International Journal of Sustainable Energy Planning and Management Vol. 49 2026 69–82

International Journal of
Sustainable Energy Planning and Management

F|Heat: A GIS-based compliance tool for municipal heat planning in Germany

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ABSTRACT

Municipal heat planning is becoming a mandatory element of local climate policy in Germany, yet many smaller municipalities lack geospatial tools that are transparent, reproducible and aligned with the German Heat Planning Act (WPG). This paper presents F|Heat, an open-source QGIS extension that supports early-stage municipal heat planning by automating data acquisition, building-level heat-demand preparation, heat-density and heat-line-density analyses, preliminary district-heating network routing, pipe dimensioning, heat-loss estimation and load-profile generation. The method is demonstrated for a district in Barntrup, North Rhine-Westphalia, Germany. The case study connects 268 buildings with an annual heat demand of 11.9 GWh and generates a 9.1 km preliminary network. Simulated annual heat losses amount to 1.6 GWh with standard insulation and 1.4 GWh with enhanced insulation. Using DN-specific network investment assumptions, the annualised network cost contribution is estimated at 0.042 EUR·kWh^{-1}. The results show that F|Heat can provide a reproducible GIS-based workflow for suitability assessment, status-quo analysis and preliminary district-heating area assessment. The tool does not replace detailed techno-economic optimisation, heat-source assessment or engineering design, but narrows the gap between statutory heat planning requirements and the data-processing capacity of municipalities.

Keywords

District heating;
Municipal heat planning;
Open-source;
Regulatory compliance;
Spatial analysis

http://doi.org/10.54337/ijsepm.11250

1. Introduction

The urgent need to decarbonise Germany's energy sector has elevated municipal heat planning (MHP) to a central role in national energy policy. Heating and hot water provision in the residential sector alone account for 84% of final energy consumption in buildings and nearly a third of the country's greenhouse gas emissions [1]. This critical situation necessitates comprehensive strategies to transition towards climate neutrality, especially within the building sector, by 2045 [2].

The recently enacted German Heat Planning Act (WPG) accelerates this transition by mandating municipalities to develop heat plans with the goal of achieving climate neutrality by 2045 [3]. The objective of these plans is to guide local heating sectors towards the efficient utilisation of regional renewable energy resources, with the aim of reducing reliance on fossil fuels and decarbonising heat networks [4,5]. Many municipalities lack both suitable tools and in-house expertise, creating delays in early planning stages and underscoring the need for accessible, standardised, and automated solutions [2]. This paper introduces F|Heat, an open-source QGIS extension designed to bridge this gap by providing a comprehensive, partially automated framework for municipal heat planning in Germany.

2. Legal context and literature review

This section summarises the German legal context and positions F|Heat against existing GIS- and optimisation-centred tools. It first outlines the statutory planning

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Received 17.12.2025 | Accepted 09.06.2026 | Published 19.06.2026

tasks, then clarifies the software categories used in the literature review and finally identifies the open-source workflow gap addressed by the proposed extension.

2.1. Heat planning act

The WPG mandates that all municipalities in Germany develop comprehensive heat plans (§ 23 WPG), outlining strategies for decarbonising their heating sectors and fostering the expansion of district heating networks [3]. These plans must detail existing heat demand, assess local renewable energy potentials and identify economically viable zones for district heating expansion, including the integration of excess heat [6]. The legislative framework also requires a detailed assessment of potential supply technologies, such as large-scale geothermal systems, and the socio-economic implications of transitioning away from conventional fossil-fuel-based heating solutions [7].

Furthermore it specifies a structured, multi-stage planning process that includes suitability assessment (§ 14 WPG), status quo analysis (§ 15 WPG), potential assessment (§ 16 WPG), and the development of concrete implementation strategies to ensure a systematic and compliant approach to the municipal heat transition (§§ 17-20 WPG). Despite these clear mandates, the practical implementation of such plans presents significant challenges due to the fragmented nature of available planning tools and the complexity of integrating diverse data sources [8].

2.2. Overview of existing planning tools and their limitations

Planning tools can be grouped by their primary data model. In this paper, "GIS-centred" tools denote workflows in which georeferenced objects such as buildings, parcels, road segments are the main modelling entities. "Simulation- or optimisation-centred" tools denote energy-system models, mathematical optimisation formulations in which temporal operation, component behaviour or system optimisation are central, and spatial detail may be optional, aggregated or provided as external input.

While a variety of tools, both GIS-based and model-based, have emerged to support heat planning at different scales, many exhibit significant limitations in terms of data integration, usability and direct alignment with regulatory requirements for German municipalities [9].

Höffner & Glombik [9] provide a comprehensive review of energy system planning tools for urban applications and DH. They highlight the dominance of open-source tools based on Python and Modelica, particularly those originating from the research community. For instance, existing tools, including *Heat4Future*, are designed for strategic planning with minimal input data and lack the detailed resolution required for regulatory compliance and the granular spatial analysis necessary for specific municipal requirements [10].

Banze & Kneiske [11] address data scarcity with *DAVE*, a synthetic-network generator currently focused on electricity and gas with planned DH extension. While currently focused on electricity and gas, *DAVE* is expected to expand towards DH, offering a valuable complement to open-source GIS workflows such as *FlexiGIS* [12,13].

Similarly, Vieth et al. [14] propose a co-planning framework that integrates GIS data, surrogate optimisation and dynamic Modelica-based simulations. Fuchs & Müller [15] use OpenStreetMap (OSM)-derived data to generate static and dynamic DH-network models, demonstrating the importance of automation in model construction. Such methods increase modelling fidelity but require detailed input data, which are often unavailable in early heat planning phases such as §§ 15-16 WPG (status quo and potential analysis).

The approach proposed by Vieth et al. [14] requires cost parameters specific to each street segment for pipe installation, which are rarely known at the feasibility design stage. But optimisation-centric approaches remain a major research driver. Wirtz [16] focuses on 5th-generation DH, emphasising renewable integration and thermal storage. Sporleder et al. [17] provide a systematic overview of DHN optimisation methods and highlight the growing importance of low-temperature heat sources, large heat pumps and thermal storage within future-proof DH infrastructures. Multi-temporal optimisations further face computational limits in larger districts according to Lambert et al. [18].

2.3. Open-Source software for heat planning

A wide range of open-source frameworks is available to support heat planning, each addressing specific elements of the planning process [11]. GIS-based spatial analysis tools such as *FlexiGIS* [12,13] or *Citiwatts/Hotmaps* [19] provide harmonised heat demand layers, renewable potentials and geospatial pre-processing essential for identifying technically and economically feasible supply areas. Urban-scale modelling platforms including the *City Energy Analyst (CEA)* [20], address building-level energy demand and supply at district scale.

For thermo-hydraulic network simulation and optimisation, frameworks such as *DHNx* from *oemof.solph* [21,22], *pandapipes* [23,24] and the open-source release of *Sophena* [25] offers the possibility to carry out the technical and economic planning of a heat supply project quickly and thoroughly, but relies on external input data. Additional tools such as *THERMOS* [26,27] support cost-optimal routing and early-stage network layout generation, while recent developments like *open_plan 2.0* [28] enable integrated energy system assessments, provide a user-friendly interface and support economic evaluations through various scenarios with diverse energy system components.

F|Heat addresses a narrower but specific gap. The current version covers automated project setup and data acquisition, preparation of building-level heat-demand attributes, generation of heat density (HD) and heat line density (HLD) indicators for WPG-oriented suitability and status-quo analyses, delineation of candidate heat-network areas, preliminary street-based routing from a user-defined heat source to selected buildings, pipe sizing, annual heat-loss estimation and load-profile generation.

It does not currently include automatic heat-source potential assessment, operational dispatch optimisation, tariff modelling, financing, subsidy assessment or final engineering design. The novelty is therefore not a universal optimisation model, but a transparent QGIS workflow that transforms public geodata and user input into WPG-oriented spatial indicators and first network KPIs without requiring planners to build custom pipelines. Knies [29] also highlights that spatial planning is indispensable for effective, transparent, and sustainable heat planning process.

3. Methodology

The methodology follows the sequence from data acquisition to spatial indicators and preliminary network assessment. The subsections describe the workflow architecture, data requirements and transferability, building-data adjustment, density indicators and the routing and pipe-sizing procedure.

3.1. Workflow and architecture

The extension`s design allows for flexible application across diverse municipal contexts, encompassing various scales and specific planning challenges, while ensuring adherence to the strict requirements of the WPG [3]. This design integrates various functionalities, from initial data collection and preparation to advanced spatial analysis and comprehensive report generation. The workflow is not restricted to a single administrative unit: by defining a custom area of interest, the tool can be applied to several districts or to the perimeter of larger cities without the surrounding area.

The underlying architecture leverages open-source libraries, e.g. *GeoPandas* [30] for geospatial analysis and *NetworkX* [31] for graph-based routing and initial district heating network designs, supporting community-driven extension as regulatory and technical requirements evolve.

Figure 1 provides a high-level overview of the extension's architecture, illustrating the interconnected modules and their respective roles within the heat planning workflow related to the corresponding paragraphs of the WPG.

The extension initialises required dependencies, data paths, and administrative boundaries before launching automated data acquisition and analysis workflows. Local data storage and processing are essential, as users may work with consumption- or building-specific data subject to data protection requirements [3,32].

3.2. Data acquisition and pre-processing

The primary source of data is the LANUK database, which provides a space heating demand model for the entire state of NRW [33]. This model encompasses building-specific heating requirements, space heating provision, and modernisation potential, with a detailed level of analysis extending down to the building block level for each municipality [33]. Upon selection of a city/municipality or district, the buildings and road centre lines are automatically downloaded. The collected data is stored in Shapefile (.shp) or GeoPackage (.gpkg) format. The core is not limited to NRW if equivalent user-provided layers are available. For use in other German states or in another country, such as France, users must provide building geometries with heat-demand or floor-area attributes, road-centre-line data, optional parcel or block polygons and a mapping table equivalent to *building_info.xlsx*. The WPG threshold values and automated download routines are Germany-specific, whereas the density calculations, routing and pipe-sizing workflow can be applied to harmonised input layers after attribute mapping.

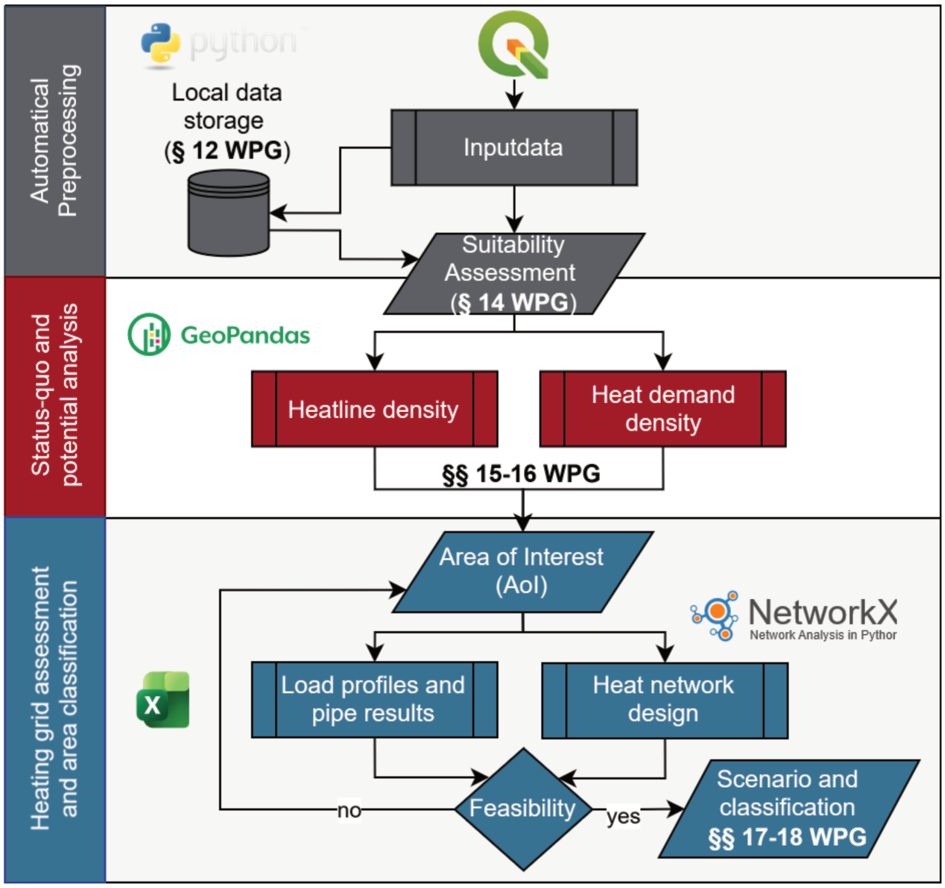

Figure 1: Conceptual overview of the software architecture and alignment with the WPG.

In a subsequent stage, the internally stored data are filtered according to the selected city or district name, and the corresponding municipality code is extracted. The filtered data is saved as a variable for subsequent utilisation in the process of downloading the parcels. Parcels are retrieved via a WFS (Web Feature Service) from *GEObasis.NRW* [34].

Only parcels within the current district boundary are loaded from the WFS in each iteration and then merged. Because buildings and streets can only be downloaded for an entire municipality, for district-level analyses they are spatially intersected with the parcels so that only geometries on relevant parcels are retained. In addition to building, parcel and road geodata, there is the option of loading census data on heating types and energy sources as a 100-metre grid. These data can be utilised to identify infrastructure such as existing gas networks, which facilitates the planning of heat supply. The census data are provided by the Federal Statistical Office [35].

3.3. Data adjustment

The downloaded files are then prepared for subsequent analysis. In the context of the present study, relevant attributes (full load hours, load profile and thermal output) are added. Furthermore, sub-buildings are aggregated into one main building. A central component of data adjustment is the Excel spreadsheet *building_info.xlsx*, located in the data directory [36]. The spreadsheet contains ALKIS numerical building-function codes and parameters such as load profile, full-load hours and specific heat-demand characteristics. Based on the building type and function in the raw data, the parameters are assigned automatically.

The data basis comprises several specialist sources [37–42]. Once a valid attribute selection and, if necessary, the path specifications are available, the range and designations for the building age classes are defined (see table 1). Initially, all building structures without heating demand are filtered out. Building type and construction year are parsed from LANUK attributes and assigned as separate fields. An investigation of the raw

Table 1: Building age range and classes according to TABULA classification [43].

Building age range	0 - 1918	1918 - 1948	1948 - 1957	1957 - 1968	1968 - 1978	1978 - 1983	1983 - 1994	1994 - 2001	> 2001
Building age class	B	C	D	E	F	G	H	I	J

data reveals that the buildings are divided into individual sub-buildings. These are combined into a single building based on the parcel identifier, building use type (ALKIS code), update identifier and building type.

In the following step, the parcel age is transferred to the respective building via a spatial intersection of buildings and parcels and used to determine an additional building age, which is also added to the attribute table. The age of the buildings is then used to assign them to the relevant building age class, as outlined in Table 1 (building age classification).

The corresponding load profile and full load hours are assigned to the buildings from the Excel spreadsheet *building_info.xlsx* based on the ALKIS function code. The thermal power is then calculated per building from the heat demand and full load hours:

$$P_{th} = \frac{Q_{WB}}{V_{lh}} \tag{1}$$

where P_{th}: thermal power in kW, Q_{WB}: annual heat demand in kWh and V_{lh}: full load hours in h.

The specific and annual heat demand is added based on the consumption values documented in the spreadsheet *building_info.xlsx.* The columns “Connection” and “Possible Route” are added to the buildings, indicating whether the building is to be connected to the heating network and which streets are potential routes.

3.4. Heat demand and density analysis

The heat line density (HLD) and heat density (HD) are calculated based on the newly merged buildings and assigned to the street geometry. The parcels belonging to neighbouring buildings are then consolidated into a single building block, with additional attributes facilitating the identification of suitable areas for heating networks, such as total heat demand and heat demand per unit area.

Areas with particularly high heat demand density according to the federal guidelines are then automatically visualised. The categorisation process is conducted in accordance with the federal guidelines for heat planning [32]. Tables 2 and 3 show the specific thresholds and methodologies used for classifying these areas based on HD per building block and HLD, which represents the heat demand aggregated along street segments illustrating potential district heating network routes.

Using both indicators avoids relying on a single spatial aggregation. HD describes the spatial concentration of demand within a block and is useful for identifying candidate supply areas. HLD relates the demand of nearby buildings to the length of potential pipe routes and is therefore closer to the economic logic of heat-network infrastructure. A block may have a high HD but require long or complex pipe routes, while a street corridor may show high HLD even when surrounding block polygons have heterogeneous sizes.

The thresholds are used as screening indicators rather than automatic go/no-go criteria. Municipal planners should combine them with information on existing infrastructure, available low-cost heat sources, renewable and excess-heat potentials, expected connection rates, construction constraints and stakeholder preferences. In areas with large low-cost heat sources or short distances to existing networks, lower-density areas may be worth investigating as high density alone does not guarantee feasibility.

Table 2: Suitability for heating networks depending on heat density [32].

Heat density	Assessment of suitability for the construction of heating networks
$MWh \cdot (ha \cdot a)^{-1}$	–
0–70	No technical potential
70–175	Recommendation for heating networks in new development areas
175–415	Recommended for low-temperature networks in existing buildings
415–1,050	Benchmark for conventional heating networks in build urban areas
> 1,050	Very high suitability for heating networks

Table 3: Suitability for heating networks depending on heat line density [32].

Heat line density	Assessment of suitability for the construction of heating networks
$MWh \cdot (m \cdot a)^{-1}$	–
0–0.7	No technical potential
0.7–1.5	Recommendation for heating networks in new residential, commercial or industrial developments
1.5–2	Recommendation for heating networks in built-up areas
> 2	Benchmark value in case the laying of district heating pipes involves additional obstacles (e.g. road crossings, railway crossings or water crossings)

It should be noted that the thresholds for heat line density are only valid for conventional heating networks and not for 5GDHC, as described by Lund et al. (2021) [44]. Furthermore, the economic feasibility of expanding district heating networks is often assessed by considering a maximum distance from existing infrastructure, typically around 1,000 metres, to identify primary areas for development, increase customer connections and exploit a usable heat source [6].

3.4.1. Heat line density

HLD or linear heat density measures the heat demand (or load) distributed along the length of a potential or existing heat network [29]. It is calculated by dividing the total annual heat demand of buildings connected to a network segment by the length of that segment [29]. Upon completion of the data import, the HLD is calculated. The initial step in the process entails the determination of the centroids of all buildings, thereby establishing a central reference point for the allocation of street elements.

The nearest road segment for each of the identified centroids is then determined. The lengths of the road segments are appended to the roads data. Moreover, the process aggregates the heat demand of all buildings connected to a segment and adds this value as an attribute to the road data. Finally, the heat line density is calculated and added to the road data by dividing the aggregated heat demand by the segment length.

The road centre lines are derived from the pre-processed official data source as opposed to raw OpenStreetMap geometries. Consequently, the segmentation exhibits a higher degree of proximity to the "Straßenabschnitt" granularity specified by the WPG when compared to conventional OSM data. However, it is important to note that HLD values remain sensitive to the underlying road-network topology. Residual effects of over-segmentation or of dual carriageways coded as parallel lines are not explicitly corrected in the current version and are left for future refinement.

3.4.2 Heat density blocks

The polygons for building blocks are derived from parcel geometries rather than from OSM land-use polygons in accordance with §3 (1) of the WPG "Baublock" definition. As the spatial reference data, all parcels are selected on which at least of 10% of a building's footprint is situated. This prevents the inadvertent selection of parcels such as roads that intersect with buildings. The method also offers the option of only considering buildings located on a road that exceeds a certain heat line density, e.g. to directly exclude areas with low HD.

Given that the objective of the inventory analysis is to provide a comprehensive overview of the entire study area, this threshold has been set at $0.1\ kWh \cdot (a \cdot m)^{-1}$. The expanded parcels that overlap are then merged and the resulting multi-polygon geometries are divided back into individual areas. This process generates building blocks from the individual parcels, which are separated from each other by roads.

This geometric operation enables the delineation of contiguous land parcels associated with structures, facilitating a more accurate representation of heat demand distribution [45]. Attributes like area, number of building connections, cumulative heat demand, cumulative heating output, heat demand per area and average heating output are added to the resulting polygon elements.

3.5 District heating network assessment

The assessment evaluates the potential for new or expanded district heating networks by analysing the spatial distribution of heat demand and identifying optimal routing options [46]. There is the possibility to manually define a polygon inside QGIS environment which functions as the supply area for a pipe-based supply via a heating network. Currently, it is required to add a "heat source" as a point layer at a desired location for a potential heat source to supply the district heating network.

There is the option to select streets and buildings that are not to be included in the network analysis. The algorithm generates a radial pipe network with the shortest routes from the buildings to be supplied to the heat source. For each selected building, the shortest path from the user-defined heat source to the building connection point is calculated in the road graph with the Dijkstra algorithm. The resulting layout is a radial, shortest-path-based network proposal. It is not a global least-cost or hydraulic optimum. A central component of pipe dimensioning is the Excel spreadsheet entitled with *pipe_data.xlsx,* which is located in the data directory [36].

The spreadsheet presents a collection of pipe data, including such metrics as diameter, U-value and approved flow velocities from a range of manufacturers [47–49]. In addition, the table provides estimates of flow velocities in accordance with the methodologies established by Nussbaumer and Thalmann [50].

3.5.1 Network modelling and optimisation

Initially, parameters such as flow and return temperatures are recorded and evaluated for plausibility. This is followed by the initialisation of the building, source and streets objects. The geometry of buildings and roads are filtered based on their attributes for the purpose of establishing a possible connection or route for the network.

The subsequent stage of the process is to generate connection points between buildings and roads, as well as between the source and the road network. The centroid of each building is selected as the connection point for the buildings, which is then connected to the nearest point on the road network. Nearest point refers to the geometric projection onto the road geometry, not merely to the nearest existing vertex; the road graph is split at this projection where required.

Using building centroids is a conservative simplification and can overestimate house-connection length, particularly for large parcels or buildings set back from the street. On this basis, a graph is constructed in which all points of the roads, the source and the centroids of the buildings are represented as nodes and connected by edges.

3.5.2 Routing algorithm and simultaneity factor

A routing algorithm is employed to formulate proposals for district heating network layouts, with simultaneous factors (SF) incorporated to model peak load demands and ensure optimal sizing of network infrastructure [51]. The routing algorithm is informed by graph theory principles, leveraging shortest-path calculations based on street networks [14], while SFs account for the probabilistic nature of peak demand occurrences across multiple consumers, which is essential for avoiding oversizing or under sizing of network components [52].

The shortest path in the road graph is utilised, using the source as the starting point and the building as the end point. The *Dijkstra* algorithm is utilised within the *NetworkX* package [31]. The nodes and edges constituting this path are transferred to the network graph, where they are enriched with relevant attributes. Consequently, the connected thermal output and the number of connected buildings are accumulated at each edge.

The aggregation of Dijkstra edges does not internalise the non-linear relationship between pipe diameter, flow, pressure losses and specific investment cost; a cost function with economies of scale could favour fewer shared routes or alternative choices. Following the completion of the iteration across all buildings, additional attributes are appended to the sections of the resulting network graph. The SF is calculated for each edge using the connected buildings, according to Winter and Haslauer [52].

$$SF(n) = a + \frac{b}{1 + \left(\frac{n}{c}\right)^{d}} \tag{2}$$

where SF(n): Simultaneity factor, n: Number of buildings supplied via the pipe section and parameters with a = 0.4497; b = 0.5512; c = 53.8483 and d = 1.7627.

The *SF(n)* has been designed to prevent oversizing of the pipes. In the subsequent step, the *SF(n)* is multiplied by the thermal power P_{th} of the edges to obtain an adjusted output that takes simultaneity into account:

$$P_{th,SF} = P_{th} \cdot SF \tag{3}$$

where $P_{(th,SF)}$ Adjusted thermal output with simultaneity factor in kW, P_{th}: Thermal output in kW and *SF*(n): simultaneity factor.

The adjusted thermal power $P_{(th,SF)}$ is utilised to ascertain the volume flow in the pipes. Consequently, the density $\rho(T_{VL})$ and the specific heat capacity $c_p(T_{VL})$ are determined as a function of the flow temperature T_{VL}. For this purpose, tabulated values are interpolated linearly to obtain the current values. The volume flow $\dot{V}$ is then calculated from:

$$\dot{V} = \frac{P_{th,SF}}{\rho(T_{FT}) \cdot c_p(T_{FT}) \cdot \Delta T} \tag{4}$$

where $\dot{V}$: volume flow rate in $m^3 \cdot s^{-1}$; $P_{((th,SF)\ )}$: thermal output with simultaneity factor in kW; $\rho(T_{FT})$: density of water at flow temperature in kg/l; $c_p(T_{FT})$: specific heat capacity of water at flow temperature in kJ/(kg·K); ΔT:T_{FT}–T_{RT} = Temperature difference between flow and return in K.

The pipe diameter is selected based on the assignment of the maximum permissible volume flow to the nominal diameter DN stored in the *pipe_data.xlsx* table, with smaller diameters reserved for house connections and a minimum of DN ≥ 32 for network pipes.

The table also provides the internal diameter (DI) and the heat transfer coefficient for standard and reinforced insulation (U and Uadd). The flow velocity is calculated from the volume flow and cross-sectional area:

$$v = \frac{\dot{V}}{A} = \frac{\dot{V} \cdot 1{,}000}{\pi \cdot r^2} \tag{5}$$

where v: flow velocity in $m \cdot s^{-1}$, $\dot{V}$: volume flow rate in $l \cdot s^{-1}$ and r: inner radius = DI/2 in mm

The average temperature of the pipeline is determined as follows:

$$T_m = \frac{T_{FT} + T_{RT}}{2} \tag{6}$$

where T_m: Average temperature of the pipe in °C, T_{FT}: Flow temperature in °C and T_{RT}: Return temperature in °C

To ascertain the quantity of heat losses ΔT_m, it is assumed that the ambient soil temperature is constant at 10°C. It is appropriate for early screening but does not replace detailed EN 13941 design calculations for construction-level planning. Eq. (7) provides the average temperature difference:

$$\Delta T_m = T_m - T_{soil} \tag{7}$$

Annual heat losses are calculated for each pipe using U-values from *pipe_info.xlsx*, with Eq. (8) for standard and Eq. (9) for reinforced insulation:

$$Q_{Loss} = \frac{8{,}760 \cdot 2 \cdot U \cdot \Delta T_m \cdot L}{1{,}000} \tag{8}$$

$$Q_{Loss,add} = \frac{8{,}760 \cdot 2 \cdot U_{add} \cdot \Delta T_m \cdot L}{1{,}000} \tag{9}$$

where U: heat transfer coefficient for standard insulation in $W \cdot (m \cdot K)^{-1}$, U_{add}: heat transfer coefficient for additional insulation in $W \cdot (m \cdot K)^{-1}$, ΔT_m: Average temperature difference in K, L: Pipe length in m; 8,760 hours per year with factor 2, as both flow and return are taken into account.

The pipe type and dimensions are automatically assigned for the purpose of route construction, with this assignment depending on the volume flow. A distinction is made between cross-linked polyethylene pipes (PEX) and plastic-coated pipes (KMR) according to the table *pipe_data.xlsx*.

4. Case study and results

The tool is applied to the town of Barntrup (8,500 inhabitants) in NRW. In the legal context of NRW, the "State Heat Planning Act" [53] allows municipalities with < 10,000 inhabitants to fulfil their obligation by means of a shortened heat planning procedure. The case study area (a small sub-parish in Barntrup) is characterised by a predominantly residential single family home stock, complemented by a smaller share of multi-family and non-residential buildings (see table 4).

After processing the workflow as described, the results reveal building blocks with high HD values in the town centre and along main access roads, while peripheral areas exhibit substantially lower densities. Applying the recommended thresholds for HD and HLD, several building blocks qualify as suitable or highly suitable for district heating, whereas low-density areas are more appropriate for individual solutions. These spatially explicit classifications form the basis for defining a prospective district heating supply area and for dimensioning a proto heat centre (see figure 2).

Within the designated research area, a radial district heating network is generated. In total, 268 buildings were connected, corresponding to an aggregated annual heat demand of approximately 11.9 GWh. The resulting network comprises roughly 4.9 km of building connection lines and 4.2 km of main pipes. Under the assumed supply and return temperatures (80°C / 50°C), the calculated annual heat losses amount to around 1.6 GWh (13%) with standard insulation. For pipes with enhanced insulation, these losses decrease to approximately 1.4 GWh (12%) (see table 5).

Table 4: Case study results for area of research of city Barntrup.

Typology	Total number	Net floor space (median)	specific heat demand (median) (SH and HW)	Main year of construction	Heated area in relation to total heated area	Heated floor area (sum)	Age class* (mode)
–	–	m²	$kWh \cdot m^{-2}$	–	%	m²	–
SFH	151	185	190	1960	49	27,991.01	F
GMFH	14	511	207	1945	13	7,159.46	G
MFH	40	350	201	1945	25	13,986.85	F
NRB	63	120	134	1945	13	7,572.89	F

*designated by F|Heat logic; Abb.: SFH = Single family house, GMFH = Great multi family house, MFH = Multi family house, NRB = non-residential buildings, SH = Space heating, HW = Hot water

In parallel, the hourly load profile of the connected buildings was derived and adjusted using simultaneity factors, enabling the estimation of a peak load of about 3.5 MW_{th} for the design of the heat centre (see figure 3). The hourly profile is generated with *oemof.demandlib* [54]. Due to the unavailability of measured operator data for a directly comparable existing network, the results can only be considered as a plausibility benchmark against literature and practice values, as opposed to a formal validation.

To obtain an indicative estimate of the cost contribution of the network, an annuity-based calculation is used. The total investment cost for the district heating pipes is calculated from the total network length L_{tot} and a uniform specific investment cost c_{pipe} of 750 $EUR \cdot m^{-1}$:

$$I_{tot} = c_{pipe} \cdot L_{tot} \tag{10}$$

The value of 750 $EUR \cdot m^{-1}$ is used here as an illustrative assumption and lies within the range of indicative pipe investment costs reported in recent technical catalogues for heat planning (e.g. *Technikkatalog Wärmeplanung* [55]).

The annualised investment cost C_{ann} is then derived using the standard annuity factor $\alpha(i,n)$ for an interest rate i = 4 % and an economic lifetime n = 20 years. The period is an economic comparison horizon and not an assumption about the physical lifetime of district-heating pipes, which is typically longer:

$$a(i,n) = i \cdot \frac{(1+i)^n}{(1+i)^{n-1}} \tag{11}$$

$$C_{ann} = I_{tot} \cdot a(i,n) \tag{12}$$

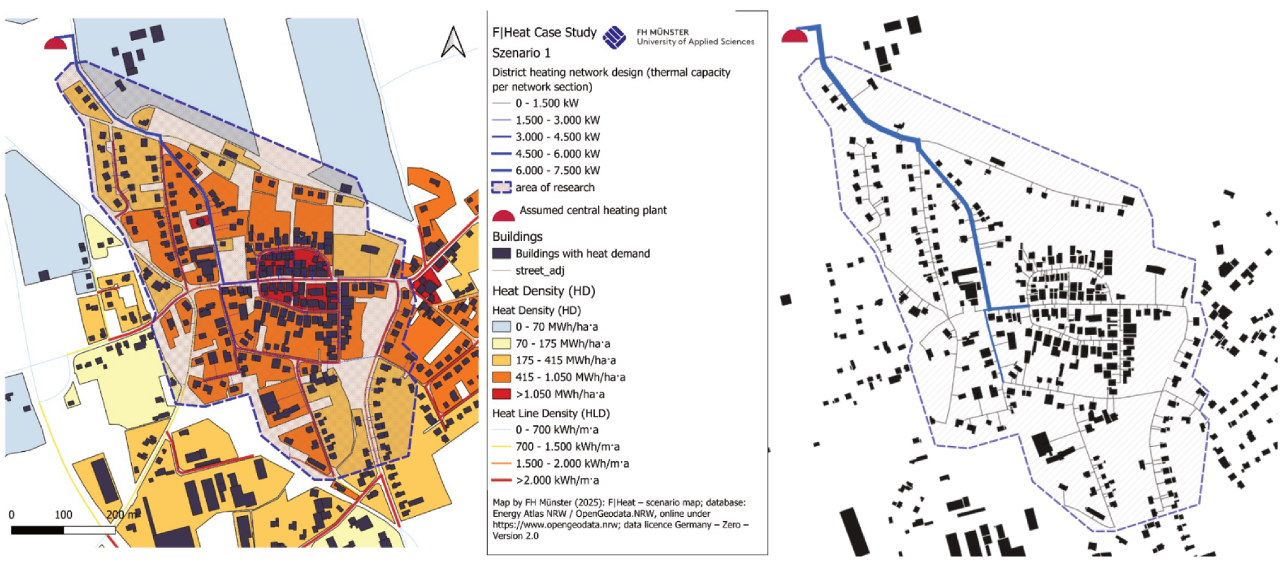

Figure 2: Case study map for the selected supply area in Barntrup, North Rhine-Westphalia, Germany. Left panel shows the full picture. Right panel shows district heating network design (thermal capacity per network section).

Table 5: Case study results: number and length of pipe types with dimensions for connections and distribution.

DN	Number of building connections	Building connection length	Distribution pipeline length	Annual Losses	Losses with enhanced insulation
mm	–	m	m	MWh	MWh
PEX 20	148	2,733	0	339.8	339.8
PEX 25	107	1,819	0	296.2	250.6
PEX 32	9	159	974	208.7	173.7
PEX 40	4	204	545	128.5	109.0
PEX 50	0	0	656	134.6	112.5
PEX 65	0	0	490	114.7	114.7
PEX 80	0	0	497	91.0	77.6
PEX 100	0	0	330	87.0	69.3
KMR 100	0	0	0	–	–
KMR 125	0	0	373	94.1	80.0
KMR 150	0	0	325	96.3	79.4
KMR 200	0	0	0	–	–
KMR 250	0	0	0	–	–
KMR 300	0	0	0	–	–
Sum	268	4,915	4,190	1,590.8	1,406.5

Dividing the annualised cost C_{ann} by the aggregated annual heat demand Q_{ann} of all connected buildings yields a specific cost contribution of the network per unit of heat in EUR·kWh^{-1}:

$$c_{heat\_net} = \frac{C_{ann}}{Q_{ann}} \tag{13}$$

For this example, the total network length of about 9.1 km and a cost of 750 EUR·m^{-1} result in a total pipe investment of roughly 6.8 M EUR. With an annuity factor of $\alpha(0.04,20) \approx 0.0736$, the corresponding annualised cost is around 0.50 M EUR. Related to the aggregated annual heat demand of 11.9 GWh, this yields an indicative network cost contribution of approximately 0.042 EUR·kWh^{-1} (4.2 ct·kWh^{-1}) for the distribution infrastructure.

The figure represents only the network cost component, operation, heat generation and financing are excluded and is intended for plausibility checks and comparison of routing or expansion options at the early planning stage. A subsequent feasibility study should add local heat-source options, technology-specific generation costs, expected connection rates, financing assumptions and customer-side investments. A municipal planner should therefore add these components in a subsequent feasibility study by combining local heat-source options, technology-specific generation costs,

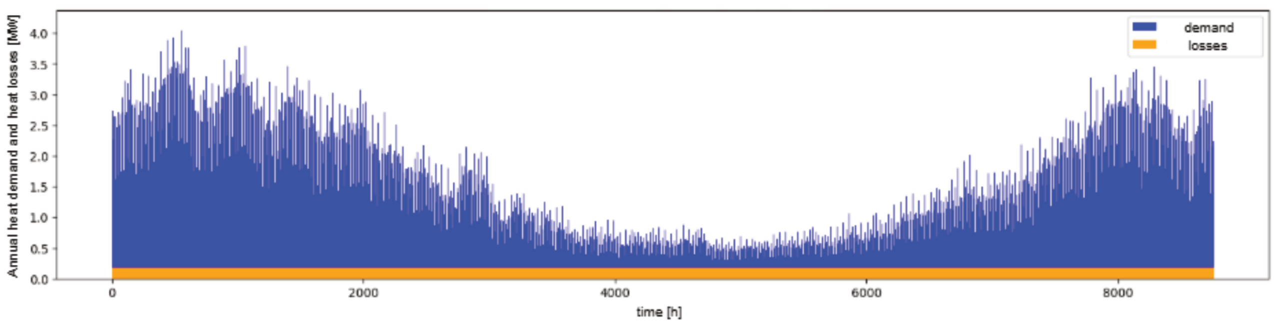

Figure 3: Simulated hourly heat demand and heat losses for the selected district-heating supply area in Barntrup, North Rhine-Westphalia, Germany. The profile is generated with oemof.demandlib and adjusted with simultaneity factors

expected connection rates, financing assumptions and customer-side investment requirements.

This use case illustrates that the current version provides a basis for the design of a prototype heat centre and the associated district heating network in small municipalities. Even in a relatively modest supply area, the tool supports the identification of suitable high-density clusters, generating hydraulically plausible network layouts and quantifying key performance indicators such as network length, annual losses and peak load.

5. Discussion

The results demonstrate that F|Heat supports several WPG-relevant early planning tasks under real-world data constraints. It directly contributes to suitability assessment (§ 14 WPG), status-quo analysis (§ 15 WPG) and demand-oriented parts of potential assessment (§ 16 WPG). It also supports the preparation of candidate heat-network areas and scenario discussion under §§ 17–18 WPG by generating spatial density indicators and preliminary network design.

Future enhancements will broaden its data compatibility to encompass diverse regional data sets across Germany, thereby increasing its national applicability and enabling more comprehensive potential analyses [56,57]. Furthermore, the integration of more advanced thermodynamic and techno-economic models, comparable to those employed in other specialised tools, is anticipated to enhance the precision of network design and operational cost estimations [8].

The simplified pipe investment cost of 750 $EUR \cdot m^{-1}$ includes the cost of pipes, house connections, civil engineering, and a flat-rate charge for the heat transfer station. To obtain a more detailed result, a more in-depth calculation could be performed using the obtained pipe sizes and applying different costs based on DN size and civil engineering factors.

In future development stages, special attention will be paid to the automated classification of areas that are particularly suitable for district heating networks. Taking into account changing gas prices, subsidy schemes and regulatory conditions, it is expected that the implementation strategies of municipal heat plans will have to remain adaptable in order to ensure sufficient pace while still providing planning certainty. Consequently, subsequent versions are expected to facilitate the flexible updating and re-evaluation of network concepts in response to evolving boundary conditions, while concurrently prioritising the augmentation of spatial planning features [29].

In relation to the issue of determining which buildings to connect and the delineation of supply districts, F|Heat offers support for this decision-making process but does not yet automate it. Planners are responsible for defining or revising the area of interest and the set of connected buildings manually, guided by the heat-density and heat-line-density indicators. The following features are planned to strengthen this decision support: automated selection of the highest-density areas, their aggregation into a coherent supply area, and building selection by energy carrier or demand (for example worst-performing or public buildings) under different connection rates.

Regarding usability, existing planning tools often lack user-friendly interfaces or demand significant training, limiting their accessibility to a broader audience, including non-expert municipal planners and smaller energy providers [8]. In terms of regulatory compliance, the framework is specifically developed to align with the WPG. While existing research emphasises the need for tools that can evaluate socio-economic feasibility and cost–benefit relationships, F|Heat integrates functionalities to support these aspects, including the consideration of different insulation variants and the calculation of aggregated values such as length and loss by DN material choice (flexible or fixed pipes).

6. Conclusion

This work introduced F|Heat, a GIS-based tool for regulatory compliance in MHP in Germany. F|Heat addresses gaps observed in existing tools by providing automated workflows for data acquisition, detailed heat demand analysis and comprehensive network assessment, thereby enhancing data integration, usability, and regulatory compliance. Its core functionalities encompass the generation of structured data, aggregated values, and building statistics, alongside the calculation of load profiles.

The tool further supports visualisation of results, including annual load profiles and scenario-based analyses, with seamless export capabilities. By offering a comprehensive and compliance-oriented solution, the extension enables municipalities, regardless of their technical and personnel resources, to start with their own heat planning.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data and software availability

The software is published under the GPL 3.0 license and the source code is available on GitHub [36] alongside with the documentation and the current version (v0.1.1) is published on Zenodo [58].

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