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Shallow geothermal energy as an enabler of system flexibility: comparative modelling of 4GDHC and 5GDHC networks in the Catalan Pyrenees within the FlexGeo project

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INTRODUCTION

Modern low and ambient temperature district heating and cooling (DHC) networks – also referred to as 4th- and 5th- generation DHC networks (4GDHC and 5GDHC, respectively) – enable the integration of multiple renewable and residual heat sources from urban and industrial environments (Buffa et al., 2019; Lund et al., 2014). However, selecting between 4GDHC or 5GDHC configurations depends on several interrelated factors that cannot be assessed through conventional design approaches. Network size, building demand profiles, local energy prices, and interactions between energy vectors (e.g. electricity and thermal fluids) all require a more holistic evaluation, which can be effectively undertaken through dynamic modelling. This decision-making process is explored through a case study in Southern Europe, where neither ground-source heat pumps (GSHPs), nor DHC networks are yet widespread, despite their significant potential (García-Céspedes et al., 2023) for the decarbonization of heating and cooling (H&C) demand.

Vielha is a town (within the municipality of Vielha e Mijaran) with around 3,700 inhabitants (2024). However, the population can increase up to fivefold in winter, as it is a major ski destination. It is located at about 980 m above sea level in the southeastern Pyrenees, in a mountainous setting and a glacial valley in northern Catalonia (Spain), surrounded by high mountain peaks reaching nearly 3,000 m. It has a Cfb-type climate in the Köppen climate classification system, with the coldest month averaging above 0 °C, all months remaining below 22 °C on average, and at least four months averaging above 10 °C. Despite the presence of local renewable resources such as hydropower and biomass, the town still relies almost entirely on the national electricity grid and on fossil fuels transported daily by truck to meet its energy needs. This dependence underscores the need for a more sustainable, affordable, and secure local energy supply. In response, the local authority (*Conselh Generau d'Aran*) has launched the "*Vielha Smart Multi-RES micro DHC grid*" initiative, which aims to integrate shallow geothermal and photovoltaic solar energy (SGE and PVSE, respectively) into an innovative DHC network. The project involves replacing obsolete gas and gasoil boilers in selected public buildings with GSHP systems coupled with vertical borehole heat exchangers (BHEs), interconnected through a common thermal grid. This has the dual objective of demonstrating how decarbonization and enhancement of energy security of supply can be achieved through SGE. Nevertheless, several aspects must be addressed to design the most suitable district energy solution. These concern the hydrogeological context, the buildings involved and their retrofitting needs, the possibility to integrate additional renewable energy sources, the district concept and control strategy, the contribution to a more flexible electricity market, as well as financial and business model considerations (Garcia-Cespedes et al., 2025).

Part of these challenges are being addressed by the Catalan Geological Survey (ICGC) through dynamic modelling within the EU-funded FlexGeo project (*Pathing the Way for Flexible Geothermal Energy Systems with Reversible ORC Systems, Advanced Control and Novel System Designs, 2024-2028*), led by the Technical University of Munich (Germany). This study explores the advantages and drawbacks of implementing a centralized low-temperature district energy network (4GDHC) versus a decentralized ambient-temperature network (5GDHC) to provide heating, cooling and domestic hot water (DHW). The analysis has been conducted in terms of energy efficiency, greenhouse gas (GHG) emissions and the levelized cost of heat (LCOH).

1 METHODS & RESULTS

1.1 Approach and Methods

The candidate buildings to be connected to the future DHC network in Vielha include an ice rink adjacent to a swimming pool, a multisport center, a primary school, and a secondary school. The 5GDHC concept was initially considered as a way to replace each building's individual heating and/or cooling system with a GSHP, allowing the DHC network to adapt to the existing distribution systems and their respective supply temperatures. In contrast, adopting a 4GDHC configuration would require centralized equipment but would enable the integration of local biomass as a renewable resource, an attractive option given its abundance in the area and the potential for local energy autonomy (see Figure 1). Both concepts include PVSE installations, contributing to a more self-sufficient and resilient electricity supply for the region.

The most interesting feature of this approach lies in its synergy with SGE. The surplus electricity generated by the solar PV panels can be monetized directly via feed-in tariff schemes, or indirectly as "free heat" (transformed by Joule effect). This heat can be used to compensate for long-term imbalances in ground heat extraction and injection – especially in largely heating-dominated systems – helping to maintain stable ground temperatures and providing indirect economic benefits through higher GSHP efficiency and greater electricity savings.

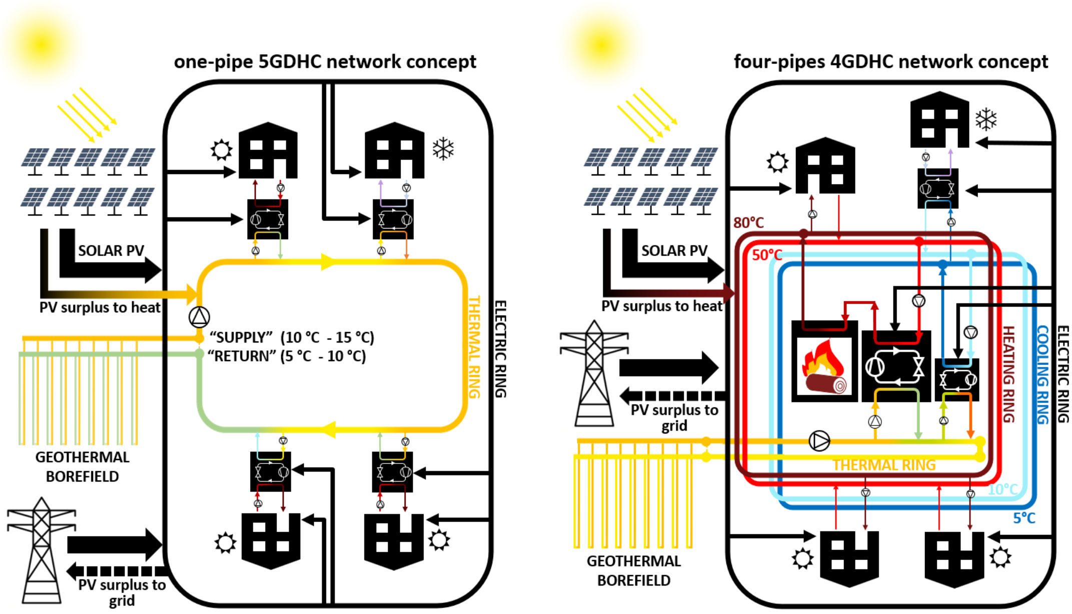

Figure 1. Illustration of the network concepts developed for the Vielha case study. The 5GDHC network (left) consists of a one-pipe ring with decentralized heating/cooling production, whereas the 4GDHC network (right) features a four-pipes system with centralized thermal generation. Additionally, a biomass boiler is included as a temperature booster. An additional chiller would be required in the ice rink building (upper right in each scheme) for ice production. In both cases, self-produced electricity can be used instantly by heat pump equipment, sold to the grid, or injected in the form of heat into the DHC network.

Dynamic modelling was employed as the analytical tool to assess which configuration is best suited to the case study. For this, conceptual dynamic models of 5GDHC and 4GDHC networks were developed in the OpenModelica environment (OMEdit), using original and modified components from the Modelica Standard Library v4.0.0 (Modelica Association, 2020) and the Modelica Buildings Library v.10.0.0 (Lawrence Berkeley National Laboratory, 2023). The models represent simplified systems comprising two buildings (prosumer stations, since they can absorb/inject heat from/to the grid) connected to a DHC network, yet they are constructed upon a set of common elements to enable a valid common-ground comparison framework.

The 5GDHC concept consists of a one-pipe ring (primary loop) with a centralized geothermal borefield acting as the balancing unit. Each prosumer station forms a secondary loop, in which primary and secondary pumping are decoupled, similar to the "reservoir network" introduced by Tobias Sommer and co-authors (Sommer et al., 2020), in which the pumping of the primary is decoupled from that of the secondary loops. Heating, cooling and domestic hot water (DHW) are produced locally by ON/OFF-operated GSHP sub-models (based on reciprocating compressors) following hourly demand profiles loaded from .txt files. Thus, the building dynamics are not explicitly simulated but implicitly represented by the demand data. Internal heat recovery is considered, so simultaneous heating and cooling within the same hour do not require water circulation from the main network.

Regarding the 4GDHC network, the main variation with respect to its 5GDHC counterpart concerns heating and cooling production in the system. This is undertaken by centralized heating and cooling stations (CHS and CCS, respectively), which comprise mainly GSHP sub-models that absorb/inject heat from/to a one-pipe ring connected to the geothermal borefield (this part is completely analog to that of the 5GDHC concept). A biomass boiler sub-model can be activated within the CHS, so this can be used as a temperature booster or to downsize the heat pump of the CHS, but also to guarantee a well-balanced heat exchange with the ground, especially in heating-dominated networks. Prosumers are modelled as ideal heat exchangers drawing constant heating/cooling power from the network according to the same hourly demand profiles used in the 5GDHC case.

From a hydraulic standpoint, both networks are unidirectional in mass flow but bidirectional in heat transfer. Circulation pumps operate at constant speed, only at the time when heating or cooling demand takes place. They are automatically sized to meet maximum flow conditions, while pipe diameters are manually adjusted to maintain pressure losses below 100 Pa/m in primary loops and 250 Pa/m in secondary loops. To minimize circulation pump power consumption, flow through the borefield occurs only when the temperature of the heat-carrying fluid in the primary loop falls outside a defined deadband, here set as the undisturbed ground temperature ± 5 °C. All pipes are assumed buried 1 m below ground level and thermally coupled to the soil, whose temperature is described by the Kusuda sinusoidal model. Pipes are uninsulated in the 5GDHC models but insulated downstream of the CHS and CCS in the 4GDHC ones.

Heat transfer between the borefield and the ground is computed using g-functions generated automatically from the borehole layout, although groundwater flow effects are not considered in the Modelica Building Library version employed here. A fast algorithm was implemented in order to automatically pre-size the total length of the BHEs inspired by the German guide VDI 4640 (Verein Deutscher Ingenieure, 2001). PVSE sub-model converts hourly solar irradiation data into electricity according to user-defined parameters. Power is used instantly to drive the heat pumps, while any surplus is injected into the power grid. The surface area of the solar PV panels is a free parameter of the model and presents the same value in both network schemes (40 m^2).

Building demand profiles were synthetically generated with the nPro software (Wirtz, 2023) for different building types, such as single-family buildings (SFB), fishery facilities (FSH), among others (see Figure 2). Three representative two-building combinations were selected for analysis: FSH+FSH, SFB+SFB, and FSH+FSH.

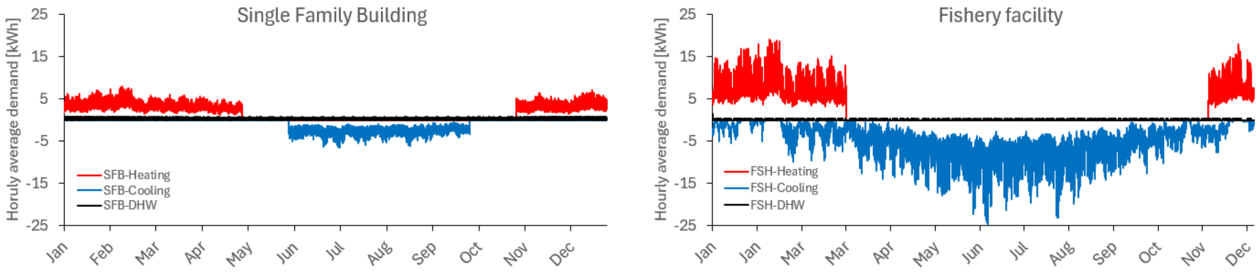

Figure 2. Hourly average demand profile (heating, cooling, and DHW) for a single-family building (left) and a medium-sized fish processing and retail facility (right) in a warm climate, for model testing purposes.

The main performance indicator was the overall seasonal performance factor (SPF, see expression (1)), defined as the ratio between total useful thermal energy delivered by the buildings – heating (E_h), cooling (E_c), and DHW (E_{DHW}), all after distribution losses – and the total electricity consumption (E_e), of both the network and the buildings. According to this definition, the calculated yearly SPF corresponds to values between "SPF$_3$" and "SPF$_4$" metrics (Nordman et al., 2012). Additionally, a modified indicator, SPF$_{PV}$ (see expression (2)), was introduced to account for electricity savings resulting from PVSE self-production (E_{e-PV}). It is important to note that E_c is defined as a negative magnitude, representing the heat extracted from the buildings.

GHG emissions were accounted for exclusively from an operational perspective. For the economic assessment, the Levelized Cost of Heat (LCOH) was calculated according to expression (3), assuming a project lifetime of 30 years. Capital expenditure (CAPEX) included heat pump equipment, borehole drilling and network infrastructure, while operational expenditure (OPEX) mainly comprised electricity consumption and maintenance costs. A discount rate (r) of 3% was applied to the annual cash flow. An efficiency degradation rate of 0.5% per year was assumed for the thermal production equipment across the three analysed scenarios. An average annual inflation rate of 2% was applied to OPEX-related costs.

$$SPF = \frac{\sum_{i=1}^{i=8760} E_h^i - E_c^i + E_{DHW}^i}{\sum_{i=1}^{i=8760} E_e^i} \quad (1)$$

$$SPF_{PV} = \frac{\sum_{i=1}^{i=8760} E_h^i - E_c^i + E_{DHW}^i}{\sum_{i=1}^{i=8760} E_e^i - E_{e-PV}^i} \quad (2)$$

$$LCOH = CAPEX + \frac{\sum_{t=1}^{t=30} \frac{OPEX(t)}{(1+r)^{t-1}}}{30 \cdot (E_h - E_c)} \quad (3)$$

1.2 Results

One-year simulations were carried out for the dynamic models of the 4GDHC and 5GDHC networks to assess the influence of the PVSE system on overall performance. Across the different scenarios analyzed, the variation in SPF ranges from 6.8 % to 16.5 %. In all cases, the 5GDHC networks exhibit clearly higher SPF values than their 4GDHC counterparts, with differences ranging between 23.6 % and 35.4 % (see Table 1).

Table 1. Overall SPF (including heating, cooling, and DHW) for the three analyzed scenarios, comparing 4GDHC and 5GDHC network concepts, with and without accounting for electricity savings from the PVSE installation.

	Case 1: FSH+SFB			Case 2: FSH+FSH			Case 3: SFB+SFB		
	4GDHC	5GDHC	$\Delta\left(\frac{SPF^{5G}}{SPF^{4G}}-1\right)$	4GDHC	5GDHC	$\Delta\left(\frac{SPF^{5G}}{SPF^{4G}}-1\right)$	4GDHC	5GDHC	$\Delta\left(\frac{SPF^{5G}}{SPF^{4G}}-1\right)$
SPF	**2.50**	**3.33**	+33.2 %	**2.68**	**3.55**	+32.5 %	**2.00**	**2.50**	+25.0 %
SPF_{PV}	**2.74**	**3.71**	+35.4 %	**2.88**	**3.79**	+31.6 %	**2.33**	**2.88**	+23.6 %
$\Delta\left(\frac{SPF_{PV}}{SPF}-1\right)$	+9.6 %	+11,4 %		+7.5 %	+6.8 %		+16.5 %	+15.2 %	

Regarding the environmental and economic analyses (Figure 2), the 5GDHC network concept shows 23.1 % – 26.5 % lower annual emissions compared to the 4GDHC configurations based solely on heat pumps. A similar trend is observed for the LCOH, although the magnitude of the difference is more sensitive to the selected demand profiles, resulting in a wider variation between the two network types (6.9 % – 22.3 % lower LCOH in the case of 5GDHC networks). The specific SFB+SFB case, in which a biomass boiler is included to support heating and DHW production in the 4GDHC network, achieves even lower emissions and LCOH values.

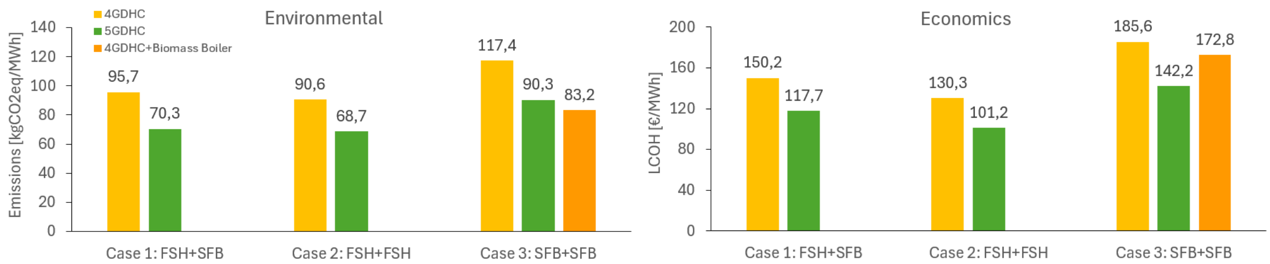

Figure 2. Comparative environmental (left) and economic (right) analyses for three case studies involving two buildings each, evaluating both 4GDHC and 5GDHC network concepts. For Case 3 (SFB+SFB), results also include a 4GDHC variant incorporating a biomass boiler as auxiliary heating equipment.

2 DISCUSSION

The higher efficiency observed in the 5GDHC network simulations (Table 1) can be attributed to several factors. First, internal heat recovery within the prosumer stations allows for regular periods of free cooling. Second, the DHW and space heating supply temperatures differ (65 °C and 45 °C, respectively), enabling the heat pumps to operate more efficiently for heating. In contrast, the 4GDHC network operates at a single heating supply temperature of 65 °C to meet both DHW and space heating demands, resulting in lower heat pump efficiency in the CHS. Moreover, in scenarios with simultaneous heating and cooling (especially SFB+FSH), effective heat recovery occurs within the primary loop of the 5GDHC model. As a result, the fluid temperature remains within the deadband for longer periods, reducing circulation through the borefield and, consequently, the central pumping energy consumption.

Regarding the impact of PVSE integration, the energy savings are most pronounced in Case 3 (SFB+SFB), as the installed PVSE capacity is proportionally larger relative to the building demands. Hence, a greater share of electricity consumption can be covered by self-produced energy.

In environmental terms (Figure 2), the higher SPF values achieved by the 5GDHC models are the primary reason for their lower emission levels. However, when a biomass boiler is integrated into the CHS of the 4GDHC network model, emissions drop even further, since biomass is considered carbon neutral. Regardless of pipe insulation, thermal losses are greater in the 4GDHC network due to the higher temperature of the heat-carrying fluid.

From an economic standpoint, the 5GDHC networks yield lower LCOH values than the 4GDHC counterparts. Nevertheless, this outcome cannot be attributed solely to higher efficiency. The models represent networks too small to capture the typical economic benefits of scale associated with DHC systems. Under such conditions, the centralized 4GDHC configuration with only two buildings shows a clear disadvantage. A more refined cost calibration and larger-scale simulations would be necessary to contextualize these results. For this reason, the LCOH results should only be interpreted comparatively. Additionally, the nominal COP used for the GSHP sub-model in the Modelica Buildings Library (3.2 under W10/W45 conditions) is notably lower than that of modern GSHPs (> 4.5), leading to higher operational costs over the system's lifetime. Interestingly, in Case 3, integrating a biomass boiler in the 4GDHC CHS yields a lower LCOH than using only a GSHP. This occurs because biomass boilers have a lower specific cost (€/kW), while the downsized GSHP reduces both capital expenditure (CAPEX) and operating costs, despite requiring two thermal units instead of one.

3 CONCLUSIONS

Dynamic simulations carried out in OpenModelica indicate that, under the analysed conditions, the 5GDHC configuration outperforms the 4GDHC concept across all explored building combinations. The overall SPF of 5GDHC systems is up to 35.4% higher than that of 4GDHC networks within the considered scenarios, mainly due to decentralized heat production, differentiated supply temperatures for DHW and space heating, enhanced internal heat recovery, and reduced primary circulation through the borefield.

These efficiency gains translate into up to 26.5% lower operational GHG emissions and 22.3% lower LCOH compared to centralized 4GDHC systems relying exclusively on heat pumps.

The results suggest that, for small-scale networks with heterogeneous demand profiles, ambient temperature 5GDHC systems provide superior thermodynamic performance and operational efficiency within the modelling framework adopted. However, when locally available biomass is integrated into the 4GDHC concept, environmental and economic performance can improve significantly.

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