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Stakeholder-informed multi-criteria decision-making for sustainable heat supply

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ABSTRACT

The heating transition presents municipalities with the challenge of integrating technical, economic, and socially acceptable aspects into the planning and implementation of climate-neutral heating systems. This paper introduces a Multi-Criteria Decision Analysis (MCDA) approach to support heat planning processes. The goal is to facilitate investment decisions by incorporating the priorities of various stakeholders and evaluating heating supply options based on a shared factual basis. At the same time, conflicts of interest are identified and addressed. The developed decision-making model consists of six steps, including the selection and weighting of criteria as well as the evaluation of alternative scenarios. The methodology was applied within the WAERMER project, supported by stakeholder participation and a prototype interactive visualization. The evaluation is based on twelve quantitative and qualitative criteria across the categories of environment, economy, technology, and social compatibility. Using a case study in an urban district of a mid-sized city in Northern Germany, scenarios were compared to identify optimal solutions for heat supply. The paper illustrates how a participatory MCDA process can support municipal heat planning by making stakeholder priorities visible and enabling transparent scenario evaluation. While implementation remains context-dependent, the structured approach lays a foundation for informed and socially accepted planning decisions.

Keywords

Heat transition;
Decision support tool;
Multi-Attribute Decision-Making;
Social acceptance;
Municipal heat supply

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1. Introduction

The heating transition is a key component of the energy transition and is critical for achieving climate protection goals, particularly in Europe and Germany, where approximately 70% of final energy consumption within private households is attributed to space heating [1]. Currently, most of this consumption relies on fossil fuels, while renewable energies account for only around 16.9% [2], highlighting the urgent need for structural changes and the expansion of renewable energy sources such as geothermal and solar thermal energy.

Municipalities play a central role in this transformation. According to the Heat Roadmap Germany and broader European planning initiatives, local authorities are key in implementing integrated, cost-effective, and socially inclusive decarbonization strategies [3]. However, planning must balance technical feasibility, economic efficiency, and social acceptance. This is complicated by diverging interests: municipalities prioritize public welfare, network operators focus on profitability, and householders emphasize affordability and reliability.

Studies show that societal acceptance significantly affects the successful implementation of heating projects [4]. Place attachment and identity, for example, can provoke opposition when changes are perceived as disruptive, making early and respectful stakeholder engagement essential [5]. Particularly for vulnerable groups, such as residents of low-income households, equitable

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participation and tailored financing models are needed to ensure that the heating transition does not exacerbate existing inequalities [6].

The Multi-Criteria Decision Analysis (MCDA) approach was chosen to support decision-making in a context characterized by conflicting goals, long-term implications, and diverse stakeholder interests. Its primary objective was to structure this complexity and facilitate a transparent evaluation of supply scenarios from environmental, economic, and social perspectives. The MCDA results were used to identify heat supply options that align with stakeholder preferences and serve as a basis for further planning steps. Target groups included municipal decision-makers, planners, and local stakeholders such as network operators and residents.

Traditional planning approaches often fall short in integrating these varying priorities and dealing with data uncertainty. Moreover, the success of transformation strategies relies not only on technical or economic performance but also on stakeholder acceptance, which strongly influences implementation outcomes. Therefore, new planning approaches are required that support informed, inclusive, and comprehensible decision-making processes.

This paper proposes a participatory MCDA framework for municipal heat planning, developed and tested in the WAERMER project. It combines quantitative and qualitative criteria and integrates stakeholder perspectives through workshops and interactive visualization tools inspired by the Decision Theatre approach [7].

The case study district, in a mid-sized Northern German city, comprises around 500 residential buildings with approximately 1,300 inhabitants and a total heat demand of about 15,000 MWh per year. Due to its infrastructural characteristics and exclusion from the central district heating network, the area currently relies on decentralized gas heating. It was selected as a representative example for many urban districts in Germany facing similar challenges, including ageing infrastructure, refurbishment needs, and diverse ownership structures.

The district level was deliberately chosen as the focus of analysis, as it provides an effective planning scale between the building and city levels. While building-level approaches may lack system-level integration, and city-wide assessments often generalize local specifics, the district level enables a context-sensitive yet holistic evaluation of heating supply options.

This paper is structured as follows: Section 2 reviews the current state of research and identifies the remaining gaps. Section 3 introduces the methodological approach. Section 4 presents the case study and results. Section 5 discusses the findings and limitations. Section 6 concludes with an outlook.

2 Participatory multi-criteria approaches in heat planning

Municipal heat planning involves navigating complex and often conflicting technical, environmental, economic, and social considerations. Traditional approaches have struggled to integrate these diverse dimensions in a systematic and participatory way. Multi-Criteria Decision Analysis (MCDA) provides a structured approach to support decision-making under these conditions by allowing for the evaluation of alternatives using multiple, often non-commensurable, criteria [8].

MCDA has been widely applied in the field of sustainable energy planning. A comprehensive review by Wang et al. [9] identifies its value in comparing energy technologies and scenarios under uncertainty and incomplete data. Similarly, a systematic review of city energy-system modelling highlights that participatory and societal aspects remain underrepresented, pointing to the need for approaches that integrate stakeholder perspectives more explicitly [10]. In addition, Lahdelma et al. [11] emphasized the importance of MCDA for addressing stakeholder preferences in environmental planning, highlighting the method's capacity to facilitate inclusive and transparent decisions.

Recent research stresses that MCDA methods should not only provide analytical rigor but also address socio-political dynamics in planning processes. Banville et al. [12] argue for a more consistent integration of stakeholder perspectives, stating that MCDA methods often neglect the socio-political dimension of decision-making and calling for stakeholder-centered MCDA (SMCDA) approaches to better manage conflicts and improve legitimacy.

Gustafsson et al. [13] underline that the legitimacy and impact of local energy strategies depend significantly on the breadth and continuity of stakeholder participation. They caution that insufficient external involvement can limit both acceptance and implementation, especially when municipalities rely solely on internal planning departments.

Similarly, Neves et al. [14] propose a holistic methodology that combines energy service-oriented modeling with participatory evaluation procedures, demonstrating how stakeholder values can be systematically integrated across the full planning cycle. Complementary process protocols show how structured stakeholder involvement can be institutionalised in local energy and climate planning frameworks [15]. Beyond methodological considerations, stakeholder mapping studies underline the importance of actor networks and governance structures in shaping energy-sector transitions [16].

At the same time, methodological challenges persist. Wilkens [17] noted issues in integrating quantitative and qualitative data, addressing data uncertainty, and systematically incorporating stakeholder interests. Østergaard [18] further emphasizes the need to carefully define optimization criteria in MCDA applications, as the chosen criteria can significantly influence outcomes, particularly when assessing renewable integration pathways.

In parallel, tool-supported approaches such as open-data heat mapping have been proposed to strengthen municipal and district-level energy planning under conditions of uncertainty [19]. Advanced MCDA applications have also explored hybrid methods such as BWM and VIKOR to support technology selection under uncertainty [20]. Yet, these contributions typically remain focused on technology-level assessments rather than systemic, participatory planning contexts.

In the context of renewable energy planning, studies such as Lee et al. [21] and Delgado & Romero [22] have used MCDA to evaluate siting and technology options under local constraints. However, few applications have explicitly addressed the scale of urban districts as units of analysis, despite their relevance for municipal infrastructure transformation. Estévez et al. [23] stress that more empirical applications are needed that integrate participation meaningfully and adapt MCDA methods to local planning contexts.

Therefore, this study aims to address these gaps by applying a participatory MCDA in a real-life planning process at the district level, integrating a broad range of quantitative and qualitative criteria, and emphasizing stakeholder engagement through visual and structured dialogue formats.

3. Developing and applying a stakeholder-based evaluation model

This section outlines the methodological framework used to evaluate the heating scenarios. It covers the process of identifying evaluation criteria in collaboration with stakeholders, the development of alternative heat supply scenarios, and the application of a multi-criteria evaluation model. Each step is detailed in the following subsections.

3.1 Selection of Criteria and Stakeholder Involvement

To evaluate the five heating supply scenarios, a structured participatory MCDA process was implemented. It consisted of two half-day workshops with 10-15 participants from four key stakeholder groups: (1) municipal administration, a local bank, and an engineering firm, (2) residents of the target neighborhood, (3) representatives of the utility company and a potential heat network operator, and (4) a craftspeople representative from the Chamber of Industry and Commerce (present only in the first workshop).

The first workshop, referred to as the “Criteria and Measures Workshop”, aimed to identify relevant evaluation dimensions for heat planning. Following an introduction to the project goals, participants developed potential evaluation criteria and transformation measures in moderated discussions. The process was facilitated by the research team using short expert inputs and joint clustering.

The results were documented, synthesized, and subsequently refined by the interdisciplinary team into twelve final evaluation criteria, drawing on both stakeholder input and established planning guidelines [24]. This process resulted in a final set of twelve evaluation criteria, divided into six quantitative and six qualitative dimensions as follows:

Quantitative Criteria:

1. GHG emissions (GHG): Amount of greenhouse gases emitted in GHG equivalents to meet the end energy demand
2. Primary energy demand: Total energy required to meet the heat demand, considering conversion and transmission losses
3. Share of renewable energy: Proportion of renewable energy in the total demand for heat supply
4. Levelized costs of heat (LCOH): Heat generation costs for households, including initial investments and operational costs
5. Infrastructure economy efficiency: Costs of supply systems, including capital, operational, and consumption-bound costs, based on VDI 2067 [25]
6. Expected investment willingness: Willingness of building owners to invest in heating technology, estimated using an agent-based model [26]

The criterion Expected investment willingness was derived from results of an agent-based model developed by Digel et al. [26]. The model simulates household decision-making in heating system replacement. For this study, specific scenario-based results were provided by I. Digel (personal communication, April 2024) and subsequently adapted for integration into the multi-criteria evaluation.

Qualitative Criteria:

1. Operational comfort: Importance of straightforward and low-maintenance operation
2. Regional value creation: Contribution of investments to the local economy
3. Future viability: Technical failure risks and lock-in effects over the system's lifespan
4. Planning security: Predictability and stability of costs, including electricity, investments, and operating expenses
5. Installation effort: Effort required for system installation and building modifications
6. Household autonomy: Degree of independence of households from external supply providers

Before the second workshop, the five supply variants were designed and evaluated by the project team using the defined criteria, combining quantitative (e.g., GHG emissions, heating costs) and qualitative (e.g., implementation effort) criteria. The second workshop, designed as a Decision Workshop, again included the same stakeholder groups and was moderated by a professional moderator. Following introductory presentations on the project objectives, the current state of the neighborhood, and the five modeled supply variants, participants were guided through the evaluation results.

Afterwards, participants assigned weights to the previously developed criteria using a digital polling tool. To ensure balanced influence in the final evaluation, each stakeholder group's weighting inputs were normalized to carry equal weight in the aggregated results, as required by the municipality. The weighted results were visualized after a short break to enable direct discussion and reflection. The workshop concluded with a moderated exchange on the most promising scenarios and remaining concerns.

3.2. Development of Scenarios

Taking into account available energy sources, regional climate targets, and stakeholder requirements, the research team developed five technically and economically feasible scenarios. These were grounded in detailed building-level data and aggregated to the district scale for system planning and cost estimation.

Specific heat demand values were estimated using the German residential building typology developed by the Institute for Housing and Environment [27]. The final energy demand per supply variant was calculated based on the assumed building-internal heating systems and the respective system efficiency factors according to Hauser et al. [28]. These results were used to size the respective technologies within each scenario.

For Scenarios 2, 3, and 5, geothermal borehole systems with a total capacity of around 5,000 kW_{th} and a central heat pump with 5 MW_{th} were assumed. Additionally, solar absorbers were included: approximately 18,000 m² in Scenario 2, 12,000 m² in Scenario 3, and 8,000 m² in Scenario 5. The data were aggregated to estimate infrastructure costs per scenario. The five scenarios are:

1. Connection to a district heating network (DH): Integration of a nearby district heating network primarily utilizing natural gas and waste [27].
2. Low-temperature local heating network (LTLH): Deployment of an energy-efficient low-temperature network using geothermal and solar thermal energy.
3. Cold heating network with heat pumps (CHHP): Combination of a cold local heating network with heat pumps, utilizing geothermal and solar thermal energy.
4. Fully decentralized solutions (FD): Implementation of biomass boilers (20%) and heat pumps (80%) in a completely decentralized structure.
5. Combined heating solution (CHS): Local heating networks and decentralized systems coexist in the district to optimize the use of local resources.

The status quo reflects the current energy supply system, which heavily relies on fossil fuels. It represents the baseline for comparing the performance of alternative scenarios in terms of environmental, technical, economic and social criteria.

For the scenarios, the potential of solar thermal energy and geothermal energy was determined. Solar thermal energy served not only as a heat source but also for regenerating geothermal probes. Additionally, primary energy and emission factors were incorporated according to the Building Energy Act (GEG, Annexes 4 and 9), along with assumptions for economic calculations from the KEA Technology Catalogue [28]. CO_2 prices were based on the main scenario from the Projection Report [29].

3.3. Evaluation and Aggregation

The scenarios were evaluated using a Multi-Criteria Decision Analysis (MCDA) that combined quantitative and qualitative criteria. Quantitative indicators were normalized using Min-Max scaling to ensure comparability, transforming values to a scale from 1 (worst) to 5 (best). Where value ranges were narrow, a reference value method was additionally applied, using the local status quo as a benchmark to better reflect small differences.

Qualitative criteria were assessed using a five-point descriptive scale with clearly defined rating levels to reduce subjectivity. For example, "comfort" ranged from "high maintenance, requiring frequent inspections" to "low maintenance, reliable operation"; "future viability" ranged from "high risk of failure" to "no risk of failure, heat source always available."

Criteria weights were collected through a digital survey. Stakeholders' weightings were manually transferred to Excel and combined with the normalized scores to compute overall scenario ratings. This approach integrated objective data and subjective evaluations, contributing to a transparent and evidence-based decision process.

4. Scenario assessment based on stakeholder-weighted criteria

In the case study conducted in the urban district of a mid-sized city in Northern Germany, various heat supply scenarios for 2030 and 2045 were evaluated. The scenarios were assessed based on the criteria described in the preceding sections. The following section presents the results of the scenario evaluation and subsequent stakeholder weighting.

4.1. Scenario Evaluation

This section evaluates the five scenarios developed in the study. It is divided into quantitative and qualitative analyses, highlighting environmental, economic, technical and social aspects to identify the strengths and weaknesses of each scenario.

4.1.1. Quantitative Evaluation

The quantitative evaluation focuses on the environmental and economic aspects of the analyzed scenarios. The results for the years 2030 and 2045 are presented in comparison to the status quo to illustrate the impact of the various scenarios on primary energy demand, greenhouse gas emissions (GHG emissions), and levelized costs of heat (LCOH).

GHG emissions and primary energy demand vary considerably between the scenarios (see Figure 1). Scenarios 2 and 3, based entirely on renewables (e.g., geothermal, solar thermal), achieve near-zero emissions. Scenario 5 also performs well environmentally due to its hybrid approach with renewable-based networks and decentralized technologies.

In contrast, Scenarios 1 and 4 exhibit higher emissions. Scenario 1 is based on an existing district heating network that still predominantly uses natural gas, while Scenario 4 includes decentralized systems based on individual biomass boilers and heat pumps. The status quo scenario performs worst, still dominated by fossil fuels.

These findings underscore the environmental benefits of system-level renewable integration, especially via centralized low-carbon networks.

The economic evaluation includes the LCOH for households and the cost-effectiveness of infrastructure. The LCOH values were calculated in Excel using the annuity method in accordance with VDI 2067 [25]. Investment and operational cost assumptions are based on the KEA Technology Catalogue [28] and adjusted to the scenario years. Energy carrier prices, including fuel and electricity costs, are based on the assumptions provided in Pehnt et al. [30]. CO_2 price assumptions follow the MWM scenario of the German Projection Report 2023 [31]. Significant differences are evident between the scenarios, with infrastructure investments playing a particularly critical role.

For the year 2030, scenarios involving heat networks show the highest LCOH (see Figure 2). Ranked by LCOH, these are Variant 2 (low-temperature network), Variant 3 (cold local heat network), Variant 1 (district heating extension), and Variant 5 (hybrid solution with a smaller network). These high costs are primarily due to the substantial infrastructure investments that must be passed on to consumers. Variant 4 (decentralized systems) shows the lowest costs due to minimal infrastructure requirements, while the status quo lies in the mid-range.

By 2045, Variant 4 maintains the lowest LCOH at 23.18 ct/kWh, whereas the status quo reaches the highest at 31.95 ct/kWh, driven by increasing CO_2 prices. Network-based scenarios remain in the mid-to high-cost range, with cold and low-temperature networks still most expensive. This underscores the long-term economic advantage of renewable-based solutions.

Infrastructure costs, also calculated via the annuity method [25], vary significantly. Variant 2 incurs the highest due to geothermal probes, solar absorbers, and

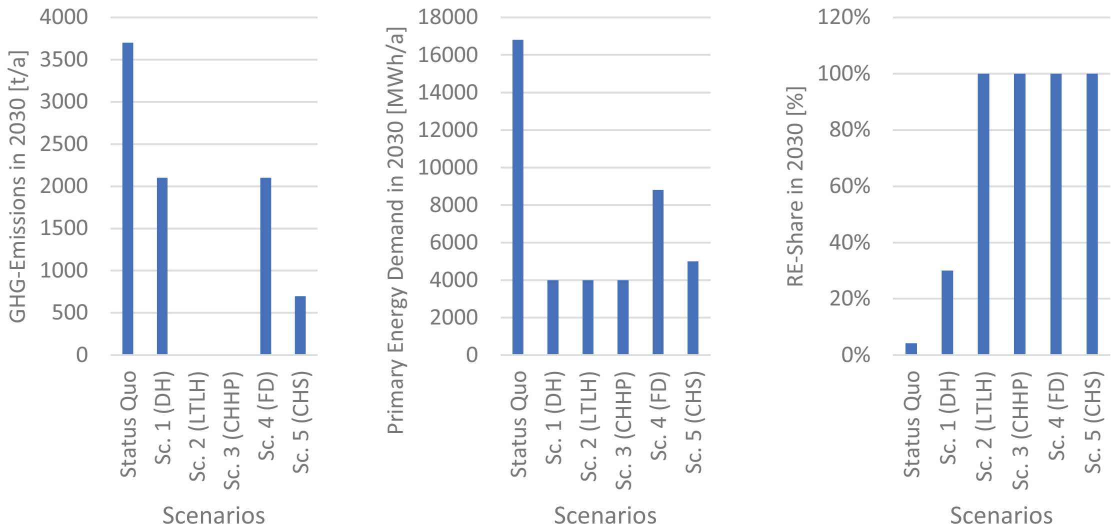

Figure 1: Environment Assessment of Quantitative Criteria in 2030. GHG emissions, primary energy demand, and renewable energy share are compared across scenarios. Abbreviations: DH = District Heating, LTLH = Low-temperature local heating network, CHHP = Cold heating network with heat pumps, FD = Fully decentralized, CHS = Combined heating solution.

large-scale heat pumps. Variant 3 is less costly, benefiting from lower system temperatures. Variant 4 has no additional infrastructure costs, as systems are installed within buildings and reflected in the LCOH. These differences illustrate the trade-offs between centralized and decentralized supply strategies.

Figure 3 shows normalized scores for environmental and economic criteria in 2030. Each criterion was scaled from 1 (least favorable) to 5 (most favorable) using min-max normalization (cf. Section 3.3). The scenarios are compared across GHG emissions, primary energy demand, renewable energy share, LCOH, infrastructure costs and expected investment willingness.

The status quo continues to show weak environmental performance, particularly regarding GHG emissions and renewable energy share, but performs relatively well in LCOH and infrastructure costs. Additionally, it achieves comparatively higher scores in expected investment willingness, indicating a stronger acceptance potential among households. Scenarios 4 (FD) and 5 (CHS) achieve the highest overall scores due to their favourable environmental-economic balance, while Scenario 1 (DH) performs moderately and Scenarios 2

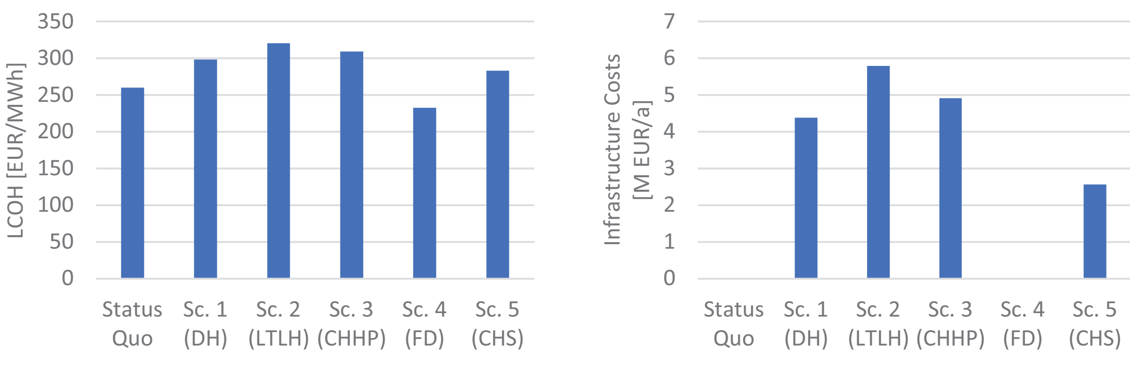

Figure 2: Economic Assessment of Quantitative Criteria in 2030. Infrastructure costs and Levelized Cost of Heat (LCOH) are compared across scenarios. Abbreviations: DH = District Heating, LTLH = Low-temperature local heating network, CHHP = Cold heating network with heat pumps, FD = Fully decentralized, CHS = Combined heating solution.

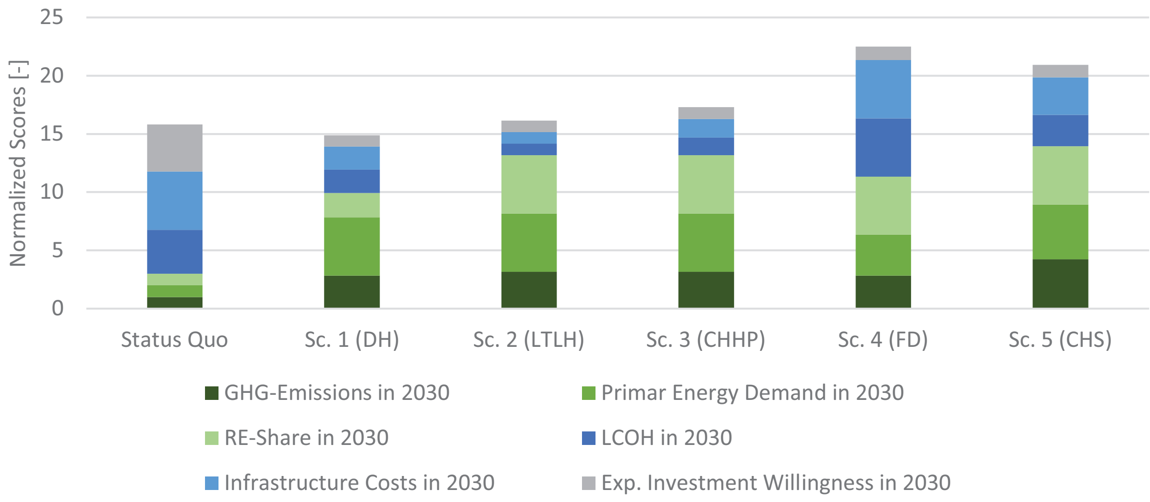

Figure 3: Normalized scores for environmental and economic criteria in 2030. Abbreviations: DH = District Heating, LTLH = Low-temperature local heating network, CHHP = Cold heating network with heat pumps, FD = Fully decentralized, CHS = Combined heating solution.

(LTLH) and 3 (CHHP) show strong environmental but cost-intensive performance.

In 2045 (see Figure 4), Scenario 1 improves significantly through a shift to renewables within the district heating network, increasing its environmental score. Across all scenarios, decarbonization of the electricity mix and rising CO_2 prices particularly benefit heat pump-based solutions (Scenarios 4 and 5). These developments lower emissions and LCOH over time. In contrast, the status quo becomes increasingly expensive and less attractive for households, reflected in lower expected investment willingness. Scenarios 2 and 3, already close to optimal in 2030, show limited further improvement.

4.1.2. Qualitative Evaluation

The qualitative evaluation of the scenarios was conducted based on six identified criteria: household autonomy, regional value creation, comfort, future viability, planning security and installation effort. The assessment of these criteria for each scenario was carried out using a descriptive scale that provides specific characteristics and ratings for the five scenarios for each criterion.

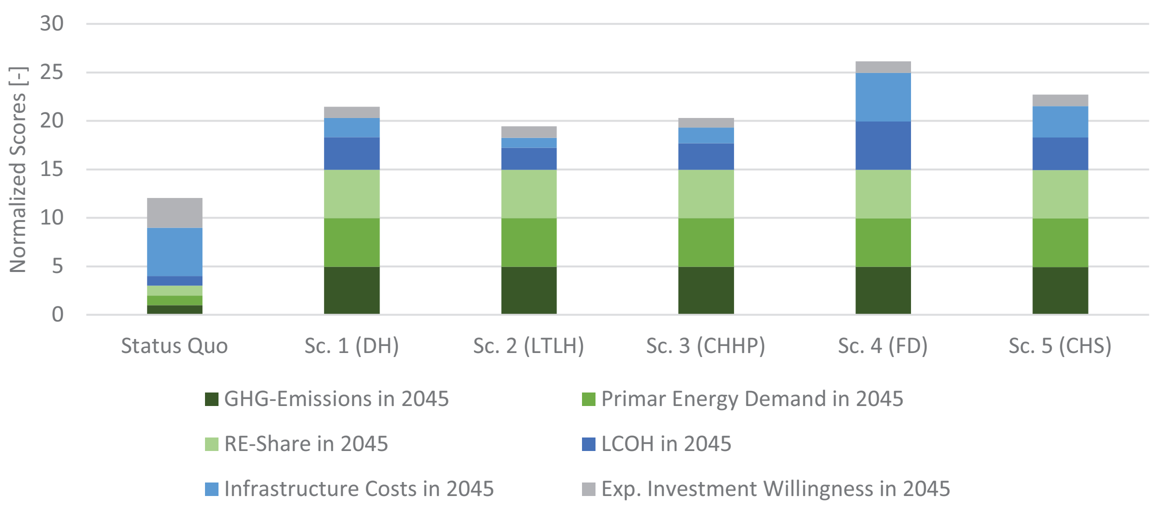

Figure 4: Normalized scores for environmental and economic criteria in 2045. Abbreviations: DH = District Heating, LTLH = Low-temperature local heating network, CHHP = Cold heating network with heat pumps, FD = Fully decentralized, CHS = Combined heating solution.

The descriptive scale (see Table 1) offers a detailed description of the respective evaluations for each criterion, to ensure that stakeholders had a shared understanding of the evaluation criteria. Each criterion was rated on a scale from 1 to 5, with 1 representing the worst and 5 the best rating. The results were summed up across the six criteria to allow for visual comparability across scenarios.

The criteria definitions and scale levels were derived through a workshop-based evaluation process. During the criteria workshop, stakeholders discussed key terms, such as “autonomy”, in an open setting. While the twelve final criteria were not yet fixed at that time, the discussions on terminology were used retrospectively to derive scale definitions based on the detailed workshop minutes.

The ratings were developed by the interdisciplinary research team based on this analysis and internal discussions. This structured scale (see Table 1) provided a common interpretive framework and minimized the risk of diverging assumptions during rating. It also enabled the research team to assess each scenario’s performance consistently.

To illustrate the qualitative evaluation, Figure 5 displays the aggregated normalized scores of the five scenarios. The ratings reflect expert assessments based on typical technology configurations for each scenario. For example, Scenario 4 (FD) includes biomass boilers and heat pumps, both of which enable self-supply using local renewable energy sources. However, the reliance on grid electricity prevents a rating of

Table 1: Descriptive evaluation scale for the scenarios assessment (1 = least favorable, 5 = most favorable). Abbreviations: Pellet = Pellet boiler systems; Oil = Oil heating systems; DHW-HP = Domestic Hot Water Heat Pumps; Gas = Gas heating systems; HP = Heat Pumps; DH = District Heating.

Criterion	**Rating Levels (1-5)**				
	1	**2**	**3**	**4**	**5**
Household Autonomy	Complete dependence: no provider choice, centralized systems, long-term contracts	Limited autonomy: Limited choice of provider, no self-supply options	Limited choices: freedom of choice in all aspects but no self-supply (power)	Partial self-supply: Freedom of choice, partial self-supply using local and regional sources	Complete self-supply: Fully autonomous, decentralized and cost-effective with local heat and power sources
Regional Value Creation	External energy supplies: Full reliance on imports, environmental impacts considered, use of established markets	Value creation with external support: Mainly outside the region, but no market dominance	Stable regional value creation: Sustained by local businesses (e.g. heating installers), supported by competition and diversity	Moderate promotion of regional value creation: Boosted through decentralized renewable systems	Maximized regional value creation: Local resources used, new jobs created, independence from imports via renewable central supply
Operational Comfort	High maintenance: Frequent inspections, broad service network required	Frequent maintenance: Regular servicing with limited availability of specialized companies	Conventional standard: Comparable to current norms for inspection and maintenance	Reliable and low maintenance: Minimal servicing required, reliable operation, supported by several providers	Efficient and minimal maintenance: Very low service needs, long intervals, operable with one service provider
Future Viability	High risk: Significant failure risk, challenges in long-term availability of heat source	Moderate risk: Innovative systems, limited operational experience	Manageable risk: Limited risks, established systems with some uncertainties	Low risk: Reliable systems with high availability	Maximum viability: No risk of failure, continuous and secure access to heat supply
Planning Security	Limited cost security: No stability or flexibility, high uncertainties in cost	Low-cost security: Low predictability, potential cost fluctuations and high investments	Moderate cost security: Some cost variations, moderate investment requirements	High-cost security: Low cost fluctuations or low investment costs	Maximum cost security: Low costs with high security and maximum flexibility
Installation Effort [h]	40-50 (e.g. Pellet 48)	30-40	20-30 (e.g. Oil 24, DHW-HP 28, Gas 30)	10-20 (e.g. HP 20, DH 16)	0-10

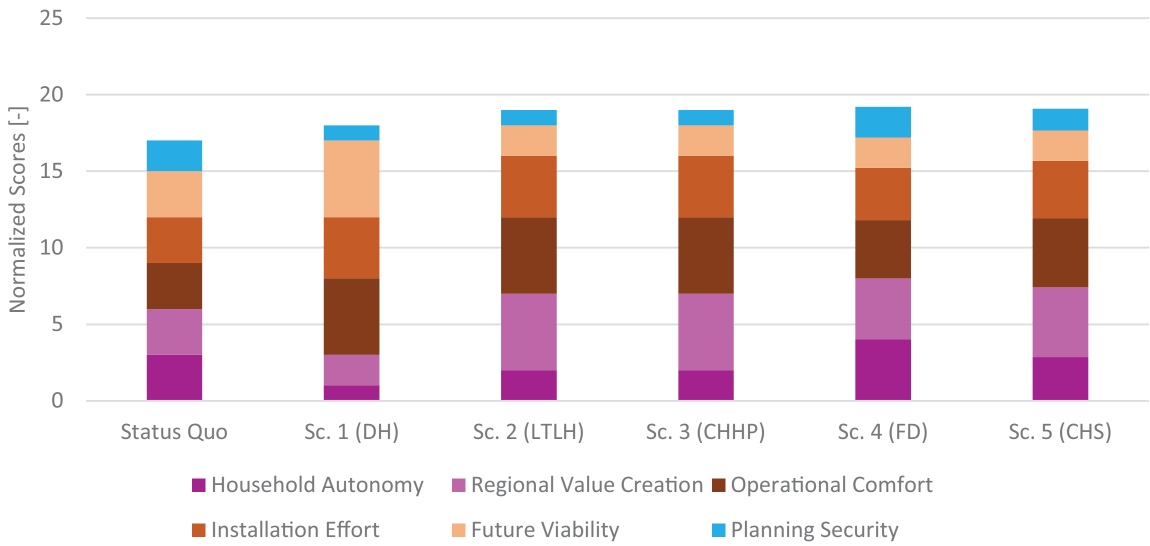

Figure 5: Normalized scores for qualitative criteria. The scores are based on a descriptive evaluation scale that assesses Household Autonomy, Regional Value Creation, Operational Comfort, Installation Effort, Future Viability, and Planning Security. Abbreviations: DH = District Heating, LTLH = Low-temperature local heating network, CHHP = Cold heating network with heat pumps, FD = Fully decentralized, CHS = Combined heating solution.

complete autonomy. Scenario 5 (CHS), although combining local heating networks and decentralized systems, was rated lower in autonomy due to its dependency on the network operator and the absence of electricity self-sufficiency. In this context, autonomy refers to both thermal and electricity self-sufficiency at the household level.

Maintenance ratings consider only the in-house installations. All district and local heating scenarios (Sc. 1–3) include comparable heat transfer stations, which require minimal servicing and regular inspections, and are therefore rated 5. Heat pump systems are rated 4 due to their low but periodic maintenance requirements. Pellet and gas boiler systems are rated 3, reflecting the need for regular servicing by specialized providers. Scenario 4 combines heat pumps and biomass boilers, resulting in an intermediate rating between 4 and 3, while Scenario 5 represents a mixed system with approximately equal shares of local heating networks and decentralized heat pumps.

Installation effort reflects the household-level installation time only, which is highest for systems such as pellet boilers due to the additional on-site integration of storage and feed systems. Planning security reflects user-side uncertainty, such as pricing flexibility, while future viability accounts for system maturity and long-term availability of resources and technical support.

Scenarios 2 (LTLH), 3 (CHHP), 4 (FD), and 5 (CHS) all reach 19 points and thus perform best in the qualitative evaluation. While the strengths vary by scenario, e.g., LTLH and CHHP excel in Operational Comfort and Regional Value Creation, FD in Household Autonomy, and CHS in combining high comfort with broad value creation, each also faces specific trade-offs, especially in terms of Planning Security and Future Viability.

Scenario 1 (DH) follows closely with 18 points, benefiting from well-established infrastructure and low operational effort, but scores low in Autonomy and Regional Value Creation due to its fossil-based supply. The status quo scenario achieves 17 points, reflecting moderate performance across most criteria but weaknesses in Planning Security and future value creation.

Overall, the differences between scenarios are relatively small, which underscores that no solution is clearly superior across all dimensions. Instead, each scenario presents distinct strengths and weaknesses. The qualitative evaluation therefore highlights the importance of context-sensitive and multidimensional decision-making in heating transition planning.

4.1.3. Criteria Prioritization by Stakeholders

In the context of the overall MCDA, the weighting of criteria by stakeholders represents a crucial step between

Table 2: Relative weighting of evaluation criteria by stakeholder group.

Criteria	Municipality Weighting [%]	Citizens Weighting [%]	Network Operator Weighting [%]	Total [%]
PED	7.70	9.20	6.50	7.80
GHG Emissions	8.70	7.40	9.70	8.60
Share of Renewable Energy	8.90	5.20	7.50	7.20
Infrastr. Economy efficiency	8.00	4.70	10.00	7.60
LCOH	8.00	10.20	8.10	8.80
Household Autonomy	4.50	8.20	5.40	6.00
Regional Value Creation	9.60	5.70	8.70	8.00
Exp. Investment Willingness	8.60	5.90	8.60	7.70
Planning Security	9.90	10.80	8.10	9.60
Operational Comfort	8.00	11.30	7.50	9.00
Future Viability	11.80	10.00	10.20	10.70
Installation Effort	6.40	11.30	9.70	9.10

the definition of evaluation criteria and the scenario assessment. Table 2 captures the preferences of three stakeholder groups regarding the relative importance of each criterion. Unfortunately, no representative from the crafts sector was able to participate in the Decision Workshop session. The resulting weights were used to aggregate the performance of each scenario into a weighted evaluation, meaning that the prioritization directly influenced the final ranking and reflects the normative perspective of each participating group.

Municipalities (see stakeholder group (1) in Section 3.1) prioritize future viability (11.8%), reflecting the importance of a long-term stable and reliable heat supply. Closely following future viability is planning security (9.9%), highlighting the significance of long-term stability and predictability in planning. Infrastructure costs (8.0%) and greenhouse gas emissions (8.7%) are also highly weighted, emphasizing the need for cost-efficient and climate-friendly heat supply solutions. The share of renewable energy (8.9%) indicates the intention to promote climate-friendly supply through renewable energy sources.

Another important criterion is household investment willingness (8.6%), as active citizen participation plays a crucial role in implementing solutions. LCOH (8.0%) reflects the importance of a predictable and fair implementation for the population. Operational comfort (7.9%) ensures that users can expect a reliable and efficient supply with minimal maintenance effort. Technical criteria such as installation effort (6.4%) are moderately weighted, viewed as important but less critical. Household autonomy (4.5%) receives the lowest weighting, suggesting that municipalities place greater importance on integrating renewable energy and collaborating with existing infrastructures and systems.

The weighting of criteria by the citizen stakeholder group (cf. Section 3.1) reveals a clear prioritization of technical and practical aspects of heat supply. The highest weights are assigned to Operational Comfort and Installation Effort, each at 11.3 %, followed by Planning Security at 10.8 % and LCOH at 10.2 %. These weightings highlight the importance of simplicity, reliability, and cost security in the decision-making process of citizens.

The criterion Household Autonomy received a moderate weighting of 8.2 %, suggesting that the citizens' group did not view it as a top priority overall. This reflects the heterogeneity of views within the group: while some citizens preferred decentralized solutions such as heat pumps to increase independence, others favored network-based solutions for reasons of convenience and reliability.

Criteria such as Primary Energy Demand (PED) and Future Viability are in the mid-range, with weights of 9.2 % and 10.0 %, respectively, while environmental criteria like GHG Emissions and Share of Renewable Energy are weighted comparatively lower, at 7.4 % and 5.2 %. This indicates that while citizens value environmental aspects, practical and economic criteria hold greater significance for them. The lowest weights are assigned to Regional Value Creation (RVC) and Economic Efficiency of Infrastructure, at 5.7 % and 4.7 %, respectively.

Network operators (see stakeholder group (3) in Section 3.1) prioritize future viability (10.2%) and infrastructure costs (10.0%), emphasizing the importance of profitability and long-term stability. Installation effort (9.7%) is also highly weighted, reflecting an interest in the efficient integration of new technologies and minimizing disruptions to the existing network. Greenhouse gas emissions (9.7%) are similarly significant, highlighting the growing importance of sustainability and climate friendliness.

Regional value creation is weighted at 8.7%, emphasizing the promotion of the local economy through job creation, strengthening regional supply chains, and supporting sustainable economic activities during the transition to climate-neutral energy systems. Household investment readiness (8.6%) underscores the importance of household involvement, as it directly influences connection rates. LCOH for households and planning security (8.1%) reflect the importance of financial predictability and long-term stability.

The share of renewable energy is weighted lower at 7.5%, which may indicate that network operators view emission reductions through efficient technologies and infrastructure optimization as equally effective as increasing the quantitative share of renewable energy. Operational comfort and primary energy demand (7.5% and 6.5%, respectively) are less of a priority. Household autonomy receives the lowest weighting at 5.4%.

5. Insights and limitations of participatory MCDA in municipal heat planning

Another area for improvement lies in the integration of dynamic visualizations that respond directly to stakeholder inputs and preferences. Interactive, real-time representations of changes in criteria weighting or scenario parameters could significantly simplify and increase the transparency of the decision-making process.

To enable this, an automated data flow is needed that establishes a seamless connection between stakeholder inputs and the visual outputs. In the current process, inputs were manually transferred from polling tools into Excel. These limitations caused concrete delays during the workshop, as the manual data transfer hindered rapid adjustments in response to stakeholder questions.

These challenges were explicitly addressed by several stakeholders during the final reflection phase of the Decision Workshop. They expressed a desire for more interactive exploration of the data, such as simulating alternative connection rates or cost trajectories, disaggregating the evaluation results by stakeholder group, and gaining greater transparency on intra-group differences. Some participants noted that they found it difficult to recognize their own priorities in the aggregated results. It remains to be determined whether such adjustments are best shown in a single consolidated graphic or multiple targeted visualizations, as each approach has its own advantages in terms of usability and clarity.

While the research team currently prepared the data basis and operated the dialog tool, these steps could be carried out by external engineering firms and local administrations in future applications. The scenario evaluation would then be automated, and the diagrams would adjust dynamically to entered values. Criteria weighting could be performed during workshops organized by municipalities, provided that a neutral moderator is involved. This would increase transferability and reduce dependence on scientific support.

A key challenge in applying the MCDA approach to heat planning is the uncertainty in data collection and the availability of information. In practice, it is often difficult to obtain precise and complete data for all relevant criteria. Specifically, areas such as regional value creation or the future development of CO_2 prices require assumptions that can significantly influence the results.

Previous strategic analyses underline that assumptions regarding heat-demand mapping and connection rates are equally critical, as they can fundamentally shape heating-sector pathways [32]. This further highlights the importance of transparent handling of uncertainties and the need for systematic sensitivity analyses to test the robustness of scenario evaluations.

In this paper, realistic assumptions from existing literature and data from expert interviews were used to address these uncertainties. However, it is important to emphasize that such assumptions can skew evaluation results, introducing a degree of uncertainty into the final outcomes. These factors are difficult to predict, as they depend on numerous variable and long-term unpredictable influences.

Therefore, the decision-making process could be understood as a dynamic, continuously monitored process. Regular data collection and analysis over extended periods could help reduce these uncertainties and adapt scenario evaluations to changing conditions, resulting in realistic adjustments and more precise outcomes.

Moreover, the relatively small differences in the LCOH across the evaluated options underline the importance of carefully considering these uncertainties. In future work, a dedicated sensitivity analysis could be conducted to examine how assumptions regarding key parameters such as CO_2 prices or regional economic impacts affect the robustness of the results. This would further support transparent and informed decision-making under uncertainty.

In future applications, tool-supported approaches such as open-data heat mapping could complement participatory MCDA processes, reducing reliance on assumptions and strengthening the robustness of municipal and district-level evaluations [19].

Additionally, the complexity of the scenarios posed challenges in communicating the results. Heating supply systems are inherently complex due to the multitude of parameters, technologies, and long-term implications involved. The MCDA approach was employed to structure this complexity in a transparent and comprehensible way. However, it also introduces additional demands, such as understanding weighting procedures and result aggregation.

In future applications, it may be beneficial to implement preparatory formats, such as an exploratory workshop on heating supply options, between the MCDA phases. This could help stakeholders develop a clearer understanding of the underlying scenarios and assumptions before engaging in the multi-criteria evaluation. This need for prior scenario co-design and transparent communication formats has also been emphasized in the GECKO project. [4]

These operational and communication-related limitations point to a broader need for methodological reflection on the application of participatory MCDA in heat planning contexts. Compared to traditional applications focusing mainly on techno-economic assessment [9, 21], the integration of diverse stakeholder groups and criteria types reflects a deliberate effort to address the socio-political dimensions of planning, as demanded by Banville et al. [12] and Neves et al. [14].

The two-step design, involving stakeholder-driven criteria development followed by interactive evaluation, aligns with recent recommendations for continuous and inclusive participation [13]. The integration of stakeholders at multiple stages, from criteria definition to final assessment, was perceived as highly valuable for building mutual understanding. However, the coordination of these participatory elements proved time-intensive and required careful facilitation to avoid stakeholder fatigue.

Estévez et al. [23] stress that more empirical applications are needed that integrate participation meaningfully and adapt MCDA methods to local planning contexts. Compared to other MCDA applications described in the literature [8, 11], the innovative aspect of this study lies in the combination of participatory criteria development, stakeholder weighting, and a moderated Decision Workshop format.

Future MCDA processes could benefit from a stronger integration of automation and real-time feedback loops, as well as from further simplification of the evaluation framework to enhance usability. These insights contribute to the broader discourse on how MCDA methods can be adapted to complex, participatory planning contexts and serve as valuable input for similar applications in other municipalities or sectors.

A limitation of the weighting process was the absence of a crafts sector representative during the Decision Workshop session, which meant that this stakeholder perspective was not included in the quantitative results. Future applications should ensure full participation across all relevant groups to strengthen representativeness.

One methodological insight concerns the trade-off between comprehensiveness and usability. Including too many criteria risks overwhelming participants and diluting the evaluation. To address this, the criteria list should be deliberately streamlined, such as by consolidating strongly correlated indicators like GHG emissions and primary energy demand. This would help to reduce redundancy and cognitive load.

The number, type, and presentation of criteria could have influenced the weightings given by participants. Although no systematic analysis of such framing effects was conducted, their potential influence should be considered in future studies. Another methodological limitation concerns the simplified representation of installation effort, which was restricted to household-level installation time for heating systems. Refurbishment measures such as radiator replacement or hydraulic adjustments were not included, as they depend strongly on the existing building stock and would have introduced significant uncertainty to the comparative assessment.

The MCDA approach presented in this study offers a structured framework that can support municipal planning processes by integrating diverse stakeholder perspectives. While further empirical evidence is needed to assess its long-term practical application, the approach provides a transparent foundation for more inclusive and data-informed decision-making.

6. Conclusion and Outlook

This paper developed and applied a MCDA process to support the planning of climate-neutral heat supply systems in neighborhoods. By incorporating technical, environmental, economic, and social criteria, the model enabled a structured evaluation of complex scenarios and made trade-offs between options transparent.

The results of the scenario evaluation demonstrate that scenarios with higher utilization of renewable energy are environmentally advantageous and lead to lower GHG emissions, reduced primary energy demand and LCOH in the long term. However, the successful implementation of these scenarios requires close collaboration among stakeholders. The participatory approach to criteria weighting has shown that incorporating diverse perspectives improves decision-making and increases acceptance by identifying and addressing conflicts early.

To fully realize the potential of the MCDA approach, it should be embedded into a broader, iterative participatory process. Rather than serving as a one-time decision tool, MCDA can support an ongoing dialogue between municipalities, citizens, and other stakeholders throughout the planning and implementation phases. This approach enables trust-building, fosters mutual understanding, and ensures that affected stakeholders remain informed and engaged over time. Especially in the context of the heat transition, such a process helps to convey complex decisions in a transparent and accessible manner and can contribute to stronger societal ownership of the transformation.

The need for long-term involvement was particularly emphasized by municipal representatives. They noted that social acceptance of climate-neutral heating solutions cannot be achieved through one-time participation alone, but requires continuous dialogue throughout all phases of implementation. This corresponds with recent findings that emphasize the necessity to address acceptance not only at the level of individual projects but across all system levels. Studies show that expanding the techno-economic perspective and integrating user preferences and potential acceptance conflicts early in the innovation process can significantly improve the success of heating transition strategies [4].

Therefore, this study aims to address these gaps by applying a participatory MCDA in a real-life planning process at the district level, integrating a broad range of quantitative and qualitative criteria, and emphasizing stakeholder engagement through visual and structured dialogue formats.

In addition to supporting decision-making in this specific case, the process also offers insights for future MCDA applications. The combination of participatory criteria development, stakeholder weighting, and a moderated Decision Workshop setting proved helpful for integrating diverse perspectives. However, the manual data handling and the complexity of criteria presentation limited the flexibility of the process. Future applications should therefore focus on simplifying the evaluation framework, automating feedback loops, and systematically involving all relevant stakeholder groups. These adjustments could enhance transferability and improve the usability of MCDA approaches in local planning contexts.

The study also highlights the need for more dynamic and responsive planning tools. Automated data flows and interactive visualizations could enable real-time adjustments to stakeholder inputs, making the evaluation process more transparent and adaptive to changing conditions. Future work should focus on developing such tools and exploring strategies for sustained engagement in municipal planning contexts. MCDA can make a valuable contribution by combining transparency, structure, and inclusiveness in a single decision-support framework.

Overall, the MCDA approach presented here demonstrates how transparent, participatory and structured evaluation methods can support more inclusive and adaptive planning processes for climate-neutral heat supply, while also revealing key conditions and limitations for its broader applicability.

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