Determination of the heat density of centralized heat networks in Austria 2050 under the 1.5°C climate target

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Abstract

Achieving the 1.5 °C climate target requires, among others, a sustainable transformation of the heat supply. We downscale different European decarbonization scenarios of the heating sector to the Austrian grid level, using tailor-made downscaling techniques accounting for infrastructure requirements of renewable heat sources and topology of centralized heat networks. We demonstrate that district heating networks are crucial in the highly efficient decarbonized heat supply in Austria in 2050 and identify eight different representative district heating networks, supplying heat demand between 0.6 and 12 TWh. Nevertheless, seven of these networks do not reach the heat density required for economic and technical efficiency from today's techno-economic perspective. We conclude that the decarbonization leads to centralized heat networks with lower heat densities.

Keywords: Centralized heat networks, heat density, district heating, 1.5°C climate target, downscaling, 2050

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1. Introduction

The Paris Climate Agreement sets the global framework for mitigating climate change [1]. It stipulates that the increase in the global average temperature should be kept well below 2 °C compared to 1990. In addition, further measures are developed, aiming at a maximum increase of 1.5 °C. However, it is also about humanity adapting to the negative effects of climate change that are already being felt. The IPCC Special Report on 1.5 °C (SR1.5) summarizes the state of scientific knowledge globally on the consequences of global warming [2].

1.1. Long-term global sustainable transformation plans of energy systems

To implement the Paris Climate Agreement and the SR1.5, the European Commission has set deep decarbonization targets together with national governments. In particular, the "EU Green Deal" describes the concrete goals in Europe, namely a climate-neutral and resource-conserving economy and society (see, e.g., in [3]). The overarching goal is emissions neutrality 2050. To achieve this long-term ambition, the European Commission recently presented "Fit for 55", a concrete roadmap to 2030. This program commits to a 55 % reduction in CO_2 emissions in 2030 compared to 1990 [4]. The concrete measures affect almost all sectors of the energy system and should lead to a significant efficiency improvement and a massive overall reduction in fossil fuels. It implies, among others, binding annual targets for reducing energy consumption and an extension of the already established EU emissions trading system (EU ETS) to new sectors. In addition to transportation, the building sector will also be part of the EU ETS in the future. A separate new emissions trading system for fuel supply in these sectors will be introduced. In the buildings sector, through the annual anchored emissions reduction, this means a defined roadmap to complete decarbonization of heating and cooling demand, as the two reasons for emissions in this sector. In this paper, we look at what deep decarbonization of building heating demand may look like in 2050 in Austria and the implications of the corresponding sustainable energy mix for centralized heating networks.

The scope of changes required by 2030/2050 in the heating sector become even clearer at the national level. In Europe, the average share of renewable energies in the heating and cooling sector 2018 is only just above 20 % on average for all EU member states [5]. It is in fact higher in some countries, for example in Austria, where it is above 34 %. However, fossil fuels continue to dominate there as well. To be even more specific for the heating sector: of the nearly 4,000,000 residential dwellings in Austria, more than 900,000 are heated with natural gas, and more than 500,000 with oil [6]. If these heating systems are converted to renewable energy supply by 2050, this corresponds to a retrofitting of 50,000 units per year, or more than 130 per day - only in Austria. To achieve this goal makes measures necessary that go beyond the electrification of heat and leads to an expansion of district heating networks [7].

Centralized heating networks are particularly advantageous for supplying densely populated or urban areas resulting from high heat densities there [8]. In addition to heat density, the connection rate is a key factor determining the efficiency of district heating/cooling networks and thus their implementation. For example, currently in Austria, at a connection rate of 90 %, 10 GWh/km^2 is used as a benchmark for supplying an area with district heating[1]. The reference value of 10 GWh/km^2 is in line with findings regarding district heating networks also from the Scandinavian region (Denmark, Sweden, and Finland) [9]. These are rough estimates, but they do allow an initial assessment of the economic viability or feasibility of a district heating network. In a detailed consideration and evaluation of district heating networks numerous factors play a decisive role. Nussbaumer and Thalmann [10] thoroughly elaborate on the network design and its impact on the profitability of centralized heat networks. Laasasenaho et al. [11] emphasize in their study the optimal location of heat generation units/sources within centralized heat networks enabling a cost-optimized heat

[1] `http://www.austrian-heatmap.gv.at/ergebnisse/`

supply. Gopalakrishnan and Kosanovic [12] focus in their study on the optimal heat generation technology dispatch. When examining the economic viability of district heating networks, building renovation measures must also be taken into account (see, e.g., in [13] and [14]). Hietaharju et al. [15] recently show in their analysis that a $2-3\%$ building renovation rate per year results in a decrease of $19-28\%$ of the long-term district heating demand. This reduces also the heat density. However, studies show that a reduction in heat density is not necessarily a barrier to district heating networks [16]. Reidhav and Werner [17] show in their study how energy taxes can improve the profitability of sparse district heating networks in Sweden. Following these considerations and in light of ambitious CO_2 reduction targets, it can also be assumed that the rising CO_2 price can have a similar effect as the energy tax. Of course, this is only valid in case of deep decarbonization of the generation mix feeding into centralized heat networks. Di Lucia and Ericsson [18] show that biomass significantly contributed to the decarbonization of the district heating network and replaced fossil fuels in the feed-in generation mix in Sweden. Ghafghazi et al. [19] also identify in their mutli-criteria study wood pellets as the optimal system options for fueling district heating networks. Eventually, also the increasing cooling demand and the co-design of centralized networks for heating and cooling can increase the economic viability of these and counteract the reduction of heat density from an economic point of view [20].

1.3. Lack in the implementation of decarbonization in different sectors

However, the concrete implementation to achieve predefined climate change mitigation goals still is lacking in many cases. For this reason, numerous studies go beyond and show roadmaps for the rapid decarbonization. For example, Rockström et al. [21] conduct such a study and propose pathways for halving gross anthropogenic CO_2 emissions every decade. Other works go into more depth regarding optimal solutions for the decarbonization of individual energy services. There are relevant differences between the individual sectors of the energy system related to decarbonization. How a sustainable energy service can be provided in the different sectors must therefore be examined in detail. This perspective is supported by a large number of detailed decarbonization studies covering specific energy service needs (e.g., for the building sector Leibowicz et al. [22], transport sector Pan et al. [23], and industries Habert et al. [24]).

Despite all the details associated with the sector-specific decarbonization strategies, the principles of a net-zero society base on three key points: (i) reduction of the energy demand (see, e.g., Oshiro et al. [25] and Grubler et al. [26]), (ii) deployment and generation of renewable energy technologies (see, e.g., Bakhtavar et al. [27] focusing on net-zero districts by deployment of renewable energy generation), and (iii) increase in efficiency regarding the provision of energy services and the associated optimal utilization of sustainable energy sources. The third point (iii) includes, among others, two main aspects, namely: on the one hand, that potentials of renewable resources are exploited locally and, on the other hand, that energy carriers with various fields of application are utilized with the highest possible efficiency. We like to refer to just a few selected references without claiming to be exhaustive and focus here on hydrogen as one example of an energy carrier with high potentials in sustainable energy systems and a significant bandwidth of efficiency in terms of its generation, storage and use. Van Ruijven et al. [28] highlight that the introduction of hydrogen in global energy systems only leads to lower emissions with high end-use efficiency and low-carbon production. Van Ressen [29] systematically investigates the possibilities and challenges of hydrogen and discusses extensively its role in the energy transition. Recently, Böhm et al. [30] comprehensively elaborate on hydrogen-related synergies and its role in sustainable heat supply.

1.4. Implications of large-scale numerical model results on the local level

In many cases when it comes to the question of optimal solutions, researcher use numerical models. In general, these models strike a balance between complexity and aggregation. Integrated assessment models (IAMs) are large numerical models covering complex interrelations between climate, society, economics, policy, and technology. Dowlatabadi [31] provided 1995 a fundamental review on IAMs focusing on their role in the context of climate change. Krey et al. [32] discuss and systematically compare different IAMs. Harmsen et al. [33] elaborates on the modeling behaviour of IAMs. Wilkerson et al. [34] and van Vuuren et al. [35] deal with IAMs and their role in understanding global energy decarbonization pathways. In particular, both studies examine CO_2 budget and price developments. Schwanitz [36] evaluates IAMs of global climate change and discusses, among others, the appropriate level of regional (spatial) aggregation of countries in the modeling analysis. Generalizing this aspect reveals an aspect already known but essential in the context of large numerical models. It becomes necessary for modelers to set priorities regarding the level of detail, which inevitably creates trade-offs in the analysis regarding the granularity of the temporal, spatial, and other dimensions [37]. Gambhir et al. [38] also highlight this aspect of aggregation bias in their critical review of IAMs. They propose, among others, that IAMs should be increasingly be supplemented with other models and analytical approaches. Not least for this reason, (large) energy models also play a significant role in the analysis of energy systems in the context of climate change. Compared to IAMs, they more strongly emphasize the level of detail in terms of techno-economic characteristics (see the review of modeling tools of energy systems in [39]). However, the lack of granularity remains, that these (global) energy models consider only a highly aggregated spatial resolution. To name just two selected approaches, Capros et al. [40] (PRIMES) and Löffler et al. [41] (GENeSYS-MOD) provide energy system models focusing on the European energy system with a spatial resolution on the country level. Further approaches are needed to disaggregate results obtained at the country level to finer scales, such as districts, neighborhoods, and other local levels. In this context, Backe et al. [42] provided a novel approach in the context of merging local activities/behavior in sustainable local communities into a large energy system model (bottom-up linkage). In their study, they integrated local flexibility options into the global energy system model EMPIRE, which provides in principle only country-level resolution. This and other work confirms the emerging trend of making top-down and bottom-up linkages between different spatial-temporal levels of resolution to drive decarbonization across all sectors.

1.5. Objective and contribution of this work

Against this background, the core objective of this work is downscaling European decarbonization scenarios of the heating sector to the community/distribution grid level serving end-users in 2050. In particular, downscaling considers the highly efficient and local use of sustainable heat sources in centralized heat networks (e.g., co-firing hydrogen in cogeneration plants and large-scale waste utilization, etc.). In addition, the topography of district heating networks is of particular importance and plays a crucial role in applied downscaling. This allows estimates of realistic decarbonized district heating networks in 2050 to be obtained, which can be compared with existing networks. Thereby, the heat density of district heating networks serves as a comparative indicator and permits a rough estimation of the changes needed of centralized heating networks considering the 1.5°C climate target. An Austrian case study is conducted, downscaling the results of the heating sector in 2050 from the large numerical energy system model GENeSYS-MOD, from the country to community/distribution grid level.

The method applied consists of three different scenario-independent downscaling techniques. As the first, proportional downscaling using population as proxy is used as reference (Section 2.1). As the second, an sequential downscaling approach is presented, dissaggregating from the country level to the sub-region level. Thereby, population density and the infrastructure requirements of heat technologies serve as additional criterion in the downscaling (Section 2.2). And finally, an iterative downscaling algorithm is presented. The algorithm is based on graph-theory benchmarking and projects centralized heat supply on the local (community) level (Section 2.3). Section 3 presents and discusses the results of this work. Section 3.1 and 3.2 show heat generation by source on different spatial levels. Section 3.3 and 3.4 present centralized heat networks on a high spatial granularity. Section 3.5 synthesizes the results of centralized heat networks and compares heat densities of centralized heat networks in 2050 with today's values. Section 4 concludes this work and provides an outlook for future work.

2. Materials and methods

This section explains the methodology developed in this work. First, Section 2.1 describes the proportional spatial downscaling using population as a proxy. This downscaling technique is a well-established approach for disaggregation and is often used in scientific and practical studies. Building upon, Section 2.2 presents the sequential downscaling and Section 2.3 the iterative downscaling algorithm in detail. Finally, Section 2.4 concludes this section and explains the open-source tools used in this work.

2.1. Proportional spatial downscaling using population as a proxy

Proportional downscaling is a well-established technique and is commonly used. Equation 1 shows the primary expression of proportional downscaling, exemplarily, for the disaggregation of the energy demand d from the country to the local level, using population p as a proxy.

$$d_{local} = \frac{p_{local}}{p_{country}} \cdot d_{country} \tag{1}$$

The fields of application are not limited to the modeling of energy systems. Moreover, it is applied in different fields of scientific and practical studies. The reason for this is the intuitive application and that it offers possibilities for tailor-made adaptions, in particular, related to the downscaling driver and proxy [43]. In this context, van Vuuren et al. [43] provide a comprehensive analysis of different proxies for the downscaling of global environmental change, including, among others, gross domestic product (GDP) and emissions as a proxy. However, in the context of downscaling aggregated values of energy systems, one often finds proportional downscaling using population as a proxy (see, e.g., Ahn et al. [44], van Vuuren et al. [45], and Alam et al. [46]). For further information, we refer the reader here to the study in [45], providing a systematic classification of downscaling techniques going far beyond the simple proportional downscaling method discussed so far. The reader can find population-based downscaling in their categorization under algorithmic and proportional downscaling. In addition, they showed that novel downscaling methods have emerged in recent years as the scientific community has increasingly recognized the necessity for spatially and temporally disaggregation.

2.2. Sequential downscaling (from the country to the sub-region level)

The sequential downscaling algorithm (Algorithm 1) is developed to downscale the heat generation by source from the country to the sub-region level. Before explaining the algorithm in detail, Table 1 provides an overview of the spatial nomenclature of this work using the European nomenclature of territorial units for statistics[2] (NUTS) and gives some examples of Austria. In particular, the different spatial levels of the applied downscaling are marked in gray. According to the NUTS nomenclature, Algorithm 1 downscales from NUTS0 to the NUTS3 level.

The purpose of the sequential downscaling algorithm is to provide a downscaling technique that considers the variation in efficiency of renewable heat sources and the increasingly role of biomass and waste heat sources, in particular, in densely populated areas. Hence, we claim that

- the limited amounts of hydrogen (and or "green" gas) should preferably be used in district heating networks if it is used for heat supply (similar to Gerhardt et al. [47] and Zwickl-Bernhard and Auer [48]).
- high shares of biomass in the heating sector result in a high utilization rate of waste sources in waste incineration plants [49]. These waste incineration plants feed into district heating and are therefore dependent on the infrastructure of centralized heating networks (see, exemplarily, Sahlin et al. [50]).

Besides, we claim that high shares of air-source heat pumps (or geothermal sources) in the heat supply can only be realized if it is used as a co-firing heat

[2] `https://ec.europa.eu/eurostat/web/nuts/background`.

NUTS level	Description	Number	Example (population)
NUTS0	Country level	1	AT Austria (8.86 millions)
NUTS1	Major socio-economic regions	3	AT3 Western Austria (2.78 millions)
NUTS2	Basic regions for the application of regional policies (federal states)	9	AT31 Upper Austria (1.48 millions)
NUTS3	(Small) sub-regions for specific diagnoses (political/court districts)	35	AT312 Linz-Wels (529 thousands)
LAU (former NUTS4/5)	Subdivision of the NUTS 3 regions (communities)	2095	Enns AT312 Linz-Wels (11 thousands)

Table 1: Spatial nomenclature of different spatial levels using the NUTS nomenclature. Besides the number of regions per NUTS level, examples for the Austrian case study (incl. population) are given. The gray-colored rows mark the spatial levels used for downscaling in this work.

source in district heating networks. We therefore consider two main aspects, namely that geothermal sources will contribute significantly to decarbonizing the feed-in energy mix of existing district heating grids in the future (see, exemplarily in [51]), and that provision of high shares of geothermal-based heat supply requires the distribution through district heating infrastructure [52]. Besides, it is highly uncertain if small-scale geothermal units on the end-user's level are be economically viable in the future resulting due to expected high investment costs.

In order to incorporate the above mentioned relevant technology-specific aspects, heat technologies/sources are downscaled according to their necessity of distribution infrastructure. Therefore, population density serves as a criterion, indicating the possibility of centralized heat networks. Table 2 provides a qualitative overview of the different heat generation technologies/sources and their heat network/infrastructure requirements.

Source Heat technology	Requirements Heat network	Rural Sparsely	Town/Mixed Moderate	Urban Dense	Supporting references
Biomass	Middle		x	x	[53, 54, 49]
Direct electric	None	x	x	x	
Synthetic gas	Low	x	x	x	
Hydrogen	High			x	[55, 56, 57]
Heat pump (air)	None	x	x	x	[58]
Heat pump (ground)	High			x	[59, 60, 51]
Heat storage	None	x	x	x	

Table 2: Qualitative overview for heat generation technologies/sources and their requirments for heat network infrastructure. The prioritized preferences (gray cell color) of heat sources in sub-regions is marked by the gray color. In addition, selected references supporting this assumptions are cited.

The sub-regions used for downscaling the corresponding heat source are marked. Note that the different types are characterized by population density. Exemplarily, direct electric heating is a heat generation technology with no significant heat network requirements. It is downscaled to all types of sub-regions. In contrast, hydrogen is a heat source with high requirements and thus prioritized preferences (marked by the gray cell color). The right column refers to selected references whose key findings are in line with this approach/assumptions. Building upon, the sequential downscaling algorithm is presented below (Algorithm 1).

Algorithm 1: Sequential downscaling algorithm (NUTS0 to NUTS3)

t: Heat generation by technology/source ($t \in T$);
r: Sub-region (or NUTS3 region) ($r \in R$);

input : Heat generation by technology/source at NUTS0 level: (q_t);
Population density per region r (ρ_r);
Total population per region r (p_r);
Minimal network infrastructure requirements of t (σ_t);
Available potential of heat network infrastructure at r (π_r);

output: Heat generation by technology/source on NUTS3 level ($\hat{q}_{t,r}$);

Initialization:
Sort elements t in T descending by σ_t;
$q_r^{heat} \longleftarrow \sum_t q_t \cdot \frac{p_r}{\sum_r p_r}$; `// Calculate heat demand at each sub-region`
$\tilde{q}_t \longleftarrow q_t$; `// Available heat generation for each technology/source`
$\pi_r \longleftarrow \rho_r$; `// Population density determines network potential`

begin
  foreach t **do**
    $List = [\,]$; `// Collect valid sub-regions`
    $demand = 0$; `// Reamining demand that needs to be covered`
    $R^{'} = R \setminus \{\forall r \in R : \pi_r \leq \sigma_t\}$; `// Get valid sub-regions by criteria`
    foreach $r^{'} \in R^{'}$ **do**
      if $q_r^{heat} \geq 0$ **then**
        $List = List \cup r^{'}$; `// Add valid sub-regions to collection`
        $demand \mathrel{+}= q_r^{heat}$; `// Total demand of valid sub-regions`
      end
    end
    foreach $l \in List$ **do**
      $\hat{q}_{t,r} = \frac{q_r^{heat}}{demand} \cdot \tilde{q}_t$; `// Population-based downscaling`
      $q_r^{heat} \mathrel{-}= \hat{q}_{t,r}$; `// Reduce heat demand at r`
    end
  end
end

The inputs are as follows: (i) heat generation by technology/source at the NUTS0 level, (ii) population as well as population density on the NUTS3 level, and (iii) empirical assumptions in terms of network infrastructure requirements per heat technology/source and potentials for heat network infrastructure (see Table 2). The algorithm itself consists of three main parts: initialization, pre-calculations, and downscaling. First, the initialization of the algorithm sorts the heat generation technologies/sources in descending order in terms of network infrastructure requirements. Then the calculation starts with the first technology/source (highest requirements) (line 6). For this technology/source, all possible sub-regions are collected (line 9). Those sub-regions already fully supplied (no remaining heat demand) are filtered out (line 11). After further pre-calculation steps, the available amount of heat generation is downscaled to all valid sub-regions using population as a proxy. This procedure is repeated sequentially for each heat technology/source. The output of the sequential downscaling algorithm are heat generation by source and the amount of heat demand covered by centralized heat networks on the NUTS3 level.

2.3. Iterative downscaling (from the sub-region to the community level)

This section explains the methodology of the iterative downscaling algorithm. We propose this downscaling technique projecting heat generation by technology/source from the sub-region (NUTS3) to the community level (LAU) (see Table 1). This in-depth spatial resolution is imperative for realistic network infrastructure planning as stated by Zvoleff et al. [61]. The underlying concept of iterative downscaling bases on graph theory and assessing network topology using benchmark indicators.

Algorithm 2: Iterative downscaling algorithm (NUTS3 to LAU level)

s: Stage of iteration ($s \in \{0, 1, *\}$);
G^s: Centralized heat network graph at stage s;
N^s: List of nodes at stage s: ($n^s \in N^s$);
L^s: List of lines connecting nodes k and j at stage s: ($l^s_{k,j} \in L^s$);
Q^s: Centralized heat generation at stage s: ($q^s_{n^s} \in Q^s$);
$\tilde{Q}^s$: On-site heat generation at stage s: ($\tilde{q}^s_{n^s} \in \tilde{Q}^s$);
Π^s: Benchmark indicator value at stage s ($\pi^s_{n^s} \in \Pi^s$);

input : $G^0 = \{N^0, L^0, Q^0, \tilde{Q^0}\}$;
output: $G^* = \{N^*, L^*, Q^*, \tilde{Q^*}\}$;

Initialization:
$s = 0$, $iter = True$;

begin
  while $iter = True$ **do**
    foreach $n \in N^s$ **do**
      $\Pi^s_{n^s} = f(N^s, L^s, Q^s)$; `// Calculate benchmark indicator value`
    end
    i with $\pi^s_i = min(\Pi^s)$; `// Get node with lowest indicator value`
    $N^{s+1} = N^s \setminus i$; `// Remove node from graph obtaining next stage`
    $\tilde{q} = \sum_{N^{s+1}} \tilde{q}^s_{n^s}$; `// Calculate available on-site heat generation`
    if $\tilde{q} \geq q^s_i$ **then**
      foreach n^{s+1} **do**
        $q^{s+1}_{n^{s+1}} = q^s_{n^s} + \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; `// Increase centralized heat amount`
        $\tilde{q}^{s+1}_{n^{s+1}} = \tilde{q}^s_{n^s} - \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; `// Decrease on-site heat amount`
      end
      $L^{s+1} = L^s \setminus \{\forall l^s_{k,j} : k = i \vee j = i\}$; `// Remove connecting lines`
      $G^{s+1} = \{N^{s+1}, L^{s+1}, Q^{s+1}, \tilde{Q^{s+1}}\}$; `// Create new network graph`
      $G^s = G^{s+1}$; `// Set updated heat network graph as new input`
    else
      $iterate = False$; `// Stop iteration because of no reallocation`
      $G^* = G^s$; `// Set heat network graph as result`
    end
  end
end

2.3.1. Algorithm description

The iterative downscaling algorithm is presented in Algorithm 2. The idea is to assess, benchmark, and improve the topology of centralized heat networks. This is achieved in our proposed approach by iterative downscaling. Essentially, the main steps of the algorithm can be summarized as follows:

1. Downscale the results of the sequential downscaling algorithm from NUT3 to the LAU level using population as downscaling driver for obtaining the initial heat network graph G^0 (input)
2. Benchmark each node of the heat network graph (line 11), identify node with the lowest indicator value and remove the node from the graph generating a reduced heat network graph (lines 13 and 14)
3. Check if the amounts of centralized and on-site heat generation can be reallocated (line 16)
4. If yes, reallocate centralized and on-site heat generation for all nodes (lines 18 and 19), otherwise stop algorithm
5. Update heat network graph and jump to step 2. Otherwise, the algorithm stops and resulting from the termination criterion.

Recent studies support this approach focusing on the topography of energy systems and networks (see for example in [62]). Bordin et al. [63] conduct an approach for the optimized strategic network design of centralized heat systems. In any case, the topography of supply areas plays an important role not only in centralized heat supply. Therefore, another look at approaches in general in the context of energy systems is worthwhile here. We refer to Shekoofa and Karbasian [64] focusing in their study on design criteria for electrical power systems' topology selection. Many further contributions can be found in the literature. However, the underlying concept of these studies can be applied to the heating system and in particular to the topography of centralized heat networks. Allen et al. [65] evaluate the topology of centralized heating systems and conclude that the optimization of the topology is promising to facilitate the adoption of centralized heat networks.

2.3.2. Heat network topology benchmarking using a graph theory based indicator

So far, we have only introduced the function $f(N^s, L^s, Q^s)$ (see line 11 in the iterative algorithm (Algorithm 2)) as calculation procedure of the benchmarking indicator value. Below, we describe and discuss the approach of using a weighted cluster coefficient as function and benchmarking indicator.

The proposed benchmarking indicator value is derived from graph-theory. Detailed information in the context of network analysis using indicators can be found in the fundamental work by Strogatz in [66]. Morever, we refer the reader to the study in [67] where Sanfeliu and Fu elaborate in detail on network topologies and their transformation. In this work, we use a weighted cluster coefficient as benchmark indicator and determining the transformation path of the centralized heat network graph. Equation 2 shows the calculation of the weighted cluster coefficient

$$c_{n^s} = \frac{q_{n^s}}{max\ q^s} \cdot \frac{\alpha_{n^s}}{\beta_{n^s}} \tag{2}$$

where q is the amount of centralized heat supply, α the number of triangles that can be formed with direct neighboring nodes, and β the number of lines connecting to the graph for node n at stage s. In the context of the fundamental concept of *alpha*, we refer again to the literature. In particular, the study in [68] comprehensivley deals with cluster coefficients and provides related generalized concepts. In addition, relevant aspects of the cluster(ing) coefficient are shown in [69]. In the works cited and also in the one presented here, the aim is to achieve a high value of the cluster coefficient for each node considered (i.e., $\frac{\alpha}{\beta} \approx 1$). However, we extend the basic concept of the cluster coefficient from literature and propose a weighting with the relative centrally supplied heat quantity. From an energy economics point-of-view, at least two important aspects are considered in the benchmarking process: (i) a high connection rate to the centralized heat network and (ii) a connection of those areas to the network which have a high heat demand and heat density, respectively. Both aspects are investigated in the literature. For example, Nilsson et al. [70] focus in their study on the importance of the connection rate of centralized heat networks. Besides, Dochev et al. [71] investigate in their study the impact of linearly decreasing heat densities and the influence on the profitability of the centralized heat networks.

2.4. Development of an open-source package building upon pyam

The described method will be released as an open-source python package in the course of publishing this work at the author's GitHub account. In this package, we build upon the existing open-source python package *pyam* [72]. *Pyam* is an open-source package for the analysis and visualization of integrated assessment and macro-energy scenarios [73]. In this work here, it is used in particular for (i) the linkage between the sequential and the iterative downscaling algorithm, (ii) for the internal calculation steps within both downscaling algorithms, and (iii) for the visualization of the results. Besides, we used the open-source python package *networkx* [74], when implementing the iterative downscaling algorithm. We refer to the repository for the codebase, data collection, and further information.

3. Results and discussion

This section presents the results of the Austrian case study. Four different storylines are investigated, covering a wide range of possible future developments of the Austrian energy system in the context of European deep decarbonization. Section 3.1 shows the heat generation mix supplying the heat demand (residential and commercial) on the country level. In Section 3.2, the obtained heat generation mix is described on more granular geographical scale, sub-regional and community level. Potentials of centralized heat network are presented further in Section 3.3. Section 3.4 shows the centralized heat networks on the community level. Finally, Section 3.5 compares the projected centralized heat networks in 2050 with today's networks based on heat density.

3.1. Heat supply of the Austrian residential and commercial sector in 2050: four different decarbonization scenarios obtained from the H2020 project openENTRANCE

This section presents the heat generation mix covering the Austrian residential and commercial heat demand in 2050 for four different storylines, which have been developed within the H2020 openENTRANCE project. They are named as follows: *Directed Transition*, *Societal Commitment*, *Techno-Friendly*, and *Gradual Development*. Within each of them, specific fundamental development of the energy systems is described while aiming for a sustainable transition of the provision of energy services. The first three storylines consider the achievement of the 1.5 °C global warming climate target. The latter storyline (*Gradual Development*) can be interpreted as a more conservative storyline aiming for the less ambitious 2.0 °C climate target. Below, the storylines are briefly described before the quantitative results on the country level are presented. For a more detailed description of the storylines, it is referred to [75] and [76]. Further informations also are available on the website of the project [3] and GitHub[4].

[3] `https://openentrance.eu/`
[4] `https://github.com/openENTRANCE`

The underlying concept of the four storylines is a three-dimensional space spanned by the following parameters: technology, policy, and society. Each storyline describes a specific pathway to reach a decarbonized energy system taking into account a pronounced contribution of two dimensions. Regarding the third dimension, a development is assumed that leads to no significant contribution to the decarbonization of the energy system.

- *Directed Transition* looks at a sustainable provision of energy services through strong policy incentives. This bundle of actions becomes necessary because neither the markets nor society adequately pushes sustainable energy technologies.

- *Societal Commitment* achieves deep decarbonization of the energy system by a strong societal acceptance of the sustainable energy transition. Thereby, decentralized renewable energy technologies together with policy incentives lead to a sustainable supply of energy service needs. Parallel, no fundamental breakthroughs of new clean technologies are within sight.

- *Techno-Friendly* describes a development of the energy system where a significant market-driven breakthrough of renewable energy technologies gives rise to the decarbonization of energy service supply. Alongside, society acceptance supports the penetration of clean energy technologies and the sustainable transition.

- *Gradual Development* differs from the other storylines as on the one hand, this storyline only aims for the less ambitious 2.0 °C climate target, and on the other hand, a little of each possible sustainable development of the energy system is described here. While all three dimensions contribute to decarbonization, they do not push it sufficiently and result in a more conservative storyline than the others.

Table 3 shows the heat generation by technology/source in Austria in 2050 for the four different storylines. These values were obtained in course of the

H2020 project openENTRANCE and are the modeling results calculated using the open-source model GENeSYS-MODv2.0 [77]. According to the underlying assumptions in the storylines, the heat generation of the different sources/technologies vary in some cases significantly (e.g., hydrogen-based heat generation in *Directed Transition* and *Gradual Development* (7.62 TWh) or Heat pump (ground) generation in *Techno-Friendly* and *Societal Commitment* (14.78 TWh)). The gray-colored column Σ presents the total of heat generation using centralized heat networks, which varies between 19.49 (*Techno-Friendly*) and 35.23 TWh (*Gradual Development*).

	Heat generation by source in TWh	Biomass	Direct Electric	Synthetic gas	Heat pump (air)	Heat pump (ground)	Heat storage	Hydrogen	Σ
Storyline	Directed Transition	5.37	2.13	0.36	22.73	19.50	14.84	1.03	25.90
	Societal Commitment	5.37	1.98	1.35	15.71	21.47	10.58	2.18	29.02
	Techno-Friendly	5.37	1.53	2.79	25.95	6.69	16.36	7.43	19.49
	Gradual Development	5.37	1.81	5.35	9.68	21.21	15.57	8.65	35.23

Table 3: Heat generation by source in TWh supplying the residential and commercial heat demand in Austria 2050 for the different scenarios. Values obtained from the H2020 project openENTRANCE and GENeSYS-MOD.

3.2. Heat technology generation in 2050 on different spatial granularities

Figure 1 shows the heat generation per technology/source on different spatial granularities: the country (NUTS0), sub-region (NUTS3) and community (LAU) level (from left to right). The level of spatial details increases from the left to the right. In the middle, the residential and commercial heat supply in a representative rural and urban sub-region, respectively, is presented. The rural sub-region *Mostviertel-Eisenwurzen* (NUTS3 code AT121) shows high shares of heat pumps (air sourced) and small-scale heat storage systems. In addition, synthetic gas and direct electric heating systems supply the heat demand. The urban sub-region *South Viennese environs* (AT127) is mainly supplied by ground-sourced heat pumps, biomass, and hydrogen. Air-sourced heat pumps and again heat storage cover the remaining demand. Throughout the pie charts within the figure, shares of heat generation using centralized heat networks are indicated using blue-colored edges. On the very right, an example of the resulting centralized heat network on the community level for the four different scenarios is presented. Within the four subfigures presenting centralized heat networks (each for one storyline), the size of the points represents the amount of heat demand using centralized supply in a community. The comparably high heat demand in the *Gradual Development* scenario results in an extensive centralized heat network infrastructure (see lower right subfigure in Figure 1). The other three centralized heat networks are characterized by fewer (less supplied small sub-regions) and smaller points (less supplied heat demand by the centralized heat network). Figure 2 compares the heat generation by source between 2020 (today) and 2050 for the four different scenarios. The height of the bars shows the absolute differences by source between both years, whereby a negative difference indicates less heat generation by this source in 2050 of the *Societal Commitment* scenario. This scenario is more prominently presented since this is the scenario with the lowest total heat demand (-18.15 TWh) compared to the others. In addition, the scenario with the lowest and highest difference respectively is marked for each heat source and the total demand. For instance, the highest decrease is seen in natural gas in the *Directed Transition* scenario (-53.76 TWh).

3.3. Sub-regions in Austria 2050 with high potentials for centralized heat supply

The potentials of centralized heat supply in Austria in 2050 are limited to densely populated areas (urban areas). In particular, the results indicate eight different sub-regions (NUTS3 regions) that are supplied by centralized heat networks (see Figure 3). Although the exact numerical numbers differ, the eight sub-regions in each scenario are (partially) supplied by centralized heat networks. Table 4 shows the centralized and on-site (decentralized) heat supply in the sub-regions. Thereby, the connection rate is assessed by the share of cen-

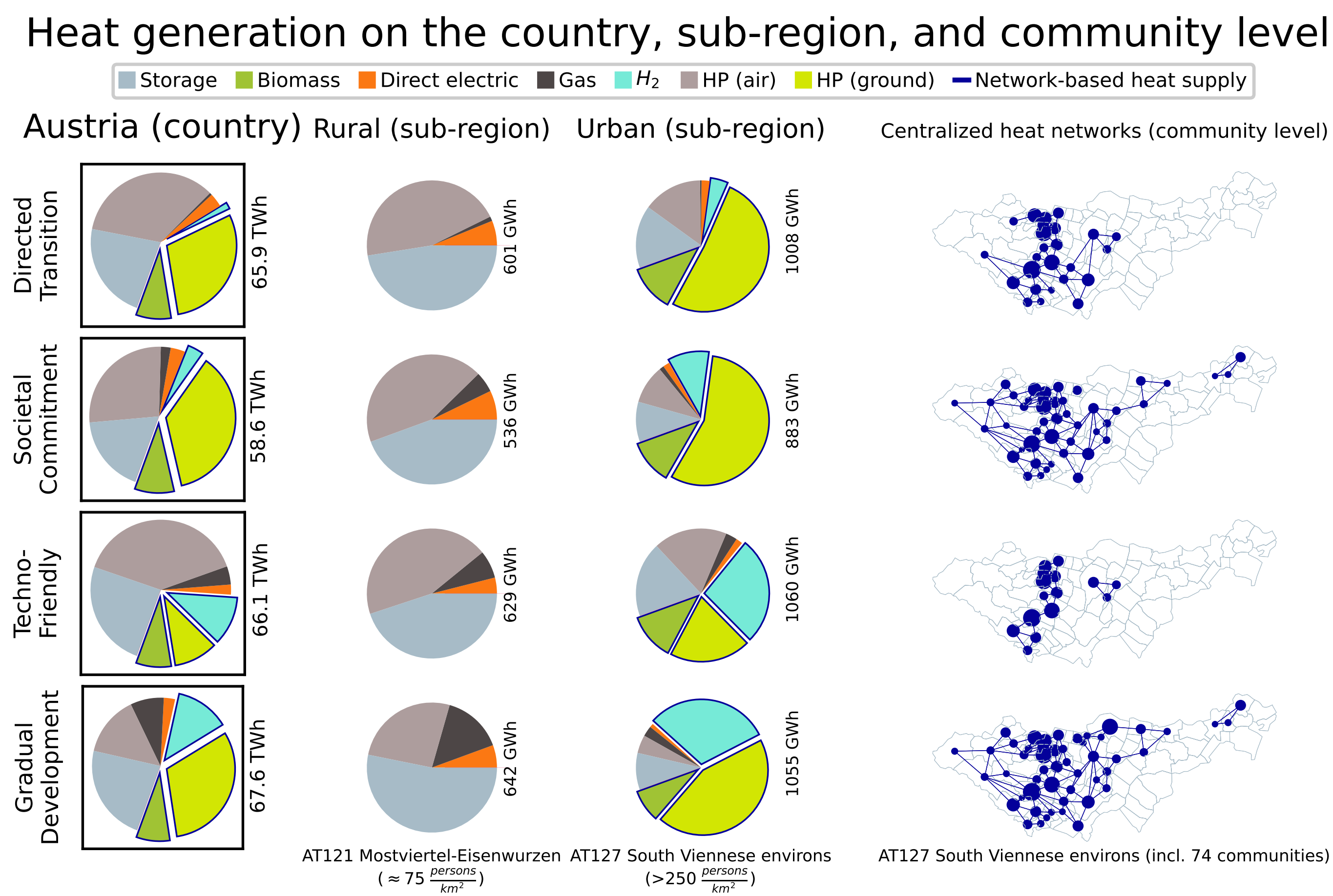

Figure 1: Heat technology generation on different spatial granularity levels in the different scenarios supplying the residential and commercial heat demand. left: on the country level. middle: comparison of a rural and urban sub-region. right: centralized heat network topology (size of the points represent the amount of heat demand supplied by the network)

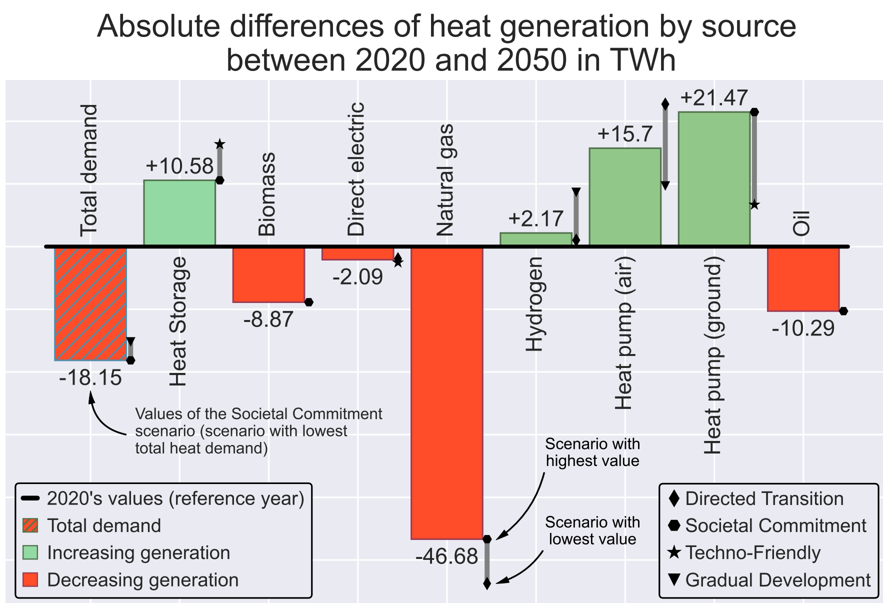

Figure 2: Comparison of heat generation by source between the reference year 2020 (black line) and 2050 in Austria. The height of the bars shows the absolute increase/decrease 2050 in the *Societal Commitment* scenario. The scenario with the lowest and highest difference, respectively, is indicated by the markers.

tralized heat supply in the total heat demand. Note that the population density varies in these sub-regions between 163 persons/km^2 (AT211 - Klagenfurt-Villach) and 5124 persons/km^2 (AT130 - Vienna).

3.4. Centralized heat network topology on the community level

This section presents the centralized heat network topology of the sub-region *South Viennese environs* (AT127) and all included communities. In Figure 3, this particular sub-region is marked by the orange box. Figure 4 shows the projected centralized heat network topology. In particular, the network topology is presented for the initial condition (as result of the sequential downscaling, $i = 1$) and in the final condition ($i = 51$) of the network. The distribution of the benchmark indicator values of the centralized heat network depending on the number of iterations is presented in the middle. The mean value is marked in orange. The supply area decreases with an increasing number of iterations. In the final condition, 25 communities are connected (starting from 75 in the initial condition). The number of connected population decreases by 38 %, starting from a population of 386 k being connected to centralized heating network in the initial condition. After the final iteration ($i = 51$), the termination criterion is reached. Note that the iterative reduction of supplied small sub-regions does not necessarily result in one contiguous graph (see the network graph in the *Gradual Development* scenario in Figure 1).

3.5. Comparison of 2050's and today's centralized heat networks using heat density as criterion

In the following, the centralized heat network in *Graz* (AT221) is investigated in detail. This area is selected since it provides representative results in terms of both the applied downscaling and achievable heat density benchmarks of centralized heat networks. Figure 5 shows the heat density of the centralized heat network in the *Techno-Friendly* scenario.

The x-axis shows the three different downscaling techniques. The numerical numbers indicate a significant increase of the heat density by the sequential

		in TWh		in %
Sub-region	Storyline	Centralized	On-site	Connection rate
South Viennesse environs (AT127)	Directed Transition	1.56	1.01	61
	Societal Commitment	1.80	0.49	79
	Techno-Friendly	1.13	1.45	44
	Gradual Development	2.28	0.36	86
Vienna (AT130)	Directed Transition	8.60	5.58	61
	Societal Commitment	9.90	2.70	79
	Techno-Friendly	6.25	7.80	44
	Gradual Development	12.57	1.96	87
Klagenfurt-Villach (AT211)	Directed Transition	1.31	0.90	60
	Societal Commitment	1.50	0.46	77
	Techno-Friendly	0.56	1.66	25
	Gradual Development	1.83	0.43	81
Graz (AT221)	Directed Transition	1.99	1.29	61
	Societal Commitment	2.30	0.62	79
	Techno-Friendly	1.45	1.85	44
	Gradual Development	2.92	0.46	86
Linz-Wels (AT312)	Directed Transition	2.68	1.74	61
	Societal Commitment	3.09	0.84	44
	Techno-Friendly	1.95	2.49	44
	Gradual Development	3.92	0.61	87
Salzburg and surroundings (AT323)	Directed Transition	1.61	1.05	61
	Societal Commitment	1.86	0.51	78
	Techno-Friendly	1.17	1.49	44
	Gradual Development	2.36	0.37	86
Innsbruck (AT332)	Directed Transition	1.36	0.93	59
	Societal Commitment	1.56	0.48	76
	Techno-Friendly	0.58	1.72	25
	Gradual Development	1.90	0.45	81
Rheintal-Bodensee (AT342)	Directed Transition	1.42	0.92	61
	Societal Commitment	1.64	0.45	78
	Techno-Friendly	1.03	1.32	44
	Gradual Development	2.08	0.32	87

Table 4: Centralized heat supply and on-site heat generation in the eight Austrian sub-regions, with potentials of centralized heat networks in 2050

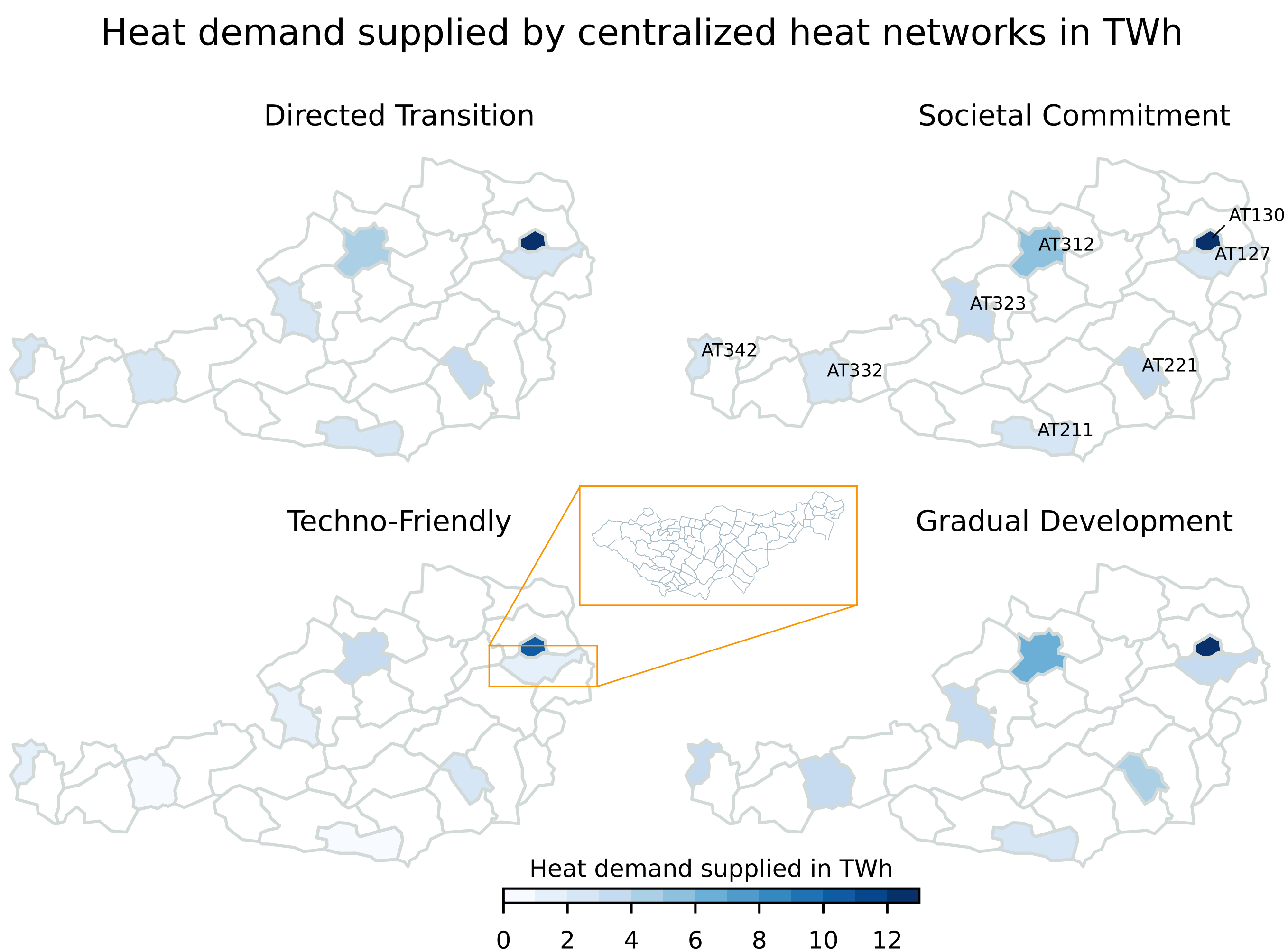

Figure 3: Heat demand supplied by centralized heat networks in Austria 2050. The white areas are supplied by on-site (decentralized) sustainable heat generation technologies/sources.

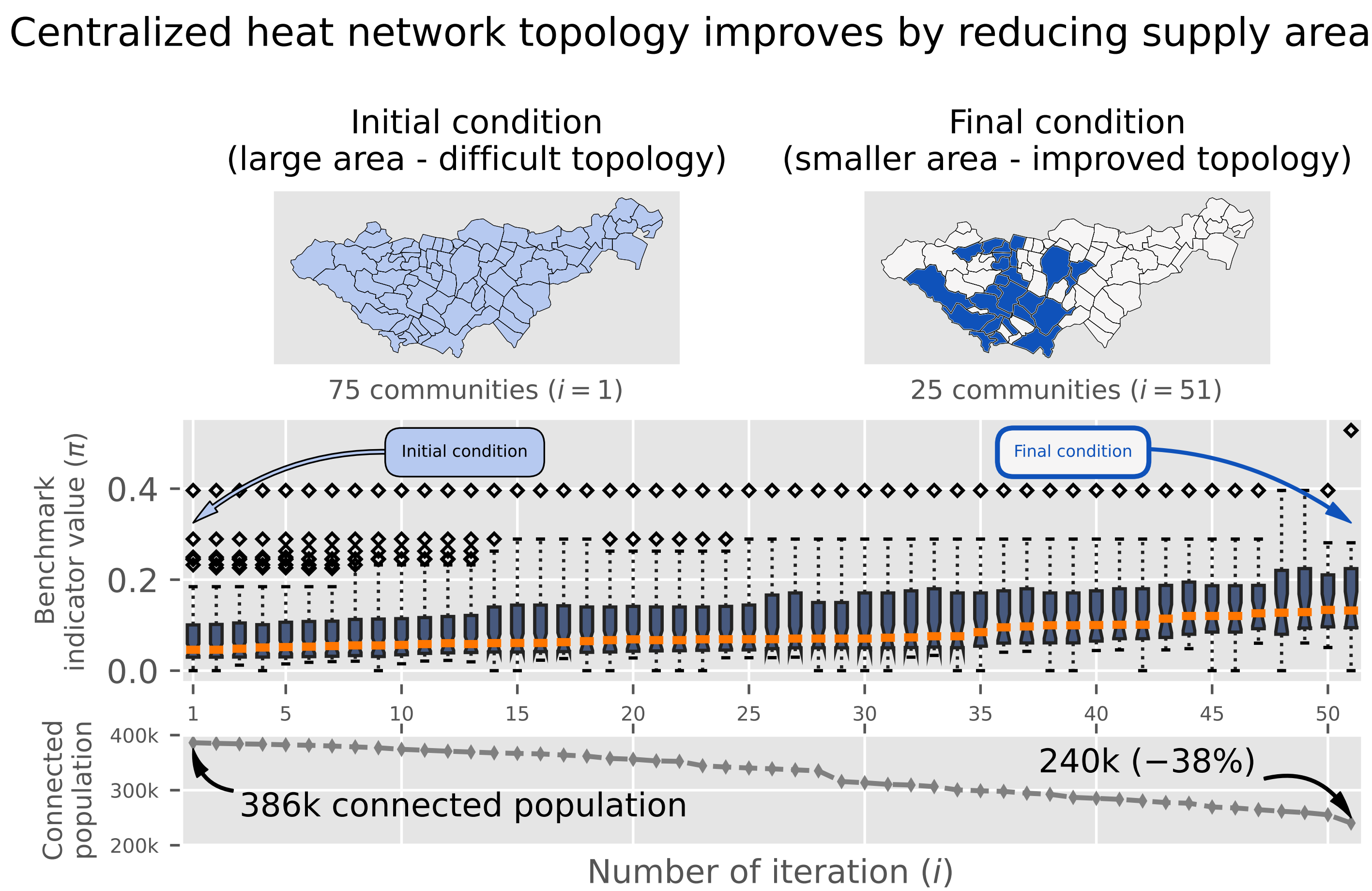

Figure 4: Centralized heat network topology in the initial and final condition. The boxplot (middle) indicates the improved network topology by an increasing benchmark indicator mean value (orange line). In the final condition, the connected population declines by $-13.3\,\%$ compared to the initial condition.

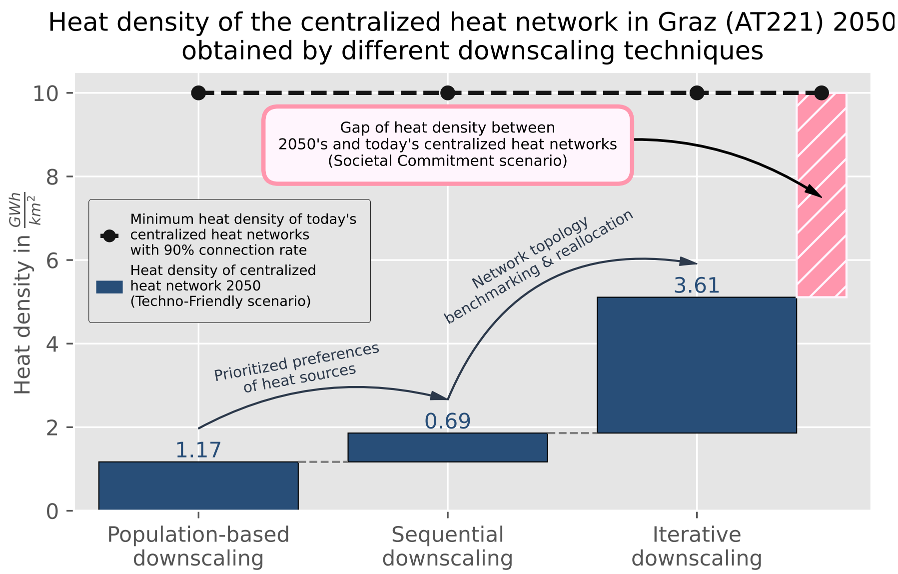

Figure 5: Heat density of the centralized heat network in *Graz* (AT221) 2050 in the *Techno-Friendly* scenario. The gap of heat density between 2050's and today's heat density (black dashed line) is marked by the pink bar.

(+0.69 GWh/km^2) and, in particular, the iterative downscaling (+3.61 GWh/km^2). However, comparing the obtained heat density value with heat density values of today's centralized heat networks reveals a signifcant gap (see the hatched pink bar). Here in the *Techno-Friendly* scenario, it is 4.53 GWh/km^2. According to references from the practice (see, e.g., in `http://www.austrian-heatmap.gv.at/ergebnisse/`), the heat density of today's networks is assumed to be 10 $\frac{\text{GWh}}{\text{km}^2}$ with a connection rate of 90 %. The gap of heat density varies between the different scenarios. Figure 6 shows the heat densities in the sub-regions and compares the results in the different scenarios. It shows the scenario with the lowest and the highest heat density. The bottom bar shows the value and scenario with the lowest heat density among the four different scenarios for each sub-region. The hatched bar indicates the increase of heat density and the corresponding scenario compared to the lowest value. In five sub-regions, the *Techno-Friendly* scenario is the scenario with the lowest heat density. The

Directed Transition scenarios is the scenario with the highest heat density in four sub-regions. Note that Vienna (AT130) is not shown for the sake of clarity. The heat density there varies between 15.1 $\frac{\mathrm{GWh}}{\mathrm{km}^2}$ in the *Techno-Friendly* and 30.3 $\frac{\mathrm{GWh}}{\mathrm{km}^2}$ in the *Gradual Development* scenario.

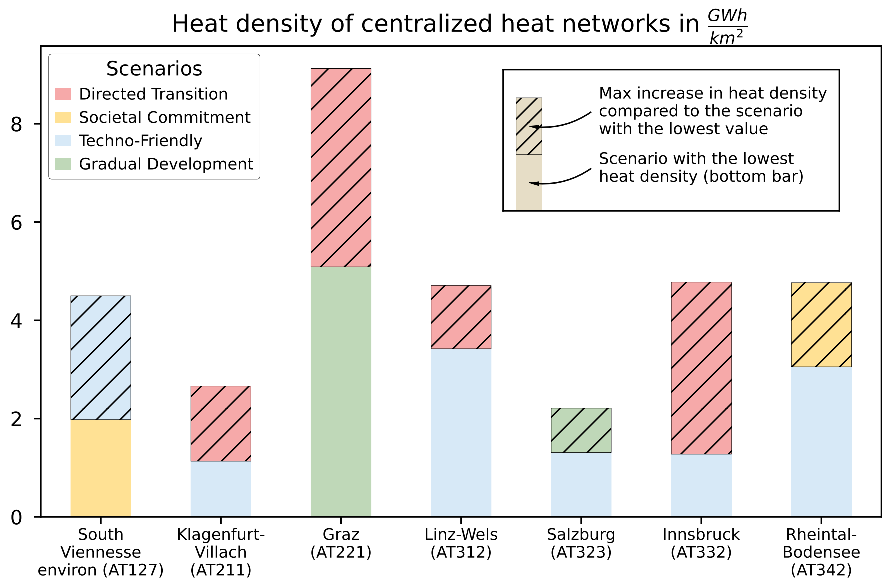

Figure 6: Comparison of the heat density in different scenarios for each sub-region. The bottom bar shows the scenario with the lowest heat density. The hatched bar indicates the increase of heat density and the corresponding scenario compared to the lowest value.

4. Conclusions and recommendations

The sustainable energy transition requires methods to bridge the gap between global decarbonization plans and the resulting necessary measures at the local level. This work emphasizes the development of different downscaling algorithms in general, and downscaling of the Austrian heating sector (residential and commercial) under the 1.5°C climate target to the community and grid level in particular, considering technology-specific infrastructure requirements for the highly efficient usage of heat sources.

We found that the prioritized perspective of efficiency and local utilization of renewable heat sources leads to a crucial treatment of the further development of district heating networks in the decarbonized Austrian heat supply towards 2050. It is shown that this implies small-scale (< 1 TWh) and large-scale ($>$ 12 TWh) district heating networks in terms of the amount of heat delivered. The results demonstrate that particularly densely populated areas are still beneficial supply areas for district heating networks and offer adequate heat densities. Nevertheless, most district heating networks in 2050 (seven out of eight) will not reach the heat density benchmarks of today's networks and have a significant heat density gap. However, taking into account the increasing importance of local renewable heat sources feeding into district heating networks, we assume that these centralized networks will become required in the future and crucial in the decarbonization of the heating sector.

We anticipate our work as a starting point discussing the role of centralized heat networks as an infrastructure hub in the light of enabling large-scale, highly efficient, and local integration of renewable heat sources (such as biomass/waste, hydrogen, ground-sourced heat pumps or geothermal). In particular, we see a need for further research on the trade-off analysis between the efficiency/local integration of heat sources and the cost-intensive deployment of district heating networks. Future work may elaborate on the increasing cooling demand and how the cooperative design of district heating and cooling networks can contribute to the profitability of centralized heating and cooling infrastructure.

Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Data and further empirical settings

	Description	Data availability	Data source
GENeSYS-MOD v2.0	Heat generation by source	[78]	[41]
Austrian population density	in 2019	*Statistik Austria*	
Austrian population	in 2050	*Eurostat*	

Table A.1: Empirical data settings

Appendix B. Further methodology illustrations

Figure B.1 shows an illustrative example for the iterative downscaling Algorithm (Algorithm 2). It shows two different conditions of a simple graph. In the first condition (i), the network topology consist of four nodes (A-D) and four lines. It is shown in the subfigure in the top left. The table below (bottom left) shows the amount of centralized and on-site heat supply as well as the value of the indicator value for each node. Note that the numbers are only for illustration.

Node A has the lowest indicator value (see marker [1] in the left table) and, therefore, its amount of centralized heat supply (marker [2]) is reallocated to the remaining nodes of the network (marker [3]). This process increases the on-site heat supply accordingly at node A since this node is not connected to the network in conditon $i + 1$ and increases the amount of centralized heat supply at node B-D (see the larger nodes in the top right subfigure). The heat demand of node A in condition $i + 1$ is only covered by on-site heat supply. Node A is removed from the graph and thus dissconnected from the network.

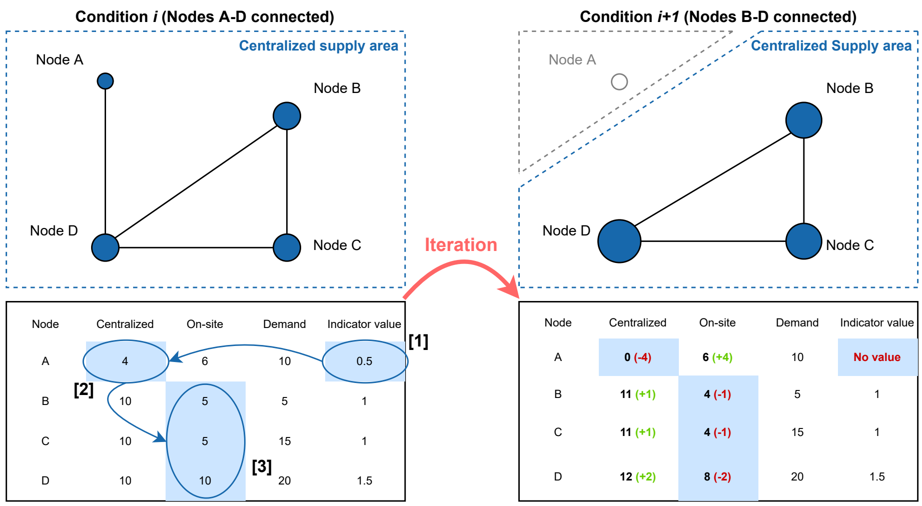

Figure B.1: Illustrative example of Algorithm 2 showing a simple graph with four nodes in two different conditions. The node with the lowest indicator value in condition i (node A) is removed from the graph (markers [1]-[3] in the table at the bottom left). The amount of centralized heat supply from node A is reallocated to the reamaining nodes B-D (see table at the bottom right).