

# Disclosing 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 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 2050 and identify six different district heating networks, supplying heat demand between 0.7 and 6.6 TWh. Nevertheless, five of these networks do not reach the heat density required for economic and technical efficiency from today's techno-economic perspective (heat density of  $2.58 \frac{\text{GWh}}{\text{km}^2}$  and less). We conclude that the decarbonization leads to centralized heat networks with lower heat densities.

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

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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. 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<sub>2</sub> emissions 2030 compared to 1990. 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 set 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 2050 and the implications of the sustainable energy mix for centralized heating networks.

### *1.2. Implications and effects of the decarbonization on the heating sector*

The scope of changes required by 2030/2050 in the heating sector become even clearer at the national level. 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<sup>1</sup>. It is in fact higher in some countries, for example in Austria, where it is 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. If these heating systems are changed to renewable energy by 2050, this corresponds to a retrofitting of 50,000 appliances per year, or more than 130 per day - only in Austria. To achieve this goal, we need a massive expansion of centralized heating (and cooling) networks in addition to the retrofitting of on-site heating end-user devices.

Centralized heating networks are particularly advantageous for supplying densely populated or urban areas resulting from high heat densities there [3]. In addition to heat density, the connection rate is a key factor influencing 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<sup>2</sup> is a rough guide for supplying an area with district heating<sup>2</sup>. The reference value of 10 GWh/km<sup>2</sup> is in line with findings regarding district heating networks also from the Scandinavian region (Denmark, Sweden, and Finland) [4]. These are rough estimates, but they do allow an initial assessment of the economic viability or feasibility of a district heating network. If one goes into more detail when considering and evaluating district heating networks, numerous factors play a decisive role. Nussbaumer and Thalmann [5] thoroughly elaborate on the network design and its impact on the profitability of centralized heat networks. Laasasenaho et al. [6] emphasize in their study the optimal location of heat generation units/sources within centralized heat networks enabling a cost-

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<sup>1</sup><https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200211-1>

<sup>2</sup><http://www.austrian-heatmap.gv.at/ergebnisse/>

optimized heat supply. Gopalakrishnan and Kosanovic [7] 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 [8] and [9]). Hietaharju et al. [10] recently show in their analysis that a 2 – 3% building renovation rate 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 [11]. Reidhav and Werner [12] 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<sub>2</sub> reduction targets, it can also be assumed that the rising CO<sub>2</sub> 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 [13] 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. [14] also identify in their mutli-criteria study wood pellets as the optimal system options for fueling district heating networks. And, 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 [15].

### *1.3. Lack in the implementation of decarbonization 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 of the system. For example, Rockström et al. [16] conduct such a study and propose pathways for halving gross anthropogenic CO<sub>2</sub> 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. [17], transport sector Pan et al. [18], and industries Habert et al. [19]).

Despite all the details associated with the sector-specific decarbonization strategies, the principles of a net-zero society base on three key points: (i) deployment and generation of renewable energy technologies (see, e.g., Bakhtavar et al. [20] focusing on net-zero districts by deployment of renewable energy generation), (ii) reduction of the energy demand (see, e.g., Oshiro et al. [21] analyzing the impact of energy service demand reduction on the decarbonization and Grubler et al. [22] investigating a low energy demand decarbonization scenario), 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 and use. Van Ruijven et al. [23] 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 [24] systematically investigates the possibilities and challenges of hydrogen and discusses extensively its role in the energy transition. Recently, Böhm et al. [25] comprehensively elaborate on hydrogen-related synergies and its role in sustainable heat supply. Thus, it is necessary to develop optimal strategies ensuring the utilization of renewable energy sources prioritized and in the most efficient way related to the provision of energy service needs.

#### *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 uses 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 [26] provided 1995 a fundamental review on IAMs focusing on their role in the context of climate change. Krey et al. [27] discuss and systematically compare different IAMs. Harmsen et al. [28] elaborates on the modeling behaviour of IAMs. Wilkerson et al. [29] and van Vuuren et al. [30] deal with IAMs and their role in understanding global energy decarbonization pathways. In particular, both studies examine CO<sub>2</sub> budget and price developments. Schwanitz [31] 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. Gambhir et al. [32] 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 [33]). 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. [34] (PRIMES) and Löffler et al. [35] (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. [36] 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.

Against this background, the core objective of this work is downscaling European decarbonization scenarios of the heating sector to the community/grid level 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 change of centralized heating networks considering the 1.5°C climate target. An Austrian case study is conducted, downscaling the results of the heating sector 2050 from the large numerical energy system model GENeSYS-MOD, from the country to community/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, disaggregating 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 as the third, an iterative downscaling algorithm is presented. This algorithm bases 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 shows heat generation by source on different spatial levels. Section 3.3 and 3.4 presents 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.

$$d_{local} = \frac{p_{local}}{p_{country}} \cdot d_{country} \quad (1)$$

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 adaptations, in particular, related to the downscaling driver and proxy, respectively [37]. In this context, van Vuuren et al. [37] 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. Sherba et al. [38] focus in their study on the downscaling of global land-use projections and use the character and distribution of land area as a proxy. Pretis and Roser [39] disaggregate in their study growth rates from the global level using emission intensity 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. [40], van Vuuren et al. [41],

and Alam et al. [42]). We also apply this concept here, defining it as a reference technique and comparing our novel developed downscaling techniques.

For further information, we refer the reader here to the study in [41], 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 aggregated values of the heating sector from the country to the sub-region level. Before explaining the algorithm in detail, we describe the spatial nomenclature used in this work. This work’s spatial nomenclature uses the definition of the European nomenclature of territorial units for statistics<sup>3</sup> (NUTS). Table 1 shows the different NUTS categories with a short description<sup>4</sup>. In addition, it includes the number of regions per NUTS level in which Austria is divided. For example, Austria is split into 35 different NUTS3 regions. Algorithm 1 downscales from NUTS0 to the NUTS3 level.

The purpose of the sequential downscaling algorithm is to provide a downscaling technique that considers at least two crucial aspects of renewable heat sources in the heating sector that are already addressed in some works in literature. First, that the efficiency of renewable heat sources can vary significantly depending on the integration option into heating systems. Exemplarily, renewable-based hydrogen should preferably be used in district heating networks if it is used for heat supply [43]. From a techno-economic point of view, use directly by the end-user does not play a significant role. Zwickl-Bernhard and Auer [44] recently

<sup>3</sup><https://ec.europa.eu/eurostat/web/nuts/background>.

<sup>4</sup>Note that the gray-colored rows mark the spatial levels used for downscaling in this work.

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.

investigated the role of district heating networks when decommissioning the existing natural gas distribution grid on the neighborhood level. They stated that limited amounts of "green" gas should be used in centralized heat networks. And second, that in the future, biomass in the form of waste incineration plants, especially in densely populated areas using centralized heat networks [45] will provide a sustainable option for integrating renewable heat sources [46].

Thus, some heat sources/technologies are downscaled only to regions that provide the potentials for centralized heat networks. 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. The sub-regions used for downscaling the corresponding heat source are marked. Note that the different types are characterized by population density.

Source	Requirements	Rural	Town/Mixed	Urban	Reference
Heat technology	Heat network	Sparsely	Moderate	Dense	
Biomass	Middle		x	x	[47, 48, 45]
Direct electric	None	x	x	x	
Synthetic gas	Low	x	x	x	
Hydrogen	High			x	[49, 50, 51]
Heat pump (air)	None	x	x	x	[52]
Heat pump (ground)	High			x	[53, 54, 55]
Heat storage	None	x	x	x	

Table 2: Qualitative overview for heat generation technologies/sources and their requirements for heat network infrastructure. The prioritized preferences (gray cell color) of heat sources in sub-regions is marked by the gray color.

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 on page 13. The inputs are: (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).

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**Algorithm 1:** Sequential downscaling algorithm (NUTS0 to NUTS3)

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

input : Heat generation per technology/source at NUTS0 level: ( $q_t$ );
        Population density per region  $r$  ( $\rho_r$ );
        Total population per region  $r$  ( $p_r$ );
        Minimal network infrastructure requirements of  $t$  ( $\sigma_t$ );
        Available potential of heat network infrastructure at  $r$  ( $\pi_r$ );

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

Initialization:
Sort elements  $t$  in  $T$  descending by  $\sigma_t$ ;
 $q_r^{heat} \leftarrow \sum_t q_t \cdot \frac{p_r}{\sum_r p_r}$ ; // Calculate heat demand at each sub-region
3  $\tilde{q}_t \leftarrow q_t$ ; // Available heat generation for each technology/source

4 begin
5   foreach  $t$  do
6      $List = []$ ; // Collect valid sub-regions
7      $demand = 0$ ; // Remaining demand that needs to be covered
8      $R' = R \setminus \{r \in R : \pi_r \leq \sigma_t\}$ ; // Get valid sub-regions by criteria
9     foreach  $r' \in R'$  do
10      if  $q_r^{heat} \geq 0$  then
11         $List = List \cup r'$ ; // Add valid sub-regions to collection
12         $demand += q_r^{heat}$ ; // Total demand of valid sub-regions
13      end
14    end
15    foreach  $l \in List$  do
16       $\hat{q}_{t,r} = \frac{q_r^{heat}}{demand} \cdot \tilde{q}_t$ ; // Population-based downscaling
17       $q_r^{heat} -= \hat{q}_{t,r}$ ; // Reduce heat demand at  $r$ 
18    end
19  end
20 end

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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 5). For this technology/source, all possible sub-regions are collected (line 8). Those sub-regions already fully supplied (no remaining heat demand) are filtered out (line 10). After further pre-calculation steps, the available amount of heat generation is downscaled to all valid sub-regions (lines 11 and 15) using population as a proxy (line 16). 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 (in the Austrian case 35 different sub-regions).

### *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 translating 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 [56]. The underlying concept of iterative downscaling bases on graph theory and assessing network topology using benchmark indicators.

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**Algorithm 2:** Iterative downscaling algorithm

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1  $s$ : Stage of iteration ( $s \in \{0, 1, *\}$ );
2  $G^s$ : Centralized heat network graph at stage  $s$ ;
3  $N^s$ : List of nodes at stage  $s$ : ( $n^s \in N^s$ );
4  $L^s$ : List of lines connecting nodes  $k$  and  $j$  at stage  $s$ : ( $l_{k,j}^s \in L^s$ );
5  $Q^s$ : Centralized heat generation at stage  $s$ : ( $q_{n^s}^s \in Q^s$ );
6  $\tilde{Q}^s$ : On-site heat generation at stage  $s$ : ( $\tilde{q}_{n^s}^s \in \tilde{Q}^s$ );
7  $\Pi^s$ : Benchmark indicator value at stage  $s$  ( $\pi_{n^s}^s \in \Pi^s$ );

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

Initialization:
 $s = 0, iter = True$ ;
8 begin
9   while  $iter = True$  do
10     foreach  $n \in N^s$  do
11        $\Pi_{n^s}^s = f(N^s, L^s, Q^s)$ ; // Calculate benchmark indicator value
12     end
13      $i$  with  $\pi_i^s = \min(\Pi^s)$ ; // Get node with lowest indicator value
14      $N^{s+1} = N^s \setminus i$ ; // Remove node from graph obtaining next stage
15      $\tilde{q} = \sum_{N^{s+1}} \tilde{q}_{n^s}^s$ ; // Calculate available on-site heat generation
16     if  $\tilde{q} \geq q_i^s$  then
17       pass
18     else
19        $\tilde{q} = q_i^s$ ; // Set upper bound of centralized heat generation that
                // is used for reallocation among nodes if necessary
20     end
21     foreach  $n^{s+1}$  do
22        $q_{n^{s+1}}^{s+1} = q_{n^s}^s + \frac{q_i^s}{\tilde{q}} \cdot \tilde{q}_{n^s}^s$ ; // Increase centralized heat generation
23        $\tilde{q}_{n^{s+1}}^{s+1} = \tilde{q}_{n^s}^s - \frac{q_i^s}{\tilde{q}} \cdot \tilde{q}_{n^s}^s$ ; // Decrease on-site heat generation
24     end
25      $L^{s+1} = L^s \setminus \{\forall l_{k,j}^s : k = i \vee j = i\}$ ; // Remove connecting lines
26      $G^{s+1} = \{N^{s+1}, L^{s+1}, Q^{s+1}, \tilde{Q}^{s+1}\}$ ; // Create new network graph
27      $\Pi_{n^{s+1}}^{s+1} = f(N^{s+1}, L^{s+1}, Q^{s+1})$ ; // Calculate new indicator values
28     if  $mean(\Pi^{s+1}) \geq mean(\Pi^s)$  then
29        $G^s = G^{s+1}$ ; // Set updated heat network graph as new input
30     else
31        $iterate = False$ ; // Stop iteration if no improvement
32     end
33   end
34    $G^* = G^s$ ; // Set heat network graph as result
35 end

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### 2.3.1. Algorithm description

The iterative downscaling algorithm is presented on page 15. 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 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. Reallocate centralized and on-site heat generation for all nodes (lines 22 and 23)
4. Recalculate benchmark indicator value for all remaining nodes within the network graph (line 27)
5. Compare the average value of the indicator value of the initial and reduced heat network graph (lines 28 and 29)
6. Update heat network graph in case of an higher average indicator value and jump to step 2. Otherwise, the termination of the algorithm is achieved.

Recent studies support this approach focused on the topography of energy systems and networks (see for example in [57]). Bordin et al. [58] 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 here to Shekoofa and Karbasian [59] 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. [60] 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 on page 15) 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 [61]. Moreover, we refer the reader to the study in [62] 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

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

where  $q$  is the amount of centralized heat supply,  $\alpha$  the number of triangles that can be formed with direct neighboring nodes, and  $\beta$  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 [63] comprehensively deals with cluster coefficients and provides related generalized concepts. In addition, relevant aspects of the cluster(ing) coefficient is shown in [64]. 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 so 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 has a high heat demand and heat density, respectively. Both aspects are investigated in the literature. For example, Nilsson et al. [65] focus in their study on the importance of the connection rate of centralized heat networks. Besides, Dochev et al. [66] 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* [67]. *Pyam* is an open-source package for the analysis and visualization of integrated assessment and macro-energy scenarios [68]. In this work here, it is used in particular used 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* [69], 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 finer 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 were (or "are currently") 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 [70] and [71]. Further informations also are available on the website of the project <sup>5</sup>

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<sup>5</sup><https://openentrance.eu/>

and GitHub<sup>6</sup>.

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.

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<sup>6</sup><https://github.com/openENTRANCE>

Table 3 shows the heat generation by technology/source in Austria 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 [72]. 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  $\Sigma$  presents the sum 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								$\Sigma$
		Biomass	Direct Electric	Synthetic gas	Heat pump (air)	Heat pump (ground)	Heat storage	Hydrogen	
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 addi-

tion, 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. The height of the bars indicates the values of the *Societal Commitment* scenario since this is the scenario with the lowest total heat demand ( $-18.15$  TWh). 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 2050 are limited to densely populated areas (urban areas). In particular, the results indicate only six different sub-regions (NUTS3 regions) that are supplied by centralized heat networks (see Figure 3). Although the exact numerical numbers differ, the six sub-regions in each scenario are (partially) supplied by centralized heat networks. Table 4 shows the centralized and on-site heat supply in the six sub-regions. Thereby,

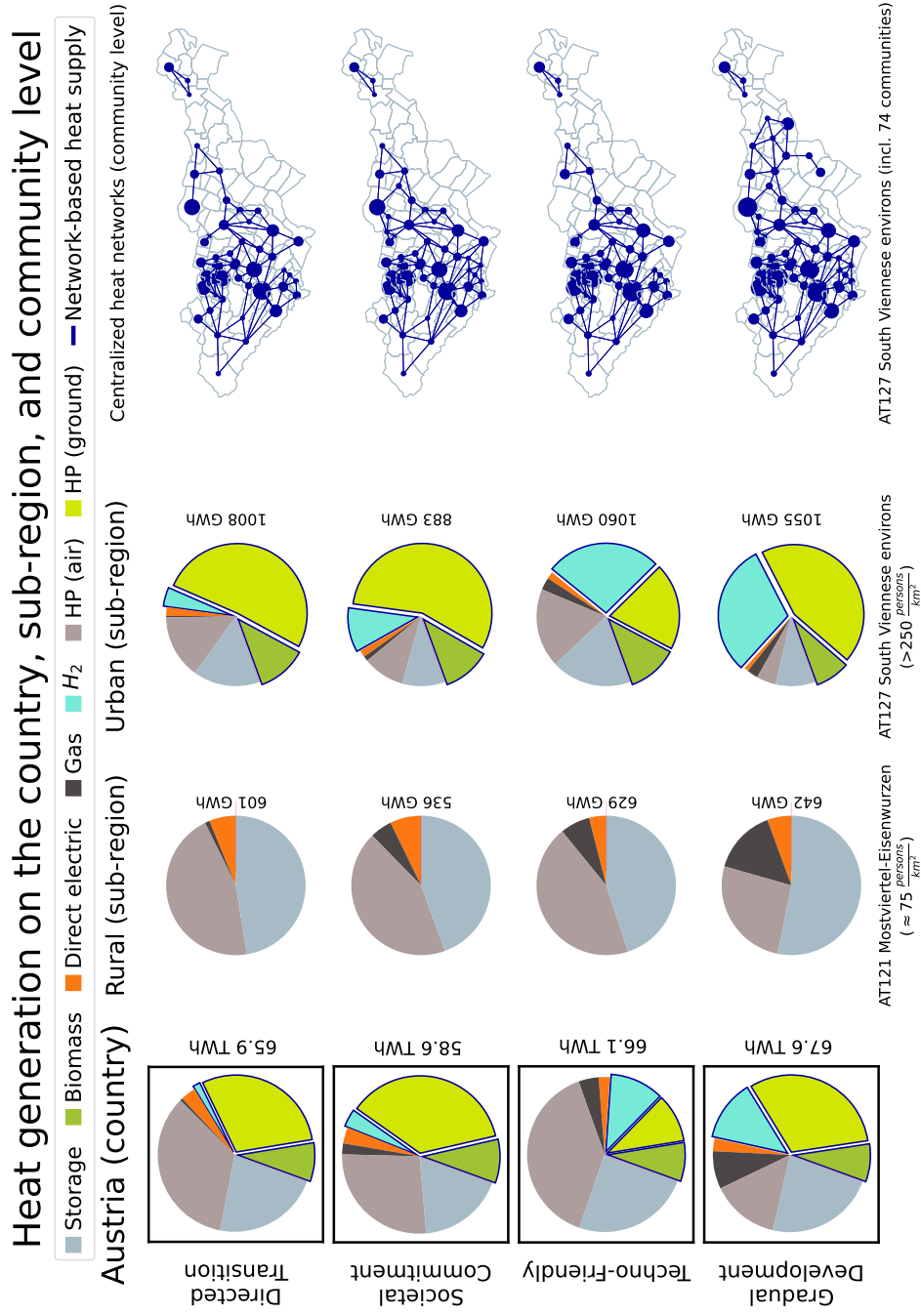


Figure 1: Heat technology generation on different spatial granularity levels in the different scenarios supplying the residential and commercial heat demand. left: on the country level. middle: comparison of a rural and urban sub-region. right: centralized heat network topology (size of the points represent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

Absolute differences of heat generation by source  
between 2020 and 2050 in TWh

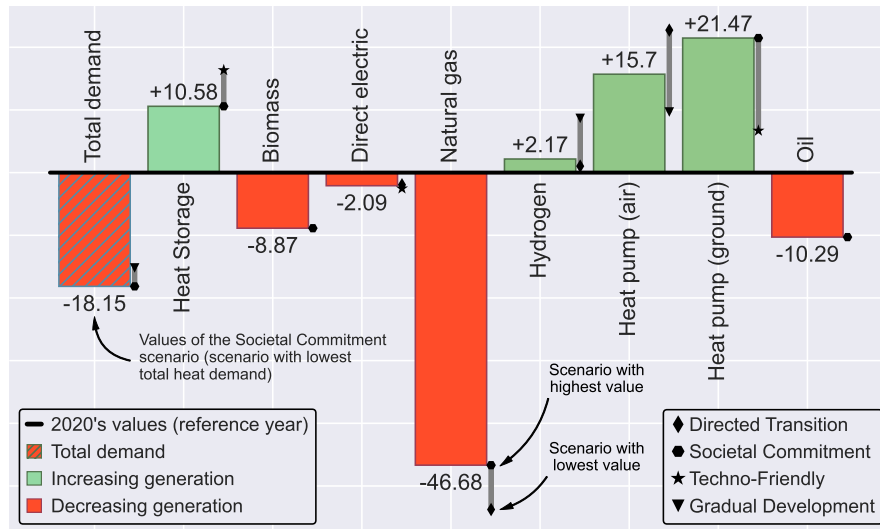


Figure 2: Comparison of heat generation by source between the reference year 2020 (black line) and 2050 in Austria. The height of the bars shows the absolute increase/decrease 2050 in the *Societal Commitment* scenario. The scenario with the lowest and highest difference, respectively, is indicated by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



the connection rate is assessed by the share of centralized heat supply in the total heat demand. The population density varies in the six sub-regions between 229 persons/km<sup>2</sup> (AT323 - Salzburg and surroundings) and 5124 persons/km<sup>2</sup> (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 and 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 ( $i = 29$ ) 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. Thereby, the mean value is marked in orange and increases with the number of iterations (increase from one third to almost two). Within the algorithm, this is achieved by reducing the supply area (decline in connected communities from 75 to 47). At the same time, the number of connected population decreases by 13.3 %, starting from a population of 386 k being connected to centralized heating network in the before the first iteration. After the final iteration ( $i = 29$ ), the termination criterion is reached. A possible following step of iteration could not increase the benchmark indicator mean value any further. The iterative reduction of supplied small sub-regions does not necessarily result one contiguous graph. For example, three communities form a subgraph that is separate from the other network (see upper right in the final condition network graph). The results discussed above suggest that reducing the number of small sub-regions supplied by the centralized heat network increases the indicator value and thus the efficiency of the heat network topology. Simultaneously, this also increases the heat density of the supply area. In the following subsection, the obtained heat density values of the heat networks are compared with existing values and today's minimum required values for centralized heat networks.

Sub-region	Storyline	in TWh		in %
		Centralized	On-site	Connection rate
South Viennese environs (AT127)	Directed Transition	0.72	0.17	81
	Societal Commitment	0.78	0.11	88
	Techno-Friendly	0.90	0.24	79
	Gradual Development	1.20	0.09	93
Vienna (AT130)	Directed Transition	3.98	0.95	81
	Societal Commitment	4.28	0.61	88
	Techno-Friendly	4.98	1.33	79
	Gradual Development	6.59	0.47	93
Graz (AT221)	Directed Transition	0.92	0.22	81
	Societal Commitment	1.53	0.14	92
	Techno-Friendly	1.16	0.31	79
	Gradual Development	1.53	0.11	93
Linz-Wels (AT312)	Directed Transition	1.24	0.30	81
	Societal Commitment	1.34	0.19	88
	Techno-Friendly	1.56	0.42	79
	Gradual Development	2.06	0.15	93
Salzburg and surroundings (AT323)	Directed Transition	0.75	0.18	81
	Societal Commitment	1.24	0.11	92
	Techno-Friendly	0.93	0.25	79
	Gradual Development	1.24	0.09	93
Rheintal- Bodensee (AT342)	Directed Transition	0.66	0.16	81
	Societal Commitment	0.71	0.10	88
	Techno-Friendly	0.82	0.22	79
	Gradual Development	1.09	0.08	93
Average connection rate				85.25 %

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

# Centralized heat supply in Austrian NUTS 3 regions 2050 in TWh

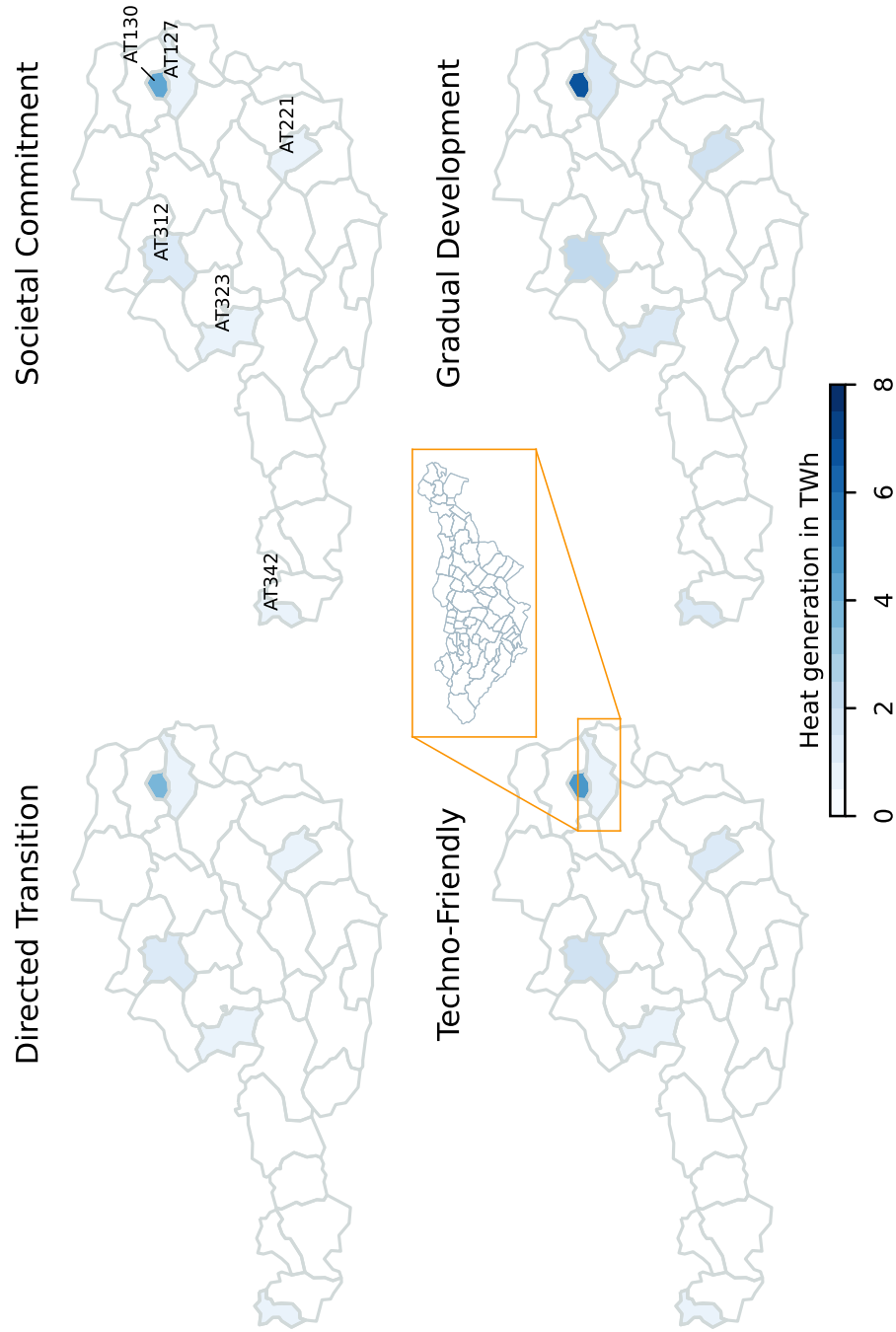


Figure 3: Centralized heat supply in Austria 2050

# Centralized heat network topology improves by reducing supply area

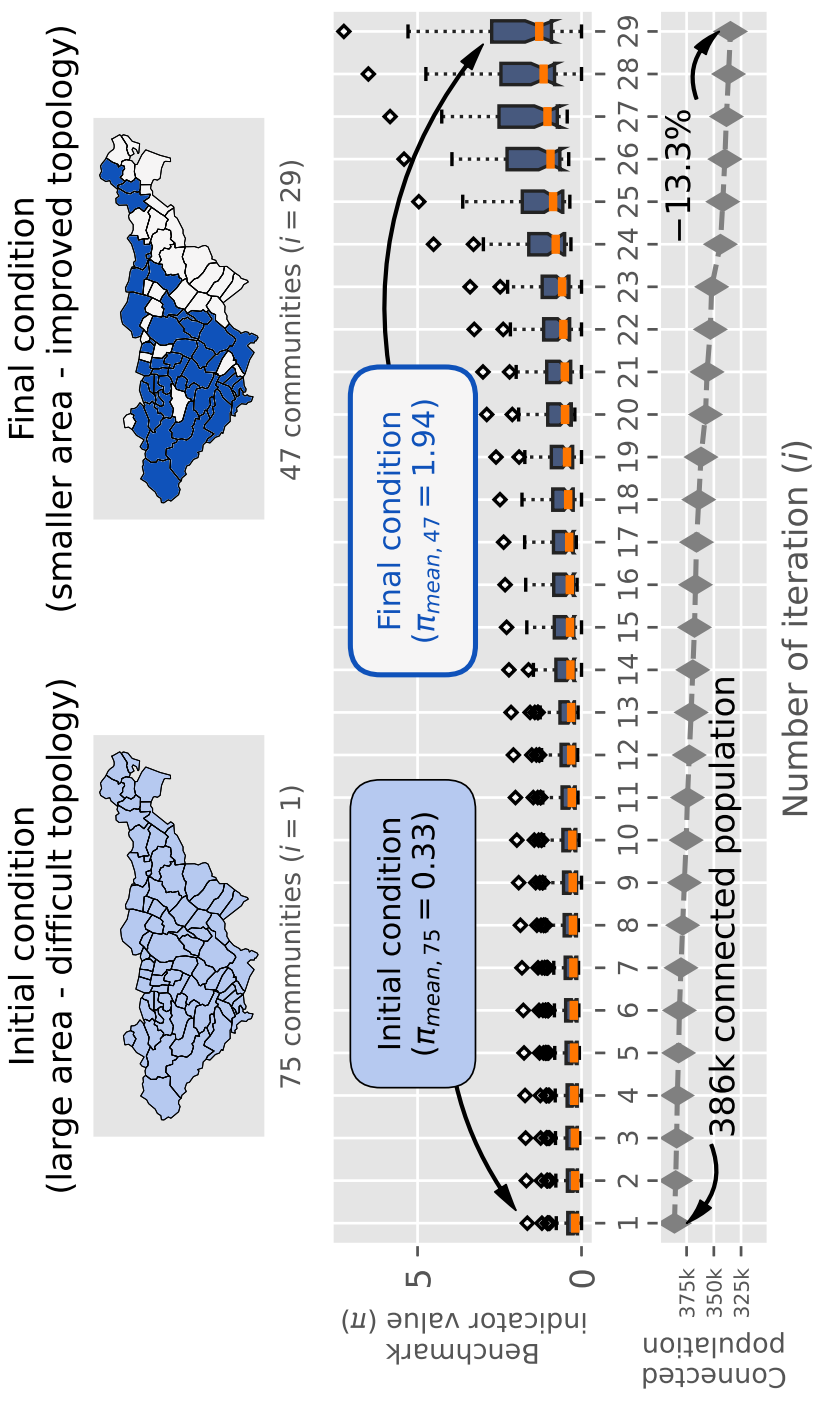


Figure 4: Centralized heat network topology in the initial and final condition. The boxplot (middle) indicates the improved network topology by an increasing benchmark indicator mean value (orange line). In the final condition, the connected population declines by  $-13.3\%$  compared to the initial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

### 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. Figure 5 shows the heat density of the centralized heat network in the *Techno-Friendly* scenario.

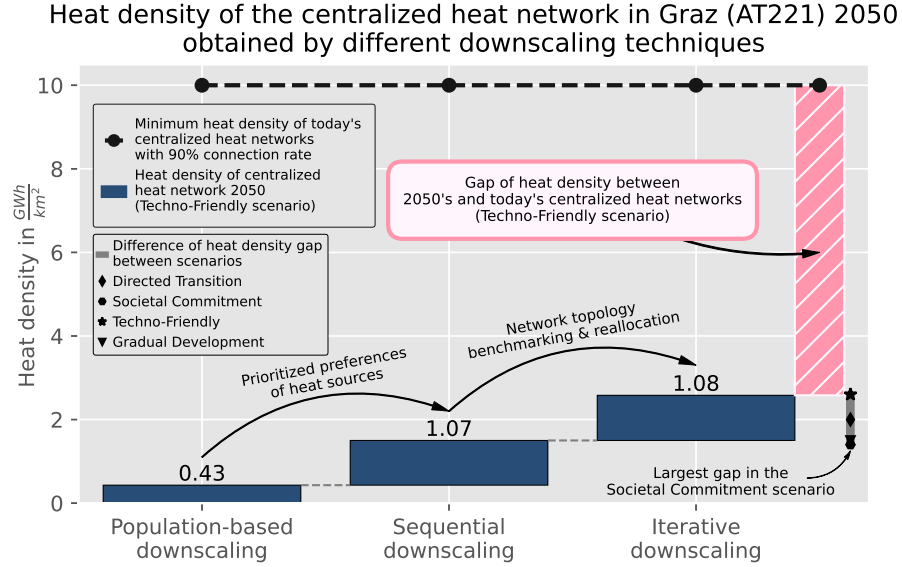


Figure 5: Heat density of the centralized heat network in *Graz* (AT221) 2050 in the *Techno-Friendly* scenario. The gap of heat density between 2050's and today's heat density (black dashed line) is marked by the pink bar. The differences of the heat density gap between the scenarios is marked by the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

The x-axis shows the three different downscaling techniques. The numerical numbers indicate an significant increase of the heat density resulting by the prioritized preference of heat sources (+1.07 GWh/km²) and the network topology benchmarking (+1.08 GWh/km²). However, comparing the obtained heat density value with heat density values of today's centralized heat networks reveals a significant gap (see the pink bar). 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%. In general, the gap of heat density varies between the different sce-

narios. The smallest is achieved in the *Techno-Friendly* scenario and amounts to  $7.42 \frac{\text{GWh}}{\text{km}^2}$  as presented in Figure 5 by the pink bar. The largest gap is seen in the *Societal Commitment* scenario and is  $8.41 \frac{\text{GWh}}{\text{km}^2}$ . The presented results of the sub-region are representative for the other sub-regions with potentials of centralized heat networks (excluding *Vienna* (AT130)). Figure 6 presents for the six different sub-regions the heat density values 2050. In particular, the results indicate no heat density gap for *Vienna* (AT130) in all the scenarios, except a minor one in the results obtained using *Directed Transition* scenario (i.e., heat density lower than  $10 \frac{\text{GWh}}{\text{km}^2}$ ).

Heat density of centralized heat networks in Austrian sub-regions 2050  
in the four different decarbonization scenarios in  $\frac{\text{GWh}}{\text{km}^2}$

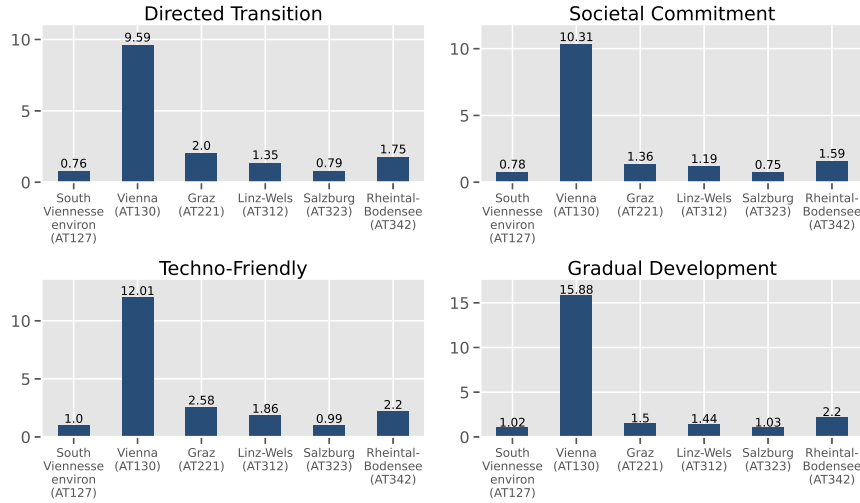


Figure 6: Heat densities (blue bars) of centralized heat networks in the six Austrian sub-regions and in the four different decarbonization scenarios

#### **4. Conclusions and outlook**

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 downscaling of the Austrian heating sector under the 1.5°C climate target to the grid level, 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 role of district heating networks in the decarbonized Austrian heat supply 2050. It is shown that this implies small-scale ( $< 1$  TWh) and large-scale ( $> 6$  TWh) district heating networks in terms of the amount of heat delivered. The results demonstrate that particularly densely populated areas are beneficial supply areas for district heating networks and offer adequate heat densities. Nevertheless, most district heating networks in 2050 (five out of six) will not reach the heat densities of today’s networks and have a significant heat density gap. We identify heat densities there of  $2.58 \frac{\text{GWh}}{\text{km}^2}$  and less.

We anticipate our work as a starting point discussing the role of centralized heat networks in the light of enabling large-scale, highly efficient, and local integration of renewable heat sources (such as biomass/waste and hydrogen). 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.

#### **Declaration of interests**

None.

#### **Declaration of Competing Interest**

The authors report no declarations of interest.

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## References

- [1] Agreement, Paris, Paris agreement, in: Report of the Conference of the Parties to the United Nations Framework Convention on Climate Change (21st Session, 2015: Paris). Retrived December, Vol. 4, HeinOnline, 2015, p. 2017.
- [2] O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, et al., IPCC special report on renewable energy sources and climate change mitigation, Prepared By Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK (2011).
- [3] S. Inage, Y. Uchino, Development of an integrated infrastructure simulator for sustainable urban energy optimization and its application, Sustainable Energy Technologies and Assessments 39 (2020) 100710. doi:<https://doi.org/10.1016/j.seta.2020.100710>.
- [4] H. Zinko, B. Bøhm, H. Kristjansson, U. Ottosson, M. Rama, K. Sipila, District heating distribution in areas with low heat demand density, The 11th International Symposium on District Heating and Cooling, Reykjavik, Iceland (2008).
- [5] T. Nussbaumer, S. Thalmann, Influence of system design on heat distribution costs in district heating, Energy 101 (2016) 496–505. doi:<https://doi.org/10.1016/j.energy.2016.02.062>.



- [6] K. Laasasenaho, A. Lensu, R. Lauhanen, J. Rintala, Gis-data related route optimization, hierarchical clustering, location optimization, and kernel density methods are useful for promoting distributed bioenergy plant planning in rural areas, *Sustainable Energy Technologies and Assessments* 32 (2019) 47–57. doi:<https://doi.org/10.1016/j.seta.2019.01.006>.
- [7] H. Gopalakrishnan, D. Kosanovic, Economic optimization of combined cycle district heating systems, *Sustainable Energy Technologies and Assessments* 7 (2014) 91–100. doi:<https://doi.org/10.1016/j.seta.2014.03.006>.
- [8] I. Andrić, J. Fournier, B. Lacarrière, O. Le Corre, P. Ferrão, The impact of global warming and building renovation measures on district heating system techno-economic parameters, *Energy* 150 (2018) 926–937. doi:<https://doi.org/10.1016/j.energy.2018.03.027>.
- [9] M. Rabani, H. B. Madessa, N. Nord, Achieving zero-energy building performance with thermal and visual comfort enhancement through optimization of fenestration, envelope, shading device, and energy supply system, *Sustainable Energy Technologies and Assessments* 44 (2021) 101020. doi:<https://doi.org/10.1016/j.seta.2021.101020>.
- [10] P. Hietaharju, J. Pulkkinen, M. Ruusunen, J.-N. Louis, A stochastic dynamic building stock model for determining long-term district heating demand under future climate change, *Applied Energy* 295 (2021) 116962. doi:<https://doi.org/10.1016/j.apenergy.2021.116962>.
- [11] U. Persson, S. Werner, Heat distribution and the future competitiveness of district heating, *Applied Energy* 88 (3) (2011) 568–576. doi:<https://doi.org/10.1016/j.apenergy.2010.09.020>.
- [12] C. Reidhav, S. Werner, Profitability of sparse district heating, *Applied Energy* 85 (9) (2008) 867–877. doi:<https://doi.org/10.1016/j.apenergy.2008.01.006>.

- [13] L. Di Lucia, K. Ericsson, Low-carbon district heating in sweden—examining a successful energy transition, *Energy Research & Social Science* 4 (2014) 10–20. doi:<https://doi.org/10.1016/j.erss.2014.08.005>.
- [14] S. Ghafghazi, T. Sowlati, S. Sokhansanj, S. Melin, A multicriteria approach to evaluate district heating system options, *Applied Energy* 87 (4) (2010) 1134–1140. doi:<https://doi.org/10.1016/j.apenergy.2009.06.021>.
- [15] D. Zhang, B. Zhang, Y. Zheng, R. Zhang, P. Liu, Z. An, Economic assessment and regional adaptability analysis of cchp system coupled with biomass-gas based on year-round performance, *Sustainable Energy Technologies and Assessments* 45 (2021) 101141. doi:<https://doi.org/10.1016/j.seta.2021.101141>.
- [16] J. Rockström, O. Gaffney, J. Rogelj, M. Meinshausen, N. Nakicenovic, H. J. Schellnhuber, A roadmap for rapid decarbonization, *Science* 355 (6331) (2017) 1269–1271. doi:<https://doi.org/10.1126/science.aah3443>.
- [17] B. D. Leibowicz, C. M. Lanham, M. T. Brozynski, J. R. Vázquez-Canteli, N. C. Castejón, Z. Nagy, Optimal decarbonization pathways for urban residential building energy services, *Applied Energy* 230 (2018) 1311–1325. doi:<https://doi.org/10.1016/j.apenergy.2018.09.046>.
- [18] X. Pan, H. Wang, L. Wang, W. Chen, Decarbonization of china’s transportation sector: in light of national mitigation toward the paris agreement goals, *Energy* 155 (2018) 853–864. doi:<https://doi.org/10.1016/j.energy.2018.04.144>.
- [19] G. Habert, S. Miller, V. John, J. Provis, A. Favier, A. Horvath, K. Scrivener, Environmental impacts and decarbonization strategies in the cement and concrete industries, *Nature Reviews Earth & Environment* 1 (11) (2020) 559–573. doi:<https://doi.org/10.1038/s43017-020-0093-3>.

- [20] E. Bakhtavar, T. Prabatha, H. Karunathilake, R. Sadiq, K. Hewage, Assessment of renewable energy-based strategies for net-zero energy communities: A planning model using multi-objective goal programming, *Journal of Cleaner Production* 272 (2020) 122886. doi:<https://doi.org/10.1016/j.jclepro.2020.122886>.
- [21] K. Oshiro, S. Fujimori, Y. Ochi, T. Ehara, Enabling energy system transition toward decarbonization in japan through energy service demand reduction, *Energy* 227 (2021) 120464. doi:<https://doi.org/10.1016/j.energy.2021.120464>.
- [22] A. Grubler, C. Wilson, N. Bento, B. Boza-Kiss, V. Krey, D. L. McCollum, N. D. Rao, K. Riahi, J. Rogelj, S. De Stercke, et al., A low energy demand scenario for meeting the 1.5 c target and sustainable development goals without negative emission technologies, *Nature energy* 3 (6) (2018) 515–527. doi:<https://doi.org/10.1038/s41560-018-0172-6>.
- [23] B. Van Ruijven, D. P. Van Vuuren, B. De Vries, The potential role of hydrogen in energy systems with and without climate policy, *International Journal of Hydrogen Energy* 322 (12) (2007) 1655–1672. doi:<https://doi.org/10.1016/j.ijhydene.2006.08.036>.
- [24] S. van Renssen, The hydrogen solution?, *Nature Climate Change* 10 (9) (2020) 799–801. doi:<https://doi.org/10.1038/s41558-020-0891-0>.
- [25] H. Böhm, S. Moser, S. Puschnigg, A. Zauner, Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials, *International Journal of Hydrogen Energy* (2021). doi:<https://doi.org/10.1016/j.ijhydene.2021.06.233>.
- [26] H. Dowlatabadi, Integrated assessment models of climate change: An incomplete overview, *Energy Policy* 23 (4-5) (1995) 289–296. doi:[https://doi.org/10.1016/0301-4215\(95\)90155-Z](https://doi.org/10.1016/0301-4215(95)90155-Z).

- [27] V. Krey, F. Guo, P. Kolp, W. Zhou, R. Schaeffer, A. Awasthy, C. Bertram, H.-S. de Boer, P. Fragkos, S. Fujimori, et al., Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models, *Energy* 172 (2019) 1254–1267. doi:<https://doi.org/10.1016/j.energy.2018.12.131>.
- [28] M. Harmsen, E. Kriegler, D. P. van Vuuren, K.-I. van der Wijst, G. Luderer, R. Cui, O. Dessens, L. Drouet, J. Emmerling, J. F. Morris, et al., Integrated assessment model diagnostics: key indicators and model evolution, *Environmental Research Letters* 16 (5) (2021) 054046. doi:<https://doi.org/10.1088/1748-9326/abf964>.
- [29] J. T. Wilkerson, B. D. Leibowicz, D. D. Turner, J. P. Weyant, Comparison of integrated assessment models: carbon price impacts on US energy, *Energy Policy* 76 (2015) 18–31. doi:<https://doi.org/10.1016/j.enpol.2014.10.011>.
- [30] D. P. Van Vuuren, H. Van Soest, K. Riahi, L. Clarke, V. Krey, E. Kriegler, J. Rogelj, M. Schaeffer, M. Tavoni, Carbon budgets and energy transition pathways, *Environmental Research Letters* 11 (7) (2016) 075002. doi:<https://doi.org/10.1088/1748-9326/11/7/075002>.
- [31] V. J. Schwanitz, Evaluating integrated assessment models of global climate change, *Environmental Modelling & Software* 50 (2013) 120–131. doi:<https://doi.org/10.1016/j.envsoft.2013.09.005>.
- [32] A. Gambhir, I. Butnar, P.-H. Li, P. Smith, N. Strachan, A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS, *Energies* 12 (9) (2019) 1747. doi:<https://doi.org/10.3390/en12091747>.
- [33] H.-K. Ringkjøb, P. M. Haugan, I. M. Solbrekke, A review of modelling tools for energy and electricity systems with large shares of variable renewables, *Renewable and Sustainable Energy Reviews* 96 (2018) 440–459. doi:<https://doi.org/10.1016/j.rser.2018.08.002>.

- [34] P. Capros, N. Tasios, A. De Vita, L. Mantzos, L. Paroussos, Model-based analysis of decarbonising the EU economy in the time horizon to 2050, *Energy Strategy Reviews* 1 (2) (2012) 76–84. doi:<https://doi.org/10.1016/j.esr.2012.06.003>.
- [35] K. Löffler, K. Hainsch, T. Burandt, P.-Y. Oei, C. Kemfert, C. Von Hirschhausen, Designing a model for the global energy system—GENeSYS-MOD: an application of the open-source energy modeling system (OSeMOSYS), *Energies* 10 (10) (2017) 1468. doi:<https://doi.org/10.3390/en10101468>.
- [36] S. Backe, M. Korpås, A. Tomasgard, Heat and electric vehicle flexibility in the European power system: A case study of Norwegian energy communities, *International Journal of Electrical Power & Energy Systems* 125 (2021) 106479. doi:<https://doi.org/10.1016/j.ijepes.2020.106479>.
- [37] D. Van Vuuren, P. Lucas, H. Hilderink, D. P. van Vuuren, Downscaling drivers of global environmental change, Enabling use of global SRES scenarios at the national and grid levels. MNP Report 550025001 (2006) 2006.
- [38] J. T. Sherba, B. M. Sleeter, A. W. Davis, O. Parker, Downscaling global land-use/land-cover projections for use in region-level state-and-transition simulation modeling, *AIMS Environmental Science* 2 (3) (2015) 623–647. doi:<http://dx.doi.org/10.3934/environsci.2015.3.623>.
- [39] F. Pretis, M. Roser, Carbon dioxide emission-intensity in climate projections: Comparing the observational record to socio-economic scenarios, *Energy* 135 (2017) 718–725. doi:<https://doi.org/10.1016/j.energy.2017.06.119>.
- [40] Y.-H. Ahn, J.-H. Woo, F. Wagner, S. J. Yoo, Downscaled energy demand projection at the local level using the iterative proportional fitting procedure, *Applied Energy* 238 (2019) 384–400. doi:<https://doi.org/10.1016/j.apenergy.2019.01.051>.

- [41] D. P. van Vuuren, S. J. Smith, K. Riahi, Downscaling socioeconomic and emissions scenarios for global environmental change research: a review, *Wiley Interdisciplinary Reviews: Climate Change* 1 (3) (2010) 393–404. doi:<https://doi.org/10.1002/wcc.50>.
- [42] M. S. Alam, P. Duffy, B. Hyde, A. McNabola, Downscaling national road transport emission to street level: A case study in dublin, ireland, *Journal of Cleaner Production* 183 (2018) 797–809. doi:<https://doi.org/10.1016/j.jclepro.2018.02.206>.
- [43] N. Gerhardt, J. Bard, R. Schmitz, M. Beil, M. Pfennig, T. Kneiske, Hydrogen in the energy system of the future: Focus on heat in buildings, Retrieved from Fraunhofer Institute for Energy Economics and Energy System Technology: <https://www.iee.fraunhofer.de/en/presse-infothek/press-media/overview/2020/Hydrogen-and-Heat-in-Buildings.html> (2020).
- [44] S. Zwickl-Bernhard, H. Auer, Demystifying natural gas distribution grid decommissioning: An open-source approach to local deep decarbonization of urban neighborhoods, *Energy* (2021) 121805doi:<https://doi.org/10.1016/j.energy.2021.121805>.
- [45] T. Fruergaard, T. H. Christensen, T. Astrup, Energy recovery from waste incineration: Assessing the importance of district heating networks, *Waste Management* 30 (7) (2010) 1264–1272. doi:<https://doi.org/10.1016/j.wasman.2010.03.026>.
- [46] J. Sahlin, D. Knutsson, T. Ekvall, Effects of planned expansion of waste incineration in the swedish district heating systems, *Resources, Conservation and Recycling* 41 (4) (2004) 279–292. doi:<https://doi.org/10.1016/j.resconrec.2003.11.002>.
- [47] I. Vallios, T. Tsoutsos, G. Papadakis, Design of biomass district heating systems, *Biomass and bioenergy* 33 (4) (2009) 659–678. doi:<https://doi.org/10.1016/j.biombioe.2008.10.009>.

- [48] K. Ericsson, S. Werner, The introduction and expansion of biomass use in swedish district heating systems, *Biomass and bioenergy* 94 (2016) 57–65. doi:<https://doi.org/10.1016/j.biombioe.2016.08.011>.
- [49] I. G. Jensen, F. Wiese, R. Bramstoft, M. Münster, Potential role of renewable gas in the transition of electricity and district heating systems, *Energy Strategy Reviews* 27 (2020) 100446. doi:<https://doi.org/10.1016/j.esr.2019.100446>.
- [50] P. E. Dodds, I. Staffell, A. D. Hawkes, F. Li, P. Grünewald, W. McDowall, P. Ekins, Hydrogen and fuel cell technologies for heating: A review, *International Journal of Hydrogen Energy* 40 (5) (2015) 2065–2083. doi:<https://doi.org/10.1016/j.ijhydene.2014.11.059>.
- [51] A. Arsalis, Thermodynamic modeling and parametric study of a small-scale natural gas/hydrogen-fueled gas turbine system for decentralized applications, *Sustainable Energy Technologies and Assessments* 36 (2019) 100560. doi:<https://doi.org/10.1016/j.seta.2019.100560>.
- [52] Y. Yang, J. Ren, H. S. Solgaard, D. Xu, T. T. Nguyen, Using multi-criteria analysis to prioritize renewable energy home heating technologies, *Sustainable Energy Technologies and Assessments* 29 (2018) 36–43. doi:<https://doi.org/10.1016/j.seta.2018.06.005>.
- [53] S. A. Kyriakis, P. L. Younger, Towards the increased utilisation of geothermal energy in a district heating network through the use of a heat storage, *Applied Thermal Engineering* 94 (2016) 99–110. doi:<https://doi.org/10.1016/j.applthermaleng.2015.10.094>.
- [54] J. Unternährer, S. Moret, S. Joost, F. Maréchal, Spatial clustering for district heating integration in urban energy systems: Application to geothermal energy, *Applied Energy* 190 (2017) 749–763. doi:<https://doi.org/10.1016/j.apenergy.2016.12.136>.

- [55] J. M. Weinand, M. Kleinebrahm, R. McKenna, K. Mainzer, W. Fichtner, Developing a combinatorial optimisation approach to design district heating networks based on deep geothermal energy, *Applied Energy* 251 (2019) 113367. doi:<https://doi.org/10.1016/j.apenergy.2019.113367>.
- [56] A. Zvoleff, A. S. Kocaman, W. T. Huh, V. Modi, The impact of geography on energy infrastructure costs, *Energy Policy* 37 (10) (2009) 4066–4078. doi:<https://doi.org/10.1016/j.enpol.2009.05.006>.
- [57] M. Abuelnasr, W. El-Khattam, I. Helal, Examining the influence of micro-grids topologies on optimal energy management systems decisions using genetic algorithm, *Ain Shams Engineering Journal* 9 (4) (2018) 2807–2814. doi:<https://doi.org/10.1016/j.asej.2017.09.002>.
- [58] C. Bordin, A. Gordini, D. Vigo, An optimization approach for district heating strategic network design, *European Journal of Operational Research* 252 (1) (2016) 296–307. doi:<https://doi.org/10.1016/j.ejor.2015.12.049>.
- [59] O. Shekoofa, S. Karbasian, Design criteria for electrical power subsystem’s topology selection, in: 2013 6th International Conference on Recent Advances in Space Technologies (RAST), IEEE, 2013, pp. 559–564. doi:<https://doi.org/10.1109/RAST.2013.6581274>.
- [60] A. Allen, G. Henze, K. Baker, G. Pavlak, Evaluation of low-exergy heating and cooling systems and topology optimization for deep energy savings at the urban district level, *Energy Conversion and Management* 222 (2020) 113106. doi:<https://doi.org/10.1016/j.enconman.2020.113106>.
- [61] S. H. Strogatz, Exploring complex networks, *Nature* 410 (6825) (2001) 268–276. doi:<https://doi.org/10.1038/35065725>.
- [62] A. Sanfeliu, K.-S. Fu, A distance measure between attributed relational graphs for pattern recognition, *IEEE transactions on systems, man, and*



- p>cybernetics (3) (1983) 353–362. doi:
- <https://doi.org/10.1109/TSMC.1983.6313167>
- .
- [63] Z. Huang, Link prediction based on graph topology: The predictive value of generalized clustering coefficient, Available at SSRN 1634014 (2010). doi:<https://dx.doi.org/10.2139/ssrn.1634014>.
  - [64] Y. Cui, X. Wang, J. Li, Detecting overlapping communities in networks using the maximal sub-graph and the clustering coefficient, Physica A: Statistical Mechanics and its Applications 405 (2014) 85–91. doi:<https://doi.org/10.1016/j.physa.2014.03.027>.
  - [65] S. F. Nilsson, C. Reidhav, K. Lygnerud, S. Werner, Sparse district-heating in sweden, Applied Energy 85 (7) (2008) 555–564. doi:<https://doi.org/10.1016/j.apenergy.2007.07.011>.
  - [66] I. Dochev, I. Peters, H. Seller, G. K. Schuchardt, Analysing district heating potential with linear heat density. a case study from hamburg., Energy Procedia 149 (2018) 410–419. doi:<https://doi.org/10.1016/j.egypro.2018.08.205>.
  - [67] M. J. Gidden, D. Huppmann, pyam: a python package for the analysis and visualization of models of the interaction of climate, human, and environmental systems, Journal of Open Source Software 4 (33) (2019) 1095. doi:<https://doi.org/10.21105/joss.01095>.
  - [68] D. Huppmann, M. Gidden, Z. Nicholls, J. Hörsch, R. Lamboll, P. Kishimoto, T. Burandt, O. Fricko, E. Byers, J. Kikstra, et al., pyam: Analysis and visualisation of integrated assessment and macro-energy scenarios, Open Research Europe 1 (2021) e74. doi:<https://doi.org/10.12688/openreseurope.13633.1>.
  - [69] A. Hagberg, P. Swart, D. S Chult, Exploring network structure, dynamics, and function using networkx, Tech. rep., Los Alamos National Lab.(LANL),

Los Alamos, NM (United States) (2008).  
URL <https://www.osti.gov/biblio/960616>

- [70] H. Auer, P. C. del Granado, D. Huppmann, P.-Y. Oei, K. Hainsch, K. Löffler, T. Burandt, Quantitative Scenarios for Low Carbon Futures of the Pan-European Energy System, Deliverable D3.1, openENTRANCE, <https://openentrance.eu/> (2020).
- [71] H. Auer, P. C. del Granado, P.-Y. Oei, K. Hainsch, K. Löffler, T. Burandt, D. Huppmann, I. Grabaak, Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5°C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE, *e & i Elektrotechnik und Informationstechnik* (2020) 1–13. doi : <https://doi.org/10.1007/s00502-020-00832-7>.
- [72] T. Burandt, K. Löffler, K. Hainsch, GENeSYS-MOD v2.0 - Enhancing the Global Energy System Model: Model improvements, framework changes, and European data set, Tech. rep., DIW Data Documentation (2018).
- [73] D. Huppmann, E. Kriegler, V. Krey, IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (2019).  
URL <https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/>

## Appendix A. Data and further empirical settings

	Description	Data availability	Data source
GENeSYS-MOD v2.0	Heat generation by source	[73]	[35]
Austrian population density	in 2019		<i>Statistik Austria</i>
Austrian population	in 2050		<i>Eurostat</i>

Table A.1: Empirical data settings