Disclosing the heat density of district heating networks for Austria in 2050 under the remaining European CO_2 budget of the 1.5°C climate target

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Abstract

We downscale the cost-effective heat supply of different European decarbonization scenarios generated by the aggregate model GENeSYS-MOD from the national to the community level in Austria. The remaining European CO_2 budget (and related CO_2 prices) of the 1.5°C climate target is considered in the values to be downscaled. The results show, among others, that district heating covers parts of the heat demand in four of the thirty-five sub-regions in Austria in 2050. The district heating networks are located in densely populated areas with high heat demands and are supplied by geothermal, synthetic gas, hydrogen, and waste. Not all of these networks reach the heat density required for economic and technical efficiency from today's techno-economic perspective and industry benchmarks. The identified heat density gap, mainly driven by lower heat demands, can be reduced and even closed by an optimal allocation of large-scale heat pump generation into district heating. We conclude that district heating networks still reach economic viability in 2050.

Keywords: District heating, heat density, network topology, 1.5°C climate target, downscaling, 2050

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Nomenclature

Type	Description	Unit
Set and index		
$t \in \mathcal{T} = \{1, \ldots, T\}$	Set of heat sources/generation technologies, index by t	
$r \in \mathcal{R} = \{1, \ldots, R\}$	Set of sub-regions, index by r	
$s \in \mathcal{S} = \{0, 1, *\}$	Stage of iterations, index by s	
Variables		
q_t	Heat generation per t	TWh
ρ_r	Population density per r	1//km^2
p_r	Total population per r	1
σ_t	Minimal network infrastructure requirements per t	1//km^2
π_r	Available potential of network infrastructure per r	1//km^2
$\hat{q}_{t,r}$	Heat generation per t and r	TWh
q_r^{heat}	Heat demand per r	TWh
$\tilde{q}_t$	Available heat generation per t	TWh
G^s	District heating network graph at s	
n^s	Node of district heating network graph at s	
$l_{k,j}^s$	Line connecting nodes k and j at s	
$q_{n^s}^s$	Nodal district heating at s	TWh
$\tilde{q}_{n^s}^s$	Nodal on-site heat generation at s	TWh
$\pi_{n^s}^s$	Nodal benchmark indicator value at s	1
α_{n^s}	Number of triangles with direct neighboring nodes	1
β_{n^s}	Number of connection lines to the graph	1

1. Introduction

To implement the pathway in line with the Paris Climate Agreement [1] as analyzed by the IPCC's *Special Report on Global Warming of 1.5°C* (SR15) [2], 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 [3]. The overarching goal is to reduce CO_2 emissions to net-zero and hence achieve climate neutrality by 2050. The principles of a net-zero, decarbonized society are based on three key points: (i) reduction of the energy demand [5], (ii) deployment and generation of renewable energy technologies [6], and (iii) an increase in efficiency regarding the provision of energy services and the associated optimal utilization of sustainable energy sources.

To achieve these long-term ambitions, the European Commission recently presented *Fit for 55*, a roadmap with specific actions and targets until 2030. This program commits to a 55 % reduction in CO_2 emissions in 2030 compared to those in 1990 [7]. 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 to reduce energy consumption and to extend the already established EU emissions trading system (EU ETS) to new sectors. In addition to transportation, the building sector will be part of the EU ETS in the future. In the building sector, using the annual anchored emissions reduction, this means a defined roadmap to complete decarbonization of the heating and cooling demand. In this paper, we look at what deep decarbonization of building heat demands may look like in 2050 in Austria and the implications of the corresponding sustainable energy mix for district heating.

1.1. Implications of decarbonization on the heating sector

The scope of changes required by 2030/2050 in the heating sector becomes even clearer at the national level. In Europe, the share of renewable energies in the heating and cooling sector in 2018 is only just above 20 % on average [8]. In Austria, it reaches 34%. However, fossil fuels continue to dominate there as well. In 2015, the heat demand for low-temperature heat services in Austria was approximately 96 TWh [9]. Thereby, natural gas, oil and coal account for almost 45% of space heating and hot water demand in the residential building sector [10]. The share of district heating reaches almost 15% and more than one million households are connected to district heating networks.[1] Nevertheless, of the nearly 4,000,000 residential dwellings in Austria, more than one million are heated with natural gas, and more than 500,000 with oil [12]. If these heating systems are converted to renewable energy supply by 2050, this corresponds to a retrofitting of 50,000 units per year, or more than 130 per day - only in Austria. To achieve this goal, measures that go beyond the electrification of heat supply are necessary, which may require an expansion of district heating networks. This holds true even when substantial heat saving measures are implemented [13].

In Europe, there are good conditions for district heating [14], especially in the provision of heat services in densely populated or urban areas [15] because of high heat densities that are found there. In addition to heat density, the connection rate is a key factor determining the efficiency of district heating/cooling networks and thus their implementation. In Austria, a benchmark of 10 GWh/km^2 at a connection rate of 90 % is currently used when deciding whether to supply an area with district heating[2]. This reference value is in line with findings regarding district heating networks also from the Scandinavian region (Denmark, Sweden, and Finland) [16]. These are rough estimates, but they do allow an initial assessment of the economic viability or feasibility of a district heating network. In a detailed consideration and evaluation of district heating networks, numerous factors play a decisive role. For example, the design and topology of district heating networks has a significant impact on their cost-effectivness [17].

[1] See Appendix A for a detailed overview of the Austrian heat market as well as references [10] and [11] for more details.
[2] http://www.austrian-heatmap.gv.at/ergebnisse/

In addition, the cost-optimized heat supply is also influenced by the location of heat generation units/sources within the networks [18]. When examining the economic viability of district heating networks, building renovation measures must also be taken into account [20]. Recently, the results in [22] show that a $2-3\%$ building renovation rate per year results in a $19-28\%$ decrease of the long-term district heating demand, which consequently also reduces the heat densities of district heating networks. However, studies show that a reduction in heat density is not necessarily a barrier to district heating networks [23]. For example, energy taxes which can certainly be expected in the future (e.g., higher taxes on fossil fuels) can improve the profitability of sparse district heating networks [24]. Following these considerations and in light of ambitious CO_2 reduction targets, it can also be assumed that rising CO_2 prices have an similar effect. However, this is valid only in the case of deep decarbonization of the generation mix feeding into district heating networks. In general, there are a variety of alternatives to decarbonize the energy mix of district heating networks. Among others, geothermal [25], biomass [26], waste [27] and heat recovery from industrial excess heat [28] are likely to be the primary heat sources in sustainable district heating networks. Eventually, the increasing cooling demand and the co-design of district heating and cooling networks can also increase the economic viability of these and counteract the reduction of heat density from an economic point of view [30].

1.2. Implications of large-scale numerical model results at the local level

For quantifiying solutions of complex planning problems, researchers use numerical models. In general, these models strike a balance between complexity and aggregation. Integrated assessment models (IAMs) are large numerical models covering complex interrelationships between climate, society, economics, policy, and technology [31]. Particularly, IAM contribute to the understanding of global energy decarbonization pathways [32]. Evaluating and discussing IAM involves, among others, the appropriate level of regional (spatial) aggregation of countries in the modeling analysis [34]. 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 temporal, spatial, and other dimensions [35]. Accordingly, IAMs should increasingly be supplemented with other models and analytical approaches [36]. Not least for this reason, large-scale detailed energy systems 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. However, the lack of granularity remains: these global systems models consider only a highly aggregated spatial resolution. To name just two selected approaches, PRIMES [37] and GENeSYS-MOD [38] are aggregate energy system models focusing on the European energy system with a spatial resolution at 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, a novel approach in the context of merging local activities/behavior in sustainable local communities into a large energy system model (bottom-up linkage) is presented in [39]. In this study, local flexibility options are integrated into the global energy system model EMPIRE, which provides, in principle, only country-level resolution. This and other work confirms the emerging trend of making top-down and bottom-up linkages between different spatial-temporal levels of resolution to drive decarbonization across all sectors.

1.3. Objective and contribution of this work

Against this background, the core objective of this work is downscaling European decarbonization scenarios of the heating sector to the community levels serving end-users in 2050. In particular, downscaling considers the highly efficient and local use of sustainable heat sources in district heating (e.g., geothermal sources, co-firing synthetic gas and hydrogen in cogeneration plants and large-scale waste utilization). In addition, the topography of district heating networks is of particular importance and plays a crucial role in applied downscaling. This allows estimates of realistic decarbonized district heating networks in 2050 to be obtained, which can be compared with existing networks. Thereby, the heat density of district heating networks serves as a comparative indicator and permits a rough estimation of the changes needed for district heating networks considering the 1.5°C and 2.0°C climate target. An Austrian case study is conducted, downscaling the cost-effective results of the heating sector in 2050 from the large numerical energy system model GENeSYS-MOD, from the country to the community levels. The GENeSYS-MOD results, and thus the values to be downscaled implicitly include the remaining European CO_2 budget in line with the 1.5°C and 2.0°C climate target.

The method applied (section 2) consists of three different scenario-independent downscaling techniques. In the first technique, proportional downscaling uses population as a stylized proxy (section 2.2). In the second, a sequential downscaling approach is presented, disaggregating from the country level to the subregion level. Thereby, the population density and infrastructure requirements of heat sources/generation technologies serve as additional criteria in the downscaling (section 2.3). Finally, an iterative downscaling algorithm is presented. The algorithm applies benchmarking based on graph-theory. It computes district heating at the local (community) level, see section 2.4. Section 3 presents and discusses the results of this work. Section 3.1 shows heat generation by source at different spatial levels. Sections 3.2 and 3.3 present district heating networks at a high spatial granularity. Section 3.4 synthesizes the results of district heating networks and compares heat densities of district heating in 2050 with today's values. Section 3.5 presents a sensitivity analysis of the heat density of district heating networks regarding the allocation of heat generation by heat pump (air) feeding into district heating. Section 4 concludes this work and provides an outlook for future work.

2. Materials and methods

This section explains the methodology of this work. First, section 2.1 presents the output from the Horizon 2020 project openENTRANCE (incl. GENeSYS-MOD results), since this is the main input for the downscaling. Therein, information about the different heat sources/generation technologies that are downscaled is provided. Then, the different downscaling techniques are explained. Section 2.2 describes proportional spatial downscaling using population as a proxy. Building on this, section 2.3 presents the sequential downscaling and section 2.4 presents the iterative downscaling algorithm in detail. Section 2.5 discusses limitations of the proposed downscaling technique. Finally, section 2.6 concludes this section and explains the open-source tools used in this work.

2.1. Heat supply of the Austrian residential and commercial sector in 2050: four different decarbonization scenarios

This section presents the heat generation mix covering the Austrian residential and commercial heat demand in 2050 for four different scenarios, which have been developed within the Horizon 2020 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 scenarios assume different approaches to limit global warming to around 1.5 °C as laid out in the Paris Agreement. Particularly, the results of these scenarios implicitly consider the remaining European fraction of the CO_2 budget of the 1.5°C climate target. The last scenario (*Gradual Development*) can be interpreted as less ambitions scenario, limiting global warming to around 2.0 °C climate target. Accordingly, the results of this scenario consider the remaining European fraction of the CO_2 budget of the 2.0°C climate target. Below, the scenarios are described briefly, before the quantitative results at the country level are presented. For a more detailed description of the scenarios, refer to [40] and [41]. Further information is also available on the website of the project[3] and on GitHub[4].

The underlying concept of the four scenarios is a three-dimensional space consisting of the following parameters: technology, policy, and society. Each scenario 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 the 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 and shifts in energy demand patterns. Thereby, decentralized renewable energy technologies together with policy incentives facilitate a sustainable satisfaction of energy service needs. Due to the shift in energy demand, no fundamental breakthroughs of new clean technologies are required.

- *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. Additionally, society acceptance supports the penetration of clean energy technologies and the sustainable transition.

- *Gradual Development* differs from the other scenarios: it assumes emissions reductions that (only) stabilize the global temperature increase at 2.0 °C. At the same time, a combination of each possible sustainable development initiative of the energy system is realized in this scenario.

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

Although the other three dimensions contribute to decarbonization, they do not push it sufficiently and result in a more conservative scenario than the others.

Table 1 shows the heat generation by source/technology in Austria in 2050 for the four scenarios. These values were obtained during the course of the Horizon 2020 project openENTRANCE and are generated by the open-source aggregate model GENeSYS-MOD [9]. In this work, the naming convention of heat sources/generation technologies from GENeSYS-MOD is essentially followed to ensure consistency between aggregated (i.e., downscaling input values) and local (i.e., dowmscaling output values) levels. Nevertheless, we introduced the heat sources waste and geothermal that were initially not included in the list of heat sources from openENTRANCE results. We separated waste as part of biomass and geothermal from heat pump (ground) heat generation using estimates from national Austrian studies in [42] and [11] to complement the GENeSYS-MOD results.

	2020	2050			
Generation by source in TWh	-	DT	SC	TF	GD
Biomass	13.00	3.37	3.37	3.37	3.37
Direct electric	4.10	2.13	1.98	1.53	1.81
Geothermal	0	2	2	2	2
Natural gas (fossil)	43.67	0	0	0	0
Heat pump (air)	11.37	22.73	15.71	25.96	9.68
Heat pump (ground)	0	17.50	19.47	4.69	19.21
Hydrogen	0	1.03	2.18	7.43	8.65
Oil	0.66	0	0	0	0
Synthetic gas	0	0.36	1.35	2.79	5.35
Waste	1.2	2	2	2	2
Total	74.0	51.12	48.06	49.77	52.07
Rel. reduction compared to 2020	-	-31%	-35%	-33%	-30%
District heating		5.39	7.53	14.22	18.00

Table 1: Heat generation by source in Austria in 2020 and the four different decarbonization scenarios in 2050. Source: [41],[42],[11]

The total heat generation (and thus total heat demand) is significantly reduced when comparing the values of 2020 and 2050. The heat demand reduction varies between -30% and -35% and is highest in the *Societal Commitment* scenario. District heating (bottom row in Table 1) describes the amount of heat generation used for district heating. It is the sum of heat generation by geothermal, hydrogen, synthetic gas, and waste. Note that section 2.3 and particularly Table 3 explain this and the related underlying assumptions in detail.

2.2. Proportional spatial downscaling using population as a proxy

Proportional downscaling is a well-established technique for spatial disaggregation and is often used in scientific and practical studies. Equation 1 shows a mathematical formulation of proportional downscaling for disaggregation of energy demand d from the country to the local levels, using population p as a proxy.

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

The fields of application of proportional downscaling are not limited to the modeling of energy systems but to different fields of scientific and practical studies. The reason for this is the intuitive application and that it offers possibilities for tailor-made adaptions, in particular, related to the downscaling driver and proxy. In this context, the study in [43] provides a comprehensive analysis of different proxies for the downscaling of global environmental change, including gross domestic product, emissions and other indicators. However, downscaling aggregated values of energy system often uses proportional downscaling and population as a proxy [46]. Further information can be found in the review study in [45], providing a systematic classification of different downscaling techniques. The reader can find population-based downscaling in the authors' categorization under algorithmic and proportional downscaling. In addition, the study shows that novel downscaling methods have emerged in recent years as the scientific community has increasingly recognized the necessity for spatial and temporal disaggregation.

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

The sequential approach (Algorithm 1) downscales the heat generation by source from the country to the sub-region levels. Before explaining the algorithm in detail, Table 2 provides an overview of the spatial nomenclature of this work using the European nomenclature of territorial units for statistics[5] (NUTS) and gives some examples of Austria. In particular, the different spatial levels of the applied downscaling are marked in gray. According to the NUTS nomenclature, Algorithm 1 downscales from the NUTS0 level to the NUTS3 level.

The purpose of the sequential downscaling algorithm is to provide a downscaling technique that considers the variation in efficiency of renewable heat sources and thus the prioritized use of heat sources/generation technologies in district heating. Hence, we claim that

- geothermal sources contribute to the decarbonization of heat supply through the integration into district heating [47]. Accordingly, geothermal sources depend on district heating networks and have high heat network infrastructure requirements in the downscaling.
- the limited amounts of synthetic gas and hydrogen are preferably used in district heating (i.e., co-firing in cogeneration plants [48]) if they supply (residential and commercial or low-temperature) heat demands [49]. Accordingly, both heat sources have high heat network infrastructure requirements in the downscaling.
- waste as a renewable heat source is integrated into district heating [50] (e.g., waste incineration plants [51]). Therefore, waste is characterized by high heat network infrastructure requirements in the downscaling.

To incorporate the abovementioned relevant technology-specific aspects, heat technologies/sources are downscaled according to their necessity of distribution

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

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

Table 2: Spatial nomenclature of different spatial levels using the NUTS nomenclature. Besides the number of regions per NUTS level, examples for the Austrian case study (incl. population) are given. The gray-colored rows mark the spatial levels used for downscaling in this work.

and heat network infrastructure. Therefore, population density serves as a criterion, indicating the possibility of district heating networks. Table 3 provides a qualitative overview of the different heat sources/generation technologies and their heat network/infrastructure requirements.

Heat supply		Type of sub-region (pop. density)			
Source/ technology	Network requirement	Rural (sparse)	Town/Mixed (moderate)	Urban (dense)	Supporting references
Biomass	Low	✓	✓	✓	
Direct electric	Low	✓	✓	✓	
Geothermal	High			✓	[53, 47]
Heat pump (air)	Low	✓	✓	✓	
Heat pump (ground)	Low	✓	✓	✓	
Hydrogen	High			✓	[54, 55]
Synthetic gas	High			✓	[54]
Waste	High		✓	✓	[50, 56]

Table 3: Qualitative overview of heat sources/generation technologies and their requirements for heat network infrastructure. The prioritized preferences of heat sources in sub-regions are marked by the gray cell. In addition, selected references supporting this assumptions are cited.

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

Algorithm 1: Sequential downscaling algorithm (NUTS0 to NUTS3)

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

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

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

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

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

The inputs are as follows: (i) heat generation by technology/source at the NUTS0 level, (ii) population as well as population density at 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 3). The algorithm itself consists of three main parts: initialization, pre-calculations, and downscaling. First, the initialization of the algorithm sorts the heat generation technologies/sources in descending order in terms of network infrastructure requirements. Then, the calculation starts with the first technology/source (highest requirements) (line 6). For this technology/source, all possible sub-regions are collected (line 9). Those sub-regions already fully supplied (no remaining heat demand) are filtered out (line 11). After further pre-calculation steps, the available amount of heat generation is downscaled to all valid sub-regions using population as a proxy. This procedure is repeated sequentially for each heat technology/source. The outputs of the sequential downscaling algorithm are heat generation by source and the amount of heat demand covered by centralized heat networks at the NUTS3 level.

2.4. Iterative downscaling (from the sub-region to community levels)

This section explains the methodology of the iterative downscaling algorithm. We propose this downscaling technique projecting heat generation by source and technology from the sub-region (NUTS3) to the community levels (LAU) (see Table 2). This in-depth spatial resolution is imperative for realistic network infrastructure planning [57]. The underlying concept of iterative downscaling is based on graph theory and assessing network topology using benchmark indicators.

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

s: Stage of iteration ($s \in \{0, 1, *\}$);
G^s: District heating 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: District heating at stage s: ($q^s_{n^s} \in Q^s$);
$\tilde{Q}^s$: On-site heat generation at stage s: ($\tilde{q}^s_{n^s} \in \tilde{Q}^s$);
Π^s: Benchmark indicator value at stage s ($\pi^s_{n^s} \in \Pi^s$);

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

Initialization:
$s = 0$, $iter = True$;
begin
  while $iter = True$ **do**
    foreach $n \in N^s$ **do**
      $\Pi^s_{n^s} = f(N^s, L^s, Q^s)$; // Calculate benchmark indicator value
    end
    i with $\pi^s_i = min(\Pi^s)$; // Get node with lowest indicator value
    $N^{s+1} = N^s \setminus i$; // Remove node from graph obtaining next stage
    $\tilde{q} = \sum_{N^{s+1}} \tilde{q}^s_{n^s}$; // Calculate available on-site heat generation
    if $\tilde{q} \geq q^s_i$ **then**
      foreach n^{s+1} **do**
        $q^{s+1}_{n^{s+1}} = q^s_{n^s} + \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; // Increase district heating
        $\tilde{q}^{s+1}_{n^{s+1}} = \tilde{q}^s_{n^s} - \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; // Decrease on-site heat amount
      end
      $L^{s+1} = L^s \setminus \{\forall l^s_{k,j} : k = i \vee j = i\}$; // Remove connecting lines
      $G^{s+1} = \{N^{s+1}, L^{s+1}, Q^{s+1}, \tilde{Q^{s+1}}\}$; // Create new network graph
      $G^s = G^{s+1}$; // Set updated heat network graph as new input
    else
      $iterate = False$; // Stop iteration because of no reallocation
      $G^* = G^s$; // Set heat network graph as result
    end
  end
end

2.4.1. Algorithm description

The iterative downscaling algorithm is presented in Algorithm 2. The idea is to assess, benchmark, and improve the topology of district heating 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 the NUT3 to the LAU levels using population as the downscaling driver, to obtain the initial district heating network graph G^0 (input).
2. Benchmark each node of the district heating network graph (line 11), identify the node with the lowest indicator value, and remove the node from the graph, generating a reduced heat network graph (lines 13 and 14).
3. Check if the amounts of district heating and on-site heat generation can be reallocated (line 16).
4. If yes, reallocate district heating and on-site heat generation for all nodes (lines 18 and 19); otherwise stop algorithm.
5. Update district heating network graph and jump to step 2.

Recent studies support this approach, focusing on the topography of energy systems and networks [58]. Against this background, the study in [59] presents an optimization approach for district heating strategic network design. Further works also evaluate the impact of the heating system topology on energy savings [60].

2.4.2. Heat network topology benchmarking using graph theory

So far, we have introduced only the function $f(N^s, L^s, Q^s)$ (see line 11 in the iterative algorithm (Algorithm 2)) as a calculation procedure of the benchmarking indicator value. Below, we describe and discuss the approach of using a weighted cluster coefficient as a 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 in [61]. Morever, we refer the reader to reference in [62], which describes network topologies and their transformation in detail. In this work, we use a weighted cluster coefficient as a benchmark indicator and determine the transformation path of the district heating network graph. Equation 2 shows the calculation of the weighted cluster coefficient

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

where q is the amount of district heating, α is the number of triangles that can be formed with direct neighboring nodes, and β is the number of lines connecting to the graph for node n at stage s. In the context of the fundamental concept of *alpha*, we refer again to the literature. In particular, the study in [63] comprehensively deals with cluster coefficients and provides related generalized concepts. In addition, relevant aspects of the cluster(ing) coefficient are shown in [64]. In the works cited and also in this study, 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 the literature and propose a weighting with the relative centrally supplied heat quantity. From an energy economics point-of-view, at least two important aspects are considered in the benchmarking process: (i) a high connection rate to the centralized heat network and (ii) a connection of those areas to the network that have a high heat demand and heat density, respectively. Both aspects are investigated in the literature (connection rate in [65] and the linearly decreasing heat densities and the influence on the profitability of district heating networks in [66]).

2.5. Limitation of the developed downscaling technique

This section discusses three limitations of the developed downscaling technique. Note that we use the term downscaling technique in this section and mean by this the sequential and iterative downscaling technique.

2.5.1. Limited number of heat sources/generation technologies at the aggregated and local level

The GENeSYS-MOD results of the heating sector in 2050 include the heat generation of six different sources/technologies only. Even though we explicitly added two more heat sources (geothermal and waste), we neglect other heat sources.

Exemplarily, industrial excess heat is not shown explicitly in GENeSYS-MOD results and thus in the values to be downscaled. It can be argued that some heat sources not listed are implicitly included in the six (aggregated) heat sources. However, the proposed downscaling is capable only of one individual heat network requirement per heat source.

2.5.2. Neglection of construction and investment costs for district heating networks

The benchmark indicator value proposed to generate the district heating networks at the local levels focuses primarily on the network topology. Therefore, construction and investment costs of district heating networks (pipelines, delivery stations, etc.) are neglected. In addition, distribution pipeline capacities between the individual supply areas of a district heating network (i.e., distribution pipelines between LAUs) are not considered. Existing district heating networks are not taken into account.

2.5.3. Estimation of local heat demands using population as a proxy

Since the proposed downscaling uses population as a proxy, heat demands are calculated linearly. Therefore, individual heat demands of sub-regions and communities can be under-or overestimated. Besides, other heat demands, such as those from small industries or the public sector, are neglected.

2.6. Development of an open-source package building on pyam

The method described 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 on the existing open-source Python package *pyam* [67]. *Pyam* is an open-source package for the analysis and visualization of integrated assessment and macro-energy scenarios. In this work, it is used particularly for (i) the linkage between the sequential and the iterative downscaling algorithms, (ii) the internal calculation steps within both downscaling algorithms, and (iii) the visualization of the results. Besides, we used the open-source Python package *networkx* [68], when implementing the iterative downscaling algorithm. We refer to the repository for the codebase, data collection, and further information.

3. Results and discussion

This section presents the results of the Austrian case study. Particularly, the mix of heat sources/generation technologies and related district heating networks in the four different scenarios (section 2.1) are presented. Section 3.1 presents the heat generation mix on the country, sub-regional and community levels. Potentials of district heating networks are presented further in section 3.2. Section 3.3 shows district heating networks at the community level. Furthermore, section 3.4 compares the projected district heating networks in 2050 with today's networks, based on heat density. Finally, section 3.5 presents a sensitivity analysis of heat density on large-scale heat pump (air) generation feeding into district heating networks.

3.1. 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) levels (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 representative rural and urban sub-regions, respectively, is presented. The rural sub-region Mostviertel-Eisenwurzen (NUTS3 code AT121) shows high shares of heat pump (air and sourced) generation. Furthermore, biomass and direct electric heating systems supply heat demands. The urban sub-region Rheintal-Bodenseegebiet (AT342) is supplied by synthetic gas and waste in addition to the heat sources already mentioned. Throughout the pie charts within the figure, shares of heat generation used in district heating networks are indicated by blue edges. On the extreme right, an example of district heating at the community level in Rheintal-Bodenseegebiet (AT342) for the four scenarios is presented by highlighting the supply areas. The largest supply areas of district heating are in the *Gradual Development* and *Techno-Friendly* scenarios. Note that the obtained district heating supply areas not necessarily are interconnected. Exemplarily, two separated communities are supplied by district heating in the *Directed Transition* scenario.

3.2. Sub-regions in Austria 2050 with potentials for district heating

Figure 2 presents heat demand supplied by district heating in Austria in 2050 on the NUTS3 level. Heat demands in the four sub-regions Vienna (AT130), Graz (AT221), Linz-Wels (AT312), and Rheintal-Bodenseegebiet (AT342) are covered by district heating in each scenario. The remaining sub-regions (31 out of 35) are supplied exclusively by on-site heat generation technologies/sources. However, the amount of district heating in the sub-regions varies significantly between the scenarios (see also the bottom column in Table 1). For each sub-region, the highest amount of district heating is in the *Gradual Development* scenario. Table 4 presents the quantitative results of district heating and on-site heat supply in the four sub-regions and scenarios. The share of district heating in the *Directed Transition* scenario is between 15% and 38% in the sub-regions. Against this, the *Gradual Development* scenario has shares between 86% and 99%.

3.3. District heating network topology at the community level

This section presents the district heating network topology of the sub-region *Linz-Wels* (AT312) and all included communities in the *Directed Transition* scenario. Figure 3 (the two subfigures at top) shows the projected district heating supply area. In particular, the network topology is presented for the initial condition (as a result of the sequential downscaling, $i = 1$) and the final condition of the network (as a result of the iterative downscaling, $i = 65$). The distribution of the benchmark indicator values of the district heating network depending on the number of iterations is presented in the middle. Particularly, the median is marked in orange. The supply area decreases with an increasing number of iterations. In the community analyzed here, the termination criterion

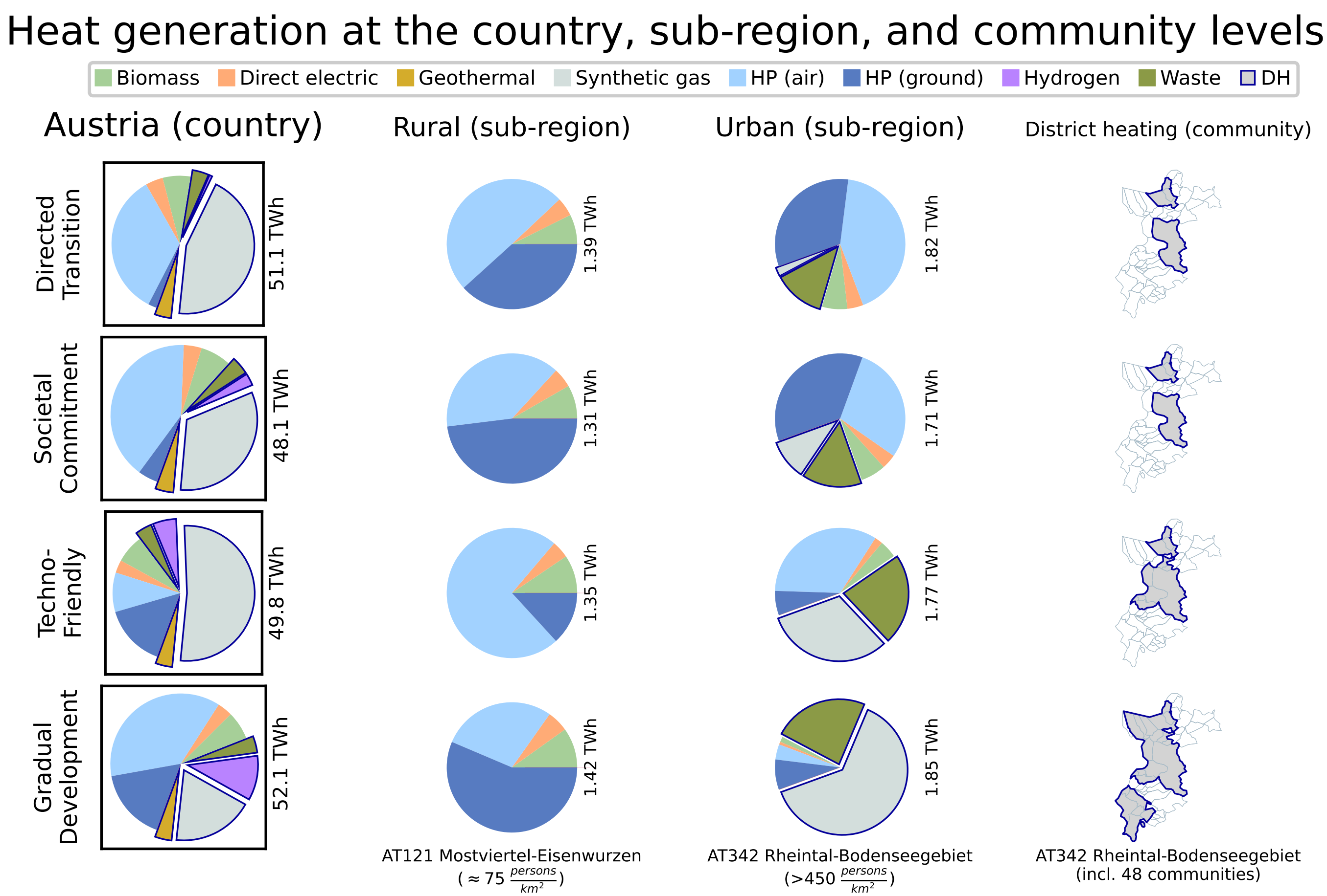

Figure 1: Heat technology generation on different spatial granularity levels in the different scenarios supplying the residential and commercial heat demand. left: on the country level. middle: comparison of a rural and urban sub-region. right: district heating at the community level

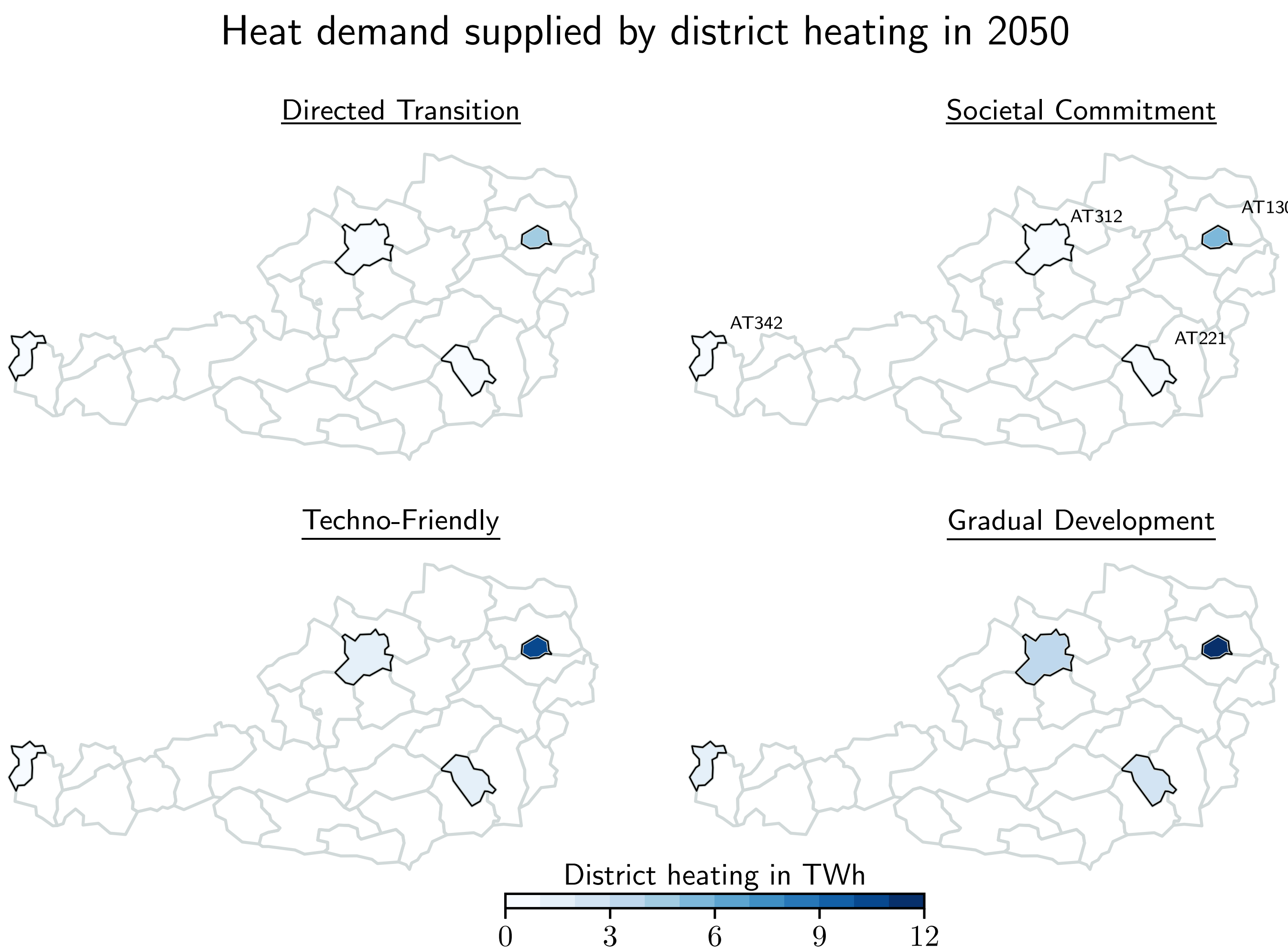

Figure 2: Heat demand supplied by district heating in Austria 2050. White sub-regions are supplied exclusively by on-site heat generation technologies/sources.

		in TWh		in %
Sub-region	Scenario	District heating (DH)	On-site	Share of DH
Vienna (AT130)	Directed Transition	4.22	6.76	38
	Societal Commitment	5.70	4.62	55
	Techno-Friendly	10.11	0.58	95
	Gradual Development	11.12	0.07	99
Graz (AT221)	Directed Transition	0.38	2.17	15
	Societal Commitment	0.60	1.80	25
	Techno-Friendly	1.34	1.14	54
	Gradual Development	2.25	0.35	87
Linz-Wels (AT312)	Directed Transition	0.51	2.91	15
	Societal Commitment	0.80	2.42	25
	Techno-Friendly	1.80	1.53	55
	Gradual Development	3.03	0.46	87
Rheintal-Bodensee (AT342)	Directed Transition	0.27	1.54	15
	Societal Commitment	0.42	1.28	25
	Techno-Friendly	0.96	0.81	54
	Gradual Development	1.60	0.25	86

Table 4: District heating and on-site heat supply in the four Austrian sub-regions with district heating networks in 2050.

of the algorithm is reached when 10 communities are connected (starting from 74 in the initial condition). The population of connected communities decreases by 40%, starting from a population of 663,000 in the initial condition. After the final iteration ($i = 65$), the termination criterion is reached, and the population of connected communities is 397,000.

3.4. Comparison of 2050's and today's district heating networks using heat density as a criteria

In the following, the district heating network in Linz-Wels (AT312) is shown in detail. This area is selected for illustrative purpose, because it provides representative results in terms of both the applied downscaling and achievable heat density benchmarks of district heating networks. Figure 4 shows the heat density of district heating in the *Techno-Friendly* scenario. The x-axis shows the three different downscaling techniques. The numerical numbers indicate a significant increase of the heat density by the sequential ($+0.49\,\mathrm{GWh/km^2}$) and, in particular, the iterative downscaling ($+3.21\,\mathrm{GWh/km^2}$). However, comparing the heat density value obtained with the heat density values of today's district

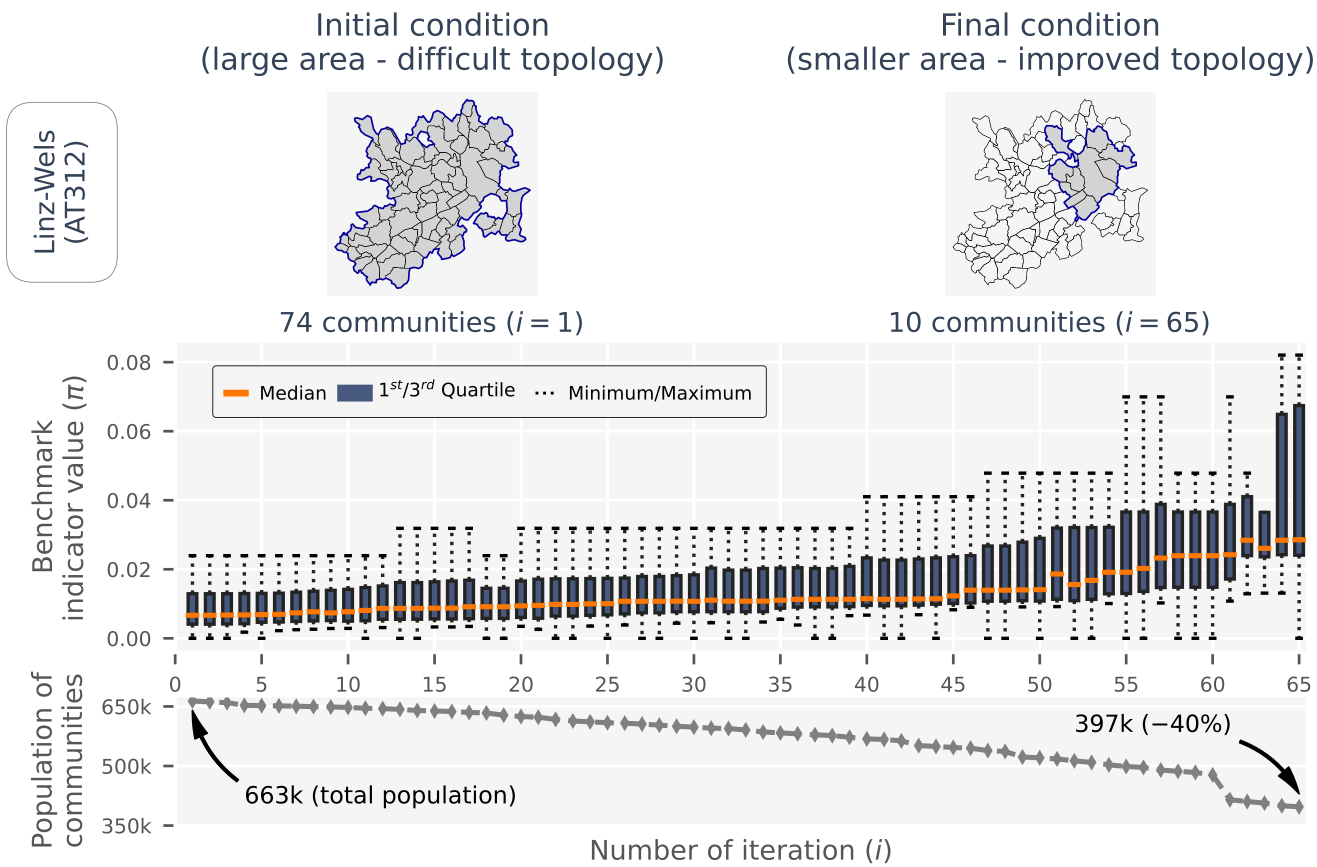

Figure 3: District heating network topology in Linz-Wels (AT312) in the *Directed Transition* scenario. The boxplot (middle) indicates the improved network topology by increasing benchmark indicator values. In the final condition 10 communities; i=65, the population of connected communities declines by −40 % compared to the initial condition (74 communities; i=1).

heating networks reveals a significant gap (see the hatched pink bar). Here, in the *Techno-Friendly* scenario, it is 5.75 GWh/km^2. According to references from the practice (`http://www.austrian-heatmap.gv.at/ergebnisse/`), the threshold heat density of today's networks is assumed to be 10 $\frac{\text{GWh}}{\text{km}^2}$ with a connection rate of 90 %.

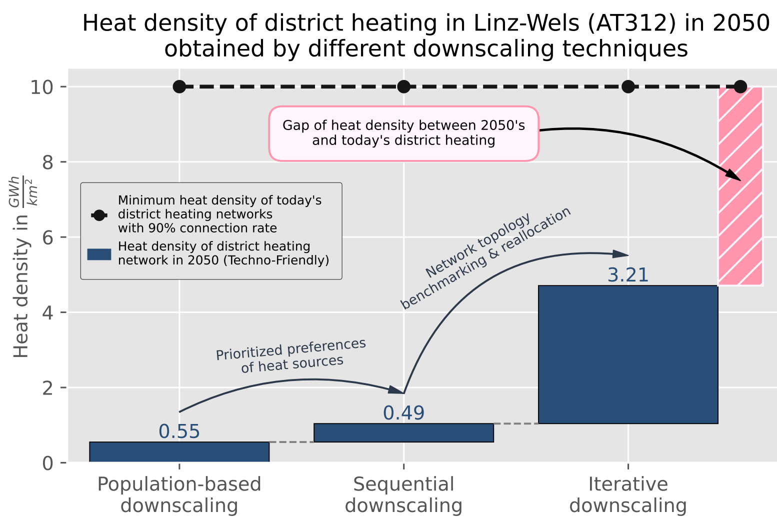

Figure 4: Heat density of the district heating in Linz-Wels (AT312) 2050 in the *Techno-Friendly* scenario. The gap of heat density between 2050s and today (black dashed line) is marked by the pink bar.

3.5. Allocation of heat pump (air) generation into district heating

Building upon Figure 4, the following sensitivity analysis examines the heat density for each network and scenario under an increasing allocation of heat pump (air) generation into district heating. In particular, it investigates how the heat density (and its gap) change under an increasing amount of district heating (i.e., heat generation used in district heating). The total heat pump (air) generation of the cost-effective GENeSYS-MOD results is divided into small- and large-scale heat pump (air) generation. Here, large-scale heat pump (air) generation is used in district heating. Figure D.2 in Appendix D shows the heat density of the the district heating network in Graz (AT221) in the *Directed Transi-*

tion scenario. The figure illustrates the influence of the increasing allocation of large-scale heat pump (air) generation into district heating on the heat density. For example, the maximum heat density is reached at a share of two-thirds of large-scale heat pump (air) generation.

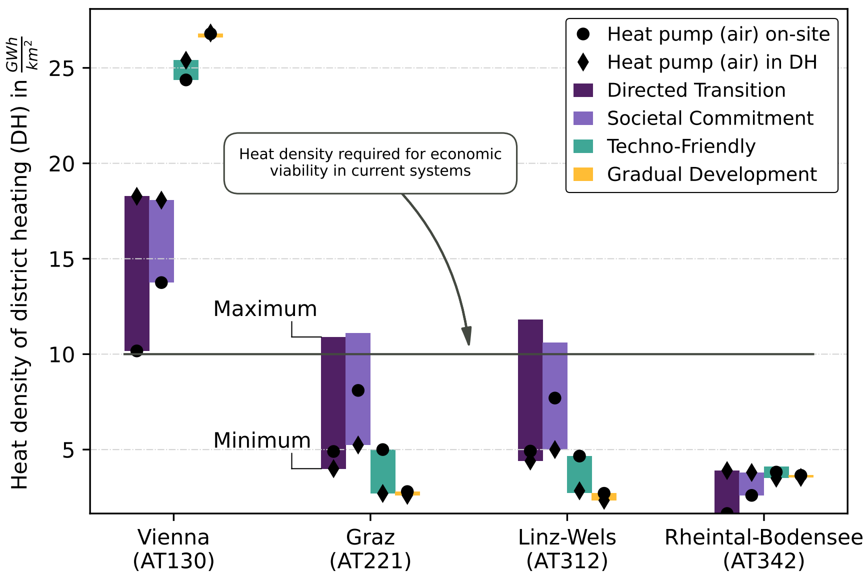

Figure 5: Heat density of district heating networks in the four sub-regions and scenarios in 2050 for varying allocation of heat pump (air) generation between large- and small-scale. The optimal allocation of large-scale heat pump (air) generation results in some cases in heat densities above the threshold required for economic viability in current systems (e.g., Graz (AT221) in the *Directed Transition* scenario).

Figure 5 shows the heat density in the four sub-regions and scenarios. The range of heat density resulting from different shares of large-scale heat pump (air) generation is presented. The two extreme points that only small-scale or large-scale heat pump (air) units are used in the sub-regions are marked by the black circle (i.e., heat pump (air) on-site) and diamond (i.e., heat pump (air) in district heating). Particularly, the heat density in the *Directed Transition* and *Societal Commitment* scenario increases significantly compared with on-site heat pump (air) generation only (e.g., Graz (AT221) and Linz-Wels (AT312)). In Vienna (AT130), the heat density remains almost the same in the *Techno-*

Friendly and *Gradual Development* scenario. At the same time, the heat density there increases and reaches 18 GWh/km^2 in the *Directed Transition* and *Societal Commitment* scenario. In Rheintal-Bodensee (AT342), the heat densities are relatively low compared to the others, independently of the allocation of large-scale heat pump (air) generation to district heating.

4. Conclusions and recommendations

The sustainable energy transition requires methods to bridge the gap between global decarbonization pathways and the corresponding measures at local levels. This work emphasizes the development of different downscaling techniques, which we apply to the European heating sector under several scenarios in line with the Paris Agreement and its remaining CO_2 budget. We use the cost-effective European heat supply from the aggregate model GENeSYS-MOD to analyze results at the community level in Austria. The remaining European CO_2 budget (and related CO_2 prices) in line with the 1.5°C climate target is considered by the GENeSYS-MOD results. The downscaling includes the technology-specific infrastructure requirements for the highly efficient usage of heat sources in district heating.

We found that the cost-effective heat supply at the European and national level in 2050 implies that district heating covers parts of the heat demand in four of the thirty-five sub-regions in Austria. Furthermore, the results demonstrate that district heating continues to be picking cherries from beneficial areas (i.e., densely populated with high heat densities) as only some communities of the four mentioned areas are supplied by district heating. Nevertheless, not all district heating networks and supply areas in 2050 reach the heat density required for economic and technical efficiency from today's techno-economic perspective and industry benchmarks. This heat density gap (mainly driven by a significant reduction of heat demands by building renovation measures) poses a challenge for district heating but can be reduced by the optimal allocation of large-scale heat pump (air) generation into district heating.

We anticipate our work as a starting point for discussing the role of district heating enabling large-scale, highly efficient, and local integration of renewable heat sources such as geothermal, synthetic gas, hydrogen, and waste in sustainable energy systems with decreasing heat demands. Further research should follow on how obtained district heating networks and their heat densities (incl. the generation of large-scale heat pump (air) units) could be returned into more aggregate models, such as GENeSYS-MOD, in the sense of a feedback loop. That allows refining assumptions in the large-scale models, which in turn will increase the plausibility and realism of pathways at the European level.

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. Part of the research was developed in the Young Scientists Summer Program (YSSP) at the International Institute for Applied Systems Analysis(IIASA), Laxenburg (Austria). The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Programme.

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Appendix A. Current Austrian heat market

Table A.1 provides an overview of the Austrian heat market in 2017. Particularly, the proportion per heat source/generation technology on the total heat demand for space heating and hot water is shown. Note that the absolute number of households supplied by heat pumps and solarthermal is in total 294,075 (see row 6 in the table). According to [69], the total heat production from district heating was around 24 TWh in 2016. Thereby, the share of renewable energy was 45%. Besides, the share of waste sources was 9%.

	Proportion in %	Abs. number
Heat source/technology	on space and hot water demand	of households supplied
Biomass	28.3	725,439
Natural gas	26.5	913,448
Oil	17.2	626,109
District heating	14.6	1,112,734
Direct electric	8.2	210,648
Heat pumps	3.0	294,075
Solarthermal	1.9	
Coal	0.4	7,640

Table A.1: Proportion of heat sources/generation technologies on the total heat demand (space and hot water) and absolute number of households supplied for Austria in 2017. Source: [10].

Appendix B. Illustration of the benchmark indicator value

Figure B.1 shows an illustrative example of the iterative downscaling algorithm (Algorithm 2). It shows two different conditions of a simple graph. In the first condition (i), the network topology consists of four nodes (A-D) and four lines. It is shown in the subfigure in the top left. The table below (bottom left) shows the amount of district heating and on-site heat supply as well as the indicator value for each node. Note that the numbers are only for illustration. Node A has the lowest indicator value (see marker [1] in the left table) and, therefore, its amount of district heating (marker [2]) is reallocated to the remaining nodes of the network (marker [3]). This process increases the on-site heat supply accordingly at node A as this node is not connected to the network in condition

$i+1$ and increases the amount of district heating at nodes B-D (see the larger nodes in the top right subfigure). The heat demand of node A in condition $i+1$ is covered only by on-site heat supply. Node A is removed from the graph and thus disconnected from the network.

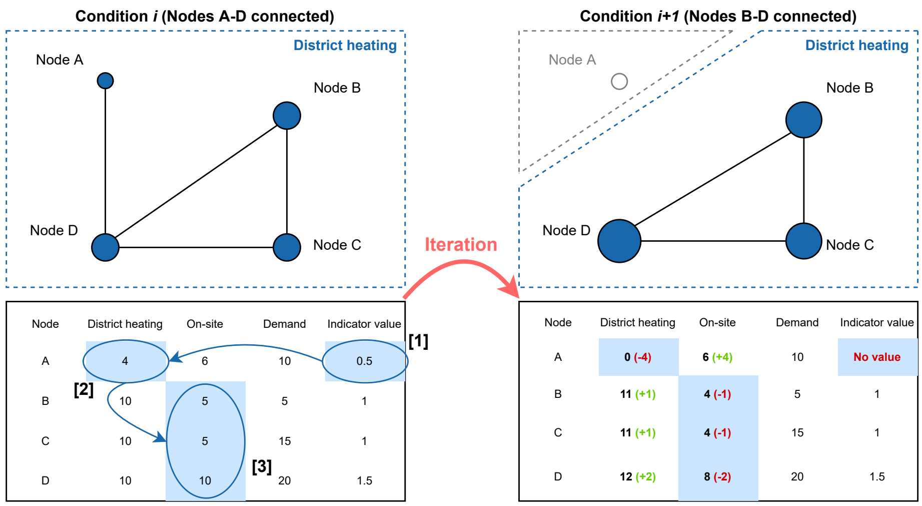

Figure B.1: Illustrative example of Algorithm 2 showing a simple graph with four nodes in two different conditions. The node with the lowest indicator value in condition i (node A) is removed from the graph (markers [1]-[3] in the table at the bottom left). The amount of district heating from node A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

Appendix C. Data and further empirical settings

	Description	Data availability	Data source
GENeSYS-MOD v2.0	Heat generation by source	[70]	[38]
Austrian population density	in 2019	*Statistik Austria*	
Austrian population	in 2050	*Eurostat*	

Table C.2: Empirical data settings

Appendix D. Heat density for varying allocation of heat pump generation into district heating

Figure D.2 shows the heat density of the district heating network in Graz (AT221) in the *Directed Transition* scenario. On the x-axis, the amount of district heating is shown. District heating in the *Directed Transition* scenario includes synthetic gas and waste only. The corresponding heat density is indicated by the black circle (top). The range between the two dotted lines marks the heat generation by heat pump (air) units. The left dashed line indicates heat pump (air) generation if used exclusively on-site (i.e., small-scale heat pump (air) units). Similarly, the right dashed line indicates heat pump (air) generation if used exclusively in district heating (i.e., large-scale heat pump (air) units). Each point between the two dashed lines corresponds to an individual split between small- and large-scale heat pump (air) units. The maximum heat density of 10.9 $\mathrm{GWh/km^2}$ is reached by a share of two-thirds of large-scale heat pump (air) units feeding into district heating while one-third is on-site.

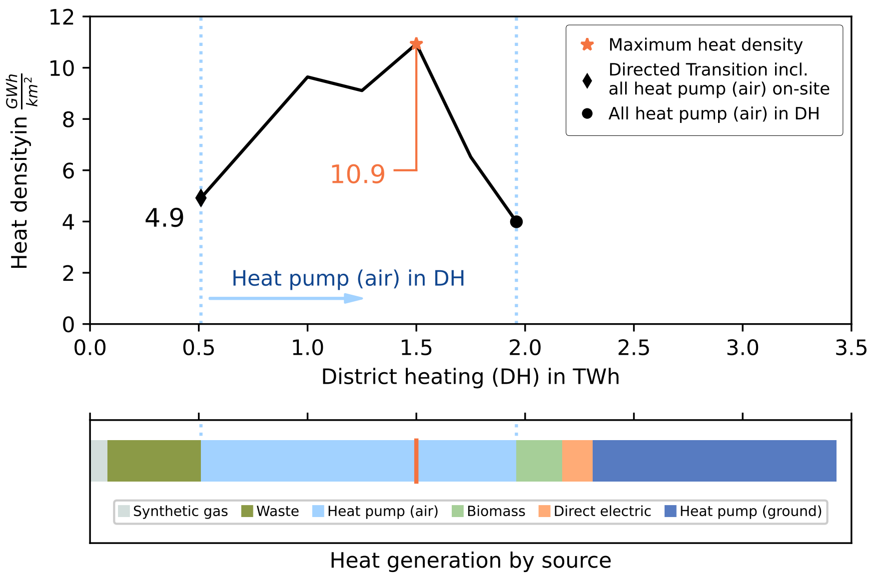

Figure D.2: Heat density of the district heating network in Graz (AT221) in the *Directed Transition* scenario (black circle) and for varying allocation of heat pump (air) generation into district heating (black line). The maximum heat density of 10.9 GWh/km^2 is reached by a share of two-thirds of heat pump (air) generation feeding into district heating.