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Risk assessment in district heating: Evaluating the economic risks of inter-regional heat transfer networks with regards to uncertainties of energy prices and waste heat availability using Monte Carlo simulations

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ABSTRACT

Most district heating (DH) networks are largely based on fossil or biogenic fuels. As these fuels are phased out or their use will be prioritized for other sectors respectively, significant amounts of alternative heat sources (heat pumps, waste heat, solar and geothermal energy) will be required. However, there are various uncertainties regarding the development of key factors such as energy prices and the availability of alternative heat sources. In addition, individual heat supply systems are competing with DH networks. This paper quantifies the economic risks of DH networks with respect to uncertainties in energy prices (electricity and biomass) and waste heat availability and compares them with individual heating systems. Therefore, a hypothetical inter-regional heat transfer network ("HTN") in Austria is investigated as a case study and a Monte Carlo approach based on seasonal energy balances is used. The results show that in individual heating systems, uncertainties in energy prices have a strong influence on the economic risks. In contrast, HTNs can optimize the use of industrial waste heat at stable prices and integrate large scale heat pumps operating at low electricity prices as well as combined heat and power plants operating at high electricity prices, leading to a reduced dependency on the uncertainties of energy prices and thus a lower economic risk.

1. Introduction

Most district heating (DH) networks are largely based on combustion processes using fossil or biogenic fuels [1]. As the former will no longer be available for DH networks in a climate-neutral future and the latter will be very limited available for DH networks due to competing uses with hard-to-decarbonize sectors (e.g. industry [2]), significant amounts of alternative heat sources such as heat pumps (HP), waste heat (WH), solar and geothermal energy will be required [3,4].

However, the associated CAPEX in heat network infrastructure, heat supply plants and storages, as well as their integration are high and at the same time there are uncertainties regarding the future development of key factors such as.

- Electricity prices (annual average, hourly fluctuations)
- Prices of biogenic energy sources
- Availability and characteristics of alternative heat sources (mainly WH, but also deep geothermal) and seasonal storage
- Demand side developments (connection rates to the existing DH network, retrofitting rates, demand side flexibility (peak load reduction), return temperature reduction).

The aim of this paper is to assess the economic risks of district heating networks with respect to uncertainties in energy prices and WH availability, and to compare the results with individual heating systems as a reference. For individual heating systems, specific decarbonization pathways for heat supply to municipalities and regions at the building level are considered (shifting fossil fuel demand to decarbonized alternatives).

A Monte Carlo simulation (MCS) is used for this purpose. It generates a large number of scenarios within a range of possible uncertain conditions and assumptions to calculate the system's levelized cost of heat (LCOH) and associated economic risks.

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For this investigation, a hypothetical large scale inter-regional heat transfer network (HTN) in Tyrol, Austria is used as a case study (see section 4). HTNs allow for the interconnection of several industrial WH and renewable heat sources, local district heating networks, industrial process heat sinks and storage, thus reducing some of these risks, see e.g. Refs. [5,6]. To calculate the LCOH of a decarbonized HTN and to compare it with the decarbonization of the individual heat supply of each building (or some already existing local heat networks), the simulation program SEEET is used (see section 3.3).

2. State of the Art

On the one hand, there are different approaches to evaluate the economic feasibility and to support the planning and design of DH networks. For example [7] considers five concepts of DH with different temperature levels and analyzes the costs and benefits of each of them. In Ref. [8] a coherent approach to redesign the European heat supply at the secondary and local levels is presented. Furthermore [9], proposes a tool that could be considered as a first step towards an integrated methodology to support designers and planners, capable of combining classical methods for optimizing the architecture of DHNs and reliability techniques. The tool links the energy and the reliability analyses of the DHNs through the interaction between a thermo-hydraulic simulator and a module based on MCS, with a special focus on the effects of the implementation of thermal energy storage systems. Finally [10], refers to the combination of knowledge on the integration of renewable energy in the various sectors of the energy system, to minimize overall costs and fuel consumption (fossil or biogenic). However, these approaches don't consider the uncertainty of future key parameters and the associated investment risks.

On the other hand, risk assessment methods have been widely used in various sectors to evaluate the technical reliability, financial and environmental risks of different systems. These techniques analyze the interaction of system components and evaluate overall probability of failure, financial loss and environmental damage. Risk assessment methods can be divided into two categories [11].

a) Quantitative Methods:
   a. Mean-Variance Portfolio Analysis
   b. Real Options Analysis
   c. Stochastic Optimization
   d. MCS
b) Semi-quantitative methods:
   a. Multi-Criteria Decision Making
   b. Scenario Analysis

MCS adds value to financial analysis in the risk management of renewable energy projects by allowing the simultaneous variation of multiple uncertain input parameters. This helps to reduce risk and increase investor confidence [12].

MCS has been used in a wide range of applications including power plants [13,14] and transportation systems [15], to name a few, where a MCS has been developed to help select the best technology for financial investment. A simple but effective computer-based model for assessing the merits of each of the available investment options for low-carbon power plants is presented in Ref. [13]. MCS allows for quantification and analysis of the uncertainty associated with forecasting the costs of relevant emerging technologies and assessing the feasibility of investing in these technologies. Another application of MCS in the energy generation sector is the multi-criteria ranking of energy generation scenarios in Ref. [16], which aims to rank energy development scenarios for the EU using multi-criteria decision making techniques. To follow a sustainable approach, the ranking proposed in the paper considers both economic and environmental dimensions.

Regarding DH, MCS have previously been used to derive optimal day-ahead operation schedules [17,18] and to assess the failure probability of DH systems [19]. In the first application, the goal is to develop optimal bidding strategies for the market, considering start-up costs, power balance and technical limitations. Market prices and load levels are treated as random variables with correlations between consecutive hours. The second application assesses the failure probability of the pipe network in energy systems, considering uncertainties in material properties, loading and geometry.

Furthermore, an initialization method has been devised for branch and bound solvers to optimize scheduling of DH production with storage [20]. In this paper, several improvements are proposed, namely running the optimizations of each time window in parallel to decrease computation time and increasing the number of runs to further improve the consistency of the method.

MCS is an efficient method for solving problems involving deterministic models depending on stochastic parameters. The main advantage of this method is its ability to predict outcomes over a wide range. In general, its approach is based on random sampling of stochastic input parameters. For each scenario, an output is calculated considering a set of predefined rules, in the case of this paper a simulation model. On average, the law of large numbers guarantees a sufficient approximation of the expected value and distribution for a sufficiently large sample size.

This paper takes up the general MCS methodology described above and adapts it to investment decisions in inter-regional heat transfer networks. In previous work on DH, MCS has mainly been used to assess the feasibility of technical configurations, component failure probabilities and to derive operating schedules. Little information is available on MCS focusing on investment decisions in DH. This work focuses on using MCS to speak the "language of stakeholders", to support in investment decisions for large scale DH infrastructure.

3. Method

This section describes the chosen approach to risk assessment using MCS. The approach consists of the following steps (see Fig. 1 below).

1. Probability density functions (PDF) and/or and cumulative density functions (CDF) are developed for each stochastic parameter considered (electricity prices, biomass prices, and WH availability)
2. Random samples of each stochastic parameter considered are generated as an input for the calculation of the distribution of the relevant key performance indicator(s) (KPI). Based on a sample, a large number of concrete scenarios are created to provide the input files for the economic evaluation.
3. The seasonal-energy-economics-evaluation-tool (SEEET) is used to calculate the levelized cost of heat (LCOH) as a KPI for each scenario from step 2.
4. The LCOH of the considered configurations is presented as a distribution density function to assess the economic risk (e.g., quantified by the width of the distribution function).

Each step and the case study analyzed are described in the following sections.

3.1. *Probability density functions and cumulative density functions*

The applied approach to assign a probability density function (PDF) to each stochastic parameter is derived from the following observations and assumptions.

3.1.1. *Uncertainty of energy prices*

In this study, electricity and biomass prices are considered as the most relevant energy prices.

To generate uncertainties in future **electricity prices**, the historical hourly day-ahead electricity prices in Austria from the ENTSO-E data platform [21] are considered. Then, the expansion paths of the Austrian

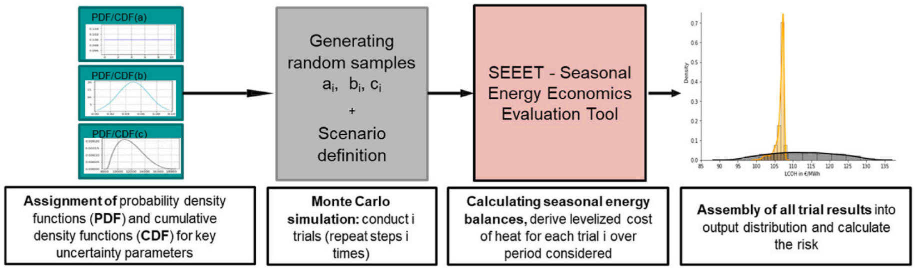

Fig. 1. Block diagram of the methodology.

national energy and climate plans (NECPs) [22] for installed wind and solar capacity and increasing future load are considered. Together with the associated future prices from the third quarter of 2022 from the European Energy Exchange AG (EEX) data [23], possible future day-ahead prices until 2042 are estimated, using a vector autoregressive model fitted with the above data. The resulting output prices have the average future prices as their absolute level and a daily pattern with a peak in the morning and a peak in the afternoon. The daily pattern is more volatile when more renewable energy is produced.

To determine the uncertainty range of the electricity price, the historical monthly average (μ) ± the standard deviation (σ), both derived from the historical hourly day-ahead electricity prices in Austria, are considered (see Fig. 2). Hourly values are aggregated to monthly values to gain an understanding of how electricity price patterns behave over larger timeframes. The analysis for the period from January 2015 to October 2022 shows that (μ+σ)/μ is about 1.37 times the mean value and (μ-σ)/μ is about 0.63 times the mean value. For a more conservative approach, 0.5 and 1.5 were used to create an uncertainty range for the future hourly electricity price. A convex combination of the upper and lower bounds is considered, where the convex combination is the drawn energy price input.

To generate uncertainties of future **biomass prices,** historical monthly values in a period between January 2015 and 10/2022[1] are considered based on information from the Austrian Biomass Association [24]. As biomass can be considered as one of the key technologies to replace natural gas heating [25], a correlation between the prices is assumed. In parallel with gas prices, pellets also show a very strong price increase in the period in 2021–23. This is mainly explained by the fact that pellets represent a very close substitute for gas for heating purposes. Therefore, demand shifted away from gas towards biomass products. In the short term, supply of biomass is not able to adjust to the higher demand, which resulted in a strong price increase [26]. Comparing the monthly gas price index of Austria (ÖGPI) (01/2015–06/2023) [27] with the pellets price in the same period leads to a correlation index of 0.9, which further supports the link between them (see Fig. 3).

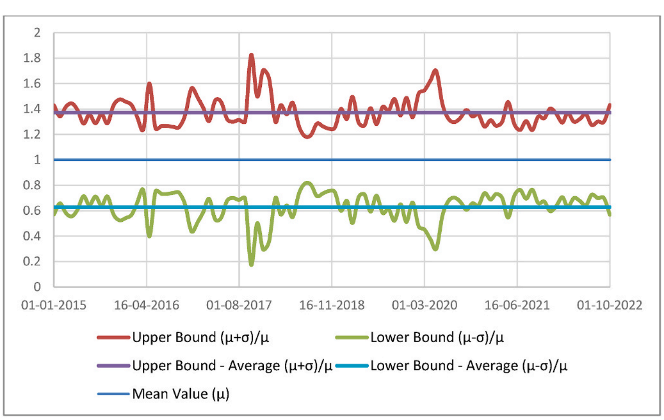

Fig. 2. Comparison of the standard deviation and the average electricity price [21].

[1] the price of wood pellets is used as a representative value for biomass.

For simplicity, the model links the future biomass price to the future natural gas price.

The future natural gas price analysis used in this paper originates from Energy BrainReports [28]. Here, an assumed uncertainty of ±20% is applied, which increases by 1.5%/yr, resulting in ±48.5% in 2042. Other projections for the price of natural gas [29,30] are roughly in the same range as the values used in this paper. Recent events regarding the supply of natural gas require further research into the possible future price developments and associated uncertainties. A cone-shaped distribution (due to the increasing uncertainty) is obtained from which possible future gas prices are drawn.

3.1.1.1. *A correlation between (future) electricity and natural gas prices.*

Natural gas power plants are often the price-determining power plants in the merit order. Consequently, there is a strong correlation between the electricity price and the natural gas price. However, the increasing integration of wind and solar energy in the electricity mix, along with rising CO_2 prices, has the potential to significantly reduce the number of full load hours of natural gas power plants. As a result, cheaper technologies could become price-setting, which could weaken the correlation between electricity and natural gas prices [31].

Austria currently relies on 59 natural gas power plants [32], which contribute to 16% of its gross electricity generation. Natural gas also plays an important role in heating and for industrial processes, accounting for 36% of the final energy consumption in 2019 [25]. The uptake of biomethane as an alternative to natural gas is low [33], and there is also limited market-readiness for balancing technologies to manage the fluctuations associated with renewable energy sources [34]. Moreover, there is a draft law proposing the phase-out of natural gas for heating purposes until 2040. However, the passage of this law is uncertain at this time [35].

Based on these factors and assumptions made in the study, it is expected that the correlation between electricity and natural gas prices is expected to continue to exist for the foreseeable future.

3.1.2. *Uncertainty of WH availability and price*

No data was available for the availability of WH. As a proxy, historical data from Statista database [36] on the number of annual bankruptcies in Austria is used. Due to a lack of data, no distinction is made between different sectors. This number is divided by the total number of companies in Austria in each year [37] to estimate the probability of bankruptcy, which is calculated as an average over the years at 7.6‰. This value is assumed to be constant over the years. For simplicity, it is assumed here that no new companies are founded in the considered area.

The companies included in the case study are described in section 4. The price of WH is highly dependent on local factors and involved stakeholders. In this work, the WH price is not considered as an

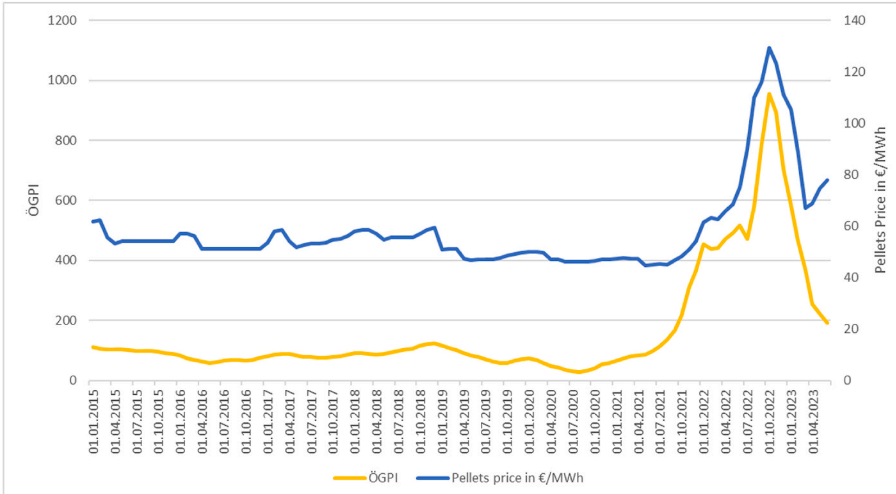

Fig. 3. Comparison of the Austrian gas price index (ÖGPI) [27] to the average pellets price in Austria [24].

uncertainty because a fixed price can be agreed bilaterally between supplier and network operator. It is assumed to be stable over the period considered. However, since the WH price has a large impact on the total system cost, a sensitivity analysis was performed varying the WH price from 0 to 60 €/MWh.

3.2. Sample generation and scenario definition

Random samples of the each considered stochastic parameter (energy price and WH availability) are generated as an input for the calculation of the distribution of the LCOH as the main KPI.

A Beta (2,2) distribution[2] is assumed to represent the probability density function of all energy prices.

This beta distribution was chosen because.

- Medium scenario for energy prices is considered most likely
- Minimum and maximum scenarios are considered equally likely
- Going beyond the minimum or maximum scenario would make it irrelevant
- A normal distribution would tend to infinity and result in unreasonably high or low prices

To create a random sample, a value Lambda is drawn (see Fig. 4), which describes the energy price scenario applied. A high value represents a high price scenario, while a low value represents the opposite.

Starting with the forecasted electricity prices in €/MWh, the first input is the convex combination of (1 – Lambda) times the minimum case plus Lambda times the maximum case scenario. For the gas price and biomass price, it is continued analogously. By applying the same Lambda for all energy sources, the correlation between the prices as described above is considered.

Next, the average probability of a company discontinuing the WH supply in the considered area over the course of one year is considered (as described in 3.1.2). Then, considering the future time span, the "dice" are rolled uniformly each year to decide whether the supply is due to be discontinued. The calculated year of the discontinuation of the WH supply of a company is added to the baseline scenario, which is iterated in a next step (see Table 1).

Scenario definition: For illustration purposes, a possible scenario

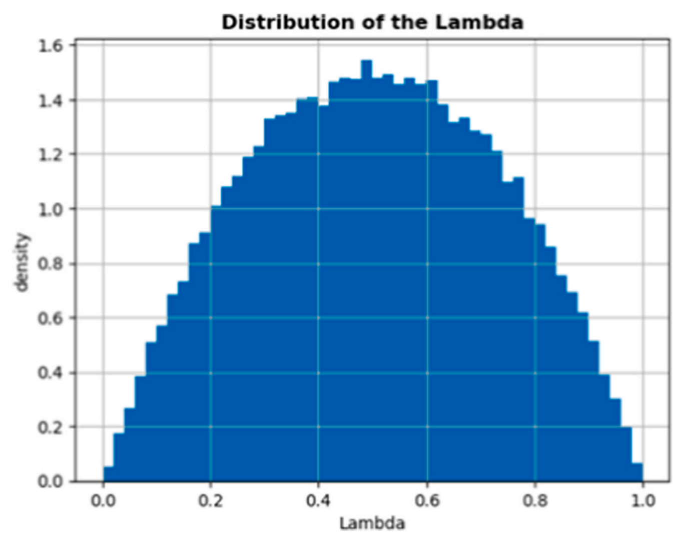

Fig. 4. Exemplary histogram of the Beta (2,2) drawn Lambda.

could be as shown in Table 2, where Lambda equals 0.7 and the WH supply of company (comp.) 1 and comp. 3 is discontinued in the years 2033 and 2040 respectively, while the other companies remain constant suppliers. The whole process is iterated for a large number of scenarios.

3.3. Seasonal energy economics evaluation

Table 1
Gas price scenarios [28].

Year	Gas Price in €/MWh	Assumed Uncertainty
2023	100	±20%
2024	90	±21.5%
2025	65	±23%
2042	40	±48.5%

The seasonal-energy-economics-evaluation-tool (SEEET) is used to calculate the levelized cost of heat (LCOH) as a KPI of the economic performance of the HTN for each scenario from 3.2 and comparing it with the LCOH of individual heating systems as a reference.

SEEET was developed in Refs. [39–41] with the aim of quickly

[2] Beta(α, β) describes a distribution function between 0 and 1 where the probability density function has the following form: $f(x;\alpha,\beta) = \text{constant}\cdot x^{\alpha-1}(1-x)^{\beta-1}$. It is often used when considering stochastic variables lying between 0 and 1 [38].

Table 2
Example scenario.

Scenario	Lambda	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5	Comp. 6	Comp. 7	Comp. 8
1	0.7	2033	–	2040	–	–	–	–	–

assessing the economic performance of different heat supply systems using simple energy balances. In SEEET, a seasonal time resolution[3] is used as it considers the main demand and supply variations during a year. Further on, seasonal data is usually easier to obtain than hourly or monthly data, especially at an early planning stage. As the case study is hypothetical, no high-resolution data was available. Due to the low time resolution and thus fast calculation times, the SEEET tool is particularly suitable for use in stochastic observations such as the chosen MCS approach.

The main input parameters of SEEET are the current and future heating demand and supply options, CAPEX and OPEX values and interest rates, as well as the energy prices over a given time period.

For simplicity, a "heat-lake" approach is used, neglecting possible hydraulic limitations of the HTN. Other key assumptions can be found in 10.1 of the appendix.

3.3.1. Sector coupling technologies

SEEET considers different heat supply technologies. In this work, HPs and CHPs are described at a more detailed level since their performance is highly dependent on energy prices:

Heat pump COP: The coefficient of performance (COP_t) for different HP technologies is calculated according to equation (1) [42] for each timestep t. It is determined by the temperature relationship of the source and sink according to the Carnot efficiency and the HP efficiency.

$$COP_t = \frac{\overline{T_{Hot\,t}}}{\overline{T_{Hot\,t}} - \overline{T_{Cold\,t}}} \bullet \eta_{HP} \tag{1}$$

$\overline{T_{Hott}}$ represents the average flow temperature in timestep t to which the HP must raise the average source temperature $\overline{T_{Cold}}_t$. The source temperatures of air [43], groundwater [44] and geothermal heat [45] were considered. The HP efficiency (η_{HP}) accounts for the losses occurring when a HP is operated in a real environment. The overall COP is calculated as a weighted average based on the distribution of technologies. In the following, groundwater and geothermal HPs are considered together as ground/water HPs and air HPs are considered as air/water HPs. The same average COP is used for large scale HPs and for household systems because a higher source temperature for the large-scale HP is assumed.

The average investment costs (CAPEX) and the maintenance costs for ground/water and air/water HPs in Austria for single-family houses (SFH) and multi-family houses (MFH) originate from Ref. [46] and can be found in Table 4 in the appendix.

In this study, HPs at household level use the electricity market price plus variable costs for taxes [47] and grid costs [48] at grid level 7. Large-scale HPs and CHPs are assumed to operate at grid level 5 [49], using the hourly electricity market price plus variable taxes and network costs, a capacity price and the monthly biomass price (the latter is assumed to be stable during the month).

Operation of HPs and CHPs: In this study, a heat merit order inspired by Ref. [50] is used to estimate the total heat generation costs of the HTN. Fig. 5 shows an exemplary merit order for summer and winter, were CHP, HP, WH and biomass heat-only boilers (BHoB) are ranked according to their specific heat generation costs.

Full load hours for each generation technology result from the analysis of the heat merit order on an hourly basis compared to the seasonal heating demand. These full load hours are aggregated per season to derive the energy supplied for the seasonal economic evaluation.

Whenever the existing suppliers cannot meet the demand (e.g., due to discontinuation of WH supply, increasing demand from new customers, or higher costs associated with existing suppliers), the capacity of the BHoBs is increased to cover the shortfall.

3.3.2. Calculation of the levelized cost of heat

To calculate the levelized cost of heat ($LCOH$) in €/MWh an equation for the levelized cost of electricity is used from Ref. [51]. In equation (2) both, the annual profit (P_t) and the generated heat MWh/yr (Q_t), representing the total demand in the area, are discounted. The calculation of P_t is shown in equation (2). Fuel costs and maintenance costs are considered as OPEX. Furthermore, the calculation of the LCOH requires the initial investment (I_0) and the discounting factor (i).

$$LCOH = \frac{I_0 + \sum_{t=1}^{n} \frac{P_t}{(1+j)^t}}{\sum_{t=1}^{n} \frac{Q_t}{(1+j)^t}} \tag{2}$$

$$P_t = OPEX_t - Revenue_{CHP,t} + Depreciation_t + Reinvest_t \tag{3}$$

The levelized cost of heat consists of the following parts.

- Energy costs in €/yr (including profits from electricity sales for the HTN configuration)
- Investment costs for residential systems in year 0
- Depreciation (only large-scale systems are depreciated)
- Maintenance costs
- Reinvestment (existing systems are assumed to be at 50% of their lifetime and need to be replaced accordingly)

4. Case study

This paper examines the application of the methodology described above to a hypothetical HTN, in the region of the Inn Valley of Tyrol, Austria, see also [52]. A total of 32 municipalities along the Inn Valley and in the Zillertal are part of this region. The hypothetical HTN would unite all municipalities and WH producers and include new supply units such as biomass CHP units, as well as large-scale HPs, for which the Inn River could be a potential heat source.

4.1. Current heating demand and supply structure

4.1.1. Heating demand

The total residential and tertiary heating demand of the individual municipalities in the region and the distribution of the heating demand among the different types of dwellings (SFH, MFH, service buildings (SB)) are considered. The total heating demand of 1220 GW h is based on the Tyrolean spatial information system [53].

The heating demand of households consists of the space heating demand and the domestic hot water (DHW) demand. The TABULA WebTool [54] provides specific space heating demands in Austria for different house types per building period and per refurbishment status. For simplicity, an equal distribution between the refurbishment types is chosen. A weighted average of the heating demand per house type is derived based on the average distribution of building periods in Tyrol [55]. The DHW demand for Austria in 2019 originates from Eurostat

[3] Seasons are considered here as four consecutive timesteps per year, each lasting three months. For Europe, spring (March–May), summer (June–August), fall (September–November) and winter (December–February) are considered.

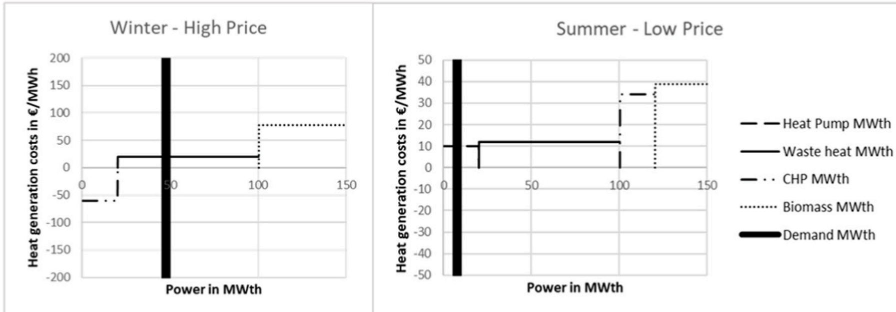

Fig. 5. Exemplary merit order.

[56]. This value is divided by the Austria population in 2019 [57] to derive an average value for the DHW consumption. The total heating demand of SFH and MFH depends on the specific space heating demand, the area per house type, the number of persons per house type and the DHW demand per person [58,59]. The total heating demand of SB is derived from the difference between the total heating demand of the municipality and the heating demand of SFH and MFH.

In this study, the future heating demand is assumed to be stable. It is assumed, that retrofit rates, climate change, population growth, demolition of old and construction of new buildings willbalance each other out. Cooling demand is also not considered due to missing data.

A seasonal demand distribution, as described in 3.3 is calculated. Therefore, standard hourly demand profiles for the residential and the tertiary sectors from the "Hotmaps" project [60] are considered and recalculated to a seasonal distribution. The seasonal profile for natural gas is modelled from the total annual gas demand in Austria per sector [61] and the monthly gas sales volume of the gas network operator of Tyrol [62]. Both profiles are aggregated to a seasonal level as percentages, shown in Figs. 10–1 in the appendix.

4.1.2. Individual heat supply technologies

In Tyrol, biomass heating is very common [63]. Heating oil and coal are considered together, as both are boiler-based technologies. Direct electric heating accounts for <2% of the total heating demand (see Figs. 10–3), at the household level. As no piping system is installed for direct electric heating, the costs for more efficient heating systems, such as HPs, would be much higher. Therefore, it is neglected and counted as a part of heating oil and coal ("HCE"). Regarding HPs, a constant technology distribution between ground-source HPs utilizing geothermal energy and groundwater and air-source HPs is considered based on the average of the annual Tyrolean energy monitoring of 2020 [64] and 2021 [65].

4.1.3. Local DH networks and WH

There are in total 22 existing local DH networks in the region [53], representing 18% of the total heating demand (see Figs. 10–3 in the appendix). In general, the local DH networks are fueled by biomass, sometimes with back-up boilers based on fossil fuels, while some networks in larger towns are fueled by industrial WH. It is assumed that all fossil fuel-based back-up capacity will be replaced by expanding either the biomass or WH source (see Table 3). Some of the local WH sources are not fully utilized due to the limitations of the current systems. For simplicity no flexible components were considered for the local DH networks. More details regarding the companies, the available industrial WH, the current heat supply, and their high-temperature potentials and the supply units can be found in Table 5 to Table 7 and Figs. 10–2 in the appendix.

4.1.4. Share of heat supply technologies per municipality

The percentage distribution of heat supply technologies per municipality is required to assess the necessary decarbonization efforts at household level. Due to lack of detailed data several assumptions have to be made based on local studies and information.

Table 3
Decarbonization paths for the "individual configuration".

currently used heating system	Share of heating systems in the decarbonizations scenario		
	Biomass	Ambient Heat	WH
Natural Gas	50%	50%	0%
HCE	50%	50%	0%
heating oil and natural gas in the existing local DH networks	100%[a]	0%	100%[a]

[a] Depending on the current main source of the network.

The results of the study "How will Tyrol heat in 2050" [66] are used as reference value for the distribution of energy sources in the municipalities. Moreover, the distribution is refined with local details on DH coverage [67–74]. Regarding gas supply, it is assumed that there is no use of natural gas if the main pipeline does not connect to the main town of a municipality [53]. Figs. 10–3 in the appendix shows the overall distribution of energy carriers in the considered region.

4.2. Decarbonization scenarios

To assess whether a long inter-regional HTN is a feasible and robust decarbonization option, it is compared to an individual configuration, where the status quo fossil heat supply technologies are replaced with renewable energy sources at the individual level. Both scenarios are compared in the timeframe between 2023 and 2042.

4.2.1. Individual configuration

In this configuration, all fossil-based heating supply systems at building level are by biomass boilers and HPs. According to Refs. [75,76], green gases for heating buildings, such as biomethane, should be given the lowest priority. Therefore, green gases for residential heating are not considered in this paper.

Future shares of each technology are based on assumptions about technical characteristics. Regarding the existing local DH networks, it is assumed that coverage will remain the same; and that currently used heating oil and natural gas are replaced by biomass. Table 3 summarizes the assumptions for the decarbonization paths for the individual configuration. See also Figs. 10–4 in the appendix.

If a local DH network is already using WH, this will be unchanged (providing WH is still available in a future scenario).

4.2.2. HTN configuration (the "HeatHighway")

This configuration considers the interconnection of the local DH networks in the municipalities with an inter-regional HTN. If there is no local DH network in a municipality, the construction of a new local DH network is considered. As a result, in the HTN configuration, 91% of the heating demand in the whole area is covered by DH.

It is assumed that the remaining 9% are not covered by DH due to very low connection densities. These buildings are decarbonized like the heating systems using HCE in the individual configuration. As the existing HPs at a household level represent a renewable heat supply already, their share is not changed. As a result, 8% are covered by ambient heat and 1% by biomass. See also Figs. 10–5 in the appendix.

4.2.2.1. Heat supply structure and WH utilization. Due to the size of the HTN system, the existing WH sources can provide a continuous supply compared to the individual configuration (where the WH supply exceeds the summer demand of the local DH networks and therefore cannot be fully utilized); and further additional WH potential (see Table 5 in the appendix) can also be fed into the network and delivered to other municipalities (assuming 50% of the WH potential identified can be used). It is further assumed that WH suppliers can provide a constant supply throughout the year, which is assumed to be four times the winter supply (full load) of the individual configuration. Since WH does not normally vary seasonally, the current winter supply is assumed to be the maximum capacity.

The effect of 0, 10 and 20 MW_{th} CHPs and HPs has also been included. The maximum of 20 MW_{th} is used since it can cover the average summer load and to avoid the use of seasonal storage (assuming, that seasonal energy storages are difficult to integrate in the area) or investment in additional re-cooling capacity

4.2.2.2. Piping network. Fig. 6 below shows the proposed route of the main HTN connecting all municipalities in the focus area[4] with a total length of about 82 km. Approximately 34 km pass through urban areas, while 48 km pass through rural, unpaved terrain. The pipes for the HTN are assumed to be larger than DN400.[5] Costs at this size for urban areas are around 2500 €/m and for rural, unpaved terrain around 1700 €/m [77]. This results in a total CAPEX of 222 Mio. € for the HTN.

Municipal distribution networks may need to be extended or constructed, based on the current and the target levels of DH coverage. The network length and the construction costs are estimated using data from existing DH projects (see Table 7 and Figs. 10–6 to Figs. 10–8 in the appendix). This results in a total CAPEX of 552 Mio. € for the distribution networks in the municipalities.

The cost of connecting additional WH suppliers and to expand existing ones are assumed to be included in the total network investments. In addition, the cost of short-term small storage to smooth the seasonal demand profile is also assumed to be part of it.

The depreciation period for DH pipes (heat transfer and distribution) is 20 years according to Ref. [78].

4.2.2.3. Heat losses. The relative heat losses are calculated using the connection density based on “QM Holzheizwerke” [79]. With a total heating demand of 1220 GW h (see 4.1.1) and a length of 82 km, relative heat losses can be expected to be below 5%. To account for heat losses in the distribution networks, a more conservative value for the overall heat loss of 20% is assumed. The absolute value for the heat losses is divided equally between the timesteps.

5. Results

MCS considers a large number of scenarios to derive the LCOH distribution function. In total, 10,000 scenarios were evaluated per WH price for both scenarios (individual decarbonization and HTN). Each scenario considers a certain energy price scenario (see Fig. 4) and possible discontinuation of WH supply in the set timeframe. In addition, the sizing of the HP and the CHP was modified.

A period a period of twenty years (2023–2042) is considered for the evaluation. Costs for individual heating systems are incurred in year 0 and new systems are purchased when their technical lifetime has expired. Large components, like the HTN or a central CHP, are depreciated on a straight-line basis over their economic life, with no residual value considered.

In general, a wide distribution of the LCOH implies a high risk, as the resulting LCOH is highly dependent on fluctuating input parameters. A narrow distribution leads to the conclusion of a low-risk system, as the LCOH shows a high stability over the considered period.

5.1. Sensitivity analyses for the WH price

As a sensitivity analysis, the price of WH was varied between 0 and 60 €/MWh. The WH price is assumed to be stable over the period considered.

The aim of this comparison is to show the robustness of a HTN compared to an individual scenario with regards to fluctuating energy prices and the possible discontinuation of WH sources. As the price of WH in a HTN is a subject to be defined by the stakeholders, the influence of different WH prices is also presented.

Fig. 7 below illustrates the annual energy output in GWh from different suppliers, including network losses, for different WH prices in the HTN depending on the energy price scenario (Lambda). The HP is mostly chosen for low energy prices (low Lambdas), but due to the high electricity prices in this consideration it is chosen less often by the merit order (see Fig. 4). As WH price increases, it is chosen more often for low Lambdas, reaching a peak at 60 €/MWh. In most cases, the CHP is chosen first, due to its ability to achieve negative fuel costs from electricity sales. There is only a small difference between low and high Lambdas, but it follows the reverse pattern of the HP. As biomass and waste heat are the largest suppliers in the HTN they mirror each other. At WH price 40 €/MWh below a Lambda of 0.6, WH is hardly used. The sharp increase from 0.6 to 0.7 is due to the fact that WH is in most cases cheaper than biomass. The dots between the solid lines reflect the discontinuation of WH supply.

Fig. 8 illustrates the density function of the LCOH for the individual (bottom) and HTN configuration (top) at different prices for WH. Overall, the density functions of the HTN suggest a lower LCOH compared to individual configuration. Also, the individual configuration has a much higher standard deviation, suggestion more risk associated with fluctuating parameters. The price of WH and the discontinuation of it has much less influence, as it only affects five municipalities.

For low WH prices (<40 €/MWh), the LCOH of HTNs tends towards lower prices, with a shoulder to the right, where some WH supply is discontinued, and more expensive technologies need to be used. At a WH price of 40 €/MWh (see Fig. 7) a peak can be observed, resulting from the sudden switch from more expensive biomass to cheaper and stable WH. A similar, but less prominent peak can be observed in the individual configuration. As the WH price increases (>60 €/MWh), it is no longer used and the density function becomes similar the individual density function, but remains at cheaper LCOHs and narrower, due to the distributed costs caused by the HTN.

Fig. 9 illustrates the relationship between the energy price scenario (Lambda) and the LCOH for both configurations at different WH prices. It shows the strong dependence of the individual configuration on the energy price. It illustrates for the HTN an increasing slope with less waste heat being in the system due to increasing WH prices. It also shows the vulnerability of it in case of the discontinuation of WH, leading to a higher demand of the large, centralized supplier infrastructure in the HTN configuration, leading to high LCOHs at low Lambdas. For the individual configuration this has little impact, as it only affects single municipalities, leading to less scattering. The same peak at 40 €/MWh,

[4] For simplification it is assumed that all municipalities in the focus area will connect to the HTN, alternative configurations are currently investigated.

[5] A detailed analysis of the required pipe diameter for each network section has not been done, since it is assumed that the impact of different pipe diameters is small compared to the other factors considered.

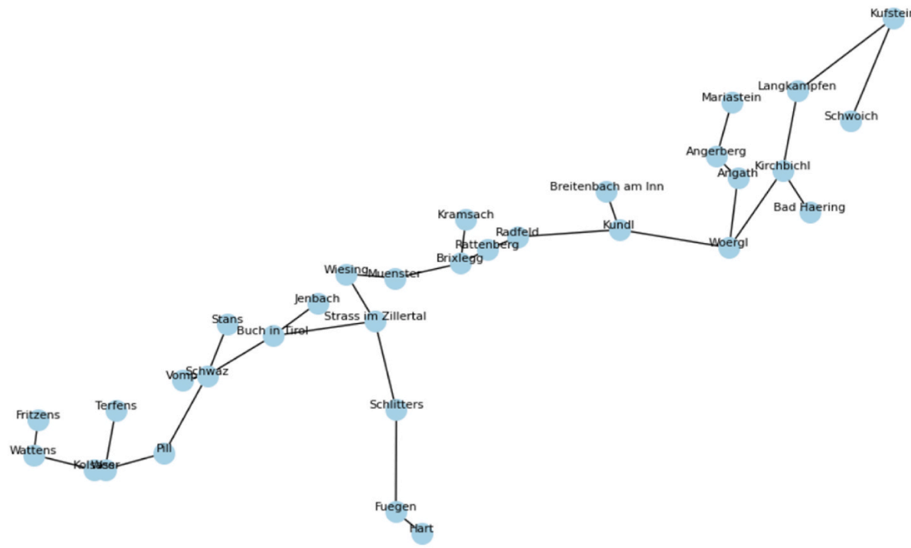

Fig. 6. Proposed HTN

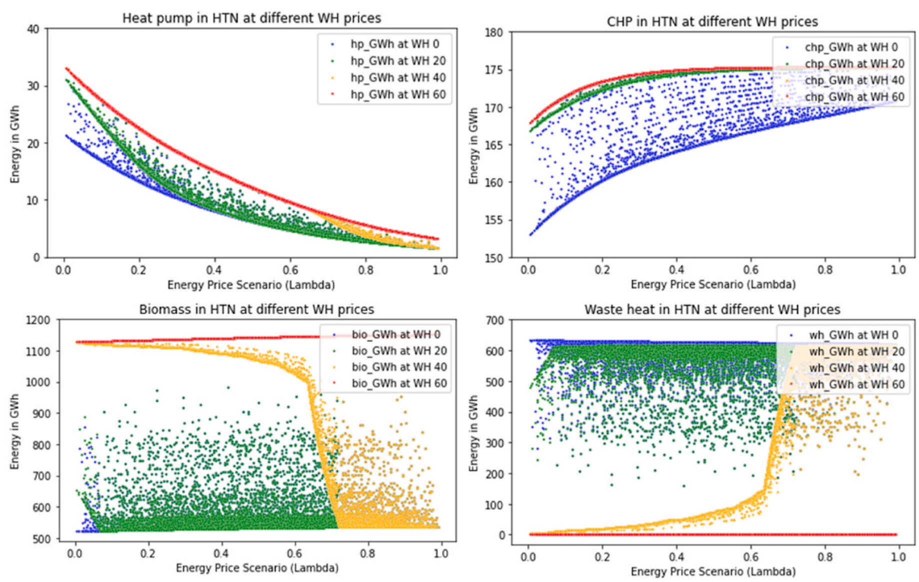

Fig. 7. Annual energy output from different suppliers for different WH prices and energy price scenarios.

as described above, can also be seen here for both configurations. Also, at 20 €/MWh, a small upward shift can be observed for the HTN at low Lambdas, resulting from biomass being cheaper than WH. In conclusion, the HTN configuration presents a lower economic risk, due to a more stable LCOH (lower slope).

5.2. Sensitivity analyses of the size of CHP and a HP

Fig. 10 below shows the influence of a CHP and a HP in the HTN at 0, 10 and 20 MW_{th} installed capacity. At a WH price of 0 €/MWh, the LCOH is shifted to lower values and with increasing power of the flexible components, the density function of the LCOH becomes narrower and the right shoulder shifts toward cheaper prices. At a WH price of 60€/MWh, WH is used due to merit order (see Fig. 4), resulting in higher and more evenly distributed LCOH. In conclusion, a WH price can lead to a low-risk system. Additionally, especially the CHP (see Fig. 7) can further stabilize the LCOH, with the remaining risk of discontinuation of the WH at 0€/MWh, leading to a shoulder towards higher LCOH at 20 MW.

6. Conclusion

This paper quantifies the economic risks of DH networks with respect to uncertainties in energy prices (electricity and biomass) and WH availability and compares them with to individual heating systems for a case study. As a result of these uncertainties, the LCOH in the investigated HTN vary by ± 4%, whereas in individual systems it varies by ± 9%.

DH networks with an optimized use of industrial WH (low-cost base load), large-scale HPs operating at low electricity prices, and CHP's operating at high electricity prices represent a very stable business case despite their low heat densities. With properly sized CHP's, it can be possible to achieve a negative LCOH at very high electricity prices; and thus making the system profitable.

The use of WH at a stable price can help mitigate the LCOH gradient in high energy price scenarios. Flexible components combined with WH shift the LCOH to lower values and provide more price stability, as the density functions become narrower. However, the risk of the discontinuation of WH supply remains, potentially leading to stranded

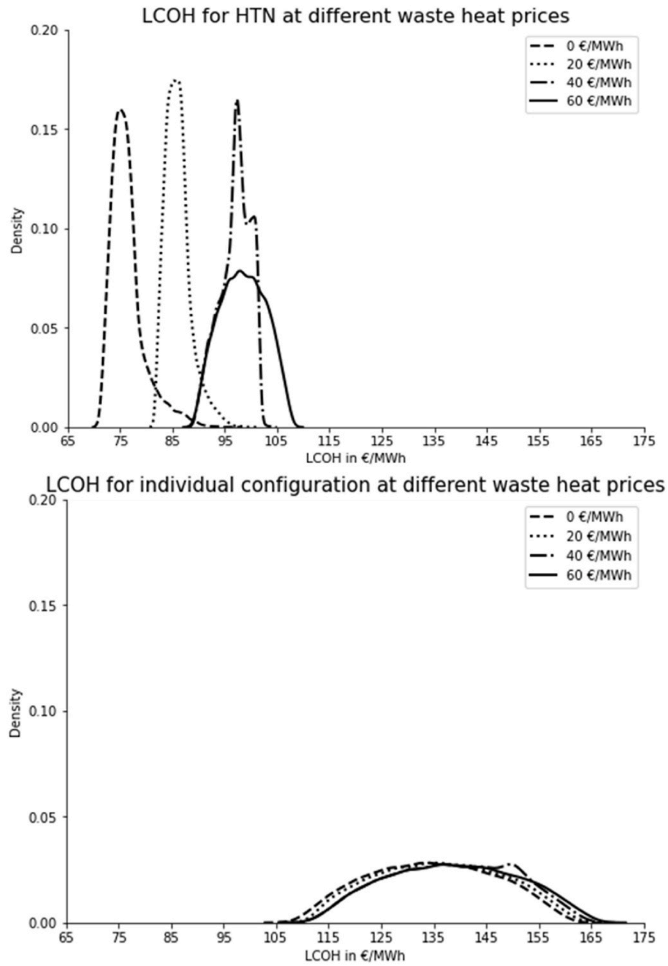

Fig. 8. Comparison of the LCOH for the individual (bottom) and the HTN configuration (top) at different WH prices.

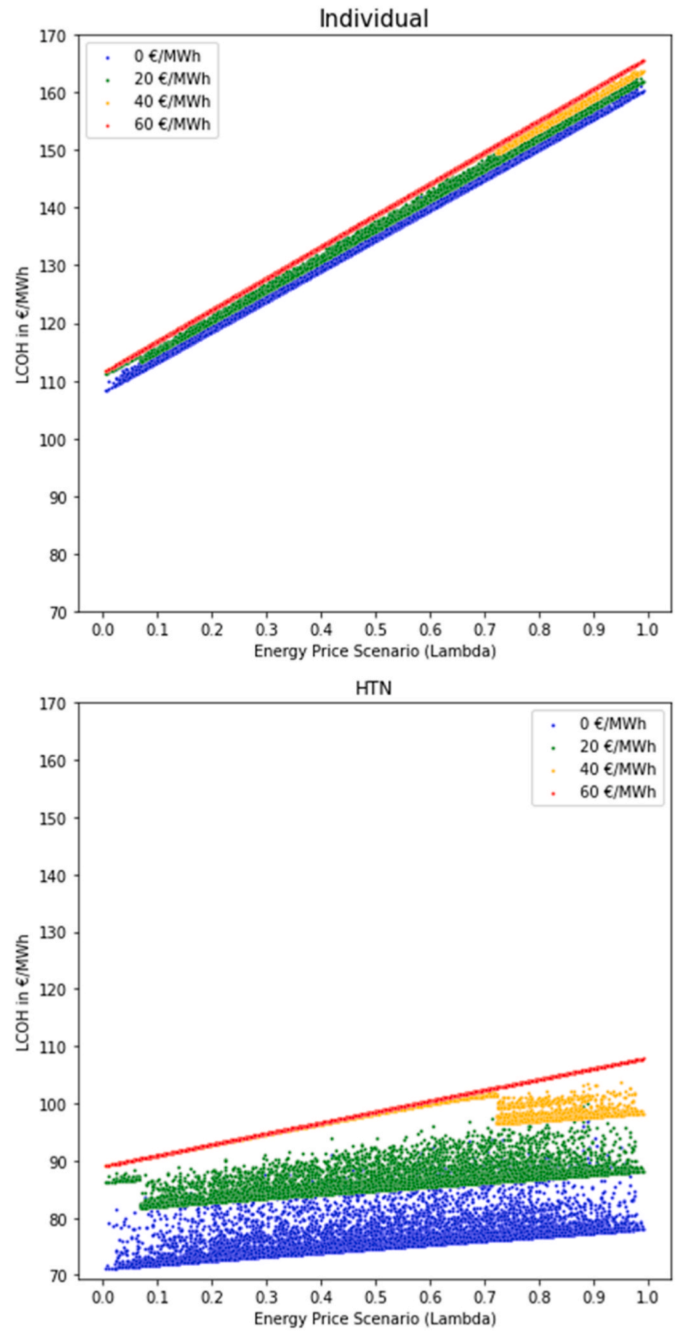

Fig. 9. Comparison of the LCOH depending on the energy price scenario (Lambda).

investments and a return to dependence on fluctuating energy prices.

7. Uncertainties and limitations

While energy price scenarios, the configuration of CHPs and HPs, and the WH availability have been in the focus of this investigation, other factors have been simplified and may require further attention.

- A stable development of energy prices and a continued perfect correlation between the electricity and natural gas price were assumed. Increasing trends towards decentralization of supply and increasing shares of renewables may lead to a decoupling of the prices. Potential disruptions in the energy markets could also destabilize the development of energy prices.
- Future developments such as climate change or retrofitting of buildings will have an impact on the future heating demand, which is assumed to be stable in this work.
- With changing regulations, new suppliers entering the market and increasing efficiency, CAPEX, OPEX and availability of technologies will change and need to be considered.
- The decarbonization of households not supplied by DH was assumed to follow a certain percentage distribution, while no changes in the supply portfolio of local DH networks, other than replacing fossil backup capacities, were assumed. As chosen technologies have a great impact on the LCOH, different decarbonization pathways need to be considered.

More research is required to represent the factors mentioned by adequate probability functions. In addition, various simplifications have been made where improvements are possible.

- A seasonal approach allows faster computation times, but as hourly demand can vary greatly, the supplier's infrastructure may be inadequately designed. Although small-scale storages have been considered, a comparison should be made in the future to check plausibility.
- Although a large-scale seasonal thermal storage is difficult to implement in practice due to high CAPEX and large space requirements, this option should be investigated further, as it is expected to provide significant benefits.

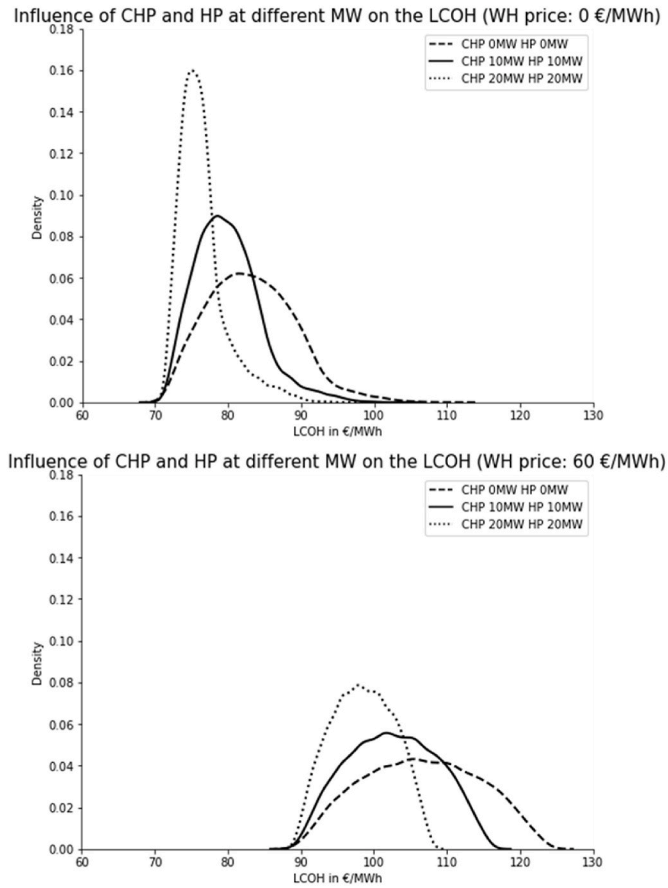

Fig. 10. Influence of the flexible components on the LCOH in the HTN, top: WH price = 0 €/MWth, bottom: WH price = 60 €/MWth.

- The price of WH and the discontinuation of it could be related to energy prices, company types or efficiency gains. Currently WH prices are assumed to be stable over the year. Identifying and incorporating influencing factors correctly in the model is essential. Also, new WH sources, such as data centers should be considered.
- In the current investigation, all municipalities are connected to one large HTN, although it might be more feasible to create smaller HTNs connecting only a few municipalities. However, in this case, the positioning of large-scale supply infrastructures needs to be reconsidered.
- In general, individual HPs enable the use of locally generated PV, the participation in energy communities, provision of cooling, etc., which has not been considered in the context of this study. As a large number of individual HPs is installed in the individual configuration, efficiency gains have a great influence on the overall LCOH, especially in times of high electricity prices.
- For the electricity price development considered in this paper, a higher uptake of HPs in households represents a higher risk compared to an increased uptake of biomass boilers, due to very high prices. Also, the large-scale HP is barely used in the HTN. However, with an increasing share of renewables and a stabilization of the energy markets the electricity price may become cheaper, leading to a prioritization of HPs. Biomass prices may also be subject to change with changing regulations and increasing demand for biogas

Finally, to validate and refine the existing data and to push the HTN towards realization, it is crucial to intensify the contact and exchange with local stakeholders. Important issues are, among others, the actual WH-potential of companies and the status quo of the individual heating systems in Tyrol. It is planned to discuss practical possibilities and barriers for the development of a HTN.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2023.100119.

APPENDIX

Key assumptions

- The annual maintenance cost for biomass boiler at household level are set at 400 €/yr, and are made up of the maintenance contract for the system and the chimney sweep costs [81].
- Capital costs for a biomass boiler are set at 13,460 € for single-family houses (SFH) and at 7300 €/household for multi-family houses (MFH). For service buildings (SB) the same CAPEX as for SFH are assumed. This includes the technology and the conversion CAPEX for exchanging the current system [82].
- The efficiency of household biomass boilers is set at 90% [83].
- The annual Tyrolean energy monitoring for 2021, using data until January 7, 2022, states that ground-source HPs utilizing geothermal energy and groundwater make up for 4365 systems (66%) of the HPs installed for residential and tertiary use in the state of Tyrol. Air-source HPs make up for 2224 systems (34%). Chilled water systems, with 145 systems installed, are neglected in this work. From the energy monitoring 2020 to 2021 the share of ground-source HPs has decreased from 71% to 66%, while the share of air-source HPs has increased from 29% to 34%. An average value is taken into consideration for the distribution of HP technologies.
- In this work, η_{HP} is set to 50% [84].

- The maintenance costs for a connection to the DH network originate from the EU project: "Overview of Heating and Cooling Markets" [46], and are 42 €/yr for SFH and 43 €/yr and household for MFH.
- For the specific heating demand of SFH, 90.1 kW h/m^2 and year and for MFH 78.6 kW h/m^2 and year are considered.
- In the calculation 1250 kW h/Person and year is considered as DHW demand.
- An overall efficiency of 90% for BHoBs supplying DH grids is assumed [83].
- The necessary nominal power of a BHoB is derived from the maximum remaining demand of all timesteps considered divided by the hours in the respective timestep. Thereby, possible additional heating plants can be considered.
- Investment costs of 650 €/kW and maintenance costs of 6% of the CAPEX per year are set. These values are based on the project "Flexi-Sync[6]". The depreciation period is set at 10 years [78].
- The CHP in this consideration is fueled by biomass, with a thermal efficiency of 65% and an electric efficiency of 25% [85].
- Cost parameters for flexible components both originate from the "Flexi-Sync[7]" project.
- The discounting factor j is set to 5%.
- It is assumed that 50% of the waste heat potential specified in Table 5 is realized.

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