

# Downscaling European decarbonization scenarios of the heating sector: An open-source approach assessing centralized heat networks in Austria 2050

Sebastian Zwickl-Bernhard<sup>a,\*</sup>, Daniel Huppmann<sup>b</sup>, Antonia Golab<sup>a</sup>, Hans Auer<sup>a</sup>

<sup>a</sup>*Energy Economics Group (EEG), Technische Universität Wien, Gusshausstrasse 25-29/E370-3, 1040 Wien, Austria*

<sup>b</sup>*Energy, Climate and Environment (ECE) Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*

---

## Abstract

*Keywords:*

---

---

\*Corresponding author

Email address: [zwickl@eeg.tuwien.ac.at](mailto:zwickl@eeg.tuwien.ac.at) (Sebastian Zwickl-Bernhard)

## 1. Introduction

Climate change and its already apparent negative effects are likely to be the greatest challenge of humanity - both today and in the next decades [1]. What is encouraging in this regard, however, is that humanity has recently built a deep understanding of existing natural [2] and human-influence solutions to mitigate climate change and global warming. At the same time, studies show that two-thirds of impacts with regard to the increase of global temperature (atmospheric and ocean) can be attributed to anthropogenic activities [3]. Thus, to speak of natural variability is far from justified. There is already a broad consensus to make it our prioritized concern to reduce anthropogenic emissions and get them down to net-zero rapidly.

In the field of a sustainable energy system, the scientific community has produced a large number of strategies, recommendations, and studies aimed at contributing to the achievement of climate change mitigation and the clean energy transition. First and foremost, the reports of the Intergovernmental Panel on Climate Change (IPCC) [4], and the Paris Agreement [5] but also many others. However, the concrete implementation to achieve the predefined 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. [6] 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. [7], transport sector Pan et al. [8], and industries Habert et al. [9]).

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. [10] focusing on net-zero districts by deployment of renewable energy generation), (ii) reduction of the energy demand (see, e.g., Oshiro et al. [11] analyzing the impact of energy service demand reduction on the decarbonization and Grubler et al. [12] 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. [13] 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 [14] systematically investigates the possibilities and challenges of hydrogen and discusses extensively its role in the energy transition. 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.

In many cases when it comes to the question of optimal solutions, academic 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 [15] provided 1995 a fundamental review on IAMs focusing on their role in the context of climate change. Krey et al. [16] discuss and systematically compare different IAMs. Harmsen et al. [17] elabo-

rates on the modeling behaviour of IAMs. Wilkerson et al. [18] and van Vuuren et al. [19] 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. Huppmann et al. [20] provide an open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. Schwanitz [21] 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. [22] also highlight this aspect of aggregation bias in their critical review of IAMs. They propose, among others, that IAMs should 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 [23]). However, the lack of granularity remains resulting, that these (global) energy models consider only a highly aggregated spatial resolution. To name just two selected approaches, Capros et al. [24] (PRIMES) and Löffler et al. [25] (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. [26] 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 the downscaling of decarbonization scenarios of the residential and commercial heating sector, taking into account the infrastructure requirements of heat generation technologies/sources from the country to the local level. In particular, the prioritized preference of heat sources in centralized heat networks plays a key role, ensuring highly efficient usage of heat sources covering heat service needs. The assessment of centralized heat networks using heat density as a criterion is important in this analysis.

The method applied is the development of two scenario-independent downscaling techniques. As the first, an sequential downscaling approach is presented, disaggregating from the country level to different sub-regions. Thereby, population density and the infrastructure requirements of heat technologies serve as additional criterion in the downscaling. As the second, an iterative downscaling algorithm is presented. This algorithm bases on graph-theory benchmarking and projects centralized heat supply on the local level. An Austrian case study is proposed, downscaling four different decarbonization scenarios, obtained from the large numerical energy system model GENeSYS-MOD, from the country to 2095 local districts. In particular, the focus is put on the year 2050.

This paper is organized as follows. Section 2 explains the method including the description of the different downscaling techniques (Section 2.1 default downscaling method using population as criteria, Section 2.2 sequential, and Section 2.3 iterative downscaling). Section 3 presents and discusses the results of this work. Section 3.1 and 3.2 showing heat generation by source on different spatial levels. Section 3.3 and 3.4 presenting 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. In the beginning, we motivate downscaling in the context of decarbonization scenarios and elaborate on different approaches for disaggregation. Thereby, Section 2.1 deals with population-based downscaling since this technique is a well-established and often used approach. Based on this, Section 2.2 presents the sequential downscaling and Section 2.3 the iterative downscaling algorithm in detail. Section 2.4 concludes this section and highlights the proposed open-source approach building upon the analysis and visualization toolbox *pyam* and other open-source software packages.

As already stated in the introduction of this work, downscaling is crucial related to climate change mitigation. It enables the opportunity to map aggregated values from a high level to a finer scale. For example, van Vuuren et al. [27] provide a review of downscaling socio-economic and emissions scenarios for global environmental research. They showed that in recent years novel methods and approaches for downscaling have been improved. In addition, Gaffin et al. [28] focus in their analysis on downscaling of socio-economic projections from the IPCC Special Report on emission scenarios. See also Gidden et al. [29] focusing on global emission pathways under different socio-economic scenarios.

In principle, downscaling can be used for temporal and spatial disaggregation. Considering the scope of this work, Michel et al. [30] recently published a study where they focus on downscaling of climate change scenarios on the country level and proposed an enhanced temporal downscaling approach. Spatial downscaling to the country level is exemplarily shown by Sferra et al. in [31]. As already indicated, there has been a considerable amount of methodological development in spatial downscaling. At the same time, well-established methods, such as proportional downscaling for spatial disaggregation, are often used in studies. The reason for this is that it is a simple method that is intuitive and easy to

apply in different fields.

### *2.1. Proportional spatial downscaling using population as downscaling driver*

We are consistent with existing approaches for spatial disaggregation and use proportional downscaling as a downscaling reference technique and for comparison. In general, different parameters can be used as a downscaling driver (proxy). In this work, we use population as a proxy. Equation 1 shows the proportional downscaling, for example, of the energy demand  $d$  from the country to the local level using population  $p$  as a proxy.

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

Other parameters can also serve as a proxy (for example, gross domestic product (GDP) and emissions [32]). However, we focus on the population as a downscaling driver and do not go further into other proxy parameters. We refer the reader to the literature for more information in the context of different proxies and related approaches (e.g., [33] and [27]). Moreover, van Vuuren et al. provide in the latter systematic classification of downscaling techniques going far beyond the default population-based downscaling discussed here. The reader can find population-based downscaling in their described classification in the category algorithmic and proportional downscaling. In this work, we stay as mentioned by the agreed approach using population. There are two main reasons for this. First, the availability of data related to future population projections on the one hand and the consistency with the two novels developed downscaling techniques in this work since their base fundamentally on population density as an additional criterion on the other hand.

### *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 def-

inition of the European nomenclature of territorial units for statistics<sup>1</sup> (NUTS). The country-level corresponds to the NUTS0, and the sub-region level corresponds to NUTS3. Considering our Austrian case study, we downscale here from the country level (AT) to 35 different Austrian sub-regions (e.g., AT127).

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 1 provides a qualitative overview of the different heat generation technologies/sources and their heat 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     | [34, 35, 36] |
| Direct electric    | None                | x        | x          | x     |              |
| Synthetic gas      | Low                 | x        | x          | x     |              |
| Hydrogen           | High                |          |            | x     | [37, 38]     |
| Heat pump (air)    | None                | x        | x          | x     |              |
| Heat pump (ground) | High                |          |            | x     | [39, 40, 41] |
| Heat storage       | None                | x        | x          | x     |              |

Table 1: 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 prioritized preferences. Hence, it is downscaled to all types of sub-

<sup>1</sup><https://ec.europa.eu/eurostat/web/nuts/background>.



regions. In contrast, hydrogen is a heat generation source that has prioritized preferences in densely populated areas using centralized heat networks. The prioritized preference of sub-regions in the downscaling is marked by the gray cell color. The right column refers to references that support the assumptions in terms of prioritized use heat sources in centralized heat networks.

---

**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

```

---

Building on this prioritization of heat sources considered in the downscaling, the sequential downscaling algorithm is presented on page 9. 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 1). 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 small sub-region 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 small sub-region level. This finer scale corresponds to the local administrative unit (LAU) of the NUTS definition (2095 small sub-regions in the Austrian case study). The underlying concept of iterative downscaling bases on graph theory and assessing network topology using benchmark indicators.

---

**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

```

---

### 2.3.1. Algorithm description

The iterative downscaling algorithm is presented on page 11. 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 [42]). Bordin et al. [43] 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 [44] 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. [45] 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 11) 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 [46]. Moreover, we refer the reader to the study in [47] 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 [48] comprehensively deals with cluster coefficients and provides related generalized concepts. In addition, relevant aspects of the cluster(ing) coefficient is shown in [49]. 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. [50] focus in their study on the importance of the connection rate of centralized heat networks. Besides, Dochev et al. [51] 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* [52]. *Pyam* is an open-source package for the analysis and visualization of integrated assessment and macro-energy scenarios [53]. 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* [54], especially 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 conducted Austrian case study in 2050. 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 of the supply of the residential and commercial heat demand on the country level. Section 3.2 provides a finer scale and presents the heat generation mix on the sub-region and small-subregion level. Section 3.3 presents the potentials of centralized heat supply on the sub-region level. Section 3.4 shows the centralized heat networks on the small sub-region level. Finally, Section 3.5 compares the obtained centralized heat networks in 2050 with today's networks using heat density as the criterion.

#### *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 and takes into account the 2.0°C 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 [55] and [56]. Fur-

ther informations also are available at the website of the project <sup>2</sup> and GitHub.<sup>3</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

---

<sup>2</sup><https://openentrance.eu/>

<sup>3</sup><https://github.com/openENTRANCE>



to decarbonization, they do not push it sufficiently and result in a more conservative storyline than the others.

Table 2 shows the heat generation by technology/source in Austria 2050 for the four different storylines. As mentioned, these values are obtained from the H2020 project openENTRANCE and are the modeling results from the open-source model GENeSYS-MODv2.0 [57]. 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<br>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 2: 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 the country (NUTS0), sub-region (NUTS3) and small sub-region (LAU) level (from left to right). Thus, 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 (NUTS3 code AT121 (Mostviertel-Eisenwurzen)) shows high shares of heat pumps (air sourced) and small-scale heat storage systems. In addition, synthetic gas and direct electric heating systems supply the heat demand. The urban sub-region (NUTS3 code AT127 (South Viennese environs)) 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 figure, shares of heat generation using centralized heat networks are marked by the blue-colored edge. On the very right, an example of the resulting centralized heat network on the small sub-region level for the four different scenarios is presented. In the four subfigures presenting centralized heat networks (each for one storyline), the size of the points indicates the amount of centralized heat supply in a specific small sub-region. The comparably high 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). Heat generation per technology in Austria 2017 can be found in Appendix A.

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

As already indicated in Figure 1, the potentials of centralized heat supply in Austria 2050 is limited. In particular, only six different sub-regions (NUTS3 regions) are supplied by heat networks (see Figure 2). Although the exact numerical numbers differ, the six sub-regions in each scenario are (partially) supplied by centralized heat networks. Table 3 shows the centralized and on-site heat supply in these six sub-regions. Thereby, 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).

# Heat generation on the country, sub-region, and small sub-region level

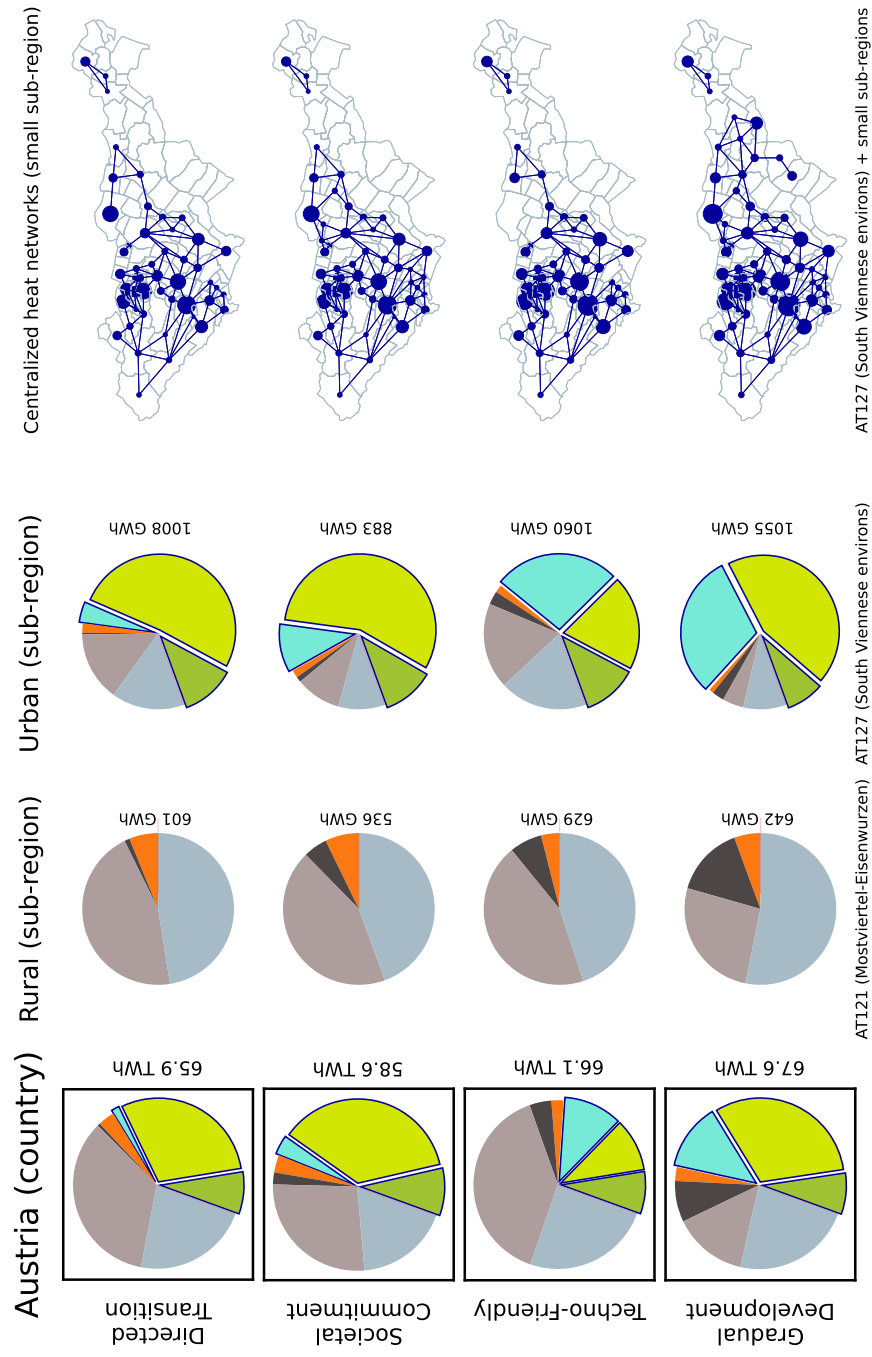


Figure 1: Heat technology generation on different spatial granularity levels in the different scenarios supplying the residential and commercial heat demand. left: on the country level. middle: comparison of a rural and urban sub-region. right: centralized heat network topology (size of the points represent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

| Sub-region              | Storyline           | in TWh      |         | in %            |
|-------------------------|---------------------|-------------|---------|-----------------|
|                         |                     | Centralized | On-site | Connection rate |
| 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              |
| 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              |
| 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              |
| 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              |
| 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              |
| 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 3: 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

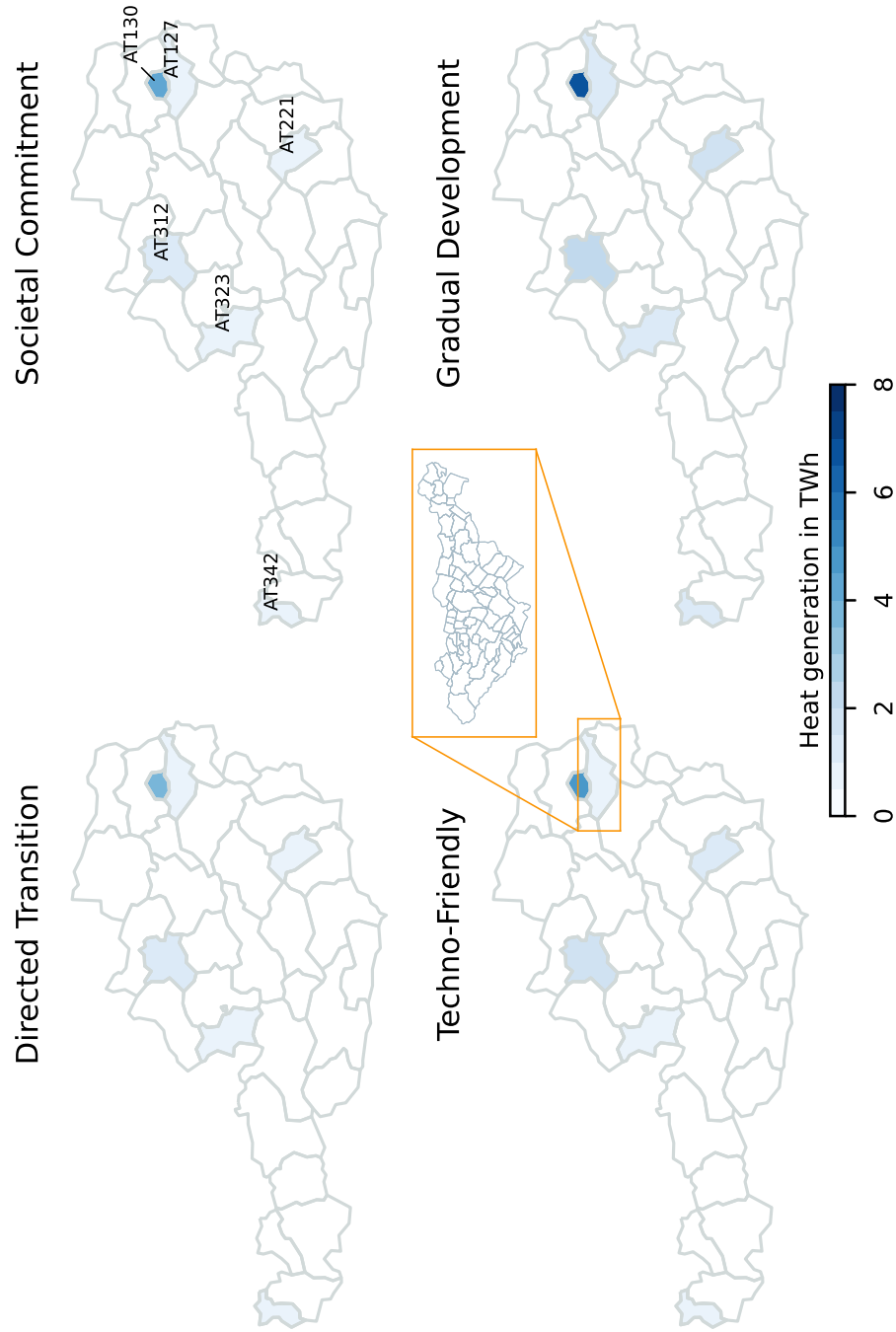


Figure 2: Centralized heat supply in Austria 2050

### *3.4. Centralized heat network topology on the small sub-region level*

This section presents the centralized heat network topology of the sub-region AT127 (including all small sub-regions). Note that this is the highlighted sub-region in Figure 2 marked by the orange box. Figure 3 shows the results of the iterative downscaling algorithm. The number of small sub-regions supplied by the centralized heat network is plotted on the horizontal axis. Note that this number decreases from left to right. The blue-marked area highlights the initial state of the centralized heat network ( $G^0$ ). The boxplot illustrates the distribution of the indicator values benchmarking the network graph. It becomes visible that by removing small sub-regions, namely iteratively those with the smallest indicator value, the mean indicator value of the entire remaining heat network increases. In addition, the maximum value of the indicator also increases from under 1.64 to over 7.16. In the present example, the number of small sub-regions supplied by the centralized heat network decreases from 75 to 47 ( $-37.3\%$ ). The green-marked area highlights the improved centralized heat network topology ( $G^*$ ). The iterative reduction of supplied small sub-regions does not necessarily result in a contiguous graph. For example, three small sub-regions form a subgraph that is separate from the other network (see upper right in the green box in Figure 3). 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.

### *3.5. Comparing centralized heat networks in 2050 with of existing and future projections of low temperature heat networks using heat and population density*

This section synthesizes the results of the centralized heat network topologies accounting for heat densities. Again, the quantitative results of the sub-region

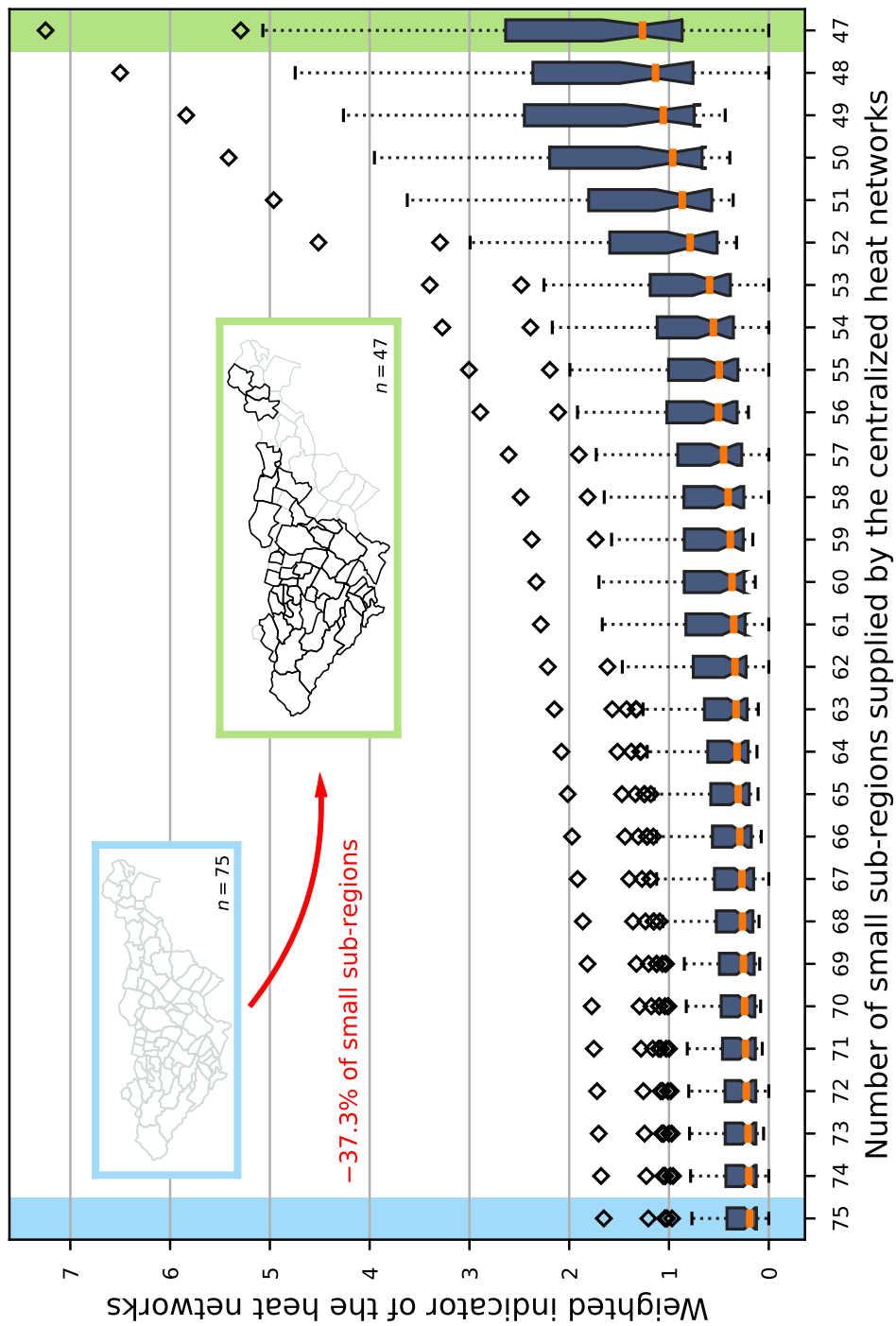


Figure 3: Benchmark indicator value of the centralized heat network at the sub-region AT127 (South Viennese environs) for different numbers of areas supplied.

AT221 (Graz, district of Graz environs) are used to illustrate the comparison between the future and today's centralized heat networks. Figure 5 presents the heat density of the centralized heat network in the sub-region for the three different downscaling techniques. The iterative downscaling algorithm generates the highest heat densities. This downscaling technique increases the heat density of the centralized network by  $2.15 \frac{\text{GWh}}{\text{km}^2}$  compared to population-based downscaling and by  $1.08 \frac{\text{GWh}}{\text{km}^2}$  compared to the sequential downscaling algorithm. However, the gap in heat density compared to today's centralized heat networks becomes apparent. As reference, a heat density of  $10 \frac{\text{GWh}}{\text{km}^2}$  with a connection rate of 90 % is assumed<sup>4</sup>. The gap of heat density varies between the different scenarios. The smallest is achieved in the *Directed Transition* scenario and amounts to  $7.42 \frac{\text{GWh}}{\text{km}^2}$ . The highest value is  $8.41 \frac{\text{GWh}}{\text{km}^2}$  in the *Societal Commitment* scenario. Figure 4 below shows the heat density of centralized heat networks in the different sub-regions.

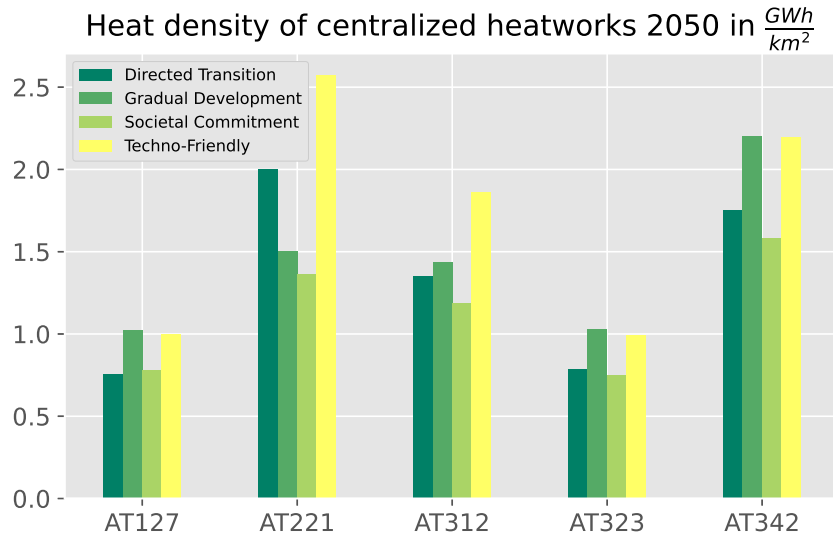


Figure 4: Heat densities of centralized heat networks at the sub-region level for the different scenarios

<sup>4</sup><http://www.austrian-heatmap.gv.at/ergebnisse/>



The *Techno-Friendly* scenario shows the highest values of obtainable heat densities in the sub-regions. For reasons of clarity, the values for AT130 (Vienna) are not shown in the figure. These amount to  $9.6 \frac{\text{GWh}}{\text{km}^2}$  in the *Directed Transition*,  $10.3 \frac{\text{GWh}}{\text{km}^2}$  in the *Societal Commitment*,  $12.0 \frac{\text{GWh}}{\text{km}^2}$  in the *Techno-Friendly*, and  $15.9 \frac{\text{GWh}}{\text{km}^2}$  in the *Gradual Development* scenario.

#### 4. Conclusions and outlook

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

Results indicate that centralized heat systems undergo a fundamental shift going beyond the decarbonization of the supplying energy mix. In particular, the reduction of heat density of centralized heat networks compared to today's networks poses massive challenges to heat supply companies and fundamentally jeopardizes associated business models. At the same time, however, the heat network infrastructure may play a crucial role in expected energy systems since both use of local energy sources efficiently and on a large scale (e.g., geothermal sources, waste incineration, waste heat from industry, etc.) and unburden the electricity sector taking into account the aim of high electrification of different energy services. These trade-offs should be given greater consideration in the

## Assessment of centralized heat networks in 2050 by heat density (top) and gap to today's centralized networks (bottom)

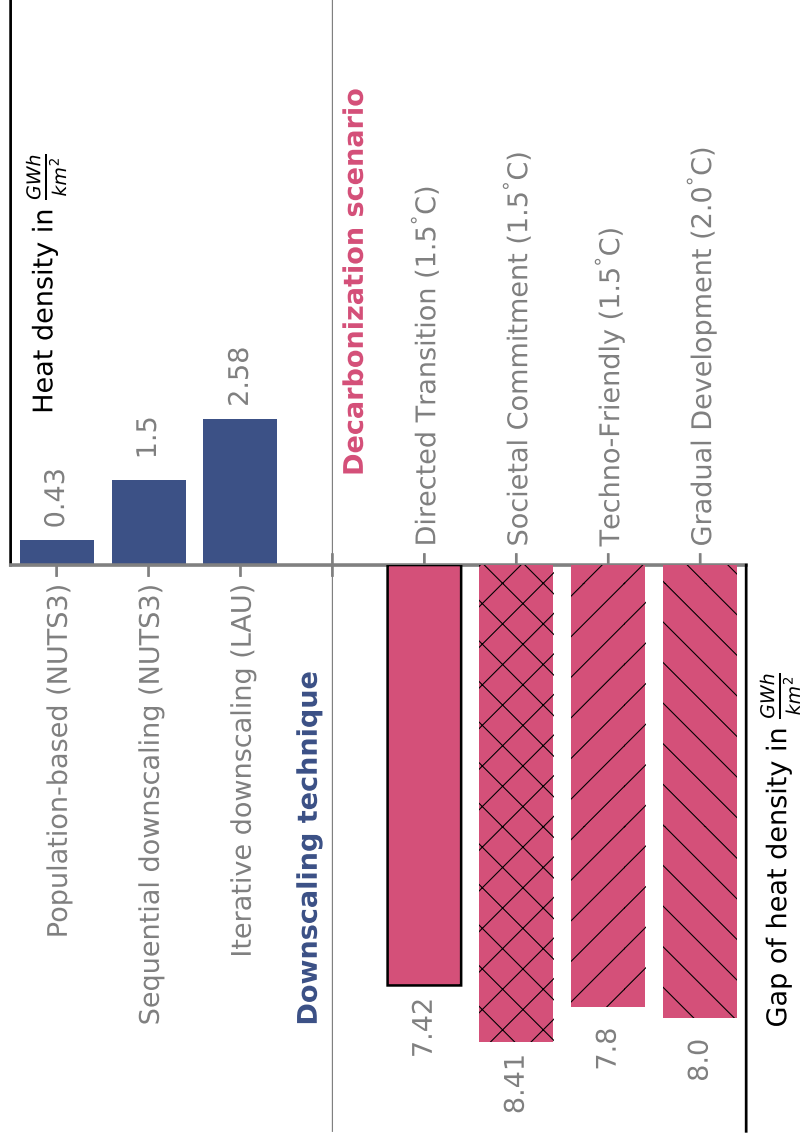


Figure 5: Heat density obtained by the different downscaling techniques (top) and heat density gap between centralized heat networks in 2050 and today for the four different scenarios. Numerical values shown for the sub-region AT221.

future and may have implications for the regulation and benchmarking of heat supply companies that provide centralized heat network infrastructure.

Future work may address improvements of the proposed downscaling technique for the heating sector, taking into account a finer scale of spatial granularity, extensions of the introduced benchmarking of centralized heat networks using indicator values in the context of heat sources and local characteristics, higher resolution of the heat generation technologies/sources in terms of requirements for heat network infrastructure, and a detailed cost-benefit analysis of the centralized heat systems obtained by the downscaling (e.g., distribution line capacities, connection capacities to the public grid, etc.).

#### **Declaration of interests**

None.

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

The authors report no declarations of interest.

#### **Acknowledgments**

This project has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. 835896.

#### **References**

- [1] T. R. Karl, K. E. Trenberth, Modern global climate change, *Science* 302 (5651) (2003) 1719–1723. doi:<https://doi.org/10.1126/science.1090228>.
- [2] B. W. Griscom, J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H. Schlesinger, D. Shoch, J. V. Siikamäki, P. Smith,

- et al., Natural climate solutions, *Proceedings of the National Academy of Sciences* 114 (44) (2017) 11645–11650. doi:<https://doi.org/10.1073/pnas.1710465114>.
- [3] G. Hansen, D. Stone, Assessing the observed impact of anthropogenic climate change, *Nature Climate Change* 6 (5) (2016) 532–537. doi:<https://doi.org/10.1038/nclimate2896>.
- [4] 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).
- [5] 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.
- [6] 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>.
- [7] 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>.
- [8] 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>.
- [9] 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>.
- [10] 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>.
- [11] 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>.
- [12] 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>.
- [13] 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>.
- [14] S. van Renssen, The hydrogen solution?, *Nature Climate Change* 10 (9) (2020) 799–801. doi:<https://doi.org/10.1038/s41558-020-0891-0>.
- [15] 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).
- [16] 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>.
- [17] 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>.
  - [18] 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>.
  - [19] 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>.
  - [20] D. Huppmann, M. Gidden, O. Fricko, P. Kolp, C. Orthofer, M. Pimmer, N. Kushin, A. Vinca, A. Mastrucci, K. Riahi, et al., The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development, *Environmental Modelling & Software* 112 (2019) 143–156. doi:<https://doi.org/10.1016/j.envsoft.2018.11.012>.
  - [21] 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>.
  - [22] A. Gambhir, I. Butnar, P.-H. Li, P. Smith, N. Strachan, A review of criticisms of integrated assessment models and proposed approaches to ad-

- dress these, through the lens of BECCS, *Energies* 12 (9) (2019) 1747. doi:<https://doi.org/10.3390/en12091747>.
- [23] 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>.
- [24] 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>.
- [25] 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>.
- [26] 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>.
- [27] 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>.
- [28] S. R. Gaffin, C. Rosenzweig, X. Xing, G. Yetman, Downscaling and geospatial gridding of socio-economic projections from the IPCC Special Report on Emissions Scenarios (SRES), *Global Environmental Change* 14 (2) (2004) 105–123. doi:<https://doi.org/10.1016/j.gloenvcha.2004.02.004>.

- [29] M. J. Gidden, K. Riahi, S. J. Smith, S. Fujimori, G. Luderer, E. Kriegler, D. P. v. Vuuren, M. v. d. Berg, L. Feng, D. Klein, et al., Global emissions pathways under different socioeconomic scenarios for use in cmip6: a dataset of harmonized emissions trajectories through the end of the century, *Geoscientific model development* 12 (4) (2019) 1443–1475. doi:<https://doi.org/10.5194/gmd-12-1443-2019>.
- [30] A. Michel, V. Sharma, M. Lehning, H. Huwald, Climate change scenarios at hourly time-step over switzerland from an enhanced temporal downscaling approach, *International Journal of Climatology* 41 (6) (2021) 3503–3522. doi:<https://doi.org/10.1002/joc.7032>.
- [31] F. Sferra, M. Krapp, N. Roming, M. Schaeffer, A. Malik, B. Hare, R. Brecha, Towards optimal 1.5° and 2° C emission pathways for individual countries: A Finland case study, *Energy Policy* 133 (2019) 110705. doi:<https://doi.org/10.1016/j.enpol.2019.04.020>.
- [32] D. P. van Vuuren, P. L. Lucas, H. Hilderink, Downscaling drivers of global environmental change: Enabling use of global sres scenarios at the national and grid levels, *Global environmental change* 17 (1) (2007) 114–130. doi:<https://doi.org/10.1016/j.gloenvcha.2006.04.004>.
- [33] 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.
- [34] 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>.
- [35] 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>.



- [36] 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>.
- [37] 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>.
- [38] 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>.
- [39] 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>.
- [40] 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>.
- [41] 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>.
- [42] 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>.

- [43] 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>.
- [44] 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>.
- [45] 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>.
- [46] S. H. Strogatz, Exploring complex networks, *Nature* 410 (6825) (2001) 268–276. doi:<https://doi.org/10.1038/35065725>.
- [47] A. Sanfeliu, K.-S. Fu, A distance measure between attributed relational graphs for pattern recognition, *IEEE transactions on systems, man, and cybernetics* (3) (1983) 353–362. doi:<https://doi.org/10.1109/TSMC.1983.6313167>.
- [48] 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>.
- [49] 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>.
- [50] 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>.

- [51] 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>.
- [52] 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>.
- [53] 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>.
- [54] 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>
- [55] 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).
- [56] 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>.

- [57] 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).
- [58] 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/>
- [59] Austria, Statistik, Statistik Austria, Energiebilanz 2017 und Nutzen-  
ergieanalyse für Österreich 2017 (2017).

## Appendix A. Data and further empirical settings

|                    | Description               | Data availability        | Data source     |
|--------------------|---------------------------|--------------------------|-----------------|
| GENeSYS-MOD v2.0   | Heat generation by source | [58]                     | [25]            |
| Population density | in 2019                   | <i>Statistik Austria</i> | as availability |
| Population         | in 2050                   | <i>Eurostat</i>          | as availability |

Table A.1: Empirical data settings

| Heat generation by source in 2017 | in GWh    | in %  |
|-----------------------------------|-----------|-------|
| Biomass                           | 47.4      | 29.7  |
| Direct electric                   | 21.7      | 13.6  |
| Natural gas                       | 58.1      | 36.4  |
| Heat pump (air & ground)          | 2.8       | 1.7   |
| Solarthermal                      | 2.1       | 1.3   |
| Other fossil fuels (oil, coal)    | 27.6      | 17.3  |
| Total                             | 159.7 GWh | 100 % |

Table A.2: Heat generation by source/technology in Austria 2017 [59]