Disclosing the heat density of district heating~~centralized heat~~ networks for~~in~~ 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 analyz~~s~~ed 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*~~”EU Green Deal”~~ describes the concrete goals in Europe, namely, a climate-neutral and resource-conserving economy and society ~~(see, e.g.,~~ [3]~~)~~. The overarching goal is to reduce CO_2~~carbon~~ 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 ~~(see, e.g., Oshiro et al. [4] and Grubler et al.~~ [5]~~)~~, (ii) deployment and generation of renewable energy technologies ~~(see, e.g., Bakhtavar et al.~~ [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*~~”Fit for 55”~~, a ~~concrete~~ roadmap with specific actions and targets until~~to~~ 2030. This program commits to a 55 % reduction in CO_2 emissions in 2030 compared to ~~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~~centralized heating networks~~.

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 ~~average~~ share of renewable energies in the heating and cooling sector in 2018 is only just above 20 % on average~~, for all EU member states~~ [8]. In Austria, it reaches 34%~~It is, in fact, higher in some countries, for example, in Austria, it is above 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] ~~To be even more specific for the heating sector, o~~Nevertheless, of the nearly 4,000,000 residential dwellings in Austria, more than one million~~900,000~~ 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 (Den-

[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/`

mark, 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].~~Nussbaumer and Thalmann [17] thoroughly elaborate on the network design and its impact on the profitability of centralized heat networks.~~ In addition, the cost-optimized heat supply is also influenced by the location of heat generation units/sources within the networks [18]. ~~In their study, Laasasenaho et al. [18] emphasize the optimal location of heat generation units/sources within centralized heat networks, enabling a cost-optimized heat supply.~~ ~~Gopalakrishnan and Kosanovic [19] focus on the optimal heat generation technology dispatch.~~ When examining the economic viability of district heating networks, building renovation measures must also be taken into account ~~(see, e.g.,~~ [20]~~ and [21])~~. Recently, the results in [22] show~~Hietaharju et al. [22] recently show in their analysis~~ 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].~~Reidhav and Werner [24] show how energy taxes can improve the profitability of sparse district heating networks in Sweden.~~ 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~~Of course~~, this is valid only in the case of deep decarbonization of the generation mix feeding into district~~centralized~~ 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.~~Di~~

~~Lucia and Ericsson [26] show that biomass significantly contributed to the decarbonization of the district heating network and replaced fossil fuels in the feed-in generation mix in Sweden. In their multi-criteria study, Ghafghazi et al. [29] also identify wood pellets as the optimal system option for fueling district heating networks.~~ Eventually, the increasing cooling demand and the co-design of district~~centralized networks for~~ 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].~~Wilkerson et al. [32] and van Vuuren et al. [33] deal with IAMs and their role in understanding global energy decarbonization pathways.~~ Evaluating and discussing IAM involves~~Schwanitz [34] evaluates IAMs of global climate change and discusses~~, 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, ~~Gambhir et al. [36] also highlight this aspect of aggregation bias in their critical review of IAMs. They propose, among others, that~~ IAMs should ~~be~~ increasingly be supplemented with other models and analytical approaches [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, ~~Capros et al. [37] (~~PRIMES~~)~~ [37] and ~~Löffler et al. [38] (~~GENeSYS-MOD~~)~~ [38] are aggregate~~provide~~ 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, ~~Backe et al. [39] 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) is presented in [39]. In this~~their~~ study, ~~they integrated~~ 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~~centralized~~ heating (e.g., geothermal sources, co-firing synthetic gas and hydrogen in cogeneration plants and large-scale waste utilization~~, etc.~~). In addition, the topography of district heating networks is of particular importance and plays a crucial role in applied downscaling. This allows estimates of realistic ~~and cost-effective~~ 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~~centralized~~ 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~~centralized heat supply~~ at the local (community) level, see section 2.4. Section 3 presents and discusses the results of this work. Section~~s 2.1 and~~ **??** shows heat generation by source at different spatial levels. Sections **??** and **??** present district heating networks~~centralized heat networks~~ at a high spatial granularity. Section **??** synthesizes the results of district~~centralized~~ heating networks and compares heat densities of district heating~~centralized heat networks~~ in 2050 with today's values. Section **??** 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 developed in 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 mathematical formulation of the optimization model that is used to downscale. 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 ~~obtained from the Horizon 2020 project openENTRANCE~~

This section presents the heat generation mix covering the Austrian residential and commercial heat demand in 2050 for four different scenarios~~storylines~~, 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~~storylines~~ 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~~storyline~~ (*Gradual Development*) can be interpreted as less ambitions scenario~~storyline~~, 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~~storylines~~ are described briefly, before the quantitative results at the country level are presented. For a more detailed description of the scenarios ~~storylines~~, refer to [40] and [41]. Further information is also available on the website of the project[3] and on GitHub[4].

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

The underlying concept of the four scenarios~~storylines~~ is a three-dimensional space consisting of the following parameters: technology, policy, and society. Each scenario~~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 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~~storylines~~: 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 ~~storyline~~. Although the other three dimensions contribute to decarbonization, they do not push it sufficiently and result in a more conservative scenario~~storyline~~ than the others.

Table 1 shows the heat generation by source/technology in Austria in 2050 for the four scenarios~~storylines~~. 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.~~According to the underlying assumptions in the storylines, the heat generation of the different sources/technologies varies significantly in some cases (e.g., hydrogen-based heat generation in *Directed Transition* and *Gradual Development* (7.62TWh) or heat pump (ground) generation in *Techno-Friendly* and *Societal Commitment* (14.78TWh)). The gray-colored column Σ presents the total heat generation using centralized heat networks, which varies between 19.49TWh (*Techno-Friendly*) and 35.23TWh (*Gradual Development*).~~

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~~[43]~~. In this context, the study in [43]~~van Vuuren et al. [43]~~ provides a comprehensive analysis of different proxies for the downscaling of global environmental change, including gross domestic product, emissions and other indicators~~However, in the context of downscaling aggregated values of energy systems, one often finds proportional downscaling using population as a proxy (see, e.g., Ahn et al. [44], van Vuuren et al. [45], and Alam et al. [46])~~. 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~~For further information, we refer the reader to van Vuuren's study~~ [45], providing a systematic classification of different downscaling techniques~~going far beyond the simple proportional downscaling method discussed so far~~. The reader can find population-based downscaling in the authors' categorization under algorithmic and proportional downscaling. In addition, the study shows~~they showed~~ 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.~~ and the increasing role of biomass and waste heat sources, in particular, in densely populated areas.~~ 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

[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.

(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.

~~Besides, we claim that high shares of air-source heat pumps (or geothermal sources) in the heat supply can only be realized if they are used as a co-firing heat source in district heating networks. We therefore consider two main aspects, namely that geothermal sources will contribute significantly to decarbonizing the feed-in energy mix of existing district heating grids in the future (see, e.g., [47]), and that the provision of high shares of geothermal-based heat supply requires the distribution through district heating infrastructure [52]. Besides, it is highly uncertain whether small-scale geothermal units at the end-user's level will be economically viable in the future, because of the high investment costs expected.~~

To incorporate the abovementioned relevant technology-specific aspects, heat technologies/sources are downscaled according to their necessity of distribution and heat network infrastructure. Therefore, population density serves as a criterion, indicating the possibility of district heating networks~~centralized heat networks~~. Table 3 provides a qualitative overview of the different heat sources/generation technologies and their heat network/infrastructure requirements.

~~The sub-regions used to downscale the corresponding heat sources are marked.~~ 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

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.

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~~, as stated by Zvoleff et al.~~ [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 ~~(see, e.g., [58])~~[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].~~Bordin et al. [59] conduct an approach for the optimized strategic network design of centralized heat systems. Allen et al. [60] evaluate the topology of centralized heating systems and conclude that the optimization of the topology is promising to facilitate the adoption of centralized heat networks.~~

2.4.2. 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]~~by Strogatz [61]~~. Morever, we refer the reader to reference in~~Sanfeliu and Fu~~ [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]).~~For example, Nilsson et al. [65] focus on the importance of the connection rate of centralized heat networks. Besides, Dochev et al. [66] investigate the impact of linearly decreasing heat densities and the influence on the profitability of the centralized heat networks.~~

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 in 2050. The focus is put on the mix of heat sources/generation technologies and district heating in the four different scenarios. Section 3.1 shows the heat supply of a representative Austrian NUTS3 region in detail. Building upon, section 3.2 compares heat supply in an urban and a rural LAU/district. Section 3.3 presents the obtained heat densities of district heating networks. Finally, section 3.4 syntheses the results of district heating and provides indications/information that could be returned into more aggregate models, such as GENeSYS-MOD, in the sense of a feedback loop.

3.1. Heat supply in a representative NUTS3 region in 2050

This section presents the results of the NUTS3 region 'Salzburg and Surroundings' (AT323). Figure 1 shows the most relevant results in this region on LAU/district level for the four different scenarios. District heating supplies heat demands in 5 different LAUs/districts. In particular, the LAUs are in the surrounding area of Salzburg city (marked by the star). The remaining LAUs in the NUTS3 region are supplied decentralized/on-site. Details of the heat sources that supply heat demands in LAUs with district heating and with decentralized/on-site heat systems are presented in the following section 3.2. The amount of district heating varies between 1.045 and 1.132 TWh per year (Figure 1, top right). The highest value is achieved in the Gradual Development scenario since this is the scenario with the lowest heat demand reduction. The heat density of district heating in the 5 LAUs is shown in Figure 1, bottom right. The highest heat density is achieved in Salzburg city and reaches approximately 30 GWh/km^2 in each scenario. The comparable low heat densities in two of the five LAUs (marked by rectangle and plus) is further discussed in section 3.4.

3.2. Comparison of heat supply in urban and rural LAUs/districts

Building upon the so-far presented results of the NUTS3 region 'Salzburg and Surroundings', this section shows the heat sources/generation technologies sup-

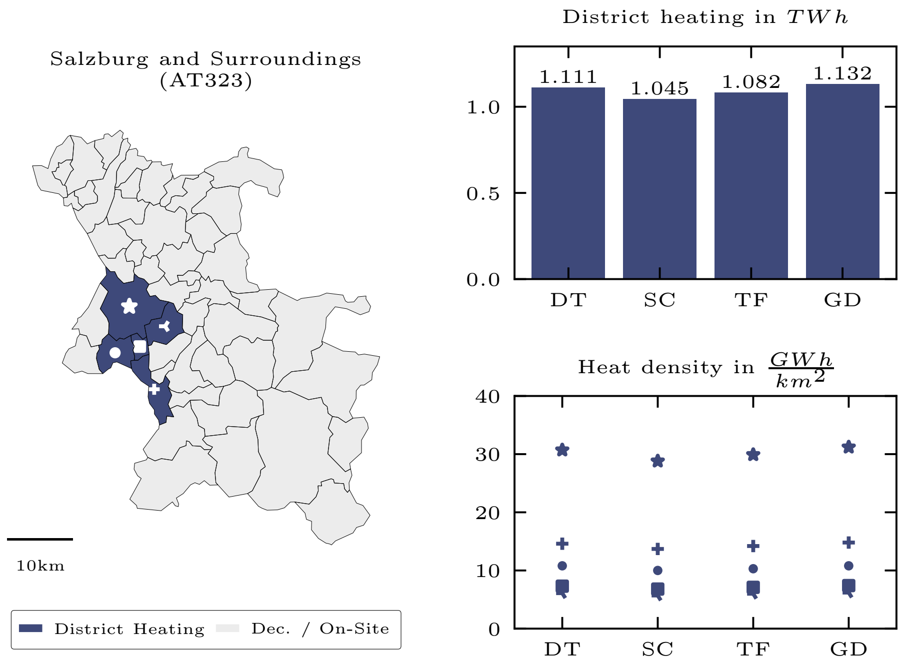

Figure 1: District heating and decentralized/on-site heat supply in the representative NUTS3 region (incl. LAUs/districts) 'Salzburg and Surroundings' (AT323). Left: LAUs with district heating or on-site heat supply. Top right: Total amount of district heating in the four different scenarios. Bottom right: heat density of district heating in the four different scenarios.

plying heat demands in an urban and in a rural LAU/district. We use 'Salzburg' city (urban district) and 'Abtenau' (rural district) as representative LAUs. Figure 2 shows the mix of heat sources supplying heat demands in both LAUs. The geographical location is shown on the top left in Figure 2. In 'Salzburg' city (marked by the orange edge), district heating supplies heat demands, which uses large-scale heat pumps (air-sourced), hydrogen, synthetic gas, and waste as heat sources/generation technologies. High shares of district heating particularly are generated by large-scale heat pumps (air) and using hydrogen. In contrary, the heat supply in the rural district 'Abtenau' uses small-scale heat pumps (air), heat pumps (ground-sourced), biomass, and direct electric heating systems. Among all four scenarios, high shares of heat demands are supplied by heat pumps (air- and ground-sourced). However, the share of each technologies varies to some extent significantly, which becomes evident when comparing exemplarily the Techno-Friendly and Gradual Development scenario. In the Techno-Friendly, small-scale heat pumps (air-sourced) are the dominant heat source, whereby heat pumps (ground-sourced) supply high shares of heat demands in the Gradual Development scenario.

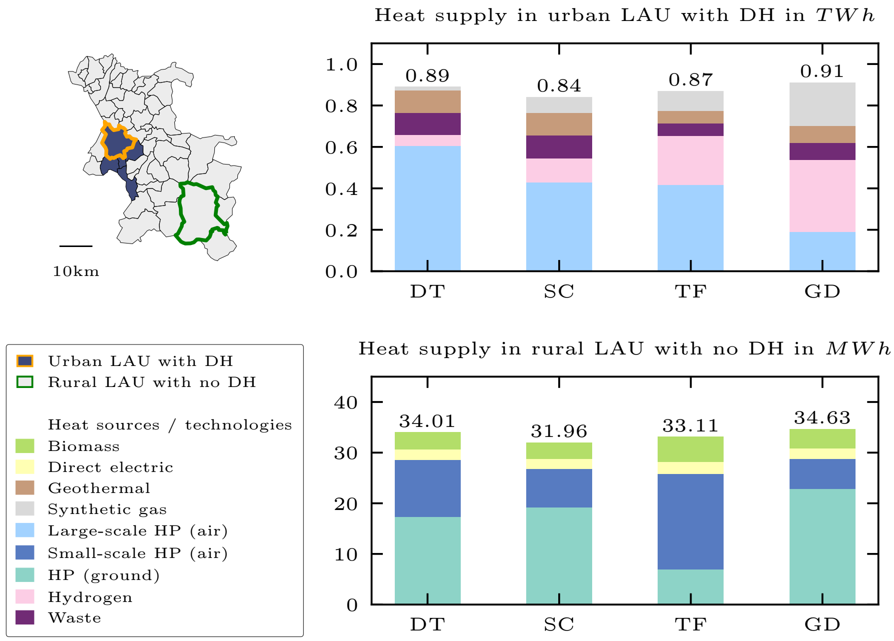

Figure 2: Comparison of heat supply in an urban LAU with district heating ('Salzburg' city) and in a rural LAU with no district heating ('Abtenau'). Top right: Mix of heat sources in the four different scenarios used in district heating. Bottom right: Mix of heat sources used to supply heat demands decentralized/on-site.

3.3. Heat densities of district heating in LAUs in 2050

This section shows the heat density of district heating at the LAU/district level in 2050. Figure 3 shows the heat density for the four different scenarios. Particularly, the values of LAU's heat densities are sorted in descending order indicating those LAUs/districts that do not reach the required heat density of economic viability, which is assumed to be 10 GWh/km^2. Exemplarily, in the Directed Transition scenario, there are 107 LAUs with district heating. In this scenario, the highest heat density is 43.17 GWh/km^2. 2 of the 5 LAUs in the

NUTS3 region 'Salzburg and Surroundings' are highlighted, namely, 'Salzburg' city (marker by the star in Figure 1) and 'Anif' (marked by the rectangle in Figure 1). Both LAUs are part of the same district heating network as already illustrated in the left subfigure in Figure 1. Accordingly, the appearance of heat densities below the assumed threshold/benchmark for economic viability can be argued as those LAUs are connected to high heat density areas. The distribution of heat density values remains mostly the same between the four different scenarios. For the sake of clarity, explicit annotations are omitted in the three (smaller) scenario subfigures at the bottom.

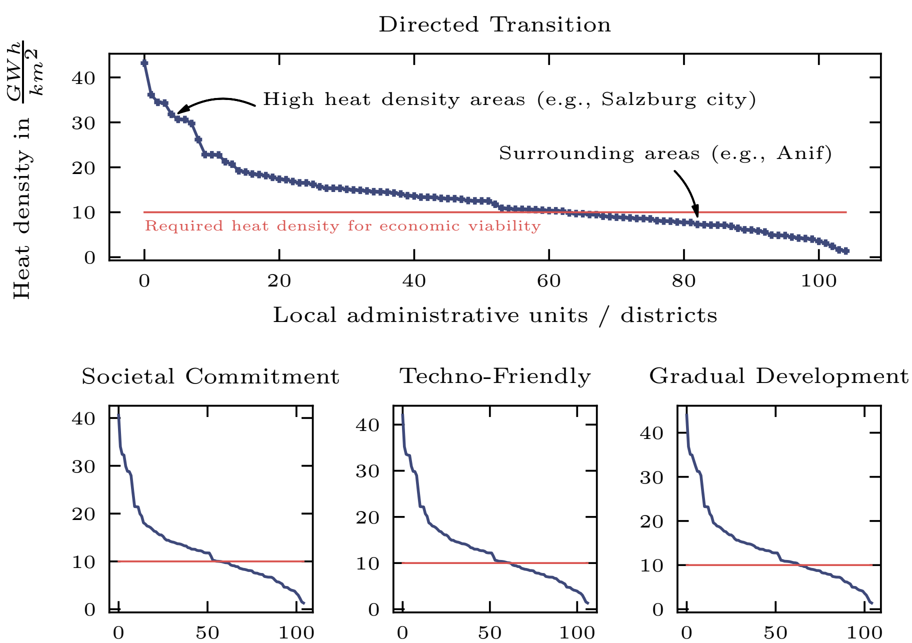

Figure 3: Heat density values at the LAU level in the four different scenarios in descending order indicating those LAUs that do not achieve the required heat density benchmark for economic viability.

3.4. Comparison of heat supply in urban and rural districts

We focus in this section on those LAUs with lower heat densites than assumed to be required for economic viability for district heating and their geographical location in respect to other district heating supply areas. As indicated in

Figure 3, LAUs with low heat densities can be quite justified in case that they are located in the surrounding area of high heat density areas (e.g., Salzburg city and Anif). However, other LAUs that do not achieve the required heat density benchmark (of 10 GWh/km^2) and at the same time are not closely located to high heat density areas are unlikely to be implemented. Accordingly, Figure 4 shows the heat map of district heating in Austria at the LAU level under the requirement that district heating achieves the required heat density benchmark within NUTS3 regions in the Directed Transition scenario. As previously mentioned, the model basically decides to supply heat demands in 105 LAUs by district heating. 63 of them already achieved heat densities higher than the benchmark value. The heat map in Figure 4 still shows 68 LAUs since 5 are closely located to high heat density areas and thus achieve in total the benchmark (at the NUTS3 level).

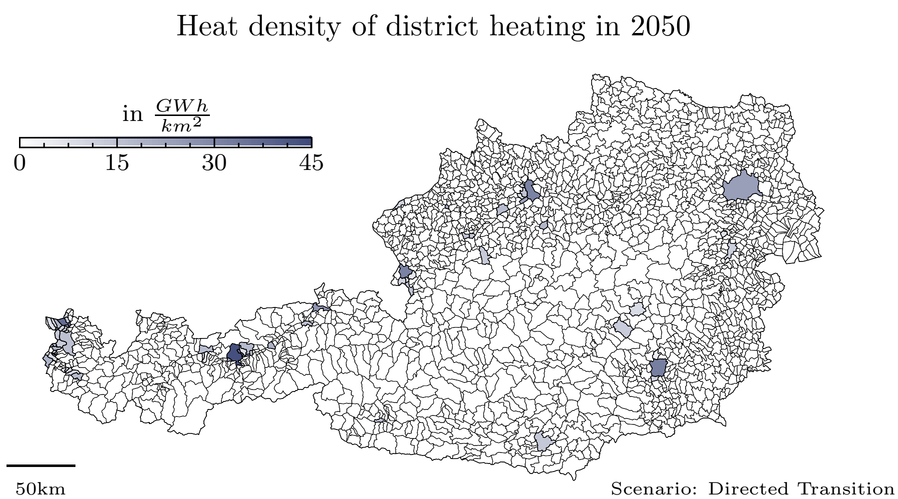

Figure 4: Heat density of district heating in the Directed Transition scenario in 2050 achieving the required heat density benchmark value of 10 GWh/km^2 at the NUTS3 level.

Accordingly, district heating is unlikely to be implemented in 37 LAUs. Table 4 summarizes the results for district heating in the four different scenarios. It is shown that as a result of the heat density benchmark at the NUTS3 level the share of implemented district heating varies between 74 and 90%. In particular, this means exemplarily that in the Techno-Friendly scenario, 74% of the assumed heat supply using district heating leads to heat density values higher than 10 GWh/km^2. In view of the previous assumptions that 50% of heat pumps (air-sourced) are used in district heating, this results in implemented shares between 23% and 40%, whereby the highest share is achieved in the Directed Transition scenario.

Results in the four scenarios (from Sec. 2.1)	DT	SC	TF	GD
District Heating (from GENeSYS-MOD) in TWh	16.75	15.38	27.20	22.84
LAUs with district heating (from downscaling)	105	105	107	105
- of which with more than 10 GWh/km^2	63	57	62	64
- of which with less than 10 GWh/km^2	42	60	45	41
LAUs with district heating (10 GWh/km^2 at NUTS3)	68	66	68	68
District heating (10 GWh/km^2 at NUTS3) in TWh	14.57	13.08	20.09	20.62
- share in district heating from GENeSYS-MOD in %	87	85	74	90
- share of large-scale heat pumps (air) in %	40	35	23	26

Table 4: Overview of district heating supplying heat demands in 2050 in the four different scenarios Directed Transition (DT), Societal Commitment (SC), Techno-Friendly (TF), and Gradual Development (GD). The resulting district heating that reaches the heat density benchmark of 10 GWh/km^2 at the NUTS3 level is marked in gray.

In view of the underlying narratives of particularly the three ambitious decarbonization scenarios from Section 2.1 (therefore excluded the Gradual Development scenario), two interesting implications can be derived from the results here:

- In absolute terms, the Techno-Friendly scenario has the highest share of district heating with 20.09 GWh/km^2 under the condition that district heating networks within the NUTS3 levels achieve the heat density benchmark of 10 GWh/km^2. The main driver for this is the significant penetration of (large-scale) heat pumps (air-sourced) that takes place in this scenario.
- Nevertheless, the implemented share of district heating in GENeSYS-MOD's district heating is the highest in the Directed Transition scenario and reaches 87 %. This result is also reflected in the fact that the share

of large-scale heat pumps (air-sourced) achieves here its maximum with 40 % between the scenarios.

4. Conclusions and recommendations

Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

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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. 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 B.2: Empirical data settings

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

Figure ?? 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 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.