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Determination of the heat density of centralized heat networks under the 1.5°C climate target

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open ENTRANCE

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The scope of changes in the European heating sector

- The average share of renewables in the heating & cooling sector is only just above 20% on average in all EU member states[1]
- In Austria it is 34% - but fossil fuels continue to dominant the provision of heating and cooling services here as well
- $900{,}000$ dwellings are heated with natural gas and $500{,}000$ with oil (Austria 2020)
- Retrofitting of $50{,}000$ appliances per year, or more than 130 per day since the viability of green gas is uncertain at the end-user device level[2]
- Requires to a massive expansion of centralized heating (and cooling) networks to…
    - …ensure a highly efficient usage of renewable heat sources (e.g., biomass/waste, hydrogen)
    - …achieve significant retrofitting rates by high connection rates
    - …unburden the electricity sector (high electrification of different energy service needs)

[1]Eurostat https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200211-1
[2]Zwickl-Bernhard & Auer, *Energy*, (2021). doi: 10.1016/j.energy.2021.121805

The core objective of this work

- The core objective is the downscaling of decarbonization scenarios[1] of the heating sector, taking into account the infrastructure/network requirements of heat generation technologies/sources, from the country to the community level.
- In particular, the prioritized preference of heat sources in centralized heat networks plays a crucial role, ensuring highly efficient usage of heat sources.
- The assessment of centralized heat networks using heat density as a criterion is important in this analysis.
- An Austrian case study is conducted, downscaling cost-minimizing heat generation portfolios 2050, obtained from the large numerical energy system model GENeSYS-MOD[2], from the country to the grid level.

[1]Developed in the European H2020 project openENTRANCE aiming for the 1.5/2.0°C global warming climate target
[2]Löffler et al., *Energies*, (2017). doi: 10.3390/en10101468

Methodology

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

Spatial levels

- Three different scenario-independent downscaling techniques
  1. **Proportional downscaling** using population as a proxy (NUTS0 to the LAU level)
  2. **Sequential downscaling** algorithm using population density and infrastructure requirements of heat technologies/sources as additional criterion (NUTS0 to the NUTS3)
  3. **Iterative downscaling** algorithm based on graph-theory benchmarking (NUTS3 to the LAU level)

Reference technique

Techniques developed

The Nomenclature of Territorial Units for Statistics (NUTS) were created by Eurostat in order to define territorial units for the production of regional statistics across the European Union.

Sequential downscaling algorithm (Algorithm 1)

Algorithm 1: Sequential downscaling algorithm (NUTS0 to NUTS3)

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

input : Heat generation per technology/source at NUTS0 level: (q_t);
Population density per region r (ρ_r);
Total population per 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 per technology/source on 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

begin
  foreach t **do**
    $List = [\,]$; // Collect valid sub-regions
    $demand = 0$; // Reamining 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

Iterative downscaling algorithm (Algorithm 2)

Algorithm 2: Iterative downscaling algorithm

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 ($\pi^s_{n^s} \in \Pi^s$);

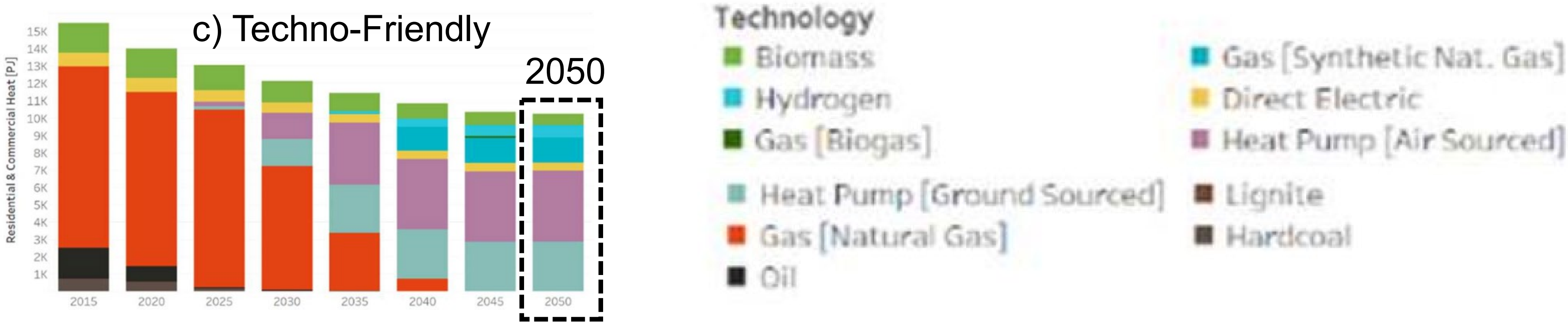
input : $G^0 = \{N^0, L^0, Q^0, \tilde{Q^0}\}$;
output: $G^* = \{N^*, L^*, Q^*, \tilde{Q^*}\}$;

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**
      pass
    else
      $\tilde{q} = q^s_i$; // Set upper bound of centralized heat generation that is used for reallocation among nodes if necessary
    end
    foreach n^{s+1} **do**
      $q^{s+1}_{n^{s+1}} = q^s_{n^s} + \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; // Increase centralized heat generation
      $\tilde{q}^{s+1}_{n^{s+1}} = \tilde{q}^s_{n^s} - \frac{q^s_i}{\tilde{q}} \cdot \tilde{q}^s_{n^s}$; // Decrease on-site heat generation
    end
    $L^{s+1} = L^s \setminus \{\forall l^s_{k,j} : k = i \vee j = i\}$; // Remove connecting lines
    $G^{s+1} = \{N^{s+1}, L^{s+1}, Q^{s+1}, \tilde{Q^{s+1}}\}$; // Create new network graph
    $\Pi^{s+1}_{n^{s+1}} = f(N^{s+1}, L^{s+1}, Q^{s+1})$; // Calculate new indicator values
    if $mean(\Pi^{s+1}) \geq mean(\Pi^s)$ **then**
      $G^s = G^{s+1}$; // Set updated heat network graph as new input
    else
      $iterate = False$; // Stop iteration if no improvement
    end
  end
  $G^* = G^s$; // Set heat network graph as result
end

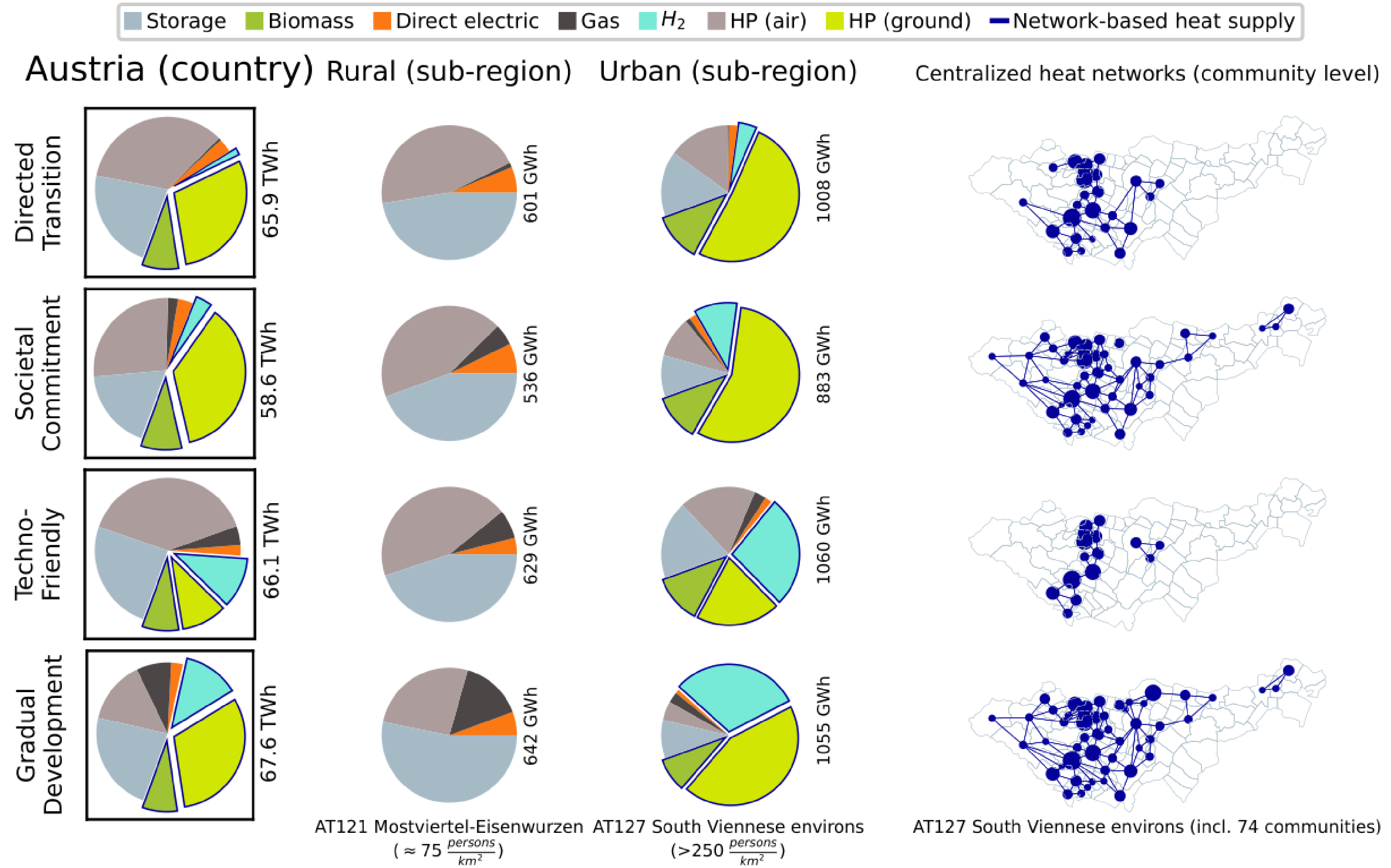
Numerical example and scenarios

- Four different decarbonization scenarios of the European energy system aiming for the 1.5/2.0°C global warming climate target[1]
  a) Directed Transition scenario (strong policy incentives)
  b) Societal Commitment scenario (strong societal acceptance, decentralized renewables)
  c) Techno-Friendly scenario (market-driven breakthrough of renewables)
  d) Gradual Development scenario (“little of each”)
- Values of the decarbonized heating sector in Austria 2050 obtained by the large-numerical energy system model GENeSYS-MOD

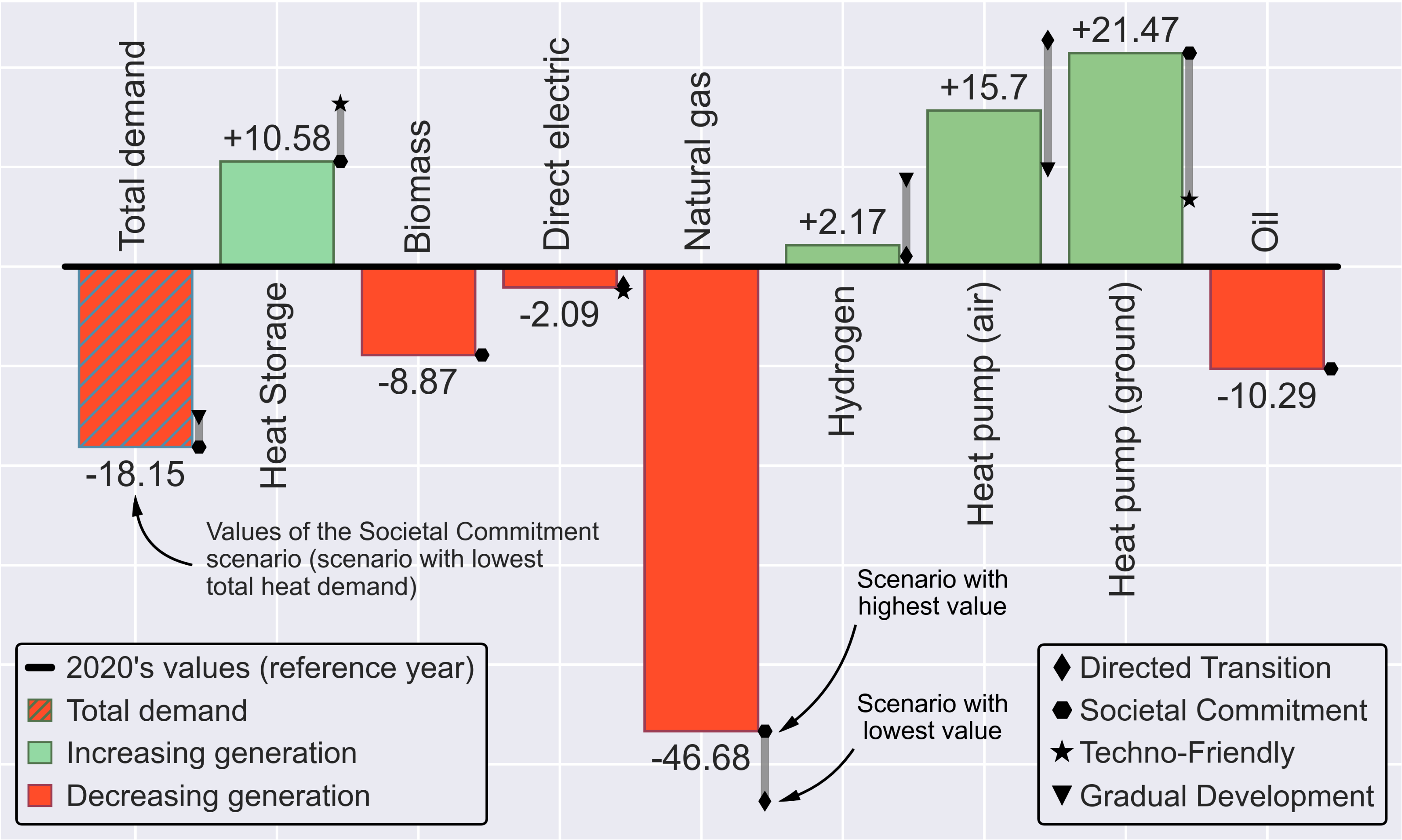


[1]Scenario a) to c) considers the 1.5°C global warming target and d) the less ambitious 2.0°C.

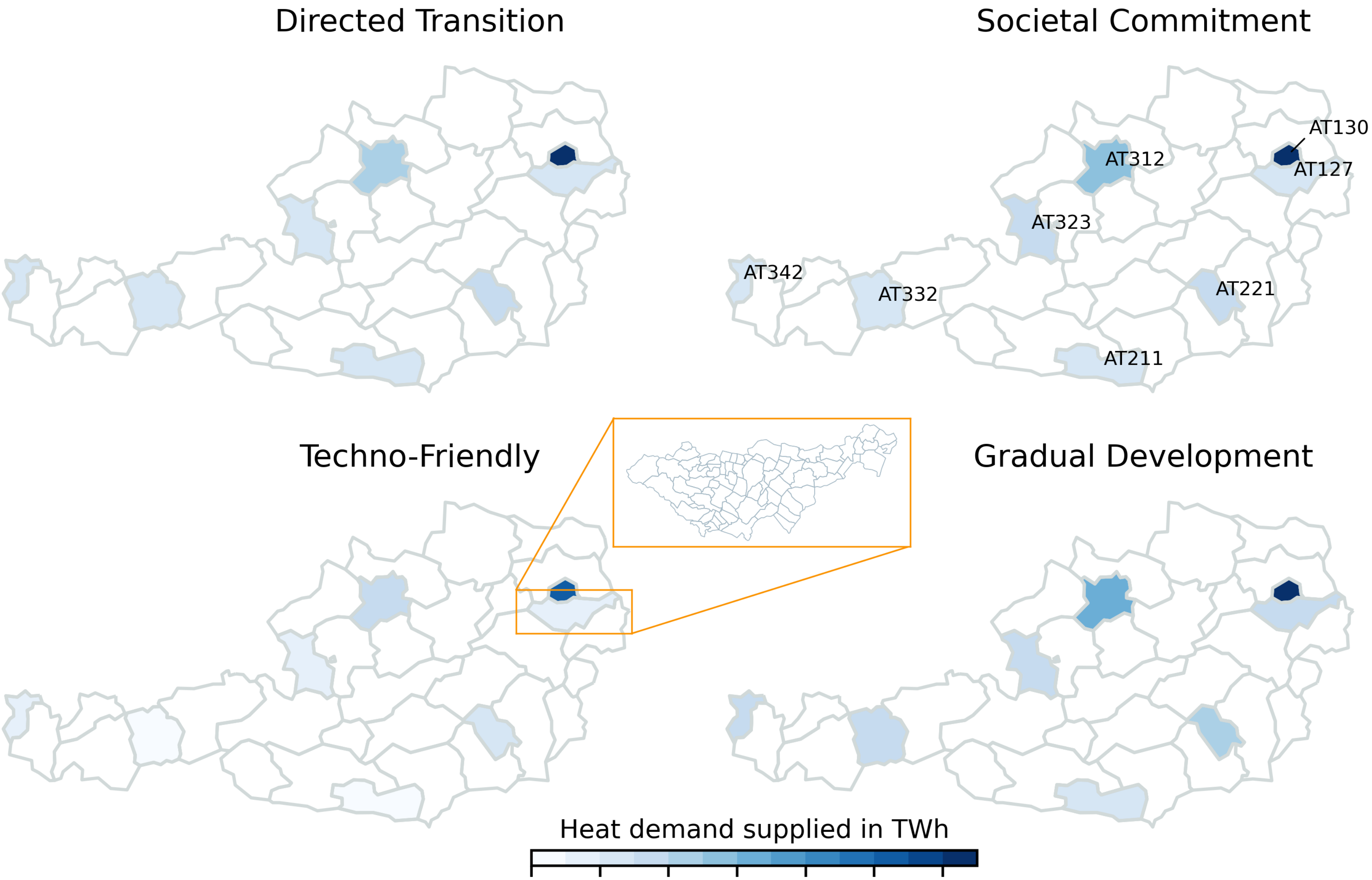
Heat generation on the country, sub-region, and community level



Absolute differences of heat generation by source between 2020 and 2050 in TWh

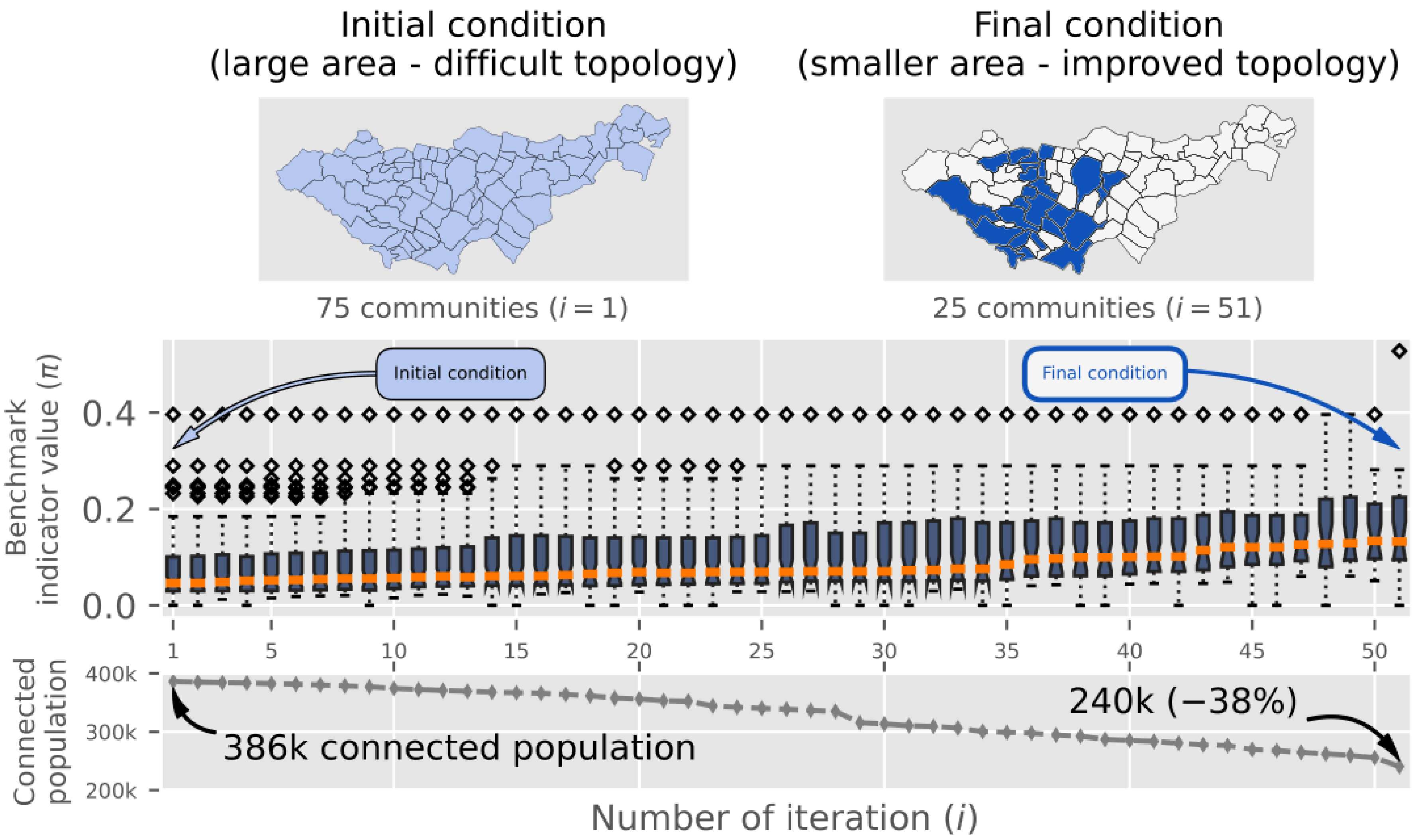


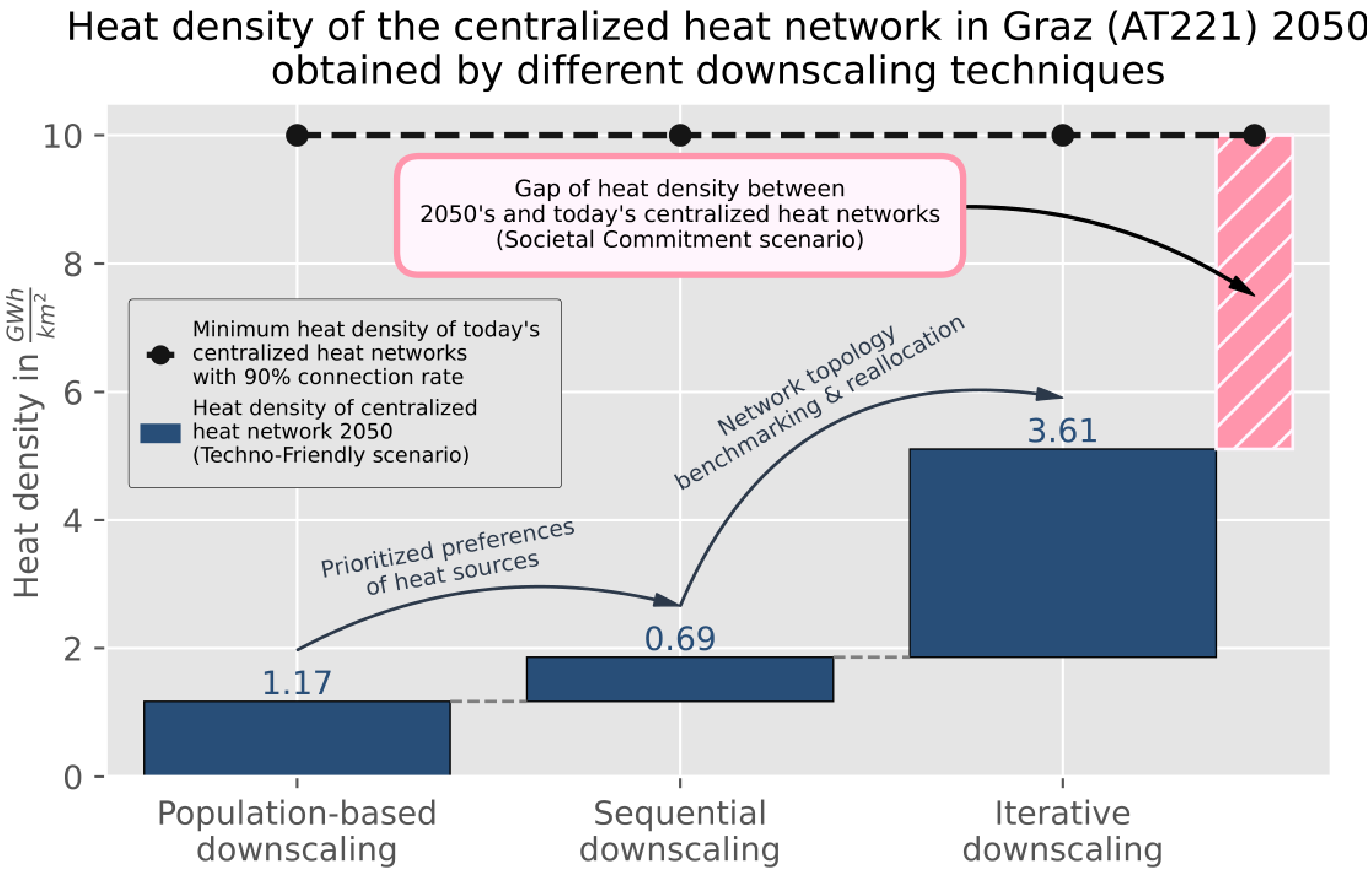
Heat demand supplied by centralized heat networks in TWh



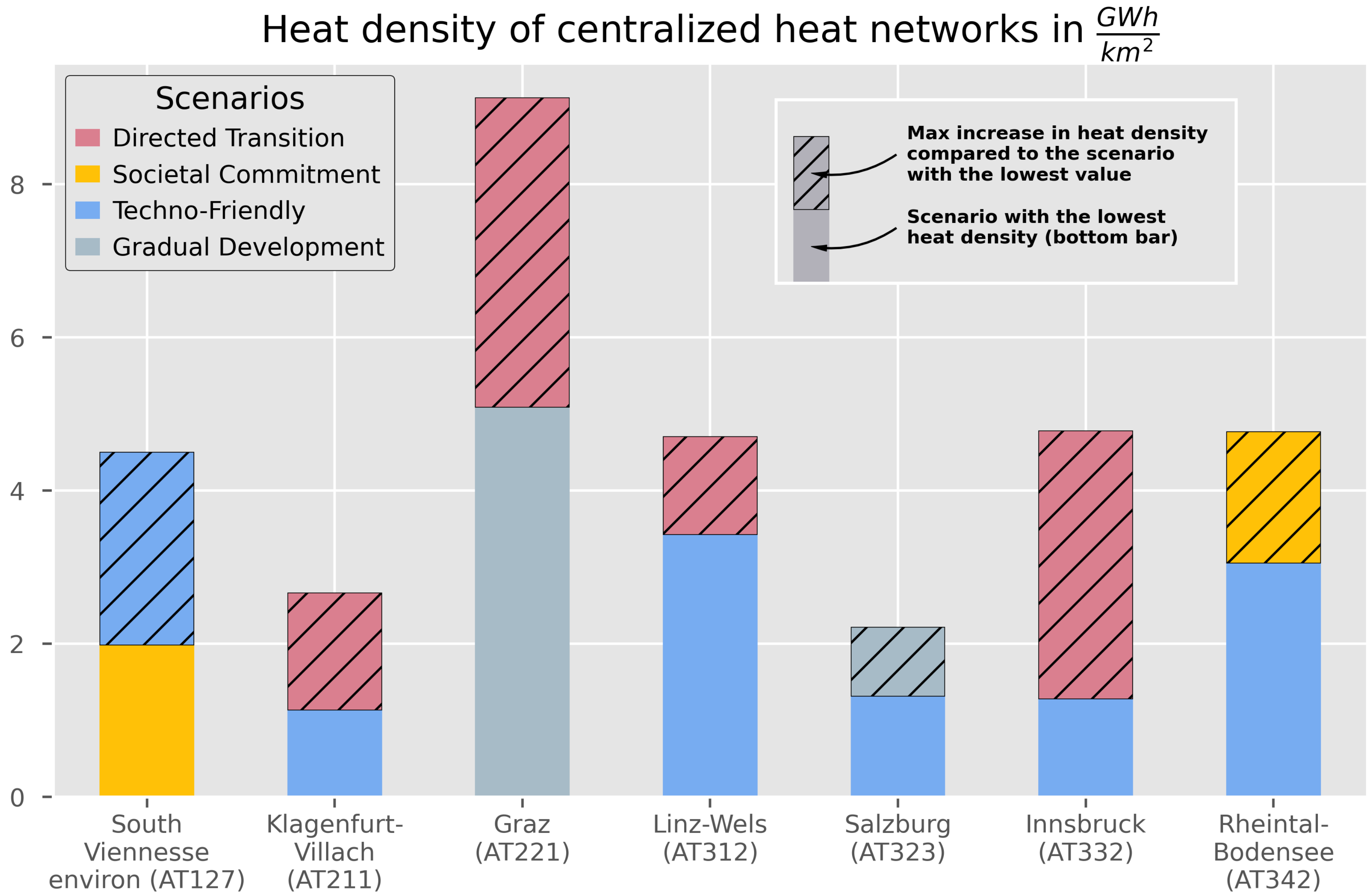
Results (3/6)

Centralized heat network topology improves by reducing supply area





http://www.austrian-heatmap.gv.at/karte/



Heat density of centralized heat networks in $\frac{GWh}{km^2}$
Scenarios
Directed Transition
Societal Commitment
Techno-Friendly
Gradual Development
Max increase in heat density compared to the scenario with the lowest value
Scenario with the lowest heat density (bottom bar)
0
2
4
6
8
South Viennesse environ (AT127)
Klagenfurt-Villach (AT211)
Graz (AT221)
Linz-Wels (AT312)
Salzburg (AT323)
Innsbruck (AT332)
Rheintal-Bodensee (AT342)

Conclusions

- Sophisticated downscaling techniques in the heating sector are crucial bridging the gap between global decarbonization plans and the resulting necessary measures at the local level
- Prioritized perspective of efficiency and local utilization of renewable heat sources leads to a crucial treatment of the further development of district heating networks in the decarbonized Austrian heat supply towards 2050
- Most district heating networks in 2050 will not reach the heat density benchmarks of today's networks and have a significant heat density gap
- Resulting from the increasing importance of local renewable heat sources feeding into district heating networks, centralized heat networks will become required in the future and crucial in the decarbonization of the heating sector

Acknowledgments / References

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References

H. Auer et al. (2020). Development and modelling of different decarbonization scenarios at the European energy system until 2050 as a contribution to achieving the ambitious 1.5°C climate target – establishment of open source/data modelling in the European H2020 project openENTRANCE, *e&i Elektrotechnik und Informationstechnik*, 1-13. doi: 10.1007/s00502-020-00832-7

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