Thermal and Economic Assessment of 5GDHC for Private Residential Decarbonization: A Scenario-Based Study

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Abstract:
The study examines early-stage design of fifth-generation district heating and cooling (5GDHC) systems in small residential communities where complete geospatial data are often missing, waste-heat sources are absent, and synergy between buildings is limited. To overcome data gaps, Building Information Modeling (BIM) inputs are combined with spatial attributes derived from GIS, while a GIS-based workflow is used to evaluate rooftop photovoltaic (PV) potential and mitigate the impact of low thermal-load complementarity. Because renewable-based solutions carry higher upfront costs and greater investment risk for small communities, a multi-scenario assessment is carried out using an integrated design framework that couples thermodynamic, electrical, and economic models. This framework enables a consistent comparison between fossil-based systems, hybrid configurations, and renewable options, including geothermal integration, both with and without thermal network coupling. The framework employs thermodynamic and electrical models to quantify energy balances, flows, losses, and system efficiencies, while the economic and environmental analyses evaluate costs, payback periods, investment feasibility, and reductions in greenhouse-gas emissions. The results show that adding PV supply to a 5GDHC network significantly increases its applicability even under low-synergy conditions. A fair comparison between PV-equipped and non-PV scenarios indicates a 26% improvement in savings and a 24% reduction in payback time, yielding payback periods below 20 years. These findings highlight the strong decarbonization potential of sector-coupled, electrified 5GDHC systems in heating-dominated communities and support stakeholders in designing future clean-energy configurations that incorporate thermal networks.

Keywords:
Urban energy systems; Spatial analysis; Waste heat; Decarbonization; Total cost of ownership; Sector coupling, PV share ; Synergy ; Heating and Cooling

1. Introduction

Decarbonization of buildings is a central pillar of the energy transition, which requires large-scale integration of renewables and the electrification of thermal networks through advanced district heating and cooling (DHC) solutions. Among these, ultra-low-temperature DHC, or 5th-generation DHC (5GDHC), enables low-grade waste-heat recovery and flexible prosumer operation by circulating water near ambient temperatures and using decentralized heat pumps (act as booster heat pump) to exchange energy among network participants [1, 9, 15, 19]. The potential of these networks depends largely on the diversity and complementarity of the thermal-demand profiles within the community [15], often referred to as synergy [11]. When heating and cooling demands do not coincide, the resulting mismatch is absorbed by a balancing node, whose required capacity is determined by the residual imbalance in the network [6, 7]. Despite its potential, 5GDHC deployment remains limited due to the novelty of the technology, higher substation costs compared to DH substation ([4,5]), complex prosumer-based operation ([13]), and the lack of mature design guidelines [9]. Economic studies also show that conventional 4GDH often retains cost advantages over 5GDHC [10]. Uncertainties in energy demand, energy prices, and equipment costs complicate both planning and operational optimisation [6], and these challenges are even more pronounced in small-scale networks with limited demand synergy and few available waste-heat sources. This combination reduces investor confidence and makes strategic decisions harder, highlighting the need for structured evaluation frameworks such as CPAEX—particularly in cases where traditional approaches like SWOT [3] cannot adequately assess emerging, uncertainty-driven 5GDHC concepts.

1.1. Previous work

Several studies have examined building-connected heating and cooling configurations. [7, 19] compared multiple designs in terms of energy costs and emissions, while [14] highlighted emerging business models for district heating and cooling (DHC). With increasing cooling needs under climate change, DHC becomes more relevant by jointly supplying heating and cooling and enabling prosumers to sell surplus heat—creating revenue streams not available in conventional systems [9]. However, these developments also highlight a persistent challenge: the transition toward electrified thermal networks increases exposure to uncertainty. Prior work [6, 7, 15] shows that in locations with limited demand diversity or small-scale networks, long-term financial feasibility becomes highly sensitive to fluctuations in energy prices, load profiles, and investment costs. Electrification amplifies this sensitivity because renewable generation—particularly rooftop PV—is inherently variable. To address this, recent studies combine GIS-based rooftop solar mapping with PVGIS performance modelling to quantify irradiance, feasible PV capacity, and expected energy generation [7]. Such integrated workflows, as demonstrated in [17, 18], provide spatially explicit insights that support local energy planning and help reduce uncertainty in PV-driven electrification strategies.

1.2. Novel contributions

Small-scale energy communities often face limited demand diversity, which constrains the feasibility of emerging 5GDHC concepts [16]. These districts typically lack waste-heat sources, show weak heating–cooling complementarity, and include few prosumers, reducing the natural synergy that larger networks benefit from [16]. This work develops an integrated workflow to evaluate how such low-synergy areas can still benefit from 5GDHC by strengthening sector coupling through local PV integration and analysing how PV-driven electrification influences thermal-network behaviour.

The work delivers four key advances: a GIS-based workflow to quantify rooftop irradiance, identify usable PV areas, and estimate maximum PV capacity; a coupling of these spatial outputs with PVGIS to model realistic PV generation and assess how much local electricity can support heat-pump electrification; an evaluation of how increased PV deployment affects grid dependence, system feasibility, and the technical, economic, and CO_2-reduction performance of the community; and an identification of robust electrification–PV scenarios capable of reliably meeting building energy needs. Together, these elements form a coherent methodology for analysing electrification pathways in small-scale energy communities and guiding planning and investment decisions.

1.3. Organization of paper

The paper is structured as follows: Section 2 introduces the generic framework and the KPIs used in the assessment; Section 3 presents the case study; Section 4 discusses and evaluates the results; and Section 5 provides the conclusions.

2. Material and methods

A generic thermodynamic framework introduced in [6, 7] is extended to incorporate a renewable energy supply based on photovoltaic energy - by optimizing the installation of the panels according to the usable roof area of the buildings. This enhancement enables a systematic comparison of network performance with and without PV penetration and helps identify locations where limited comple-

mentarity between thermal demands may constrain the potential of 5GDHC systems. The resulting insights support stakeholders in judging whether 5GDHC remains viable in small private communities with scarce waste-heat resources.
The methodology developed in this work consists of three main steps, illustrated in Fig. 1. Step 1 performs geospatial processing to extract building footprints, available rooftop area for PV installations, network routes, and local energy potentials. Step 2 conducts network design and performance analysis for the 5GDHC scenario. Step 3 benchmarks the results against present-day technologies using key techno-economic and environmental KPIs. These steps are described in detail in the following sections, followed by an explanation of the KPIs used to evaluate the suitability and potential of 5GDHC for small-scale energy communities.

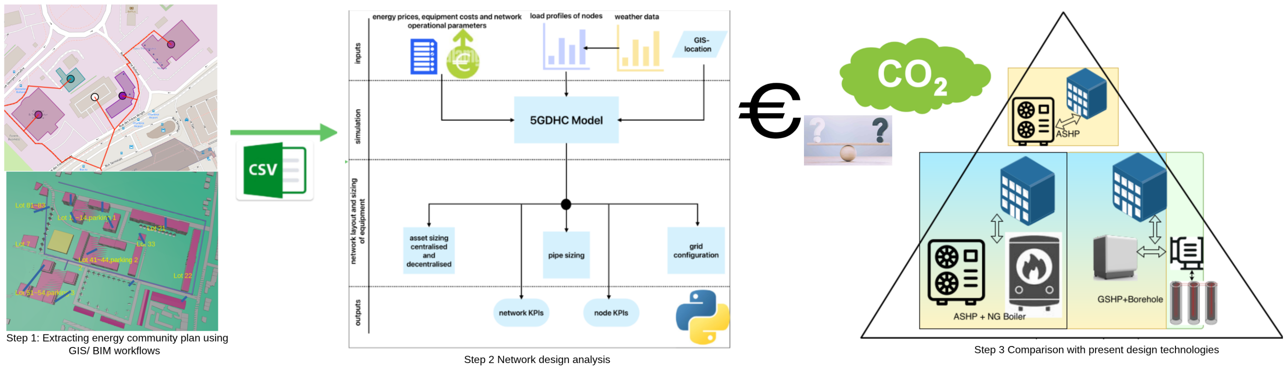


Figure 1: Schematic layout for assessing potential 5GDHC locations using a combined GIS and Python-based approach

2.1. Geospatial processing

The process begins with the collection of high-resolution spatial data, including building footprints, rooftop available are for PV installations [18],road layouts, and infrastructure coordinates (via a dedicated file exchange Industry Foundation Classes (IFC)), which are then used to generate a two-dimensional spatial graph. In this graph, buildings and available heat sources (e.g., data centers, thermal energy storage units) are represented as nodes, while potential pipeline routes are modeled as weighted edges. These edges are assigned costs based on Euclidean distances and unit installation prices, ensuring that spatial constraints like road paths and building placement are respected as discussed in [21].
The District Planner exchanges information with the GIS and BIM environments through a CSV-based data interface, as summarised in Tables 1 and 2. These exchanges are executed using dedicated workflows implemented with a (PyQt-based interface), which automates the import, processing, and synchronisation of spatial and building-level attributes.
In this format, columns x and y denote the prosumer node's coordinates in meters within the Earth's reference system; column SA specifies the building's surface area, while column EPC represents the building's energy performance certificates (EPC). Another exchange format given in Table 2, provides

Table 1: Data exchange format from the BIM to the district planner, listing the position, surface area, consumption, and waste heat production

ID	Name	EPC [MWh/m^2]	E [MWh]	SA [m2]	x [m]	y [m]
N01	apartment1	xxxx	xxxx	xxxx	xxxx	
N02	office1	xxxx	xxxx	xxxx	xxxx	
....	....	xxxx	xxxx	xxxx	xxxx	

details about the connection between the prosumers. Each participating prosumer node, $n \in 1, N$, is linked to the network through a pipe, $D_{i,j}$, where i and j correspond to the 'From' and 'To' node columns [6].

Table 2: Data exchange format from BIM to district planner, listing the size of each network section

ID	From	To	D [mm]
D01	apartment1	office1	xxx
D02	office1	fork1	xxx
....	....	....	xxx

2.2. 5GDHC network design and analysis

The framework uses EPC labels extracted either from GIS layers, IFC files, or directly provided by the user. These EPC values are combined with the available building surface area (SA) from Table 1 to generate heating and cooling time-series. The total annual thermal demand Q [MWh] is computed as:

$$Q = \mathrm{EPC} \cdot \mathrm{SA}. \tag{1}$$

Hourly energy profiles are then generated for the period `YYYY:MM:DD hr:min:sec` to `YYYY:MM:DD hr:min:sec` following the methodology in [11].
E [MWh] is the building's non-HVAC electricity (lighting and appliances). HVAC electricity is excluded and approximated as 30% of the thermal demand Q.
Similarly, the district planner imports photovoltaic (PV) system data from a dedicated exchange file. This includes the available rooftop area, installed PV panel area, geographic coordinates, installation year, tilt angle (from the horizontal), azimuth angle, standard test condition irradiance (G_{STC} [kW/m²]), and the specific investment cost of the PV system ($\mathrm{CAPEX}_{\mathrm{PV}}$ [EURO/kWp]). Hourly solar irradiance and outdoor temperature data are retrieved via an API based on the location of buildings using Photovoltaic Geographical Information System (PVGIS). The power output from the PV system at each time step is estimated using:

$$P_{\mathrm{out}}(t) = \gamma \cdot G(t) \cdot A_{\mathrm{roof}} \cdot \eta_{\mathrm{pv}}, \tag{2}$$

where $\gamma = 0.86$ is a correction factor to account for approximately 14% system losses, $G(t)$ is the solar irradiance [W/m^2] at time t , A_{roof} is the total rooftop area available for PV installation [m^2], η_{pv} is the efficiency of PV panels.
The total monthly energy output is computed by aggregating the hourly outputs:

$$E_{\text{PV, monthly}} = \sum_{t \in \text{month}} P_{\mathrm{out}}(t) \cdot \Delta t, \tag{3}$$

where Δt is the time step in hours.
The information given in Table 2 is used by framework to draw and size the network and to analyze energy flows using graph theory [8]. Moreover, the prosumer nodes are referred to as external nodes, while junctions or forks are termed internal nodes, as discussed in [8].
As discussed earlier, in a 5GDHC scenario, prosumers exchange heat within the network, while a balancing node covers residual mismatches using seasonal storage and auxiliary units. Its required capacity grows with increasing prosumer imbalance or limited local synergy. Candidate locations for balancing nodes are derived from IFC-based parcel areas, excluding building footprints, transport zones, and protected or unsuitable natural areas. A 3m buffer from parcel boundaries and buildings is applied as opted in [21]. This study considers BTES as the seasonal storage option ([22]). The volume of the storage can be calculated as [20]:

$$V_{\mathrm{storage}} = \frac{Q}{\rho \cdot \mathrm{cp} \cdot \Delta T}, \tag{4}$$

where ΔT is the temperature difference of working fluid in the supply network (T_h) and cold network (T_c). Seasonal storage can be installed wherever sufficient parcel area is available, and the framework allows multiple storage sites to be selected simultaneously. These units collectively form part of the balancing node. As seasonal storage capacity increases, only one auxiliary asset—either a boiler or a chiller—is required to compensate for the inherent thermal imbalance between heating and cooling demands. Together, the storage and auxiliary unit provide long-term grid balancing, with their production profiles determined by the residual mismatch that must be compensated over time [7]. The framework also sizes the remaining HVAC components and thermal pipelines, after which their investment and operational costs are computed following the methodology in [6]. Capital expenditures (both total CAPEX and annualised CAPEX) and operating expenditures (OPEX) are evaluated for each technology ($i \in [\mathrm{ASHP}, \mathrm{GSHP}, \mathrm{BHP}, \mathrm{Boiler}]$), using cost functions that link equipment capacity to installation and operating costs

$$\mathrm{CAPEX}_{\mathrm{HVAC,i}} = c_{\mathrm{h}} \cdot \max(\dot{Q}_{\mathrm{HVAC,i}}) + h_i, \tag{5}$$

$$\mathrm{OPEX}_{\mathrm{HVAC,i}} = c_{\mathrm{elect,gas}} \cdot Q_{\mathrm{HVAC,i}}. \tag{6}$$

The vector h_i contains unitless regression factors used to estimate capacity factors for each technology (Table 5) For HVAC technologies, annual CAPEX is based on a 20-year lifetime, while seasonal storage and pipe infrastructure are amortized over 40–60 years. For network connections, costs include pipe investment and associated trenching or excavation work. The total connection cost is computed as:

$$\mathrm{capex}_{\mathrm{pipe},I} = p_1 \cdot D_i + \mathrm{trench\ price} + p_2. \tag{7}$$

The specific costs for two types of storage are given in [7, 20] as:

$$C_{\mathrm{specific,borehole}} = c_{\mathrm{BTES}} \cdot V_{\mathrm{storage}}^{-0.7}, \tag{8}$$

The KPIs related to investment cost are then calculated using

$$\mathrm{capex}_{\mathrm{storage\ borehole}} = C_{\mathrm{specific,borehole}} \cdot V_{\mathrm{storage}}. \tag{9}$$

$$\tag{10}$$

The emissions-related KPIs are calculated as

$$\mathrm{TE}_{\mathrm{HVAC,i}} = c_{\mathrm{emsn}} \cdot Q_{\mathrm{HVAC,i,hc}}, \tag{11}$$

$$C_{\mathrm{em,HP,i}} = c_{\mathrm{CO2}} \cdot \mathrm{TE}_{\mathrm{HVAC,i}}. \tag{12}$$

Readers are referred to [7] for the full formulation of CAPEX and OPEX calculations linked to energy flows in the network, as well as for comparisons with conventional technologies such as air-source heat pumps (ASHP) and ground-source heat pumps (GSHP), alongside standard boiler systems.

2.3. Technology comparison using KPIs

The techno-economic and environmental KPIs listed in Table 3 are evaluated for two configurations: a 5GDHC network without PV and an electrified variant where 5GDHC is coupled with rooftop PV and electricity exchange with the local grid. 5GDHC without PV case is assessed against a baseline in which all buildings rely on a Boiler+ASHP system for their energy needs (heating, cooling , electricity and domestic hot water (DHW)), following [7]. The electrified scenario is then compared with three present-day HVAC and PV design configurations to quantify the added value of integrating local renewable electricity, particularly when waste-heat sources are absent and synergy between prosumers

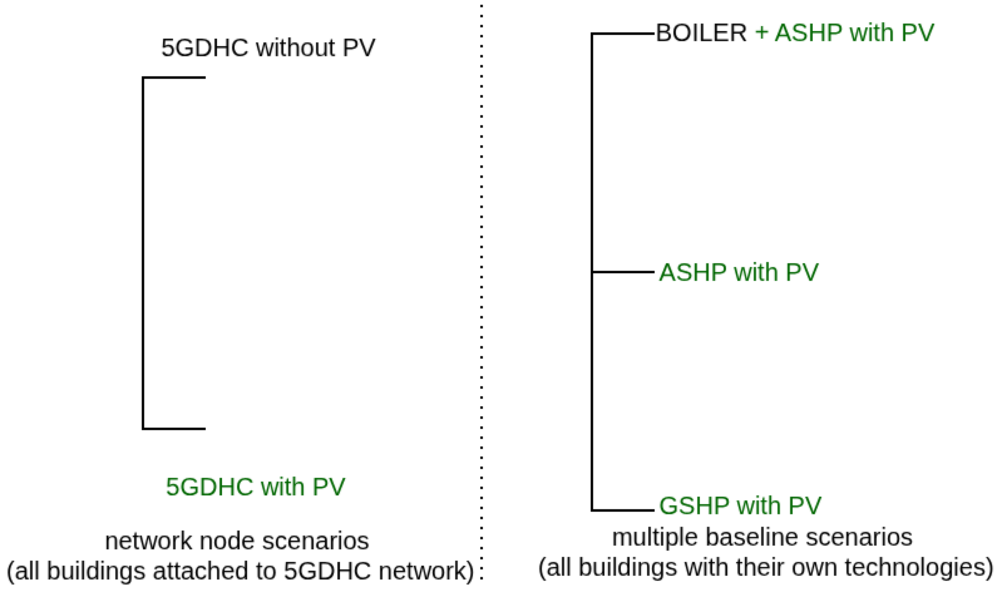


Figure 2: Scenario comparison scheme with PV (in green) and without PV (in black) supply to provide energy demands of buildings(heating, cooling , electricity and domestic hot water DHW)

Table 3: List of main KPIs metrics

no.	description	symbol	units	type
1	synergy	–	%	technical
3	total cost of ownership	TCO	kEUR/y	economic
4	net savings	χ	kEUR/y	economic
5	cost ratio	CR	%	economic
7	total emissions	TE	tonCO_2eq/y	environmental

is limited. The scenario scheme shown in Fig. 2 will be utilized to compare different design scenarios in order to cover building all energy needs.
The performance is quantified by assessing the relative change (RC) in each KPI using following

$$\Delta \mathrm{kpi}(\%) = \left(\frac{\mathrm{kpi}_{\text{with PV}} - \mathrm{kpi}_{\text{without PV}}}{\mathrm{kpi}_{\text{without PV}}} \right) \times 100. \tag{13}$$

The total cost of ownership (TCO) also called annualized cost can be calculated as

$$\mathrm{TCO}_{\mathrm{net}} = \mathrm{CAPEX}_{\mathrm{net}} + \mathrm{OPEX}_{\mathrm{net}}, \tag{14}$$

whereas both $\mathrm{CAPEX}_{\mathrm{net}}$ and $\mathrm{OPEX}_{\mathrm{net}}$ are calculated by summing all equipment investment costs including PV panel costs and operational expenditures, respectively. Similarly, $\mathrm{TCO}_{\mathrm{ref}}$ is also calculated by summing all the terms $\mathrm{CAPEX}_{\mathrm{ref}}$ and $\mathrm{OPEX}_{\mathrm{ref}}$. Total emissions($\mathrm{TE}_{\mathrm{net}}$ and $\mathrm{TE}_{\mathrm{ref}}$) are also computed for both network scenario and present design technologies scenarios, proportional to OPEX terms.
The net operational cost savings (χ), cost ratio (CR) and standard payback period (SPBP) calculated in Eqs. (15, 16 and 17), derived from network operations without PV sceanrio, are computed by comparing it with the operational expenditures ($\mathrm{OPEX}_{\mathrm{r}}\mathrm{ef}$) associated with a boiler's reference design

for heating and considering ASHP operational cost for cooling [6]

$$\chi = \mathrm{OPEX}_{\mathrm{ref}} - \mathrm{OPEX}_{\mathrm{net}}, \tag{15}$$

$$\mathrm{CR} = \frac{\mathrm{TCO}_{\mathrm{net}}}{\mathrm{TCO}_{\mathrm{ref}}}, \tag{16}$$

$$\mathrm{SPBP} = \frac{\mathrm{CAPEX}_{\mathrm{net}} - \mathrm{CAPEX}_{\mathrm{ref}}}{\chi}. \tag{17}$$

Here, it is pertinent to mention that with increased electrification by considering PV panels attached to every node except a balancing load will effect the χ by amount of energy acquired from electric grid for each scenario except for Boiler + ASHP scenario as heat demand in this scenario is covered by natural gas (NG) boiler and is therefore independent of PV generation. Moreover χ and OPEX directly influence other KPIs such as TCO, CR, and SPBP as defined in Eqs (14, 16 and 17). Improving these yearly KPIs will also enhance life-cycle costs, as discussed in [6]. However, life-cycle cost assessments are not considered in this work. Readers are referred to [6] for a detailed analysis of KPI metrics in both yearly and life-cycle cost evaluations.

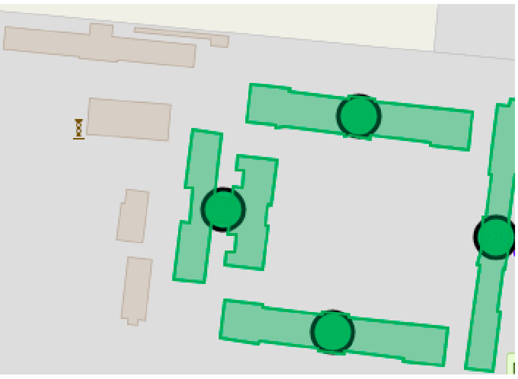
3. Case study

The case study selected to evaluate the framework is from the city of Namur, Belgium, in the Walloon part of Belgium. With the GIS interface, the footprint area of the buildings can be extracted using OSMnx street-network mapping library as shown in Fig. 3(a). However, the area of missing buildings that needs to be provided, including the number of floors and available rooftop area for solar irradiance, is adjusted using IFC plans shown in 3(a), which provides more detailed plans. This location is dominated by heating demand load as listed in Table 4. The time-series of energy demands for each building node is generated using [11],

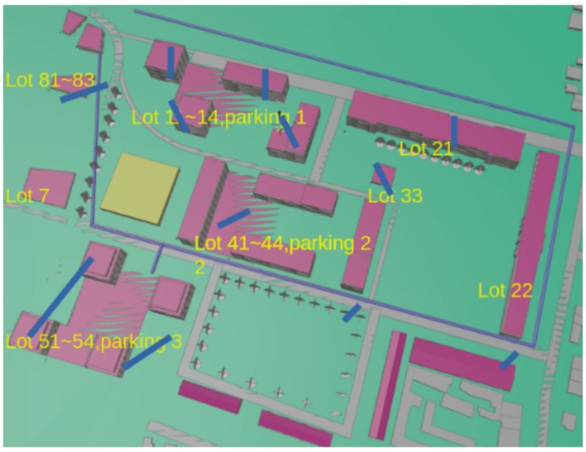
Table 4: Details of a location considered as case study

location	network length [m]	no. of buildings	Q_h [GWh]	Q_c [GWh]	synergy[%]
namur-dist	5824	19	4.4	–	14

All relevant input data for the thermal network, HVAC systems, PV generation, and energy-market equipment costs are summarised in Table 5.



(a) Identifying buildings with osmnx [2]



(b) Identifying buildings with IFC plan

Figure 3: Energy community layout to anlyze 5GDHC scenario

4. Results and discussions

To assess the scenarios including PV generation, a spatial solar-irradiance analysis using QGIS is performed. This integrates the (Walloon Region GIS platform) to obtain high-resolution, site-specific

Table 5: List of parameters used to simulate 5GDHC case and its comparison with present design technologies

descriptions	symbol	value	unit
ASHP factor	h_1	9817	–
GSHP factor	h_2	5051	–
BHP factor	h_3	5051	–
pipe factor	p_1	2.16	–
pipe factor	p_2	68	–
BTES fix	c_{BTES}	16726	$\mathrm{EUR/m^3}$
BTES fix	c_{BTES}	16726	$\mathrm{EUR/m^3}$
ATES fix	c_{ATES}	145	$\mathrm{EUR/m^3}$
boiler price	c_{boiler}	100	$\mathrm{EUR/kW}$
trench price	c_{pipe}	1.0	$\mathrm{kEUR/m}$
PV panel price	c_{pipe}	1.0	$\mathrm{kEUR/kWp}$
PV panel area	A_{p}	2.2	$\mathrm{m^2}$
energy demand	$\dot{Q}_{\mathrm{h,c}}$	–	kW
NG boiler efficiency	η_{boiler}	90	$\%$
BHP efficiency	η_{BHP}	70	$\%$
GSHP efficiency	η_{GSHP}	50	$\%$
ASHP efficiency	η_{ASHP}	40	$\%$
standard test irradiance	G_{stc}	1.0	$\mathrm{kW/m^2}$
hot network temperature	T_h	35	$^\circ\mathrm{C}$
cold network temperature	T_C	20	$^\circ\mathrm{C}$
gas price	c_{gas}	0.1	$\mathrm{EUR/kWh}$
electricity price	c_{elect}	0.3	$\mathrm{EUR/kWh}$
CO_2 penalty	$c_{\mathrm{CO_2}}$	0.1	EUR/kg$\mathbf{CO_2}$
CO_2 emission electric	c_{emsne}	0.20	$\mathrm{kgCO_2/kWhe}$
CO_2 emission gas	c_{emsng}	0.23	$\mathrm{kgCO_2/kWhg}$

irradiance values. This approach provides more accurate $G(t)$ to compute PV poptential using Eq. 2 compared to $G(t)$ obtained from PVGIS, which relies on a global solar-irradiance model [12]. The resulting irradiance distribution is shown in Fig. 4. However, this GIS workflow is limited, as it does not cover all the buildings that are provided in the IFC plan shown in Fig. 3(b). Hence, PVGIS is still used to generate PV renewable supply for the particular case studies by providing the available rooftop area for each building.

The selected location is simulated using the proposed framework and the input parameters listed in Table 5. The simulations follow the scenario-comparison scheme shown in Fig.2. Since the objective is to assess how additional PV generation can enhance 5GDHC performance, the analysis begins by computing the techno-economic KPIs listed in Table 3 for a 5GDHC with PV against present design technologies (Boiler+ASHP, ASHP and GSHP), and then compared to a set baseline scenario (5GDHC without PV) see section 2.3. Fig.5 compares the 5GDHC+PV scenario with current building-level technologies equipped with rooftop PV and shows that 5GDHC achieves a lower total cost of ownership than both GSHP and Boiler+ASHP configurations. The GSHP option exhibits the highest TCO because each building requires its own horizontal BTES field, leading to substantial decentralised upfront investment, whereas 5GDHC relies on a single centralised facility with lower overall capital intensity.

Although 5GDHC has higher initial costs than ASHPs due to the network infrastructure, its operating costs are lower thanks to reduced CO_2 taxation and lower operational emissions. As shown in Fig.7, emissions are consistently lower in the 5GDHC scenario, reflecting reduced exergy losses and more

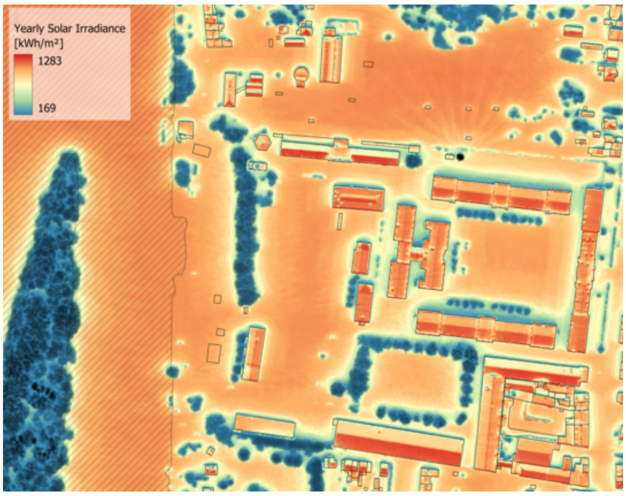


Figure 4: Solar irradiance using (Walloon Region GIS platform)

efficient heat exchange. Electricity drawn from the grid is also lower for 5GDHC (Fig.6), which increases savings potential, while the amount of electricity that can be exported to the grid is higher with 5GDHC network scenario compared to the other scenarios.

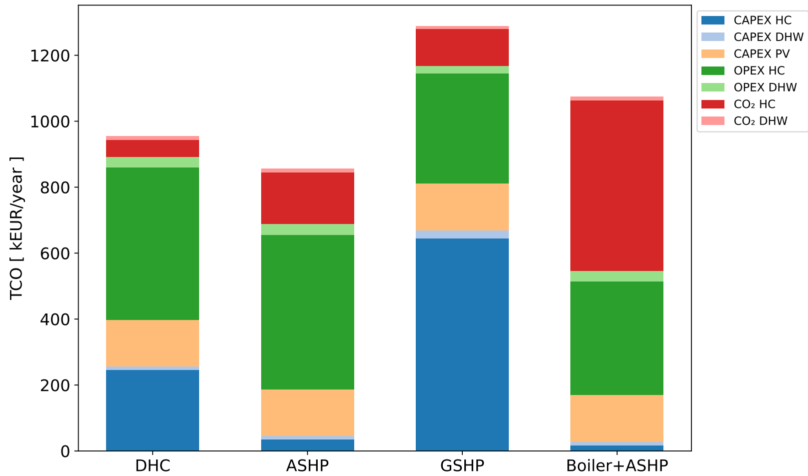


Figure 5: TCO comparison of 5GDHC with PV versus all buildings connected to their own HVAC equipment

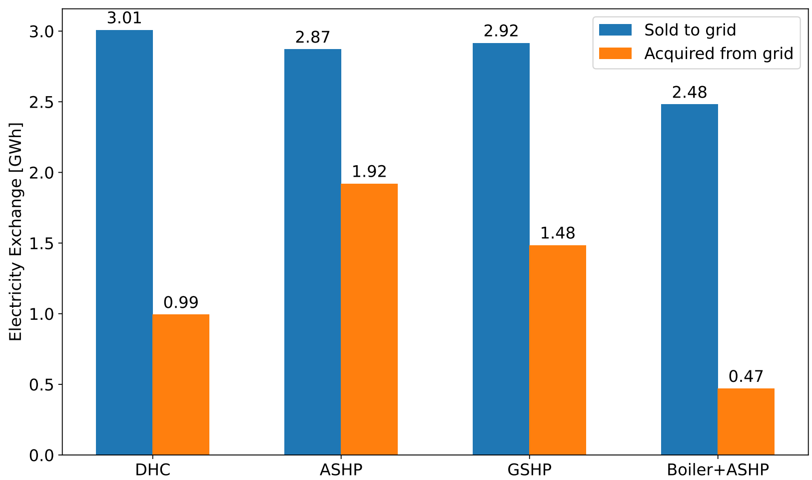


Figure 6: Electricity exchange over the year of 5GDHC with PV versus all buildings connected to their own HVAC equipment

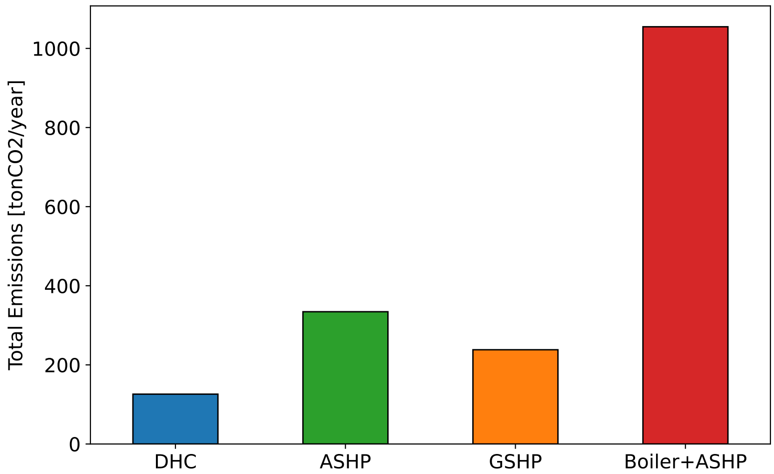


Figure 7: Total emissions of 5GDHC with PV versus all buildings connected to their own HVAC equipment

In Table 6, the comparison of main KPIs defined in Table 3 is performed with baseline 5GDHC without PV network design scenario.

Table 6: Comparison of the techno-economic KPIs (defined in Table 3) obtained from the baseline 5GDHC without PV and the 5GDHC scenarios integrating PV generation (Boiler+ASHP, ASHP, and GSHP).

KPI	5GDHC without PV	5GDHC with PV (cmp. ASHP)	RC [%]	5GDHC with PV (cmp. GSHP)	RC [%]
savings[kEUR/y]	346	**439**	**26**↑	395	14↑
cost ratio[%]	86	**42**	**40**↓	66	22↓
SPBP[yr]	25	**18**	**24**↓	20	17↓

For the most common ASHP-based setup (5GDHC with PV (cmp. ASHP)), energy savings increase by 26%, the cost ratio improves by 40%, and the simple payback period falls to 18 years, representing a 23% improvement over the baseline. The 5GDHC+PV scenario compared with GSHP shows similarly consistent gains, with performance strengthening as the share of locally generated PV electricity rises. Both PV-enabled 5GDHC variants benefit from reduced grid dependence, lower operational emissions, and improved economic outcomes as renewable supply increases. Table6 confirms that electrifying the thermal grid enhances all major KPIs relative to the 5GDHC baseline without PV. These improvements arise despite the limited thermal-load complementarity in the community, underscoring the robustness of 5GDHC even in heating-dominated networks.

5. Conclusion

The study shows that a 5GDHC network remains a feasible and advantageous option even in small-scale communities with exclusively heating demand and no accessible waste-heat sources. A bidirectional 5GDHC layout still enables meaningful energy sharing, offering benefits in settings where heating loads dominate and where a full shift from traditional DH to DHC would otherwise require extensive retrofitting. Increasing the level of electrification within the network strengthens these advantages. Across all electrified configurations, clear energy-performance gains emerge, and the improvements persist even when the existing reference technologies already include rooftop PV. A consistent comparison of the main KPIs indicates that energy savings rise by 26%, while the simple payback period drops to 18 years showing an improvement of 24% as the share of PV-based renewable supply increases. These results highlight the economic potential of electrified 5GDHC systems and underline their robustness in heating-dominated communities.

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References

[1] Marwan Abugabbara, Saqib Javed, and Dennis Johansson. A simulation model for the design and analysis of district systems with simultaneous heating and cooling demands. *Energy*, 261, 12 2022.

[2] Geoff Boeing. Modeling and analyzing urban networks and amenities with osmnx. *Geographical Analysis*, 57(4):567–577, 2025.

[3] Simone Buffa, Marco Cozzini, Matteo D'Antoni, Marco Baratieri, and Roberto Fedrizzi. 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews*, 104:504–522, 4 2019.

[4] A Chaudhry, N Lezaun, F Fontes, and Svend Bram. Model Predictive Control of a Substation of a District Heating System for Enhanced Environmental and Economic Performance — Energy Proceedings, 2021.

[5] Afraz Mehmood Chaudhry, Maxence Delvaux, Zoltán Csurcsia, Stanislav Chicherin, Jonathan Hachez, and Svend Bram. Enhancing operational optimization of district heating substations through refined estimations of network campus buildings heat demands to achieve a low return from the network. *Energy and Buildings*, 313:114241, 2024.

[6] Afraz Mehmood Chaudhry, Ghader Ghorbaniasl, Jonathan Hachez, Stanislav Chicherin, and Svend Bram. Improving the potential of fifth-generation district heating and cooling networks through robust design and operational optimization under future energy market and demand uncertainties. *Energy and Buildings*, 325:114998, 2024.

[7] Afraz Mehmood Chaudhry, Jonathan Hachez, Stanislav Chicherin, Ghader Ghorbaniasl, and Svend Bram. Potential site evaluation of fifth-generation district heating and cooling networks under uncertain energy market conditions: A two-step robust design analysis approach. *Energy*, 311:133334, 2024.

[8] Paul Egberts, Can Tümer, Kelvin Loh, and Ryvo Octaviano. Challenges in heat network design optimization. *Energy*, 203, 7 2020.

[9] Kristian Gjoka, Behzad Rismanchi, and Robert H. Crawford. Fifth-generation district heating and cooling systems: A review of recent advancements and implementation barriers, 1 2023.

[10] Oddgeir Gudmundsson, Ralf Roman Schmidt, Anders Dyrelund, and Jan Eric Thorsen. Economic comparison of 4GDH and 5GDH systems – Using a case study. *Energy*, 238:121613, 1

2022.

[11] Jonathan Hachez, Stanislav Chicherin, Afraz Mehmood Chaudhry, and Svend Bram. Regression versus probabilistic approach for operational data – Heat demand of buildings to be connected to a district heating system. *Energy and Buildings*, 294:113209, 9 2023.

[12] Thomas Huld, Richard Müller, and Attilio Gambardella. A new solar radiation database for estimating pv performance in europe and africa. *Solar Energy*, 86(6):1803–1815, 2012.

[13] Thomas Licklederer, Daniel Zinsmeister, Lorenz Lukas, Fabian Speer, Thomas Hamacher, and Vedran S. Perić. Control of bidirectional prosumer substations in smart thermal grids: A weighted proportional-integral control approach. *Applied Energy*, 354, 1 2024.

[14] Kristina Lygnerud, Tobias Popovic, Sebastian Schultze, and Hanne Kortegaard Støchkel. District heating in the future - thoughts on the business model. *Energy*, 278:127714, 2023.

[15] Michael Allan Millar, Zhibin Yu, Neil Burnside, Greg Jones, and Bruce Elrick. Identification of key performance indicators and complimentary load profiles for 5th generation district energy networks. *Applied Energy*, 291, 6 2021.

[16] Michael Allan Millar, Zhibin Yu, Neil Burnside, Greg Jones, and Bruce Elrick. Identification of key performance indicators and complimentary load profiles for 5th generation district energy networks. *Applied Energy*, 291, 6 2021.

[17] Adelaida Parreño-Rodríguez, Angel Molina-García, Alice Mugnini, Alessia Arteconi, and Alfonso P. Ramallo-González. Thermal energy characterization methodology based on gis for energy communities and demand response strategies. *Results in Engineering*, 27:105769, 2025.

[18] J.A. Romero-Ramos, J.D. Gil, J.M. Cardemil, R.A. Escobar, I. Arias, and M. Pérez-García. A gis-ahp approach for determining the potential of solar energy to meet the thermal demand in southeastern spain productive enclaves. *Renewable and Sustainable Energy Reviews*, 176:113205, 2023.

[19] Puneet Saini, Pei Huang, Frank fiedler, Anna Volkova, and Xingxing Zhang. Techno-economic analysis of a 5th generation district heating system using thermo-hydraulic model: A multi-objective analysis for a case study in heating dominated climate. *Energy and Buildings*, 296, 10 2023.

[20] Dadi Sveinbjörnsson, PlanEnergi Linn Laurberg Jensen, PlanEnergi Daniel Trier, PlanEnergi Federico Bava, PlanEnergi Ilyes Ben Hassine, HFT Stuttgart Xavier Jobard, and HFT Stuttgart. Project Title: Fifth generation, low temperature, high exergy district heating and cooling networks Project Acronym: FLEXYNETS Deliverable Title: D2.3 Large Storage Systems for DHC Networks. Technical report, PlanEnergi, 2019.

[21] Alina Walch, Xiang Li, Jonathan Chambers, Nahid Mohajeri, Selin Yilmaz, Martin Patel, and Jean-Louis Scartezzini. Shallow geothermal energy potential for heating and cooling of buildings with regeneration under climate change scenarios. *Energy*, 244:123086, 2022.

[22] Tianrun Yang, Wen Liu, Gert Jan Kramer, and Qie Sun. Seasonal thermal energy storage: A techno-economic literature review. *Renewable and Sustainable Energy Reviews*, 139:110732, 2021.