Evaluating the impact of the district heating resolution on renewable heat production in Germany: A Sensitivity Analysis

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***Abstract*—This paper evaluates the effects of varying spatial resolutions of district heating (DH) networks in energy system modeling. The analysis employs a hierarchical clustering algorithm to categorize 1228 DH areas in Germany in the year 2050 according to their renewable and excess heat potentials into DH types. These DH types are then integrated into the sector-coupled energy system model *Enertile*, with each scenario representing DH in a different spatial resolution. The findings reveal a "pooling effect" in scenarios with highly aggregated DH types characterized by two primary model behaviors: Firstly, scenarios with lower spatial resolutions tend to overestimate local DH generation potentials. Secondly, lower spatial resolutions of DH lead to an underestimation of the necessary heat generation capacities, particularly the need for seasonal thermal storages. The sensitivity analysis indicates that representing DH networks with 12 DH types effectively reduces this pooling effect while maintaining acceptable computational times.**

***Index Terms*—Energy system modeling, optimization, district heating, district heating types, modeling resolution**

I. INTRODUCTION

Global heat consumption accounts for nearly half of total final energy consumption and contributed to 38 % of energy-related CO_2 emissions in 2022 [1]. Transforming the heat supply is therefore crucial to achieving climate and energy targets. District heating (DH) networks can integrate substantial shares of renewable energies such as geothermal and solar thermal energy, as well as excess heat from industrial processes. Consequently, they can make a significant contribution to the decarbonization of the heat supply in the energy system of the future [2, 3].

Energy system models (ESM) can be applied to develop a target picture of a climate-neutral energy system and to find efficient transformation pathways towards the target. A fundamental challenge in modelling sector-coupled energy systems (i.e. which cover electricity, DH, hydrogen etc.) is the substantial amount of data required to mathematically describe the energy system at an appropriate level of detail [4]. Achieving a high resolution across temporal, spatial and techno-economic dimensions is one of the key challenges in modeling sector-coupled energy systems, necessitating the implementation of simplifications [5].

In sector-coupled ESM, the spatial resolution of DH networks varies greatly [6] and they are often integrated in a strongly spatially simplified way, such as one single DH network for one country [7, 8]. This approach causes the models to incorporate aggregated heat supply quantities that significantly differ from the actual locally available generation potentials, which can be called "pooling effect". This discrepancy arises from spatial balancing of heat supply and heat demand within the model, which is in reality not feasible due to the lack of a long-distance DH transport network. This results in an underestimation of DH generation capacity and an inaccurate assessment of thermal storage needs.

To address these shortcomings, previous research has enhanced the resolution of DH grids in ESM by categorizing them into DH type networks [9–11]. A higher resolution typically enhances accuracy. However, the model complexity must be considered to ensure acceptable runtimes and computational feasibility. Consequently, a comprehensive examination of the pooling effect through a sensitivity analysis can help to find a balance between accuracy and computational feasibility.

The aim of this paper is to analyze the impact of different spatial resolutions of DH in sector-coupled ESM and thus contribute to the overall question how DH should be represented in ESM. In particular, this sensitivity analysis seeks to identify a trade-off between model complexity and accuracy of the results. To achieve this, the following research questions are examined:

- How does varying spatial resolution of DH in ESM affect heat generation, capacities, and storage?
- What is an appropriate number of DH types to accurately represent local heat generation potentials?

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To address these research question, we perform a hierarchical clustering algorithm to categorize DH renewable and excess heat potentials with high spatial resolution into multivalent DH types. Subsequently, a scenario-based analysis is conducted using the cost-minimizing ESM *Enertile*, with each scenario employing a different spatial resolution of DH, i.e. a different number of DH types. This methodological framework enables a varied spatial representation of DH within the model, enabling the analysis of the pooling effect through the evaluation of optimization results.

The paper is structured as follows: Section 2 describes the methodology and data used to answer the research questions. Section 3 presents the main results obtained from the scenario-based analysis and contextualizes them. Finally, Section 5 concludes the paper by summarizing the key findings.

II. METHODOLOGY AND DATA

To investigate the impact of varying spatial resolutions of DH in ESM, a scenario-based sensitivity analysis as shown in Figure 1 is performed. In a first step, DH areas are categorized into DH type networks using a clustering algorithm. The aggregated potentials of these DH type networks are then used as input for an energy system analysis with the *Enertile* model [12]. The methodological steps are described in more detail in the following subsections.

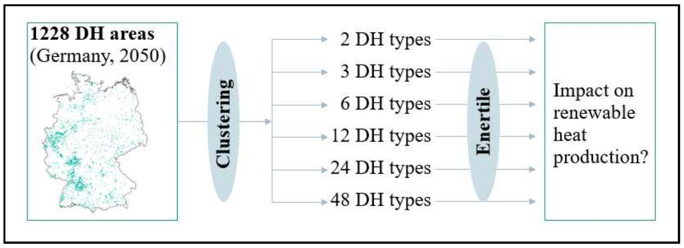

Figure 1. Graphic representation of the methodology

A. *Clustering*

Input data for the clustering are 1228 future DH areas for Germany in 2050, along with their renewable and excess heat utilization potentials in near spatial proximity from [13]. The dataset (available open access in [14]) encompasses utilization potentials from renewable sources, including deep geothermal heat, biomass and ambient heat from surface water and wastewater (in conjunction with a heat pump), as well as biogas produced from sewage sludge. Furthermore, the dataset incorporates utilization potentials from the following excess heat sources: excess heat from industrial processes and thermal treatment of waste. To minimize the impact of different magnitudes of the DH areas during clustering, the potentials are translated into a percentage of demand as in [13].

As shown in [9, 13, 15], hierarchical clustering is a proven approach to define DH types. In line with this, a hierarchical agglomerative clustering algorithm using the Ward's minimum variance method and Euclidean distance is performed in this paper by employing the python package SciPy. DH areas that exhibit similar renewable and excess heat potentials are thus categorized into DH types.

Varying the termination results in different numbers of clusters, which are referred to below as DH types. By analyzing the dendrogram and key figures that evaluate the quality of a cluster for the underlying data (i.e. Silhouette score, Calinski-Harabasz index, Davies-Bouldin index and Dunn index), favorable termination, i.e. number of clusters, are defined.

This approach results in the following different resolutions of DH: a representation of DH by 2, 3, 6, 12, 24 and 48 DH types. A higher number of DH types was excluded to ensure realizable calculation times in ESM (see subchapter III.F).

The different resolutions are illustrated in Figure 2. In Figure 2 (left), "2.1" represents the first DH type network and "2.2" the second DH type network in the *2-DH-types* scenario. The DH types serve as input for the scenario-based energy system analysis in *Enertile* to examine the effects on the optimization results.

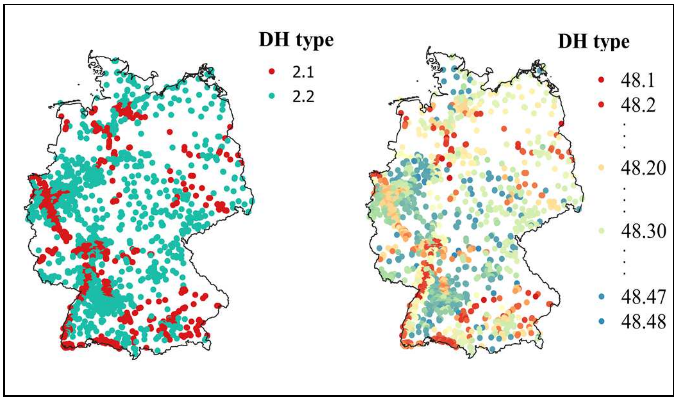

Figure 2. DH types based on clustering (exemplary for lowest and highest resolution examined here)

Table I lists and shortly describes the six scenarios calculated with the *Enertile* model in this paper.

TABLE I. SCENARIO DESIGN

Scenario	**Varying resolution of DH in ESM *Enertile***
2-DH-types	DH areas strongly aggregated and represented by 2 types
3-DH-types	DH areas represented by 3 types
6-DH-types	DH areas represented by 6 types
12-DH-types	DH areas represented by 12 types
24-DH-types	DH areas represented by 24 DH types
48-DH-types	Highest resolution of DH, represented by 48 types

B. *Energy system model Enertile*

1) *Modelling approach*

Enertile is a bottom-up optimization model with high spatial, temporal and technical resolution covering all EU member states [9]. Linear optimization is used to identify the cost-minimizing portfolio of technologies required to satisfy the exogenously specified hourly demands for electricity, DH and hydrogen in each model region [16]. The optimization simultaneously addresses both capacity expansion and dispatch of relevant infrastructure and generation technologies [17]. The objective function for the linear optimization in *Enertile* is expressed in an abbreviated version in the following (cf. [9]):

$$\begin{aligned}\min_{\vec{x}\vec{X}} \Big[&\mathrm{cost}_{\mathrm{el}}^{\mathrm{fix}}(\vec{X}) + \mathrm{cost}_{\mathrm{el}}^{\mathrm{var}}(\vec{x}) + \mathrm{cost}_{\mathrm{heat}}^{\mathrm{fix}}(\vec{X}) \\ &+ \mathrm{cost}_{\mathrm{heat}}^{\mathrm{var}}(\vec{x}) + \mathrm{cost}_{\mathrm{el,chp}}^{\mathrm{var}}(\vec{x}) \\ &+ \mathrm{cost}_{\mathrm{hydrogen}}^{\mathrm{fix}}(\vec{X}) \\ &+ \mathrm{cost}_{\mathrm{hydrogen}}^{\mathrm{var}}(\vec{x})\Big]\end{aligned}$$

with:

$\vec{X}$: variables for installed capacity

$\vec{x}$: variables for generation

$\mathrm{cost}_{\mathrm{el}}^{\mathrm{fix}}$: fixed costs of electricity capacity expansion in €

$\mathrm{cost}_{\mathrm{el}}^{\mathrm{var}}$: variable costs of electricity generation in €

$\mathrm{cost}_{\mathrm{heat}}^{\mathrm{fix}}$: fixed costs of capacity expansion in DH in €

$\mathrm{cost}_{\mathrm{heat}}^{\mathrm{var}}$: variable costs of heat generation in DH in €

$\mathrm{cost}_{\mathrm{el,chp}}^{\mathrm{var}}$: variable costs of electricity generation from CHP in €

$\mathrm{cost}_{\mathrm{hydrogen}}^{\mathrm{fix}}$: fixed costs of hydrogen capacity expansion in €

$\mathrm{cost}_{\mathrm{hydrogen}}^{\mathrm{var}}$: variable costs of hydrogen generation in €

Enertile is capable of modeling multiple consecutive years at hourly resolution. However, in this paper, we focus on modeling the target year 2050 and run the model exclusively for Germany using a greenfield strategy since the approach of this analysis is exploratory.

2) *District heating types in Enertile*

As mentioned in section A., data on renewable and excess heat potentials, aggregated into DH types, is used and integrated into *Enertile*. Thereby, the utilization potentials are incorporated into the optimization process as constraints, specifying maximum generation limits. Building on the *RES* scenario outlined in [9], the potentials for geothermal energy and industrial excess heat are fixed at their respective utilization potentials, while solar thermal energy is set to a maximum contribution of 10% of the DH demand for the corresponding DH type.

For each DH type, the hourly DH supply is optimized with respect to the potential constraints to meet a given exogenous heat demand at the lowest total system cost. The DH demand for 2050 is derived from [13] and is converted in *Enertile* from an annual demand to a hourly profile, taking into account daily outdoor temperatures.

The model includes the following DH generation technologies: electric heaters, large heat pumps (based on air, surface water and wastewater), geothermal energy plants, solar thermal plants, biomass boilers and combined heat and power (CHP) systems, waste CHP, hydrogen boilers and CHP systems. As a storage solution, we (newly) implemented pit thermal energy storages as an option for large-scale seasonal heat storage. Its implementation is described in [18] in more detail. A more detailed description of the integration of DH types in the model and heating technologies included in *Enertile* can be found in [7–9]. Demand data for other sectors are taken from the *Elec_60* scenario [19] in the project “Potentials and levels of electrification of space heating in buildings” (ENER C1 2019-481). The representation of the electricity system in *Enertile* can be found in [20] and a description of the hydrogen system within the model in [21].

III. RESULTS

The following presents the results of the scenario-based energy system analysis in *Enertile*.

A. *DH generation mix*

Figure 3 illustrates the DH generation mix for the *2-DH-types* and the *48-DH-types* scenarios in Germany in 2050.

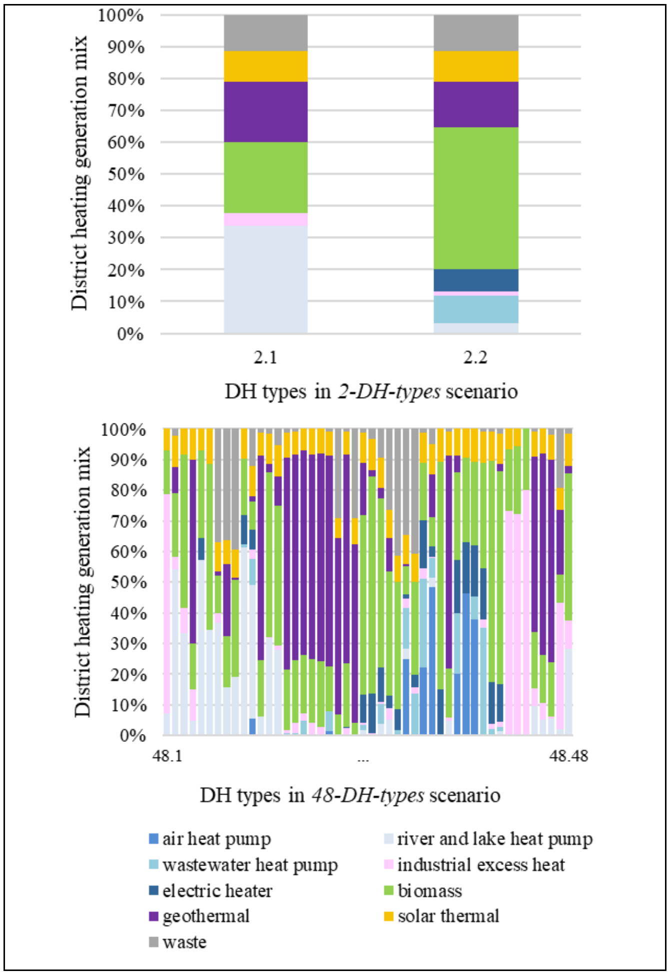

Figure 3: DH generation mix per DH type

In line with [9], all DH types are multivalent networks with varying shares of generation technologies due to the different available potentials aggregated within the DH types.

In the *2-DH-types* scenario, the dominant technology in DH type 2.1 is the river and lake heat pump, while in DH type 2.2 biomass CHP is the technology with the highest share of the DH generation. Figure 3 shows that the composition of technologies in the DH types varies more when represented by 48 types. In the *48-DH-types* scenario, there are also DH types that are dominated by other technologies, such as DH type 48.1 which relies mainly on industrial excess heat, as well as a total of 15 DH types that are dominated by geothermal energy. This result underlines that a higher spatial resolution with more DH types leads to a more accurate representation of the local potentials.

To analyze the influence of different spatial resolutions of DH on the overall result, the aggregated heat generation across all DH types is considered in the following. The total DH generation hardly differs between the scenarios. The reason for this result is that the (exogenously defined) demand for DH in total remains constant in all scenarios, which determines the amount of heat produced. However, the shares of the heat generation technologies change in a relevant magnitude, as can be seen in Figure 4. At a higher resolution, the optimization results show an increased production of heat generated by air heat pumps, whereas the production from biomass CHP decreases.

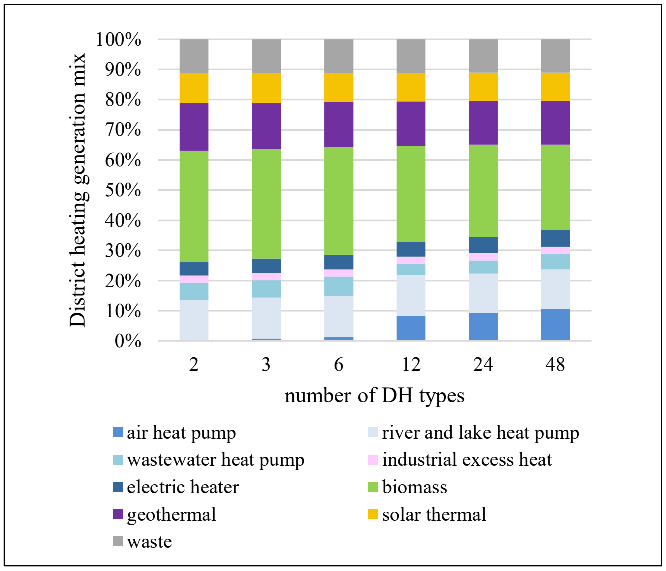

Figure 4. Aggregated DH generation mix across all DH types

B. *Pooling of DH potentials*

The result in the previous subchapter demonstrates that scenarios involving fewer number of DH types (*2-DH-types*, *3-DH-types*, *6-DH-types*) overestimate the local potential of generation technologies. The pooling of potentials is particularly evident for DH generation from biomass due to its larger share in the generation mix, but it also occurs for other technologies.

In the *48-DH-types* scenario, 18 out of 48 DH types fully exploit their available biomass potential. These potential limits are not reached in the *2-DH-types* scenario, where the high aggregation of potentials prevents both DH types from achieving 100% biomass potential exploitation, despite significantly higher generation volumes. Furthermore, in 8 of these 18 DH types (in *48-DH-types*), the potentials from river and lake heat pumps, as well as from wastewater heat pumps, are already fully utilized, requiring DH production from alternative sources. Consequently, air source heat pumps are utilized more extensively to meet the DH demand in the scenarios with higher DH resolution. Employing a higher spatial resolution (12 DH types or more) prevents this “pooling of potentials” through sufficiently detailed regional representation enabled by less aggregated potentials.

C. *Pooling of DH generation capacities*

When looking at the heat generation capacities in the optimization results (see Figure 5), the pooling effect becomes visible again: the optimization results indicate that an increased number of DH types correlates with higher DH generation capacities. Compared to the *48-DH-types* scenario, the simplified representation of DH in the *2-DH-types* scenario results in 10 % lower generation capacities. This can be explained by increased spatial balancing opportunities in the highly aggregated DH types, which, however, is only feasible in the model and does not adequately reflect the real-world conditions of DH. The observed difference in capacities is primarily attributed to a rise in the deployment of air heat pumps.

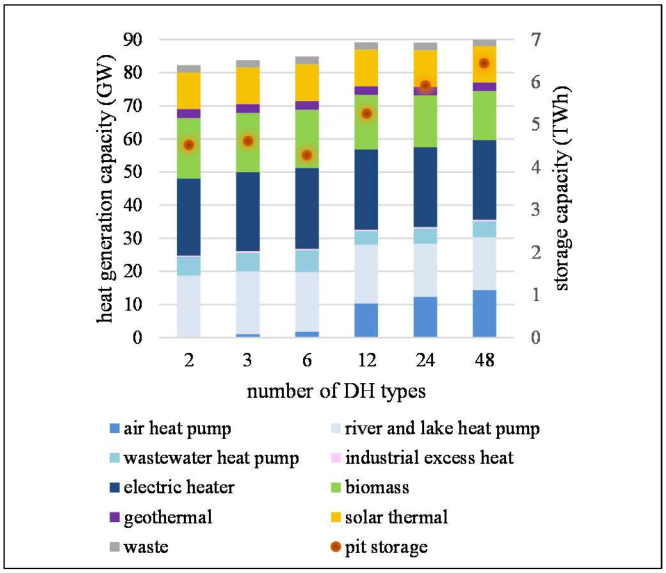

Figure 5. Heat generation capacities for different DH resolutions

Moreover, the varying resolutions of DH demonstrate great impact on storage capacities. As shown in Figure 5, storage capacities range from 4.5 TWh (*2-DH-types*) to 6.4 TWh (*48-DH-types*) for the temporal balancing of heat generation and demand. This 30 % difference between the *2-DH-types* scenario and the *48-DH-types* scenario clearly indicates that excessive aggregation of DH type networks, as is mostly done in the literature employing ESM, leads to an underestimation of the required storage capacity.

D. *Role of heat pumps*

A closer examination of the heat pump technology is warranted, given the differences exhibited by air heat pump technology in terms of heat generation mix and capacity across the scenarios. River and lake heat pumps, followed by wastewater heat pumps, have a larger share in the generation mix due to their lower specific investment costs (see Table A1 in the appendix). The more expensive and less efficient air heat pump is only utilized when the generation potential limits of the other two heat pump technologies is reached. Due to the pooling of potentials in the scenarios with lower resolution, this hardly happens in the scenarios with 2, 3 or 6 DH types. However, only when 12 or more DH types are modelled, the spatial resolution is adequate to identify the potential exploitation of different heat pump technologies, leading to a more adequate share of air-source heat pumps in the DH technology mix.

E. *Electricity system*

Overall, the effects of the DH spatial representation on the electricity system are negligible. No significant changes are observed in the amount of electricity generated, the required generation capacities, or the electricity shadow prices across the scenarios.

F. *Appropriate number of DH types*

Figure 6 illustrates the increasing computation time related to a higher spatial resolution of DH in ESM. The exponential increase in computation time is primarily driven by the solver time required to solve the linear problem, highlighting the importance of finding a reasonable trade-off between spatial resolution (i.e. accuracy) and computational limitations (i.e. time and server resources). This trade-off is particularly important for future research involving optimizations with larger geographical coverage (e.g. Europe and its member states) at high spatial DH resolution, as it ensures the feasibility of computing times.

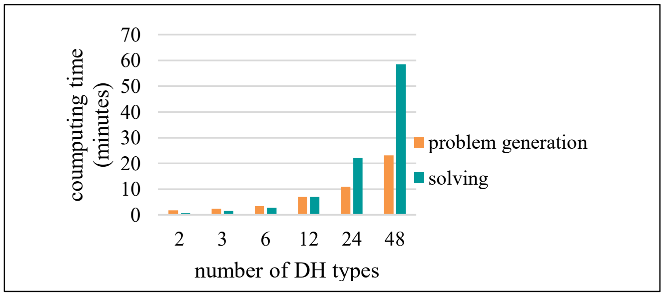

Figure 6. Computation times for different DH resolutions

Among the scenarios of this sensitivity analysis, the *12-DH-types* scenario represents an effective trade-off between computational time and spatial resolution for three key reasons: Firstly, the aggregated generation capacities in the *12-DH-types* scenario are comparable to those in the scenario with highest spatial resolution *(48-DH-types)*. Secondly, the necessity for air heat pumps is already recognized at this level of spatial resolution, indicating that the over-regional pooling effect is less pronounced in this scenario. Thirdly, this approach offers significant computational time savings compared to the *48-DH-types* scenario. However, it is important to note that thermal storage capacities remain underestimate, showing an 18 % reduction relative to the *48-DH-types* scenario. Overall, different levels of aggregation may be appropriate depending on the research question. If the focus is on thermal storage, a higher resolution should be considered. If the focus is on the electricity system, a highly simplified representation of DH may be sufficient.

IV. CONCLUSION

To evaluate the effects of varying spatial resolutions of district heating (DH) networks in energy system modeling (ESM), six scenarios with different spatial resolutions of DH were calculated in this paper. The analysis focuses on Germany, utilizing 1228 DH areas and their renewable and excess heat potentials, aggregated into DH types through a hierarchical clustering algorithm. Following this, a scenario-based analysis was conducted using the sector-coupled model *Enertile*, and the impact on optimization results was analyzed.

The optimization results reveal a “pooling effect”, which occurs when DH networks are represented in a spatially simplified manner in ESM (cf. section 1). This effect manifests primarily in two ways: Firstly, scenarios with lower spatial resolution tend to overestimate the local potential of DH generation technologies due to the regional aggregation of DH potentials. The strong spatial aggregation (i.e. less than 12 DH types) leads to larger heat volumes available than can actually be exploited on-site due to geographical constraints. Secondly, this results in an underestimation of the necessary heat generation capacities to meet DH demand. In particular thermal storage capacities are underestimated.

In conclusion, the sensitivity analysis conducted for this paper indicates that the use of 12 DH types to represent DH networks is an appropriate approach to effectively reduce the pooling effect while maintaining acceptable computational times. As demonstrated in [8], the isolated optimization of the German energy system as conducted here, underestimates electricity-side flexibility and results in a reduced deployment of heat pumps. Consequently, further research encompassing EU member states is necessary. The feasibility of achieving such a high spatial resolution of DH networks (e.g. 12 DH types) within an expanded geographical coverage warrants further investigation.

The necessity for high spatial resolution in DH is thus found to be dependent on the focus of the analysis. For research questions where the electricity system is the primary focus, it is permissible to implement a simplified model to represent DH networks as the impacts of DH network spatial resolution on the electricity system are found to be negligible. Conversely, if the focus is on heat supply technologies, required capacities, or generation potentials, a higher resolution is crucial in order to minimize model endogenous pooling effects that distort the results. Consequently, there is a need for ESM that can be flexibly configured to different levels of resolution depending on the specific research question.

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DECLARATION OF AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used "deepl write" to correct potential grammar mistakes and improve readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

APPENDIX

TABLE A1. TECHNO-ECONOMIC ASSUMPTIONS FOR HEAT PUMPS IN ENERTILE IN 2050 [22]

Technology options	**Life-time**	**Investment €/kW**	**Fixed O&M in €/kW**	**Variable O&M in €/MWh**
Air source heat pump	25	760	2.0	1.7
River and lake heat pump	25	380	4.0	1.7
Wastewater heat pump	25	570	2.0	1.7

REFERENCES

[1] International Energie Agency (IEA), Ed., "Renewables 2023: Analysis and forecast to 2028," Paris, Jan. 2024. Accessed: Jan. 31 2025. [Online]. Available: https://iea.blob.core.windows.net/assets/96d66a8b-d502-476b-ba94-54ffda84cf72/Renewables_2023.pdf

[2] S. Blömer, C. Götz, P. Mellwig, M. Pehnt, and P. Jochum, "Die Rolle von Wärmenetzen im Wärmemarkt der Zukunft: GIS-Analyse technisch-ökonomischer Potenziale," 7. Accessed: Nov. 11 2024. [Online]. Available: https://www.ifeu.de/publikation/die-rolle-von-waermenetzen-im-waermemarkt-der-zukunft-gis-analyse-technisch-oekonomischer-potenziale

[3] M. Blesl, A. Burkhardt, and F. Wendel, "Transformation und Rolle der Wärmenetze," 2023. Accessed: Nov. 7 2024. [Online]. Available: https://coilink.org/20.500.12592/mqx1kx

[4] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, "Classification and challenges of bottom-up energy system models: A review," *Renewable and Sustainable Energy Reviews*, no. 129, 2020. [Online]. Available: https://doi.org/10.1016/j.rser.2020.109917

[5] S. Pfenninger, A. Hawkes, and J. Keirstead, "Energy systems modeling for twenty-first century energy challenges," *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 74–86, 2014, [Online]. Available: https://doi.org/10.1016/j.rser.2014.02.003

[6] P. Manz, S. Alibas, T. Fleiter, and A. Billerbeck, "Finding an optimal district heating market share in 2050 for EU-27: Comparison of modelling approaches", 2022.

[7] C. Bernath, "Auswirkungen der Sektorkopplung von Strom und Wärme durch Wärmenetze auf das europäische Stromerzeugungssystem : Eine modellbasierte Szenarioanalyse," Ph.D. dissertation, Karlsruher Institut für Technologie, 2023.

[8] C. Bernath, G. Deac, and F. Sensfuß, "Influence of heat pumps on renewable electricity integration: Germany in a European context," *Energy Strategy Reviews*, vol. 26, p. 100389, 2019, [Online]. Available: https://doi.org/10.1016/j.esr.2019.100389

[9] A. Billerbeck *et al.,* "Integrating district heating potentials into European energy system modelling: An assessment of cost advantages of renewable and excess heat," *Smart Energy*, vol. 15, p. 100150, 2024, [Online]. Available: https://doi.org/10.1016/j.segy.2024.100150.

[10] J. Gea-Bermúdez *et al.,* "The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050," *Applied Energy*, vol. 289, p. 116685, 2021, [Online]. Available: https://doi.org/10.1016/j.apenergy.2021.116685.

[11] M. Yuan, J. Z. Thellufsen, P. Sorknæs, H. Lund, and Y. Liang, "District heating in 100% renewable energy systems: Combining industrial excess heat and heat pumps," *Energy Conversion and Management*, vol. 244, p. 114527, 2021, [Online]. Available: https://doi.org/10.1016/j.enconman.2021.114527.

[12] Fraunhofer Institute for Systems and Innovation Research (ISI), Enertile. proprietary software, (version used: 2025).

[13] P. Manz *et al.,* "Spatial analysis of renewable and excess heat potentials for climate-neutral district heating in Europe," *Renewable Energy*, no. 224, 2024, [Online]. Available: https://doi.org/10.1016/j.renene.2024.120111.

[14] P. Manz, A. Billerbeck, and M. Fallahnejad, *Spatial analysis of renewable and excess heat potentials for climate-neutral district heating in Europe [tabular data].* [Online]. Available: https://fordatis.fraunhofer.de/handle/fordatis/341.5

[15] M. S. Triebs, E. Papadis, H. Cramer, and G. Tsatsaronis, "Landscape of district heating systems in Germany – Status quo and categorization," *Energy Conversion and Management: X*, vol. 9, p. 100068, 2021, [Online]. Available: https://doi.org/10.1016/j.ecmx.2020.100068.

[16] B. Lux *et al.,* "The role of hydrogen in a greenhouse gas-neutral energy supply system in Germany," *Energy Conversion and Management*, vol. 270, p. 116188, 2022, [Online]. Available: https://doi.org/10.1016/j.enconman.2022.116188.

[17] B. Lux, J. Gegenheimer, K. Franke, F. Sensfuß, and B. Pfluger, "Supply curves of electricity-based gaseous fuels in the MENA region," *Computers & Industrial Engineering*, vol. 162, p. 107647, 2021, [Online]. Available: https://doi.org/10.1016/j.cie.2021.107647.

[18] A. Burkhardt, M. Frömel, G. Deac, and A. Billerbeck, "Modeling thermal energy storage – the effect of self-discharge rates on dispatch," unpublished, submitted to the EEM2025 (conference), Lisbon, Portugal, 2025.

[19] B. Tersteegen *et al.,* "Potentials and levels for the electrification of space heating in buildings," ENER C1 2019-2481, 2013.

[20] B. Pfluger, "Assessment of least-cost pathways for decarbonising europe's power supply: A model-based long-term scenario analysis accounting for the characteristics of renewable energies," Ph.D. dissertation, Karlsruher Institut für Technologie, 2014.

[21] B. Lux, "Supplying Europe with Hydrogen and Negative Emissions – A Model-Based Assessment," Ph.D. dissertation, Karlsruher Institut für Technologie, 2023.

[22] The Danish Energy Agency, Ed., "Technology Data for Generation of Electricity and District Heating," Energistyrelsen, Copenhagen, Jun. 2022. [Online]. Available: https://ens.dk/en/analyses-and-statistics/technology-data-generation-electricity-and-district-heating