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Techno-economic assessment of district and individual heating and cooling systems: Assessing the accuracy and limitations of a simplified seasonal methodology and validation through a UK case study

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ABSTRACT

Various renewable and infrastructure options are available for decarbonising the heating sector, while cooling is also becoming increasingly important. Existing urban heat planning methodologies often require detailed modelling and often only address a limited range of heating and cooling (H&C) options. This paper analyses the accuracy and limitations of a simplified seasonal methodology for early-stage techno-economic assessment of 4th generation district heating (4GDH), thermal source networks and individual solutions. Using publicly available datasets, a seasonal representation of energy balances and a modular calculation structure, it determines levelised costs for multiple system types with reduced computational effort. Compared with detailed hourly feasibility tools, it reduces the data and time requirements for screening multiple configurations, although it provides less detail in peak load representation, network sizing and operational modelling. The method is validated by comparison with a detailed hourly feasibility study for a 4GDH case study in the UK. Results show cost deviations within ± 30%, mainly due to simplified representations of peak loads and network structures, which lead to differences in component capacities and costs. As this range is generally acceptable for pre-feasibility screening, the methodology enables rapid and transparent comparison of H&C systems to support early planning decisions.

Keywords

District heating and cooling;
Individual heating and cooling systems;
Techno-economic assessment;
Urban energy planning;
Smart energy systems

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1. Introduction

This section outlines the background of current developments in heating and cooling (H&C) systems, defines the planning challenge addressed in this work and motivates the simplified assessment methodology analysed in the paper.

1.1 Background

The decarbonisation of the H&C sector represents one of the most pressing challenges in achieving Europe's climate and energy goals. H&C accounts for nearly half of the EU's final energy consumption [1].

In this context, District Heating and Cooling (DHC) systems offer a promising pathway to decarbonise dense urban environments. Over the past decade, district heating (DH) has evolved towards lower-temperature and more integrated systems. This is exemplified by 4th Generation District Heating (4GDH), which introduced low-temperature operation and improved integration with renewable and waste heat sources [2]. Recently, hybrid solutions combining DH and individual

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List of Abbreviations

4GDH	4th Generation District Heating
CAPEX	Capital Expenditure
COP	Coefficient of Performance
DHC	District Heating and Cooling
DH	District Heating
DHW	Domestic Hot Water
EU	European Union
FAST DHC	Feasibility Assessment Tool for District Heating and Cooling
FLH	Full-Load Hours
GIS	Geographic Information System
H&C	Heating and Cooling
HP	Heat Pump
IEA DH	International Energy Agency Technology Collaboration Programme on District Heating and Cooling
LCOE	Levelised Cost of Energy
OPEX	Operating Expenditure
PPP	Purchasing Power Parity
SC	Space Cooling
SES	Smart Energy Systems
SH	Space Heating
TSN	Thermal Source Network
UK	United Kingdom

technologies, thermal source networks[1] (TSN), have emerged. These consist of ambient-temperature networks, drawing on sources such as groundwater, soil or waste heat that supply decentralised heat pumps (HP) [4]. Due to their ability to also provide cooling, they are often classified under the wider term of DHC. Both concepts support “Smart Energy Systems” (SES) principles [5], enabling sector coupling, integration of renewable and waste heat sources and the use of thermal storage [6].

The suitability of collective H&C solutions such as 4GDH or TSN strongly depends on local demand density, cooling needs, infrastructure and renewable sources. Previous quantitative assessments show that centralised 4GDH can provide economic advantages over decentralised TSN concepts [7-9]. However, TSNs may be advantageous in climates with significant cooling demand or where traditional DH infrastructure is absent [10].

1.2 Motivation

Planning modern DHC systems requires robust methods that can support complex decision-making. As highlighted in recent research reviewing energy system planning tools [11], a range of software solutions exists, from simple calculation tools to advanced simulation environments, scenario-analysis platforms and optimisation tools. These tools enable detailed evaluation of technology options, integration of renewable or waste heat sources and operational analysis of future DHC networks.

Table 1 provides a high-level comparison of selected planning tools relevant to DHC system assessment, highlighting their modelling scope, data requirements and applicability across planning phases. Further information can be found in [12].

Most existing DHC planning tools rely heavily on detailed input data to generate scenario analyses or optimisation-based system modelling [11]. This creates barriers for municipalities, energy planners and policymakers who need rapid, flexible assessments of DHC potential. Moreover, many tools do not allow direct comparison between 4GDH, TSN and individual H&C systems such as standalone HPs. This is particularly problematic because TSNs, despite their promise, still face uncertainties related to decentralised operation, cooling integration and cost structure, while 4GDH systems depend on high-density areas to justify investment [12].

Recent research has also highlighted the importance of spatial heat demand mapping and open-data-based tools for supporting early-stage heat planning. For example, Moreno et al. developed the ODHeatMap tool, which uses open geospatial datasets to generate heat demand maps and support spatial screening and district heating feasibility assessments within sustainable energy planning frameworks [20]. Such approaches support spatial screening and heat atlas development but typically focus on identifying suitable areas for district heating rather than enabling techno-economic comparison of alternative system configurations.

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[1] IEA DHC guidance states that so-called “5th generation” systems are more accurately classified as thermal source networks, a subclass of 4th generation district heating and recommends avoiding the term to prevent misinterpretation [3]. This paper therefore uses the term TSN for clarity and consistency with international practice.

Table 1: Comparison of selected planning tools for DHC system assessment.

Tool	System types compared	Data resolution	Planning phase	Cooling	Reference
EnergyPLAN	Whole energy systems, no direct comparison of DHC typologies	Hourly, system level	Strategic scenario analysis	Yes	[13]
energyPRO	Different DHC configurations analysed as separate scenarios	Hourly operational modelling	Detailed feasibility and operation	Yes	[14]
nPro	District energy systems including low-temperature and 5GDHC concepts	Detailed demand profiles, often hourly	Concept and feasibility planning	Yes	[15]
THERMOS	Heat and cooling network planning using GIS optimisation	GIS and building-level data	Early to detailed network planning	Yes	[16]
Hotmaps	Spatial screening of DHC potential	Georeferenced spatial datasets	Strategic screening and heat planning	Yes	[17]
Waste Heat Explorer	Identification of industrial waste heat sources for DH integration	Site-specific temperature and heat potential data	Early-stage screening	No	[18]
EMB3Rs	Industrial excess heat and cooling recovery including networks	Industrial process and location data	Early feasibility assessment	Yes	[19]
FAST DHC	Comparison of 4GDH, TSN and individual H&C systems	Seasonal aggregated inputs	Early-stage screening	Yes	[12]

The reviewed DHC planning tools either require detailed input data or are limited in scope, leaving early-stage planners without a transparent, standardised framework for comparing 4GDH, TSN and individual H&C solutions under consistent assumptions [11-12]. Recent research has shown that even simpler decision-support methodologies, such as spatial prioritisation and zoning-based frameworks, can support municipalities in identifying suitable heating options at very low input complexity [21]. However, often they do not provide harmonised techno-economic comparisons across different H&C configurations.

Therefore, a gap remains: planners and policymakers lack a simple, transparent and standardised analytical framework to compare the relative advantages of different systems.

1.3 Novel contribution

To address this gap, this paper examines a simplified methodology for early-stage techno-economic assessment of district and individual H&C systems, developed within the FAST DHC (Feasibility Assessment Tool for District Heating and Cooling) project [12]. It bridges the gap between rule-of-thumb methods and detailed hourly simulation tools. The methodology applies seasonal energy balance models and cost curves to assess the performance of different configurations under consistent boundary conditions. Its seasonal approach, together with default technical parameters and cost assumptions, enables early identification of promising system typologies [22]. This paper extends earlier work presented in [23], which introduced a preliminary version of the methodology and provided initial validation results. The present work provides a detailed description of the methodology, a structured comparison of 4GDH, TSN and individual H&C typologies and a systematic analysis of deviations between it and detailed feasibility studies.

The methodology is built around four main principles:

- Simplicity – to enable rapid assessment using the limited input data available in early-stage planning.
- Transparency – to ensure that assumptions, parameters and results can be clearly understood and adapted by planners and decision-makers.
- Comparability – to provide a consistent basis for evaluating 4GDH, TSN and individual systems using the same metrics and system boundaries.
- Accessibility – to ensure it can be used by municipalities, energy planners and consultants without requiring commercial software licences.

These principles were derived from the shortcomings identified in existing energy system planning tools, namely their high input data requirements and limited ability to compare different system typologies under consistent boundary conditions [11-12].

The novelty arises from the standardisation of system boundaries and techno-economic parameters across fundamentally different configurations. Key outputs include capital expenditure (CAPEX), operational expenditure (OPEX) and levelised cost of energy (LCOE), enabling a structured comparison under consistent assumptions with minimal input data.

1.4 Aim of the paper

This paper evaluates the accuracy and limitations of a simplified seasonal methodology for the early-stage techno-economic assessment of district and individual H&C systems. More specifically, it analyses the deviations between this methodology and detailed feasibility studies, identifies the main reasons for these deviations and assesses whether they are acceptable for pre-feasibility screening. It also discusses improvements that could reduce these limitations in future applications.

2. Methodology for early-stage techno-economic assessment

This chapter outlines the methodological framework based on seasonal time steps. It describes how demands for space heating (SH), space cooling (SC) and domestic hot water (DHW) are represented, how system configurations are modelled and how component sizes and energy flows are derived.

2.1 Conceptual framework

The methodology provides an analytical framework for early-stage comparison of network-based and individual SH, SC and DHW options. It applies a simplified, component-based structure using four seasonal timesteps (three months each, as has already been implemented in [24]) and requires limited input data, typically available in early-stage screening. Hourly operational optimisation is deliberately not performed and instead deterministic sizing rules based on seasonal peak loads are applied. Component capacities are derived from aggregated seasonal demand estimates. Central components are sized to the maximum seasonal peak demand multiplied by a user-defined coverage share and a safety factor, while decentralised HPs are sized to the highest peak load across all four seasons considering SH and DHW simultaneously. A detailed description of the deterministic sizing logic, including the full set of equations and parameters used is provided in [12]. The sizing approach is combined with a simplified simulation of system behaviour.

All relevant thermal services (SH, SC and DHW) are integrated within a single system. This seasonal resolution captures long-term H&C asymmetry and seasonal parameter changes (e.g. COP (Coefficient of Performance)) without requiring detailed hourly profiles in early-stage planning. Although intraday effects and tariff-driven dispatch are not represented, this methodology provides a more differentiated representation compared to annual approaches.

The systems are described through five functional layers: supply, transformation, distribution, storage and demand. Each layer can include several technologies and links to the next, enabling a modular representation of building and district systems. The methodology focuses on the urban-district scale, where coordinated planning of multiple buildings is required and focuses on techno-economic comparison.

2.2 System representation

Three thermal energy supply configurations with different levels of centralisation, infrastructure requirements and operating temperatures are compared. Electricity demand for H&C is captured through HP performance and temperature boosting technologies. Electricity generation sources and detailed tariff structures remain outside the scope because the model focuses on simplified seasonal analysis.

The first configuration is 4GDH with centralised heat generation and distribution network operating at a supply temperature of 65°C and a return temperature of 30°C [3]. The second is a TSN operating at ground temperatures, with network supply and return temperatures of 15°C and 5°C, respectively [3]. In the TSN system, heat generation is performed at building level by water-source HPs, providing SH and DHW and rejecting SC heat to the network for seasonal reuse if desired. The third option represents individual air-source HPs installed at building level and operating without any shared thermal infrastructure. Figure 1 illustrates the three modelled system typologies and Table 2 summarises their main characteristics.

2.3 Demand & supply modelling logic

Thermal energy demands for SH, SC and DHW are determined through a simplified approach that enables transparent comparison between systems. The year is

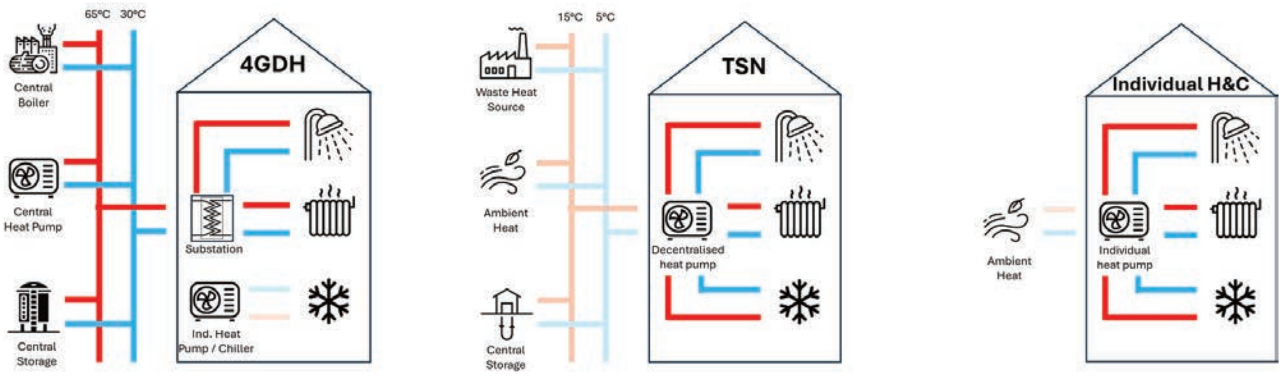

Figure 1: System typologies.

divided into four characteristic seasons. Hourly variations such as short peak clustering, rapid temperature swings or tariff-driven demand shifts are outside the scope. The seasonal approach reflects the intended use case of the methodology, for early-stage screening.

Three representative building types are used: single-family homes, apartment buildings and non-residential buildings. Each type is divided into new and existing categories. This classification is based on age categories derived from the TABULA database [25], which provides specific heating loads for different construction periods across Europe. Buildings constructed before 2000 are classified as “existing”, while those constructed after 2000 are classified as “new”. This threshold was chosen, as a significant improvement in building thermal performance can be observed in the TABULA before and after the year 2000. This improvement is associated with the introduction of stricter building energy regulations and improved construction standards across Europe. The detailed age classes are aggregated into these two categories.

Seasonal energy demand is calculated using Eq. (1):

$$Q_{Season} = A_{Floor} \cdot q_{spec} \cdot \frac{FLH}{10^6} \tag{1}$$

where A_{Floor} is the conditioned area in m²,q_{spec} is the specific thermal load in W/m² [25-27] and FLH are full-load hours-per season, which are derived from local temperature profiles based on H&C degree days [28-30]. To estimate the heat generation capacity, a diversity factor is applied to prevent oversizing generation units following Eq. (2):

$$S_{SH} = DF + \frac{1-DF}{N} \tag{2}$$

DF is the diversity factor and N is the number of connections. The factor accounts for the fact, that not all connected buildings reach their peak heat demand simultaneously and therefore reduces the aggregated peak load used for system sizing. For mixed-use areas the value approaches 0.65 for a large number of connections [7]. DHW demand is calculated using Eq. (3):

$$Q_{DHW,\,Season} = A_{Floor} \cdot q_{DHW} \cdot \frac{1}{4 \cdot 10^6} \tag{3}$$

where q_{DHW} is the specific DHW use in kWh/m² per year [31]. The required heat source capacity for covering DHW loads is derived from a probabilistic approach, based on Euroheat and Power guidelines [32], including

Table 2: System overview.

Configuration	SH supply	SC supply	DHW supply	Network temperatures
4GDH	Central, via network	Building cooling HPs or network cooling	Central, via network	65°C/30°C
TSN	Decentralised building HPs supplied by network	Direct network cooling (heat exchanger) or building HP	Decentralised building HPs supplied by network	15°C/5°C
Individual H&C systems	Stand-alone building HPs	Stand-alone building HPs	Stand-alone building HPs	N/A

DHW storage effects. Although the DHW sizing provides robust estimates at the screening stage, it does not account for short-term COP fluctuations or the impact of temperature lift during peak draw-off events.

Component capacities are derived from building design capacities and demand diversity factors. Each central configuration is based on a user-defined share of the total thermal demand supplied by the primary heat source (HP or heat exchanger), with the remaining share covered by a boiler. Back-up capacity is only activated when the resulting HP or heat source capacity does not fully meet the required seasonal peak thermal load.

Decentralised HP capacities are scaled to the maximum seasonal peak thermal load (SH or DHW). In contrast, central HPs in district configurations are not designed to cover the full peak load. Instead, the approach applies the user-defined coverage share for the primary heat source and the remaining peak capacity is supplied by a central boiler. Storage components, seasonal or DHW storage, can be added depending on configuration. Dynamic dispatch, partial cycling or tariff-responsive charging are out of scope.

For collective systems, network length is estimated from empirical relations between urban density and pipe length per hectare [33]. These relations assume typical network topology and do not represent case-specific routing or dedicated transmission lines.

System performance is represented through temperature-dependent COPs for HPs, using the Carnot formula with a fixed efficiency factor [34]. Default network losses are set at 10% for 4GDH and 1% for TSN [35]. The COP representation reflects seasonal average operation and does not account for transient behaviour such as cycling, defrosting or simultaneous SC–DHW interactions, which generally require higher-resolution simulations.

The resulting outputs include component sizes, electricity and fuel use and annual energy balances. These technical results serve as direct inputs to the economic model, which evaluates the annualised costs and LCOE.

2.4 Economic assessment

The economic performance of system configurations is assessed using a simplified cost model. It includes both CAPEX (initial investments and installation of components) and OPEX (fixed and variable maintenance costs, as well as input energy costs) [36].

Since the lifetime of a building is longer than of its technical components and component replacement cycles differ across configurations, configurations are evaluated using the LCOE, combining annualised CAPEX and OPEX. The annualised CAPEX is derived using Eq. (4):

$$CAPEX_a = \frac{CAPEX}{\frac{\left(1-(1+i)^{-T}\right)}{i}} \tag{4}$$

Where *a* denotes annualised, *T* is the technical lifetime of the investment in years and *i* is the cost of capital in %.

The input energy demand depends on the efficiency of the component using Eqs. (5a) and (5b):

$$Q_{in} = \frac{Q_{Out}}{\eta} \tag{5a}$$

$$Q_{in} = \frac{Q_{Out}}{COP} \tag{5b}$$

Where $\eta < 1$ is the thermal efficiency for fuel boilers (see 5a) and distribution systems and $COP > 1$ is the COP for HPs (see 5b). By default, energy costs are estimated based on Eurostat electricity and gas cost data, which are differentiated based on the consumption volume, with large volume buyers, e.g. utilities, accessing lower energy costs compared to low volume buyers, e.g. households [37].

The annual OPEX is calculated using Eq. (6):

$$OPEX = C_{Fixed} + C_{variable} \cdot Q_{out} + Q_{in} \cdot C_{fuel} \tag{6}$$

The LCOE is calculated using Eq. (7):

$$LCOE = \sum_i \frac{CAPEX_{a,i} + OPEX_i}{Q_{out,i}} \tag{7}$$

where *i* represents the components of the considered configuration.

The applied economic model is based on multiple elements, where each element represents a specific component of the system (Figure 2).

This modular approach enables complex configurations to be broken down into their base components, allowing LCOE to be evaluated straightforwardly for each configuration.

2.4.1 Scaling of investment costs

A common challenge when evaluating the costs of infrastructure solutions is the lack of technology-specific cost

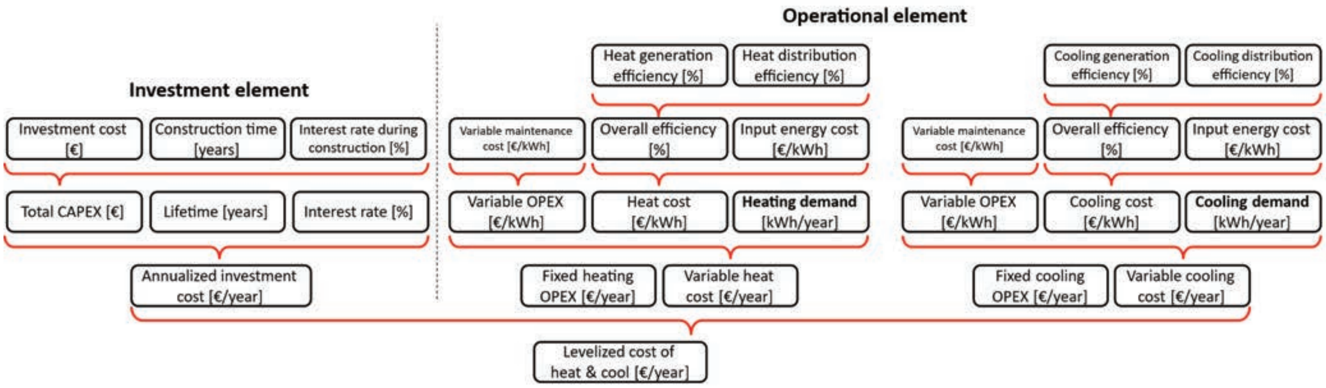

Figure 2: Economic model for evaluating LCOE.

data across a range of capacities. This often leaves only a limited number of data points. To address this issue, the methodology relies on power regression to account for the relationship between cost levels and installed capacities, based on data obtained from [30]. Cost scaling is represented using a power-law relationship of the form $C = a \cdot Q^b$, where C is the specific investment cost, Q is the installed capacity and a, and b are regression parameters derived from the available cost data. Examples of resulting correlations are shown in Figure 3.

2.4.2 Transfer of techno-economic data between countries

Although technologies are universally available, the cost of investing in and installing them can vary significantly between countries. To achieve optimal results, the local investment and installation costs of each technology should be applied; however, such data are not always available. Where technology data is lacking, Eurostat-published purchasing power parities (PPP) [38] are used to transfer economic data from one country to another. The datasets used for PPPs are Eurostat's datasets for machinery and equipment (A0501), investment costs (A050203) and installation costs.

Another common challenge is that techno-economic data is based on realised projects and can therefore be outdated. To reduce economic uncertainties due to temporal differences in data points and the corresponding economic inflation, the data are inflation-adjusted using Eurostat datasets for the manufacture of machinery and equipment (STS_INPP_A: C28) for all technology equipment costs and for the services of plumbers

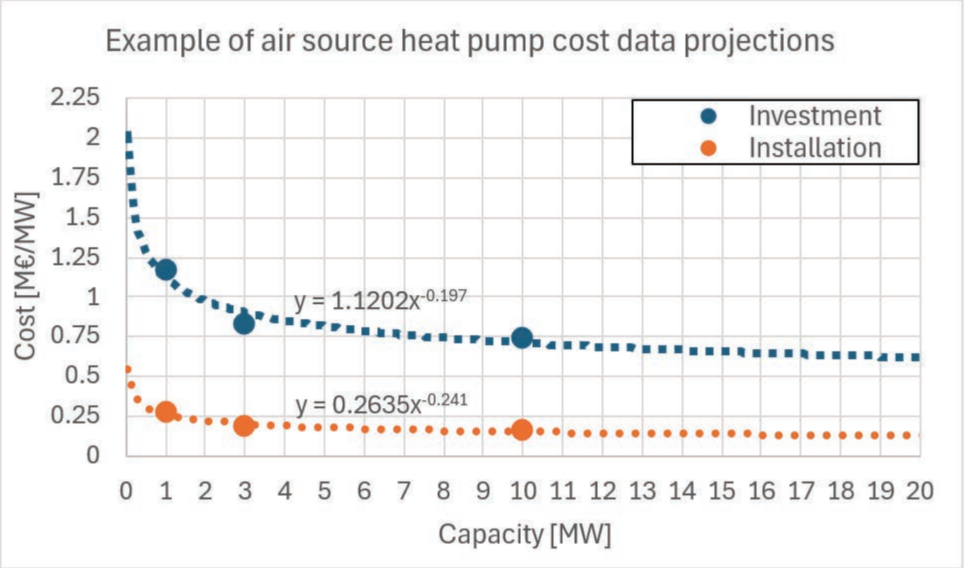

Figure 3: Examples of cost projection using power functions for investment and installation of air-source HPs.

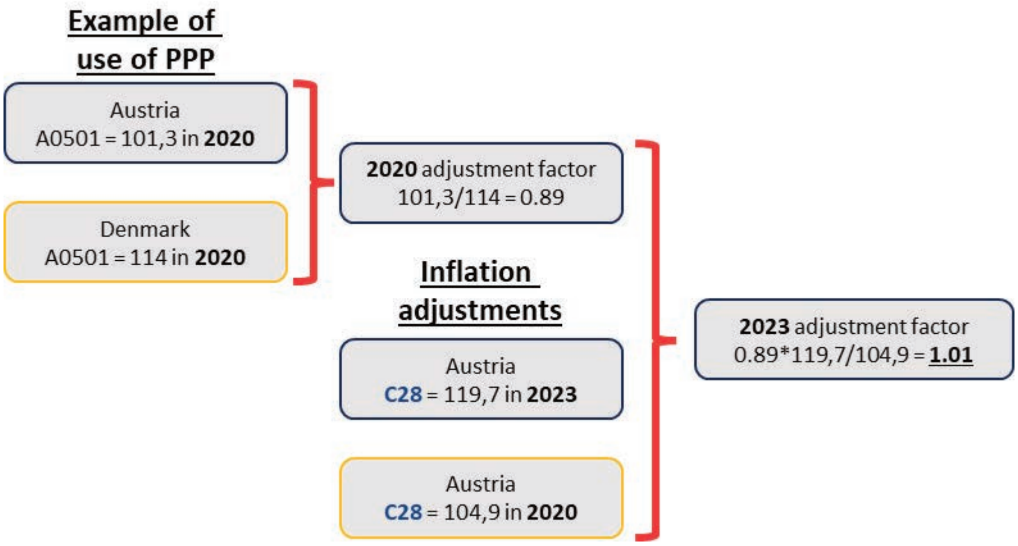

Figure 4: Example of usage of PPPs and inflation adjustments datasets.

(PRC_HICP_AIND: CP04321), which is generalised to apply to all civil engineering works. Figure 4 illustrates the main approach to using PPPs and inflation adjustments.

2.5 Data integration and flexibility

The methodology is supported by a modular database architecture that enables transparent, reproducible and adaptable application across different contexts. Input data can be updated or replaced as required. Default datasets are provided for Austria, Denmark and the United Kingdom (UK), including energy prices, technology costs and building typologies. All technical and economic parameters are derived from publicly available national and international datasets.

The open structure enables boundary conditions to be adjusted to reflect local circumstances and allows sensitivity analysis to be performed on key assumptions such as energy tariffs, economic parameters, climatic conditions and technology choices. This supports reproducible early-stage assessments under varying local boundary conditions. Overall, the design supports transparent and reproducible early-stage assessments.

2.6 Validation methodology

The methodology was validated through comparative studies using four completed feasibility studies conducted in Denmark, the UK and Austria [12]. The London Borough of Barking and Dagenham, hereafter referred to as B&D, serves as the main validation case in the following chapter. Results were compared with detailed simulations performed with modelling tools such as energyPRO, focusing on total annual energy use, technology sizing and LCOE.

3. Case Study

The case study is used to validate the methodology by applying it to an urban district heating development. The objective is to assess whether the methodology reproduces the order of magnitude and indicator structure of the established feasibility configuration.

The investigated area comprises a newly developed urban district of approximately 10,800 residential units in B&D. The heat supply is planned to rely on a 4GDH system that would recover low-temperature heat from the effluent of the Beckton Sewage Treatment Works. With an approximate dry flow rate of 5 m^3/s, the heat recovery potential is estimated at around 105 MW for an effluent temperature reduction of 5 K, making the site suitable for large, centralised heat supply. Heat is extracted centrally from wastewater using a 26 MW_{th} HP system that supplies the network at approximately 65°C. A 2,600 m^3 diurnal thermal storage tank is included to support flexible operation and reduce exposure to electricity price fluctuations.

Figure 5 illustrates the conceptual network layout and the connection to the wastewater heat source. SH and DHW demands would be fulfilled via the DH network, while SC would be provided by decentralised air-to-water HPs.

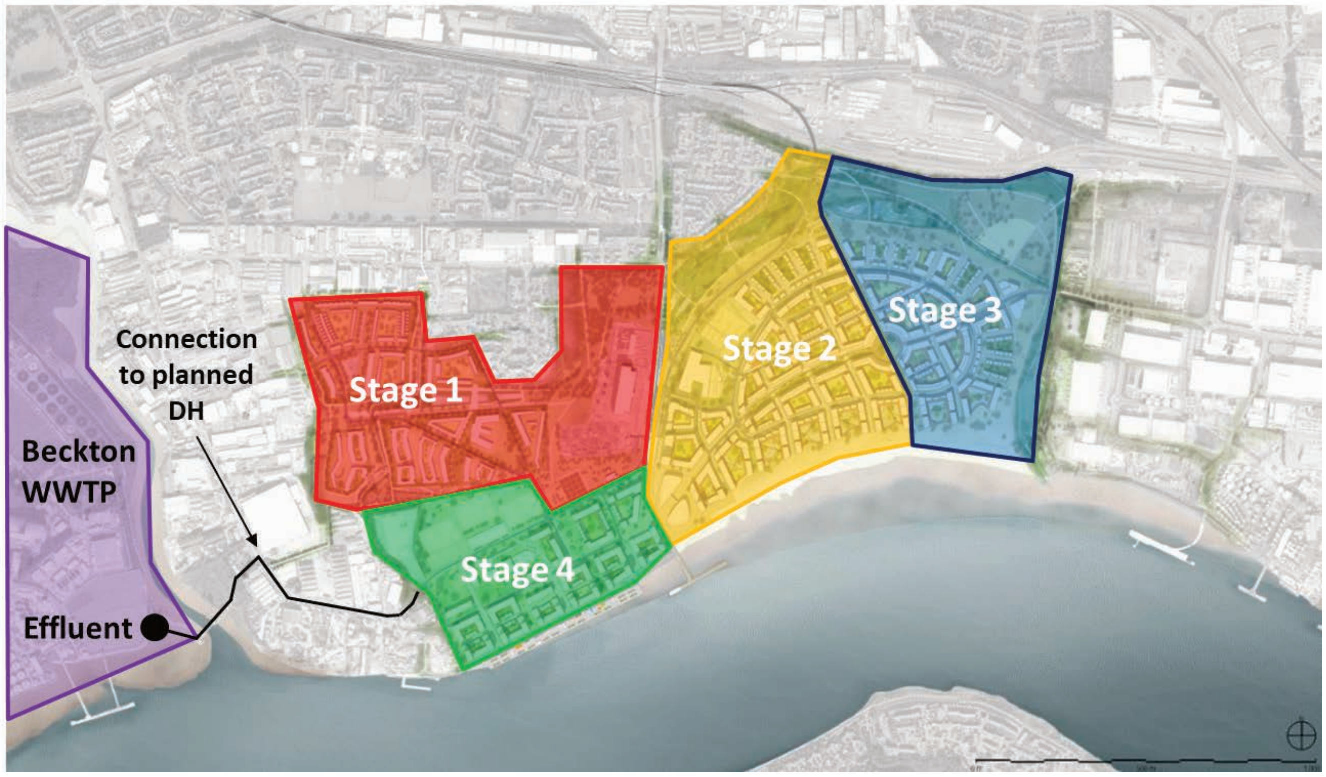

Figure 5: Map of construction stages and DH connection to the heat source in the case study.

The detailed reference case was analysed using the energyPRO [14] modelling framework, which performs hourly operational optimisation of a proposed network that was conceptually designed by a consortium of UK-based researchers and consultants as part of the GreenSCIES project [39]. In the reference feasibility study, the main component capacities were defined externally based on connected heat demands and only the operational behaviour was optimised through detailed hourly scheduling.

For the comparison, CAPEX and OPEX estimates were obtained directly from the original feasibility study and reflect market cost data for the UK in 2021. For comparison with the methodology presented, the same technical and economic input data were transferred into the format of the methodology. Hourly parameters such as electricity prices were aggregated to match the input format of the methodology, using annual or where possible seasonal averages. Likewise, FLH for SH and DHW were adjusted to represent the annual demand profile of the case study.

The comparison between the reference feasibility model and the simplified methodology therefore relies on harmonised technical and economic inputs, while differences in modelling resolution and operational representation remain inherent to the respective modelling approaches.

4. Results

This section outlines the validation of the presented methodology with the reference case studies and evaluates the B&D case in more detail.

4.1 Illustrative comparison of alternative system configurations

Building on the B&D case study, the methodology allows a comparative assessment of 4GDH, TSN and individual H&C configurations under the same boundary conditions. This comparison is not part of the validation, as no reference feasibility studies exist for TSN or individual solutions in the case of B&D. Instead, it illustrates how the methodology differentiates between alternative configurations under the same boundary conditions, without redesigning the case study.

The comparison (see Figure 6 below) illustrates that, under the given assumptions, the centralised 4GDH

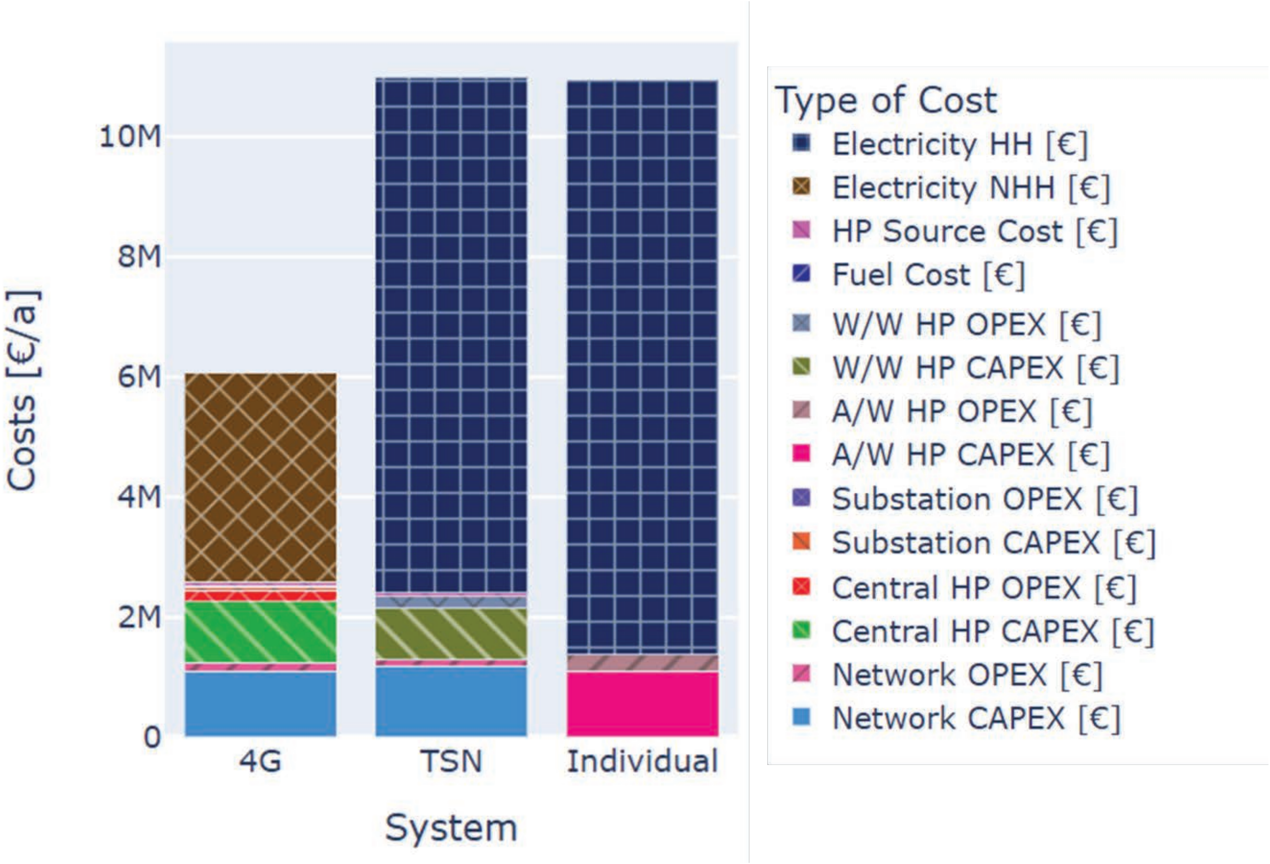

Figure 6: FAST DHC output.

configuration results in the lowest total annualised costs. This outcome is primarily driven by the combination of a higher supply temperature from the source and the scale effects of a centralised HP. In all three cases electricity costs for households and non-households are the dominant cost component, reflecting the electrification of heating. Since the reference feasibility study only provided a non-household electricity tariff, this value is applied to the centralised system as well, while for households the default value for UK is used. The same electricity tariffs are applied for the TSN and individual configurations. Furthermore, the central HP operates more efficiently due to the relatively high and consistent temperature of the wastewater source, which further reduces overall operating costs. In contrast, the individual solution requires more electricity due to lower source temperatures (air). While the individual typology avoids network-related investments it does not offset the increased OPEX, resulting in a higher overall annualised cost level than a 4GDH network.

4.2 Analysis of detailed results for the B&D case

The methodology reproduces the general techno-economic characteristics of the detailed case study at system level in an acceptable way. This confirms that the screening methodology can approximate high-level techno-economic indicators such as total annualised cost and LCOE, despite not performing hourly dispatch or using pre-defined component capacities. The results differ from the earlier validation summary in [23], as a newer version of the methodology was used. Table 3 summarises the main comparison metrics, while Figure 7 and Table 4 present the component-level breakdown of annualised costs.

Given that the methodology is intended for pre-feasibility assessments, deviations of this magnitude are consistent with the uncertainty associated with early-stage techno-economic estimates and order-of-magnitude cost assessments reported in the literature [40]. The most significant deviations occur in the sizing of the network and O&M costs. Despite these component-level discrepancies, the total annualised costs and LCOE

Table 3: Comparison of modelling results for FAST DHC and the case study.

Item	**Reference value**	**FAST DHC**	**Difference**
Total annualised CAPEX	1.672 M EUR/y	2.354 M EUR/y	+41%
Total OPEX	3.550 M EUR/y	3.825 M EUR/y	+8%
LCOE	60 EUR/MWh	72 EUR/MWh	+20%

Table 4: Breakdown of annualised costs per component for FAST DHC and case study.

Component	**Reference value [M EUR/y]**	**FAST DHC [M EUR/y]**	**Difference**
HP	1.070	1.107	+3%
Heat recovery	0.102	0.140	+37%
DH network	0.500	1.193	+139%
O&M costs	1.118	0.330	-71%
Electricity	2.432	3.495	+44%

remain in a similar range because deviations between cost components partly compensate each other.

As shown in Table 4, the largest discrepancies are associated with electricity costs, followed by O&M and DH network costs. Electricity costs differ between the reference model and the methodology because it uses an annual average electricity price and does not capture short-term or seasonal price fluctuations. The discrepancy in O&M costs arises because the case study includes additional elements not covered in the

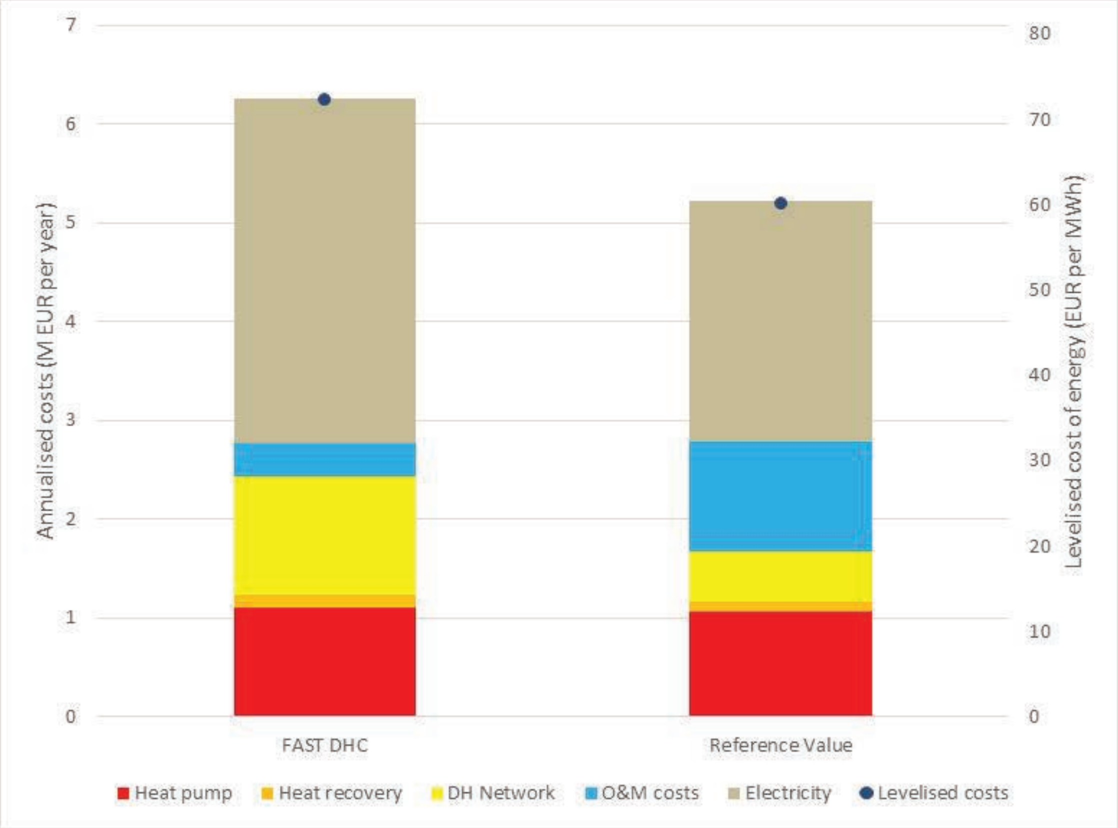

Figure 7: Breakdown of estimated costs per component and LCOE for FAST DHC and the case study.

Table 5: Comparison of deviations of modelling results for FAST DHC and the case studies.

	Bristol (UK)	**B&D (UK)**	**Vienna (Austria)**	**Midtjylland (Denmark)**
Type	4GDH	4GDH	TSN	TSN
Deviation of total annualised CAPEX in %	+44%	+41%	+4%	+47%
Deviation of total OPEX in %	+24%	+8%	-39%	+25%
Deviation of LCOE in %	+30%	+18%	-27%	+34%

methodology, such as staffing and insurance. Differences in DH network costs result from different cost-per-metre benchmarks, with the methodology applying a generalised benchmark derived from technology catalogues rather than project-specific infrastructure costs. These benchmarks represent generalized installation conditions and may therefore appear higher than the costs reported in individual case studies that benefit from favourable local installation conditions.

4.3 Validation results from the other case studies and summary

This section evaluates how well the methodology reproduces key indicators from the reference feasibility studies. The methodology has been tested using four case studies covering two 4GDH configurations (Bristol and B&D, both in the UK) and two TSN configurations (Vienna, Austria and Midtjylland, Denmark). Table 5 summarises the deviations between methodology and the reference feasibility studies for total annualised CAPEX, total OPEX and LCOE across all four validation cases.

Depending on the interaction between electricity prices, component sizing and HP aggregation, the methodology reproduces levelised and annualised cost indicators that deviate roughly by ± 30%. For TSN configurations, higher deviations result from the deterministic sizing logic for decentralised HPs, the absence of inter-temporal storage use and linearised network cost benchmarks. These effects are structural rather than input-related, reflecting the limitations of the methodology. In the B&D case, deviations in DH network and CAPEX exceed this range due to different network cost benchmarks.

5. Discussion

The SES concept provides a broader context for interpreting the results. SES emphasises sector coupling and flexibility across electricity, heating, cooling and transport. The 4GDH and TSN concepts contribute to this through low-temperature operation, waste heat integration and the possibility of decentralised HP operation [5, 41]. Although DHC has great potential for H&C decarbonisation, its suitability depends on local demand densities and system characteristics and TSN could be beneficial where cooling integration or decentralised operation is required. This highlights the need for methods that allow early comparison of such configurations.

In this context, the case study results demonstrate that the presented methodology can reproduce key cost and performance trends of detailed feasibility studies. Some deviations in component sizing are observed, reflecting seasonal aggregation and simplified cost representation. However, the aggregated indicators, particularly the LCOE, remain within a range of ± 25 to 35% compared to the reference study, consistent with uncertainty ranges reported for early-stage feasibility estimates (−30 % to +50%) [40].

The results indicate that the main analytical value of the methodology lies in rapid early-stage comparison with limited data-availability under transparent and harmonised assumptions, rather than in replicating detailed component sizing or operational behaviour.

The comparison also highlights areas where seasonal aggregation leads to differences with the reference model, for example when temporal variations in demand and electricity costs influence component sizing or storage use. These deviations follow structural patterns rather than random errors, resulting from deterministic sizing rules and the absence of intra-day storage effects, consistent with the screening role of the methodology.

The methodology provides a consistent basis for early-stage comparison of 4GDH, TSN and individual solutions with minimal data requirements and can therefore support the prioritisation of configurations for subsequent detailed assessment. Many key boundary conditions, such as energy prices, demand levels and technology shares, can be adjusted, while some structural model parameters remain fixed to preserve stable, physically correct and efficient calculations. Detailed H&C demand data or planned network lengths can also be imported from other methods, such as the GIS-based energy demand estimator developed by [42], when actual energy demands differ from generic top-down estimates such as heat atlases or published energy benchmarks [43].

The four validation cases confirm that system-level indicators can be captured within an early-stage deviation range, with LCOE deviations between −27% and +34%. The observed deviations are structural and derive from the modelling methodology rather than input errors, primarily due to seasonal aggregation, deterministic sizing rules and linearised network cost benchmark. Among all components, network CAPEX is most sensitive to these assumptions. The EUR/m benchmark dominates investment uncertainty, which leads to significantly higher deviations in B&D (+139%) and Midtjylland (+127%) despite accurate demand representation. Centralised 4GDH configurations are comparatively robust, as the seasonal peak heuristic aligns with the engineered capacity range of large HPs.

In contrast, TSN configurations exhibit larger deviations because the methodology applies deterministic per-building sizing based on the seasonal maxima of SH, DHW and SC, rather than aggregating loads across buildings. Unlike engineering design, this sizing approach does not represent operational sequencing (e.g. DHW charging temporarily replacing SH in practice), therefore, the model selects the highest seasonal service peak rather than the dominant operating regime. In engineering practice, DHW tanks, rejected-cooling reuse and diversity factors reduce the effective peak capacity of individual units, explaining why the sizing logic systematically overstates building-level capacities in TSN cases. This limitation mainly affects multi-service TSN configurations, whereas SH/DHW sizing alone generally aligns with standard practice.

Electricity cost deviations scale with temporal resolution, since hourly price response and storage cycling in the reference models reduce OPEX, while the average prices used may increase or reduce it depending on system layout. Component-level divergences tend to compensate at system level, as oversized HPs increase CAPEX, but reduce the use of backup or peak-load technologies, thereby lowering electricity consumption without implying higher COP. Consequently, the results should be interpreted as indicative for early-stage screening rather than prescriptive for optimisation or detailed design.

5.1 Limitations

The methodology is designed for pre-feasibility screening rather than detailed operational design. The seasonal approach captures structural differences, but does not represent hourly operation, defrost behaviour, simultaneous SC–DHW operation or price-responsive dispatch. Consequently, electricity price volatility and intraday storage effects are not reflected and hourly OPEX from COP modulation may differ from feasibility models. These limitations may become more relevant in future energy systems with higher shares of intermittent electricity generation and increased price volatility. Short-term load shifting and storage cycling are outside the model scope. The presented methodology therefore identifies suitable configurations and relative cost structures, while detailed sizing requires higher-resolution models.

The simplified DHW sizing represents probabilistic consumption behaviour but does not capture instantaneous DHW peaks or their COP impacts, which require more granular modelling approaches.

HPs are sized using the highest seasonal peak among SH, DHW or SC, after applying service-specific reductions (e.g. SH simultaneity and DHW tank smoothing), but without modelling operational sequencing between services. This can lead to over- or undersizing in multi-service configurations if the dominant operating regime differs from the selected peak.

Effects such as temperature-dependent losses or operational return behaviour are not explicitly modelled. Network cost estimation is based on linear EUR/m benchmarks and does not account for routing or clustering. This simplification leads to deviations in network CAPEX depending on spatial density and development geometry.

5.2 Outlook

Future work should focus on gathering more empirical data for different typologies to improve understanding of layouts and associated cost structures. This includes refined HP sizing at the building level, more advanced, but simple network and storage sizing approaches and additional validation for configurations with multi-service interaction. Extending the methodology to additional countries in Europe and internationally would further strengthen its value as a pre-feasibility indicator for emerging DHC markets.

Future validation should also assess performance under highly decentralised layouts and atypical routing contexts, where deviations are expected to increase.

Additional research may examine the sensitivity of long-term system economics to changes in electricity price structures and regulatory conditions, as variations in OPEX may influence LCOE outcomes over the lifetime of DHC investments. The methodology currently focuses on technical CAPEX and OPEX related to system components, while policy-driven price elements, tariffs or profit margins require more detailed commercial modelling beyond the scope. Future developments may also allow users to adjust currently fixed internal parameters such as network cost benchmarks in EUR/m to better reflect project-specific infrastructure conditions.

6. Conclusions

This study introduced a transparent and standardised methodology for early-stage techno-economic assessment of H&C options, enabling comparison of 4GDH, TSN and individual building-level systems under limited data-availability and harmonised boundary conditions. By combining simplified seasonal energy balances, deterministic component sizing and a modular cost calculation approach, a consistent basis for comparing collective and individual system configurations is provided.

The validation based on a 4GDH case study in B&D shows that key system-level indicators can be reproduced with an accuracy suitable for pre-feasibility analysis. The deviations were mainly arising from the deterministic seasonal sizing logic and the use of generic infrastructure and heat recovery cost benchmarks. These deviations primarily affect component-level parameters and specific cost items, while aggregated indicators such as total annualised cost and LCOE remain within ranges acceptable for pre-feasibility screening.

The presented methodology contributes to SES planning by providing an integrated representation of H&C, HPs and storage within a single system boundary. This approach is consistent with the well-established principles of sector coupling and energy system flexibility. It enables consistent comparison of centralised and decentralised configurations, supporting evaluation of 4GDH, TSN and individual solutions in urban decarbonisation strategies. Its transparent data structure and minimal input requirements make it particularly suitable for screening, zoning and first-phase assessments where rapid evaluation and reproducibility are essential.

Overall, the presented methodology provides a consistent, transparent and efficient approach for early-stage techno-economic comparison of H&C systems. It is designed for rapid screening and early decision support based on aggregated performance and cost indicators.

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