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

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open ENTRANCE

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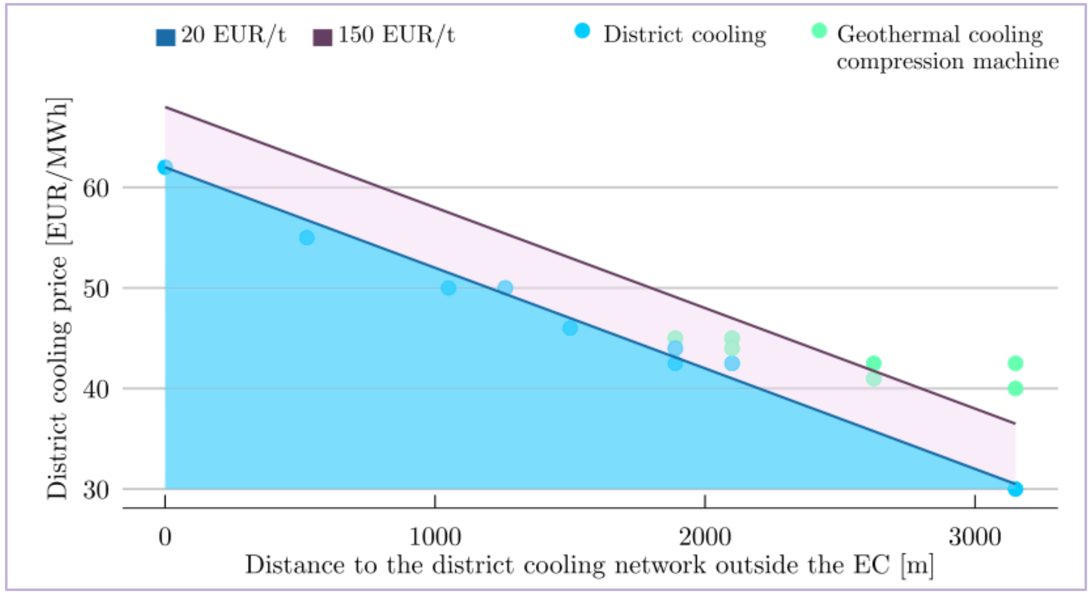
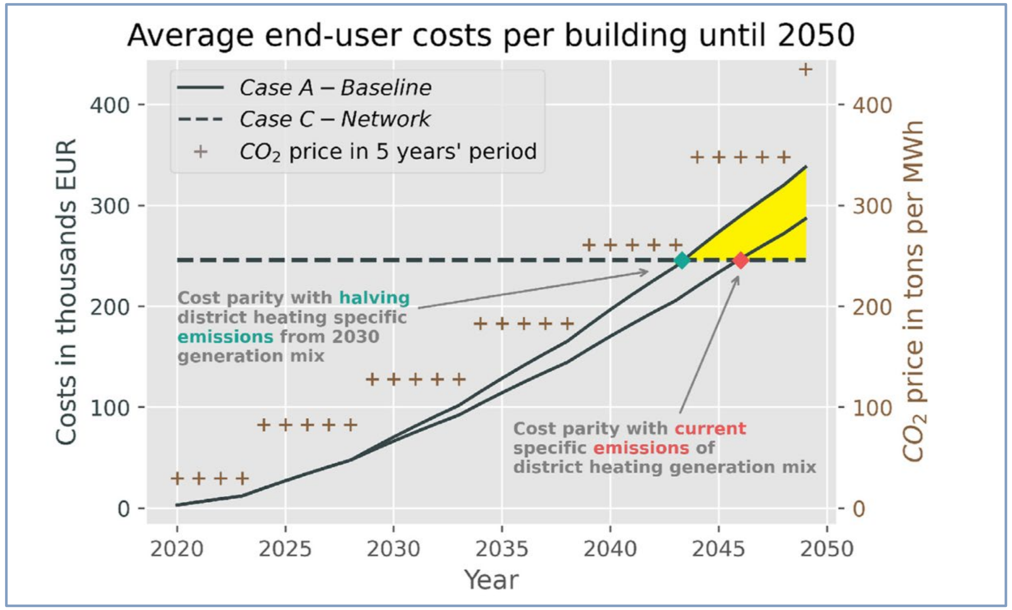
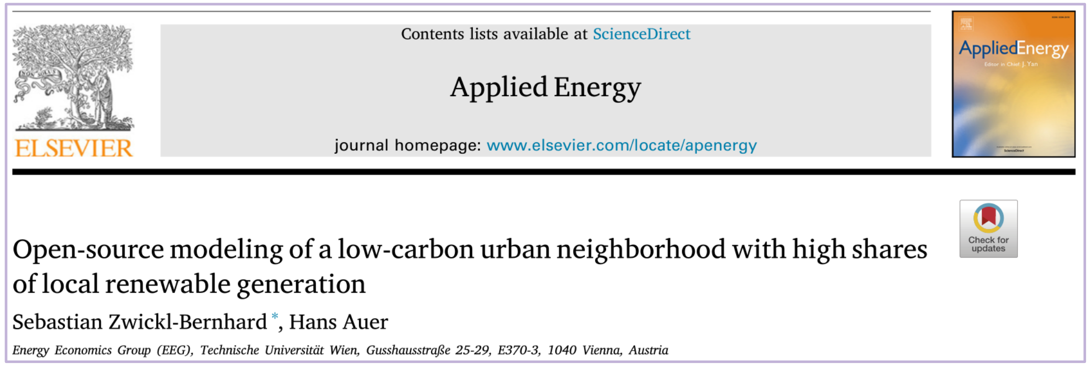
The Preamble

- This work has been developed during a research stay at the International Institute of Applied Systems Analysis (IIASA) as part of the Young Scientist Summer Programme (YSSP).
- Main idea of the application was "…*downscaling global results to higher sectoral or spatially resolved levels.*"
- Submitted to *Sustainable Energy and Technologies Assessment's* special issue "Efforts for Sustainable Development of District Heating and Cooling Systems" (under review)

Extends previous studies of local energy systems







Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Open-source modeling of a low-carbon urban neighborhood with high shares of local renewable generation

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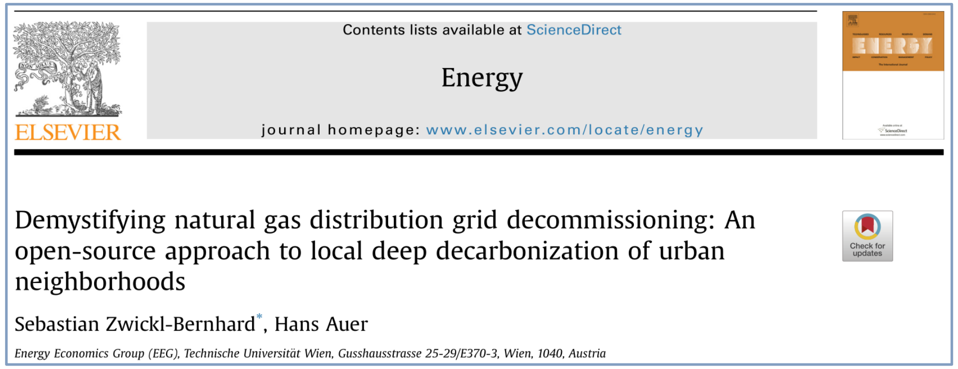

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Energy

journal homepage: www.elsevier.com/locate/energy

Demystifying natural gas distribution grid decommissioning: An open-source approach to local deep decarbonization of urban neighborhoods

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Current state of 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
- 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

The core objective of this work

- The core objective of this work is downscaling European decarbonization scenarios[1] of the heating sector to the community/distribution grid level serving end-users in 2050.
- In particular, downscaling considers the highly efficient and local use of sustainable heat sources in centralized heat networks (e.g., co-firing 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 centralized heating networks considering the 1.5°C climate target.
- An Austrian case study is conducted, downscaling the results of the heating sector in 2050 from the large numerical energy system model GENeSYS-MOD[2], from the country to the community/distribution grid levels.

[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)

- 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

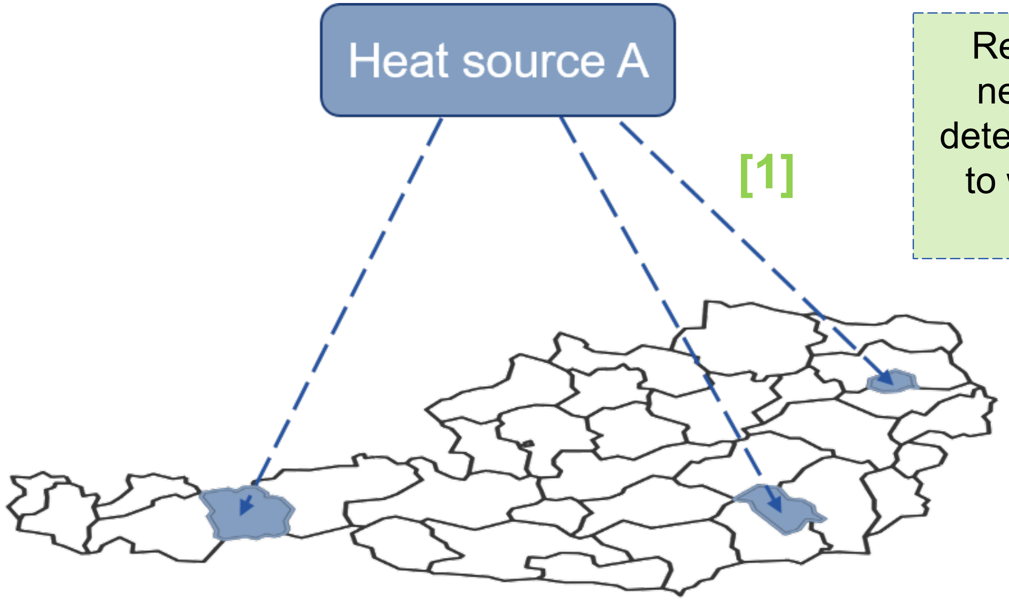
Techniques developed

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.

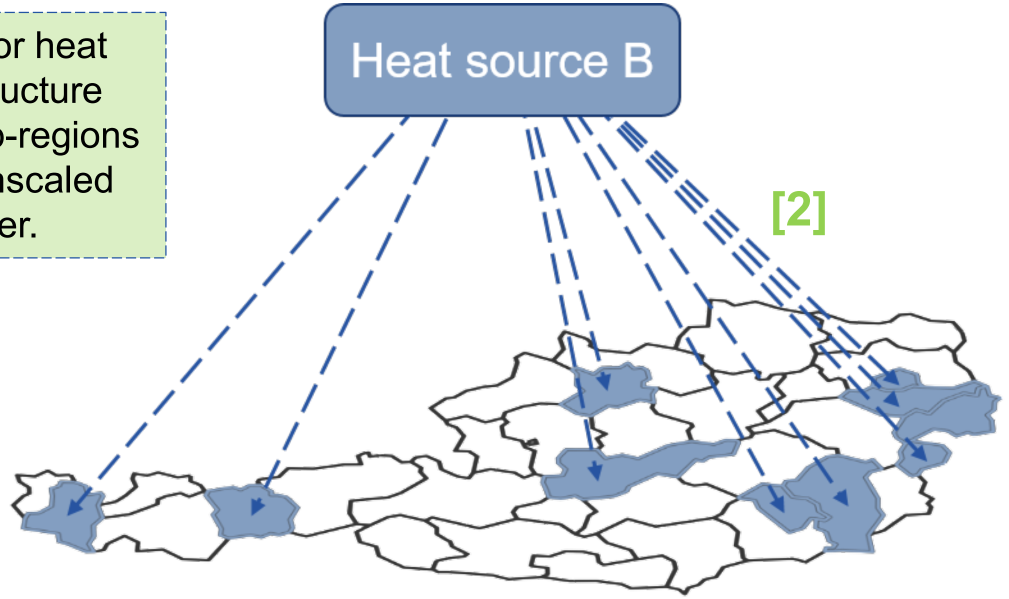
Main concept of the sequential downscaling algorithm

Heat source A has **high requirements** for heat network infrastructure (e.g., hydrogen)

Heat source B has **median requirements** for heat network infrastructure (e.g., biomass)



Requirements for heat network infrastructure determine the sub-regions to which is downscaled and the order.



[3]

Heat sources without requirements for heat network infrastructure are downscaled last. For example, direct-electric heating is disaggregated to all sub-regions proportionally.

Sequential downscaling algorithm (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

Requirements

Source Heat technology	Requirements Heat network	Rural Sparse	Town/Mixed Moderate	Urban Dense	Supporting references
Biomass	Median		x	x	[43] [44] [39]
Direct electric	None	x	x	x	
Synthetic gas	Low	x	x	x	
Hydrogen	High			x	[45] [46] [47]
Heat pump (air)	None	x	x	x	[48]
Heat pump (ground)	High			x	[49] [50] [41]
Heat storage	None	x	x	x	

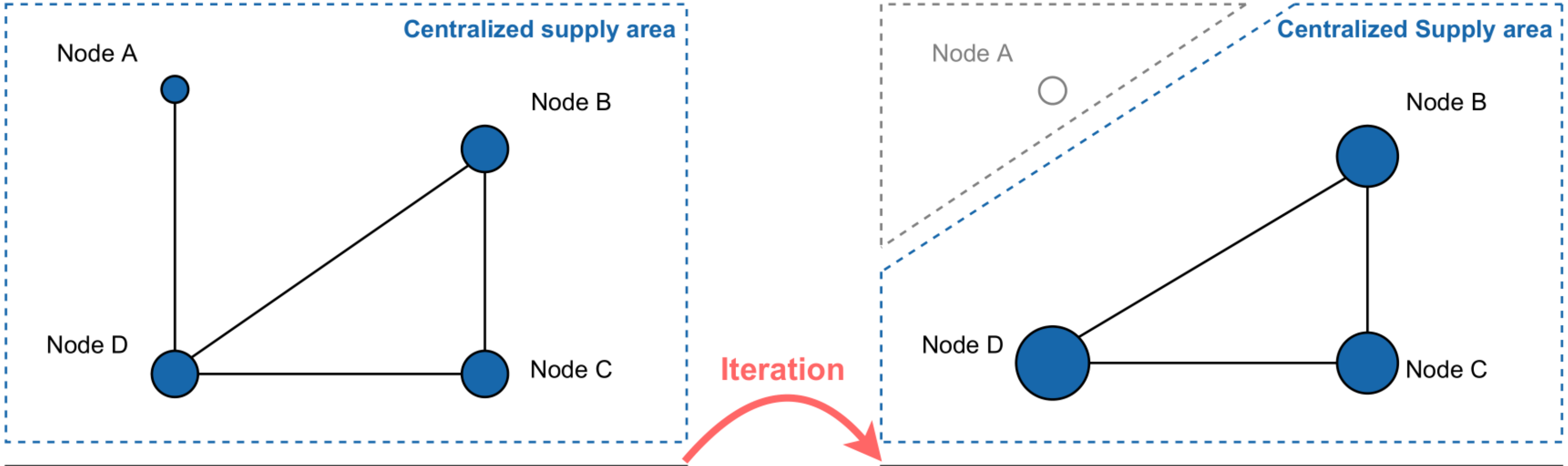
[44] Ericsson, K., & Werner, S. (2016). The introduction and expansion of biomass use in Swedish district heating systems. Biomass and bioenergy, 94, 57-65.

[45] Jensen, I. G., Wiese, F., Bramstoft, R., & Münster, M. (2020). Potential role of renewable gas in the transition of electricity and district heating systems. Energy Strategy Reviews, 27, 100446.

[50] Unternährer, J., Moret, S., Joost, S., & Maréchal, F. (2017). Spatial clustering for district heating integration in urban energy systems: Application to geothermal energy. Applied energy, 190, 749-763.

Main concept of the iterative downscaling algorithm

Condition *i* (Nodes A-D connected) | **Condition *i+1* (Nodes B-D connected)**



Node	Centralized	On-site	Demand	Indicator value
A	4	6	10	0.5
B	10	5	5	1
C	10	5	15	1
D	10	10	20	1.5

[1] [2] [3]

Node	Centralized	On-site	Demand	Indicator value
A	**0 (-4)**	**6 (+4)**	10	**No value**
B	**11 (+1)**	**4 (-1)**	5	1
C	**11 (+1)**	**4 (-1)**	15	1
D	**12 (+2)**	**8 (-2)**	20	1.5

Iterative downscaling algorithm (Algorithm 2)

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

Cluster(ing) coefficient c

$$c_n = \frac{q_n}{q_{max}} \times \frac{\alpha_n}{\beta_n}$$

q … *nodal amount of centralized heat generation*
α … *number of triangles that can be formed with neighboring nodes*
β … *number of lines connecting to the graph*

(i) High connection rate to the centralized heat network at the nodes

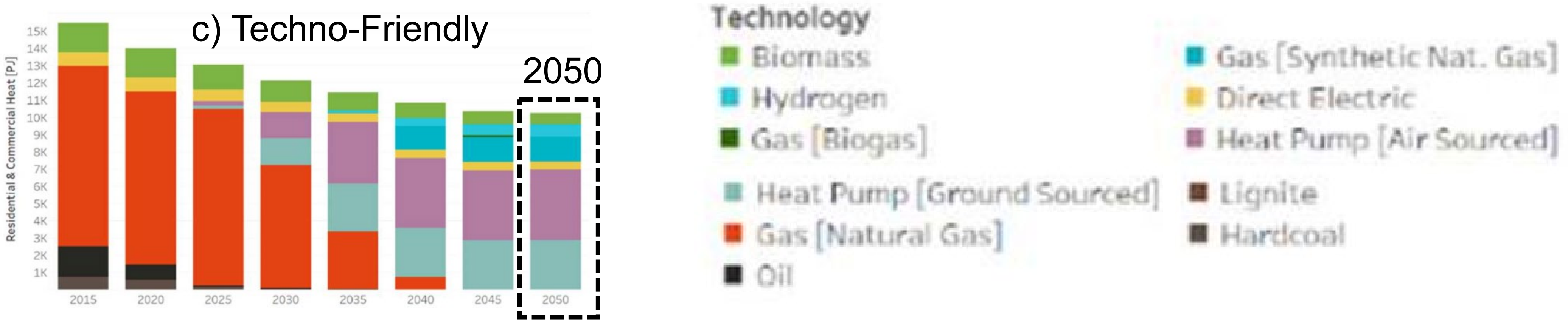
(ii) Connection of those nodes with a high amount of heat demand and heat density respectively

Cui, Y., Wang, X., & Li, J. (2014). Detecting overlapping communities in networks using the maximal sub-graph and the clustering coefficient. Physica A: Statistical Mechanics and its Applications, 405, 85-91.

Numerical example and scenarios

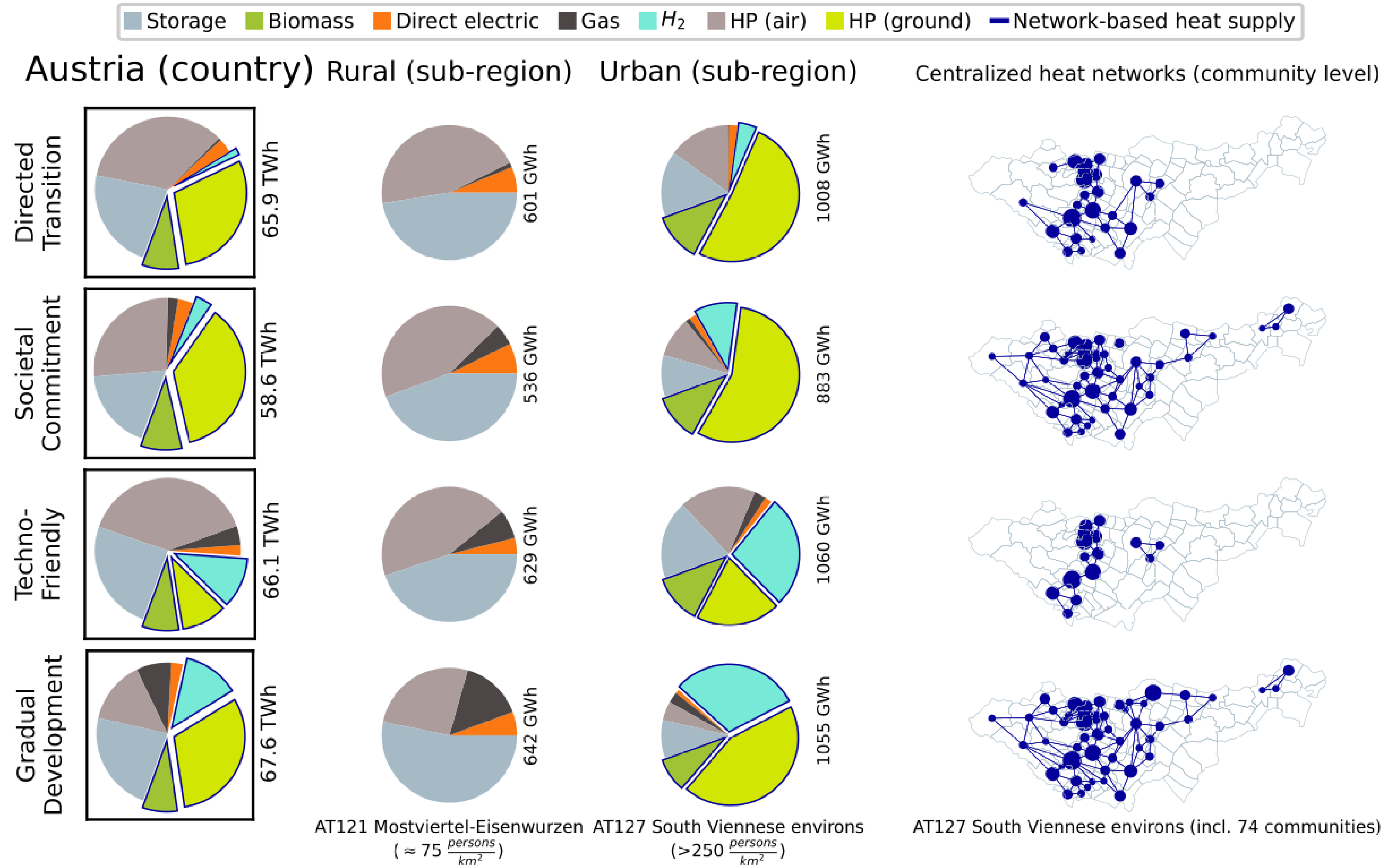
- Four different decarbonization scenarios of the European energy system aiming for the 1.5/2.0°C global warming climate target[1]
  a) Directed Transition scenario (strong policy incentives)
  b) Societal Commitment scenario (strong societal acceptance, decentralized renewables)
  c) Techno-Friendly 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

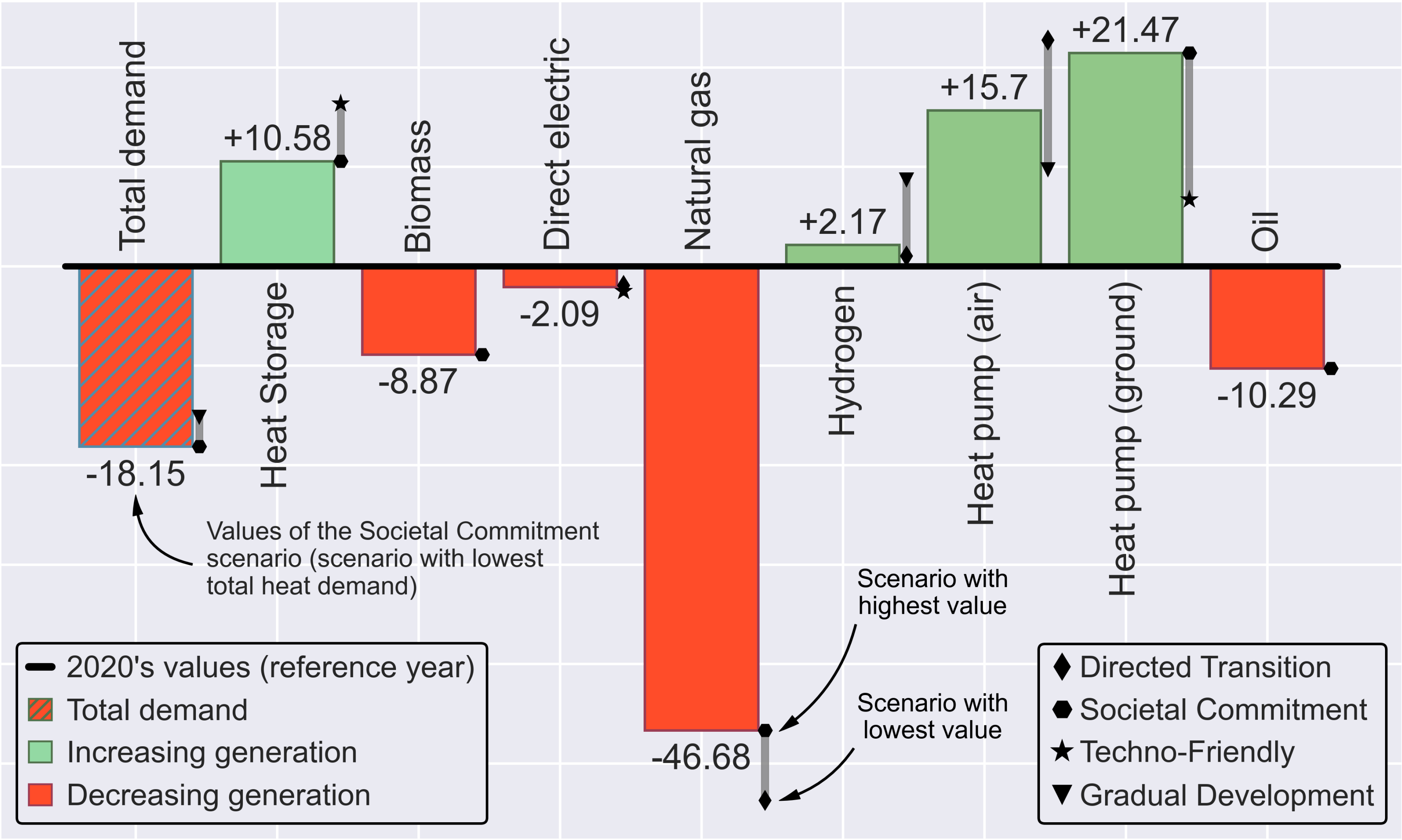


[1]Scenario a) to c) considers the 1.5°C global warming target and d) the less ambitious 2.0°C.

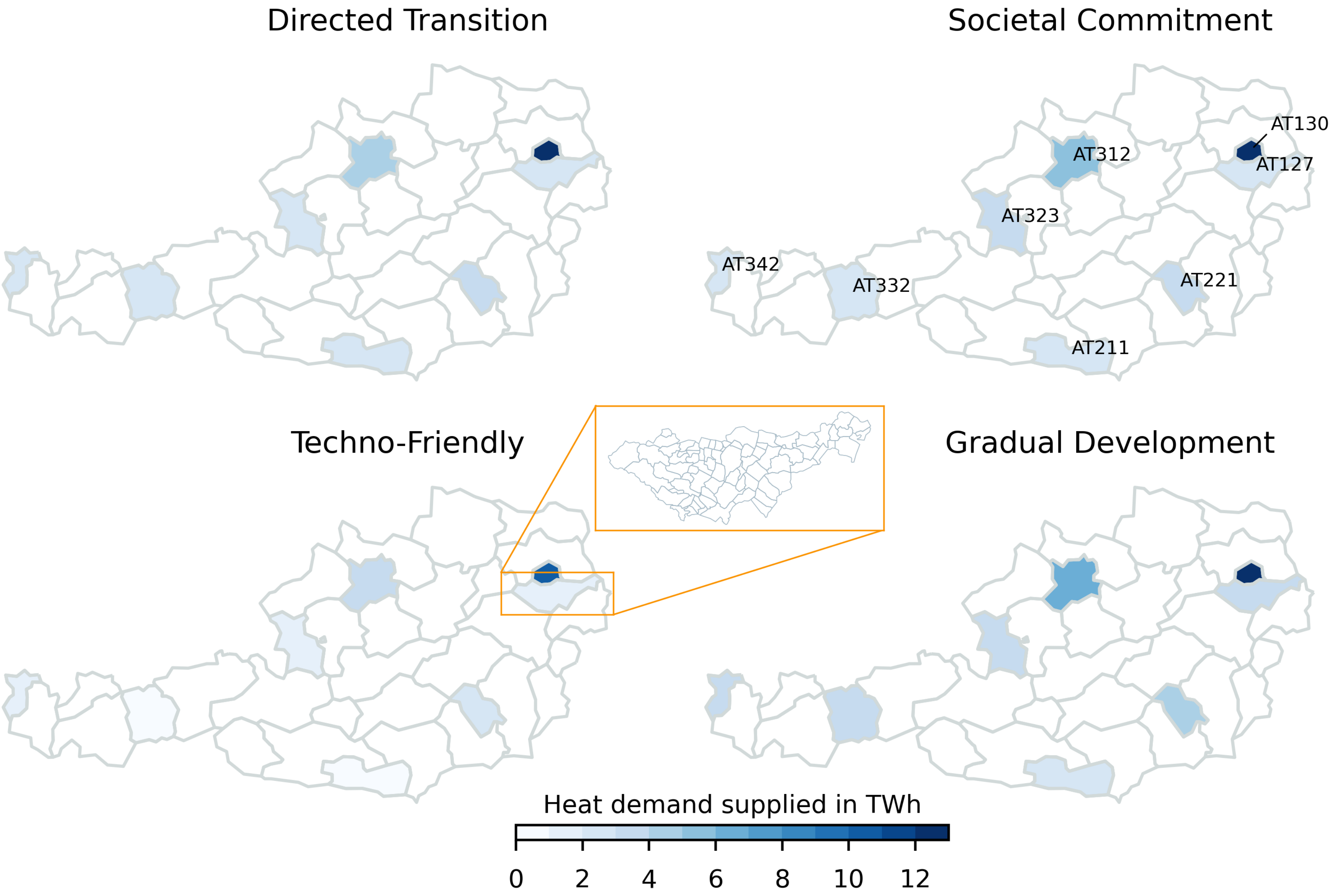
Heat generation on the country, sub-region, and community level



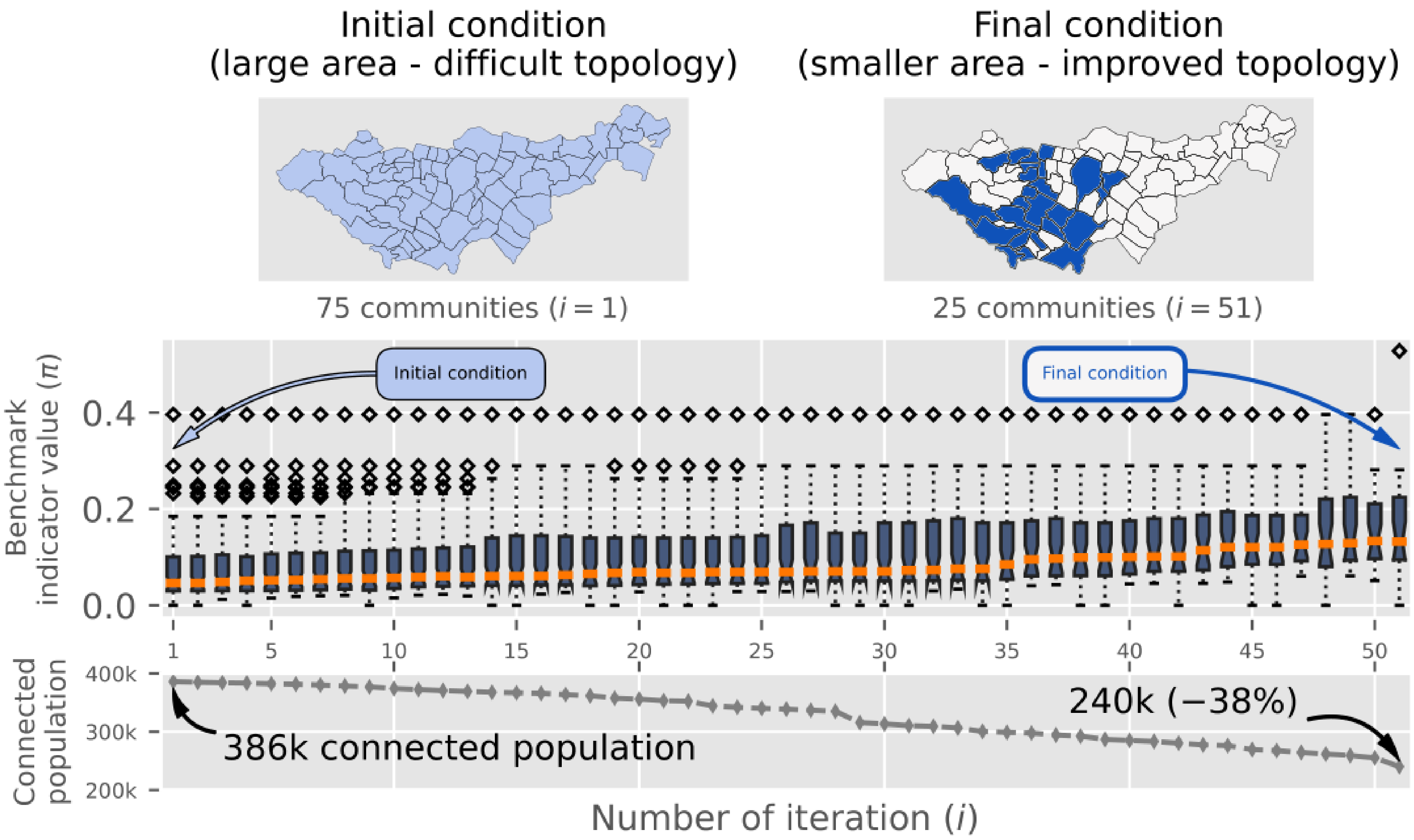
Absolute differences of heat generation by source between 2020 and 2050 in TWh

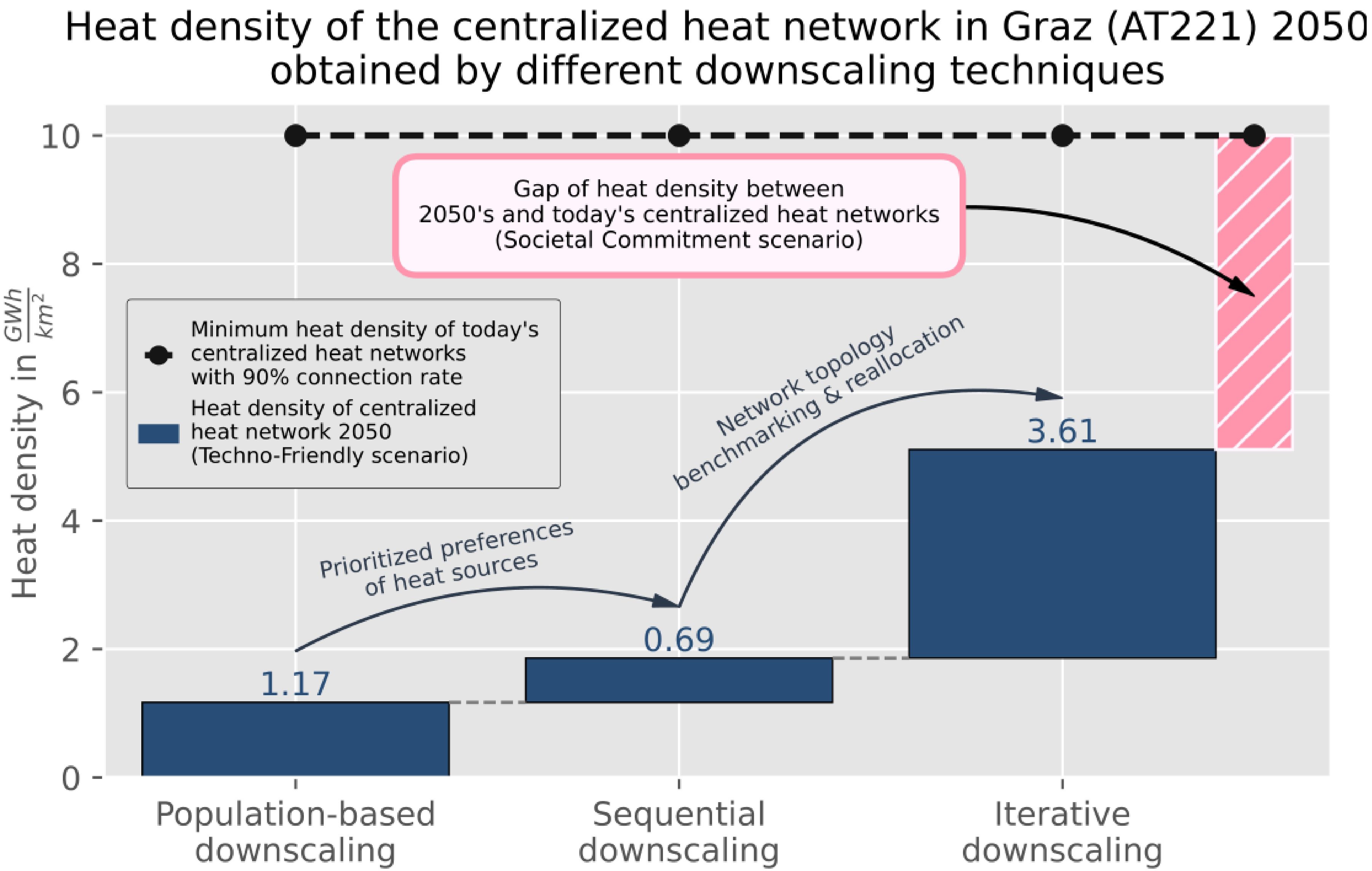


Heat demand supplied by centralized heat networks in TWh

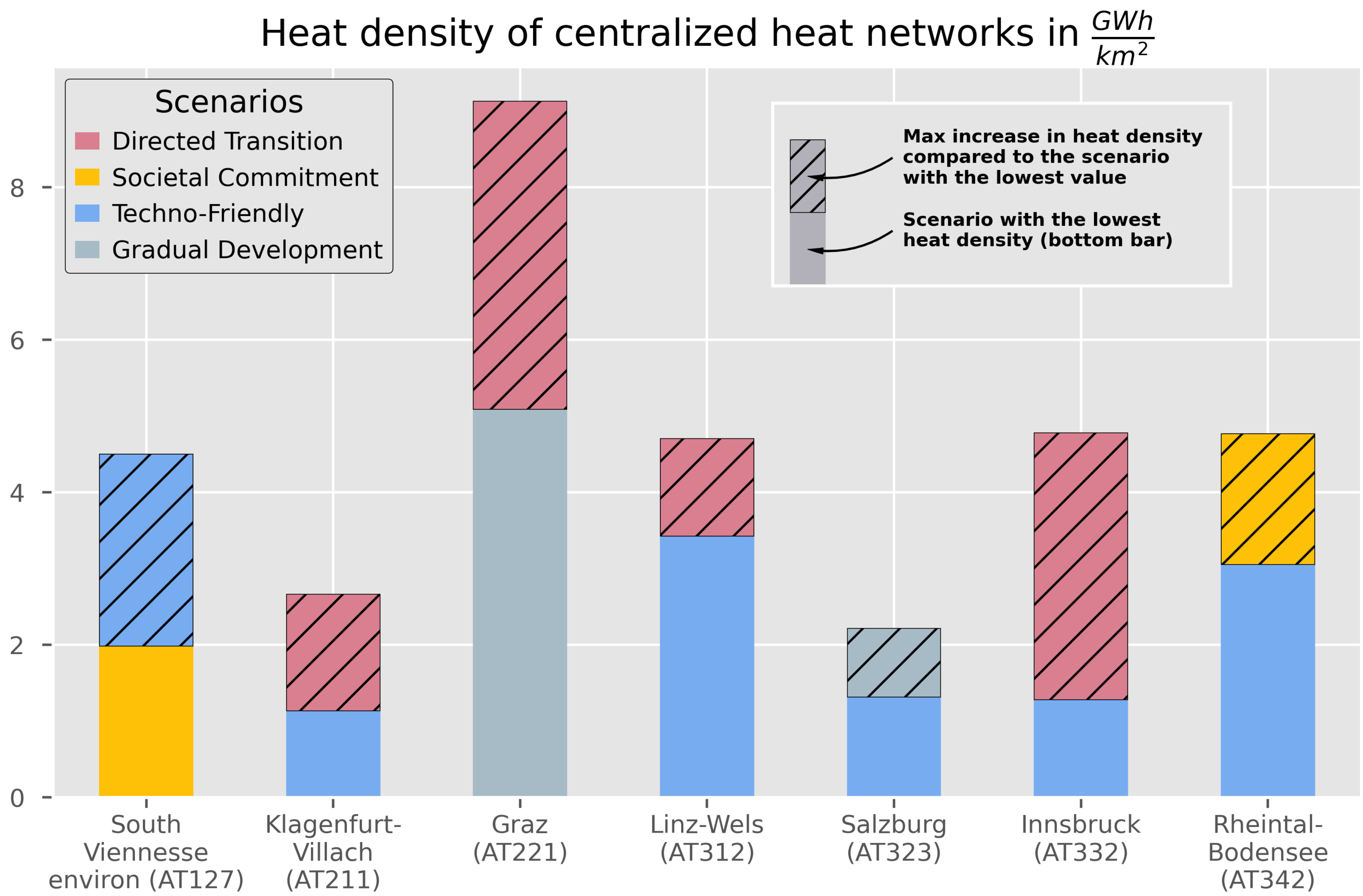


Centralized heat network topology improves by reducing supply area





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

- We found that 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.
- The results demonstrate that particularly densely populated areas are still beneficial supply areas 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.
- 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 centralized heat network infrastructure for enabling large-scale, highly efficient and local integration of renewable heat sources such as biomass/waste, hydrogen, ground-sourced heat pumps, or geothermal units.

Acknowledgments / References

Collaborators

Daniel Huppmann (International Institute for Applied Systems Analysis)
Antonia Golab (Energy Economics Group – Technische Universität Wien)
Hans Auer (Energy Economics Group – Technische Universität Wien)

Further 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](https://doi.org/10.1007/s00502-020-00832-7)

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