinction is made between necessary, concept-specific, and optional modules. A list is given in Table B.12. The definition of the heat sink and the core of the tool - the energy centre heat - as well as the heat sources required depending on the selected energy concept are necessary modules for processing. The following table shows the processing steps with application and condition. The generation is divided into energy centre (EC) and heat sources.

Table C.15: Processing steps of the individual modules with application and condition.

	Modules	Application	Necessary when ...
Energy sink	M1 Feasibility check	Optional	General feasibility unclear.
	M2 - Heat sink	Necessary	In any case.
	M3 - Cold sink	Optional	Cold supply available.
	M4 - Electricity consumers	Optional	Tenant electricity announced.
Distribution	M2 - Mains-based Distribution heat	Optional	Network losses relevant.
	M3 Network-bound Distribution cooling	Optional	Network losses relevant.
EZ	M2 - Energy centre heat	Necessary	In any case.
	M3 - Energy centre cooling	Optional	Cooling supply available.
Heat sources	M5 – Photovoltaics	Optional	Self-supply of electricity advised.
	M6 - Waste water heat exchanger	Concept-specific	WP with AWWT selected.
	M7 - Heat source air	Concept-specific	WP with source air selected.
	M8 - Geothermal use	Concept-specific	WP with geothermal source selected.

Module **2: Heat sink**

The building-side requirements for heating output, temperatures and heat quantities are combined for each consumer section. For this purpose, up to a maximum of 5 consumers are provided, which combine individual buildings if necessary. The calculation of the heat and cold sinks is limited to the types of use residential and office. Annual, monthly, and hourly values scaled with standard profiles are created separately and combined for heating, domestic hot water, and passive cooling. The building requirements for heating power, temperatures and heat quantities are summarized for each consumer section.

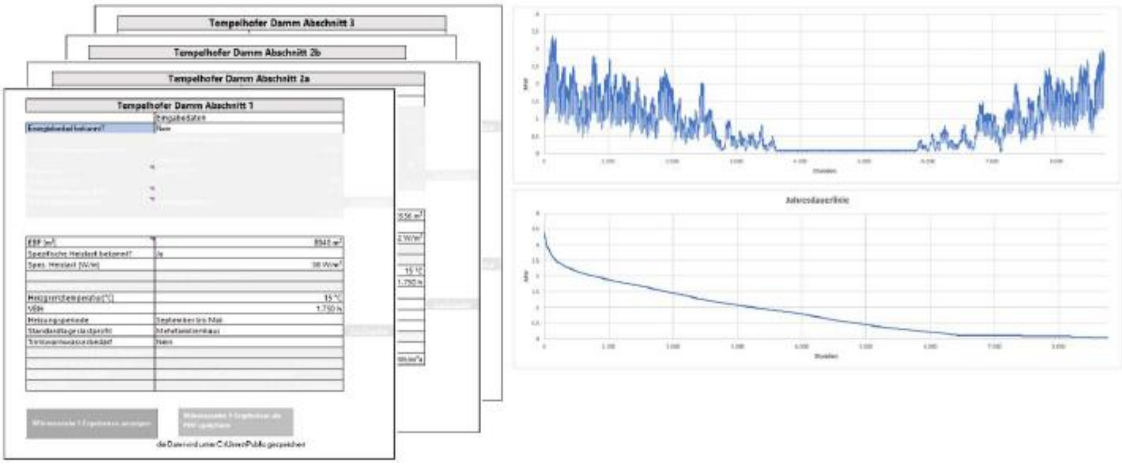

Figure C.53: Module-Heat Sink Input-Output.

Module **3: Grid based distribution**

A simplified calculation for network design is carried out. In addition to the diameters of the conductors, pressure, and heat losses as well as pre-dimensioning of the pumps and subsequent calculation of the electricity demand are carried out. Both the position of the energy centre and the number of conductors can be selected individually, depending on the requirements. The calculation can be done up to up to 8 network nodes with heat / cold sinks and the length of the house connection line to map the network structure. Corresponding graphics and the compilation of results in profile form are provided as an interface for the transfer to the subsequent module 4 “energy centre”.

Module **4: Energy centre**

Up to five different heat generators can be defined in the energy centre module. A distinction can be made between high-temperature heat generators such as boilers, CHP, and low-temperature heat generators such as heat pumps.

A priority number is set for each generator, indicating which heat generator will be switched on first. The priority of the components should be determined based on the project goal.

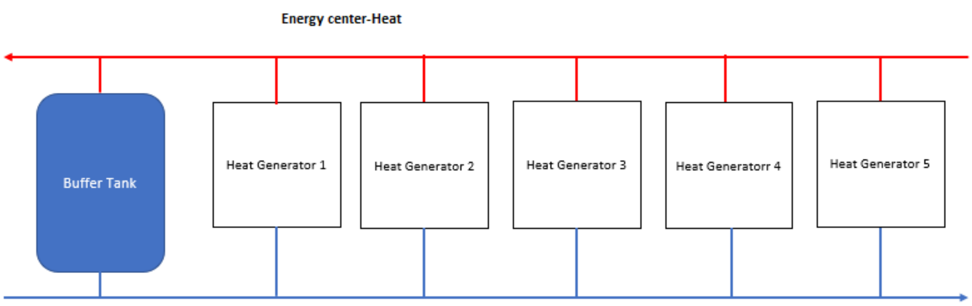

Figure C.54: Schematic representation of the energy centre.

All relevant energy flows are assigned to the systems and the energy input and output are shown electrically and thermally with corresponding parameters such as temperature and power. Cooling through the sewage system is also provided; active cooling can also be added.

An overarching simplified operational management is used as a basis to do justice to the temperature sensitivity of the systems used (the heat pumps and the influence on the COP). Corresponding graphics and a compilation of results in profile form are provided as an interface for transfer either to the subsequent module 5a "sewage water utilization" or to module 5b "subway excess heat utilization".

Module **5a: Sewage water utilization**

Only the Uhrig Term-Liner systems preferred by BWB are considered for the illustration of the sewage water utilization system. In addition to the technical designs, the investment costs for the Uhrig Term-Liner systems are shown. The requirements for the sewage water potential with the corresponding sewage water utilization system are determined.

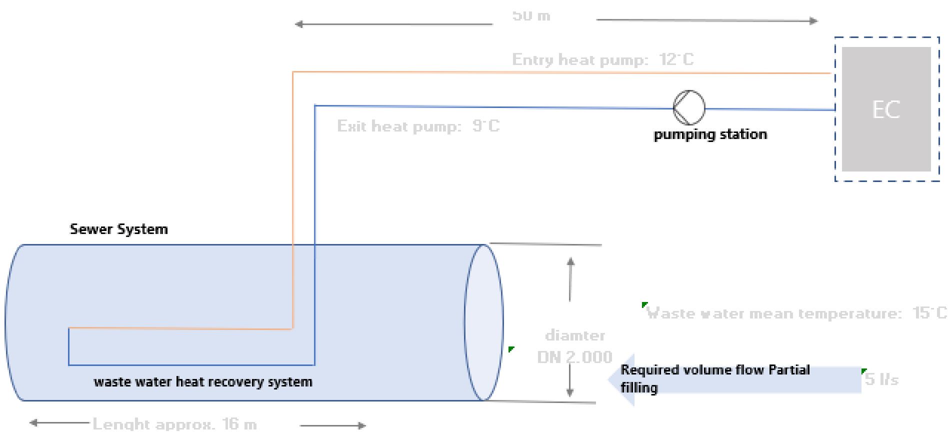

Figure C.55: Schematic representation of the sewage water utilization.

Module **5b: subway excess heat utilization**

For the dimensioning of the excess heat recovery system from the subway system, a module was developed that uses the air temperature profile to determine the relevant technical system parameters of the fans and heat exchangers to be used.

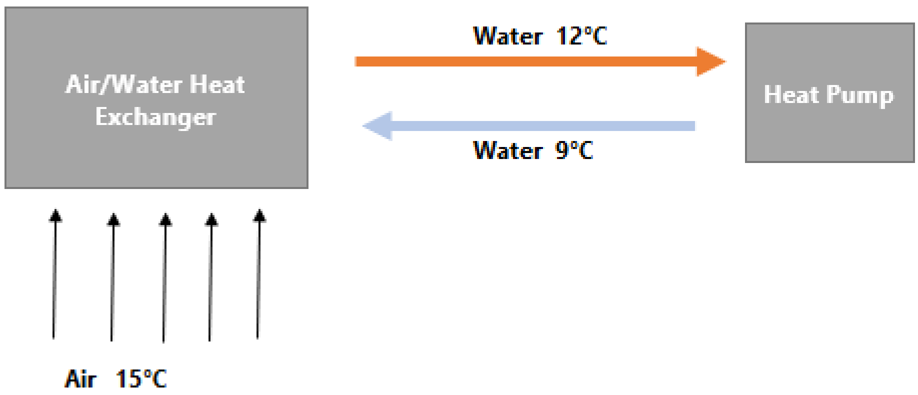

Figure C.56: Schematic representation of subway excess heat utilization.

Heat demand estimation

As first step, the estimated annual heat demand in Berlin 2050 should be fed in the calculation tool. The Total head demand of 18 TWh and 51 % market share of DH in 2050 is assumed, this corresponds to DH sales of 9.2 TWh. Additionally, 5.5 % heat grid loses is considered. 9.7 TWh should be generated based on renewable energies. The followings parameters are defined in the calculation tool to generate an hourly heat demand profile:

- Annual heat demand [9.7 TWh]
- A prediction of the Ambient temperature profile Berlin 2050 (please add short description (From whom is provided, Methods, different type of temperature profile (extreme and moderate weather data)
- Daily usage type of residence apartment blocks-Profile
- DHW (domestic hot water) share of 30 % from the total heat demand.

The demand is distributed over the reference year using a degree-day method. Degree days assume that when the outside temperature is above the heating limit temperature, e.g., 15 °C, heating is not needed.

$$G_{t_g} = 1d \cdot \sum_{n=1}^{z} (t_g - t_{m,n}) \text{ für } t_m < t_g$$ Equation 4

Where

G_{t_g}	Degree day number for a specific heating limit temperature	K•d
z	Number of heating days in the evaluation period	d
t_g	Heating limit temperature	°C
$t_{m,n}$	Daily mean temperature (outside) of the respective heating day n	°C

If, for example, the heating limit temperature is 15°C and on one day there is a daily average temperature of 12°C while on another day there is an average temperature of 7°C, then there is 15°C-12°C=3 degree days on the first day and 15°C-7°C=8 degree days on the second day. This means that only half as much heat is consumed on the first day as on the second day.
The daily calculated heat demand is distributed over an hourly daily profile based on the usage type. For our project residence apartment blocks-Profile is assumed.

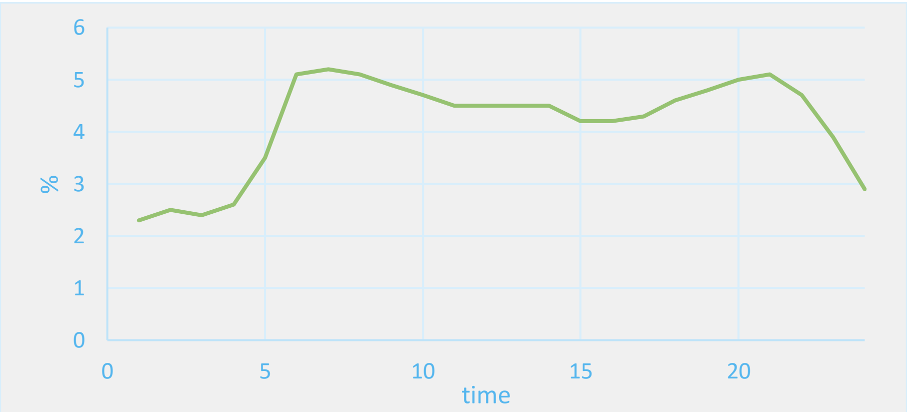

Figure C.57: Daily load profile MFH.

The following diagram shows the generated heat profile based on the above-mentioned parameters:

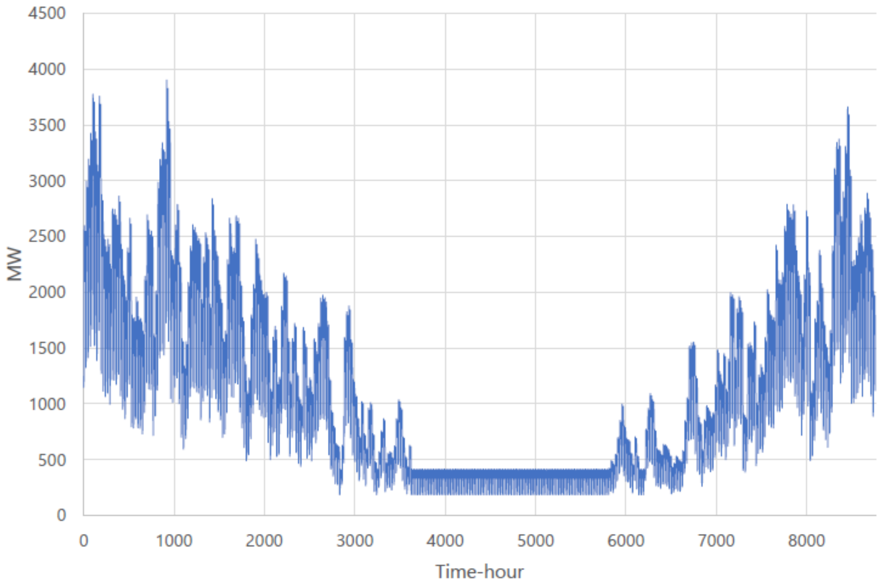

Figure C.58: Heat load profile- annual heat demand of 9.7 TWh and distribution based on average ambient temperature.

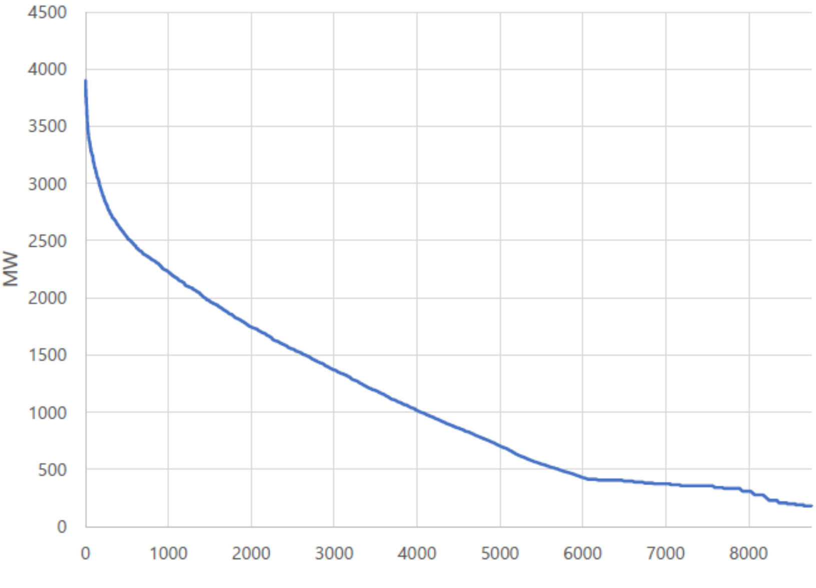

Figure C.59: Heat duration curve- annual heat demand of 9.7 TWh and distribution based on average ambient temperature, for Berlin in year 2050.

The estimated total heat demand of 9.7 TWh it depends strongly on the ambient temperature which based on moderate temperature. In case of extreme low or high temperature, the heat demand will be changed correspondingly. As a part of the project, the heat supply system should be investigated for different weather scenarios. The degree days' method is again applied to estimate the heat demand for the extreme weather data.

The annual heating days based on the heat demand of 9.7 TWh and moderate ambient temperature and heating degree are calculated the heating days then is calculated in similar way for the other weather data and correction factor can be calculated between the reference year TDY (moderate weather) and extreme year (ECY&EWY) (extreme cold & warm year) the results can be found in the following table.

Table C.16: Calculated annual heating degree days for the different scenarios.

Heat demand 2050 (TDY)	9.700 GWh
Heating days 2050 (TDY)	259 d
Heating degree 2050 (TDY)	3.476
Heating days 2050 (ECY)	321
Heating degree 2050 (ECY)	5.755
correction factor (ECY/TDY)	1,7
Heat demand 2050 (ECY)	16.060 GWh
Heating days 2050 (EWY)	186 d
Heating degree 2050 (EWY)	1.990
correction factor (EWY/TDY)	0,6
Heat demand 2050 (EWY)	5.553 GWh

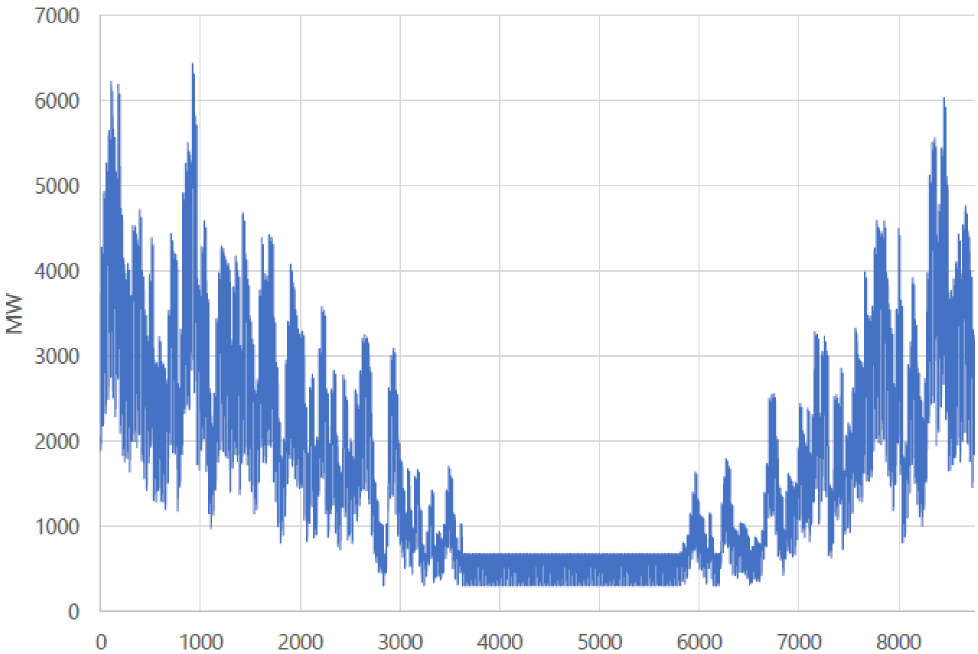

Figure C.60: Heat load profile- annual heat demand of 16 TWh and distribution based on extreme cold weather.

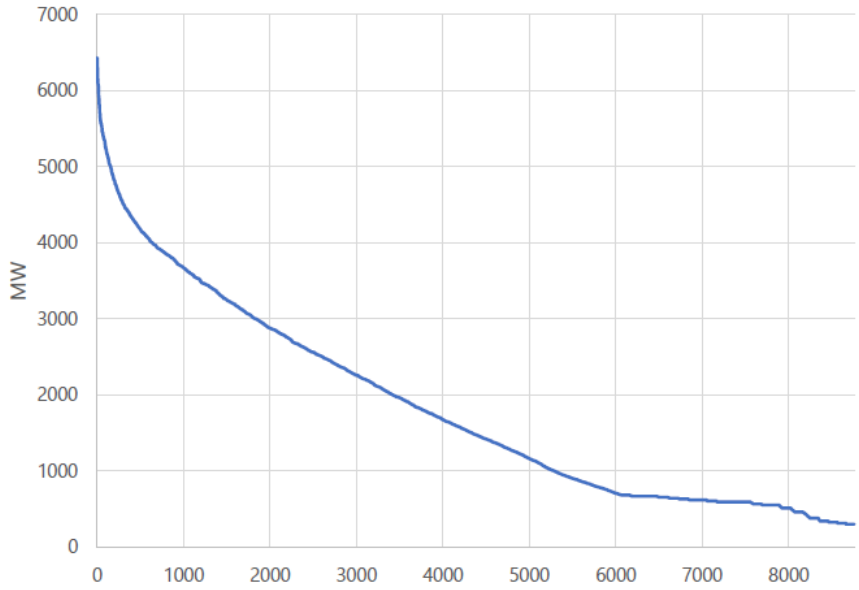

Figure C.61: Heat duration curve- annual heat demand of 16 TWh and distribution based on extreme cold weather.

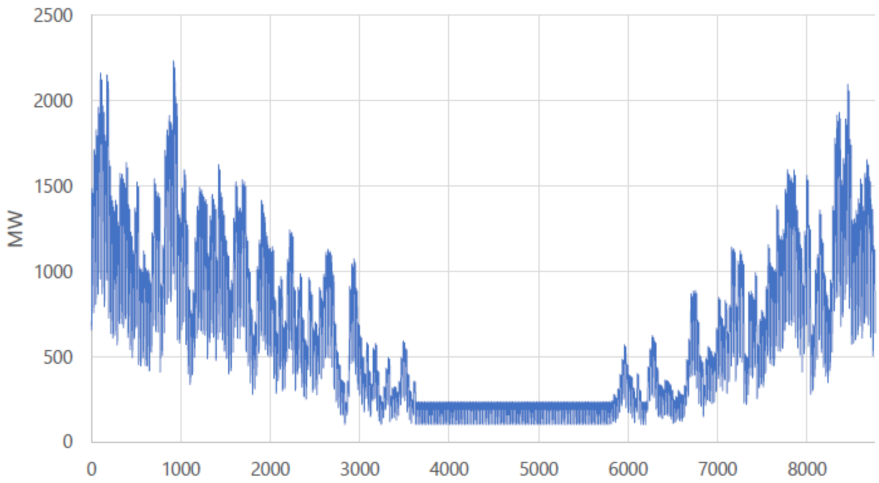

Figure C.62. Heat load profile- annual heat demand of 5.5 TWh and distribution based on extreme warm weather.

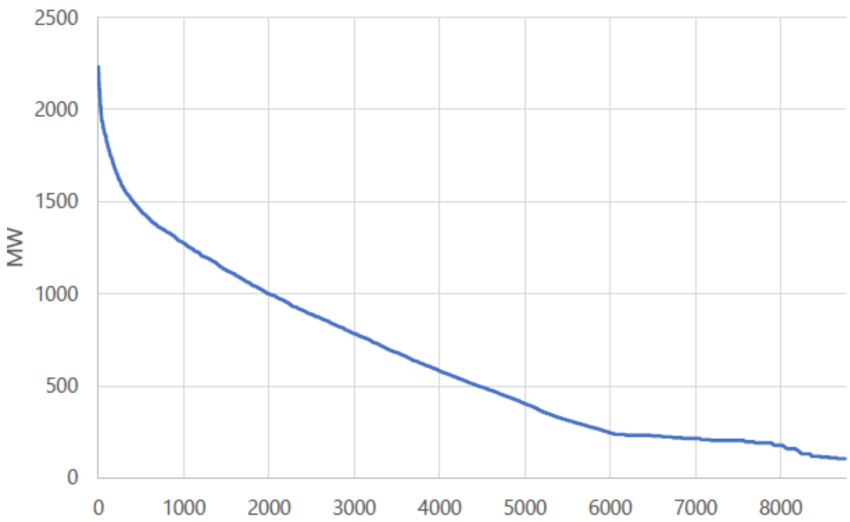

Figure C.63: Heat duration curve- annual heat demand of 5.5 TWh and distribution based on extreme warm weather.

C3.1.2 Scenarios

The conceptualisation of a renewable energy supply for the year 2050 was based on the following renewable energy potentials published in the Progress Report Vattenfall (Status Q1 2022):

1. **Excess heat from subway stations in Berlin**

   In urban centres, subway stations are interesting sources of excess heat in winter. The mean outside temperature in Berlin in winter is 1.3 ° C and the drain from underground shafts is according to studies by the University of Bochum in 2014 about 10K above the outside temperature. The potential of the available useful heat from excess heat from subway platforms is around 5 500 MWh per station, in total 900 GWh. The product "excess heat from the subway" is set up as a decentralized supply concept in combination with peak load generation and is intended to supply customers with heat in the immediate vicinity of the excess heat source.

2. **Excess heat from sewage in Berlin**

   The limiting factors for the potential use of the available excess heat are suitable heat sinks in the vicinity of the sewage pipes and upstream heat extraction points that require regeneration of the sewage. As a rule of thumb: After a sewage water heat recovery system, about two to three times the length of the system itself should be planned as a so-called regeneration section. If a sewage water heat recovery system is 100 meters long, the next sewage water heat recovery system can only be installed again about 200 to 300 meters later. According to the research project “Urbane Wärmewende” the potential of excess heat utilization from sewage water systems is 200 to 600 GWh in Berlin.

3. **Excess heat from cooling in Berlin**

   The use of excess heat from cooling processes is essentially limited by the summer heat load in the Berlin DH network, which is around 350 MW. Should the heat summer load be covered theoretically exclusively from excess heat from the cooling process and thus replace all other DH systems, 210 MW of cooling can theoretically be installed which results in excess heat of around 230 GWh in the Berlin DH system

4. **Solar power in Berlin**

   The maximum solar potential in Berlin determined in this study is 6000 GWh, which is around 44 % of the electricity consumption in Berlin. Half of the solar potential can be found on residential buildings, a third on buildings with commercial use and ten percent on public buildings.

5. **Further environmental potentials**

   Within the scope of the study, an additional expansion of environmental heat utilisation by means of ambient air via recoolers, in combination with heat pumps, was assumed in the amount of 260 MW. Since ambient air can be used without major technical or regulatory restrictions, this potential can be further increased to achieve the desired share of renewable energy.

C3.2 Results

In the following, three simulations were carried out on an hourly basis using the Excel tool presented. To simplify the simulation model, the generation technologies of one type, such as many air-to-water heat pumps, were combined into one entire system.

The renewable energy potentials shown above represent a fixed investigation criterion and were dimensioned identically for each scenario. Depending on the heat demand, depending on the scenario, only the output / heat quantity of the biogenic and fossil generators (generators with priority 4 and 5) is adjusted to cover the heat demand. The heat generator structure is shown in the following figure as an example. The priority of the generators is ascending to the right.

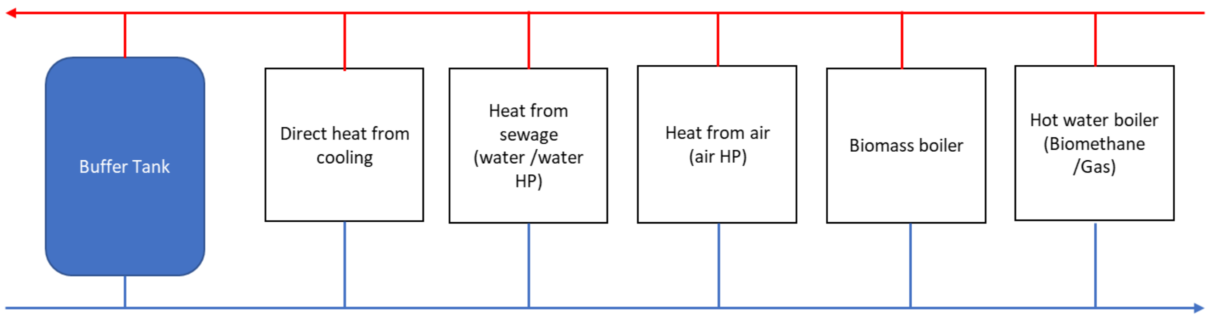

Figure C.64: Representation of the heat generation structure of all variants. Priority of generation is ascending to the right.

The following adjusted CO_2 emissions were used for the analysis. For the power supply of the heat pumps from the electricity grid, specific CO_2 emissions of 0 g/kWh were assumed for the year 2050.

Table C.17: CO_2 emissions assumed for the different fuels.

Energy source	fco2 [g/kWh]	source
Natural gas	240	AGFW FW 309 Part 1 May 2021
Biomass	20	AGFW FW 309 Part 1 May 2021
Electricity grid-related (2050)	0	Zielwert Umweltbundesamtes (UBA)
Biomethane in condensing boilers	140	AGFW FW 309 Part 1 May 2021

C3.2.1 Scenario TDY (moderate weather year)

The TDY scenario represents the previously determined moderate weather year. The following figure shows the hourly heat supply of the individual generation technologies.

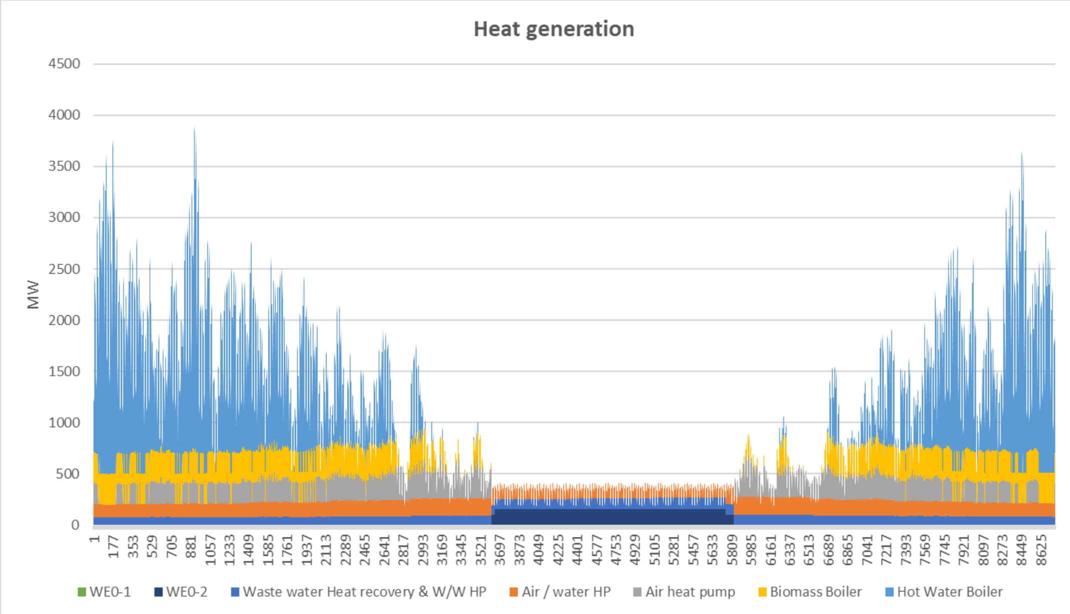

Figure C.65: Hourly heat production for heat profile TDY.

In addition to the hourly heat supply, the generation can also be represented as an annual duration curve.

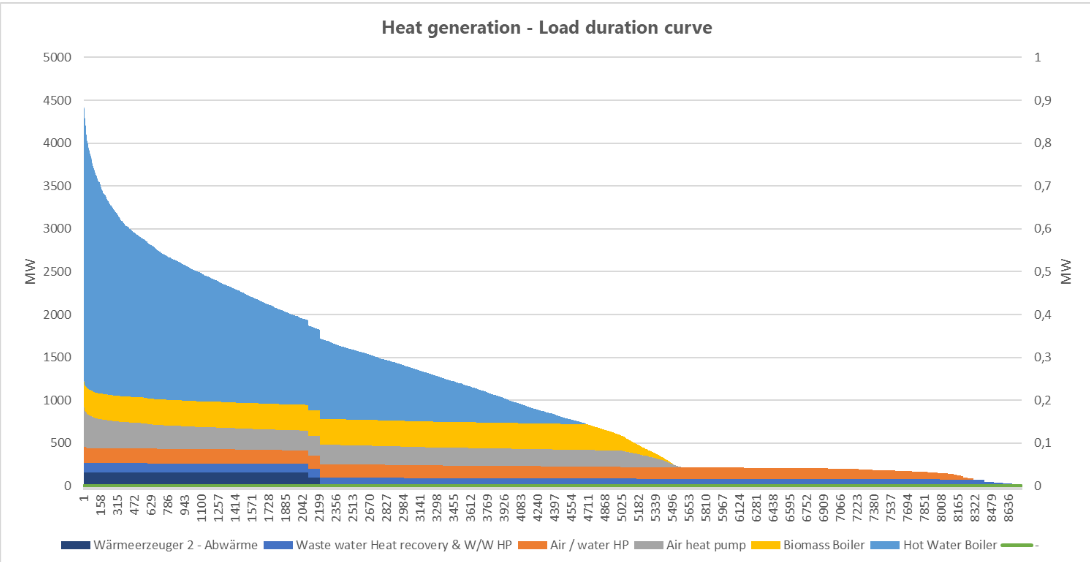

Figure C.66: Annual duration curve of the generation technologies for the heat profile TDY.

The following table shows the design of the generation technologies with their percentage share of heat generation. With the environmental potentials published in the Progress Report (status Q1 2022) plus the environmental heat source air, 36 % of the heat demand can be covered by renewable energies in the consideration for the normal temperature based on the heat profile TDY. The other 64 % of the heat in this scenario is provided by biomass boilers (16 %) and biogas combustion (48 %).

Table C.18: Generation technologies with their percentage share of heat generation for TDY (moderate weather year).

Priority	Generation technology	Thermal power [MW]	Generated heat [GWh]	Electricity consumption [GWh]	Percentage of heat production [%]
1	Direct heat from cooling	-	347	-	4
2	Heat from sewage (water / water HP)	90	767	170	8
3	Heat from subway stations (air / water HP)	160	1 158	240	12
4	Heat from air (air HP)	260	1 243	413	13
5	Biomass Boiler	300	1 528	-	16
6	Hot Water Boiler (100 % Biomethane)	3 000	4 652	-	48
	Total	**3 800**	**9 696**	**824**	**100**

The absolute CO_2 emissions of this variant are 717 261 tonnes/a or 74 g/kWh due to the generation technologies biomass and peak load boiler with biomethane. According to current calculations, the biogas used emits 94 % of the CO_2 emissions, with a specific CO_2 emission of 140 g/kWh.

C3.2.2 Scenario EWY (warm weather year)

The EWY scenario represents the previously determined warm weather year. The following figure shows the hourly heat supply of the individual generation technologies.

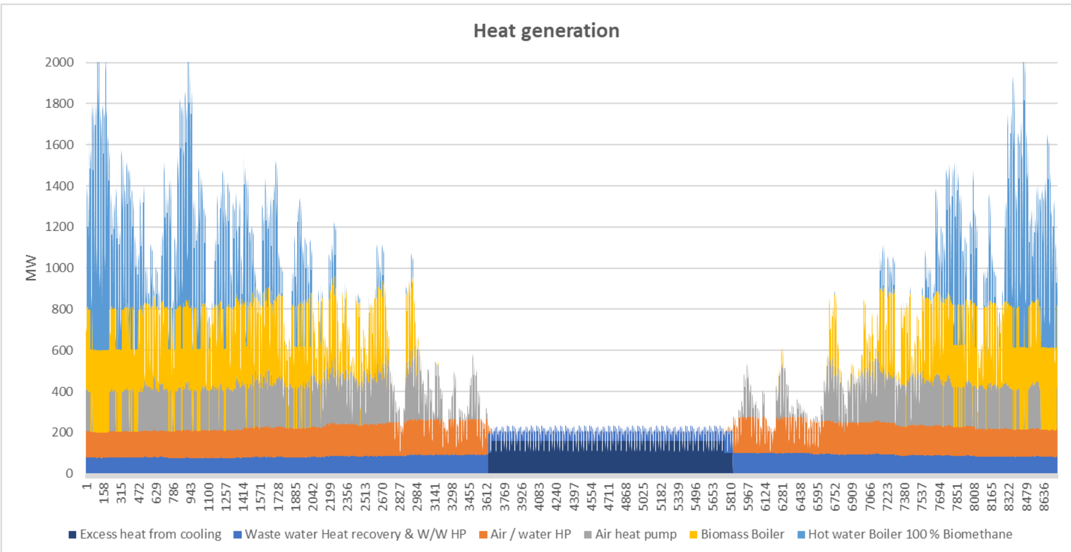

Figure C.67: Hourly heat generation for heat profile EWY.

In addition to the hourly heat supply, the generation can also be represented as an annual duration curve.

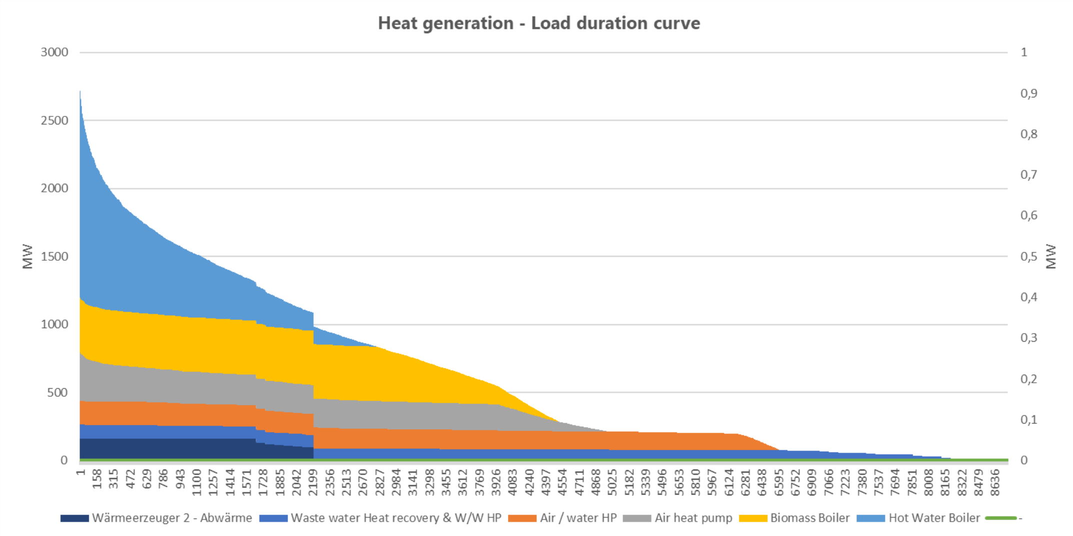

Figure C.68: Annual duration curve of the generation technologies for the heat profile EWY.

The following table shows the design of the generation technologies with their percentage share of heat generation. With the environmental potentials published in the Progress Report (status Q1 2022), 52 % of the heat demand can be covered from renewable energies in the consideration for a warm year using the EWY heat profile. The remaining 48 % of the heat in this scenario is provided by biomass boilers (21 %) and biogas combustion (27 %).

Table C.19: Generation technologies with their percentage share of heat generation for EWY (warm weather year).

Prior-ity	Generation technology	Thermal power [MW]	Gener-ated heat [GWh]	Electricity consump-tion [GWh]	percentage of heat produc-tion [%]
1	Direct heat from cool-ing	-	327	-	6
2	Heat from sewage (water / water HP)	90	659	148	12
3	Heat from subway sta-tions (air / water HP)	160	936	202	17
4	Heat from air (air HP)	260	973	337	18
5	Biomass Boiler	300	1 165	-	21
6	Hot Water Boiler (100 % Biomethane)	1 600	1 491	-	27
	total	**2 310**	**5 551**	**689**	**100**

The absolute CO_2 emissions of this variant are 249 811 tonnes/a or 45 g/kWh due to the generation technologies biomass and peak load boiler with biomethane. According to current calculations, the biogas used emits 88 % of the CO_2 emissions, with a specific CO_2 emission of 140 g/kWh. For the power supply of the heat pumps from the electricity grid, specific CO_2 emissions of 0 g/kWh were assumed for the year 2050.

C3.2.3 Scenario ECY (cold weather year)

The ECY scenario represents the previously determined cold weather year. The following figure shows the hourly heat supply of the individual generation technologies.

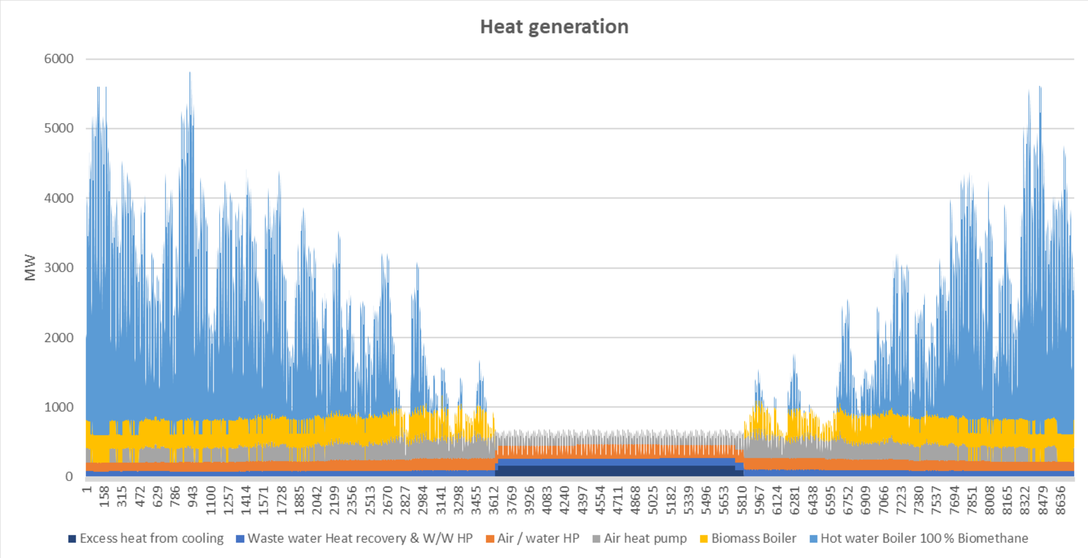

Figure C.69: Hourly heat production for heat profile ECY.

In addition to the hourly heat supply, the generation can also be represented as an annual duration curve.

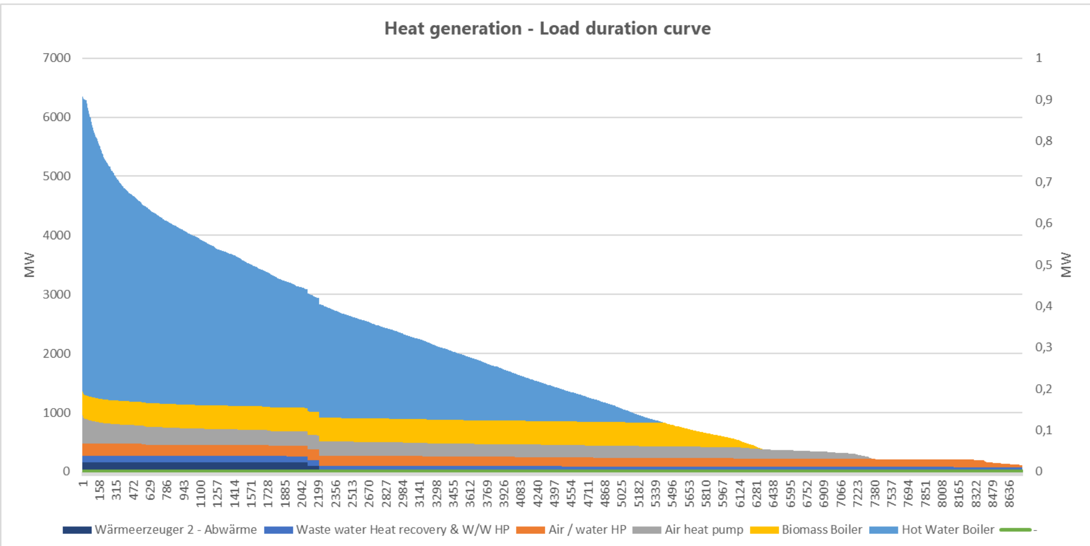

Figure C.70: Annual duration curve of the generation technologies for the heat profile CWY.

The following table shows the design of the generation technologies with their percentage share of heat generation. With the environmental potentials published in the Progress Report (status Q1 2022), 25 % of the heat demand can be covered from renewable energies in the consideration for a warm year based on the EWY heat profile. The potentials used as a basis under ... were used analogously. The remaining 75 % of the heat in this scenario is provided by biomass boilers (15 %), biogas combustion (30 %) and natural gas combustion (30 %).

Table C.20: Generation technologies with their percentage share of heat generation for ECY (cold weather year).

Priority	Generation technology	Thermal power [MW]	Generated heat [GWh]	Electricity consumption [GWh]	percentage of heat production [%]
1	Direct heat from cooling	-	346	-	2
2	Heat from sewage (water / water HP)	90	793	175	5
3	Heat from subway stations (air / water HP)	160	1 346	271	8
4	Heat from air (air HP)	260	1 627	511	10
5	Biomass Boiler	400	2 359	-	15
6	Hot Water Boiler (50 % Biomethane / 50 % gas)	5 000	9 517	-	60
	Total	**5 910**	**15 991**	**957**	**100**

The absolute CO_2 emissions of this variant are 1 973 419 tonnes/a or 123 g/kWh due to the generation technologies biomass and peak load boiler with biomethane.

In all, none of the three scenarios examined can provide the entire heat demand from renewable sources with the predicted renewable potentials. Depending on the scenario, this is limited to 25 - 52 % of the total heat demand, as shown in the following table.

Table C.21: Comparison of the shares of renewable energies, biomass, and biogas as well as natural gas for the three scenarios.

Scenario	Share of coverage from renewable energies	Share of coverage from biogenic energies	Share of coverage from fossil energies
ECY (cold)	25 %	45 %	30 %
TDY (moderate)	36 %	64 %	0 %
EWY (warm)	52 %	48 %	0 %

Table C.22: Resulting CO_2 emissions in the different scenarios.

Scenario	CO_2 emissions total	CO_2 emissions
ECY (cold)	1 973 419 ton/a	123 g/kWh
TDY (moderate)	721 057 ton/a	74 g/kWh
EWY (warm)	249 811 ton/a	45 g/kWh

Consideration of solar thermal energy for direct thermal use in the heating network and the use of geothermal energy in combination with heat pumps could increase the share of heat provided from renewable sources.

To reach the target of a CO_2 reduction of 95 % by 2050, further environmental heat sources must be considered and the efficiency of buildings must be improved more than assumed in this scenario development. The following table shows the absolute and specific CO_2 emissions of the individual scenarios under the underlying parameters. The scenario with the lowest heat demand has the lowest specific CO_2 emissions, as the renewable potentials cover not only the base load but also the medium load.

C4 Palma (Spain)

Parc Bit is a science and technology park located in Palma de Mallorca, Spain. The district energy network in Parc Bit was built in 2000 connecting a tri-generation plant to the office buildings located in Parc Bit technological center. In 2002 the network was extended by connecting another branch to the university facilities, covering including of 4 000 m^2 or 18 buildings, including the student house, a sports center, two schools and the university campus of Universitat de les Illes Balears. The heating and cooling grid provides thermal comfort to 25 different customers. For district networks located in Mediterranean climates, and this one in Parc Bit, the cooling demand may be as important as the heating demand. A noteworthy feature of this district network is that some of the branches provide heating and cooling to certain users at the same time, nevertheless most of the users are seasonal users (heating demand in winter, cooling demand in summer). Moreover, according to the energy profiles of the customer they can be split into three categories: office buildings, educational and specific usages (residential, swimming pool and IT room). These profiles are also differentiable between workdays and weekends.

Figure C.71: Parc Bit view.

Sampol (project partner) operates and maintains the tri-generation plant which produces electricity, hot water, and cold water for Parc Bit,. The tri-generation power plant is a high-efficient production plan based on a combined heat and power (CHP) gas engine and absorption chillers which provides heat through a DH and cooling networks to the heat customers. The performance of the power plant can reach 85 %, however, depending on the demand and weather conditions this performance can decrease considerably. Reasons for poor performance could be high demand (consequently, machines are working out of the nominal load and auxiliary machines must operate less efficiently) and high temperature (cooling towers performance are very sensitive to weather conditions).

Furthermore, the RES penetration is one of the main topics recently which makes even more important flexibility.

Sampol has been involved in the development of innovative solutions which increase the flexibility of the DHC of Parc Bit. This flexibility will increase the share of RES, increase the efficiency of the co-generation plant (which supplies electricity, hot and cold water to the district area) and reduce heat losses.

To increase flexibility, three pillars are essential:

1. An energy production baseline, as it is crucial to know how the energy production is going to behave if we change the production plan thanks to flexibility. Flexibility will help to produce energy when is cheaper and greener.
2. A demand forecast, as upcoming demand will determine the margin of energy to stored or flexibility required for an optimal energy production.
3. A modelling tool of the DHC grid and available storage.

The first pillar was developed by Utilifeed (project partner), who created a planning tool to calculate the optimal operation of the cogeneration power plant. Sampol worked on the second pillar, using data analytics to calculated customer demand. And the third pillar was developed by LTU, using data from blueprints and geographical data to create a model of the DHC in Parc Bit.

Furthermore, to increase the flexibility of the system, Sampol has developed an innovative solution based on 3-way valves and smart control. This solution allows the operator of the net to module the temperature of the water provided to the DHC. Also, the inertial storage of a pool was under study.

In this pilot storage flexibility, grid flexibility and singular client flexibility (heated swimming pool) were studied.

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