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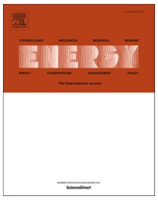

An innovative application of 5GDHC: A techno-economic assessment of shallow geothermal systems potential in different European climates

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ABSTRACT

Energy consumption for thermal purposes represents the most impacting energy issue in the European building sector. In addition to space heating, space cooling is constantly growing, due also to climate change, which provokes extreme hot events in summer even in moderate climates. To approach this challenge, it is essential to invest in lowering the overall energy demand, to increase the energy conversion efficiencies and to replace fossil fuels with renewable energy sources.

The research here presented deals with the European decarbonization goals and focuses on shallow geothermal technology in district thermal systems (DTS), i.e. Geo-5GDHC.

The research investigates whether Geo-5GDHC can be cost-effective in different scenarios based on climatic contexts, insulation levels and the possible integration of photovoltaic and thermal technology (PVT).

Through the elaboration of proper KPIs and the implementation and use of a tool specifically developed to couple a Geo-5GDHC energy assessment model with an economic analysis (PILEDHC), the research highlights results and guidelines for providing solutions for new and innovative DTS, considering both energy and economic aspects in different contexts.

1. Introduction

Space Heating (SH) accounts for approximately 50% of EU-28 final energy demand and around 80% of end-use energy in European buildings [1]. According to Refs. [2,3] a transformation wave of the energy system towards decarbonization is planned.

The heating of buildings is largely provided by individual fossil fuel solutions (Fig. 1), while cooling depends mainly on electrical appliances. For example, the share of SH is 61% in Italy and 71% in Switzerland [4]. Among the renewable energy sources (RES) available for heating at European level, biomass is the most widely used (12%), while solar thermal and geothermal are still marginal in many countries [5].

District heating (DH) refers to a mature technology for satisfying SH and domestic hot water (DHW); in fact, the first examples in Europe appeared around 1920. Currently, DH supplies only 12% of the heating demand in Europe, involving about 6000 networks, 200,000 km in total, 60 million citizens and an additional 140 million living in cities with at least one DH system [6]. In line with [7], DH systems can be classified according to two complementary approaches: the generation (i.e. chronologically, from 1st to 5th generation) and the level of the temperature of the carrier.

DH has been largely indicated as a promising solution for reaching the energy goals of decarbonization [8]. The Heat Roadmap Europe [1] shows that a future energy system with 50% DH and sector integration (the so-called sector coupling approach) is more efficient than a decentralised/conventional system and allows for higher shares of RES at a lower cost and for the integration of Combined Heat and Power (CHP) plants, waste heat from industry and services and use of electricity in large-scale Heat Pumps (HP). Overall, projections from Heat Roadmap Europe shows that the overall market share of DH at the EU level is expected to increase to 30% in 2030 and 50% in 2050.

In fact, according to Ref. [1], the contribution of fossil fuels in the DH mix in the EU is expected to decrease from 85% in 2016 to 35% in 2050

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Abbreviations

1GDH	1st Generation District Heating
2GDH	2nd Generation District Heating
3GDH	3rd Generation District Heating
4GDH	4th Generation District Heating
5GDHC	5th Generation District Heating and Cooling
ATDH	Ambient Temperature District Heating
BHE	Borehole Heat Exchanger
CAPEX	CAPital EXpenditure
CHP	Combined Heat and Power
CVRMSE	Coefficient of Variation of the Root Mean Square Error
DC	District Cooling
DD	Degree Days
DGC	Direct Ground Cooling
DH	District Heating
DHS	District Heating System
DHW	Domestic Hot Water
ERS	Energy Reference Surface
EU	European Union
Geo-5GDHC	Geothermal 5th Generation District Heating and Cooling
GIS	Geographical Information System
GSHP	Ground Source Heat Pump
High Ins	High Insulation
HIU	Heat Interface Unit
HP	Heat Pump
KPI	Key Performance Indicator
Low Ins	Low Insulation
LTDHC	Low Temperature District Heating and Cooling
NMBE	Normalised Mean Bias Error
OPEX	OPerative EXpenditure
PVT	Photovoltaic-Thermal
RES	Renewable Energy Source
SC	Space Cooling
SH	Space Heating
ULTDHC	Ultra-Low District Heating and Cooling

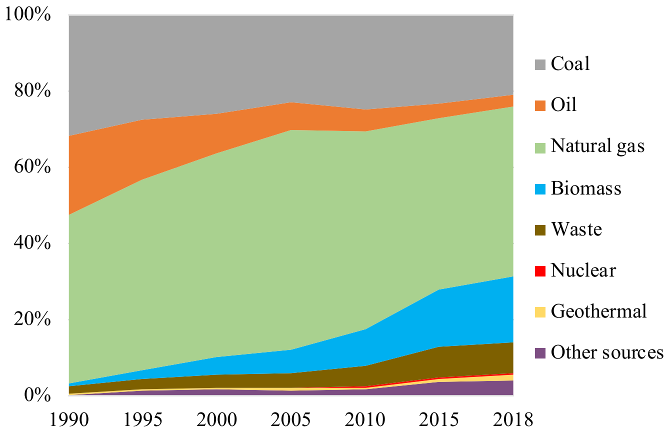

Fig. 1. Heat generation by source (%) in Europe, 1990–2018. Source [5]: OECD electricity and heat generation data sets, www.iea.org/statistics. (Elaborated by authors).

and, in parallel, large size HPs and industrial waste heat are expected to have a share of 30% and 25% respectively, in the same mix. In Europe, the increase of DH by 2050 is also in line with the current urbanization trend. Indeed, in urban areas the energy demand for heating and cooling is at its highest density and, at the same time, a huge amount of low-grade waste heat is diffused within the urban landscape.

According to Ref. [9], modern low-temperature district heating and cooling (LTDHC) can connect local demand with renewable and waste energy sources within the framework of the Fit for 55 Package [10] towards the modernization and deployment of District Heating and Cooling (DHC) systems in the next few years. The challenge is to undertake concrete measures to further underline the potential of efficient DHC under REPowerEU and national recovery and resilience plans, through the diffusion of low-temperature HP [11].

1.1. Background on 5GDHC

According to Ref. [12], 3rd Generation District Heating (3GDH) represents the evolution of the 1st Generation District Heating (1GDH) and the 2nd Generation District Heating (2GDH) and includes systems mainly realized after 1980, mostly in Europe. These networks are characterized by the adoption of hot water at temperatures in the range of 80–90 °C, control and management technologies as well as plastic jacket pipes to eliminate corrosion of the steel carrier pipes.

The evolution toward the 4th Generation District Heating (4GDH) implies a further lowering of the distribution temperatures (in the range of 30–70 °C), higher energy efficiencies and integration of RES [13].

The 5th Generation District Heating and Cooling (5GDHC) is defined as a thermal energy supply network operating at temperatures so close to the ground that is not suitable for direct heating purpose [14]. The low distribution temperature (in the range of 10–25 °C) allows for a direct exploitation of industrial, urban excess heat, renewable and low-energy heat sources and the provision of heating, cooling and DHW to users by means of decentralised HP. The main driver for 5GDHC diffusion is the ability to combine heating and cooling, using a collective network close to ambient temperature levels as a common heat source or sink for building-level HP [15]. 5GDHC can be regarded as a promising and complementary technology that may coexist in parallel with 4GDH. Indeed, dealing with the upgrading of an existing network to possible Ultra-Low Temperature DHC (ULTDHC) or 5GDHC may not be straightforward due to the great uncertainties about the practical project cost.

Despite the several benefits enabled by low supply temperatures, 5GDHC may be challenging from the technological and operational point of view, as pointed out in several studies.

By analysing a real case study, the author of [16] observed that in low-temperature networks with HP instead of heat exchangers, flow rate fluctuations may cause shut-down of HP or even freezing evaporators. The authors present strategies to cope with flow variations during the design and operation phase, analysing in depth the performances of the HP and referring to different case studies.

The authors of [17] investigate the up-to-date technologies for the optimal design of the system structure. They conclude that 5GDHC is considered an immature technology for large-scale implementation and for both optimal design and advanced control, integrated simulation of the 5GDHC system models and building models is crucial and challenging.

The authors of [18], analysing different DHC network configurations belonging to 3GDH and 5GDHC, state that HP are still not a prevalent technology in European DH and that there are several challenges, such as technological (electrical grid limitation), economic (high investment cost), and regulatory uncertainties, to overcome to achieve wider adoption. Their study compares the network investment cost, operating cost, and total cost (investment and operating). They apply a method to design 3-pipe DHC networks and ULTDHC networks, concluding that the latter are economically attractive only if a free low-temperature waste heat source is available. Indeed, as also described in Ref. [7], the cost-effectiveness of 5GDHC must be verified in each project taking into consideration energy, environmental and economic aspects and comparing them with alternative technologies.

An interesting contribution on 5GDH is reported in Ref. [12], focusing on the overall system efficiency and the levelized cost of the heat (LCOH). The authors analyse the LCOH for a mixed building area consisting of a central heat source, high or low energy buildings connected to 4GDH, 5GDH or a 4GDH variant with end-user temperature boosting for domestic hot water purposes. The analysis considers two countries: DK and the UK and explores the impact of the heat source temperature, from 10 °C to 60 °C, on the LCOH. The results indicate that 4GDH is the more competitive heat supply solution for the case considered.

The authors of [19] explore the heating and cooling networks and propose a survey about the available tools and a multi-step model for a whole system representation able to simulate buildings, network and heat resources and to visualise the true economic and environmental impacts.

The authors of [20] observe trends in the cooling demand of urban systems, which account for the research into cooling through geothermal district energy systems with a holistic model applied to a case study in Chicago, whose climate is classified as “boreal-Dfa”, according to the Koeppen-Geiger climate classification [21].

Contributions related to DHC can be also found for mild and Mediterranean climates, which traditionally have lower shares of DH, as explained in Ref. [22]. Here, the impacts of DHC on the utilization of intermittent renewable electricity sources are provided together with an optimization tool to model DC systems alongside the existing capacity to model DH systems. The results demonstrate a significant capacity of DHC systems to act as demand response tools.

The authors of [23] underline the need for a comprehensive review and analysis of the barriers and drivers for the implementation of 5GDHC, in relation to the Baltic context. They investigate the potential agents that can be used as active heat sources or sinks in 5GDHC through a multi-criteria analysis method. The barriers and drivers for the implementation of 5GDHC are dealt with in terms of economics, markets, technologies, policies, etc. referring to country-specific conditions such as heating tariffs, regulatory mechanisms, stakeholders, existing DH infrastructure, DH market etc.

The need to optimize dynamic heat supply with high temporal and spatial resolution with multiple heating technologies and for large study areas is underlined in Ref. [24]. The authors explain that the degree of utilization of a heating plant depends on intra-day and seasonal variations of the heat load, available thermal storage, and interplay with other heating technologies, which are dynamic processes, requesting a more accurate modelling of the operation of Ground Source Heat Pumps (GSHP) and heat networks.

More recently, the authors of [25] presented a review of the literature of the state of the art regarding 5GDHC underlining the need to investigate capital expenditure for specific contexts, including market surveys and direct quotes from industry; and to explore potential business models and peer-to-peer energy trading schemes in order to increase the confidence of investors and consumers.

To explore district systems with simultaneous heating and cooling demands, the authors of [26] developed and tested a simulation model for thermal, fluid, and control domains. Simulation results revealed several benefits for integrating district and HP technologies and the model can be utilised to support future research and development of new advanced DHC systems.

The contributions cited underline that the path to 5GDHC must be further investigated through methods capable of considering different aspects, such as energy and environmental performance, availability of suitable local renewable heat sources, ability to cover cooling in addition to heating demand, technological and regulatory constraints, investment and operating costs and social acceptance.

1.2. Focus on geothermal systems

Geothermal energy is suitable for exploitation in 5GDHC and is the main source explored in the work here presented (*Section 1.3*).

Several technical contributions can be investigated on the topic, such as [27], where the authors explore the use of sub-structures for heat transfer and storage as well as original structural function. The capability and feasibility of energy geo-structures within 5GDHC networks are thoroughly analysed and the need for further research to assess these opportunities is underlined.

Another interesting contribution is [28], where the authors investigate geothermal energy for DHC presenting the concept of multi-faceted systems accompanied by a SWOT (Strengths-Weaknesses-Opportunities-Threats) analysis. They underline that research is needed for the optimal ratio between refurbishment measures and integration/exploitation of geothermal energy in the multi-faceted system, in order to achieve higher technology readiness levels, to bring the costs down and to increase competitiveness on the energy market.

In dealing with Borehole Heat Exchangers (BHE) coupled with geothermal HP, different analytical models analyse the thermal behaviour and a range of simulation tools are available for analysis. For instance, the infinite [29,30] and finite line models [31,32] represents the borehole with a uniform heat flow line. Another commonly adopted approach is the cylindrical heat source [29], which is normally used to analyse the thermal performance of energy piles and can be extended also to BHE [33].

Economic issues are often mentioned in projects involving BHE, but it has to be noted that investment costs have continuously decreased as described e.g. in Ref. [34], referring to Switzerland, i.e. the country to which this research is mainly dedicated. The Swiss context, in which about 1/3 of the HP are geothermal [35], is also further explored in Ref. [36], related to the energy performance of geothermal systems and [37], reviewing the state of the art.

The ability to heat and cool through the same system is an important feature of geothermal BHE, allowing flexibility in different climates. Further details on GSHP for heating and cooling are available in Ref. [38], which deals with the climate change issue.

In addition [39], studies the potential combination of Direct Ground Cooling (DGC, called geo-cooling in the modifications performed in the present research) with DH and GSHP to compare the required borehole depths and needed drilling areas. For this technology, the ground is used as the only source for cooling and electricity demand is only about driving the circulation pumps. The results show that the required borehole depths in most cases are shorter for the DGC and DH combination than for the DGC and GSHP combination. It is also demonstrated that the optimal range of borehole outlet temperatures could be chosen based on the trade-off between borehole installation and terminal unit costs.

1.3. Renewable sources, technologies and aims of the research

The technology considered in the following sections refers to BHE coupled with geothermal HP. The BHE is a closed-circuit device for extracting geothermal heat from shallow rocks. The heat exchanger inside the borehole can be a double U-tube or two coaxial tubes (quite rare). The hole around the tubes is normally filled with a material with high thermal conductivity.

In addition to BHE, most of the scenarios considered in the present study also include Photovoltaic-Thermal systems (PVT, see *Section 2* and sub-sections). A PVT module consists of solar cells for converting solar energy into electricity and a heat exchanger for generating thermal energy. So, this technology allows the generation of electricity and heat at the same time and by the same solar collection surface. In the framework of the research here presented, and according also to previous contributions [40–42], PVT is adopted with the aim of regenerating the ground (i.e. returning to the ground part of the heat extracted during the winter season), in addition to the same effect which realized through cooling. In this sense, PVT contributes to reducing the number of BHEs needed, and thus the related investment costs.

The main aim of the present article is to investigate the optimal combinations of climatic conditions, features of the built environment and thermal RES locally available for an effective penetration of innovative DHC systems able to exploit low grade heat sources, such as geothermal (Geo) and solar energy. This investigation refers to a wide area with mild climates in Europe, i.e. the most affected by climate change in terms of reduction of the SH demand, increase of the space cooling (SC) demand and intensification of the urban density in the next few decades. More in detail, the following research questions are identified:

- Could Geo-5GDHC systems contribute to the decarbonization of the European thermal sector?
- Which criticalities emerge concerning Geo-5GDHC?
- Can Geo-5GDH be effective for heating and cooling buildings when considering economic and energy aspects?
- How does Geo-5GDHC effectiveness vary in different climates and with different heat and cooling building performance?

These research questions are dealt with in the following sections. In particular, after the detailed introduction to the subject, sources and technologies reported in *Section 1*, *Section 2* outlines the materials and methods and the scenarios considered, *Section 3* reports the results achieved and *Section 4* summarizes the lessons learnt and the main closing considerations.

2. Materials and methods

As described in *Section 1*, the diffusion of Geo-5GDHC is still hindered by the lack of detailed knowledge about cost-effectiveness and energy performance in different climates and building typologies. To address this challenge, a model-oriented and data driven approach based on technical and measured data from real case studies has been defined and adopted. The method is divided into 3 main steps:

- Energy simulations performed with TRNBuild[1] (based on the TRNSYS environment) to assess the thermal needs for heating and cooling of the district analysed;
- An iterative process carried out by the PILEDHC tool (based on the TRNSYS environment; *Section 2.2.1*) for sizing the BHE field and the PVT according to the thermal needs of the specific location previously calculated;
- An economic model to assess the energy costs in each scenario.

The results have then been evaluated according to several energy-economic Key Performance Indicators (KPI), described in *Section 2.2.4*. A general overview of the method is provided in Fig. 2, while more detailed information about each step of the entire process is provided in the following sub-sections.

2.1. Definition of the case studies, climates, data sources and scenarios

As represented in Fig. 2, the input and assumptions of the virtual case study defined, in terms of buildings' and energy system's characteristics are based on two real case studies, described in Refs. [44,45]. One real case, in the milder Ticino, consists of a residential building in operation since 2014, with 46 flats on 7 floors and an energy reference surface of 5700 m^2, equipped with 13 BHEs. The other one, in the colder Surselva Region, is a 5GDHC systems with 75 BHEs of 250 m deep and spaced about 8 m from each other (Table 1).

The energy and economic information available have been collected and elaborated for the definition and the validation of the model described in the following sections. More in detail, from all the available information, the parameters reported in Table 1 have been considered to implement the energy and economic model.

A virtual case study has been defined with the same dimensional features of the real case study in Surselva: four buildings, with a rectangular section for a total surface of 11,500 m^2, connected through a Geo-5GDHC system made of a BHE field with a heat distribution network of 500 m (Fig. 3). These four buildings are assumed to have the same thermo-physical features. The heating and cooling needs are assumed to be covered by the Geo-5GDHC system using HP for SH needs and cooling machines or geo-cooling technology (see also [36,39]) for SC needs, according to the climatic conditions and to the results obtained by the PILEDHC tool described in *Section 2.2.1*. As mentioned, geo-cooling allows the use of only a modest amount of electricity to circulate a working fluid between the building and the ground in comparison to electric-driven cooling machines which use a larger amount of electricity.

In order to include a wider range of applications in the results, the virtual Geo-5GDHC case study described has been simulated in different configurations, varying the insulation levels and the integration of PVT on the roof of the buildings. The features of the buildings considered in the model has been set according to elaborations based on the dataset available for the Swiss building stock (CAS RIM at SUPSI [49]). To limit the number of scenarios to be simulated, two envelopes have been considered: one poorly insulated and one well-insulated, as described in Table 2. According to Refs. [50–52], taking into account the aims of the work, the variety of the building stock and the need to reduce the number of scenarios to be simulated, these envelopes can be considered representative also for the Italian building stock and, for the sake of simplification, the buildings features have been kept constant in all the simulated scenarios.

These assumptions have been combined producing four scenarios, i.e. Low Ins with PVT, Low Ins without PVT, High Ins with PVT, High Ins without PVT. Moreover, five different climates were considered to cover the broadest range of typical EU climates, according to the Koeppen-Geiger climate classification [21], with a focus on the area surrounding Italy and Switzerland (see Fig. 4). Such an approach is driven by the objective of understanding the energy and economic feasibility potential of Geo-5GDHC in different climatic contexts.

Having fixed these climatic locations, the hourly data necessary for this research have been produced using Meteonorm version 7 [53] (Table 3), considering the typical meteorological year of the selected locations. Each scenario has been modelled with TRNBuild, for calculating heating (SH and DHW) and SC needs by mean of dynamic energy simulations. The hourly heating and cooling needs calculated for each scenario have then been used as input to size each component of the PVT and BHE system through PILEDHC (see *Section 2.2.1*).

In the end, 20 scenarios have been determined by combining the following parameters:

- 2 types of thermal insulation of buildings, high and low insulation (see *Table 2*);
- *5 climatic locations;*
- *2 PVT options (with or without integration in the system, i.e. installed or not).*

The 20 scenarios defined have been then reduced to 17 because of the unsuitability of PVT systems in the warmest climates among those considered, i.e. the scenarios Rome High Ins and Palermo High Ins and Low Ins (details in Fig. 5 and Section 3.1). Indeed, as clarified in the

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[1] TRNBuild is an interface for creating and editing all of the non-geometry information (thermo-physical properties, schedules, comfort calculation etc.) required by the building model in TRNSYS [43].

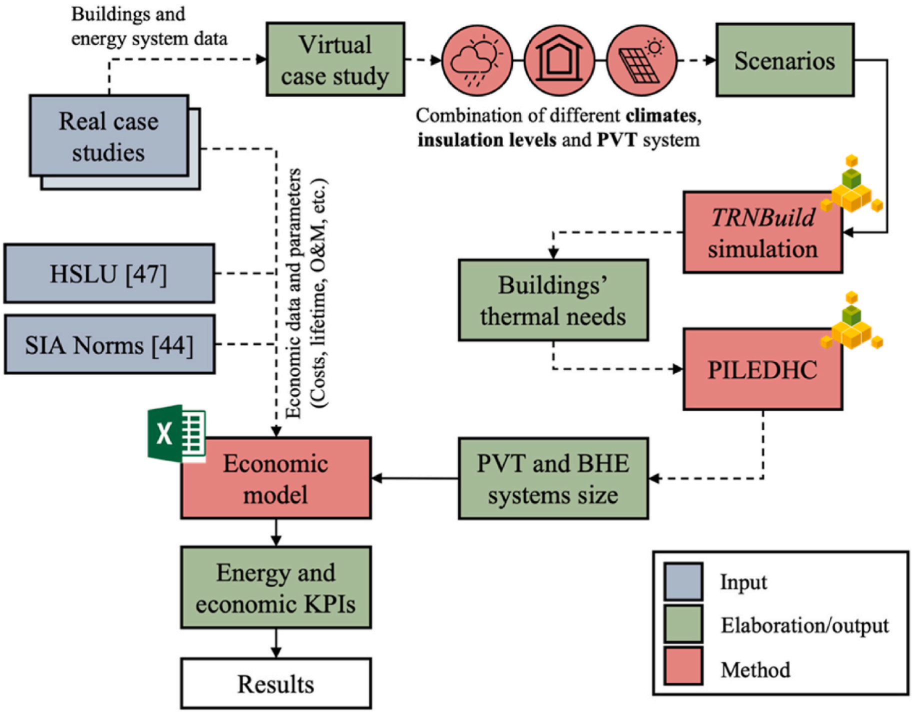

Fig. 2. Scheme of the method workflow.

Table 1

Main information for the two real case studies considered in order to implement the[1] model.

Parameter/data	Values/Notes	References
• Real case study in Ticino (BHE installation)		
Thermal response test (TRT) (thermal property of the ground, BHE parameters)	All the parameters needed to implement the energy model	[36,44]
Results from a 40 months monitoring campaign	Adopted to validate the energy model	[36,44]
• Real case study in Surselva		
Number of buildings connected	4	[46]
Total buildings' energy reference surfaces	11,500 m^2	[46]
Length of the network	500 m	[46]
BHE characteristics Drilling diameter Type Effective thermal resistance (R_{b_eff})[2]	0.135 m double – U 0.056 K/(W/m)	[44], EED tool[3]
Technical information and performance of the PVT system	Adopted to implement the energy model	[47] and confidential documents of the realized project
Investment costs	Adopted to implement the economic model	[48] and confidential documents of the realized project

results, PVT is not included in the scenarios where it does not allow a reduction of the number of geothermal BHEs and the total thermal cost by regenerating the ground.

The geometric and thermal parameters of the BHE field, and the thermal parameters of the ground are assumed to be the same as in the real case study located in the Ticino Region where a TRT has been carried out [44]. Soil temperatures, on the other hand, are calculated on the basis of the annual average outside air temperature in each of the climatic areas selected following the method described in SIA 384/6 [54].

2.2. *Energy and economic modelling approach and tools*

In the following subsections, an overview of the main steps for the definition of the method, applied to the scenarios defined, is provided. In the present paper, several assumptions and results related to the energy modelling phase (briefly provided in Section 2.2.1) has been neglected to better highlight the description and results of the techno-economic modelling and evaluation, which represents the main novelty of the present study. More details on the energy model are described in Ref. [55].

2.2.1. *Energy model*

The energy model is composed of two main parts:

1. A dynamic energy simulation framework based on TRNBuild for the calculation of the buildings' thermal needs;
2. The PILEDHC simulation tool used for the optimal sizing of the BHE system according to the hourly thermal needs of each case study and for integrating the PVT system.

For the present study, the thermal needs for the defined scenarios are modelled and simulated through TRNBuild and post-elaborated with an MS Excel file. These results are then used as input in PILEDHC to simulate and size the system's components.

PILEDHC is a tool developed by adapting PILESIM2, a tool based on TRNSYS. PILESIM2 has been updated, within the framework of the research here presented, allowing the inclusion in the model of a module for simulating a low temperature distribution network connected to the buildings' appliances from one side, and to the BHE field on the other side (Geo-5GDHC). The aim of the PILEDHC is to accurately compute the number and length of the BHE field, considering that it must respond to numerous parameters and operating conditions, including the thermal needs of buildings and the district pipes' thermal losses, together with the economic conditions. So, the hourly thermal needs of the buildings are provided as input to the model, which, based on various parameters (thermos-physical parameters of the ground, type and dimensions of BHEs, a technique used to heat and/or cool the buildings, length of the

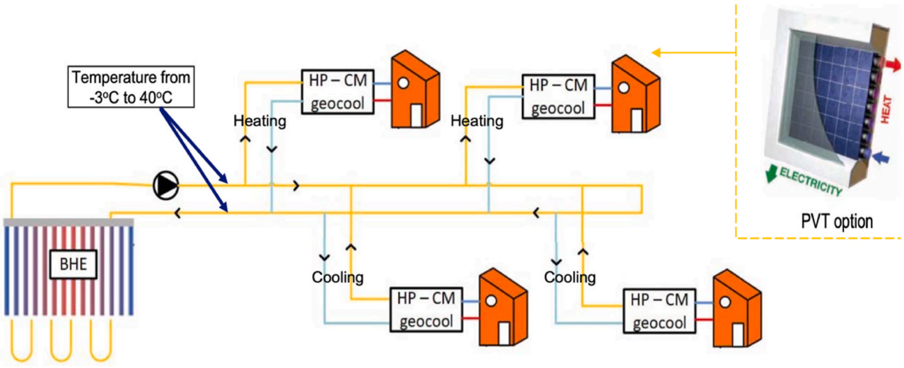

Fig. 3. Geo-5GDHC system layout.

Table 2

Summary of the main features of the envelopes of the two building types considered.

Insulation level	Walls and roof	Windows	
	U values [W/(m^{2}K)]	U values [W/(m^{2}K)]	g values [-]
Low Insulation (Low Ins)	1.0	2.83	0.76
High Insultation (High Ins)	0.2	1.23	0.44

network), provides fluid temperatures at the inlet and outlet of the BHE field. Based on these results and following the indications of the SIA 384/6 standard [54], the geothermal BHE field is dimensioned in terms of number and depth of drilling (i.e. the size of the ground heat exchangers).

In accordance with SIA 384/6, the minimum inlet temperature in the ground must never be lower than −3 °C during 50 years of system operation when using water and antifreeze, and never lower than +4 °C when using pure water. Similarly, the maximum fluid temperature must never exceed +40 °C over 50 years of operation. The annual hourly demands for heating and cooling of the building stock are thus simulated 50 times taking also into account the seasonal thermal storage effect due to the geothermal field.

PILEDHC has been validated according to the Ashrae Guideline 14 [56], the IPMVP [57] and the FEMP [58], which criteria and methodology are summarised in Ref. [59]. Such validation standards provide tolerance thresholds for the normalised mean bias error (NMBE) and the coefficient of variation of the root mean square error (CVRMSE) between simulated and measured data. Measured data available, results of a monitoring campaign on the real case study in Ticino, include the input and output temperature values from the BHE field and the corresponding thermal energy exchanged with the ground (by energy meters). The results obtained fall averagely within the boundaries of acceptability defined by the references adopted.

2.2.2. Economic model

For the implementation of the economic model, the method of investments and annualised expenditure, also known as the French mortgage, has been adopted. It consists of offsetting all the timewise mismatches of the monetary flows associated with a technical-economic activity, by bringing them all back to the “time zero” of the operation. Each annual operating expenditure is calculated and estimated, considering it representative of each year of operation.

Such an approach allows the capital and interest to be combined, together with ongoing costs, resulting in a constant annual rate over time (where there is a fixed rate of return on capital).

This method is also adopted by the study presented in Ref. [60] and it is supported by several previously mentioned regulations and standards [61].

Capital expenditures, also simply called CAPEX (CAPital EXpenditure), are expenses that a company capitalizes over a certain period related to investments and which, after the lifetime of the components, it will have to provide for again.

Operating expenditures, also simply called OPEX (OPerating EXpense), are all the ongoing costs for running the system, including maintenance, cost of energy purchased, insurances, personnel costs.

In the present study, the comparison between the case studies is made by calculating the total annualised cost per unit of heat delivered (H) as described in the following equation to calculate the thermal cost.

$$\mathrm{C_{th}} = \frac{CAPEX + OPEX}{H_{tot}} = \frac{\sum_{i=o}^{n} a_i\, C_i + \sum_{j=o}^{m} C_{joP}}{H_{tot}} \tag{1}$$

where:

- c_{th}: thermal cost of the investment;
- a_i: annualization of each i-investment;
- C_i: cost of each i-investment;
- C_{j_OP}: each j-operative cost;
- H_{tot}: total thermal energy provided to users;
- n: number of investment costs;
- m: number of operative costs.

In detail, the annualization of the investment a has been calculated with the following equation.

$$a = \frac{q^t \bullet i}{q^t - 1} \tag{2}$$

where:

- a: annuality
- q: factor 1 + i
- i: annual interest
- t: duration of the investment – according to lifetime of the components (years)

SIA 480 [61] proposes using a value of 3–3.5% for the annual interest, to be reduced by 0.5% for municipality investments and 1% for national investments. These reductions would seem plausible and

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[2] Value based on the TRT report of the drilling company. The internal thermal resistance and the thermal resistance have been set depending on the use of pure-water or mixture of the carrier fluid.

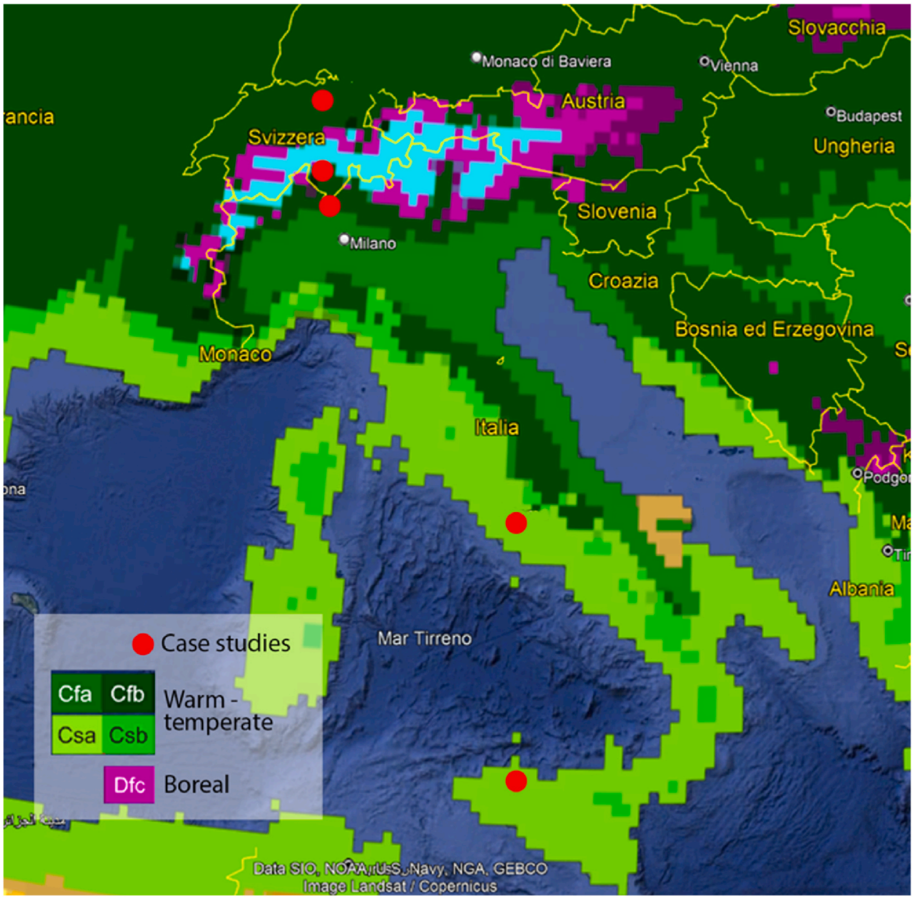

Fig. 4. Koeppen-Geiger climate classification in Europe [21].

Table 3
Summary of the selected climates' characteristics according to the Meteonorm weather file.

Climate	Description (Koepen-Keiger)	Ref. weather station	Heating DD [K-day]	Cooling DD [K-day]	T max [°C]	T min [°C]
Dfc	Boreal	Tujetsch	3820	0	25.7	−16.7
Cfb	Warm temperate	Zurich	2797	1	31.6	−9.8
Cfa	Warm temperate	Lugano	2433	18	33	−4.2
Csb	Warm temperate	Rome	1421	131	37.2	−0.5
Csa	Warm temperate	Palermo	908	144	36	4.5

appropriate in relation to what should be the proper goals of projects carried out by public bodies and institutions, for which the return on capital should not take on a predominant weight. The weight of investments, which are often responsible for most of the annual costs, can vary greatly depending on the expected annual interest rate and the lifetime duration of the component.

It must be underlined that, for the simulated scenarios, the economic model does not take into consideration the costs of insulation materials, and the possible economic benefit linked to retrofit interventions; the buildings are modelled with different levels of insulation to represent the features present in the building stock. The realization of and connection to the Geo-5GDHC is the only measure considered from the technical and economic point of view.

2.2.3. *Application of the economic model*

Different detail categories are defined to calculate the CAPEX costs for every case study through the annualization of each investment cost. This is due to the necessity to separate each investment in different lifetime values (Table 4).

Concerning the lifetime of the components, the information has been taken from SIA382/1:2014 [62], the recommendation SWKI 88–3 [63] and documentation of the association HEV [64].

To simplify the reading of results in graphical form, each detail category has been grouped into macro-categories (drilling, building, network, PVT, etc., see Table 4).

The specific costs needed for the investment calculation are mainly based on the available information from the real case located in the Surselva Region, as explained in *Section 2.1*. According to a privacy agreement with the data provider, it is not allowed to clarify the investment value for the cost items.

To complete the set of economic inputs, the HSLU database [48] has been adopted, from which some item costs have been derived through interpolation.

The investment costs and economic analyses are assumed as constant for all the climatic contexts considered, hence not dependent on the local contexts or national conditions (e.g. local market, cost of life,

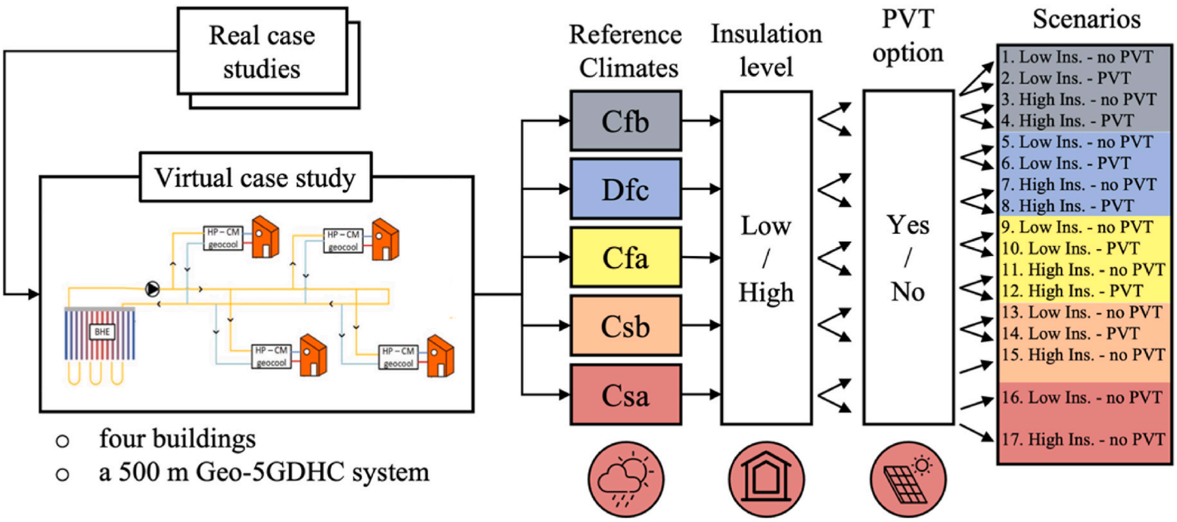

Fig. 5. Scheme of the definition of the 17 scenarios.

taxation, salaries, etc.).

As described in the European projects [65,66] and based on interviews to drilling companies in Switzerland, drilling costs are highly dependent on the drilling length, which highly depends on the thermal requirements of buildings, as well as the thermophysical characteristics of the ground.

In the above-mentioned European projects, it has emerged that drilling costs do not vary much from country to country, as the manpower cost is of minimal importance. The difference on costs depends mainly on the kind of rock and consequently on the machines used.

As far as the calculation of the OPEX costs is concerned, for each scenario, the electricity consumption for heating, cooling and pump operations, the electricity sold to the grid from PVT and maintenance have been considered. Maintenance, personnel costs and insurance have been fixed at 1% of the yearly costs (except for the category “building”, which is at 3%). Electricity cost has been set at 0.2 €/kWh for purchase from the grid and 0.1 €/kWh for feeding into the grid. The whole electricity production is assumed to be sold to the grid.

The outputs of PILEDHC, that reads and elaborates the results of the energy simulations in TRNBuild, are automatically exported in an Excel sheet, where the inputs and parameters of the techno-economic analysis can be edited by the user. In this way, it is possible to automatically calculate the investment and maintenance costs for each case study analysed. The model can evaluate capital expenditures and operating expenditures for every simulation performed with PILEDHC.

Table 4
Investments’ lifetime for the calculation of CAPEX (divided in categories).

CATEGORY	DETAIL	LIFETIME
BHE field	Drillings	50
	Horizontal connections	50
	Collector	50
	Glycol	20
Plant	Building	50
	Technical devices (short term)	20
	Technical devices (medium term)	30
	Technical devices (long term)	50
PVT system	PVT modules	30
	Hydraulic technical devices	25
	Electric technical devices	20
	Other components	35
Network	Trench and pipes (district network)	50
Building	Branch to the building	50
	Heat pumps	20
	Substation technical devices	20
	Electrical devices and control system	20
	Electro-mechanical devices	30
	Communication and connection	30
Fee	Design, building, management	15

2.2.4. *Energy and economic KPIs adopted*

The outputs of the different simulated configurations have been then evaluated through the selection and definition of a set of KPIs, useful for representing results from the energy and economic point of view. The results of the model, evaluated according to the metric defined in the present section, has then been represented in comparison with the heating Degree Days (DD). Such an approach is aimed at providing a parametrisation of the results achieved as a function of a climatic variable, making a rapid assessment of the techno-economic feasibility of Geo-5GDHC in different climates possible for further studies.

The main KPIs adopted are defined in the following list.

- Specific heating need (q_h): ratio between the total energy need for SH and DHW (E_h) and the Energy Reference Surface (ERS) (m^2)

$$q_h\left[\frac{kWh}{m^2}\right]=\frac{E_h\ [kWh]}{ERS\ [m^2]} \tag{3}$$

- Specific cooling need (q_c): ratio between the total energy need for SC (E_c) and the Energy Reference Surface (m^2):

$$q_c\left[\frac{kWh}{m^2}\right]=\frac{E_c\ [kWh]}{ERS\ [m^2]} \tag{4}$$

- Linear power density: ratio between heating and cooling powers[3] (P_h and P_c) and the length of the thermal network; defined both for heating (l_h) and cooling (l_c), respectively:

$$l_h\left[\frac{kW}{m}\right]=\frac{P_h\ [kW]}{lenght\ [m]}\ and\ l_c\left[\frac{kW}{m}\right]=\frac{P_c\ [kW]}{lenght\ [m]} \tag{5}$$

- Linear energy density: ratio between the total energy need and the length of the thermal network; defined both for heating (L_h) and cooling (L_c), respectively:

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[3] Heating and cooling powers refer to the yearly peak of heating and cooling thermal powers.

$$L_h\left[\frac{kWh}{m}\right]=\frac{E_h\ [kWh]}{lenght\ [m]}\ and\ L_c\left[\frac{kWh}{m}\right]=\frac{E_c\ [kWh]}{lenght\ [m]} \tag{6}$$

- Ground regeneration rate (R): ratio between the energy injected (E_{inj}) and the energy extracted (E_{ex}):

$$R[\%]=\frac{E_{inj}\ [kWh]}{E_{ex}\ [kWh]}\bullet 100\% \tag{7}$$

- CAPEX energy cost (c_{CAPEX}): ratio between the annualised capital costs of the plant and users (CAPEX) and the total thermal energy needs of the building ($E_{tot} = E_h + E_c$):

$$c_{CAPEX}\left[\frac{€}{kWh}\right]=\frac{CAPEX\left[\frac{€}{y}\right]}{E_{tot}\left[\frac{kWh}{y}\right]} \tag{8}$$

- OPEX energy cost (c_{OPEX}): ratio between the operating costs of the plant and users (OPEX) and the total thermal energy needs of the building ($E_{tot} = E_h + E_c$):

$$c_{OPEX}\left[\frac{€}{kWh}\right]=\frac{OPEX\left[\frac{€}{y}\right]}{E_{tot}\left[\frac{kWh}{y}\right]} \tag{9}$$

- Total thermal cost (c_{th}): ratio between the annualised capital investment costs of the plant and users (CAPEX) added to all the operating costs of the plant and users (OPEX) and the total thermal energy needs of the building (E_{tot}). It corresponds to the index described in *Section 2.2.1* for the definition of the carrier fluid and PVT surface. This index is also equivalent to the sum of the two previous indices ($c_{th} = c_{OPEX} + c_{CAPEX}$):

$$c_{th}=\frac{CAPEX\left[\frac{€}{y}\right]+OPEX\left[\frac{€}{y}\right]}{E_{tot}\left[\frac{kWh}{y}\right]}\left[\frac{€}{kWh}\right] \tag{10}$$

- Building Energy Reference Surface cost (c_{surf}): the ratio between the total annualised investment (CAPEX) and operating costs (OPEX) and the ERS of the buildings. The purpose of this indicator is to decouple the annual costs from the energy provided, and thus to be able to compare the same buildings in different conditions (climate, building insulation category and PVT installation):

$$c_{surf}=\frac{CAPEX+OPEX}{ERS}\left[\frac{€}{m^2}\right] \tag{11}$$

3. Results and discussion

According to workflow presented in *Section 2*, the main results are reported in the following subsections, referring to the KPIs presented in *Section 2.2.4*.

3.1. Energy performances and sizing of the Geo-5GDHC components

The scenarios simulated allow a coverage of a wide range of conditions. In fact, the results range from a maximum total power of 874 kW for SH (with 0 kW for SC) in Tujetsch Low Ins to a minimum total power of 298 kW for SH (with 325 kW for SC) in Palermo Low Ins.

The hourly values of the heating and cooling needs are obtained by the dynamic simulations carried out in TRNBuild and their sums in terms of yearly values are reported in Table 5.

The combination of the thermal and geometric features of the buildings and of the topology of the network determines realistic and conservative values of thermal density. In fact, in terms of power density, the results are in the range 0.3–1.8 kW/m for heating and in the range 0–0.8 kW/m for cooling (Fig. 6). As described in Ref. [67], values equal or higher than 1 kW/m can be in line with the techno-economic feasibility of the installation of a district thermal system. However, on the basis of experience gained on 3GDH systems, in the technical literature this KPI is only adopted for analysing DH. Looking at Fig. 6, the “l_h” is higher than 1 kW/m in 4 of 10 scenarios, but if the cooling power is also considered, this condition is satisfied in 9 out of 10 scenarios. In terms of linear energy density, the results are in the range 0.2–4.2 MWh/m per year for heating and in the range 0–0.3 MWh/m per year for cooling (Fig. 7). As described in Ref. [68], values equal or higher than 2.5 MWh/m per year are in line with the techno-economic feasibility of district heating system (DHS), even if other sources such as [67,69] underline lower values for many existing DHSs, so this threshold can be decreased to 1–2 MWh/m per year. Also, in this case the technical literature refers to DH only. Looking at *Fig. 7, the “L_h” is higher than* 1 MWh/m *per year in all the “Low Ins” scenarios, considering the sum of heating and cooling, and in the “High Ins” scenario of the coldest location. In conclusion, although these two KPIs are not sufficient for the evaluation of the feasibility of district thermal systems, what is clear is the opportunity to consider cooling in addition to the heating for improving the profitability of the overall system and the feasibility of such systems will be even more evident in contexts with higher energy demand density according to different combinations of the thermal and geometric features of the buildings and of the topology of the network.*

Table 5
Specific yearly heating and cooling needs (kWh/m^2) simulated in TRNBuild.

Ref. weather station	Insulation	q_h [kWh/m^2]	q_c [kWh/m^2]
Tujetsch	Low	184.7	0.0
	High	53.8	0.0
Zurich	Low	119.3	0.0
	High	34.9	0.3
Lugano	Low	92.8	1.1
	High	27.1	3.9
Rome	Low	50.7	12.1
	High	12.6	12.6
Palermo	Low	31.8	12.6
	High	7.8	13.5

According to the workflow defined (Fig. 2), the results of the dynamic simulations in TRNBuild, in terms of hourly values of the buildings’ thermal needs, are used as input for sizing the BHE field by PILEDHC. PILEDHC performs an iterative simulation, increasing or decreasing the number of BHEs as a function of the minimum and maximum temperature of the heat transfer fluid within the geothermal field, while remaining within the normative limits.

According to Figs. 2 and 5, the scenarios to be simulated by PILEDHC can be potentially 20, but, as anticipated, 3 scenarios with PVT have been discarded. This happens if, for the same location and envelope performance, the total thermal cost and the number of BHEs turn out to be higher for the with-PVT scenario compared to the without-PVT scenario. In fact, the PVT aims to reduce the number of geothermal BHEs and to lower the total thermal cost by regenerating the ground. If these conditions are not respected, the case study with PVT is considered unsuitable and discarded.

Indeed, the case studies with PVT systems were excluded for “High-Ins” insulation level in Rome and both insulation levels in Palermo. In these scenarios, characterised by relevant cooling needs, the solution with the PVT system involves energy and economic unfavourable conditions, resulting in a higher number of BHEs compared to the analogous

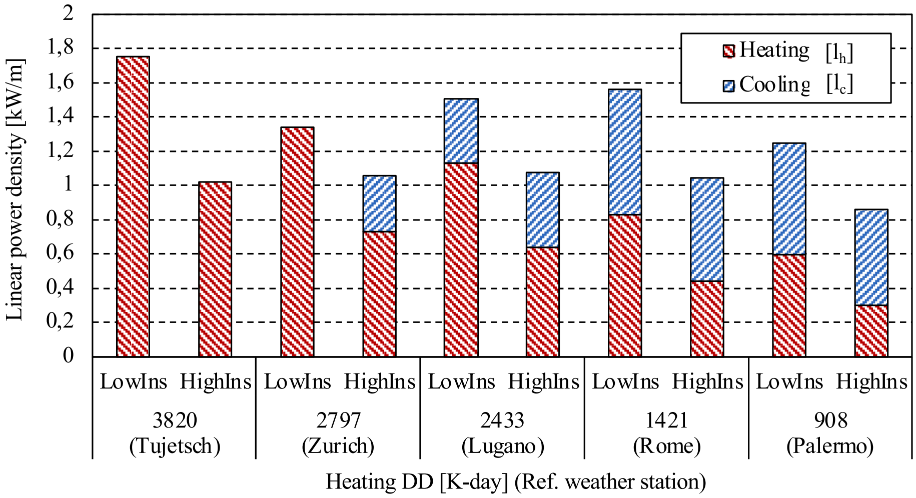

Fig. 6. Linear power density ("l_h" for heating, and "l_c" for cooling).

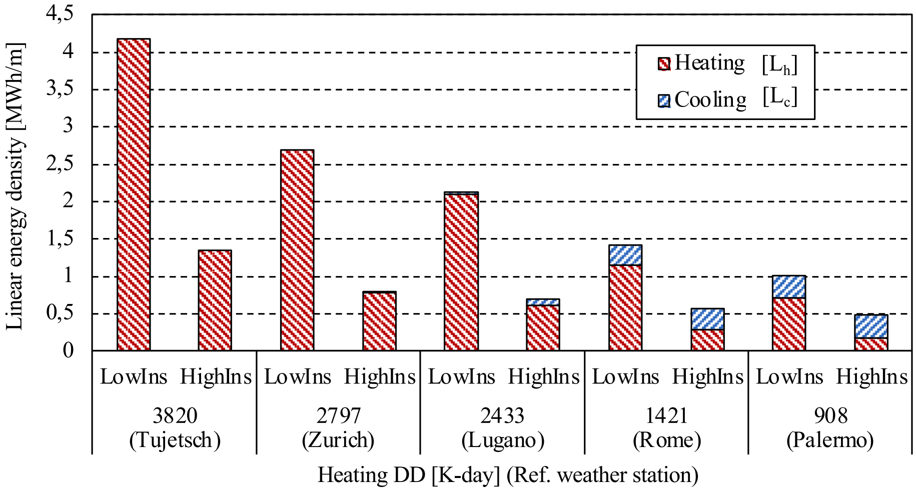

Fig. 7. Linear energy density ("L_h" for heating, and "L_c" for cooling).

Table 6
Optimal PVT surface for the 5 climatic locations.

	Tujetsch	Zurich	Lugano	Rome	Palermo
Low-Ins with PVT	1,000 m^2	1,000 m^2	1,000 m^2	300 m^2	-
High-Ins with PVT	500 m^2	300 m^2	300 m^2	-	-

case without PVT, and a higher total thermal cost.

The PVT surface has been set according to the information available for the real case study of Surselva Region (500 m^2, facing South and with a tilt of 30°). The options of 300 and 1000 m^2 have been defined according to the different offers received and they are both compatible with the geometric features of the simulated buildings. Table 6 shows the optimal PVT areas according to the results achieved.

A total of 17 case studies have been finally analysed as described in the first and second columns of Table 7. Fig. 8 shows the results in term of number of BHE for each scenario, where the number of 250 m deep BHEs needed in the four conditions for different climatic locations are represented according to heating DD.

As mentioned, the case studies with an installed PVT system allow fewer BHEs than the corresponding case without PVT, and, as expected, lower heating DD results in a lower amount of BHEs to cover heating needs. Another interesting aspect is that in climates with low heating DD, the difference between cases with and without PVT, in terms of BHEs to be installed, is smaller compared to the same difference in climates with high heating DD.

A special case is Lugano High-Ins, where the scenarios with and without PVT have the same number of BHEs, but as shown in Table 7, the case with PVT allows the adoption of pure water instead of brine as carrier. This means that the cost of the antifreeze and the electricity production/sale balance are approximately equal to the cost of the installation of a 300 m^2 PVT.

The results with PVT systems maintain regeneration rates ranging from about 40% up to about 70%. The closer the number is to 80%–100%, the less the ground is at risk of cooling down excessively, as

Table 7
Types, minimum and maximum temperatures of the carriers (based on energy and economic results, and standards' constraints).

Scenarios		T_min [°C]	T_max [°C]	Thermo-carrier fluid
Tujetsch	Low-Ins without PVT	−3.0	11.9	Brine
	Low-Ins with PVT	−3.0	17.8	Brine
	High-Ins without PVT	−3.0	11.8	Brine
	High-Ins with PVT	−3.1	19.1	Brine
Zurich	Low-Ins without PVT	−3.0	16.8	Brine
	Low-Ins with PVT	−3.1	23.4	Brine
	High-Ins without PVT	−3.1	22.4	Brine
	High-Ins with PVT	−2.6	25.6	Brine
Lugano	Low-Ins without PVT	−2.9	20.2	Brine
	Low-Ins with PVT	−2.9	33.5	Brine
	High-Ins without PVT	−2.8	31.1	Brine
	High-Ins with PVT	4.3	28.9	Water
Rome	Low-Ins without PVT	4.2	34.0	Water
	Low-Ins with PVT	4.0	41.5	Water
	High-Ins without PVT	12.8	40.1	Water
Palermo	Low-Ins without PVT	4.4	40.6	Water
	High-Ins without PVT	15.6	41.9	Water

Another KPI, i.e. the ground regeneration rate defined as described in Eq. 7, is represented in Fig. 9.

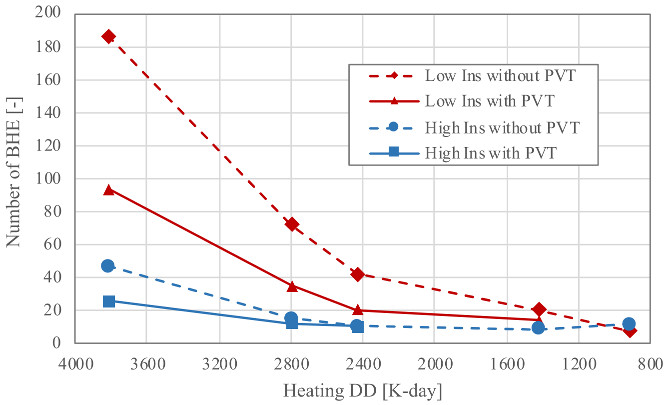

Fig. 8. Number of BHEs for each scenario and parametrisation based on heating DD.

described also in Refs. [70,71]. As shown in Fig. 9, scenarios where the system without PVT achieves suitable regeneration rates, e.g. greater than 50% as in Rome High Ins and Palermo, do not require additional thermal regeneration of the geothermal from an energy and economic point of view. Conversely, due to null or very low SC demand (Table 5), PVT allows regenerating the ground in colder climatic conditions.

3.2. Economic results

Analysing the results of the annualised cost computation (Eq. (1), Fig. 10), it is possible to observe a significant variation of the investments (CAPEX) the highest up to about 6–7 times more than the lowest among the scenarios considered (i.e. comparing poorly insulated buildings in cold climates and well insulated buildings in warm climates).

As shown in Fig. 10, the annual investment of the "network" is the same for all the case studies, because, since the topology of the network do not vary, the length is always 500 m, and other parameters that can vary this investment are not considered. The "building" item, which includes the construction of a technical structure for the installation of the equipment in the central station (hydraulic collector, circulation pumps, expansion vessel, etc.) also has quite fixed costs that do not vary much from case to case. Conversely, as mentioned, drilling is the most variable and impacting cost.

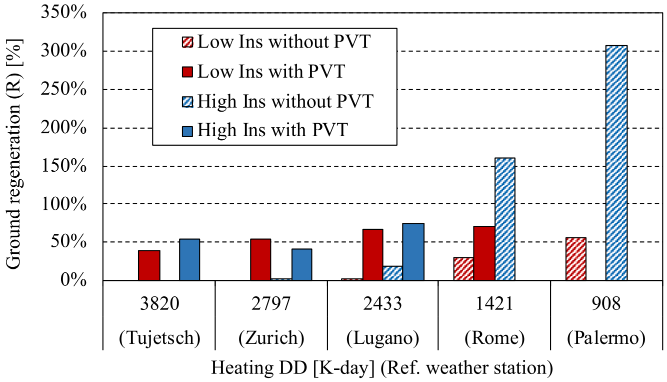

Fig. 9. Ground thermal regeneration (ratio between energy injected and energy extracted) in the 17 scenarios considered, grouped by insulation of the envelope and PVT integration.

In Fig. 11, the summary of the annual operative costs (OPEX) is presented. The electricity sold in the case of a PVT system is considered as a profit and not as an expense, and therefore has a negative value compared to the other items.

The major electricity cost is for heating production through HP. Indeed, this cost is higher in cold climates and for Low Ins buildings. The electric costs for the cooling production become relevant only for the warmer climatic sites (Rome and Palermo) where geo-cooling, which has negligible electric costs, is not able by itself to satisfy the cooling needs.

The sum of the annualised "CAPEX costs" and "OPEX costs", represented in Figs. 10 and 11, respectively, represents the "total thermal cost, c_{th}" (Eq. (8)). These results are presented in Fig. 12, showing a variation between 20 and 22 cent€/kWh for high insulated buildings (except Tujetsch which is above 18 cent€/kWh in the case with PVT), and between 15 and 14 cent€/kWh for low insulated buildings (except Tujetsch which without PVT has a cost of around 17 cent€/kWh). In Fig. 12, the coloured lines provide the total thermal cost for different climatic locations represented by their heating DD. This KPI is treated in the study [72] that analyses the total thermal cost for different DHC systems (almost 3GDH), related to real cases and feasibility studies in Switzerland. According to Ref. [72], total thermal costs of around 13–15 cent€/kWh can be attractive for investors in realizing district thermal systems (usually energy utilities, municipalities, cooperatives, etc.).

Moreover, according to Fig. 12, it is interesting to notice that only the Low Ins and without- PVT scenarios are strongly influenced by variation in climate conditions. This is because the higher the heat demand to be satisfied only through BHEs, the higher the cost for installation of the geothermal system, which represents the highest cost item in the economic evaluation.

The adoption of PVT turns out to be more interesting for Low Ins scenarios because they have a lower cooling demand and hence a lower capacity for regenerating the ground through SC. For Low Ins buildings, PVT seems convenient for climates with heating DD of at least 1400 K-day. While for High Ins buildings, PVT seems convenient for climates with heating DD of at least 2900 K-day and not effective for DD lower than 2400 K-day.

The building ERS cost "c_{surf}" (Eq. (9)), unlike the total thermal cost "c_{th}", represents the expenditures (including CAPEX and OPEX) related

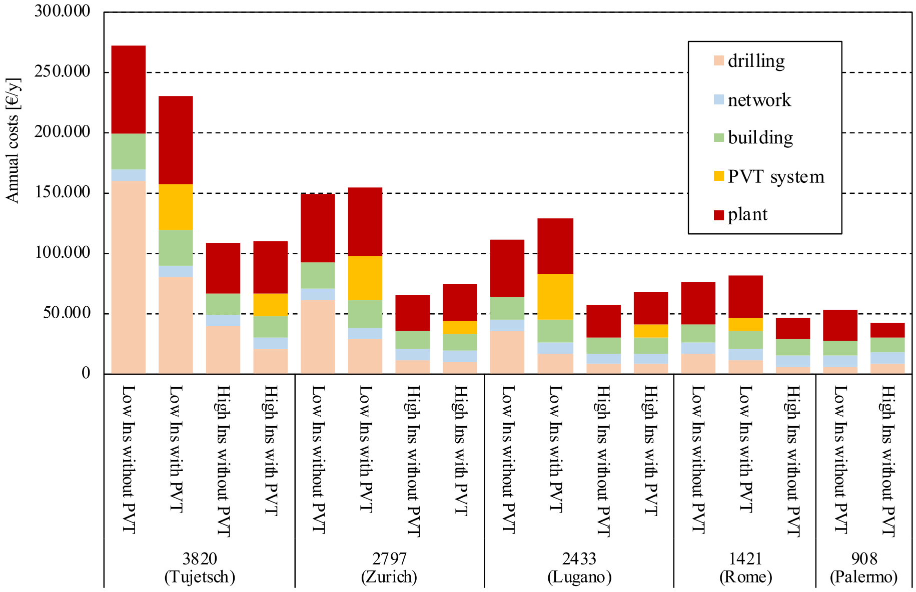

Fig. 10. Annual investments costs (CAPEX).

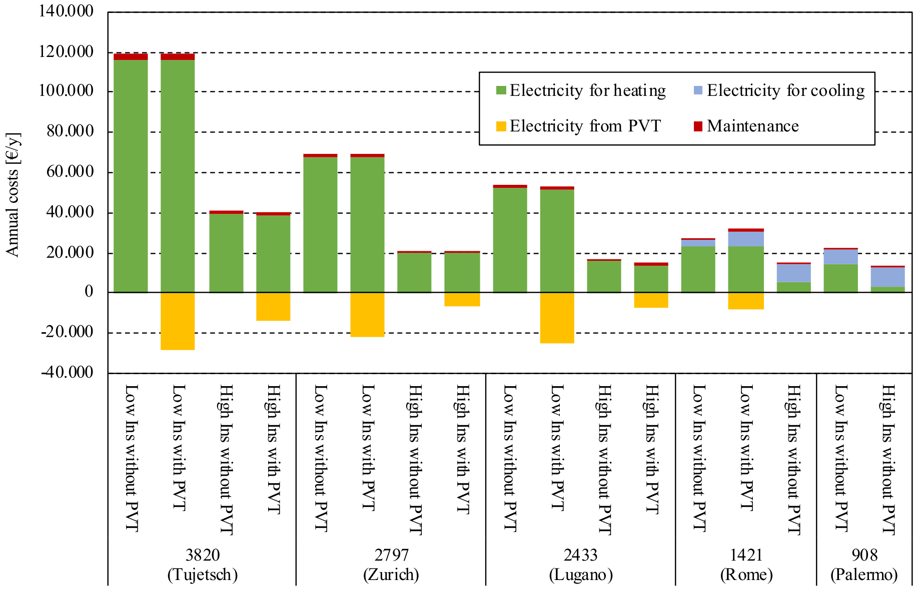

Fig. 11. Annual operative costs (OPEX).

to the reference surface unit. In Fig. 13 the ERS cost is provided for different climatic locations represented by their heating DD. The overall investment decreases passing from colder to warmer climates (lower thermal demands mean fewer BHEs, less installed power, etc.), and consequently also the “c_{surf}” decreases.

Considering ERS cost, for scenarios with Low Ins buildings, PVT seems convenient for climates with heating DD of at least 2000-2500 K-day, while there is a less appreciable convenience for scenarios with High Ins buildings.

4. Conclusions

Dealing with energy systems, the following issues have to be considered:

- a rapidly changing climate with rising temperatures;
- the need for decarbonization;
- geopolitical instabilities that have implications for the energy market and encourage energy supply from local energy renewable sources;
- need for always paying attention to economic aspects.

In this framework, district thermal systems are expected to grow drastically.

Based on the achieved results, Geo-5GDHC can contribute to increasing the penetration of district thermal systems and to decarbonizing the European thermal sector. Indeed, if coupled with compatible electric power generation systems, Geo-5GDHC can be renewable and carbon neutral, thus satisfying SC as well as SH and DHW needs through a single network and connecting just a few buildings or small neighbourhoods.

Since these systems are based on geothermal energy, the issue of the decreasing ground temperature in the mid to long term has to be faced. Results demonstrate the possibility of overcoming the problem through an optimal regeneration of the ground, thus reducing the number of

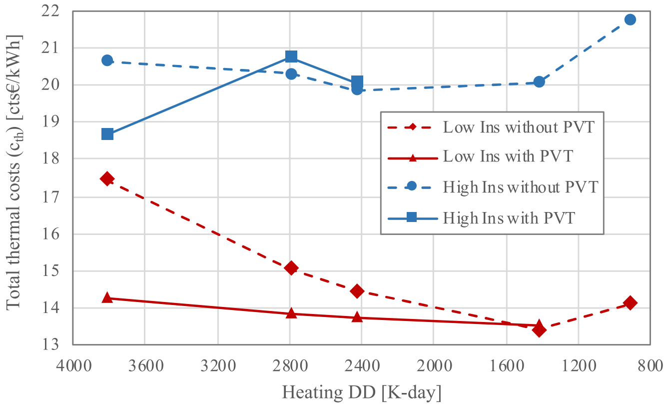

Fig. 12. Total thermal cost (c_{th}) for each scenario and parametrisation based on heating DD.

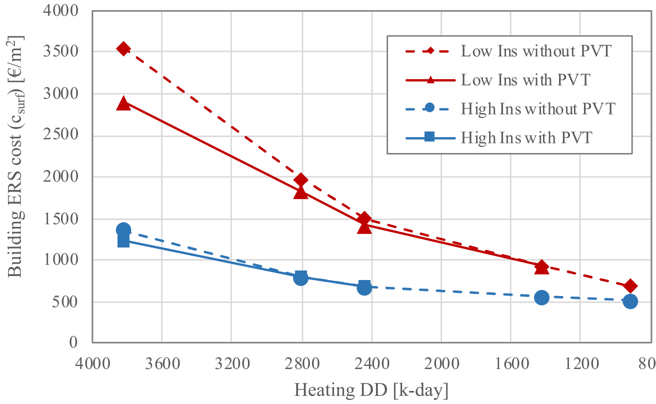

Fig. 13. Building ERS costs (c_{surf}) for each scenario and parametrisation based on heating DD.

probes and the initial investment cost. Indeed, based on the assumptions and on the results of the present research, PVT integration, i.e. exploiting also the solar source in addition to the geothermal one, allows regeneration rates ranging from about 40% to up to about 70%.

Moreover, Geo-5GDHC could push the exploitation of geothermal heat more than individual geothermal systems. In fact, the deployment of GSHP within Europe changes from one country to another, and it is also influenced by the presence or absence of a licensing system, procedures, and management of existing data [73]. In addition, individual shallow geothermal systems could thermally interfere with each other in unexpected (or not evaluated) ways, although this aspect can be controlled in Geo-5GDHC as well as in planning, technical design and plant operation.

According to the literature, the main criticalities concerning Geo-5GDHC can be related to the realization stage and to lack of information about the technologies involved, their costs and performances. So, it is suggested that further investigations are needed in terms of research, tools development and calibration and realization and monitoring of case studies. The research here presented can enrich knowledge in this field, providing methods, tools and useful energy and economic KPIs. In fact, through an innovative approach and through the specifically developed PILEDHC tool, the research here presented investigated the potential of Geo-5GDHC, considering sizing, energy and economic aspects, in various climatic contexts and applied to buildings with different levels of thermal insulation. Despite some necessary simplifications, results can be related to the European panorama, when considering the KPIs defined and elaborated. This set of KPIs indicates support for the diffusion of Geo-5GDHC under proper conditions, also in warmer climates where generally, from a DH-only vision, district thermal systems are not considered because of the low SH demands and heat density. In fact, taking SC into account in addition to SH improves the feasibility and profitability of such systems especially in contexts with high energy demand density, according to different combinations of the thermal and geometric features of the buildings and of the topology of the network.

Among the economic KPIs, the “total thermal cost” (i.e. the ratio between annual investment and operating costs and thermal requirements) demonstrates that Geo-5GDHC systems are especially advantageous in Low Ins scenarios, where this KPI has a short range of variation despite the climates. This is in line with the principle that the higher the thermal needs, the higher the cost-effectiveness. In fact, for Low Ins scenarios, the range of the “total thermal cost” is in line with that related to 3GDH, e.g. according to Ref. [72]. The total thermal cost “c_{th}”, which is lower for less performing buildings, cannot be considered as the selling price of heat, but can support the decisions of the investors and energy operators that are interested in realizing a district system to sell heating and cooling. But, even considering High Ins scenarios, a reduction of the value of this KPI can be achieved due to incentives for thermal renewables, or due to further technological innovations and consequent reduction of the related installation costs or, in the future, due to the increase in the cooling demand. Indeed, also the energy market conditions, extremely variable in the last few years, can affect the results.

On the other hand, the “building ERS cost” (i.e. the ratio between annual investment and operating costs and the reference surface of the buildings) reveals a different trend since it is lower for High Ins scenarios, showing a decreasing trend when moving towards warmer climates. This KPI can support the decisions of the energy planners during the comparison of alternatives for retrofitting a settlement, providing also heating and cooling, for example.

Based on the results discussed, Geo-5GDHC can be an appropriate technology also for renovations of small neighbourhoods or contiguous buildings and in conditions where technical and/or legislative limitations do not allow for large renovations and measures to improve building insulation (e.g. in the case of listed historic buildings as described in Ref. [74]).

In conclusion, despite some limits that characterise this stage of the research in which, for the sake of simplicity, some economic, geometric, and topologic parameters were kept constant, the results could orient and support decisions from a different perspective. In addition, according to the assumptions defined, the representation of the trends of some KPIs as function of heating DD can support analogous evaluations in different climatic contexts.

Credit author statement

M. Belliardi: Methodology, Software, Formal analysis, Data curation, Investigation, Writing – Original draft, Visualization, **P. Caputo:** Conceptualization, Methodology, Supervision, Writing – Original draft, Writing – review and editing, **G. Ferla:** Methodology, Data curation, Writing – review and editing, Visualization, **N. Cereghetti:** Supervision, Project administration, **B. Antonioli:** Supervision.

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Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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