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 **??**). 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 **??**). 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 **??**. 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. Section 2.2 explains the mathematical formulation of the optimization model in detail. Then, section 2.3 shows the workflow that is used to obtain the implemented shares of district heating. Finally, section 2.4 concludes this section and presents further data and 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, 41, 42]. 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].

	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 (Q^{dh}_{GENe} in Sec. 2.2)		16.75	15.38	27.20	22.84

Table 1: Heat generation by source in Austria in 2020 and the four different decarbonization scenarios in 2050. Geothermal, hydrogen, synthetic gas, waste, and half of heat pump (air-sourced) generation is used in district heating. Sources: [41, 43, 11]

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-sourced) heat generation using estimates from national Austrian studies in [43] and [11] to complement the GENeSYS-MOD results. 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. In this work, the assumption is made that geothermal, hydrogen, synthetic gas, waste, and half of the total heat generation by heat pumps (air-sourced) are used in district heating. Therefore, we claim that

- geothermal [44] and waste [45] as renewable heat sources contribute to the decarbonization of heat supply by the integration into district heating.
- the limited amounts of synthetic gas and hydrogen are preferably used in district heating (i.e., co-firing in cogeneration plants [46]) if they supply (residential and commercial or low-temperature) heat demands [47, 48, 49].
- half of the cost-optimal heat supply of heat pumps (air-sourced) of the aggregate model GENeSYS-MOD are used in district heating through implementation of large-scale heat pumps. Accordingly, heat pumps (air-sourced) significantly contribute to supply decarbonized district heating networks [50].

2.2. Mathematical formulation of the optimization model

Building upon the amount of district heating obtained by the aggregate model GENeSYS-MOD, this section explains the optimization model used to downscale heat supply to the LAU level in detail. Before, Table 2 shows the spatial nomenclature of this work based on the NUTS nomenclature. Particularly, this includes representative examples for the LAU level. Against this background, Equation 1 shows the objective function of the model that is used for the downscaling.

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.

$$\max_{q_l^{dh}, q_l^{dec}} \sum_l \underbrace{\frac{q_l^{dh}}{\phi_l \cdot A_l}}_{\text{within LAU } l} + \underbrace{\frac{q_l^{sur}}{A_l^{sur}}}_{\text{around LAU } l} \tag{1}$$

Therein, q_l^{dh} is the amount of district heating supply per LAU, q_l^{dec} the amount of heat demand supply decentralized/on-site, ϕ_l a scaling factor to obtain the effective supplied area of district heating based on the permanent settlement area A_l per LAU l. This becomes necessary since A_l includes the space available for agriculture, settlement and transport facilities. q_l^{env} is the amount of district heating in the surrounding LAUs of l. A_l^{sur} is the effective are of the surroundings LAUs. Equation 2 links the aggregate model GENeSYS-MOD with the developed optimization for the downscaling since the upper bound of district heating is set to the amount of district heating from GENeSYS-MOD's cost-optimal solution Q_{GENe}^{dh}.

$$\sum_l q_l^{dh} = Q_{GENe}^{dh} \tag{2}$$

Equation 3 is the demand constraint per l ensuring that the total heat demand q_l^{total} is covered either by district heating or decentralized/on-site at l.

$$q_l^{dh} + q_l^{dec} = q_l^{total} \quad : \forall l \tag{3}$$

Equation 4 calculates the amount of district heating in surrounding areas of l which is expressed by the subset L_l^{sur} containing all LAUs bordering l and the effective area A_l^{sur}. Latter is done similar to the first term (within LAU) in the objective function in Equation 1.

$$q_l^{sur} = \sum_{l \in L_l^{sur}} q_l^{dh} \quad \text{and} \quad A_l^{sur} = \sum_{l \in L_l^{sur}} \phi_l \cdot A_l \quad : \forall l \tag{4}$$

2.3. Workflow to obtain implemented shares of district heating

The described mathematical formulation of the optimization model allocates the amount of district heating to the LAU level in order to maximize the objective function value. However, this not necessarily ensures that obtained heat densities of district heating networks reach the in this work assumed benchmark of 10 GWh/km^2. Consequently, this section explains in detail how the optimal values of q_l^{dh} (i.e., district heating at the LAU level) is further processed resulting in heat densities of district heating higher than the benchmark value. The developed workflow is as follows:

1. Starting with the optimal amount of district heating q_l^{dh} at the LAU level obtained from the optimization model.

2. Identification all LAUs that do not achieve the required heat density benchmark value of 10 GWh/km^2.

3. For each of those LAUs, the heat density of district heating within the corresponding NUTS3 region and thus network level is calculated.

4. In case that the heat density reaches values higher than the benchmark at the NUTS3 level, the supply using district heating remains since LAUs are then connected to or in the surrounding area of high heat density areas.

5. Otherwise, q_l^{dh} is set to zero as no economic viability can be expected there due to lower achieved heat densities than the benchmark.

Finally, steps 1 to 5 allow to calculate implemented district heating under the condition that either the local heat density at the LAU or the network heat density at the NUTS3 level achieves the assumed heat density benchmark value of 10 GWh/km^2.

2.4. Further data and open-source tools used

In order to obtain total heat demand at the LAU level (q_l^{total}), we apply proportional downscaling using population as downscaling proxy. 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 [51] 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 [52]. Table 3 shows the data used to obtain heat demand at the LAU level in 2050 including population estimates for Austria until 2050.

	Description	Data availability/source
GENeSYS-MOD v2.0	Heat generation by source	[53, 38]
Austrian population density	in 2019	*Statistik Austria*
Austrian population	in 2050	*Eurostat*

Table 3: Empirical data settings

The developed optimization model is implemented in Python 3.8.12 using the modeling framework Pyomo version 5.7.3 [54]. It is solved with the solver Gurobi version 9.0.3. We use for data analysis the IAMC (Integrated Assessment Modeling Consortium) common data format template with the open-source Python package pyam [55]. All materials used in this work are available in the author's GitHub webpage. We refer to the correspodning repository in to be added.

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-

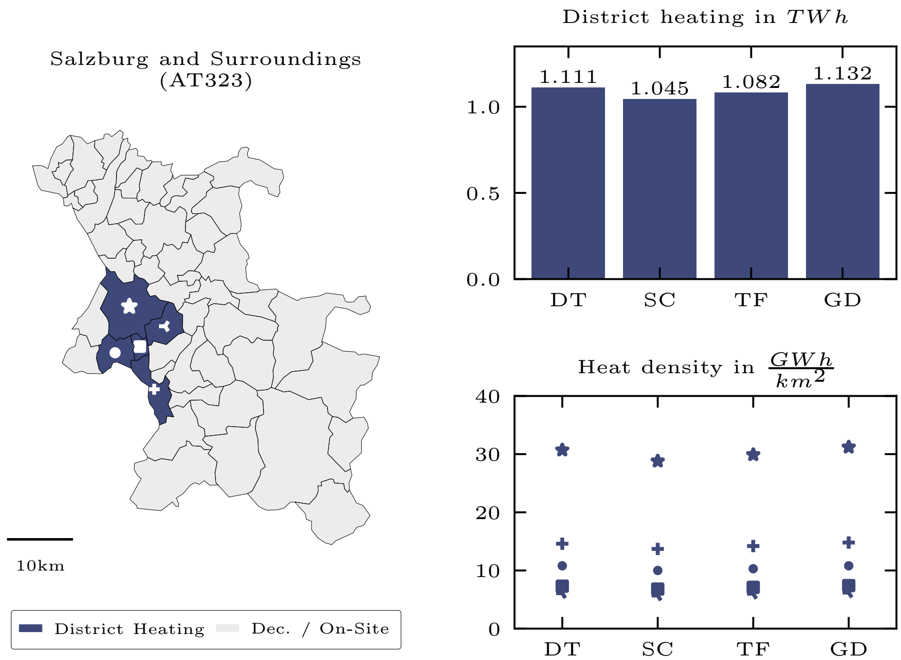

Figure 1: District heating and decentralized/on-site heat supply in the representative NUTS3 region (incl. LAUs/districts) 'Salzburg and Surroundings' (AT323). Left: LAUs with district heating or on-site heat supply. Top right: Total amount of district heating in the four different scenarios. Bottom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

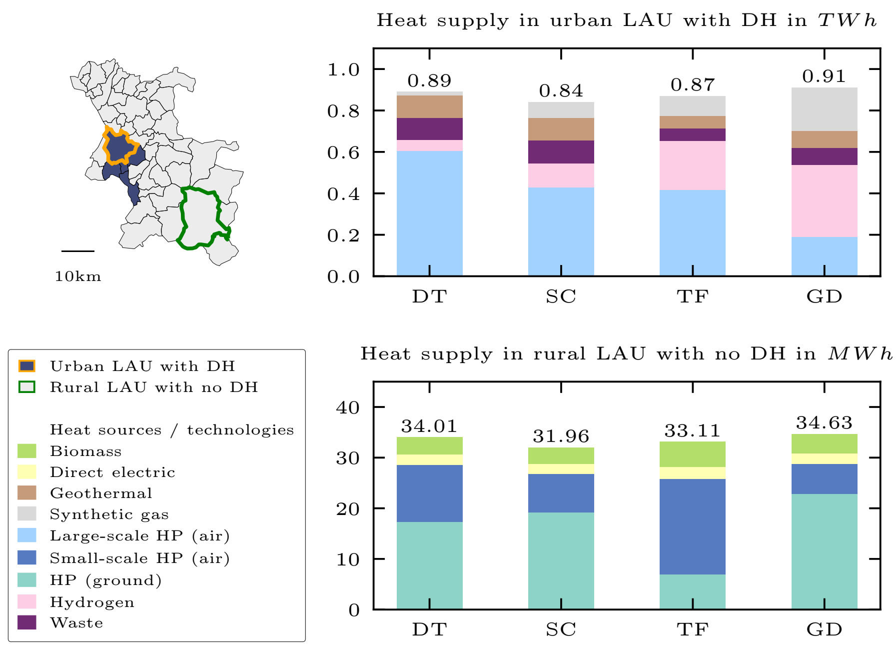

Figure 2: Comparison of heat supply in an urban LAU with district heating ('Salzburg' city) and in a rural LAU with no district heating ('Abtenau'). Top right: Mix of heat sources in the four different scenarios used in district heating. Bottom right: Mix of heat sources used to supply heat demands decentralized/on-site.

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.

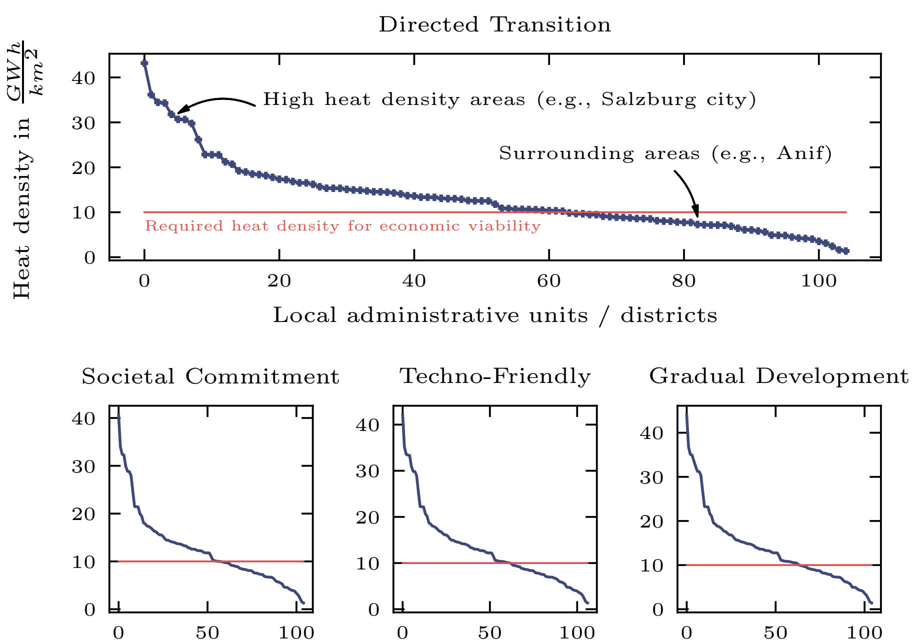

Figure 3: Heat density values at the LAU level in the four different scenarios in descending order indicating those LAUs that do not achieve the required heat density benchmark for economic viability.

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).

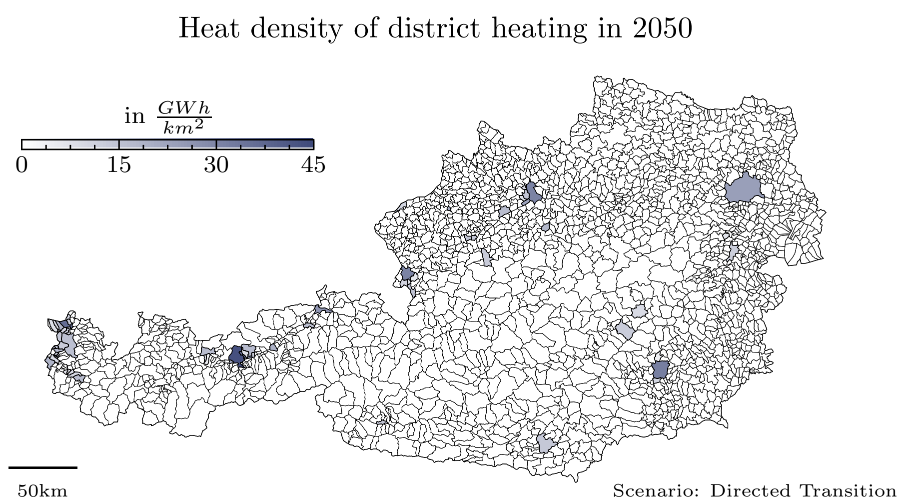

Figure 4: Heat density of district heating in the Directed Transition scenario in 2050 achieving the required heat density benchmark value of 10 GWh/km^2 at the NUTS3 level.

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 TWh 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 assumptions 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 %.

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 [57], 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%.

Heat source/technology	Proportion in % on space and hot water demand	Abs. number 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].