

Downscaling European decarbonization scenarios of the heating sector to the Austrian community level: Assessing the heat density gap of centralized heat networks between 2050 and today

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Abstract

The core objective of this work is to downscale European deep decarbonization scenarios of the heating sector to the Austrian community level in 2050. We use tailor-made downscaling techniques accounting for infrastructure needs of heat sources, the network topology of centralized heat networks, and population density. The results show that centralized heat networks play an important role in the highly efficient heat supply of densely populated areas in 2050. However, the heat density of supply areas is significantly lower than today despite high connection rates (in average greater than 85 %). We identify a heat density gap of at least $7.42 \frac{\text{GWh}}{\text{km}^2}$ considering $10 \frac{\text{GWh}}{\text{km}^2}$ as today's minimum required value. We conclude that future yes/no decisions of centralized heat networks should take enhanced account of the highly efficient use of sustainable and local heat sources in addition to the achievable heat density. Policy-makers should incorporate the development of lower heat densities resulting from decarbonization measures in the benchmarking of centralized heat networks efficiency.

Keywords: Downscaling, Centralized heat networks, Heat density, Network topology, Infrastructure requirements

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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 1.5 °C global warming [2]. Besides climate change mitigation measures, global emission pathways required for this are described.

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 in 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 percent reduction in emissions in 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

29 may look like in 2050 and the implications of the sustainable energy mix for
30 centralized heating networks.

31 The scope of the changes required by 2030/2050 in the heating sector become
32 even clearer at the national level. The average share of renewable energies in
33 the heating and cooling sector 2018 is only just above 20 % on average for all EU
34 member states¹. It is in fact higher in some countries, for example in Austria,
35 where it is 34 %. However, fossil fuels continue to dominate there as well. To
36 be even more specific for the heating sector: of the nearly 4,000,000 residential
37 dwellings in Austria, more than 900,000 are heated with natural gas, and more
38 than 500,000 with oil. If these heating systems are changed to renewable en-
39 ergy by 2050, this corresponds to a retrofitting of 50,000 appliances per year, or
40 more than 130 per day - only in Austria. To achieve this goal, we need a mas-
41 sive expansion of centralized heating (and cooling) networks in addition to the
42 retrofitting of on-site heating end-user devices. Centralized heating networks
43 are particularly advantageous for supplying densely populated or urban areas
44 resulting from high heat densities there [3]. In addition to heat density, the con-
45 nection rate is a key factor influencing the efficiency of district heating/cooling
46 networks and thus their implementation. For example, currently in Austria,
47 at a connection rate of 90 %, 10 GWh/km² is a rough guide for supplying an
48 area with district heating². The reference value of 10 GWh/km² is in line with
49 findings regarding district heating networks also from the Scandinavian region
50 (Denmark, Sweden, and Finland) [4]. These are rough estimates, but they do
51 allow an initial assessment of the economic viability or feasibility of a district
52 heating network. If one goes into more detail when considering and evaluating
53 district heating networks, numerous factors play a decisive role. Nussbaumer
54 and Thalmann [5] thoroughly elaborate on the network design and its impact on
55 the profitability of centralized heat networks. Laasasenaho et al. [6] emphasize
56 in their study the optimal location of heat generation units/sources within cen-

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

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

57 tralized heat networks enabling a cost-optimized heat supply. Gopalakrishnan
 58 and Kosanovic [7] focus in their study on the optimal heat generation technology
 59 dispatch. When examining the economic viability of district heating networks,
 60 building renovation measures must also be taken into account (see, e.g., in [8]
 61 and [9]). These reduce the heat demand and thus the heat density. However,
 62 studies show that a reduction in heat density is not necessarily a barrier to dis-
 63 trict heating networks [10]. Reidhav and Werner [11] show in their study how
 64 energy taxes can improve the profitability of sparse district heating networks
 65 in Sweden. Following these considerations and in light of ambitious CO₂ re-
 66 duction targets, it can also be assumed that the rising CO₂ price can have a
 67 similar effect as the energy tax. Of course, this is only valid in the case of deep
 68 decarbonization of the generation mix feeding into centralized heat networks.
 69 And, also the increasing demand for cooling or the co-design of centralized net-
 70 works for heating and cooling can increase the economic viability of these and
 71 counteract the reduction of heat density from an economic point of view [12].

72 However, the concrete implementation to achieve predefined climate change mit-
 73 igation goals still is lacking in many cases. For this reason, numerous studies
 74 go beyond and show roadmaps for the rapid decarbonization of the system. For
 75 example, Rockström et al. [13] conduct such a study and propose pathways for
 76 halving gross anthropogenic CO₂ emissions every decade. Other works go into
 77 more depth regarding optimal solutions for the decarbonization of individual
 78 energy services. There are relevant differences between the individual sectors of
 79 the energy system related to decarbonization. How a sustainable energy service
 80 can be provided in the different sectors must therefore be examined in detail.
 81 This perspective is supported by a large number of detailed decarbonization
 82 studies covering specific energy service needs (e.g., for the building sector Lei-
 83 bowicz et al. [14], transport sector Pan et al. [15], and industries Habert et al.
 84 [16]).

85 Despite all the details associated with the sector-specific decarbonization strate-
 86 gies, the principles of a net-zero society base on three key points: (i) deployment

87 and generation of renewable energy technologies (see, e.g., Bakhtavar et al. [17]
 88 focusing on net-zero districts by deployment of renewable energy generation),
 89 (ii) reduction of the energy demand (see, e.g., Oshiro et al. [18] analyzing the
 90 impact of energy service demand reduction on the decarbonization and Grubler
 91 et al. [19] investigating a low energy demand decarbonization scenario), and
 92 (iii) increase in efficiency regarding the provision of energy services and the as-
 93 sociated optimal utilization of sustainable energy sources. The third point (iii)
 94 includes, among others, two main aspects, namely, on the one hand, that po-
 95 tentials of renewable resources are exploited locally and on the other hand that
 96 energy carriers with various fields of application are utilized with the highest
 97 possible efficiency. We like to refer to just a few selected references without
 98 claiming to be exhaustive and focus here on hydrogen as one example of an en-
 99 ergy carrier with high potentials in sustainable energy systems and a significant
 100 bandwidth of efficiency in terms of its generation and use. Van Ruijven et al. [20]
 101 highlight that the introduction of hydrogen in global energy systems only leads
 102 to lower emissions with high end-use efficiency and low-carbon production. Van
 103 Ressen [21] systematically investigates the possibilities and challenges of hydro-
 104 gen and discusses extensively its role in the energy transition. Recently, Böhm
 105 et al. [22] comprehensively elaborate on hydrogen-related synergies and its role
 106 in sustainable heat supply. Thus, it is necessary to develop optimal strategies
 107 ensuring the utilization of renewable energy sources prioritized and in the most
 108 efficient way related to the provision of energy service needs.

109 In many cases when it comes to the question of optimal solutions, researcher
 110 uses numerical models. In general, these models strike a balance between com-
 111 plexity and aggregation. Integrated assessment models (IAMs) are large numer-
 112 ical models covering complex interrelations between climate, society, economics,
 113 policy, and technology. Dowlatabadi [23] provided 1995 a fundamental review
 114 on IAMs focusing on their role in the context of climate change. Krey et al.
 115 [24] discuss and systematically compare different IAMs. Harmsen et al. [25]
 116 elaborates on the modeling behaviour of IAMs. Wilkerson et al. [26] and van

117 Vuuren et al. [27] deal with IAMs and their role in understanding global energy
 118 decarbonization pathways. In particular, both studies examine CO₂ budget and
 119 price developments. Schwanitz [28] evaluates IAMs of global climate change and
 120 discusses, among others, the appropriate level of regional (spatial) aggregation
 121 of countries in the modeling analysis. Generalizing this aspect reveals an as-
 122 pect already known but essential in the context of large numerical models. It
 123 becomes necessary for modelers to set priorities regarding the level of detail,
 124 which inevitably creates trade-offs in the analysis regarding the granularity of
 125 the temporal, spatial, and other dimensions. Gambhir et al. [29] also highlight
 126 this aspect of aggregation bias in their critical review of IAMs. They propose,
 127 among others, that IAMs should be increasingly be supplemented with other
 128 models and analytical approaches. Not least for this reason, (large) energy mod-
 129 els also play a significant role in the analysis of energy systems in the context of
 130 climate change. Compared to IAMs, they more strongly emphasize the level of
 131 detail in terms of techno-economic characteristics (see the review of modeling
 132 tools of energy systems in [30]). However, the lack of granularity remains, that
 133 these (global) energy models consider only a highly aggregated spatial resolu-
 134 tion. To name just two selected approaches, Capros et al. [31] (PRIMES) and
 135 Löffler et al. [32] (GENeSYS-MOD) provide energy system models focusing on
 136 the European energy system with a spatial resolution on the country level. Fur-
 137 ther approaches are needed to disaggregate results obtained at the country level
 138 to finer scales, such as districts, neighborhoods, and other local levels. In this
 139 context, Backe et al. [33] provided a novel approach in the context of merging
 140 local activities/behavior in sustainable local communities into a large energy
 141 system model (bottom-up linkage). In their study, they integrated local flex-
 142 ibility options into the global energy system model EMPIRE, which provides
 143 in principle only country-level resolution. This and other work confirms the
 144 emerging trend of making top-down and bottom-up linkages between different
 145 spatial-temporal levels of resolution to drive decarbonization across all sectors.
 146 Against this background, the core objective of this work is the downscaling

147 of decarbonization scenarios of the residential and commercial heating sector,
148 taking into account the infrastructure requirements of heat generation technolo-
149 gies/sources from the country to the local level. In particular, the prioritized
150 preference of heat sources in centralized heat networks plays a key role, ensuring
151 highly efficient usage of heat sources covering heat service needs. The assess-
152 ment of centralized heat networks using heat density as a criterion is important
153 in this analysis. An Austrian case study is proposed, downscaling values of the
154 heating sector in 2050, obtained from the large numerical energy system model
155 GENeSYS-MOD, from the country to 2095 local communities.

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

171 2. Materials and methods

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

179 2.1. Proportional spatial downscaling using population as a proxy

180 Proportional downscaling is a well-established technique and is commonly used.
181 The fields of application are not limited to the modeling of energy systems.
182 Moreover, it is applied in different fields of scientific and practical studies. The
183 reason for this is the intuitive application and that it offers possibilities for tailor-
184 made adaptations, in particular, related to the downscaling driver and proxy,
185 respectively [34]. In this context, van Vuuren et al. [34] provide a comprehensive
186 analysis of different proxies for the downscaling of global environmental change,
187 including, among others, gross domestic product (GDP) and emissions as a
188 proxy. Sherba et al. [35] focus in their study on the downscaling of global
189 land use projections and use the characteristic and distribution of land area as
190 a proxy. Pretis and Roser [36] disaggregate in their study growth rates from
191 the global level using emission intensity as a proxy. However, in the context of
192 downscaling aggregated values of energy systems, one often finds proportional
193 downscaling using population as a proxy (see, e.g., Ahn et al. [37], van Vuuren
194 et al. [38], and Alam et al. [39]). In this work, we also use this proxy and
195 proportional downscaling and thus obtain a reference for comparing our novel
196 developed methods. Equation 1 shows the basic expression of proportional
197 downscaling, exemplarily, for the disaggregation of the energy demand d from
198 the country to the local level, using population p as a proxy.

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

For further information, we refer the reader here to the study in [38], providing a systematic classification of downscaling techniques going far beyond the basic proportional downscaling technique discussed so far. The reader can find population-based downscaling in their classification in the category 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. Since at least the term sub-region can be understood differently, we use the definition of the European nomenclature of territorial units for statistics³ (NUTS). The country-level corresponds to the NUTS0, and the sub-region level corresponds to NUTS3. Table 1 provides an overview of the NUTS nomenclature for Austria. Considering our Austrian case study, we downscale with the sequential downscaling algorithm from one NUTS0 region (country level) to 35 NUTS3 regions.

The purpose of the sequential downscaling algorithm is to provide a downscaling technique that considers the prioritized preferences of some heat generation technologies/sources as co-firing in cogeneration plants. Thus, these 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

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

NUTS classification	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: Nomenclature of spatial areas using the Austrian NUTS nomenclature. The gray highlighted rows mark the aggregated or disaggregated spatial levels of the sequential or iterative downscaling algorithm.

network/infrastructure requirements. From this, the types of sub-regions used for downscaling the corresponding heat source are marked. Note that the different types are characterized by population density.

<u>Source</u>	<u>Requirements</u>	Rural	Town/Mixed	Urban	Reference
Heat technology	Heat network	Sparsely	Moderate	Dense	
Biomass	Middle		x	x	[40, 41, 42]
Direct electric	None	x	x	x	
Synthetic gas	Low	x	x	x	
Hydrogen	High			x	[43, 44, 45]
Heat pump (air)	None	x	x	x	
Heat pump (ground)	High			x	[46, 47, 48]
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.

For example, direct electric is characterized as a heat generation technology with no heat network requirements. Hence, it is downscaled to all types of sub-regions. In contrast, hydrogen is a heat generation source with high requirements and thus prioritized preferences (marked by the gray cell color) in densely populated areas using centralized heat networks. The right column refers to references that support these assumptions.

Building on this prioritization of heat sources considered in the downscaling, the sequential downscaling algorithm is presented on page 12. 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).

Algorithm 1: Sequential downscaling algorithm (NUTS0 to NUTS3)

```

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      $demand = 0$ ; // Reamining demand that needs to be covered
8      $R' = R \setminus \{\forall r \in R : \pi_r \leq \sigma_t\}$ ; // 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

```

239 The algorithm itself consists of three main parts: initialization, pre-calculations,
 240 and downscaling. First, the initialization of the algorithm sorts the heat gener-
 241 ation technologies/sources in descending order in terms of network infrastruc-
 242 ture requirements. Then the calculation starts with the first technology/source
 243 (highest requirements) (line 5). For this technology/source, all possible sub-
 244 regions are collected (line 8). Those sub-regions already fully supplied (no re-
 245 maining heat demand) are filtered out (line 10). After further pre-calculation
 246 steps, the available amount of heat generation is downscaled to all valid sub-
 247 regions (lines 11 and 15) using population as a proxy (line 16). This procedure
 248 is repeated sequentially for each heat technology/source. The output of the
 249 sequential downscaling algorithm are heat generation by source and the amount
 250 of heat demand covered by centralized heat networks on the NUTS3 level (in
 251 the Austrian case 35 different sub-regions).

252 *2.3. Iterative downscaling (from the sub-region to the small sub-region level)*

253 This section explains the methodology of the iterative downscaling algorithm.
 254 We propose this downscaling technique translating heat generation by technol-
 255 ogy/source from the sub-region (NUTS3) to the community level (LAU) (see
 256 Table 1). This in-depth spatial resolution is imperative for realistic network
 257 infrastructure planning [49]. The underlying concept of iterative downscaling
 258 bases on graph theory and assessing network topology using benchmark indica-
 259 tors.

Algorithm 2: Iterative downscaling algorithm

```

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

```

260

261 *2.3.1. Algorithm description*

262 The iterative downscaling algorithm is presented on page 14. The idea is to
263 assess, benchmark, and improve the topology of centralized heat networks. This
264 is achieved in our proposed approach by iterative downscaling. Essentially, the
265 main steps of the algorithm can be summarized as follows:

- 266 1. Downscale the results of the sequential downscaling algorithm from NUT3
267 to the LAU level using population as downscaling driver obtaining the
268 initial heat network graph G^0 (input)
- 269 2. Benchmark each node of the heat network graph (line 11), identify node
270 with the lowest indicator value and remove the node from the graph gen-
271 erating a reduced heat network graph (lines 13 and 14)
- 272 3. Reallocate centralized and on-site heat generation for all nodes (lines 22
273 and 23)
- 274 4. Recalculate benchmark indicator value for all remaining nodes within the
275 network graph (line 27)
- 276 5. Compare the average value of the indicator value of the initial and reduced
277 heat network graph (lines 28 and 29)
- 278 6. Update heat network graph in case of an higher average indicator value and
279 jump to step 2. Otherwise, the termination of the algorithm is achieved.

280 Recent studies support this approach focused on the topography of energy sys-
281 tems and networks (see for example in [50]). Bordin et al. [51] conduct an
282 approach for the optimized strategic network design of centralized heat sys-
283 tems. In any case, the topography of supply areas plays an important role not
284 only in centralized heat supply. Therefore, another look at approaches in general
285 in the context of energy systems is worthwhile here. We refer here to Shekoofa
286 and Karbasian [52] focusing in their study on design criteria for electrical power
287 systems' topology selection. Many further contributions can be found in the
288 literature. However, the underlying concept of these studies can be applied to
289 the heating system and in particular to the topography of centralized heat net-
290 works. Allen et al. [53] 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 14) 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 [54]. Moreover, we refer the reader to the study in [55] 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, 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 [56] comprehensively deals with cluster coefficients and provides related generalized concepts. In addition, relevant aspects of the cluster(ing) coefficient is shown in [57]. 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

317 aspects are so considered in the benchmarking process. (i) a high connection
318 rate to the centralized heat network and (ii) a connection of those areas to the
319 network which has a high heat demand and heat density, respectively. Both
320 aspects are investigated in the literature. For example, Nilsson et al. [58] focus
321 in their study on the importance of the connection rate of centralized heat
322 networks. Besides, Dochev et al. [59] investigate in their study the impact of
323 linearly decreasing heat densities and the influence on the profitability of the
324 centralized heat networks.

325 *2.4. Development of an open-source package building upon pyam*

326 The described method will be released as an open-source python package in the
327 course of publishing this work at the author's GitHub account. In this package,
328 we build upon the existing open-source python package *pyam* [60]. *Pyam* is an
329 open-source package for the analysis and visualization of integrated assessment
330 and macro-energy scenarios [61]. In this work here, it is used in particular used
331 for (i) the linkage between the sequential and the iterative downscaling algo-
332 rithm, (ii) for the internal calculation steps within both downscaling algorithms,
333 and (iii) for the visualization of the results. Besides, we used the open-source
334 python package *networkx* [62], when implementing the iterative downscaling
335 algorithm. We refer to the repository for the codebase, data collection, and
336 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 [63] and [64]. Further informations also are available on the website of the project ⁴

⁴<https://openentrance.eu/>

364 and GitHub⁵.

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

- 371 • *Directed Transition* looks at a sustainable provision of energy services
372 through strong policy incentives. This bundle of actions becomes neces-
373 sary because neither the markets nor society adequately pushes sustainable
374 energy technologies.
- 375 • *Societal Commitment* achieves deep decarbonization of the energy sys-
376 tem by a strong societal acceptance of the sustainable energy transition.
377 Thereby, decentralized renewable energy technologies together with policy
378 incentives lead to a sustainable supply of energy service needs. Parallel,
379 no fundamental breakthroughs of new clean technologies are within sight.
- 380 • *Techno-Friendly* describes a development of the energy system where a
381 significant market-driven breakthrough of renewable energy technologies
382 gives rise to the decarbonization of energy service supply. Alongside, soci-
383 ety acceptance supports the penetration of clean energy technologies and
384 the sustainable transition.
- 385 • *Gradual Development* differs from the other storylines as on the one hand,
386 this storyline only aims for the less ambitious 2.0 °C climate target, and
387 on the other hand, a little of each possible sustainable development of the
388 energy system is described here. While all three dimensions contribute
389 to decarbonization, they do not push it sufficiently and result in a more
390 conservative storyline than the others.

⁵<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 [65]. 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 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								Σ
		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 re-
 sulting 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 cen-
 tralized 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 central-
 ized 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 differ-
 ent 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,

Heat generation on the country, sub-region, and community level

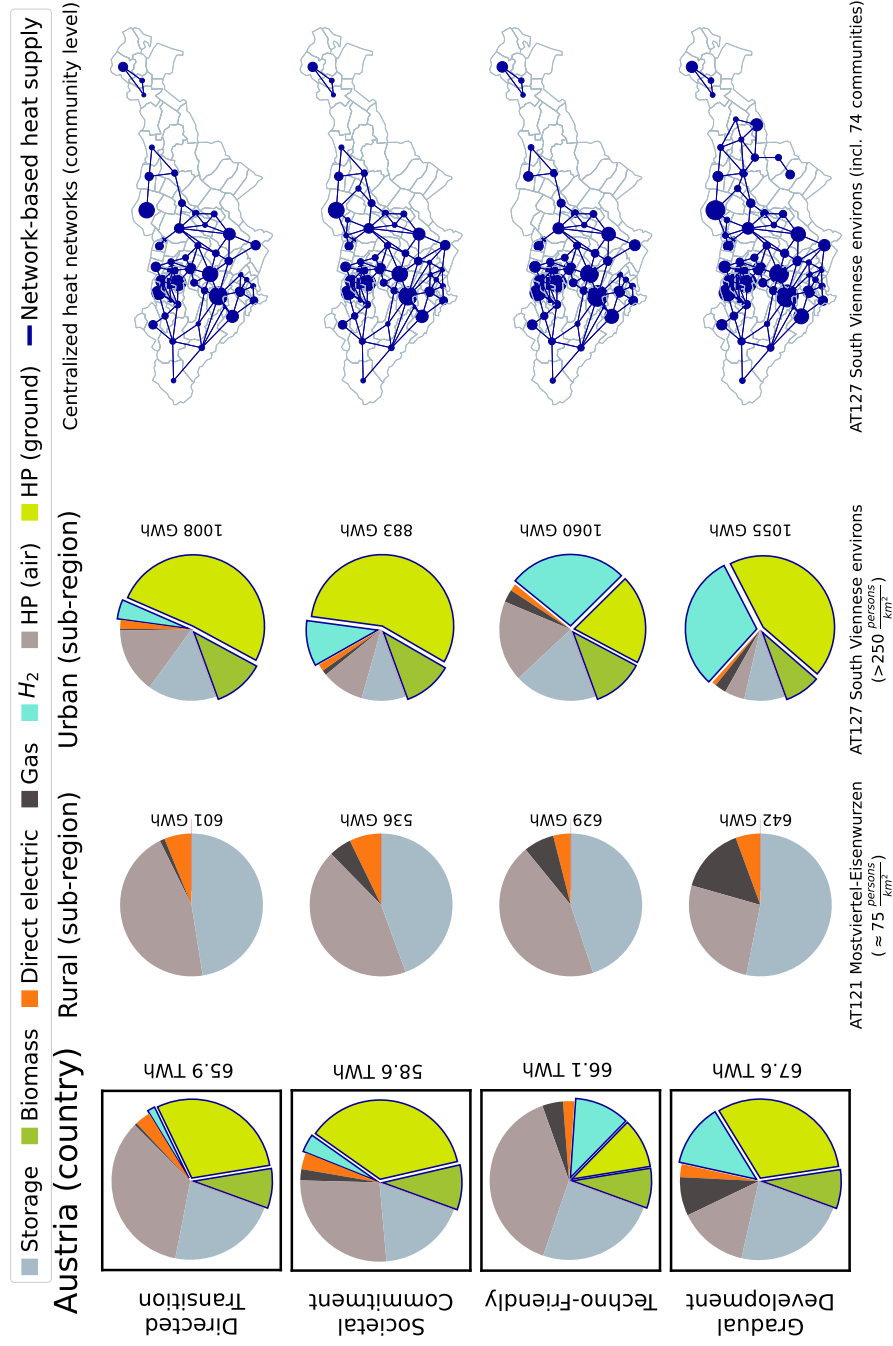


Figure 1: Heat technology generation on different spatial granularity levels in the different scenarios supplying the residential and commercial heat demand. left: on the country level. middle: comparison of a rural and urban sub-region. right: centralized heat network topology (size of the points represent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

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

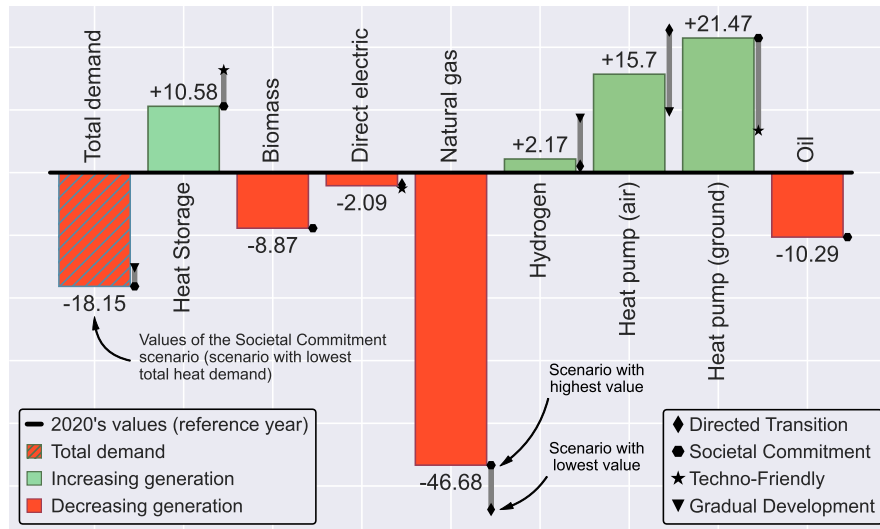


Figure 2: Comparison of heat generation by source between the reference year 2020 (black line) and 2050 in Austria. The height of the bars shows the absolute increase/decrease 2050 in the *Societal Commitment* scenario. The scenario with the lowest and highest difference, respectively, is indicated by 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/km² (AT323 - Salzburg and surroundings) and 5124 persons/km² (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

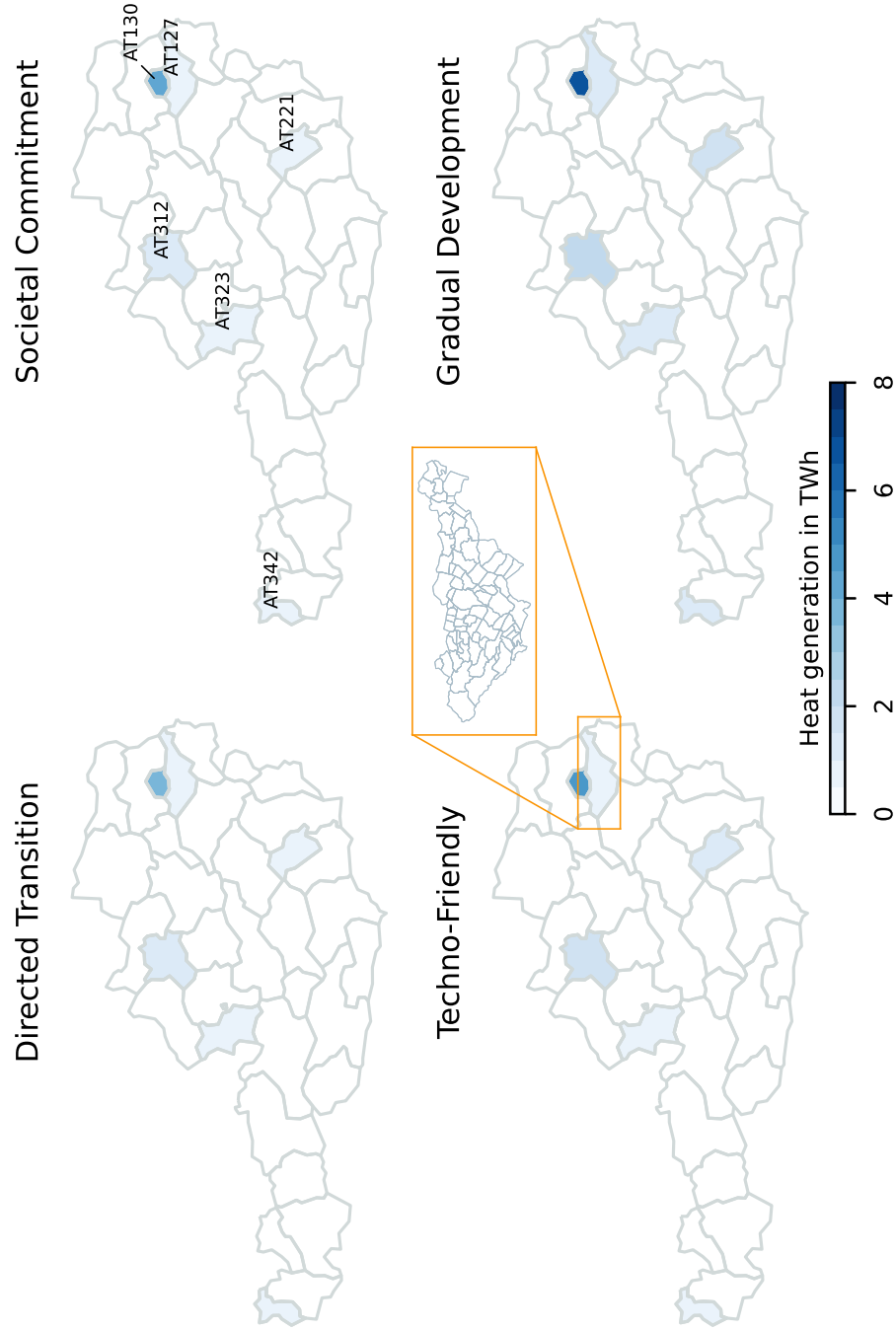


Figure 3: Centralized heat supply in Austria 2050

Centralized heat network topology improves by reducing supply area

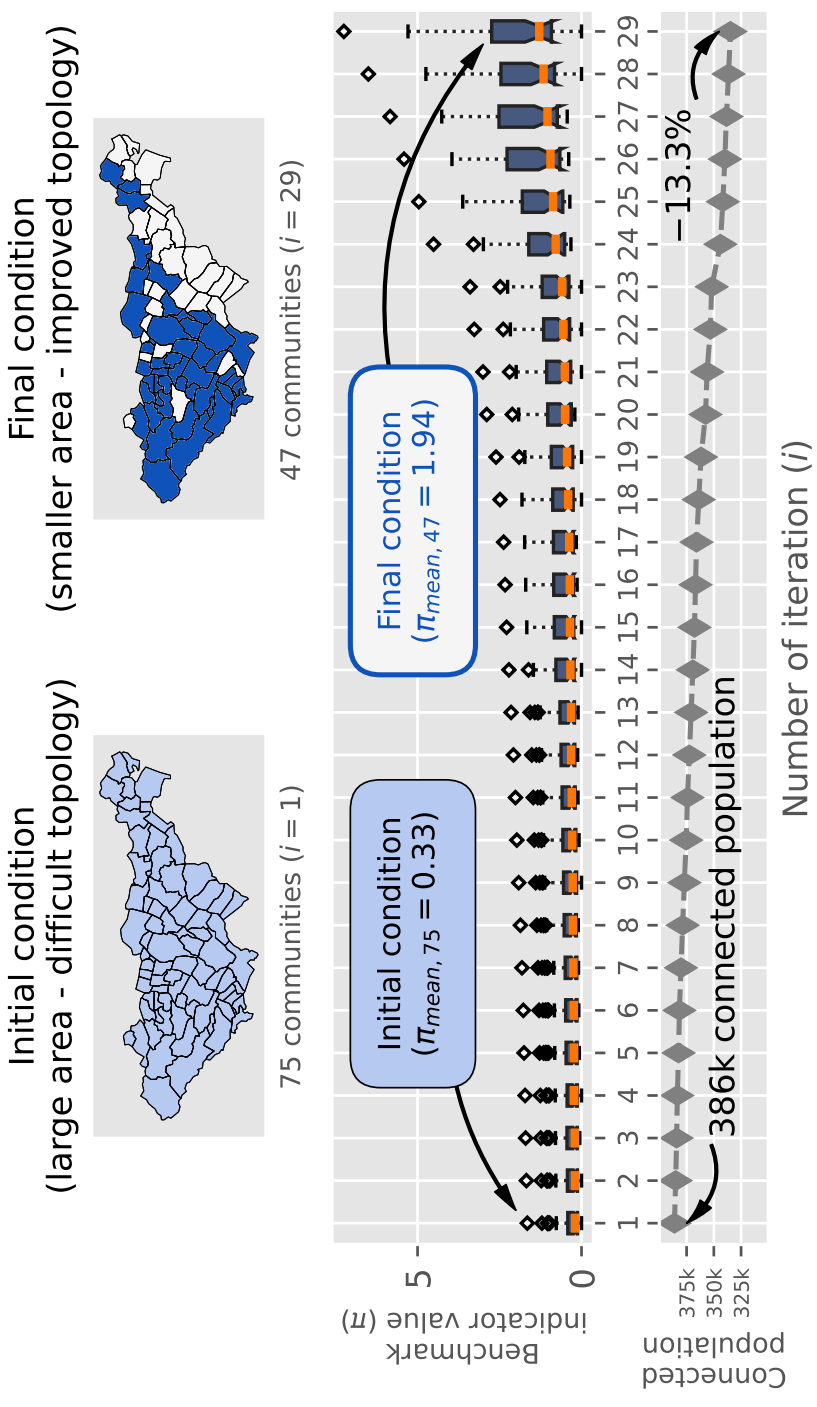


Figure 4: Centralized heat network topology in the initial and final condition. The boxplot (middle) indicates the improved network topology by an increasing benchmark indicator mean value (orange line). In the final condition, the connected population declines by -13.3% compared to the initial condition.

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.

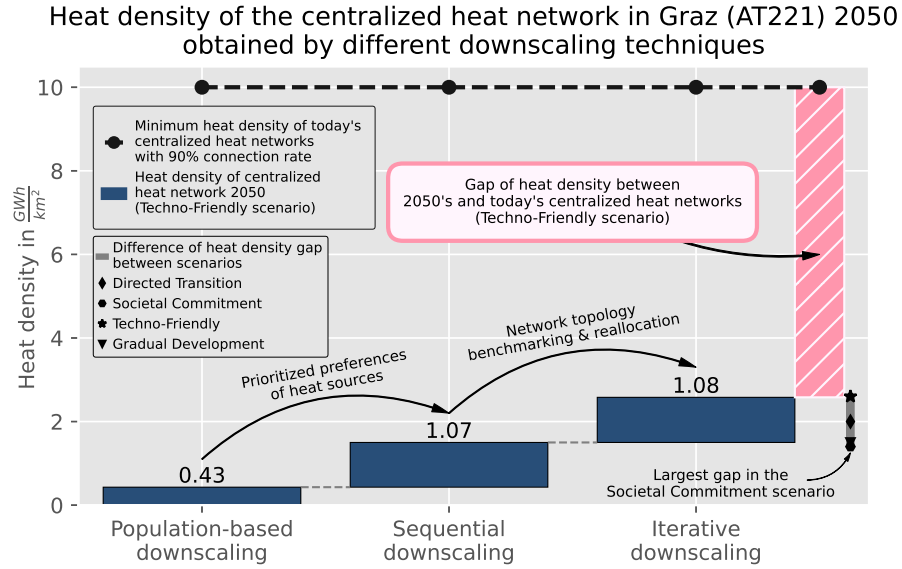


Figure 5: Heat density of the centralized heat network in *Graz* (AT221) 2050 in the *Techno-Friendly* scenario. The gap of heat density between 2050's and today's heat density (black dashed line) is marked by the pink bar. The differences of the heat density gap between the scenarios is marked by the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

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

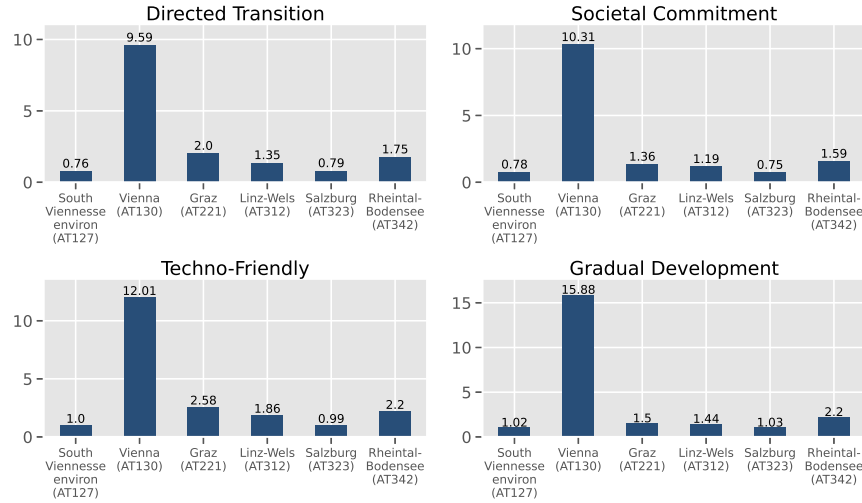


Figure 6: Heat densities (blue bars) of centralized heat networks in the six Austrian sub-regions and in the four different decarbonization scenarios.

493 4. Conclusions and outlook

494 The sustainable energy transition requires methods to bridge the gap between
495 global plans and implications and processes on the local level. Techniques for
496 downscaling of global decarbonization scenarios to finer scales will become in-
497 creasingly important in the future. Thereby, energy-policy makers have to rely
498 on the meaningfulness of the downscaled values, which requires tailor-made
499 downscaling techniques for the different fields of energy systems. This work
500 emphasizes a downscaling technique for the residential and commercial heating
501 sector, taking into account the technology-specific requirements of heat network
502 infrastructure accounting for the highly efficient use of energy carriers. In par-
503 ticular, the proposed downscaling techniques reveal the potentials of centralized
504 heat supply in four different European decarbonization scenarios on a high spa-
505 tial granularity.

506
507 Results indicate that centralized heat systems undergo a fundamental shift go-
508 ing beyond the decarbonization of the supplying energy mix. In particular, the
509 reduction of heat density of centralized heat networks compared to today’s net-
510 works poses massive challenges to heat supply companies and fundamentally
511 jeopardizes associated business models. At the same time, however, the heat
512 network infrastructure may play a crucial role in expected energy systems since
513 both use of local energy sources efficiently and on a large scale (e.g., geothermal
514 sources, waste incineration, waste heat from industry, etc.) and unburden the
515 electricity sector taking into account the aim of high electrification of different
516 energy services. These trade-offs should be given greater consideration in the
517 future and may have implications for the regulation and benchmarking of heat
518 supply companies that provide centralized heat network infrastructure.

519
520 Future work may address improvements of the proposed downscaling technique
521 for the heating sector, taking into account a finer scale of spatial granularity,
522 extensions of the introduced benchmarking of centralized heat networks using

523 indicator values in the context of heat sources and local characteristics, higher
524 resolution of the heat generation technologies/sources in terms of requirements
525 for heat network infrastructure, and a detailed cost-benefit analysis of the cen-
526 tralized heat systems obtained by the downscaling (e.g., distribution line capac-
527 ities, connection capacities to the public grid, etc.).

528 **Declaration of interests**

529 None.

530 **Declaration of Competing Interest**

531 The authors report no declarations of interest.

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799 **Appendix A. Data and further empirical settings**

	Description	Data availability	Data source
GENeSYS-MOD v2.0	Heat generation by source	[66]	[32]
Austrian population density	in 2019	<i>Statistik Austria</i>	as availability
Austrian population	in 2050	<i>Eurostat</i>	as availability

Table A.1: Empirical data settings