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Revolutionizing heat distribution: A method for harnessing industrial waste heat with supra-regional district heating networks

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HIGHLIGHTS

- Industrial Waste Heat
- Load Flow Calculation
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ABSTRACT

In both practice and literature, there is a lack of a concept for a supra-regional district heating network that efficiently transports heat from renewable and industrial waste heat sources to multiple heat sinks and regional district heating networks, like the high-voltage electricity transmission network in the electricity sector. This paper addresses this gap by presenting a novel method for the basic design of a supra-regional district heating network and its evaluation, along with key performance indicators for assessment. The method highlights essential data requirements and the derivation process necessary to enable the integration of such a heating network. Additionally, it describes how a basic design of such a network can be made feasible and evaluated. This method is then applied to a case study to demonstrate its implementation for a real-world application. Furthermore, this case study aims to either demonstrate or provisionally disprove the general feasibility of a supra-regional district heating network. The results indicate that the implementation of such a network has a positive impact on the CO_2 balance and primary energy demand. The case study further demonstrates the technical feasibility of such a network, showing that a high linear heat density can be achieved through integration and that temperature levels within the network can be maintained adequately. This study confirmed that the developed method can effectively assess whether further investigations into implementing a supra-regional district heating network in a specific region are warranted. Additionally, the method offers a guideline on how to initially design such a network.

1. Introduction

In regions situated in northern latitudes, the prolonged winter seasons give rise to a considerable demand for space heating. In addressing the challenges posed by climate change [1], there exists a dual imperative: the integration of highly efficient space heating systems and the adoption of renewable heat sources or those with minimal carbon dioxide (CO_2) emissions. This requires a balanced approach that not only maximizes energy efficiency for heating purposes, but also reduces the overall carbon footprint associated with heating systems. However,

Abbreviations: DHN, District Heating Network; Nat., Nation; 2GDH, Second-Generation District Heating; CHP, Combined Heat and Power; CO_2, Carbon Dioxide; T, Temperatures; KPI, Key Performance Indicator; Mio. €, Million Euro; m, Meters; IWH, Industrial Waste Heat; SRDHN, Supra-Regional District Heating Network; HHR, Heat Highway Region; HH, Heat Highway; Scenario 2022 State, S2022S; Scenario 2, S2; LFC, Load Flow Calculation; FLH, Full Load Hours; HPUS, Heat Plant Utilization Sequence.

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despite the pressing need for sustainable solutions, many regions still heavily rely on fossil-based sources for heat generation or maintain outdated and inefficient heating systems [2]. For instance, renewable resources cover only 32% [3] of space heating in Austria. Although there exists a considerable and mostly untapped heat source especially in highly industrialised regions in the form of industrial waste heat (IWH). Energy-intensive industries, like steel-, cement-, pulp- and paper-manufacturing, generate substantial quantities of IWH. While a portion of this heat can be employed for internal industrial needs or conserved through efficiency measures, the surplus IWH often surpasses the capacity for internal utilization. [4] However, in many cases, this heat source continues to be released into the environment without being effectively harnessed. One viable approach to harnessing this resource involves establishing connections between energy-intensive industrial sites and space heating sinks through the implementation of heat transmission lines. Currently, district heating networks (DHN) are limited to local areas or to connecting a small number of more distant heat generation units to a region. This restriction confines the utilization of IWH to a particular geographic area. To harness IWH more effectively, the establishment of a heat network spanning multiple regions and generation units akin to the high-voltage electricity transmission network is imperative. In alignment with the definition provided by Moser et al. [5], such a network would align with the definition of a supra-regional district heating network (SRDHN).

1.1. State-of-the-art

A SRDHN is characterized by the following criteria: [5].

- Traverses sub-urban or rural areas,
- Interconnects multiple IWH and other sustainable sources,
- It connects one or more district heating networks and stand-alone major customers,
- It links industrial process heat sinks and/or thermal storage facilities.

Different literature sources address the structure and properties of DHNs. Frederiksen et al. [6] classify district heating networks into five typical structures: “One Central Location”, “Central Base Load”, “Peripheral Base Load”, “Common Transmission Pipe”, and “Large Integrated Network”. The category of “Common Transmission Pipe” aligns closely with the definition of the structure of a SRDHN provided by Moser et al. [5], albeit without the specific requirement that heat generation must be CO_2-free and without detailing which district heating participants need to be interconnected. Lund et al. [7] categorize DHN networks into six main generations based on factors such as the temperature of the transport medium, energy efficiency, and the types of generation units used. A SRDHN exhibits characteristics of both 3rd generation and 4th generation DHNs.

Designing and calculating diverse DHNs necessitates load flow calculations (LFC). Literature describes various tools for this purpose, mainly categorized into two approaches: steady-state and dynamic LFC. Steady-state calculations are beneficial for network design and for computing small district heating networks for instance within multiple energy systems. On the other hand, dynamic LFCs are more suitable for pipe design and calculating single pipes due to their longer computation times. Another approach is the quasi-dynamic LFC which falls under a subcategory of dynamic LFC and offers a compromise, combining an acceptable calculation time with an accurate description of the real-world behaviour of district heating networks. Dénarié et al. [8] present a technique for the precise and rapid computation of long heat transmission lines employing a Lagrange-based methodology. Similarly, Steinegger et al. [9] propose a method introducing a Lagrange-based approach, wherein the observer moves alongside a water segment within a DHN. Dancker et al. [10] introduce an approach called the improved quasi-steady-state approach. This method, an extended version of the steady-state approach, is characterized by compromising the hydraulic and dynamic thermal behaviour in a single equation. [9]

Sporleder et al. [11] provide a comprehensive list of different research dealing with optimizing and designing DHNs. The provided compilation indicates that most research efforts are directed towards optimizing DHNs in conjunction with renewable energy sources. For instance, Blommaert et al. [12] introduce an adjoint optimization approach for the topological design of large-scale district heating networks, addressing the challenges of optimizing topology and pipe diameters. Unternährer et al. [13] introduce a methodology for spatially assessing the integration of DHNs within urban energy systems, particularly in conjunction with geothermal energy. In reference [14], a methodology is presented to minimize the investment costs associated with integrating a DHN in conjunction with a geothermal plant. In [15], a novel methodology is introduced for the design and evaluation of DHNs featuring a bidirectional and low temperature grid system. The impact on the design of a DHN in conjunction with thermal storages is discussed in [16,17].

One significant criterion for establishing a SRDHN can be the abundance of IWH in certain regions. For instance, the DHNs in Linz and surroundings, described in [5], could benefit from interconnection to utilize heat from various IWH sources. In [18] the potential of IWH in Germany is examined, along with its feasibility for integration into district heating networks. The study's findings reveal that only a fraction of the potential is currently being utilized. Fu et al. [19] outline the deployment of extended heat transmission lines to furnish major cities in Northern China with IWH. Their findings suggest that employing transmission lines spanning up to 200 km remains economically viable through the utilization of sizable pipe diameters and extensive use of IWH. The case study in [20] focus on the integration of waste heat in the DHN in Riga. It offers insights into the main drivers behind waste heat integration, namely reducing the primary energy factor and the enhancement of system efficiency within a DHN.

One key characteristic of SRDHNs is their ability to interconnect multiple DHNs [5]. This characteristic results in the development of extensive transmission line systems and long point-to-point pipelines. The economic and technical feasibility of the total length of point-to-point lines is discussed in several literature sources. In [21], it is observed that transmission capital costs decrease with increasing transmitted heat load, and a reasonable maximum-distance for piping heat is suggested to be 150 km. Ammar et al. [22] suggest that water with temperatures ranging from 90 °C to 175 °C can be economically transported in point-to-point pipelines over distances exceeding 30 km. Gadd et al. [23] discusses the significant impact of low return flow temperature on costs. The techno-economic model presented in [24] suggests that, under specific techno-economic parameters and market conditions, longer distances than 50 km may still be economically viable.

As indicated by Moser et al. [5], there are currently no existing DHNs that fully conform to all aspects of a SRDHN. Currently, only the Copenhagen network closely resembles the concept, although not all criteria, such as large-scale integration of IWH or CO2 neutrality, can be met at this time.

1.2. Scope of the work

The literature review highlights numerous scientific studies focusing on the design and optimization of DHNs in conjunction with various factors. These include the integration of renewable heat generation and thermal storages, the utilization of IWH, the implementation of low-temperature heating systems, and the usage of heat transmission lines. Additionally, various tools are described in the literature to address these topics. Furthermore, the literature provides a precise definition for district heating systems which are comparable to the high-voltage electricity transmission network in the power grid. Such networks are known as SRDHNs. Literature review also shows that there is no existing network which fulfils all criteria of this definition in real world applications and in research. At present, scientific discussions revolve around the potential establishment of such a network in Linz and its environs, while existing networks such as the Copenhagen DHN serve as the closest semblance to this definition but without the large-scale integration of industrial waste heat. In conclusion, there is a research gap concerning a method that effectively outlines the implementation and design of a heating network that satisfies all SRDHN criteria. The presented paper aims to address this research gap by answering the following research questions:

- What information is needed to design a SRDHN?
- How to design a SRDHN?
- How to evaluate the technical feasibility of a SRDHN?
- What are the key performance indicators (KPI) that can evaluate the technical feasibility of a SRDHN?
- What other indicators are needed to verify that a DHN equals the definition of a SRDHN?

The paper's primary aim is to introduce a method facilitating the design and implementation of SRDHNs in regions worldwide abundant in potential heat sources and sinks. A case study conducted at the end of the paper demonstrates the method's functionality and offers insights into the technical feasibility of a specific SRDHNs.

2. Method

Introducing a SRDHN requires a supra-regional assessment of both heat generation potential (e.g., IWH) and heat demand potential (e.g., DHNs). If this assessment verifies the availability of these factors, the SRDHN can be designed using the method described below. Subsequently, the technical feasibility of such a network can be determined based on the obtained results.

The method comprises four main steps:

- Collecting information on existing and potential heat sources, sinks, and infrastructure.
- Preparing the collected data for subsequent calculations.
- Designing the SRDHN.
- Evaluating the obtained results.

The initial two steps involve the preparation and generation of the data, while the latter two steps focus on the realization and analysis of the prepared data and the resulting outcomes.

2.1. Gathering important information

Acquiring data on potential heat generation units and information about existing DHNs in the studied regions is crucial. Information on potential heat generation units should include the following:

- Technical capacity of potential sources.
- Temperature levels of the potential sources.
- Exact location, including elevation.
- Annual temporary resolved maximal power output.

To assess the feasibility of utilizing this potential heat generation, it is necessary to first identify and analyse potential heat sinks in these regions. To achieve this, several key facts about the respective heat sinks must be obtained:

- A basic understanding of the topologies and structures of the existing DHNs.
- Obtaining information on temperatures, heat losses, and pipe diameters in the respective DHNs.
- Details concerning the capacity and locations of installed heat generators and storage facilities within these networks.
- Knowledge of the connected capacity of the heat sinks within the existing DHNs.
- Data on the annual energy consumption of these heat sinks.
- Temporally resolved temperature profiles of the outdoor temperature at consumer locations.
- Information regarding the temporal and spatially resolved heat demand of the heat sinks.

2.2. Data preparation

In many cases, gathering all the necessary data is impossible. In such situations, the following chapter presents a method to generate the required data, even with limited information about potential heat generation units and heat sinks. It's essential to note that a minimum amount of data must be known to utilize this method.

For the potential heat generation units, all described information in Chapter 2.1, excluding the point about the annual temporary resolved maximal power output, must be known. This exclusion is because the temporary resolved power can often be estimated based on the heat generation sector to which the unit belongs. For instance, IWH can be assumed to have a band load for initial calculations. This is because the method described in this paper is intended for initial analysis, and therefore such estimations are sufficient.

For heat sinks, such as existing DHNs, the following data must be known:

- A basic understanding of the topologies and structures of the DHNs.
- Information on the operating temperatures of the respective DHNs.
- Details concerning the capacity and locations of installed heat generator units.
- Knowledge of the connected load or the annual energy consumption of the heat sinks.

Even if only the connected load is known, it is still possible to estimate the annual energy consumption, if reference networks are available with both the connected load and the annual heat consumption. This process is described in the following section.

2.2.1. Calculation of the energy consumption

The connected load of consumers in DHNs often significantly exceeds the actual maximum load, primarily due to simultaneity factors and safety-oriented assumptions during load calculations [25]. As a result, it becomes imperative to determine the actual maximum load within the heating networks before accurately calculating the actual annual heat consumption. Thus, the availability of reference networks with known connected loads and actual annual heat consumption is crucial. Fig. 1 illustrates the sequential steps necessary to derive a factor F, capable of calculating the actual annual heat consumption for all DHNs.

First, the number of Heating Degree Days ($HGT_{20/12}$) needs to be calculated for each day (n) when the daily mean temperature (T_m) falls below the heating limit temperature (12 °C), within the annual period spanning from October 1st to April 30th. This is calculated as shown in Eq. (2-1). The target indoor temperature is 20 °C. [26,27]

$$HGT_{20/12} = \sum_{n=1}^{z} \left(20^{\circ}C - T_m(n)\right) \tag{2-1}$$

Second, the annual heat consumption (Q_C) is calculated using Eq. (2-2). The result from Eq. (2-2) is in the unit Kelvin Days. By multiplying the $HGT_{20/12}$ with 24 h per day and the connected load $\dot{Q}_{CL}$ (which is considered as too high) divided by the standard temperature difference ΔT_N between the standard outside temperature [28] and the target indoor temperature, the annual heat consumption is calculated in watt-hours.

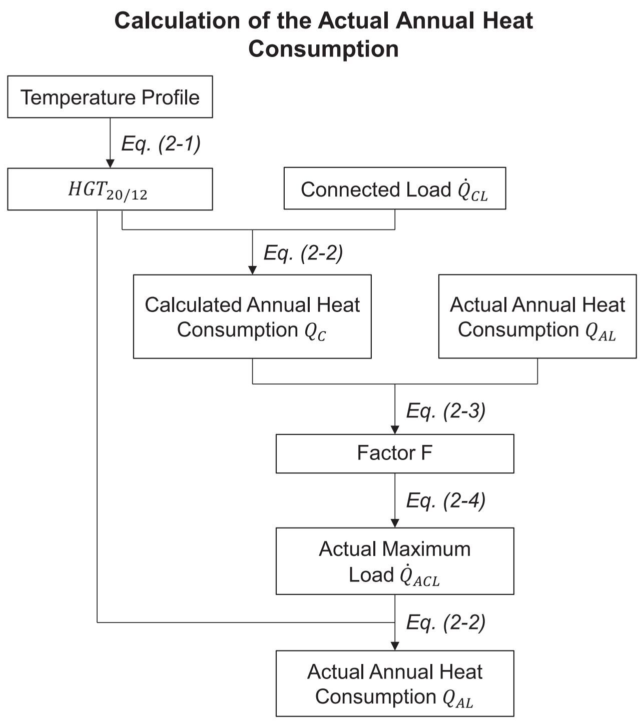

Fig. 1. Calculation of the actual annual heat consumption.

$$Q_C = HGT_{20/12} \bullet 24\text{h} \bullet \frac{\dot{Q}_{CL}}{\Delta T_N} \tag{2-2}$$

Third, the calculated annual heat consumption Q_C is compared to the actual heat consumption (Q_{AL}) from literature, and a factor F is computed for each reference DHN, as described in Eq. (2-3).

$$F = \frac{Q_{AL}}{Q_C} \tag{2-3}$$

Fourth, the reference networks are compared with each other, and the average value F can be calculated.

Fifth, with the received factor F, the actual maximum load $\dot{Q}_{ACL}$ can be calculated by multiplying the factor with the connected load $\dot{Q}_{CL}$ from the literature (Eq. (2-4)).

$$\dot{Q}_{ACL} = \dot{Q}_{CL} \bullet F \tag{2-4}$$

Last, the heat consumption of all DHNs can be determined using Eq. (2-2) by replacing the connected load from the literature, denoted as $\dot{Q}_{CL}$ with the actual maximum load, represented as $\dot{Q}_{ACL}$.

For generating time-resolved heat demand profiles, synthetic load-profiles generated with the SigLinDe function [29] can be applied. This function can create heat load profiles contingent upon temporally and spatially resolved outdoor temperature profiles, alongside other influential factors, such as the categorization of consumers into distinct categories and the annual heat consumption.

To acquire the necessary air temperature data for each consumer location, the provided hourly-resolved temperature from the renewable ninjas website [30,31] can be utilized. The website offers temperature profiles for various locations worldwide, enabling users to access temperature data for specific geographic areas.

2.2.2. *Calculation of pipe diameters*

Obtaining data on pipe diameters, generation needs and losses is crucial. However, this information is frequently absent from literature for many grids. The following section illustrates how this data can be acquired through calculations. To achieve this objective, a LFC tool is required. Literature research indicates the availability of multiple LFCs, but the suitable ones for this task must possess certain capabilities. These include the ability to compute large networks within reasonable computation times, flexibility in setting various pipe properties, and support for temporally resolved load profiles. Moreover, for realistic solutions, the chosen LFC should employ a dynamic, quasi-dynamic, or similar approach capable of replicating real-world behaviour across multiple time steps. LFC tools suitable for this purpose can be replicated using research from sources such as Dénarié et al. [8], Dancker et al. [10], Steinegger et al. [9], or other similar studies listed in the literature research of [9,10]. In the paper being presented, the LFC detailed in [9] is applied exemplarily and enhanced with a pipe diameter calculation. The extension is elaborated upon in the subsequent section, which should be applicable to each tool available in literature.

The input data required for this part of the calculation includes the network structure of the DHNs represented as a Node-Edge Graph, the spatially resolved maximum heat demand, the feed- and return flow temperature, the used heat generation units and their generated heat, and the ambient temperature of the considered DHN. The pipe diameter calculation is based on the steady-state portion of the LFC and is performed for maximum heat demand situations. The rationale is that pipes face peak stress levels during maximum heat demand periods. The diameter calculation utilizes public available data from the company Isoplus [32], which provides a comprehensive database that includes various heat pipe properties, including maximum and minimum speeds for district heating pipelines, with consideration for diameters up to 1 m. "Medium Pipe Steel - Standard Insulated" serves as the reference product for this calculation. For simplicity, the LFC assumes identical diameters, characteristics, and the absence of special components such as curved elements in both feed and return flow pipes. In the calculation, pipes with velocities outside the speed limits from Isoplus, have their diameters adjusted in an iterative way until all fall within the specified limits. In complex DHNs, the iteration process may not always yield successful results. Therefore, special precautions should be taken to ensure that no pipe exceeds the maximum velocity limit, even if it means disregarding the lower limits. This approach helps prevent significant pressure losses within the network. After completing the iteration, the new diameters should be increased to the next larger diameter size (for added safety).

2.2.3. *Calculation of generation needs and heat losses*

Once the diameters are calculated, the generation needs, and the heat losses can be subsequently determined. Therefore, an order of utilization for thermal plants across the DHNs is necessary. This involves implementing a straightforward ranking system, depicted in Table 1, listing types of heat plants in ascending order. The sequence operates on the principle of prioritizing the utilization of unavoidable heat to minimize waste. Then, whenever feasible, generators compliant with renewable energy standards are employed. Fossil fuel-based generators are reserved for peak load periods only. However, solar thermal energy depends solely on solar irradiation. A generation profile can be established using data from Renewable Ninjas [30,31]. Storage facilities are not considered in this initial technical analysis: first, the number of

Table 1
Thermal heat plant utilization sequence.

Heat Generation Plant	Rank
Solar Thermal Energy	1
Waste Incineration	2
IWH > 100 °C	3
Biomass Combined Heat and Power (CHP)	4
Biomass	5
IWH 50 °C - 100 °C	6
Geothermal Energy	7
Gas CHP	8
Gas	9
Oil	10

Table 2
Categories of load factors.

Category	Load Factor	Occurs when
Cat. 4	$> 120\%$	$\sum_{t=1}^{35040} t \geq 1$
Cat. 3	$> 100\%$ & $\leq 120\%$	$\sum_{t=1}^{35040} t \geq 97$
Cat. 2	$> 90\%$ & $\leq 100\%$	$\sum_{t=1}^{35040} t \geq 5761$
Cat. 1	$\leq 90\%$	–

existing storage facilities and the corresponding amount of energy stored in known study areas is small. Second, they require a special operating strategy. For these reasons, the existing storage facilities would not have a significant impact on the technical feasibility of a SRDHN but would lead to a large additional simulation effort.

In every network, a “slack-node” plays a crucial role in absorbing unexpected heat consumption peaks, not considered in the heat plant dispatch. To prevent the slack-node, which is usually the heat-plant with the highest-ranking value in the utilization sequence, from absorbing excess heat, a portion of anticipated consumption should be preallocated to it. This allocation provides the slack with a larger margin for manoeuvre, ensuring it serves as the peak load heat plant within the DHN. Whenever precise data concerning power plant scheduling is available from literature, it should be used. Finally, the heat plant utilization sequence (HPUS) can be employed to devise a utilization plan for the generators throughout the entire year, considering the time-resolved heat consumption.

To ensure an adequate pressure level especially during situations in which a high heat demand need to be covered, a pressure control mechanism for circulation pumps is essential. Therefore, the circulation pumps are regulated based on the inflow volume flow, as described in many literature sources.

Indeed, the generated data can now be employed to compute the heating networks using the LFC, allowing for the calculation of heat losses and determining the final heat needs. The required input data for this calculation includes the network structure as a Node-Edge Graph, the spatially and temporally resolved heat demand, the temporally resolved feed- and return flow temperature, the thermal HPUS, and the temporally resolved ambient temperature of the considered DHN.

2.2.4. Determination of connection points to a transmission line

To ensure the connection of a DHN to a transmission line, forming together a SRDHN, suitable connection points within the DHNs must be identified. Connection conditions for a DHN need to be designed to fully cover the DHN's heat demand, ensuring adequacy even in peak demand scenarios. Selecting connection points when linking a DHN to the transmission line is crucial to meet consumption needs without overloading pipes and causing pressure drops. Every network must be carefully analysed to make sure that when connected to a transmission line, overloads do not exceed those experienced by the network without it. Overloads are defined as outlined in Table 2. In this context, each time step t corresponds to a 15-min interval. The overload factors indicate the flow velocity during the respective time step (calculated by a quasi-dynamic LFC or similar) relative to the maximum permissible velocity as specified by the manufacturer [32].

The method for identifying the ideal connection points from a local DHN to a transmission line is outlined in detail in Fig. 2. First (Fig. 2a), the original DHN needs to be examined. For this purpose, the LFC is fed with the original data from the local DHN. As the local DHN is designed for this case, there are no overloads. This means all lines fall under category 1. Second, one or more connection points to a transmission line needs to be identified. These connection points operate as exclusive heat supply stations within the DHN. Typically, these are sites where a heat generation unit is already installed, because the pipes at these locations are already designed to transport a large amount of hot water to the consumers. Fig. 2a shows that there are multiple local heat suppliers for the exemplary DHN. This necessitates testing different connection points and combinations to identify an optimal connection strategy for connecting a local DHN to a transmission line. In Fig. 2b, an exemplary attempt to connect a single point in the local DHN to a transmission line is depicted. This attempt failed due to category 3 and 4 overloads. Fig. 2c ultimately presents the optimal way to connect this exemplary network, as no overloads are observed.

In the final SRDHN plan, all connection points to the local DHNs, should be calculated according to the described method.

2.3. Design principles for SRDHNs

A crucial factor in routing transmission lines is to prioritize laying pipelines along the rail network and public roads, as these infrastructures typically provide the most efficient and direct geographical routes for connections. To minimize the need for costly special constructions, crossings of railroad lines, highways, and rivers should be avoided whenever feasible. The pipelines themselves can be designed in various ways. In [55], it is recommended to use pipes with a maximum pressure of 25 bar or 40 bar for large DHNs. The investment costs of pipes increase with higher maximum pressure capabilities. In the subsequent scenarios, pipes with a maximum pressure limit of 40 bar were utilized. Consequently, a SRDHN must be dimensioned to comply with the chosen specifications. As a result, hydraulic calculations must be performed on the considered SRDHN to assess pressure variations arising from differences in elevation. Such a calculation is typically already implemented in a LFC described in the literature.

Once these fundamental factors are determined and a routing is defined (as Node-Edge Graph) according to the basic rules mentioned, the pipe diameters of the SRDHN can be calculated with the described diameter calculation method in Chapter 2.2. The calculated heat demand, including the losses of the respective underlying DHNs, serves as input data for the heat demand, with each summarized at their connection points. To achieve this, the heat demand quantities at the connection points can be derived from the individual connection calculations of the underlying heating networks. The time step for the diameter calculation should be selected to correspond with the time step featuring the accumulated maximum consumption. The heat generation sequence can be determined based on Table 1 and the total installed heat generation units in the entire SRDHN region. If the heat generation unit is situated within a underlaying DHN, the heat generated can be subtracted from the heat demand designated at the connection point(s) of the corresponding DHN. Other input parameters are the feed and return flow temperature and the ambient temperature of the SRDHN.

Using the calculated diameters and the same input data as before, excluding the heat demand, results can be computed with a LFC for both maximum and minimum demand cases. These results can then be utilized to evaluate the SRDHN.

2.4. Evaluating the results

In this paper, four main KPIs were identified for evaluating the technical feasibility and determining whether the network aligns with the definition of an SRDHN:

- The temperature within the SRDHN.
- The linear heat density.
- Changes in the carbon footprint.
- Changes in the primary energy demand.

2.4.1. Temperature

To determine the principle technical feasibility of a SRDHN, one crucial requirement must always be met: the temperature required at the connection points to the local DHNs must be adequately high. For this purpose, specific regionally adapted limit values should be defined, specifying the minimum temperature at each connection point from the

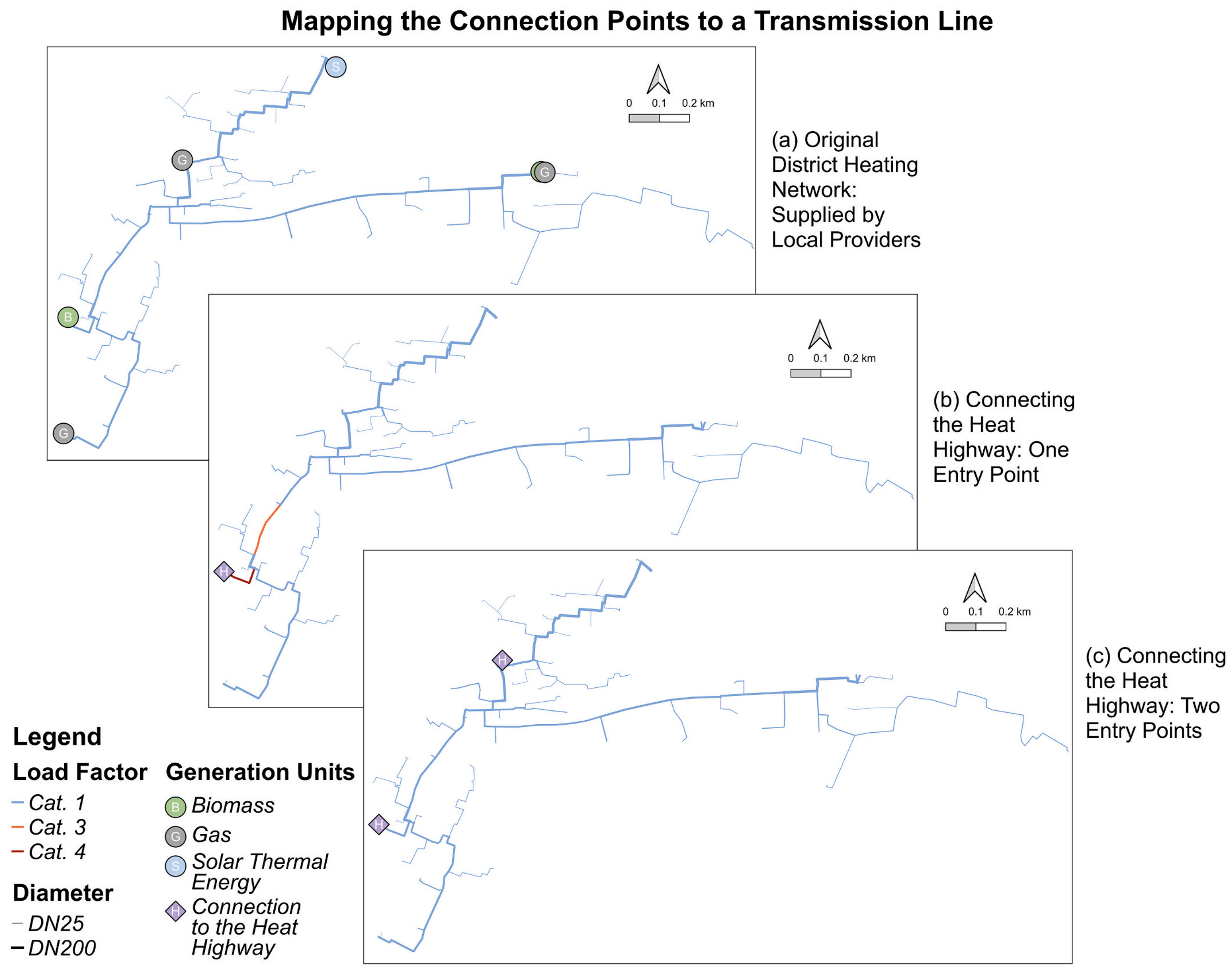

Fig. 2. Mapping the connection points to a transmission line.

heat transmission line to the underlying DHNs. It's important to differentiate between hot and cold time periods.

2.4.2. Linear heat density

Another KPI for evaluating a SRDHN is the linear heat density [33], representing the heat demand per year and per unit of trench length (excluding losses). For evaluating a SRDHN two approaches for calculating the linear heat density can be considered. The first factors in the existing underlaying DHNs. The second, treating distribution networks as single consumers. Hammer et al. [33] offer a relevant graphic depicting 377 DHNs and their linear heat density. This graphic compares linear heat density to heat distribution losses, indicating that an acceptable DHN should have a linear heat density of at least 1.5 MWh/(m*a), resulting in approximately 15% heat distribution losses. In this paper, the requerment for the linear heat density for an acceptable SRDHN are set to be equivalent to those of an acceptable DHN. This implies that both calculation approaches must achieve the recommended linear heat density of 1.5 MWh/(m*a) to be considered generally and technically feasible.

2.4.3. Carbon footprint

As defined by Moser et al. [5] a SRDHN must be supplied with heat sourced from renewable sources and/or IWH. This presupposes that a SRDHN must operate without generating a carbon footprint during its operation. Therefore, the CO_2 emissions produced can serve as a clear indicator of whether and how close a heating network is to meet the criteria of a SRDHN.

2.4.4. Primary energy demand

The final criterion for determining the general feasibility of a SRDHN in this paper is whether the integration of the SRDHN results in a reduction in the primary energy demand for supplying the heat sinks. To calculate the annual primary energy demand and the carbon footprint, it is necessary to also determine the heat losses over the course of a year. Therefore, the losses between the highest and lowest demand cases can be averaged and then multiplied by the number of hours in a year. The required annual heat sources to meet the heat demand and compensate for losses can be identified using the thermal HPUS outlined in Table 1. The primary energy demand for different heat sources can be calculated as follows:

- IWH: The influence of IWH on primary energy is assumed to be zero.
- Solar thermal energy and geothermal energy: The primary energy demand equals the heat needed in the DHN. [34] As long as the electricity which is used for heat pumps is renewable.
- Gas CHP plants, biomass CHP plants and waste incineration plants with cogeneration: The primary energy demand can be calculated with the method and the values introduced in [35,36]. This method

Table 3
SRDHN: Important KPIs.

KPI	Requirement
Temperature	Must reach a certain value at the heat substations
Linear Heat Density	Must be higher than 1.5 MWh/(m*a)
Carbon Footprint	The integration must reduce the original value
Primary Energy Demand	The integration must reduce the original value

compares the efficiency of the considered combined heat and power plants with that of comparable plants which only generate heat or electricity and calculates resulting primary energy savings accordingly.

- Biomass plants, gas- and oil-boilers: Their primary energy demand depends on their efficiency.
- Circulation pumps: Their energy demand is assumed on their electricity demand, which is assumed as renewable electricity. This means that the electricity required corresponds to the primary energy demand.

The supplementary primary energy demand for pumping can be estimated according to [37], which indicates that the energy required is approximately 10% of the overall energy demand.

The described KPIs can be summarized as outlined in Table 3.

If all criteria are met, it can be reasonably assumed in an initial approximation that the SRDHN will indeed lead to a more efficient and environmentally friendly heating system, in line with the objectives outlined in the introduction of this paper.

3. Case study

The subsequent chapter delineates the implementation of the described methodology through a use case in Styria, Austria.

3.1. Gathering important information

The state of Styria, situated in Austria, is renowned for its energy intensive industry, particularly in the Mur-Mürz region. This is corroborated by the Styrian "waste heat cadastre" detailed in [38]. Given this scenario, there is a compelling case for establishing a SRDHN that harnesses existing IWH sources to supply the existing heat networks. Additionally, Graz, the second-largest city in Austria [39] is situated in this region. The city operates a substantial heating network, still primarily reliant on fossil fuels [40]. Data about the existing DHNs was gathered from the state of Styria [41]. This data encompasses the connected load of various DHNs, pipeline lengths, installed capacities of biomass units, storage capacities, and the geographic locations of the networks in the Mur-Mürz region. In this initial analysis, only networks with an annual heat demand exceeding a boundary of 1 GWh were considered. The analysed region in Styria will now be referred to as the Heat Highway Region (HHR), and the transmission network within this region will be called the Heat Highway (HH). However, to perform precise calculations, additional details, such as the topologies and the heat-generation units of the underlaying DHNs, were required. These details were obtained from the respective network operators and conducting online research in addition to the received data. Fig. 3 presents the obtained data from the analysis, where other renewables include, solar thermal energy, geothermal energy, and waste incineration. The 2022 state represents the installed heat generation plants at the current state (information may relate also to years before 2022). Approximately 69% of the installed heat generation units are fossil-based (mostly used as peak load plants). Scenario 1 incorporates high temperature (>100 °C) IWH potentials additionally to the existing installed high temperature IWH. Scenario 2 also includes middle temperature (50 °C–100 °C) IWH-potential, and Scenario 3 additionally considers low temperature (<50 °C) IWH potentials in the overall assessment. This technical potential of IWH is obtained from [38] and, in a second step, allocated as an annual band load to various IWH locations. The

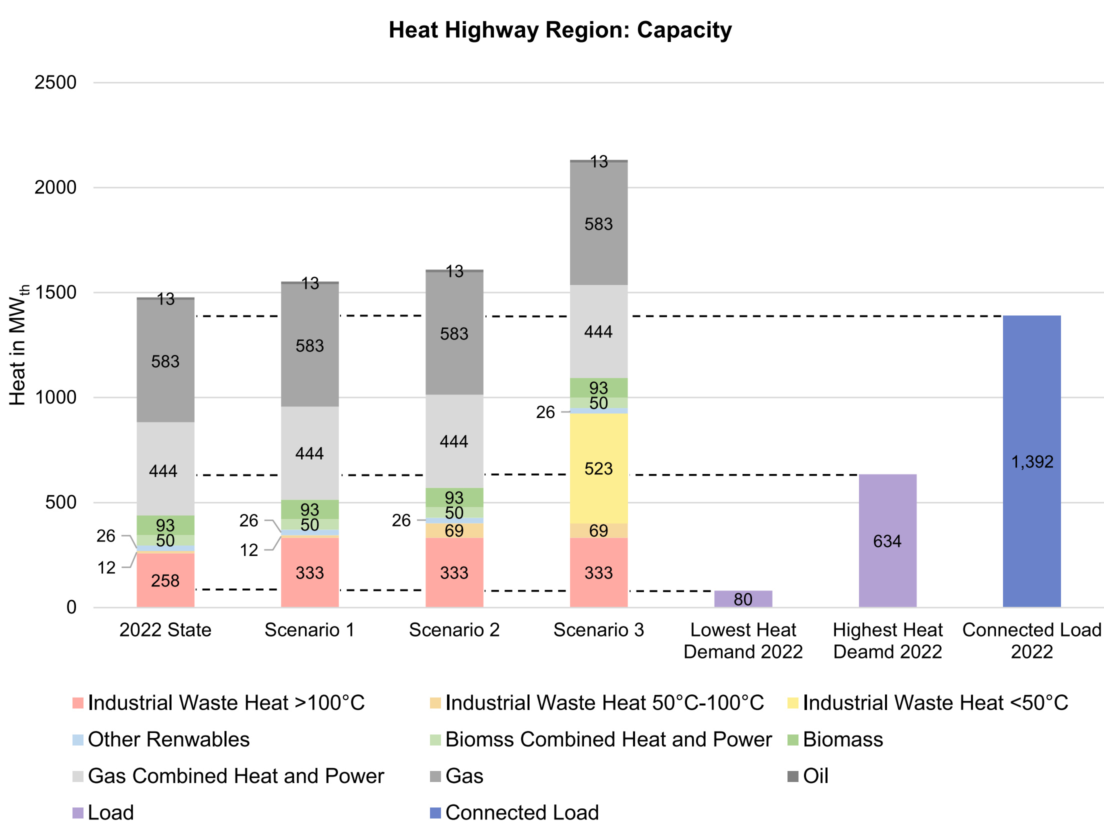

Fig. 3. HHR: Heat generation mix.

substantial installation capacity of biomass CHP plants is primarily attributed to their use in wood drying processes as organic Rankine cycle plants. Gas CHP plants contributes 444 MW to the heat supply, primarily from the CHP plant in Mellach near to the city of Graz. Future plans cap the heat output from Mellach at 200 MW, targeting a maximum of 200 GWh per year, as detailed in [40]. Comparing the installed heat capacity for IWH, biomass and heat from the CHP-unit with the required heat consumption shows, that the current state can meet the 2022 maximum heat demand without gas- or oil boilers. This highlights the potential, for further heat network expansions and claims for high energy- and CO_2-savings.

3.2. Preparing the data

To calculate the annual heat consumption for all Underlaying DHNs, the method described in Chapter 2.2 to calculate the factor F is employed. Therefore, an examination was conducted on 13 DHNs within the Mur-Mürz region, where both the connected load and the actual annual heat consumption are known. In the fourth step the 13 networks were compared with each other, and the average value *F* was calculated. The F-factor of all grids is considerably lower than one, meaning that the connected load $\dot{Q}_{CL}$ is in all cases higher than the actual maximum load $\dot{Q}_{ACL}$. The mean value of all *F* values is 0.49, which is comparable to the results of [25]. For this reason, the calculated factor *F* of 0.49 is used for all DHNs except those where the heat consumption (the previously mentioned 13 networks) is known.

Fig. 4 illustrates the results of the heat consumption calculation from the different underlaying DHNs in the HHR for the year 2022, which also accounts for heat losses in the distribution networks. The heating network in the Graz basin, comprising up to 58% of the HHR. The wood industry (which encompasses three heating networks) ranks second and has a significant heat consumption, primarily for wood drying, operating at full capacity for up to 8000 h annually [42]. The whole heat consumption of the DHNs in the region is about 2289 GWh. This accounts for approximately 70% of the district heating volume supplied in Styria in the year 2021 [43].

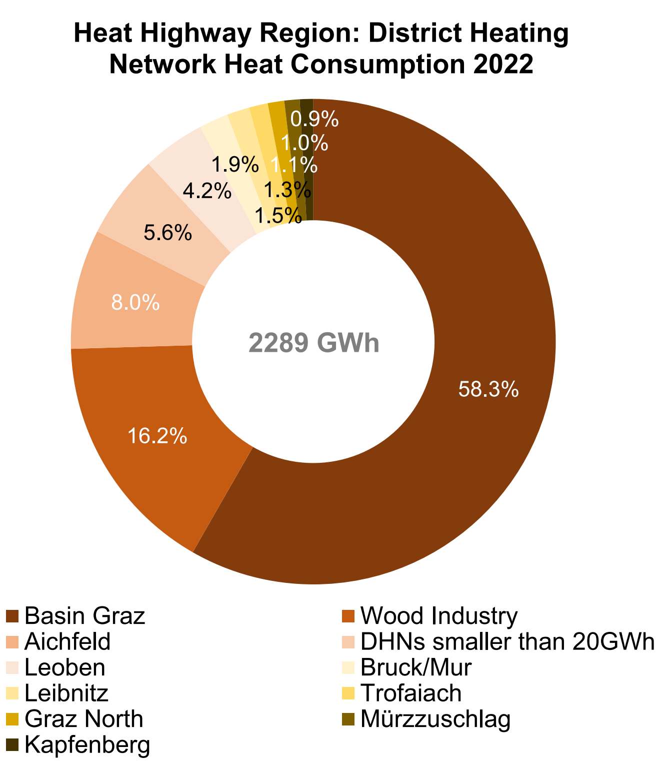

Fig. 4. HHR: DHN heat consumption 2022.

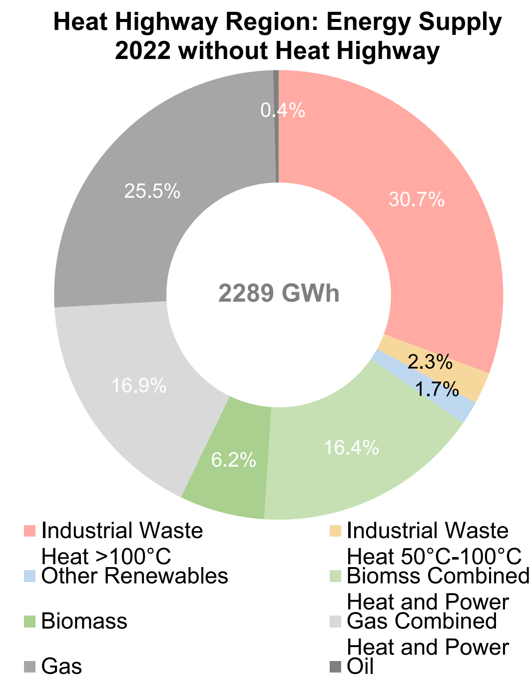

Fig. 5. HHR: heat supply 2022 without HH.

The method outlined in 2.2 is followed to calculate the pipe diameters, heat losses, and final heat generation needs. Therefore, the feed flow temperature from the heat generation units is assumed to have a maximum of 90 °C when the outdoor temperature is −10 °C or lower, and a minimum of 70 °C when the outdoor temperature is 10 °C or higher. In the temperature range between −10 °C and 10 °C, it follows a linear function, spanning from 70 °C to 90 °C, unless specific variations are detailed in the literature. The return flow is chosen constant with 55 °C if nothing else is given in the literature sources.

Fig. 5 offers a comprehensive overview of the resulting heat generation in the HHR for the year 2022 and serves as a reference for further investigations, albeit without claiming absolute accuracy. While a significant portion is generated by IWH plants, gas boilers contribute about a quarter of the total heat required in heating networks, around 584 GWh. When combined with heat from oil boilers and gas CHPs, this results in a substantial CO_2 footprint of approximately 241 ktCO_2/year.

In 2022, Austria's total CO_2 emissions reached 72.6 Mt. [44]. Consequently, the DHNs in the HHR contributed approximately 0.3% to the country's overall CO_2 emissions.

In conclusion, the connections to the HH were computed and integrated into the final HH plan, according to the method described in 2.2.

3.3. Designing the SRDHN

For the evaluation of the HH, two scenarios and corresponding load cases are employed. These scenarios are Scenario 2022 State (S2022S) and Scenario 2 (S2) (refer to Fig. 3). S2022S exclusively connects existing heat plants, while S2 explores additional IWH, assessing dimensioning practicality for expansion while remaining operational in 2022. In each scenario the pipe ambient temperature is assumed to be 5 °C. The design and input parameters necessary for both scenarios are outlined in the following chapter. The pipe type "Medium Pipe Steel - Single Reinforced Insulation" [32] is used for both scenarios. This choice allows flexibility in insulation thickness for technical or economic considerations.

3.3.1. Scenario 2022 state

This scenario relies solely on existing heat sources, prioritizing sustainability. The assumed feed temperatures (T) for the largest heat

Table 4
Heat sources temperatures.

Heat Source	Location	T in °C	Ref.
Voestalpine Donawitz	Donawitz	140	[45]
Sappi Gratkorn	Gratkorn	130	[46]
Zellstoff Pöls	Pöls	130	[46]
Mayr-Melnhof Holz Leoben	Leoben	105	[42]
Norske Skog	Bruck	130	[46]
Mayr-Melnhof Karton	Frohnleiten	110	[47]
Böhler Edelstahl	Kapfenerg	95	[48]
Energy and Waste Recycling (ENAGES)	Niklasdorf	130	[46]
Rio Tinto Minerals Naintsch	Weißkirchen	130	[46]
Other IWH Sources	–	130	–
Biomass	–	130	[49]
Gas CHP	–	130	[50]

sources are listed in Table 4, and temperatures for other IWH sources are based on major producers' temperatures in the table.

In the use-case with the highest heat demand, IWH, gas CHP, waste incineration, geothermal energy, biomass, and biomass CHP are utilized. Excluding solar thermal energy in this case is due to the absence of sunlight during the peak heat demand. Additionally, the issue of Mellach, outlined in Chapter 3.1, is considered.

In the other use-case (lowest heat demand), the following heat sources are employed:

- Voest Alpine Donawitz with about 54 MW.
- Zellstoff Pöls with 20 MW.
- Sappi Gratkorn with 20 MW.

The rationale for selecting these heat generation units is twofold. Firstly, they utilize waste heat sources, meaning that they generate heat even when they are not in active use. Therefore, using a different type of heat generation would be inefficient. Secondly, this selection includes the largest IWH plants in the region under consideration.

3.3.2. Scenario 2

To address the question of whether the HH can be dimensioned for further expansion while remaining operational in 2022, without heat and temperature losses rendering operation impractical, S2 is introduced. As depicted in Fig. 3 the generation mix in S2 also incorporates the potential for IWH, both for high and middle temperatures. In this case, the temperature for high temperature IWH is estimated at 130 °C, and the temperature for middle temperature IWH is assumed to be 110 °C, considering that this temperature can be increased by a heat pump or a similar method.

The concrete HH's configuration of S2 is depicted in Fig. 6. It spans 272 km (in Scenario 2) and fulfils an energy requirement of 2388 GWh, incorporating heat distribution losses. Fig. 6a illustrates the entire technical potential of IWH in Styria, encompassing both the already installed IWH and the additional potential. In b, the existing networks are depicted, showcasing their primary heat sources, each represented by distinct colours. Fig. 6c illustrates the HH's routing, connecting potential new IWH sources with existing DHNs and heat plants.

3.3.3. Comparison of both scenarios

The diameter calculation results in same diameters sizes for both scenarios as the heat demand remains constant and the heat from the additional sources is widely distributed. However, additional pipes are needed in S2 to connect new IWH sources to the HH, leading to an approximately 19 km increase in its total length, as shown in Table 5.

In both scenarios a hydraulic separation needs to be implemented at three points to withstand the hydrostatic pressure resulting from differences in height. Circulation pumps are also required to maintain the pressure within specified limits. Initial calculations indicate that the HH, requires 8 circulation pumps. Only 1 out of the 8 pumps need to be utilized in the lowest demand case. The difference from S2022S to S2 is noteworthy in terms of the demand for circulation pumps. The increased number of heat sources, particularly in the northern section of the HH, contributes to a higher pipe load factor, resulting in increased pressure loss and a greater requirement for circulation pumps.

4. Results: Evaluating the previously defined KPIs

The subsequent chapter provides a detailed exposition of the results obtained from the case study and offers an in-depth evaluation of the findings.

4.1. Temperature

To evaluate the temperature in the HH for both scenarios, specific regionally defined limit values are established as follows:

- The temperature at the heat substations connected to the local DHNs must be, during cold season (from October 1st to April 30th) at each time step a minimum of 100 °C (this criterion is assumed for the high demand case), and for the rest of the time, at least 75 °C (this criterion is assumed for the low demand case).
- A special condition is established for the substations connecting the HH with Graz. There, during cold season, the temperature must be a minimum of 120 °C, and for the rest of the time, at least 75 °C.

The heat and temperature losses are calculated for two cases (described in Fig. 3): one with the highest heat demand and another with the lowest. Based on the solution from the LFC, the described limit values can be achieved for both the lowest and highest demand case for S2022S and S2. The results from S2022S for the lowest heat demand case are depicted in Fig. 7.

The lowest output temperature in the lowest heat demand case in S2022S occurs at the south end, while in the highest heat demand case, it happens at Diemlach due to a low input temperature from Böhler Edelstahl. As shown in Table 6 the losses are similar in both use cases. This is primarily because the losses depend mainly on the input temperature of the transport medium and the ambient temperature, and both characteristics remain nearly constant in both use cases.

The increase in losses in the highest demand case (depicted in Table 6) from S2022S to S2 is mainly due to varying input temperatures compared to S2022S. The situation remains unchanged in the lower heat demand case since there are no alterations in diameters or heat providers.

4.2. Linear heat density

As mentioned in Chapter 2.4 the linear heat density is a main criterion for a SRDHN. The first calculation approach of the linear heat density, results in a value of 1.7 MWh/(m*a). The second, treating distribution networks as single consumers, yields a value of 6.0 MWh/(m*a) based on a length of 272 km. Both calculation approaches meet the recommended linear heat density of 1.5 MWh/(m*a). The substantial difference between these two results obviously indicates that most heat losses occur not within the HH, but rather within the underlying DHNs.

4.3. Carbon footprint

The heat losses for the HH in S2 accounts for approximately 121 GWh per year, what equals about 6.9% of the total amount of heat distributed via the HH, aligning with estimated losses for a linear heat density of 6.0 MWh/(m*a). Notably, the losses from the HH should not be directly added to total existing heat consumption, as it substitutes some existing transmission lines. This results in a total annual heat demand for the entire HHR, accounting for all losses, of 2384 GWh for S2022S and 2388 GWh for S2. Fig. 8 compares the 2022 state without

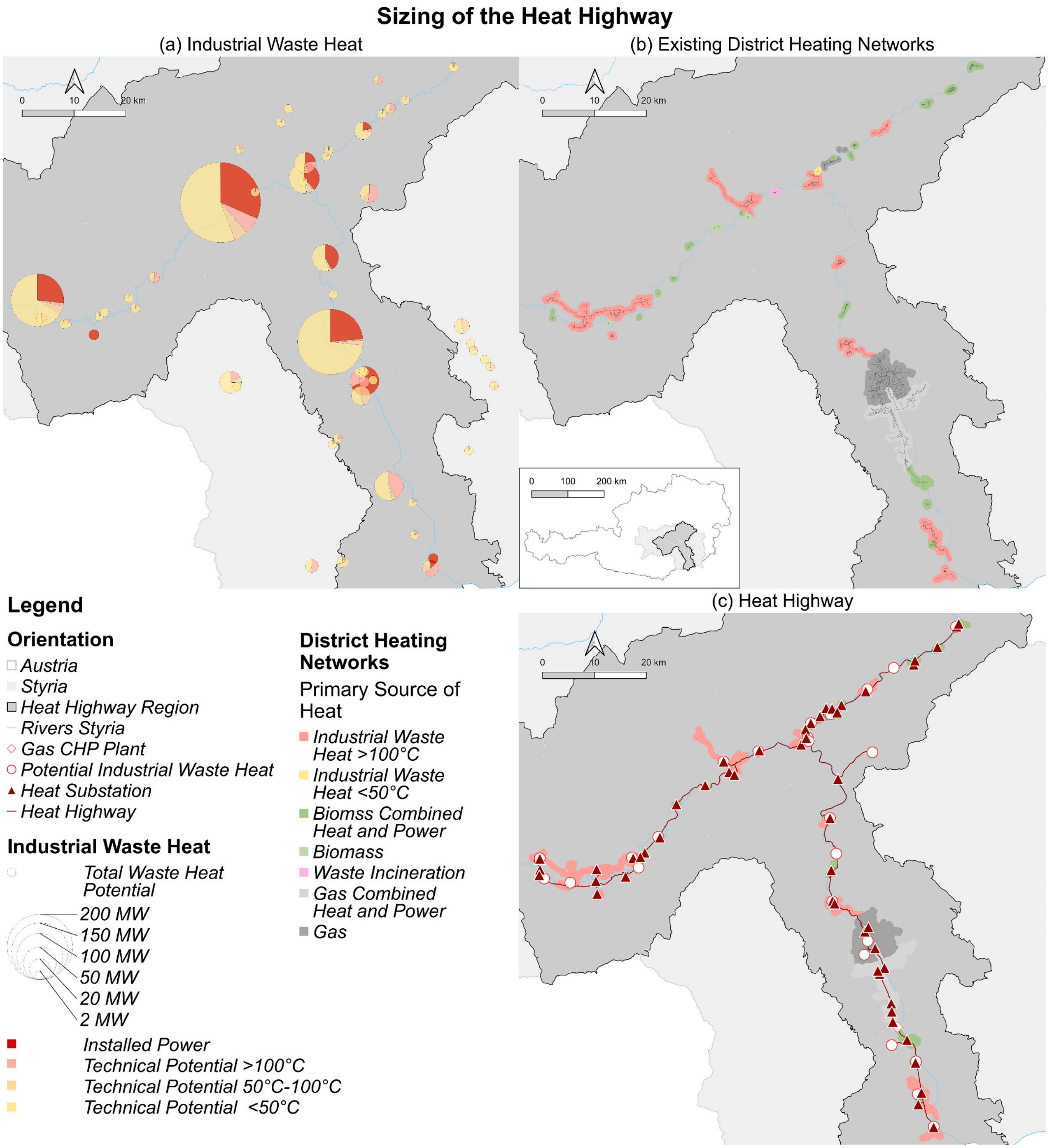

Fig. 6. Sizing of the HH [38

Table 5
HH: Comparison of the diameters.

Diameter Nominal in mm	S2022S	S2
	Pipes length in km	*Pipes length in km*
DN32	<1	1
DN40	1	1
DN50	2	3
DN65	3	4
DN80	2	2
DN100	1	2
DN125	2	3
DN150	2	2
DN200	41	51
DN250	30	34
DN300	24	24
DN350	45	45
DN500	13	13
DN550	9	9
DN600	16	16
DN650	45	45
DN700	4	4
DN750	13	13
Total length	**253**	**272**

the HH to both S2022S and S2. Utilization sequences in both scenarios align with Table 1, featuring Voest Alpine Donawitz (40 MW), Sappi Gratkorn (20 MW), and Zellstoff Pöls (20 MW) as base load providers. Integrating the HH (S2022S) reduces CO_2 emissions to about 13% of the original value. In S2, minimal CO_2 emissions are observed, with only 5.8 GWh of heat generated from the Mellach CHP plant to meet peak loads during the cold season. In the future, this gas quantity could come from renewable gas due to its small amount. The assumed CO_2 footprint of IWH is 0 kg/kWh. This situation would facilitates a substantial reduction in the reliance on heat supply from fossil resources in the district heating sector in Styria, decreasing it from approximately 45% [43] to 14%.

The adjusted energy quantities impact full load hours (FLH) of installed heat generators, as shown in Table 7. Low FLH for biomass in the 2022 State stem from their backup role rather than being the primary heat source in some networks. Notably, the integration of the HH leads to a significant increase in FLH for IWH, biomass, and waste incineration. This is attributed to the predetermined HPUS and the mitigated impact of local overcapacities across regions due to the connection of the HH. The sharp decrease in biomass CHP FLH is due to their shift from a primary role in wood drying, with high FLH, to focusing on providing space heat attributable to the HPUS. The other disparities in FLH stem from the altered generation structures in the overarching context of the HH, as opposed to the local generation structures.

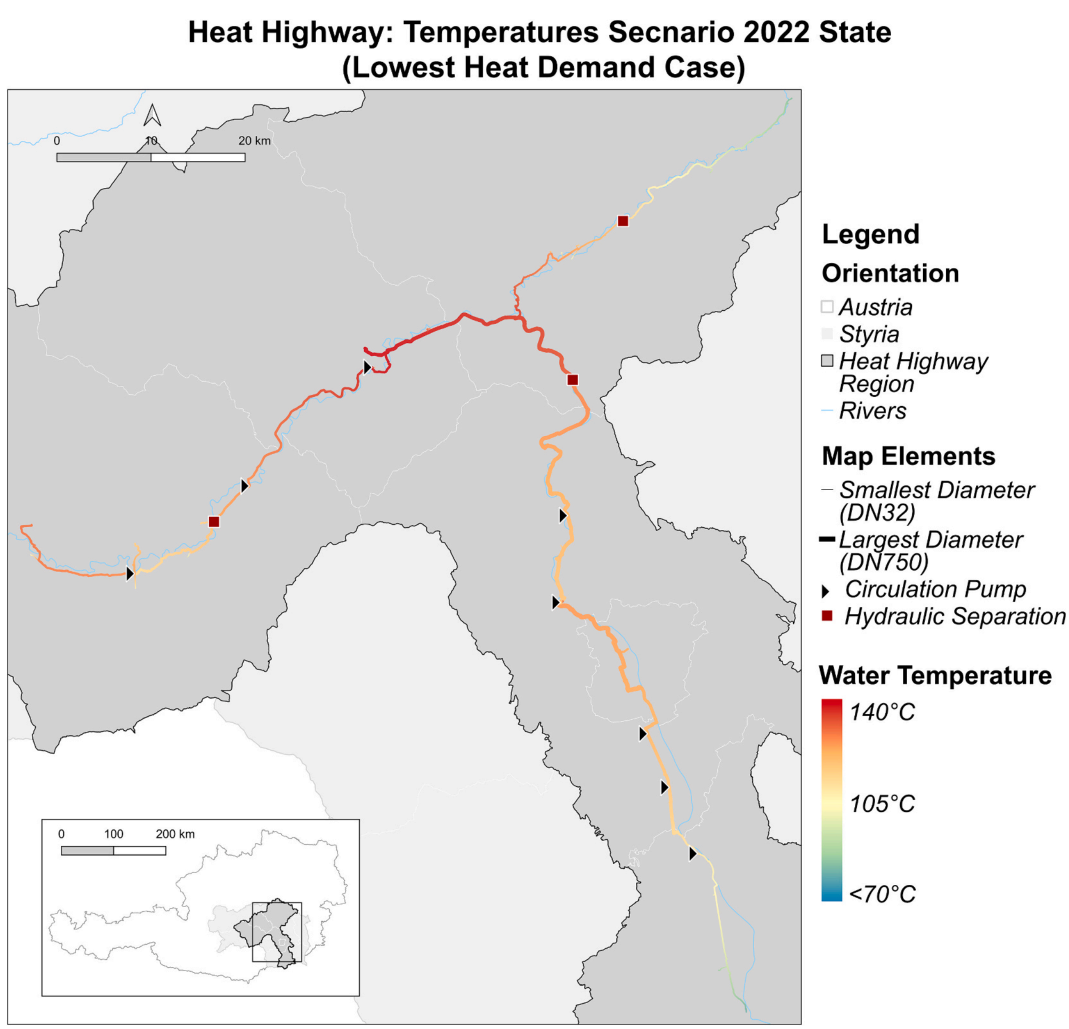

Fig. 7. HH: Temperatures and circulation pumps.

Table 6
HH: Findings.

	S2022S				S2			
	Lowest Heat Demand		Highest Heat Demand		Lowest Heat Demand		Highest Heat Demand	
	T min. in °C	*Losses in MW*	*T min. in °C*	*Losses in MW*	*T min. in °C*	*Losses in MW*	*T min. in °C*	*Losses in MW*
Graz	123	-	124	-	123	-	122	-
HH	81	13.5	104	14.1	81	13.5	113	15.0

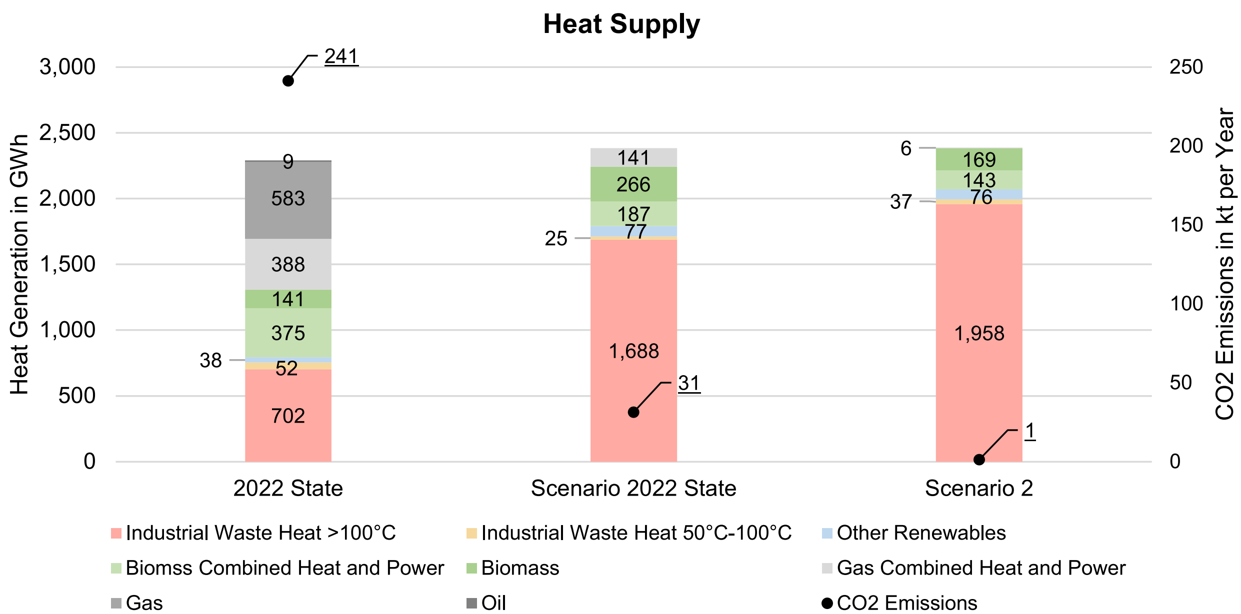

Fig. 8. Comparison heat supply and CO_2 emissions: 2022 state vs. HH scenarios.

Table 7
Comparison: Full load hours and heat generation.

Heat Generation Plant	**2022 State**		**S2022S**		**S2**	
	FLH in h	**Heat in GWh**	**FLH in h**	**Heat in GWh**	**FLH in h**	**Heat in GWh**
Biomass CHP	7463	375	3726	187	2843	143
Geothermal Energy	5312	5	2089	2	202	0
IWH 50 °C – 100 °C	4544	52	2172	25	535	37
IWH > 100 °C	2719	702	6537	1688	5881	1958
Biomass	1519	141	2867	266	1824	169
Solar Thermal Energy	1387	28	1620	33	1621	33
Waste Incineration	1162	6	8605	43	8627	43
Gas	1001	583	0	0	0	0
Gas CHP	874	388	318	141	13	6
Oil	707	9	0	0	0	0

4.4. *Primary energy demand*

To evaluate the HH using the fourth main criterion, Fig. 9 displays both the overall energy demand of the DHNs and the corresponding primary energy savings (through using IWH) for the 2022 state, the S2022S, and the S2. The difference between these values leads to the final primary energy need of the HH, illustrated as a dot in the figure. A significant improvement in the need of primary energy is evident, with a 48% enhancement in the S2022S and 63% in the S2 based on the year 2022. In this context, the additional losses and the electricity needed for pumping due to the extended pipe network are noticeably smaller compared to the saved energy from utilizing IWH.

The evaluation of the case study suggests that a SRDHN is feasible in Styria, as all KPIs exhibit positive outcomes (see also Table 8): adequate temperature levels, high linear heat density, potential for zero CO_2 emissions, and reduction in primary energy demand.

5. Discussion

This paper introduces a novel method and the requisite key performance indicators for analysing the potential implementation of a SRDHN in any location worldwide. The case study offers insights into the application of this method and the evaluation of implementing such a structure. The method relies on certain assumptions, as specific information required to assess regions for a SRDHN is often unavailable or not publicly accessible. Consequently, the results may not align perfectly with an actual implementation. Nonetheless, the method can effectively determine whether further investigations into implementing a SRDHN in a particular region are warranted and it also provides a basic design of a SRDHN.

The steady-state LFC of the HH, along with literature, indicates that transporting heat over several kilometres is feasible without significantly compromising heat quality (temperature). Furthermore, the

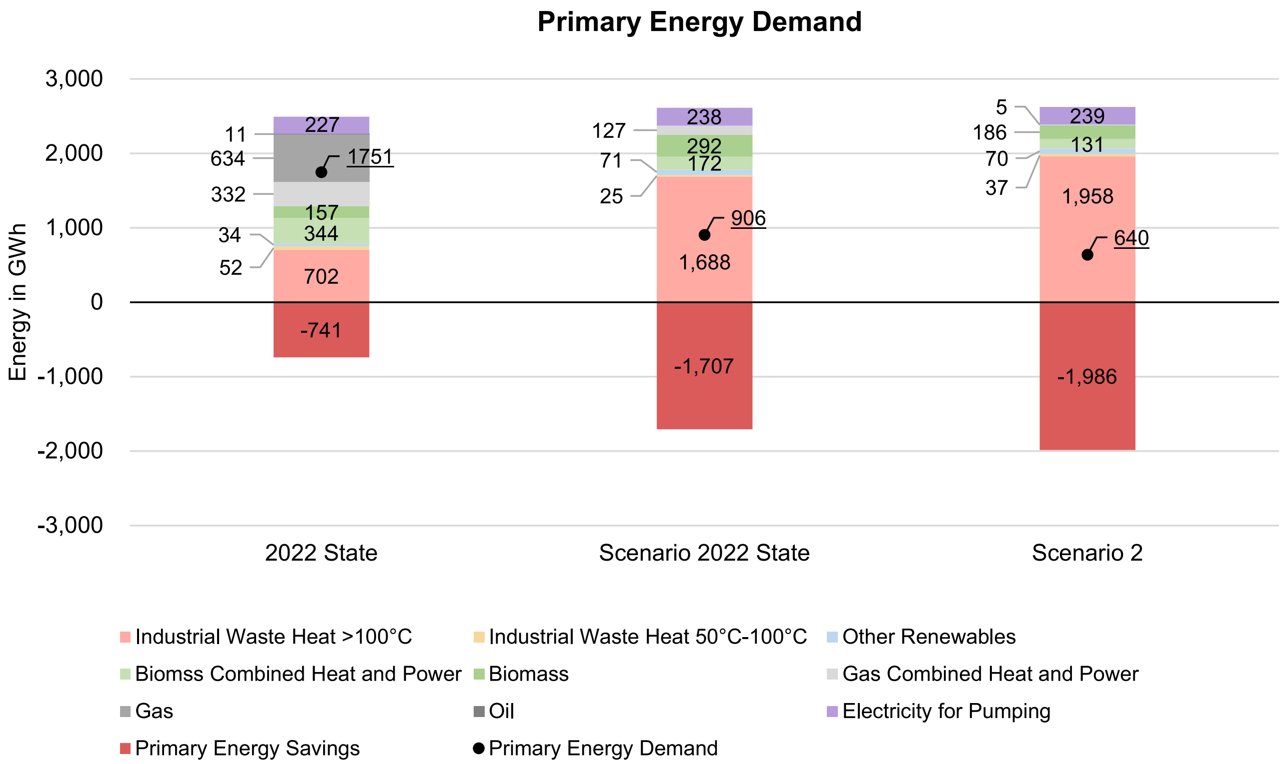

Fig. 9. Comparison: Primary energy demand.

Table 8
HH: Evaluation of the results.

KPI	Requirement	Value	Target Achievement
Temperature	Must reach a certain value at the heat substations	All temperatures are higher than the lower limit	Archived
Linear Heat Density	Must be higher than 1.5 MWh/(m*a)	1.7 MWh/(m*a) & 6.0 MWh/(m*a)	Archived
Carbon Footprint	The integration must reduce the original value	0 ktCO2/a possible	Archived
Primary Energy Demand	The integration must reduce the original value	Reduction of at least 43%	Archived

analysis leads to the conclusion that the transportation losses in the HH, designed to link district heating systems with conventional consumer structures are low. The larger losses occur in the underlaying distribution DHNs and amount to approximately twice as much as those of the HH. Consequently, the losses of a transmission line of a SRDHN do not pose a hindrance to a successful integration of SRDHNs.

However, it is important to acknowledge that initial simulations employing dynamic calculations with a time resolution of 15 min, as opposed to the steady-state LFC used for calculating the SRDHN, highlight the intricacies involved in the daily operation of an SRDHN and emphasize the constraints of steady-state LFCs. An example of this limitation can be described by the changes in the flow directions of the heat flow in the pipes during different time steps, which result in a portion of the hot water (referred to as “temperature batches” in [9]) taking longer to reach the different heat substations. The changes in flow direction are due to variations in consumption and generation ratios during different time steps. As a result, these batches can behave within the pipes like a game of ping-pong, where the batch represents the ball, the pipe is the playing field, and the heat substations are the players. This dynamic results in a significant temperature drop in the sections under consideration. To minimize these effects, a simple HPUS or a heat merit order is insufficient. A complex operating strategy is necessary to enhance the operational management of the HH and mitigate unnecessary temperature and heat losses during actual operation. This method would also enable more accurate calculations of heat losses.

According to the selected sequence of use and the interconnection of individual networks with the HH, the primary advantages are evident for heat generators from the IWH sector, biomass, waste incineration, and solar thermal energy. This is particularly apparent in the increase in FLH, exceeding 100% for IWH and nearly 100% for biomass in the S2022S scenario. This significant increase in FLH results in lower specific CAPEX for the respective plants, thereby making investment in sustainable heat generation much more attractive.

In general, a SRDHN enhances security of supply, paralleling the positive outcomes observed during the industrialization with the implementation of high-voltage transmission networks in the electricity sector. Additionally, it fosters the integration of multiple stakeholders and presents an improved opportunity for leveraging regional resources.

6. Conclusion

This paper offers a novel methodology to systematically approaching the design and evaluation of SRDHNs, providing for a first time a comprehensive guide in this regard. This enables an initial assessment of the feasibility of SRDHN implementation. The paper delineates specific criteria and KPIs necessary to guarantee a technically feasible SRDHN structure. However, it is imperative to note that the method serves as a preliminary design tool and not a final blueprint. Nevertheless, it facilitates the determination of whether further investigations for specific case studies are warranted. Given the absence of existing SRDHNs, there is uncertainty regarding their practicality. The provided case study offers a preliminary indication that a SRDHN could be technically feasible in theory. Despite several simplifications made, the solutions presented are sufficiently precise and clearly demonstrate the potential feasibility of a SRDHN.

However, to gain a deeper understanding of SRDHNs, further analysis is necessary. One area for future research involves introducing operational strategies and conducting calculations over an extended period using dynamic LFC or similar approaches. Other factors, such as the economic viability of such a structure, should also be investigated. Additionally, the way in which heat is priced in the SRDHN should be examined more closely. Moreover, additional investigations in the Styria case study should encompass the examination and analysis of smaller SRDHNs in this region.

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CRediT authorship contribution statement

Josef Steinegger: Writing – original draft, Visualization, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Andreas Hammer:** Data curation. **Stefan Wallner:** Methodology. **Thomas Kienberger:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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

The data that has been used is confidential.

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