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Rethinking Spatial Potential Analysis with New Data: Integrating Supply, Demand, and Implementation Criteria in Municipal Heat Planning

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1 ABSTRACT

The ongoing energy transition is reconfiguring socio-technical structures and places particular pressure on the heat sector, where decentralized, building-integrated systems and district heating networks must increasingly replace fossil-based infrastructures. Municipal Heat Planning has therefore emerged as a central, though nonbinding, planning instrument for translating national climate targets and legal frameworks into spatially explicit strategies at the local level, yet current practice still relies predominantly on generic, model-based potential estimations that offer limited decision support for feasibility-oriented implementation. Existing potential analyses often emphasize theoretical and technical potentials, lack a clear distinction between source and demand, and insufficiently integrate spatial feasibility criteria such as distances, environmental constraints, land availability, and property rights, which contributes to a persistent gap between potential studies and subsequent feasibility analyses. This study examines how potential-based approaches in Municipal Heat Planning can be conceptually and methodologically refined to more accurately reflect real-world implementation conditions. It combines a systematic literature review with a document analysis of existing municipal heat plans. Furthermore, semi-structured expert interviews are conducted to deepen the understanding of data-related challenges, potential analyses, and barriers in heat planning.

Building on these insights, the study develops a two-stage, potential analysis framework in which a generic, preselection using open geodata provides a transparent spatial screening of heat sources, while a second, municipality-oriented stage systematically integrates local data, ownership structures, obstacles, and project synergies to prepare feasibility studies. By structuring the potential taxonomy, screening spatial criteria, and embedding them in a reproducible geoprocessing workflow, the framework shifts Municipal Heat Planning from generic potential estimation toward a feasibility-oriented, data-driven, and context-sensitive methodology that strengthens the methodological foundations of municipal heat planning, supports evidence-based prioritization of interventions, and improves transparency and comparability across municipalities.

Keywords: Energy Transition Planning, Renewable Energy Potentials, Spatial Feasibility Assessment, Multi-Criteria Decision Analysis (MCDA), Transformation Governance

2 INTRODUCTION

Energy supply constitutes the structural backbone of modern societies, yet for a long time it has been shaped by centralized fossil and nuclear resources. This configuration is increasingly under pressure, as it is neither environmentally sustainable nor resilient in the long term. The required transition extends far beyond technological innovation; it also necessitates a fundamental rethinking of institutional routines, infrastructural path dependencies, and political steering mechanisms (PRAEGER 2025; BECKER et al. 2022). In the scholarly literature, this restructuring is conceptualized as a comprehensive transformation process unfolding within the tension between established regime structures and emerging niche solutions. Spatial dimensions play a central role in this process. The energy transition not only alters technologies but also reshapes spatial patterns of energy provision, shifting from large-scale power plants toward decentralized systems, thereby constituting a paradigmatic change in spatial organization (ENGELMANN et al. 2021).

In addition, the transformation is characterized by a mismatch across spatial scales, as federal targets impose requirements that often conflict with municipal realities marked by limited financial resources and a shortage of qualified personnel. At the same time, governance structures are changing, leading to an expansion and reconfiguration of local action spaces. This governance shift is increasingly reflected in planning processes that involve multiple stakeholders coordinating their actions toward shared objective (ROHRACHER 2022).

The heat transition is particularly critical and challenging in this context. First, the heat sector accounts for the largest share of total energy consumption in Germany, exceeding 50 % of overall demand (BRUECKMANN and EIGENDORF 2025). Second, the transformation of highly localized, fragmented, and building-specific infrastructures toward renewable heat sources constitutes a complex and resource-intensive endeavor. Especially in urban contexts, district heating networks are considered a key infrastructure for integrating such renewable heat sources. In this process, technical challenges intersect with organizational, economic, and social tensions, rendering heat supply a systemic focal point of the broader energy transition (ENGELMANN et al. 2021; SIEBEKING et al. 2025). Following MOELDERS 2022, derived from WBGU 2011, Municipal Heat Planning (MHP) can be epistemologically assigned to Transformation Planning (ToP), incorporating elements of Transformative Planning (TvP), as illustrated in Figure 1.

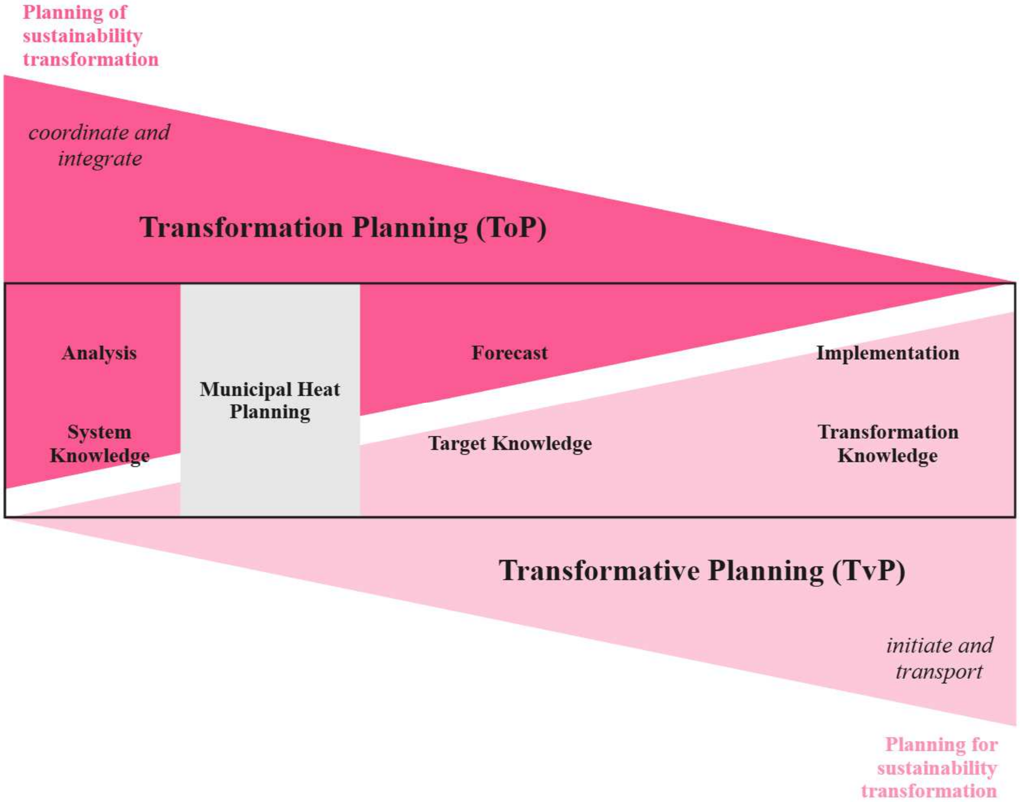

Fig. 1 MHP in transformation planning (ToP) and transformative planning (TvP) adapted according to MÖLDERS (2022)

Accordingly, it corresponds to the planning type described by MOELDERS (2022) as transformation planning. This approach is understood as a goal oriented restructuring process. It relies on analyses, scenarios, a defined transformation pathway, and an action plan. Genuinely transformative elements emerge only selectively through participation and co-production formats. However, they do not constitute the conceptual core. MHP establishes strategic guiding principles; yet, it achieves transformative effects only when supported by robust quantitative decision making foundations.

Municipalities play a central role in this context. Their proximity to local conditions and structures enables the targeted management and translation of climate objectives related to emissions reductions in the heat sector into spatially relevant infrastructure considerations. At this point, municipal heat planning, which functions as an informal planning instrument, becomes relevant. Its purpose is to systematically identify and assess suitable potentials and convert them into viable supply solutions, balancing technical feasibility, spatial suitability, and local or aesthetic acceptance. The results produced form the strategic framework for a municipality's heat transition, which, since early 2024, has been supported by two pieces of legislation: the Building Energy Act (Gebäudeenergiegesetz – GEG) and the Heat Planning Act (Wärmeplanungsgesetz – WPG) (GEG 2020; WPG 2024). The WPG, and in particular its regional implementations, establishes a legal framework with indirect legal effect, representing a hybrid planning instrument: it is not formally binding like zoning plans, but it carries indirect legal influence through the GEG (§ 71), which links new construction standards to municipal heat planning outcomes (BRUECKMANN and EIGENDORF 2025).

Within this process, municipal heat planning functions as a planning interface, connecting overarching policy objectives with concrete local implementation.

One of the central components for addressing future energy challenges is potential analysis. Potential analysis refers to the process of systematically assessing the potentials for heat generation from renewable energy sources within a planned area (ORTNER et al. 2024). Currently, such analyses are conducted based on guidelines that provide only a general description of area screening, technology-specific information sources, and potential calculations. In other words, there is currently no methodologically consistent framework that ensures the quality of potential analyses. Initial findings indicate that it is increasingly effective to focus less on comprehensive, model-based quantification of all theoretical potentials and more on the assessment of heat sources that are realistically accessible and implementable (FUCHS et al. 2025; HERING et al. 2025). This paper addresses this gap and focuses on the following research questions in the field of spatial transformation and governance studies within municipal heat planning:

(1) Conceptual: How can potential-based approaches be refined and operationalized to account for source, demand, and spatial feasibility in real-world applications?

(2) Governance: How do key stakeholders perceive the tension between theoretical potential and practical feasibility, and which criteria do they consider most critical for the successful implementation of projects?

The literature reveals a predominant focus on theoretical-technical potentials, while the distinction between source and demand potentials often remains unclear. Moreover, most heat plans lack a consistent methodological integration of spatial criteria, such as vertical and horizontal distances, obstacles, suitable corridor spaces, soil and subsurface constraints, or property rights. The linkage between spatially available energy resources and heat demand areas has also been insufficiently addressed. Current analytical practices are largely shaped by individual generic models, which offer limited transparency due to non-uniform baseline parameters (AMMON and THIELE 2025) and frequently exhibit significant discrepancies between potential analyses and feasibility studies. Against this backdrop, the present study aims to develop a methodological advancement of potential analyses and their taxonomy for transformative planning, grounded in current literature and based on expert knowledge.

3 METHODS

To address the research questions, the study employs a qualitative method design, based on four core components: a literature review including document analysis of gray literature, existing municipal heat plans and potential assessments, semi-structured expert interviews, data evaluation, and the development of a Potential Analysis Framework (PAF) (BOGNER 2014; CRESWELL and CRESWELL 2022). The aim is to classify the potential concepts and spatial potential scales discussed in the literature, identify common methodological practices, and compare them with empirical insights from planning practice. The following figure illustrates the methodological workflow:

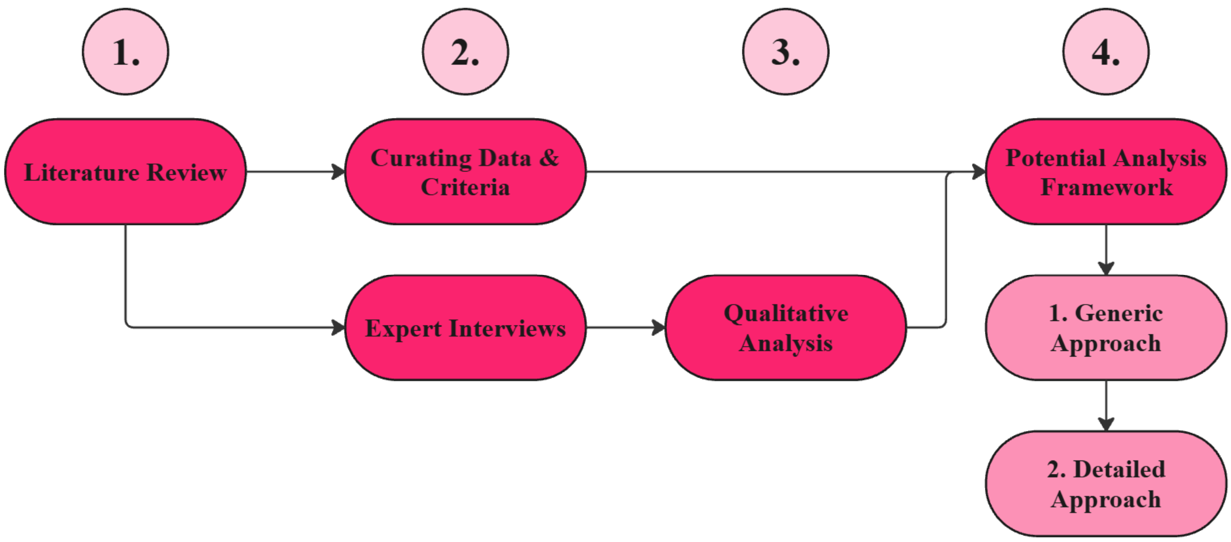

Fig. 2 Graphical representation of the methodological approach

In a first step, relevant literature was reviewed to disentangle different concepts of potential and their hierarchical organization (taxonomy), including theoretical, geographical, technical, ecological, temporal, and spatial potentials, as well as the distinction between source and demand potentials. Based on this review, a tabular overview of potential levels was created, accompanied by a figure illustrating their spatial differentiation. In parallel, a document analysis was conducted on gray literature, municipal heat plans, and additional potential assessments to capture the method sets, model structures, and data requirements employed in practice.

Second, semi-structured expert interviews were conducted with stakeholders from municipalities, engineering firms, energy providers, and state authorities. The interview design combined a pre-structured guide, with open-ended follow-up questions to capture technical, procedural, and interpretative dimensions of knowledge (BOGNER 2014; HELFFERICH 2022). A purposive expert sampling strategy was applied, selecting the participants based on predefined competency domains derived from an independent review of professional role profiles, with demonstrated expertise in the municipal heat planning process and potential analysis (BOGNER 2014). The participants were primarily from the Bavarian region. Thematic saturation was reached following the completion of the interviews, as no additional argumentative patterns emerged. Furthermore, the pairwise comparisons indicated only minor deviations in the resulting weights. All interviews were conducted online, recorded with participants' consent, and transcribed verbatim. Qualitative data analysis was performed using MAXQDA (version 24.6.0) following the simplified procedures proposed by DRESING and PEHL (2018) and KUCKARTZ et al. (2008). To validate the category structure, a trial coding was conducted before the entire interview corpus was analyzed deductively and subsequently enriched with inductive subcategories (KUCKARTZ and RAEDICKER 2024).

In parallel, the open data landscape of Bavaria was systematically examined with regard to data findability and accessibility, in accordance with the FAIR principles (Findability, Accessibility, Interoperability, and Reuse of digital assets) (WILKINSON et al. 2016; GO FAIR 2026). The evaluation focused on the following spatial criteria: (1) spatial distribution of heat demand, (2) horizontal distance between heat sources and demand, (3) proximity to the electrical grid, (4) vertical gradient between heat sources and demand, (5) protected areas and landscape conservation, (6) land-use planning regulations, and (7) heat sources, as detailed in Table 2 (BAVARIAN ENVIRONMENT AGENCY 2026; OPEN BYDATA 2026).

The findings from the literature review, document analysis, and expert interviews form the basis for developing a two-stage geoprocessing workflow within the framework of a potential analysis. Stage 1 focuses on a robust, generic pre-selection of promising heat sources – through semi-automated GIS-based modeling – using the defined criteria 1–7. Open data structures are employed for this purpose. This first stage, referred to as the pre-selection, aims to provide a transparent, quantitative justification for excluding certain sources.

In Stage 2, the heat sources identified as promising are analyzed in greater detail and enriched with local knowledge, existing data structures, and additional spatial parameters. These include obstacles along potential routes, property rights, synergies with planned construction projects, and surface- and subsurface-related constraints. The objective is to establish a realistic and well-documented foundation for subsequent feasibility studies of district heating networks, thereby enabling a methodological refinement of the potential analysis within municipal heat planning processes.

4 LITERATURE REVIEW

"The theoretical potential of a renewable energy source is the starting point for a potential assessment, but it is not practical for decision-making and planning." This statement forms the conceptual foundation for contemporary renewable energy potential analyses (ARIAS-GAVIRIA et al. 2020, p. 308). In the literature, renewable energy potentials are commonly differentiated into theoretical, geographical, technical and economic levels. Theoretical potential describes the maximum energy flux inherent in a resource, without considering spatial, ecological or technological limitations. Geographical potential reduces this value by excluding areas that do not meet minimum biophysical requirements, for example minimum wind speeds or solar radiation thresholds. Technical potential reflects additional constraints arising from conversion efficiencies, site-specific conditions and environmental regulations, while economic potential represents the fraction of the technical potential that is cost-competitive relative to relevant alternatives (ARIAS-GAVIRIA

2020; DE VRIES et al. 2007). DE VRIES et al. (2007) highlight that potential values often appear "objective", although they strongly depend on assumptions regarding average conditions, technological development and socioeconomic trends. Furthermore, geographical, environmental, social and economic restrictions can reduce theoretical potentials by up to two orders of magnitude, which underscores the need to rely on realistic potentials for planning processes (MORIARTY and HONNERY 2016). In thermal energy studies, this hierarchy is complemented by definitions of usable or practical potentials, which in this study are summarised as the realizable potential. This level accounts for ecological and legal constraints as well as the spatial and temporal match between the availability of thermal resources and the actual heating demand. It therefore reflects the share of the economic potential that can be integrated into real energy systems under existing regulatory conditions and demand patterns. The following table presents selected references that address these different potential levels and illustrates how the individual conceptual layers are applied across the literature.

Reference	JUNG et al. 2022	FUCHS et al. 2025	KALTSCHMITT et al. 2020	ORTNER et al. 2024	ARIAS-GAVIRIA 2020	DE VRIES et al. 2007
Application source	Single-Source	Multi-source	Macro-scale	Multi-source	Single-Source	Macro-scale
Theoretical potential	√	√	√	√	√	*
Geographical/Spatial potential	√	√		√	√	√
Environmental potential	√	√		√	√	
Technical potential	√	√	√	√	√	√
Temporal potential	√	√		√		
Legal potential		√				
Sustainable potential			√			
Economical potential			√	√		√
Realizable Potential			√	√		√

* "has not much practical value so we leave it out here" DE VRIES et al. 2007, p. 2591

Table 1: Different uses of potential terms in literature.

The literature review indicates that partially different terminologies are used to describe the same analytical levels. Therefore, Figure 3 should be understood as a synthesis and regenerate the taxonomy of the underlying semantics. It illustrates the pathway of potential assessment from an initial theoretical concept or potential toward practical, realizable relevance in spatial and planning contexts.

A review of German-language literature shows that it increasingly incorporates the more differentiated potential layers established in international research. The theoretical potential of a renewable energy resource defines the maximum energy that could be harnessed within a specific region during a given time period, constrained only by physical laws. Within this context, it is important to distinguish between source and demand potentials. Theoretical source potential refers to the portion of this energy that could be provided under technical-structural constraints on the source side. In contrast, demand potential represents the fraction of this energy that can realistically be utilized by end-users, considering temporal mismatches between resource availability and heating demand, as well as distribution losses (KALTSCHMITT et al. 2020). Although these aspects are sometimes implicitly addressed through generic criteria, they are not yet systematically conceptualised in studies. Moreover, no consensus has emerged in the literature regarding how potential assessments should be conducted, which hierarchical levels they should include and where the methodological boundary to feasibility studies lies. Moreover, the interactions and feedbacks between the different potential levels have so far received little attention, and a clear delineation between these levels remains difficult to establish. This lack of standardisation continues to challenge comparability across studies and highlights the need for clearer methodological frameworks in future research.

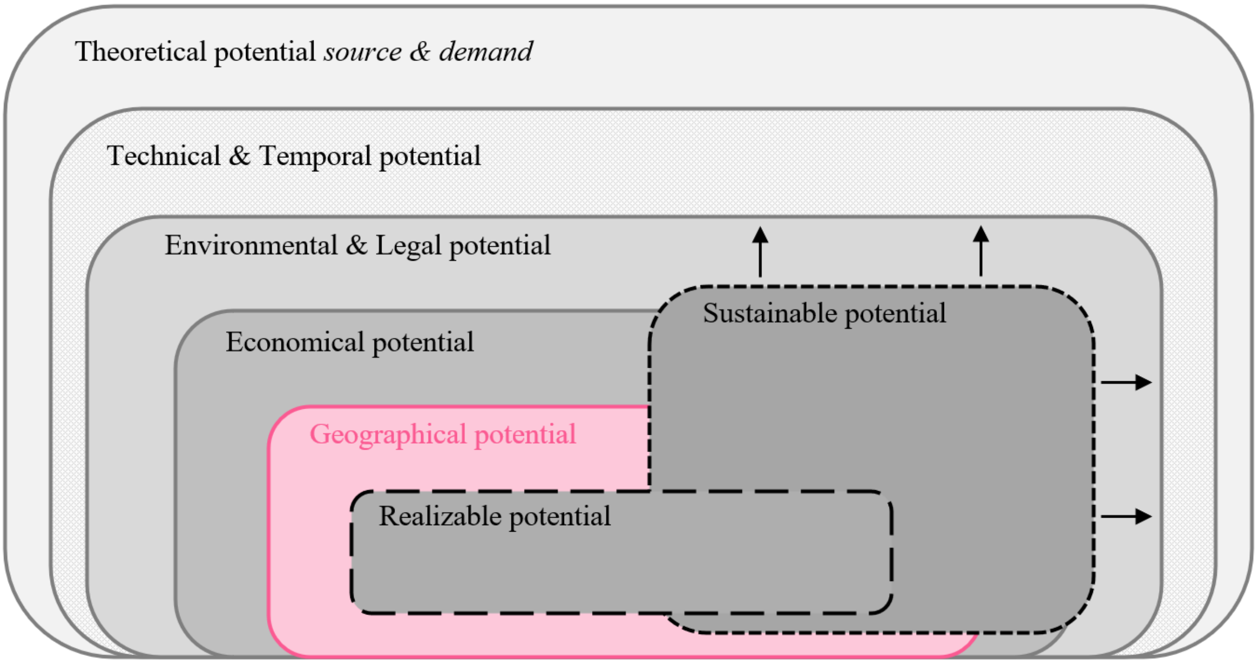

Fig. 3: Distinction between the different concepts of potential layers based on KALTSCHMITT et al. 2020.

The national heat planning guideline defines the analytical objective as "a sufficiently accurate estimation of the potentials for heat generation from compatible energy sources, as well as the potentials for energy savings through the reduction of heat demand within the designated planning area" (ORTNER et al. 2024, p. 58). In line with this objective, the available potentials are to be quantified separately by energy carrier and represented in a spatially differentiated manner, thereby providing an evidence base for subsequent scenario development and zoning. To this end, municipalities are advised to conduct an initial spatial screening that identifies areas subject to regulatory or land-use constraints (for example, nature conservation or water protection zones) and, where necessary, areas requiring explicit land reservation (for instance, for open-field solar thermal systems), in order to delineate viable options at an early stage. Building on this screening, the guideline recommends the systematic analysis of the following options: deep and shallow geothermal energy, groundwater and environmental heat, wastewater heat recovery, open-field solar thermal, biomass, locally produced hydrogen, and the utilization of unavoidable waste heat; options for central thermal energy storage; and potentials for reducing building and process heat demand through efficiency and demand-side measures (ORTNER et al. 2024).

5 RESULTS

The key findings from the literature, expert interviews, and data/criteria curation are systematically presented, analyzed and transferred to the PAF:

Renewable energy studies consistently distinguish between theoretical, geographical, technical, and economic potentials, yet these levels vary widely depending on underlying assumptions and contextual constraints. Recent literature also highlights the growing relevance of realizable potentials, which incorporate legal, ecological, and demand-related factors to better reflect real-world system integration. However, the lack of standardized definitions, limited treatment of source-demand distinctions, and minimal attention to feedbacks between potential levels continue to hinder methodological consistency across studies.

Document analysis indicates that more than half of German municipalities have now initiated municipal heat planning, and a growing share is explicitly planning to expand or newly develop district heating networks as a central pillar of future heat supply. At the same time, many plans assume significantly higher annual renovation rates than observed historically, typically around 2 % instead of the previous level of below 1 %, which underscores the key role attributed to building refurbishment in reducing heat demand that must subsequently be supplied by renewable sources identified through potential analyses. However, the comparability of existing heat plans remains limited, as there is no binding standardization and even fundamental indicators are reported in divergent ways, making it difficult to assess ambition levels and outcomes across municipalities. This highlights the importance of systematic plausibility checks that scrutinize assumptions and results and help reveal potentially unrealistic or erroneous data (AMMON and THIELE 2025).

The qualitative findings from the interview formats confirm that Bavaria has a good geodata base for creating a municipal heating plan (RACK et al. 2025). However, there is still room for improvement in individual areas of potential data. This is particularly due to the fact that the open data strategy in Bavaria are making more and more data freely available (STMD 2025).

“The potential data sets are simply too sparse ...” [municipal utilities company]

In particular, it was pointed out that the greatest potential lies in the standardization of procedures, data formats, and criteria catalogs with threshold values.

“Variable quality due to lack of specification” [public stakeholder]

Moreover, the interviews indicate that heat planning documents increasingly report theoretical and technical potentials, which offer little practical value as decision-support for future scenarios.

“Often, only a ‘maximum load’ is reported, which effectively represents the technical potential alone.” [engineering firm]

This reinforces the perception among experts that many of the existing outputs are in fact partial potential estimations rather than full analyses in the strict methodological sense. In practice, some planners attempt to supplement openly available datasets with real-world operational data to strengthen the plausibility of the results and provide a more feasibility-oriented foundation.

“But when it comes to analyzing potential, we try to collect as much real data as possible because we place a strong emphasis on feasibility. […] For instance, in the case of biogas plants, we cannot simply rely on a generic dataset and assume that all existing installations are captured, that they will remain in long term operation, or that their technical condition is adequate, for example in terms of maintenance backlogs.” [engineering firm]

In summary, key criticisms in the interview format include insufficient data quality, high methodological heterogeneity, and a lack of spatial criteria integration. Critically, the dynamic interplay between source and demand potentials is rarely addressed, while the conceptual boundary between potential assessments and feasibility studies remains poorly defined. These ambiguities create significant challenges for aligning research outcomes with policy objectives and funding requirements, as essential data are often omitted or reported inconsistently, undermining the reliability and applicability of findings.

Based on the interview findings, a criteria catalog (see table 2) was developed that integrates insights from both the literature and expert discussions and combines them with accessible datasets.

While the initial literature-based criteria established a comprehensive framework for spatial assessment, expert consultations expanded this foundation by identifying five additional implementation-relevant criteria that depend on municipal-level data and thus cannot be systematically addressed through automated processes. These criteria include (8) property rights to required land, particularly open spaces, where feasibility is often constrained by ownership structures that lack publicly available datasets; (9) physical or administrative barriers between source and demand, such as conflicts with existing infrastructure or densely built environments that limit technical implementation; (10) synergies with ongoing construction projects, where coordination with planned initiatives (e.g., scheduled roadworks) could optimize resource use but requires access to non-public planning documents; (11) surface and substrate conditions, which differentiate between undeveloped land, sealed surfaces, or technical constraints like groundwater impacts or compatibility with heat infrastructure; and (12) social structures, encompassing socio-economic factors such as income distribution, demographic patterns, and community engagement, which significantly influence planning processes and public acceptance.

Based on the problem statements identified in the literature and in structured stakeholder dialogue formats, a two stage modeling framework was developed that explicitly accounts for the current state of data availability and the perspectives of relevant actors. The primary objective was to improve the robustness of baseline parameterization and the transparency of spatial potential assessments. The criteria catalog comprises seven core spatial criteria, which are assigned to the dimensions of heat source, demand structure, land availability, and spatial constraints. In this way, it provides a conceptual link between the theoretical levels of potential discussed in the literature and the practical constraints and planning related boundary conditions that are relevant in applied contexts.

Nr.	Criterion	Basic Data Type	Open Data Findability – Accessability	Potential Analysis Framework – PAF
1	Spatial distribution of heat demand	Raster	**F** √ **|** **A** √	1. Generic Approach
2	Horizontal distance between heat source and demand	Raster/ Vector	**F** √ **|** **A** √	
3	Proximity to electrical grid	Vector	**F** √ **|** **A** x*	
4	Vertical gradient between heat source and demand	Raster	**F** √ **|** **A** √	
5	Protected areas and landscape conservation	Vector	**F** √ **|** **A** √	
6	Land-use planning regulations	Vector	**F** √ **|** **A** √	
7	Heat source	Vector	**F** √ **|** **A** √	
8	Property rights to required land – Open Spaces	Vector	**F** √ **|** **A** √	2. Detailed Approach
9	Barriers between source and demand	Vector	**F** √ **|** **A** x/√	
10	Synergies with construction projects	Vector	**F** x **|** **A** x	
11	Surface and substrate condition	Raster	**F** √ **|** **A** x/√	
12	Social Structures	Raster/ Vector	**F** √ **|** **A** x/√	
	*Due to data protection concerns, access to grid data is severely restricted | √ = Yes; x = No			

Table 2: Potential analysis criteria in connection with data availability.

Certain criteria were deliberately excluded from the catalog because they are either not available at a sufficient spatial resolution, not generally accessible as geospatial data, or only indirectly represented through other indicators. This is particularly true for the technical dimension. Heat pump specifications, the efficiency of deployed technologies, temporal performance dynamics, and environmentally relevant threshold values cannot be consistently captured using a generic spatial approach due to limited availability of open data and the highly location-specific nature of the required information. The criteria catalog is based on a transparent and reproducible scoring approach derived through pairwise comparison, which accounts for both data availability and the relevance of each criterion with respect to municipal heat planning.

Based on the availability of open data, a spatial potential analysis is conducted as an initial step using a generic approach in order to identify and filter the most relevant heat sources. Wherever possible, the open input datasets are ground-truthed and refined using municipal data to enhance the validity and robustness of the results.

Subsequently, a second step is carried out using a more detailed but time-consuming data collection and verification approach. In this phase, local knowledge and locally available information on promising heat sources that are not accessible through open data are systematically integrated and quantitatively assessed. Based on this enhanced data basis, targeted strategic recommendations are derived within the framework of municipal heat planning.

Figure 4 illustrates the two-stage PAF. The municipal, implementation-oriented stage is highlighted using a more saturated color, whereas the generic, spatially aggregated approach is represented with a less saturated color.

The proposed two-stage PAF directly addresses the gaps identified in current practice by providing a structured pathway from generic assessments toward more context-specific feasibility considerations. The implications, limitations, and regional transferability of this approach are examined in the subsequent section.

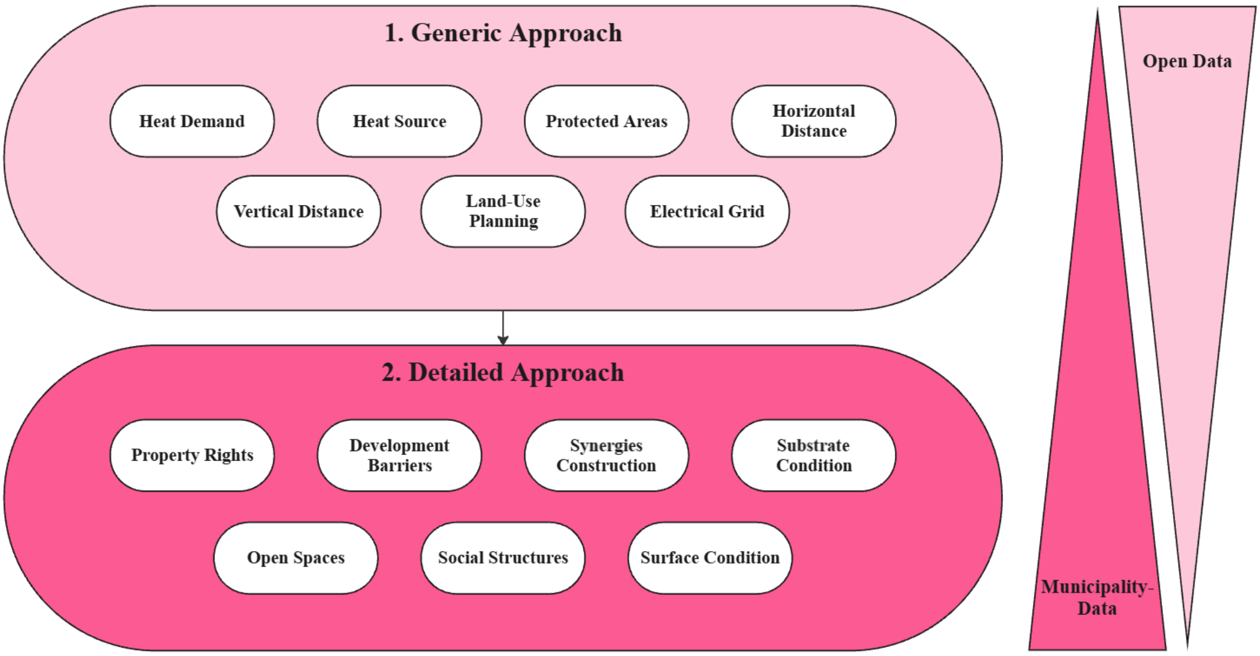

Fig. 4: Potential Analysis Framework – PAF with a focus on spatial criteria and geodata.

6 DISCUSSION

Municipal Heat Planning is a new, nonbinding planning instrument in Germany that aims to support the targeted transformation of local heat supply systems through analyses, scenarios, and transformation pathways combined with an action catalog at a strategic planning level. Certain components, such as participatory formats and the integration of target knowledge, can be clearly assigned to the field of transformative planning. However, the literature review indicates that the guidelines accompanying the legislation do not provide a structured roadmap explaining how municipalities are expected to arrive at informed decision processes for specific energy sources or potentials. Similar findings were reported by FUCHS et al. (2025), who show that the methodological toolkit for potential analysis is not systematically represented within the current legal framework. In view of the tight timeline for Germany's decarbonization targets, it is therefore essential to structure the development of low temperature heat sources in a transparent, traceable, and feasibility oriented manner. FUCHS et al. (2025) proposed an independent concept that evaluates low temperature heat sources using a simplified indicator based approach, focusing on technical potential combined with initial cost assumptions. While this approach primarily addresses technical aspects, it does not explicitly capture the feasibility oriented dimension of geographic potential. This is where the present article contributes by integrating open geodata with municipal data and local knowledge to enable a more holistic analysis. The objective is to move beyond currently applied potential estimations and to actively support transformative planning processes. The methodological framework builds on the spatial criteria proposed by JUNG et al. (2022), KAMMER (2018), LUND and PERSSON (2016), as well as NEUGEBAUER et al. (2015), who address the relationship between heat demand and heat sources through horizontal and vertical distance measures in combination with minimum heat demand thresholds for district heating systems and settlement structures. The criteria catalog was deliberately expanded to include environmental planning aspects and additional factors that are highly relevant from an implementation perspective.

The expert interviews conducted in this study substantiate the ongoing discussion surrounding MHP potential analyses and their discrepancy with subsequent feasibility studies. The experts critically assess completed heat plans, emphasizing that they often lack sufficient spatial and technical resolution. This shortcoming reveals a fundamental tension between the intended strategic steering function of MHP and the actual decision-making capacity derived from current potential analyses. As a consequence, additional feasibility studies are frequently initiated to perform final evaluations and to prioritize heat source options. However, this step should represent a core outcome of the potential analysis itself, indicating that the original objective of the analysis is not fully achieved. Moreover, the experts highlight the insufficient consideration of interdependencies between heat sources and heat demand. In this context, a stronger cross-energy-carrier harmonization of data foundations with relevant federal guidelines and regulations would be a viable first step. While some data are available through public portals, the accessibility of municipality-specific data, particularly those essential for implementation-focused planning, remains limited. Similar findings were reported by HERING et al. (2025), AMMON and THIELE (2025).

With respect to the research questions posed, the results indicate that the previous potential analysis approach can be further optimized using the two-stage PAF. Furthermore, the use of automated geodata processes enables a targeted optimization of resource allocation and allows focus on relevant planning questions while incorporating real-world data. Initial guidelines, such as the MHP-Guideline, have already identified preliminary structures and weaknesses (ORTNER et al. 2024). However, overarching elements such as the definition of criteria thresholds or the systematic embedding within a taxonomy-based framework, remain incomplete and require further methodological refinement. Building on these findings, several avenues for subsequent methodological development can be identified. At the same time, improving the underlying data requires the harmonization of existing models and the development of standardized procedures to enhance the comparability and transferability of results. In particular, digitalization opportunities, such as the deployment of a Digital Urban Twin, offer potential to increase the efficiency of planning processes and enhance support for diverse stakeholders (LEHTOLA et al. 2022). Current research demonstrates that novel heat planning digital twin frameworks can only realize their full potential if municipalities possess a clear understanding of their data structures and maintain adequate in-house expertise (DREIER et al. 2026).

Our findings provide evidence that methodological approaches need to be further refined. This particularly involves investigating feedbacks between different potential layers and evaluating weightings through development processes in case studies. Additionally, refining numerical criteria based on existing heat and energy usage plans, as well as implemented projects, is essential to derive robust functional benchmarks. A similar need exists for cooling and electrical urban planning, enabling these domains to be more strongly integrated in a data- and criteria-driven manner in the future. Overall, the transferability of these approaches to other federal states or municipalities outside Bavaria should be carefully evaluated, particularly with respect to data availability.

7 CONCLUSION

In this study, a two-stage potential analysis framework was developed through a combination of literature review, expert interviews and geodata curation. The application of this two-stage quantitative framework transforms the previously generic approach into a feasibility-oriented methodology. By systematically using spatial criteria, the framework captures the complex interplay between heat sources and heat demand in relation to district heating networks. The integration of site and context-specific expert knowledge in the second stage provides empirically grounded decision support for municipal planning actors. This enables municipal heat planning to shift from a reactive coordinating function to a proactive initiating role in the transformation toward climate-neutral heating systems.

By combining spatially explicit data with qualitative expert insights, the framework supports a structured, transparent, and reproducible approach to identifying feasible heat sources. This addresses a key gap identified in previous studies, where potential analyses often lacked sufficient spatial resolution, requiring additional feasibility studies. By focusing on both geographical potential and contextual feasibility, the proposed framework strengthens the methodological foundation of municipal heat planning, enabling evidence-based prioritization of interventions and efficient allocation of planning resources.

8 ACKNOWLEDGEMENTS

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