Disclosing the heat density of district heating ~~centralized heat~~ networks in Austria 2050 under the 1.5°C climate target

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Abstract

Adherence to the remaining CO_2 budget of~~Achieving~~ the 1.5 °C climate target requires~~, among others,~~ a sustainable transformation of the heating sector ~~supply~~. We downscale cost-effective heat supply of~~different~~ European decarbonization scenarios ~~of the heating sector~~ to the Austrian community~~municipal~~ level, using tailor-made downscaling techniques accounting for infrastructure requirements of renewable heat sources and the topology of district heating ~~centralized heat~~ networks. ~~We demonstrate that allocating district heating networks as part of the downscaling from national results to a local resolution is crucial for a cost-effective and efficient decarbonized heat supply in Austria in 2050.~~ We find~~identify~~ potential for four~~eight~~ decarbonized~~different~~ districts heating networks in Austria in 2050~~with centralized heating networks, supplying heat demand between 0.6 and 12TWh~~. Not all of these networks~~Nevertheless, seven of these networks do not~~ reach the heat density required for economic and technical efficiency from today's techno-economic perspective and industry benchmarks. However, the identified heat density gap can be reduced by an increased allocation of (large-scale) heat pump generation feeding into district heating.~~We conclude that the decarbonization leads to centralized heat networks~~

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~~with lower heat densities.~~

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

Nomenclature

Type	Description	Unit
Set and index		
$t \in \mathcal{T} = \{1, \dots, T\}$	Set of heat sources/generation technologies, index by t	
$r \in \mathcal{R} = \{1, \dots, R\}$	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	$1//\mathrm{km}^2$
p_r	Total population per r	1
σ_t	Minimal network infrastructure requirements per t	$1//\mathrm{km}^2$
π_r	Available potential of heat network infrastructure per r	$1//\mathrm{km}^2$
$\hat{q}_{t,r}$	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 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 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 heating demand 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 1,100,000 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 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 requre an expansion of district heating networks. This holds true even when substantial heat saving measures are installed such as better insulation of buildings [13].

District heating is~~Centralized heating networks are~~ particularly advantageous for supplying densely populated or urban areas because of high heat densities [14]. Particularly in Europe, there are good conditions for district heating [15]. 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

[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/

reference value is in line with findings regarding district heating networks also from the Scandinavian region (Denmark, Sweden, and Finland) [16]. These are rough estimates, but they do allow an initial assessment of the economic viability or feasibility of a district heating network. In a detailed consideration and evaluation of district heating networks, numerous factors play a decisive role. For example, the design and topology of district heating networks has a significant impact on their cost-effectivness [17].~~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])~~. A recent study shows~~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 [22] which consequently also reduces the heat densities of networks.. ~~This also reduces the heat density.~~ 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 the rising CO_2 price can have an effect similar to the energy tax. Naturally~~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~~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 or ~~/~~ distribution grid level serving end-users in 2050. In particular, downscaling considers the highly efficient and local use of sustainable heat sources in district ~~centralized~~ heating networks (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 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 communityor~~/~~ distribution grid levels.

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~~ 3.1 shows heat generation by source at different spatial levels. Sections 3.2 and 3.3 present district heating networks~~centralized heat networks~~ at a high spatial granularity. Section 3.4 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 3.5 presents a sensitivity analysis of the heat density of district heating regarding the allocation of heat generation by heat pumps feeding into district heating networks. Section 4 concludes this work and provides an outlook for future work.

2. Materials and methods

This section explains the methodology of this work.~~developed in this work.~~ First, section 2.1 presents the output from the Horizon 2020 project openENTRANCE, since this is the main input for the downscaling. Therein, information about the different heat sources/generation technologies that are downscaled and used for district heating is provided. Then, the different downscaling techniques are explained. Section 2.2 describes proportional spatial downscaling using population as a proxy. Building on this, section 2.3 presents the sequential downscaling and section 2.4 presents the iterative downscaling algorithm in detail. Section 2.5 discusses selected limitations of the methodology. 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. The last scenario~~storyline~~ (*Gradual Development*) can be interpreted as less ambitions scenario~~storyline~~, limiting global warming to around 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].

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.

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

- *Directed Transition* (DT) 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* (SC) 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* (TF) 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* (GD) 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 different scenarios~~storylines~~. These values were obtained during the course of the Horizon 2020 project openENTRANCE and are the modeling results calculated using the open-source 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., input values) and downscaled (i.e., output values). However, we introduced the heat sources waste and geothermal that were initially not included in the list of heat sources from openENTRANCE results. We separted waste as part from biomass and geothermal from heat pump (ground) heat generation using estimtes from national Austrian studies in [42] and [11].

	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. The row district heating (last row) describes the heat generation used in district heating networks and is the sum by geothermal, hydrogen, synthetic gas and waste. This is further and detailed described in section 2.3 and Table 3 therein. ~~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 significantly contribute to the decarbonization of heat demands but depend on the network infrastructure of district heating to be integrated into the heat supply [47]
- limited amounts of synthetic gas and hydrogen (~~and/~~or *green*~~”green”~~ gas) should preferably be used in district heating networks if they are used for heat supply [48]~~(similar to Gerhardt et al. [48] and Zwickl-Bernhard and Auer [49])~~.
- high shares of biomass in the heating sector result in a high utilization rate of waste sources in waste incineration plants [50]. These waste incineration plants feed into district heating and therefore depend on the infrastructure of district~~centralized~~ heating networks ~~(see, e.g., Sahlin et al.~~ [51]~~)~~.

~~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~~

[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.

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

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

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

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 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 technology/source 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: Centralized heat network graph at stage s;
N^s: List of nodes at stage s: ($n^s \in N^s$);
L^s: List of lines connecting nodes k and j at stage s: ($l^s_{k,j} \in L^s$);
Q^s: Centralized heat generation at stage s: ($q^s_{n^s} \in Q^s$);
$\tilde{Q}^s$: On-site heat generation at stage s: ($\tilde{q}^s_{n^s} \in \tilde{Q}^s$);
Π^s: Benchmark indicator 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 centralized heat amount`
        $\tilde{q}^{s+1}_{n^{s+1}} = \tilde{q}^s_{n^s} - \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; `// 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 centralized heat networks. This is achieved in our proposed approach by iterative downscaling. Essentially, the main steps of the algorithm can be summarized as follows:

1. Downscale the results of the sequential downscaling algorithm from the NUT3 to the LAU levels using population as the downscaling driver, to obtain the initial heat network graph G^0 (input).
2. Benchmark each node of the heat 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 centralized and on-site heat generation can be reallocated (line 16).
4. If yes, reallocate centralized and on-site heat generation for all nodes (lines 18 and 19); otherwise stop algorithm.
5. Update heat 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 centralized heat network graph. Equation 2 shows the calculation of the weighted cluster coefficient

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

where q is the amount of centralized heat supply, 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 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 selected limitations of the developed downscaling technique[6]. In principle, various limitations of the developed downscaling technique could be identified. In the following, we discuss three different aspects that are likely to be relevant in the context of heat supply in general, district heating and their heat densities.

2.5.1. *Neglecting of heat sources on the local level due to the composition of the heat sector at the aggregated level*

The developed downscaling technique disaggregates different heat sources/generation technologies to the local level based on their characterization in terms of heat network requirements and their prioritized use in district heating. Accordingly, it is advantageous to differentiate as many different heat sources/generation technologies as possible and take their special characteristics into account. This work essentially uses the different heat sources of the heating sector portfolio of Genesys-MOD which is why some heat sources are neglected. Exemplarily, industrial excess heat is not explicitly included in the values to be downscaled. And thus this heat source can not be reflected in the local heat supply and district heating. Adding information on the generation potential of industrial excess heat could improve the heat generation portfolio of heat sources to be downscaled, but also changes the inputs in terms of consistency of the downscaling and reduces the significance (bias by the new information) of the implications of the original input values.

2.5.2. *Downscaling global cost-effective heat generation values*

Although the values to be downscaled are the cost-effective solution of a decarbonized heat supply, the results of this work do not allow to assess cost-effective heat supply at the local level (i.e., cost-effective district heating networks). The main reason for this is that the benchmark indicator value calculation does not include infrastructure investment costs of district heating (incl. pipeline

[6] Note that for the sake of convenience in this chapter we use the term technique and mean by this the toolkit of the sequential and the iterative downscaling technique together.

capacities based on the local peak heat demand). Note that the cost-effective solution is not in the focus of this work since the downscaling puts focus on the local implications of cost-effective national modeling results. Two more aspects are important here. Cost-effectivness of district heating is also influenced by the spatial distribution of heat sources which is only limited considered in the downscaling. And moreover that the spatial granularity is restricted to communities (LAU level). The estimates of heat densities of district heating could be improved by an even more higher spatial resolution within communities (i.e., street level).

2.5.3. Influence of using population as a proxy on heat demands

The developed downscaling technique uses population as a proxy for downscaling values from aggregated to local levels. With an eye on the heating sector, this could result in a bias in the estimates of local heat demands which have an impact on the obtained heat densities of district heating. Particularly, additional (low-temperature) heat demands in densely populated and urban areas are not considered. Moreover, the values to be downscaled are values per year which is why the peak heat demand is not considered in the analysis.

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

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

3. Results and discussion

This section presents the results of the Austrian case study. Particularly, the mix of heat sources/generation technologies and related district heating networks in the four different scenarios (section 2.1) are presented. ~~Four different storylines are investigated, covering a wide range of possible future developments of the Austrian energy system in the context of European deep decarbonization.~~ ~~Section 2.1 shows the heat generation mix supplying the heat demand (residential and commercial) at the country level.~~ Section 3.1 presents the heat generation mix on the country, sub-regional and community levels.~~the heat generation mix obtained on a more granular geographical scale, at sub-regional and community levels.~~ Potentials of district heating networks~~a centralized heat network´~~ are presented further in section 3.2. Section 3.3 shows district heating networks~~the centralized heat networks~~ at the community level. Furthermore~~Finally~~, section 3.4 compares the projected district heating~~centralized heat~~ networks in 2050 with today's networks, based on heat density. Finally, section 3.5 presents a sensitvity analysis of the allocation of heat pump (air) generation into district heating networks and its impact on the related heat densities.

3.1. *Heat technology generation in 2050 on different spatial granularities*

Figure 1 shows the heat generation per technology/source on different spatial granularities: the country (NUTS0), sub-region (NUTS3), and community (LAU) levels (from left to right). The level of spatial details increases from the left to the right. In the middle, the residential and commercial heat supply in representative rural and urban sub-regions, respectively, is presented. The rural sub-region Mostviertel-Eisenwurzen (NUTS3 code AT121) shows high shares of heat pump (air and sourced) generation~~and small-scale heat storage systems~~. In addition, biomass and direct electric~~synthetic gas and direct electric~~ heating systems supply the heat demand. The urban sub-region Rheintal-Bodenseegebiet (AT342)~~*South Viennese environs* (AT127)~~ is mainly supplied by the same heat sources as before. Additionally, synthetic gas and waste cover heat demands. Throughout the pie charts within the figure, shares of heat generation using district heating are indicated using blue edges. On the extreme right, an example of the resulting district heating at the community level (Rheintal-Bodenseegebiet (AT342)) for the four different scenarios is presented by highlighting the supply areas. The largest supply areas of district heating are in the *Gradual Development* and *Techno-Friendly* scenarios. Note that the obtained district heating supply areas not necessarily are interconnected. Exemplarily, two separated communities are supplied by district heating in the *Directed Transition* scenario.~~ground-sourced heat pumps, biomass, and hydrogen. Air-sourced heat pumps and, again, heat storage cover the remaining demand. Throughout the pie charts within the figure, shares of heat generation using centralized heat networks are indicated using blue edges. On the extreme right, an example of the resulting centralized heat network at the community level for the four different scenarios is presented. Within the four subfigures presenting centralized heat networks (each for one storyline), the size of the points represents the amount of heat demand using centralized supply in a community. The comparably high heat demand in the *Gradual Development* scenario results in an extensive centralized heat network infrastructure (see lower right subfigure in Figure 1). The other three centralized heat networks are characterized by fewer (less supplied small sub-regions) and smaller points (less supplied heat demand by the centralized heat network). Figure **??** compares the heat generation by source between 2020 (today) and 2050 for the four different scenarios. The height of the bars shows the absolute differences by source between both years, whereby a negative difference indicates less heat generation by this source in 2050 for the *Societal Commitment* scenario. This scenario is more prominently presented as this scenario has the lowest total heat demand (-18.15TWh). In addition, the scenarios with the lowest and highest differences, respectively, are marked for each heat source and the total demand. For instance, the highest decrease is seen in natural gas in the *Directed Transition* scenario (-53.76TWh).~~

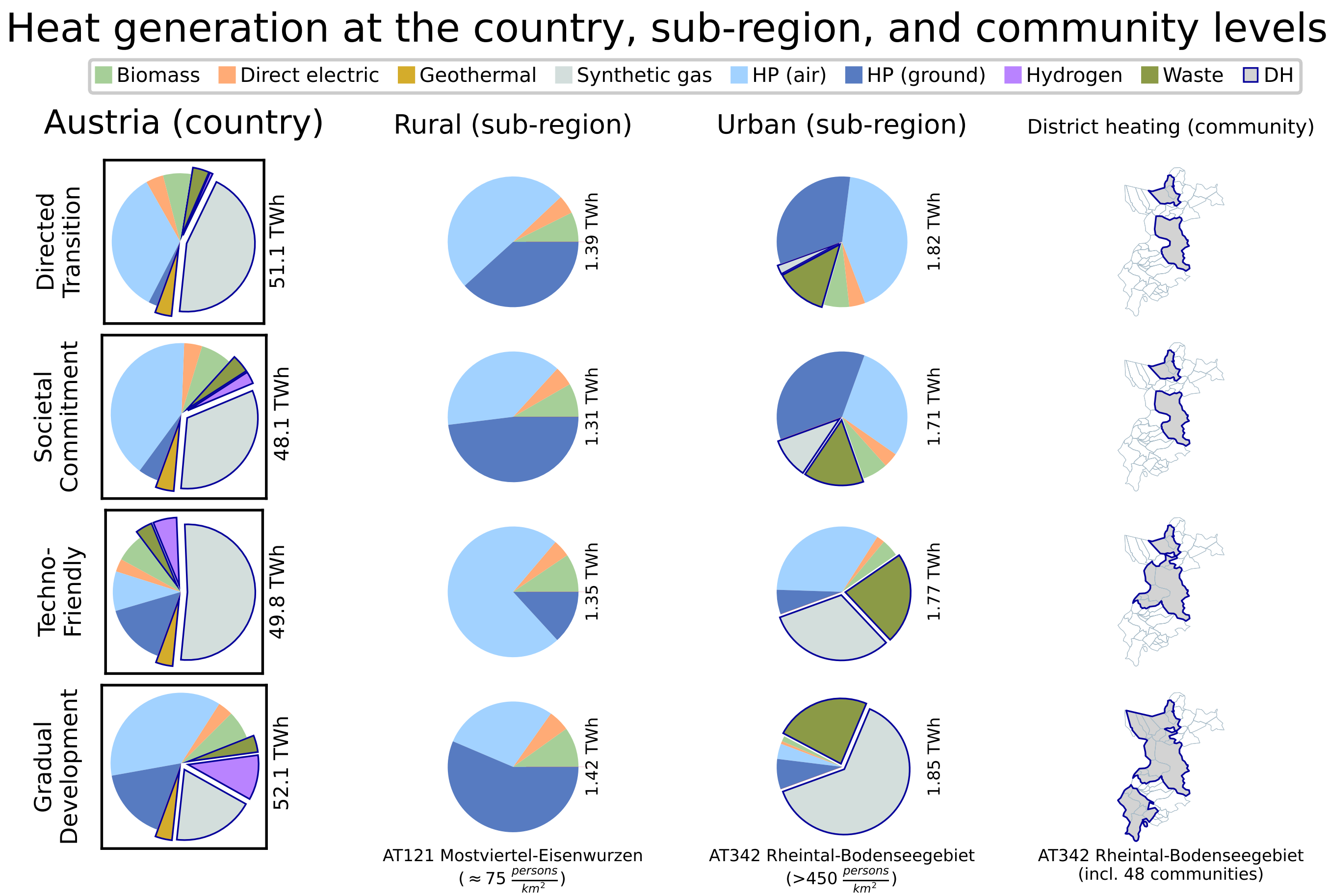

Figure 1: Heat technology generation on different spatial granularity levels in the different scenarios supplying the residential and commercial heat demand. left: on the country level. middle: comparison of a rural and urban sub-region. right: district~~centralized~~ heating ~~network~~supply areas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

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

Figure 2 presents heat demand supplied by district heating in Austria in 2050 on the NUTS3 level. There are four different sub-regions (AT130 Vienna, AT221 Graz, AT312 Linz-Wels and AT342 Rheintal-Bodenseegebiet) with district heating in the four scenarios. Although the four different sub-regions are the same in the four scenarios, the heat demand supplied by district heating varies significantly (see also the column district heating in Table 1). The highest amount of district heating is in the *Gradual Development* scenario. The exact numbers of district heating and on-site heat supply for the four different sub-regions and scenarios are presented in Table 4. For each sub-region, the share of district heating is in the *Gradual Development* the highest (between 87% and 99%). ~~The share of district heating on the total heat supply varies among the four different scenarios. The highest shares of district heating for each sub-region are in the *Gradual Development* and *Techno-Friendly* scenario. The potentials for centralized heat supply in Austria in 2050 are limited to densely populated areas (urban areas). In particular, the results indicate eight different sub-regions (NUTS3 regions) that are supplied by centralized heat networks (see Figure 2). Although the exact numerical numbers differ, the eight sub-regions in each scenario are (partially) supplied by centralized heat networks. Table 4 shows the centralized and on-site (decentralized) heat supply in the sub-regions. Thereby, the connection rate is assessed by the share of centralized heat supply in the total heat demand. Note that the population density varies in these sub-regions between 163persons/km^2 (AT211 - Klagenfurt-Villach) and 5124 persons/km^2 (AT130 - Vienna).~~

3.3. District~~Centralized~~ heating network topology at the community level

This section presents the district~~centralized~~ heating network topology of the sub-region *Linz-Wels* (AT312)~~*South Viennese environs* (AT127)~~ and all included communities in the *Directed Transition* scenario. ~~In Figure 2, this particular sub-region is marked by the orange box.~~ Figure 3 shows the projected district

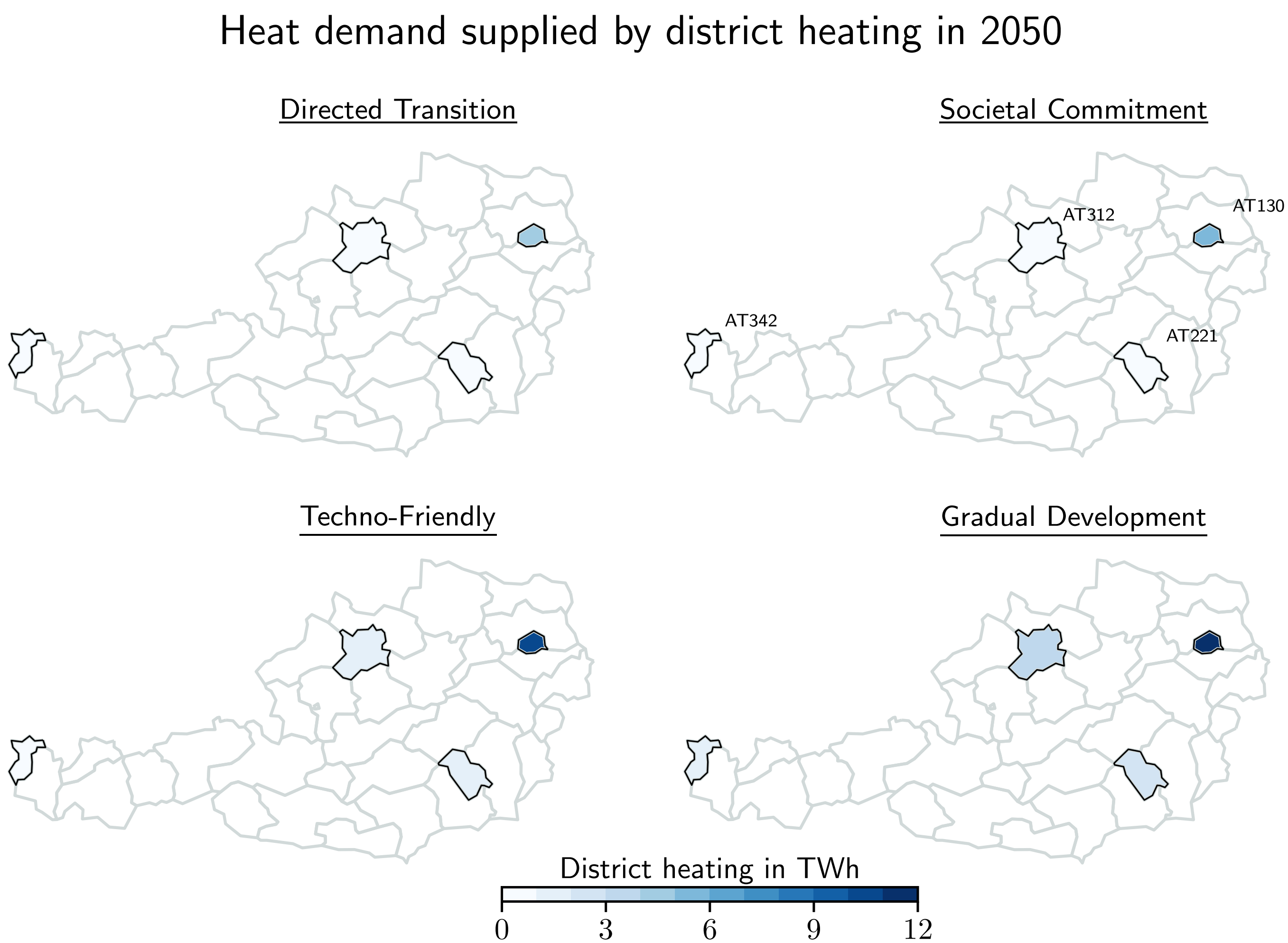

Figure 2: Heat demand supplied by centralized heat networks in Austria 2050. The white areas are supplied by on-site (decentralized) sustainable heat generation technologies/sources.

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

Table 4: Heat demand supplied by district heating and on-site (incl. share of district heating of total heat supply) in the four Austrian sub-regions in 2050.

heating supply area~~centralized heat network topology~~. In particular, the network topology is presented for the initial condition (as a result of the sequential downscaling, $i = 1$) and the final condition of the network (as a result of the iterative downscaling, $i = 65$). The distribution of the benchmark indicator values of the district~~centralized~~ heating network depending on the number of iterations is presented in the middle. The median~~mean value~~ is marked in orange. The supply area decreases with an increasing number of iterations. In the community analysed here, the termination criterion of the algorithm is reached when 10~~25~~ communities are connected (starting from 74~~75~~ in the initial condition). The number of connected population decreases by 40 %, starting from a population of 663.000 being connected (or rather having access since the in general the connection rate to district heating is not equal to one in the initial condition) to the district~~centralized~~ heating network in the initial condition. After the final iteration ($i = 65$), the termination criterion is reached. ~~Note that the iterative reduction of small sub-regions supplied does not necessarily result in one contiguous network.~~

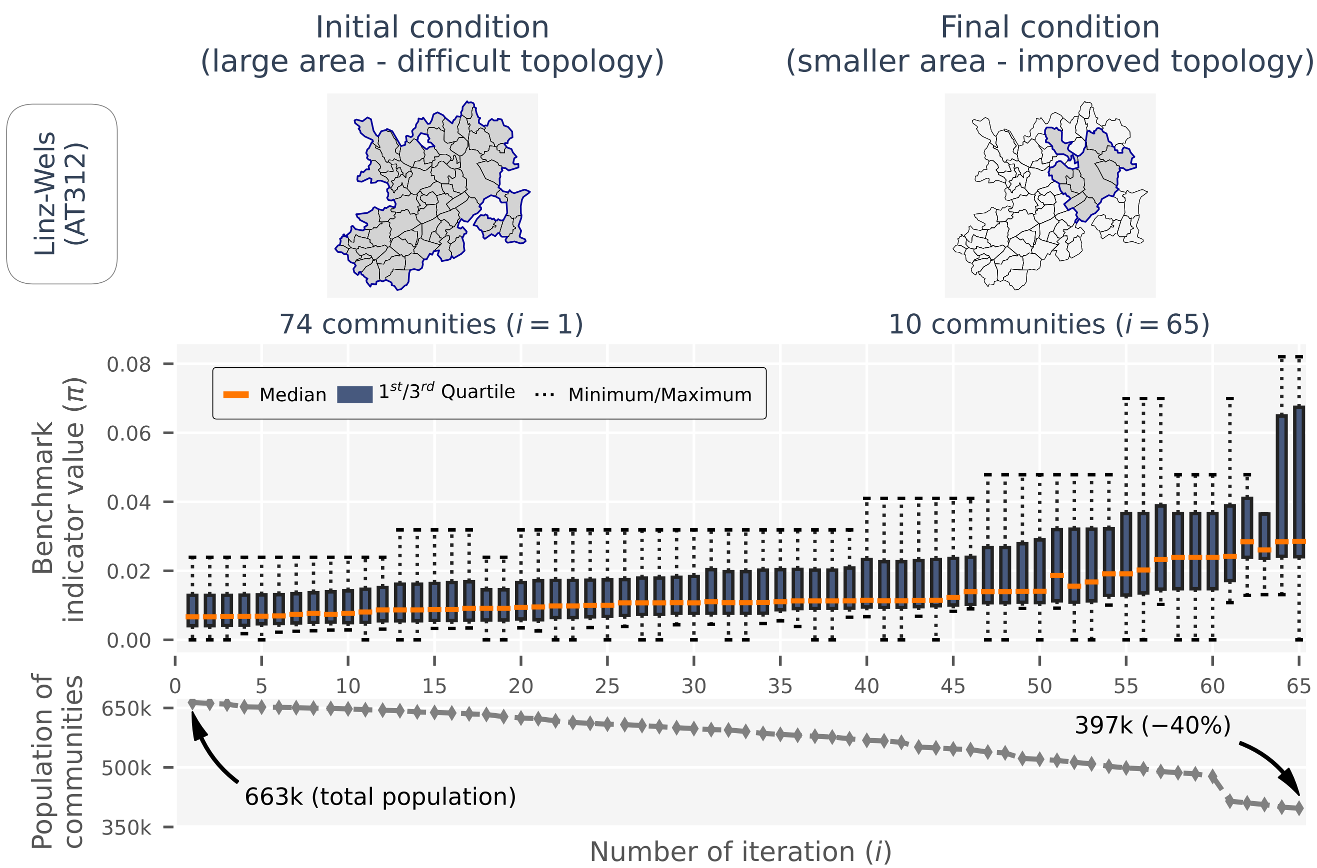

Figure 3: District~~Centralized~~ heating network topology in Linz-Wels (AT312) in the *Directed Transition* scenario~~in the initial and final condition~~. The boxplot (middle) indicates the improved network topology by ~~an~~ increasing benchmark indicator values~~mean value (orange line)~~. In the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

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

In the following, the district~~centralized~~ heating network in Linz-Wels (AT312) ~~*Graz* (AT221)~~ is shown in detail. This area is selected for illustrative purpose, because it provides representative results in terms of both the applied downscaling and achievable heat density benchmarks of centralized heat networks. Figure 4 shows the heat density of district heating~~the centralized heat network~~ in the *Techno-Friendly* scenario.

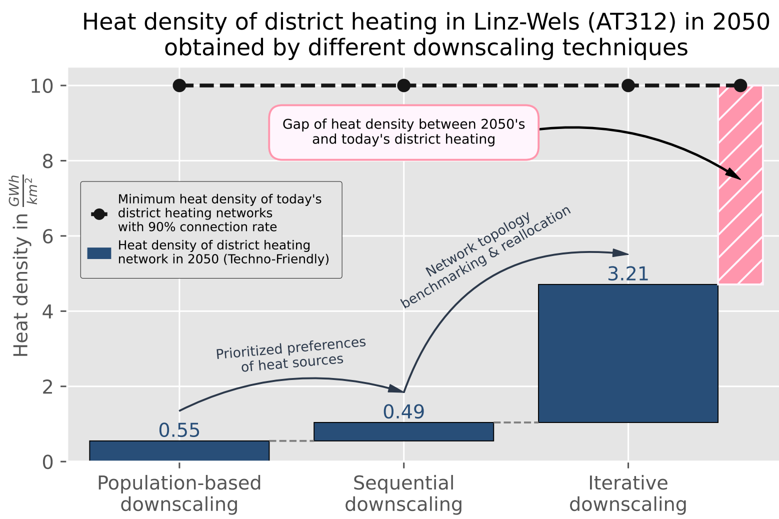

Figure 4: Heat density of the district~~centralized~~ heating ~~network~~ in Linz-Wels (AT312)~~*Graz* (AT221)~~ 2050 in the *Techno-Friendly* scenario. The gap of heat density between 2050s and today (black dashed line) is marked by the pink bar.

The x-axis shows the three different downscaling techniques. The numerical numbers indicate a significant increase of the heat density by the sequential (+0.49 GWh/km^2) and, in particular, the iterative downscaling (+3.21 GWh/km^2). However, comparing the heat density value obtained with the heat density values of today's centralized heat networks reveals a significant gap (see the hatched pink bar). Here, in the *Techno-Friendly* scenario, it is 5.75 GWh/km^2. According to references from the practice (~~see, e.g., in~~`http://www.austrian-heatmap.gv.at/ergebnisse/`), the threshold heat density of today's networks is assumed to be 10 $\frac{\text{GWh}}{\text{km}^2}$ with a connection rate of 90 %. The gap of heat density varies between the different scenarios. Figure 5 shows the heat densities in the sub-regions and compares the results in the different scenarios. It shows the scenarios with the lowest and highest heat densities. The bottom bar shows the value and scenario with the lowest heat density among the four different scenarios for each sub-region. The hatched bar indicates the increase of heat density and the corresponding scenario compared to the lowest value. In Vienna (AT130), the heat density is in each scenario higher than~~In five sub-regions, the *Techno-Friendly* scenario is the scenario with the lowest heat density. The *Directed Transition* scenario is the scenario with the highest heat density in four sub-regions. Note that Vienna (AT130) is not shown for the sake of clarity. The heat density there varies between 15.1 GWh/km^2 in the *Techno-Friendly* and 30.3 GWh/km^2 in the *Gradual Development* scenario.~~ 10 GWh/km^2 and is maximal 27 GWh/km^2 in the *Gradual Development* scenario. In Linz-Wels (AT312), the maximal heat density is 7.7 GWh/km^2 in the *Societal Commitment* scenario. The two sub-regions Graz (AT221) and Rheintal-Bodensee (AT342) reach their maximum heat densities in the *Techno-Friendly* scenario with 6.1 GWh/km^2 and 3.8 GWh/km^2 respectively. Three sub-regions (Vienna (AT130), Graz (AT221) and Rheintal-Bodensee (AT342)) have their lowest heat density in the *Directed Transition* scenario which has the lowest amount of district heating compared to the others (compare Table 1). At the same time, the three sub-regions have their highest heat density in the *Gradual Development* and *Techno-Friendly* scenario which both have the highest amount of district heating. The sub-region Linz-Wels (AT312) has its minimum heat densitiy in the *Gradual Development* and its maximum in the *Societal Commitment* scenario. The latter scenario is characterized by a comarable low amount of district heating (Table 1).

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

Building upon Figure 5, it is evident that the heat density of district heating varies significantly among the different scenarios. Moreover, the district heating networks of some sub-regions reach their highest values in scenarios with low

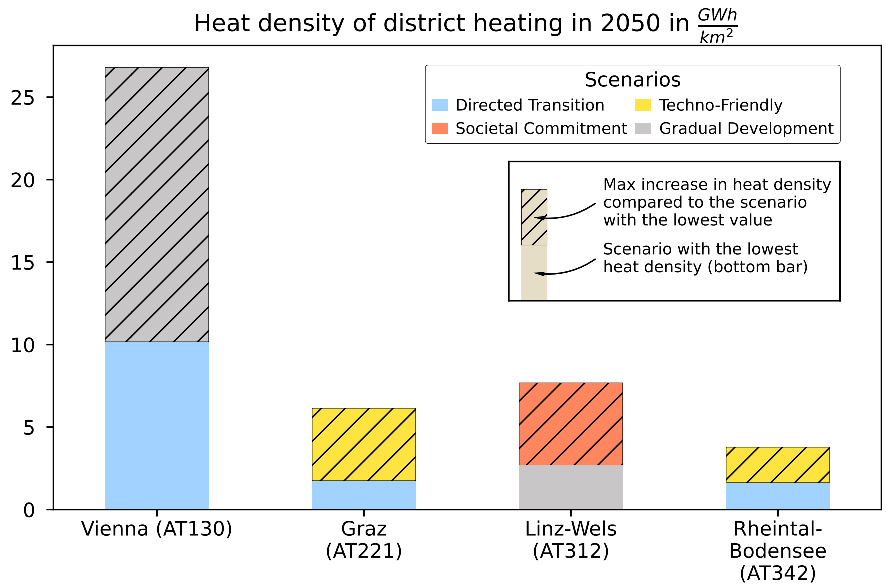

Figure 5: Comparison of the heat density per sub-region in the four different scenarios. The bottom bar shows the scenario with the lowest heat density. The hatched bar indicates the increase of heat density and the corresponding scenario compared to the lowest value.

(e.g., Linz-Wels (AT312)) and some in scenarios with high district heating shares (e.g., Graz (AT221)) on total heat supply. Accordingly, this section examines the impact of increasing shares of heat pump (air) heat generation feeding into district heating on the heat densitiy of district heating networks. Hence, a sensitivity analysis is carried out varying the proportion of large-scale (i.e. feeding into district heating) and small-scale (i.e. on-site heat generation) heat pump (air) generation on the downscaled values[7]. Figure 6 shows the heat density of district heating networks in the four different sub-regions and scenarios. Therein, the range of heat density resulting from different shares of large-scale and small-scale heat pump (air) generation is presented. The two extreme points namely that only small-scale or large-scale heat pump (air) units are used in the sub-regions are marked by the black circle (i.e. heat pump (air)

[7]See Figure D.2 in Appendix D.

on-site) and diamond (i.e. heat pump (air) in district heating). Particularly, the heat density in the *Directed Transition* and *Societal Commitment* scenario increase significantly compared with on-site heat pump (air) generation only (e.g. in Graz (AT221) and Linz-Wels (AT312)). In Linz-Wels, for example, this maximum is reached by two thirds large-scale heat pump (air) generation feeding into district heating[8]. In Vienna (AT130), the heat density remains almost the same in the *Techno-Friendly* and *Gradual Development* scenario. At the same time, the heat density there increases and reaches 18 GWh/km^2 in the *Directed Transition* and *Societal Commitment* scenario. In Rheintal-Bodensee (AT342), the heat densities are relatively low compared to the others independently of the allocation of heat pump (air) generation to district heating.

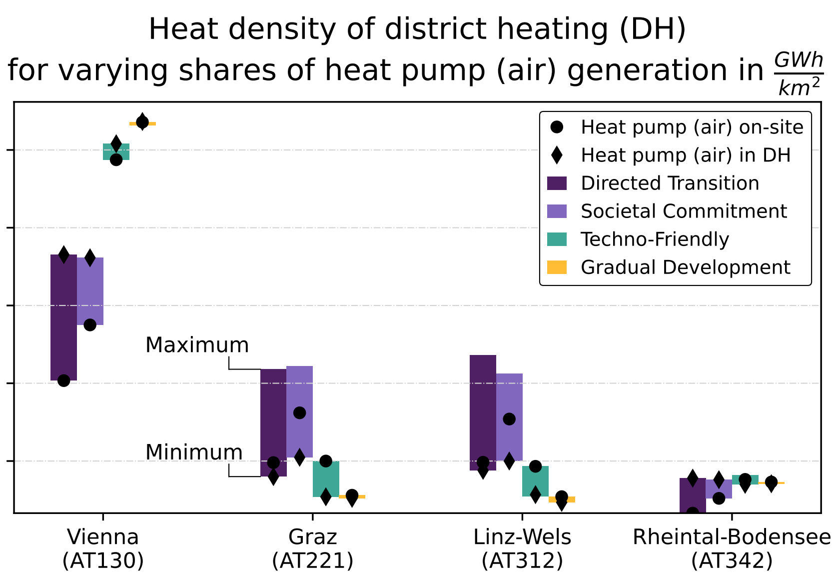

Figure 6: Heat density of district heating in the four different sub-regions and scenarios in 2050 for varying shares of heat pump (air) generation in district heating.

[8]See again Figure D.2 (bottom) where the orange bar indicates the share of large-scale heat pump (air) generation at which the heat density is reaching its maximum.

4. Conclusions and recommendations

Sustainable energy transition requires methods to bridge the gap between global decarbonization pathways and the resulting necessary measures at a local level. This work emphasizes the development of different downscaling techniques~~algorithms~~, which we apply to the Austrian heating sector (residential and commercial) under several scenarios~~storylines~~ in line with the Paris Agreement. We analyz~~s~~e results at the community ~~and grid~~ levels, considering technology-specific infrastructure requirements for the highly efficient usage of heat sources in district heating networks.

We found that the cost-effective and decarbonized heat supply in Austria in 2050 implies district heating in four different supply areas.~~the prioritized perspective of efficiency and local utilization of renewable heat sources implies substantial changes for the further development of district heating networks in the decarbonized Austrian heat supply toward 2050. This implies small-scale (1TWh) and large-scale (12TWh) district heating networks in terms of the amount of heat delivered.~~ The results demonstrate that district heating continuous to be about cherry picking from~~particularly densely populated areas are still~~ beneficial supply areas such as particularly densely populated areas albeit under different circumstances. ~~for district heating networks and offer adequate heat densities. Nevertheless, most district heating networks in 2050 (seven of eight) will not reach the heat density benchmarks of today's networks and have a significant heat density gap.~~ Because not all district heating networks in 2050 reach the heat density required for economic and technical efficiency from today's techno-economic perspective and industry benchmarks. This heat density gap (mainly driven by a sigificant reduction of heat demands by building renovation) can be reduced by an increased allocation of large-scale heat pump genertion feeding into district heating.~~However, considering the increasing importance of local renewable heat sources feeding into district heating networks, we assume that these centralized networks will become required in the future and crucial in the decarbonization of the heating sector~~.

We anticipate our work as a starting point for discussing the role of district heating~~centralized heat network infrastructure~~ for enabling large-scale, highly efficient and local integration of renewable heat sources such as synthetic gas, hydrogen, geothermal sources and waste under lower total heat demands~~biomass/waste, hydrogen, ground-sourced heat pumps, or geothermal units~~. In addition, further research should follow on how local district heating networks and their heat densities or necessary shares of large-scale heat pump generation could be returned into the large-scale energy models in the sense of a feedback loop.~~In particular, we see a need for further research on the trade-off between local integration of heat sources and the cost-intensive deployment of district heating networks. Future work may elaborate on the increasing cooling demand and how the cooperative design of district heating and cooling networks can contribute to the profitability of centralized heating and cooling infrastructure.~~

Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 835896. Part of the research was developed in the Young Scientists Summer Program (YSSP) at the International Institute for Applied Systems Analysis(IIASA), Laxenburg (Austria). The authors acknowledge TU Wien Bibliothek for financial support through its Open Access Funding Programme.

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Appendix A. Current Austrian heat market

Table A.1 provides an overview of the Austrian heat market in 2017. Particularly, the proportion per heat source/generation technology on the total heat demand for space heating and hot water is shown. 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%.

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. Source: [10].

Appendix B. Further methodology illustrations

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

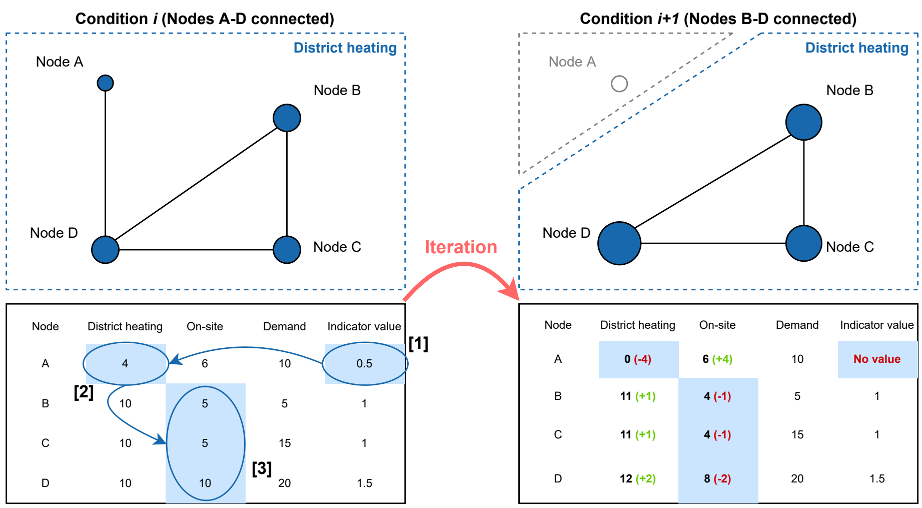

Figure B.1: Illustrative example of Algorithm 2 showing a simple graph with four nodes in two different conditions. The node with the lowest indicator value in condition i (node A) is removed from the graph (markers [1]-[3] in the table at the bottom left). The amount of district heating~~centralized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

Appendix C. Data and further empirical settings

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

Table C.2: Empirical data settings

Appendix D. Further results of the heat density of district heating for varying allocation of heat pump (air) generation to the feeding energy mix

Figure D.2 shows the heat density of district heating in Graz (AT221) in the *Directed Transition* scenario. On the x-axis the amount of district heating is shown. The heat density in the *Directed Transition* is characterized by a prioritized use of synthetic gas and waste in district heating only and is indicated by the black circle (top). Additionally, the section between the two dotted lines marks the heat generation by heat pump (air). The left dotted line marks the situation where heat pump (air) generation is exclusively on-site (i.e. small-scale heat pump units)) while the right dotted line where heat pump (air) generation is exclusively used in district heating (i.e. large-scale heat pump (air) units). Any point in between the two dotted lines is therefore a split between small-scale and large-scale heat pump (air) units. Particularly, the maximum heat density of $10.9\,\mathrm{GWh/km^2}$ is reached by a share of two thirds of large-scale heat pump (air) units feeding into district heating while one third remains on-site.

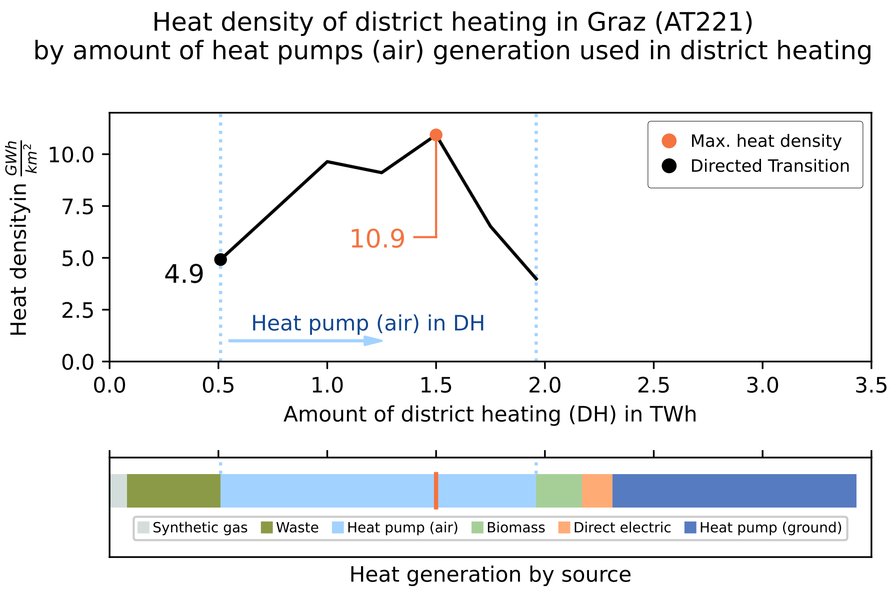

Figure D.2: Heat density of district heating in Graz (AT221) in the *Directed Transition* scenario (black circle) and varying allocation of heat pump (air) generation into district heating (black line). The maximum heat density is $10.9\,\mathrm{GWh/km^2}$ and reached by a share of two thirds of heat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