Working title of the downscaling paper at IIASA

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Abstract

Keywords:

1. Introduction

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2. Methodology

This section aims to describe the proposed approach to transform aggregated quantities of heat generation per technology to local heat network infrastructure topologies. The presented approach can be seen as a novel downscaling technique and is made, in particular, by two sequencing algorithms. Thereby, tailor-made indicators play a crucial role and serve as termination criteria for the downscaling process. Figure 1 illustrates the proposed idea to obtain local heat network topologies from IAM results. Thereby, *Algorithm1* transforms heat generation per technology from the region level (e.g., country) to the sub-region level (e.g., NUTS3) taking into account empirical settings for network infrastructure requirements of heat technologies on the sub-region level. Afterwards, *Algorithm2* disaggregates the results from the sub-region level to the small sub-region level (LAU) to obtain local heat networks and improve their network topology. The iterative application of the latter algorithm enables an improvement of the network topology by each iteration using a benchmarking with tailor-made indicators and leads to the local heat network topologies.

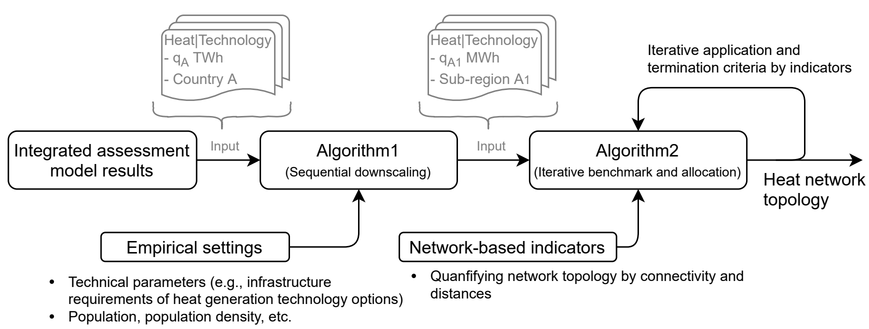

Figure 1: Basic concept of the downscaling technique using two sequencing algorithms

2.1. Algorithm1: Sequential downscaling disaggregating heat generation per technology from the region to the sub-region level

Here, we describe the technique to downscale IAM results of the low temperature residential and commercial heating sector from the region (NUTS0) to the sub-region (NUTS3) level.[1] The idea of *Algorithm1* is to extend the well-known linear downscaling technique, which essentially takes into account a single proxy as the downscaling driver. The linear approach distributes the value to be downscaled linearly in respect to the distribution of the proxy. This has often proven successful in many fields of application. However, in particular, the specific investigation of heat generation per technology of the low temperature heating sector reveals a lack of the default linear downscaling method. Without any further adaption of this methodology, there would be an impracticable disaggregation of heat generation per technology across all sub-regions. This might lead to the fact that strongly grid infrastructure-dependent heat generation technologies provide low temperature heat in very sparsly populated sub-regions as a result of their small share in the proxy. At the same time, however, it might be assumed that heat network infrastructure is being only provided in areas with sufficient heat densities since only these areas represent profitable business models for network-based low-temperature heat supply and heat supply companies.[2]. In this work, the idea of sufficient heat densities is adapted by using population density as the criteria for potentials of areas with network-based heat supply instead. There are esentially two main points for involving population density values as criteria. On the one hand, since population has established itself as the key proxy and downscaling driver along with GDP in the energy sector, the extension by population density seems to be consistent and the logical next step when focusing on spatial downscaling. On the other hand, the emprical data on the development of the population and thus on population density are often very well accessable and available. Furthermore, and this is especially the case for the analysis and empirical setting presented

[1]In principle, different tuples of spatial granularity between the spatial level of values to be downscaled and the desired spatial level of disaggregation could be analyzed using our presented technique.

[2]This is also demonstrated by the open-source toolbox (`https://www.hotmaps.eu/map`) developed in the European H2020 project *Hotmaps*. On the interactive platform, one can find feasible areas for district heating networks on a high spatial granularity by selecting a specific heat density as threshold criteria and thus filtering out areas with insufficient heat density values.

here, the values to be downscaled themeselves often implicitly include development/projections regarding heat demand and heat density (and thus can be seen to a certain extent inherent with IAM results). Algorithm 1 presents the sequential linear downscaling algorithm and each step from the IAM results to the heat generation per technology on the sub-region level.

Algorithm 1: Sequential linear downscaling algorithm

t: Heat generation technology supplying heat service needs ($t \in T$);
r: Sub-region (NUTS 3) within a country ($r \in R$);

input : Heat generation per technology on a country level obtained from IAMs: (q_t);
Population density per region r (ρ_r);
Total population per region r (p_r);
Heat network infrastructure requirement of t (σ_t);
Potential of heat network infrastructure at r (π_r);

output: Heat generation per technology on a sub-region level ($\hat{q}_{t,r}$);

Initialization:
Sort elements t in T descending by σ_t;
$q_r^{heat} \longleftarrow \sum_t q_t \cdot \frac{p_r}{\sum_r p_r}$; `// Downscale heat demand by population as proxy`
$\tilde{q}_t \longleftarrow q_t$; `// Available heat generation per technology` t

begin
  foreach t **do**
    $List = []$; `// Collect sub-regions that fulfill criterias`
    $demand = 0$; `// Used to disaggregate heat generation`
    $R^{'} = R \setminus \{\forall r \in R : \pi_r \leq \sigma_t\}$; `// Filter sub-regions by criteria`
    foreach $r^{'} \in R^{'}$ **do**
      if $q_r^{heat} \geq 0$ **then**
        $List = List \cup r^{'}$; `// Sub-regions that fulfill all criterias`
        $demand \mathrel{+}= q_r^{heat}$; `// Total demand of the sub-regions`
      end
    end
    foreach $l \in List$ **do**
      $\hat{q}_{t,r} = \frac{q_r^{heat}}{demand} \cdot \tilde{q}_t$; `// Heat technology generation at sub-region`
      $q_r^{heat} \mathrel{-}= \hat{q}_{t,r}$; `// Reduce heat demand at` r
    end
  end
end

In descending order of network infrastructure requirement, the heat generation technologies are iterated (line 5 and initialization). All sub-regions are collected that fulfill the heat network infrastructure requirements of technology t (line 8). Then, those sub-regions with zero heat demand (e.g., as a result of the supply by other heat generation technologies and the sequential process) are not further pursued and removed from the collection of sub-regions (line 10 and 11). The total heat demand of all sub-regions that fulfill all criterias and provide proper settings (line 12) are used to disaggregate heat generation to the sub-regions accounting for the individual heat demand (line 16). Finally, the heat demand at the sub-region is reduced to ensure that the total demand is covered by the heat generation technologies.

2.2. Algorithm2: Iterative heat network benchmark and heat generation allocation on the small sub-region level

Text.

Algorithm 2: Iterative benchmark and disaggregation algorithm

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

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

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

begin
  while $iter = True$ **do**
    foreach $n \in N^s$ **do**
      $\Pi^s_{n^s} = f(N^s, L^s, Q^s)$; // Calculate indicator values
    end
    i with $\pi^s_i = min(\Pi^s)$; // Get index with lowest indicator value
    $N^{s+1} = N^s \setminus i$; // Remove index from list to obtain next stage
    $\tilde{q} = \sum_{N^{s+1}} \tilde{q}^s_{n^s}$; // Remaning on-site heat generation
    if $\tilde{q} \geq q^s_i$ **then**
      pass
    else
      $\tilde{q} = q^s_i$; // Limit quantity of centralized heat generation
    end
    foreach n^{s+1} **do**
      $q^{s+1}_{n^{s+1}} = q^s_{n^s} + \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; // Increase centralized heat generation
      $\tilde{q}^{s+1}_{n^{s+1}} = \tilde{q}^s_{n^s} - \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; // Decrease on-site heat generation
    end
    $L^{s+1} = L^s \setminus \{\forall l^s_{k,j} : k = i \vee j = i\}$; // Remove unavailable lines
    $G^{s+1} = \{N^{s+1}, L^{s+1}, Q^{s+1}, \tilde{Q^{s+1}}\}$; // Create new network graph
    $\Pi^{s+1}_{n^{s+1}} = f(N^{s+1}, L^{s+1}, Q^{s+1})$; // Calculate new indicator values
    if $mean(\Pi^{s+1}) \geq mean(\Pi^s)$ **then**
      $G^s = G^{s+1}$; // Set iteratively input network graph
    else
      $iterate = False$; // Stop iteration if no improvement
    end
  end
  $G^* = G^s$; // Set improved network graph as algorithm result
end

2.3. Mixed-integer linear optimization problem maximizing heat densities

2.4. Open-source environment and availability

3. Results and discussion

This section presents the results for the proposed Austrian case study for the target year 2050. Four different storylines are investigated covering a wide range of possible future developments of the European and Austrian energy system. Section 3.1 shows the heat generation mix of the low temperature heat supply on the national level. These results are subsequently used for the demonstration of the proposed downscaling methodology. Section 3.2 goes into a higher spatial granularity and shows the heat generation on the sub-region and small-subregion level. Section 3.3 presents the potentials of network-based low temperature heat supply as implication of the four different storylines and European deep decarbonization respectively. Section 3.4 presents the low temperature heat networks on the small sub-region level. Finally, Section 3.5 compares the results of the work with existing low temperature heat networks by using heat density as criteria.

3.1. Low temperature heat supply in Austria 2050: four different decarbonization scenarios obtained from the H2020 project openENTRANCE

This section presents heat generation mix of the low temperature heat supply in Austria 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*. Whithin each of them, a specific fundamental developement of the energy systems is described while aiming for a sustainable transition of the provision of energy services. Note that 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. In the following, the storylines are briefly described, before the quantitative results of the low temperature heat supply on the national level are presented. For a more detailed description of the storylines, it is referred to [1] and [2]. Further informations also are available at the website[3] and GitHub.[4].

The underlying concept of the storylines is a three-dimensional space spanned by the following parameters: technology, policy, and society. Each storyline descibes 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. The *Directed Transition* storyline looks at a sustainable provision of energy services through strong policy incentives. This becomes necessary because neither the markets nor society adequately push sustainable energy technologies. The *Societal Commitment* storyline achieves a 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 give rise to a decarbonization of energy service supply. Alongside, society acceptance supports the penetration of the 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 ambitios 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 the three dimensions contribute to the decarbonization, they do not push it sufficiently and result in a more conservative storyline than the others.

Table 1 shows the low temperature heat technology generation in Austria for 2050 for all four storylines. The values are obtained from the H2020 project

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

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

Table 1: Low temperature heat technology generation in Austria for 2050 and the four different storylines. Values obtained from the H2020 project openENTRANCE and GENeSYS-MOD.

openENTRANCE and correspond to modeling results from the open-source model GENeSYS-MODv2.0 [3]. According to the definition of the storylines, the heat generation by the different technologies vary in some cases significantly (e.g., hydrogen-based low temperature 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)). Consequently, that share of heat generation which requires heat network infrastructure given the assumptions of this work, also differs (see gray-colored column Σ).

3.2. Decarbonized low temperature heat technology generation on different spatial granularity levels

In this section, results of the low temperature heat technology generation obtained for the region/country, sub-region, and small sub-region level are presented and discussed. As already mentioned above, the sub-region level corresponds to small political districts and the small sub-region level to (small) municipalities. Note that in Europe, the NUTS classification (Nomenclature of territorial units for statistics) and corresponding regional codes are used within the computations and illustrations of the results. Accordingly, the region/country level is defined within the NUTS classification by the NUTS0 code (e.g., AT for Austria), the sub-region level by the NUTS3 code (e.g., AT127 for South Viennese environs), and the small sub-region level by the local administrative units (LAU) code (e.g., AT127—Laxenburg for the municipality of Laxenburg).

Figure 2 shows the low temperature heat technology generation on different NUTS levels. Conseptualizing the different subfigures (in Figure 2) as 2D-matrix-like structure, each row represents results obtained from data from a different storyline. The horizontal dimension covers the different spatial resolutions, whereby the level of spatial details increases from the left to the right. On the far left, the low temperature heat generation on the country level is presented. In the middle, two different illustrative sub-regions are 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 low temperature heat demand. In contrast, the urban sub-region (NUTS3 code AT127 (South Viennese environs)) is mainly supplied by ground sourced heat pumps, biomass, and hydrogen. Moreover, air-sourced heat pumps and again heat storage supply the demand. In particular, the shares of heat generation technologies that require network infrastructure are highlighted and marked by the blue-colored edge. On the very right, an example of the resulting low temperature heat network on the small sub-region level for the four different storylines is presented. In the four subfigures presenting centralized heat networks (each for one storyline), the size of the points indicates the amount of centralized low temperature heat supply in a specific small sub-region. The comparably high demand in the *Gradual Development* storyline results in an extensive low temperature heat network infrastructure/topology (see lower right subfigure in Figure 2). In contrast, the other three centralized heat networks are characterized by fewer (less supplied small sub-regions) and smaller points (less supplied heat demand by the centralized heat network).

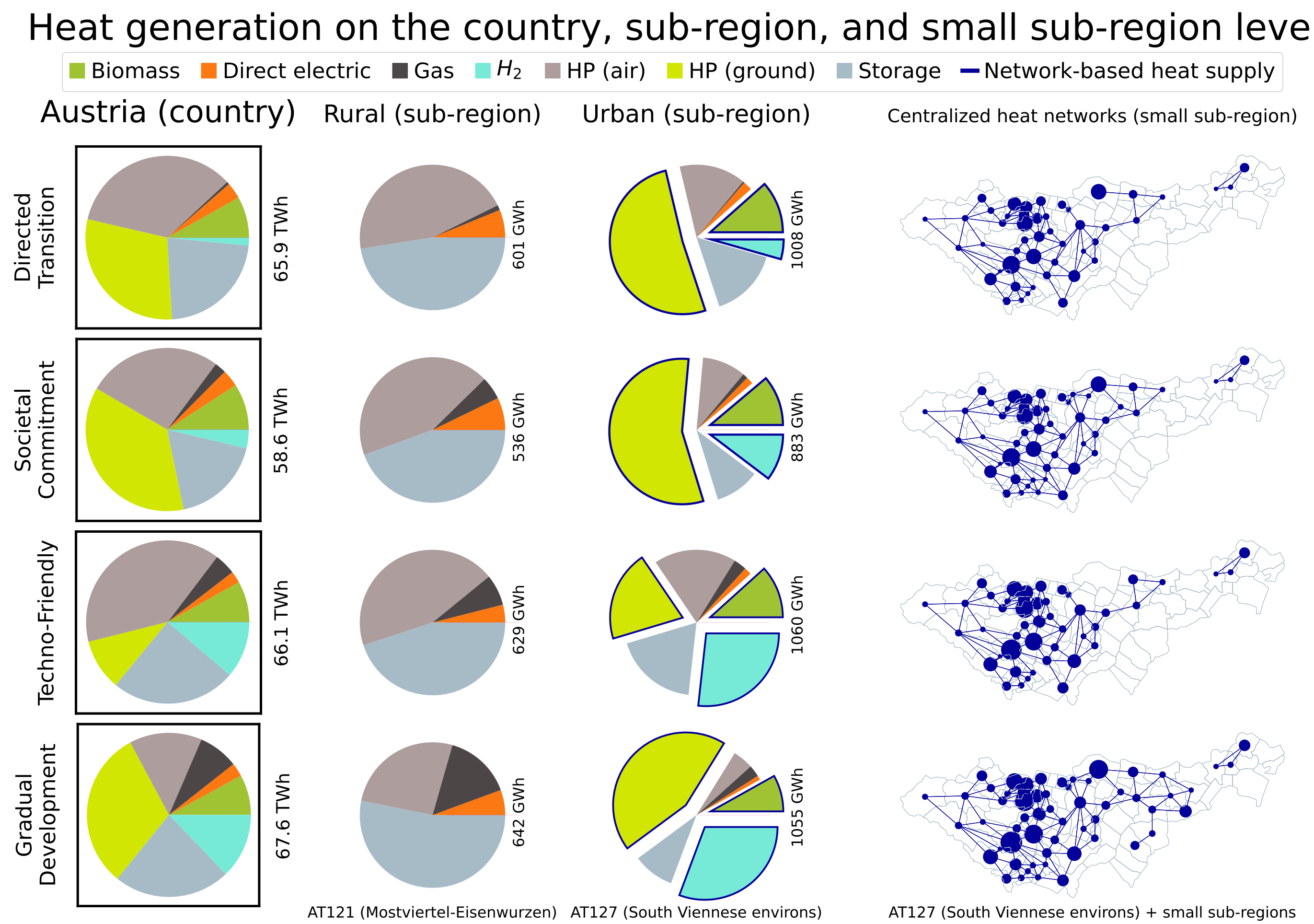

Figure 2: Low temperature heat technology generation on different spatial granularity levels for the four different storylines. left: heat technology generation mix on the country level. middle: comparison of technologies supplying the low temperature heat demand in a rural and urban sub-region. right: Centralized heat network topology (size of the points represent the amount of local heat demand supplied by the centralized heat network)

3.3. Austrian sub-regions with high potentials for centralized low temperature heat supply resulting from aiming the decarbonization

As already indicated by Figure 2, the results show that there is only a limited number of sub-regions in Austria that have sufficient population and thus heat density to allowing centralized heat supply. Figure 3 shows a heatmap for centralized heat supply in Austria 2050. Thereby, the spatial granularity corresponds to sub-regions or the NUTS3 level respectively. The corresponding six sub-regions are supplied by the heat networks, independent of the storylines. However, the individual quantities of centralized heat supply per sub-region differ between the storylines (see also the heat technology generation mix of the sub-region AT127 in the center of Figure 2 as an example for this). In addition, it is important to note here two things: Firstly, Figure 3 only shows the quantity of centralized heat supply per sub-region. At the same time, heat generation technologies which are not fixed to a central heat distribution network also supply some parts of the heat demand there (see again the heat technology generation mix of the sub-region AT127 in the center of Figure 2 as an example). Therefore, in those sub-regions in Figure 3 that are colored completely white which indicated no supply by a centralized heat network, results show that the heat demand in these regions is completely covered by technologies that do not require a heat network infrastructure. And secondly, as expected, the areas seen in Figure 3 which are projected to have centralized heat supply are those with the highest population density. The range of population density there varies between 229 persons/km^2 (AT323 - Salzburg and sourroundings) and 5124 persons/km^2 (AT130 - Vienna). As indicated in Figure 3 (orange box), in the following section, the marked sub-regions are further spatially dissaggregated and, subsequently, their heat network topology is analyzed.

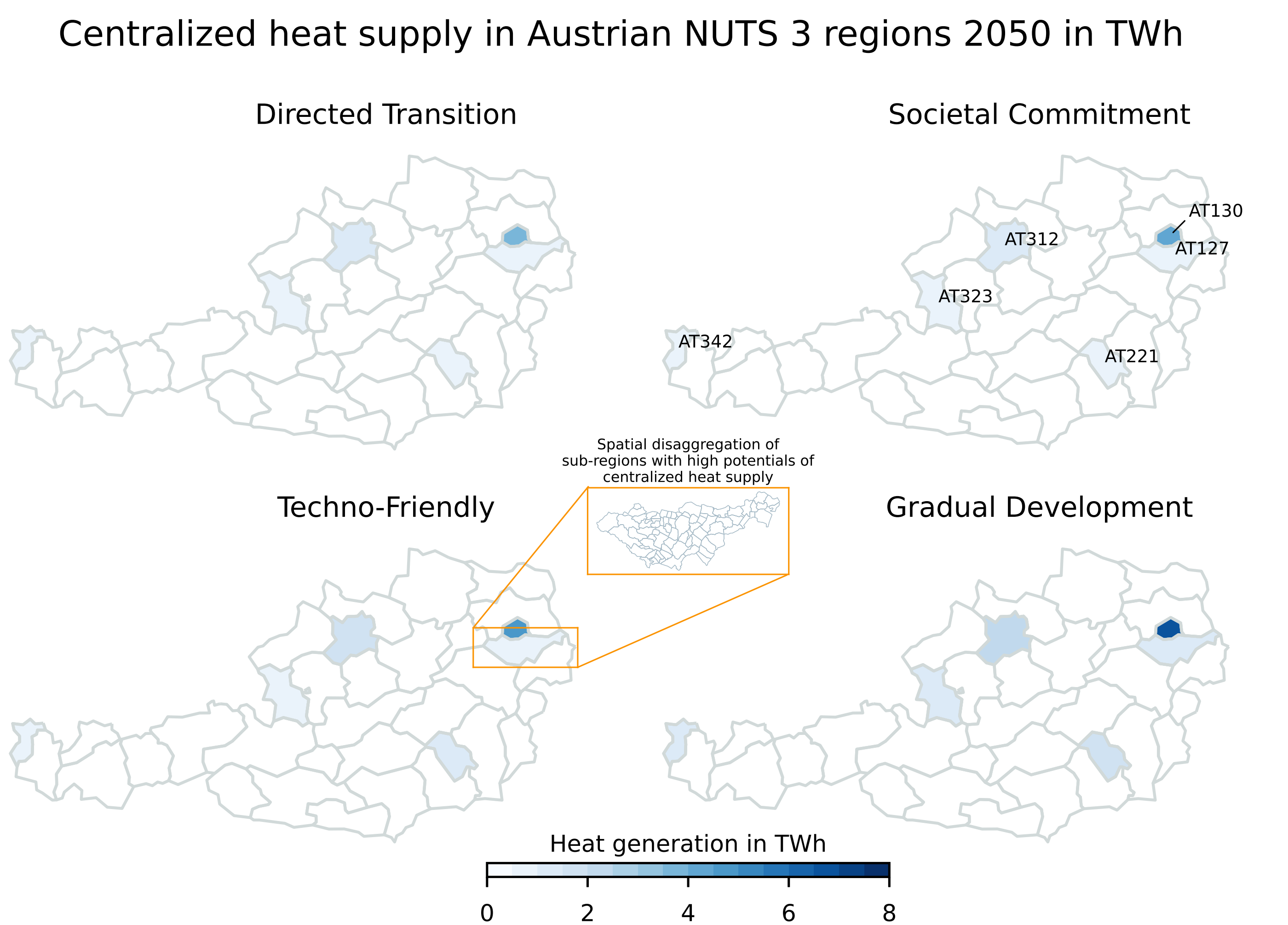

Figure 3: Centralized low temperature heat supply in Austria 2050. Six sub-regions provide sufficient values of population density to supply parts of the low temperature heat demand by heat networks. The remaining heat demand is supplied by on-site heat technology options.

3.4. Low temperature heat network topology on the small sub-region level

This section analyzes the heat network topology of those regions, that provide sufficient characteristic in terms of population density for centralized heat supply. Figure 4 shows the boxplot of the distribution of benchmark indicator value for the sub-region AT127 (including all small sub-regions). 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. 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 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 4).

The results discussed above suggest that reducing the number of small sub-regions supplied by the centralized heat network increase 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.

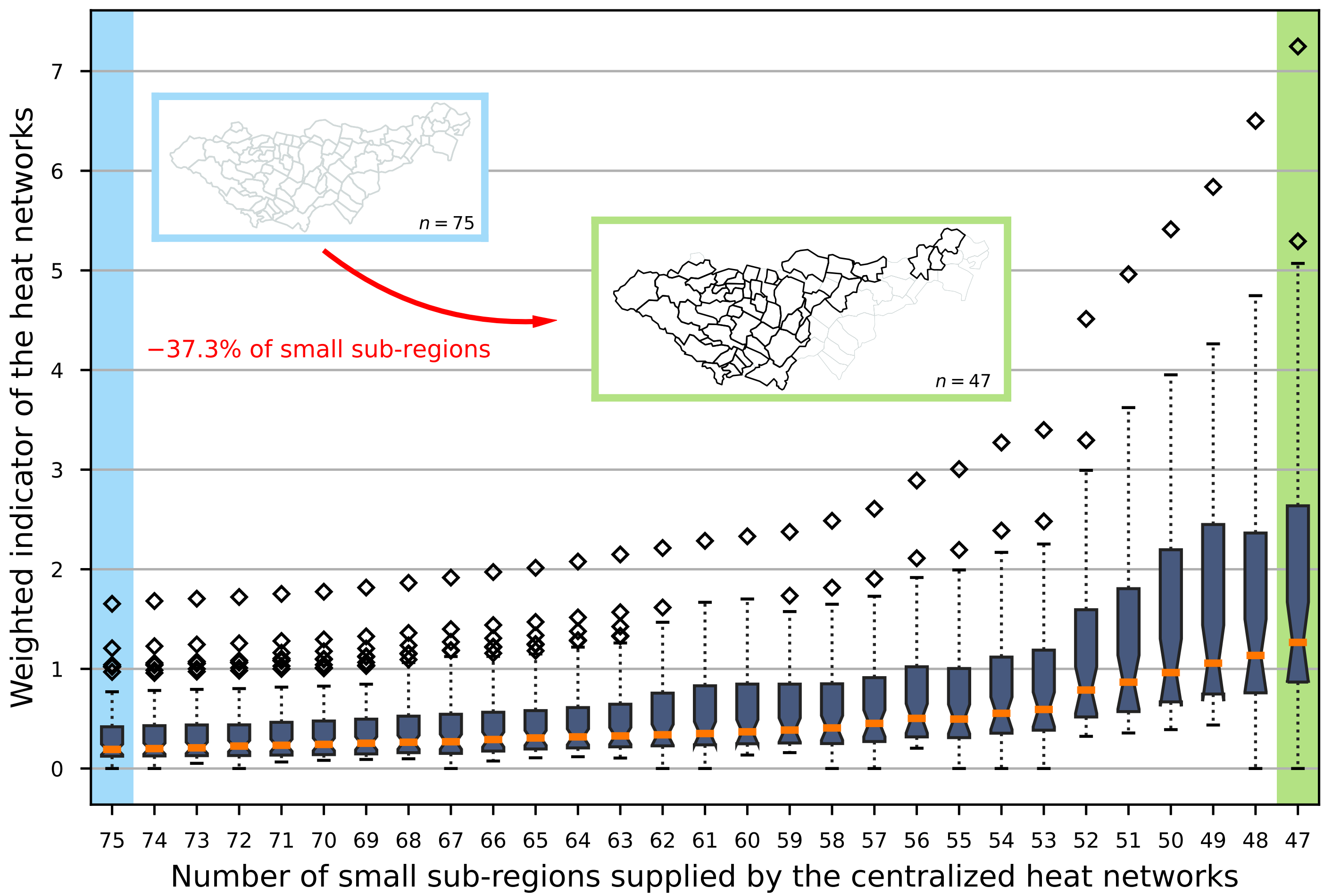

Figure 4: Weighted indicator value of the low temperature heat network at the sub-region AT127 (South Viennese environs) for different numbers of areas supplied by the centralized heat networks.

3.5. *Comparison of existing and future projections of low temperature heat networks using heat and population density*

This section synthesizes the results in the context of heat density values of centralized heat networks and compares the obtained future projections of sustainable centralized heat supply with current minimum required heat density standards of heat networks. Figure 5 shows the heat density of low temperature heat networks for different the different proposed downscaling techniques and the four different storylines. The population density is shown on the horizontal axis. The black triangles mark the minimum required heat density for today's centralized heating networks at a connection rate of 90 % in Austria.[5] The circles (●) mark the default downscaling with only population as criterion. Therefore, the heat density of the sub-regions increases linearly with the population density (see also the zoomed out area in the left subfigure with population density $\leq 150\frac{persons}{km^2}$). The diamonds (⧫) mark the heat density values obtained by Algorithm 1 (and thus without supply area reduction). As a result, the heat density per sub-region increases (see the zoomed out area in the middle subfigure with population density $\leq 500\frac{persons}{km^2}$). The stars (★) mark the heat density resulting by Algorithm 2. In order to highlight the effects of the different downscaling techniques, the differences of the resulting heat densities to today's minimum required values is shown for a sub-region by the three green bars for the *Techno-Friendly* storyline. As the comparison of the green bars shows, the difference is again significantly reduced by applying Algorithm 2.

[5]See in this context for example `http://www.austrian-heatmap.gv.at/karte/`.

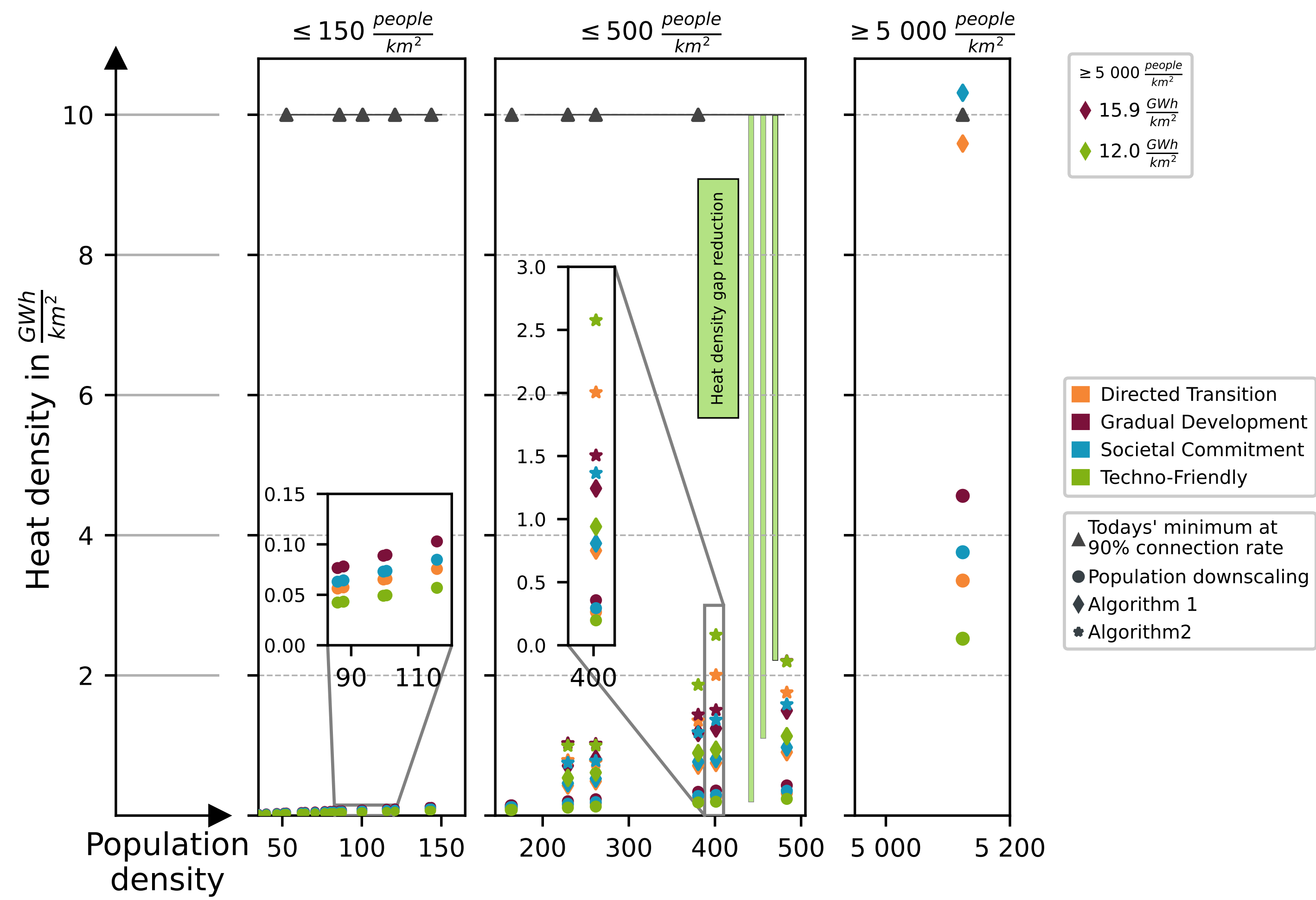

Figure 5: Heat densities for different population densities, decarbonization storylines, and downscaling techniques. Reducing significantly the gap between today's minimum required heat density ($10\ \frac{\mathrm{GWh}}{\mathrm{km}^2}$ at a connection rate of 90 %) by Algorithm 2 in comparison with default population-based downscaling.

4. Conclusions and outlook

Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

References

[1] 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).

[2] 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.

[3] 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).