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Renewable Energy 230 (2024) 120835

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

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A R T I C L E   I N F O

Keywords:
Shallow geothermal energy
Energy geo-structures
Geothermal energy potential
Energy geo-structures barriers
Geothermal energy integration

A B S T R A C T

Ground Source Heat Pumps, in the framework of Shallow Geothermal Energy Systems, outperform conventional Heating Ventilation and Air Conditioning systems, even the high efficiency Air Source Heat Pumps. At the same time, though, they require considerably higher installation costs. The utilization of dwellings' foundations as ground heat exchanger components has recently demonstrated the potential to generate significant cost reductions primarily attributed to the reduction in expenses associated with drilling and backfill material (grout). These elements are referred to in the literature as Thermo-Active Structures or Energy Geo-structures (EGs). The current study employs a 'mixed studies' review (i.e., literature review, critical review and state-of-the-art review) methodology to comprehensively examine and assess the compatibility and integration of different renewable energy sources and environmentally friendly technologies with foundation elements deployed as EGs. These mainly include heat pumps, district heating and cooling networks, solar-thermal systems, waste heat, biomass and other types such as urban structures. Emphasis has been given on the advancement on this area, with the current study identifying and addressing two primary categories. The first category involves the integration of EG elements with sources that are able to supply green electricity, referring to renewable energy electricity obtained from on-grid or off-grid integration. The second category, involves a direct or indirect integration with sources that provide heat, or vice versa. The technical and non-technical barriers of such integrations have been discussed in detail, with the technical challenges generally involving engineering design, and system optimization, whereas non-technical challenges encompassing the economic, social, and policy domains.

Abbreviations

5GDHC	5th *generation District Heat and Cooling*
ASHP	*Air Source Heat Pump*
ATES	*Aquifer Thermal Storage System*
BHE	*Borehole Heat Exchanger*
BTES	*Borehole Thermal Storage System ES*

(*continued on next page*)

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https://doi.org/10.1016/j.renene.2024.120835
Received 18 December 2023; Received in revised form 10 June 2024; Accepted 17 June 2024
Available online 18 June 2024

(continued)

CHP	*Combined Heat and Power*
COP	*Coefficient of Performance*
CPVT	*Concentrated Photovoltaic Technology*
DHC	*District Heat and Cooling or District Heating alone*
EG	*Energy Geo-structure*
EMP	*Energy Micro-Piles*
EP	*Energy Piles*
ETES	*Electric Thermal Energy Storage*
EU	*European Union*
GHE	*Ground Heat Exchangers*
GSHP	*Ground Source Heat Pump*
HGSHP	*Hybrid Ground Source Heat Pump*
HP	*Heat Pump*
HVAC	*Heating Ventilation and Air Conditioning*
LDES	*Long Duration Energy Storage*
LSC	*Large-Scale geothermal Collector systems*
nZEB	*nearly Zero Energy Buildings*
OTEC	*Ocean Thermal Energy Conversion*
P2H	*Power-to-Heat*
PCM	*Phase Changing Material*
PV	*Photovoltaic*
PVT	*Photovoltaic Thermal*
RES	*Renewable Energy Sources*
ROI	*Return of Investment*
SGE	*Shallow Geothermal Energy*
SPF	*Seasonal Performance Factor*
SUDS	*Sustainable Urban Drainage System*
TAS	*Thermo-Active Structure*
TES	*Thermal Energy Storage*
TRT	*Thermal Response Test*
UTES	*Underground Thermal Energy Storage*
WH	*Waste Heat*
WSHP	*Water Source Heat Pump*

1. Introduction

The ongoing expansion of global economy and population has resulted in a persistent rise in the need for energy. The increased demand can potentially be met with the exploration of previously uneconomical oil and gas resources by discovering novel methods of extraction. However, a long-term solution relies on sustainability and the potential of lowering global energy demand and the use of fossil fuels. This could be achieved by further expanding the use of energy derived from renewable sources. In the context of addressing the global energy demand, it is also crucial to acknowledge that public awareness plays a vital role in resource preservation, climate change mitigation, and sustainable development.

Shallow Geothermal Energy (SGE) is a form of Renewable Energy that, through the usage of Ground Source Heat Pumps (GSHP), has the potential to effectively reduce or stabilize peak energy demand by efficiently providing heating and cooling for all types of dwellings, including residential, commercial, and industrial structures [1]. A GSHP system exhibits efficiency advantages over alternative Heating Ventilation and Air Conditioning (HVAC) systems, including Air Source Heat Pump (ASHP) systems, due to its utilizing a more consistent heat exchange source/sink (the ground); specifically, the ground temperature over certain depths (vary with location) exhibits steady values. A GSHP system consists of a heat pump (HP) coupled with Ground Heat Exchangers (GHEs), the medium to release or gain heat to/from the ground [2]. The higher performance provided by GSHPs, as compared to conventional systems (including ASHPs), can contribute toward the "Fit for 55" target set by the European Union (EU) (reducing net greenhouse gas emissions by at least 55 % by 2030) and the EU's "nearly Zero Energy Buildings (nZEB)" directive. However, the high initial capital required for GSHP systems and the consequently lengthy payback periods have been the major drawbacks of such systems, deterring potential considerations from investors [3–7].

The incorporation of dwellings' foundations as GHE elements, has been recently studied and exploited, showing a potential to yield substantial cost savings for the system [8–12]; this is so mainly due to the decrease in the expenses related to drilling and backfill material (grout). These elements are referred to as Thermo-Active Structures (TAS) or Energy Geo-structures (EGs). More generally, EGs refer to foundations or other underground geotechnical structures that have been adapted to incorporate heat transfer pipes, as to function as GHEs for GSHP system [13]. Consequently, the use of EGs demonstrates prospects for mitigating capital expenditures associated with SGE systems. These elements, the EGs, serve a dual function, namely that of heat transfer and storage, in addition to their primary structural role (load-bearing capacity). EGs can come in many forms/types [5], such as energy piles (EPs) [10,14], energy walls [15,16], and energy tunnels [17,18]. In a broader context, these involve several technologies, including the repurposing of abandoned underground mine space for energy storage, the use and storage of geological carbon [19], underground coal gasification [20], subterranean data centers [21], and the simultaneous extraction of minerals and geothermal resources.

The extraction of thermal energy from foundation elements presents both potential advantages and drawbacks. As an example, the conversion of substructures into EGs will result in additional stress towards the element material (e.g., concrete), while additional ground and structural displacements may occur, due to the temperature variations. EG systems although extensively presented and reviewed in recent studies (e.g. Refs. [22,23]), their integration with other energy sources has not been addressed.

To this end, the main scientific objective of this study is to consider renewable energy sources (RES) and environment-friendly technologies for adaptation and (the novel) integration with EGs; the focus will be on such developments. New concepts, where using EG, not only as engineering structures but also as GHEs uniquely coupled with local RES, are addressed. Within this novel investigation not only renewable heat sources are considered, but also some indirect integrations, which are unusual in such a combination. Moreover, this work assesses the readiness of several technologies along with their limitations regarding the integration with EG. Possible application to deliver heating and cooling energy to dwellings, either in the residential or the industrial sector, constitutes a crucial contribution towards sustainable development. In particular, the present study aims to provide a comprehensive assessment on the integration potentials and barriers/limitations of EGs with other RES, as well as to raise awareness for the inclusion of these systems into the broader RES. Discussions on the design principles as well as the quantification of the potential of different types of EGs are excluded, as these have been adequately covered by a number of studies [15,22–28]. The aim here is to demonstrate the potential of the integration of other energy sources with EGs, together with the existing barriers on the implementation and integration of this novel type of energy exploitation. To the best knowledge of the authors, a detailed review showing the potential of the integration (and barriers) of EG with other energy sources has not been carried out yet. This work thus fills this gap, paving the way for future studies and implementations at full scale.

1.1. Methodology

Given the aim of the current paper, as mentioned in the previous section, an accurate revision of the scientific literature (more than 200 manuscripts were included) was necessary and was carried out by the authors in a hybrid form review method. Collected data and information was further integrated with notions/knowledge coming from the authors' personal experience, different backgrounds, and covered a time period from 1996 to 2024. The research was conducted in year 2023 based on personal experience, background and current expertise of each author.

The main databases used were Google Scholar, ScienceDirect, Springer, Taylor and Francis, Wiley-Blackwell, etc. The keywords/statements used to find the articles in the primary research, in conjunction with the “energy geo-structures” were, but not limited to (major keywords stated here): “state of the art”, “synergies between shallow geothermal and other sources of energy”, “integration with other energy sources”, “barriers for the diffusion”, “geothermal heat pump”, “GSHP”, “solar integration with shallow geothermal energy”, “underground thermal energy storage”, “district heating and cooling networks”, “phase-change materials”, PCM”, “Non-technical challenges”, “social impact” + “challenges”, “environmental impact” + “challenges”, “hybrid solar thermal”, etc. Due to the topic and aim of the research, various energy sources were considered (solar, wind, waste heat, PCMs, etc.); for this reason, and in order to show their synergies with the shallow geothermal energy exploited through EGs, it was necessary to briefly describe the main concepts of each in their related/pertaining section.

The methodology adopted to develop this manuscript’s review follows the common features of the ‘mixed studies review’ type, as defined by the simple analytical framework SALSA (Search, Appraisal, Synthesis and Analysis) [29]. According to Grant & Booth [29], a ‘mixed studies review’ considers the combination of different approaches, where one significant component is a ‘literature review’. In the current manuscript, the common features of a ‘critical review’, ‘literature review’ and also ‘state-of-the-art review’ can be identified. As a ‘critical review’ and ‘literature review’, the review work carried out by the authors provides an opportunity to ‘take stock’ and evaluate previous literature and work on the specific topics of integrating EGs with other sources of energy, including different types of analyses and sources. Moreover, the resulting product is a starting point for further evaluation, not an endpoint in itself. The topic evaluated is vast and addresses current matter, offering new perspectives and identifying potential areas for further research, as commonly occurs in ‘state-of-the-art review’.

The collection of information through the above-mentioned methods, together with constructing the framework for the potential integration (Fig. 1) was then followed by reviewing all selected technologies. All the information was structured to present a general description of the technology, its classification, novel developments, potential of integration assessment, barriers of the technology to be integrated with EG and further limitations. Moreover, some case studies of integration with EGs were provided.

1.2. Integration potential

It is hoped that renewable energy will be an even more important energy source in the near future, as it is expected to account for up to 34.7 % in 2030 and 47.7 % in 2040 [30]. Nuclear energy, fossil energy (oil, coal, natural gas) and RES (wind, solar, geothermal, hydropower) belong to the primary energy sources category. All of them can be converted to electricity, a secondary energy source, which flows to private homes and business facilities through transmission infrastructure such as power lines. The electricity obtained/produced from solar, wind, geothermal, biomass and hydro resources, is often called as “green electricity”.

Regarding EGs integration with other sources (see Fig. 1), two main categories are identified: one is the integration with sources providing green electricity (renewable energy electricity, see above) either from on- or off-grid integration, and the other is the direct or indirect integration with sources providing heat (or vice-versa).

SGE structures, such as EGs, can be integrated with many different types of energy sources (as schematically presented in Fig. 1), which include: (1) HPs (ASHPs or other types); (2) district heating and cooling (DHC) (5th generation – 5GDHC) or thermal grid; (3) solar (thermal or photovoltaic – PV); (4) wind (small (urban)- or large-scale wind turbines); (5) biomass (combined heat and power – CHP); (6) deep geothermal (high enthalpy geothermal); (7) ocean thermal energy conversion (OTEC) for either heat exchange or electricity generation; (8) waste heat (WH) (low or high temperatures integration); (9) thermal energy storage (TES) systems; (10) urban structures (such as roads); and (11) other types (such as novel prototypes or working concepts, etc).

The sequence of the manuscript is structured and expanded according to the identification of the presented energy sources and their integration with EGs systems, as presented in Fig. 1. Heat pumps as a key element of EGs, or as an integration element, are introduced and addressed in Section 2. The first integration category, related to green electricity, is further addressed is Section 3, while the direct and indirect integration is addressed in Section 4 of this paper. Both of the latter Sections focus on the potential and the barriers/limitations with regard to technical aspects, whereas in Section 5 the non-technical barriers are described. Non-technical challenges for both integration categories are gathered in a common Section, as similarities among integration

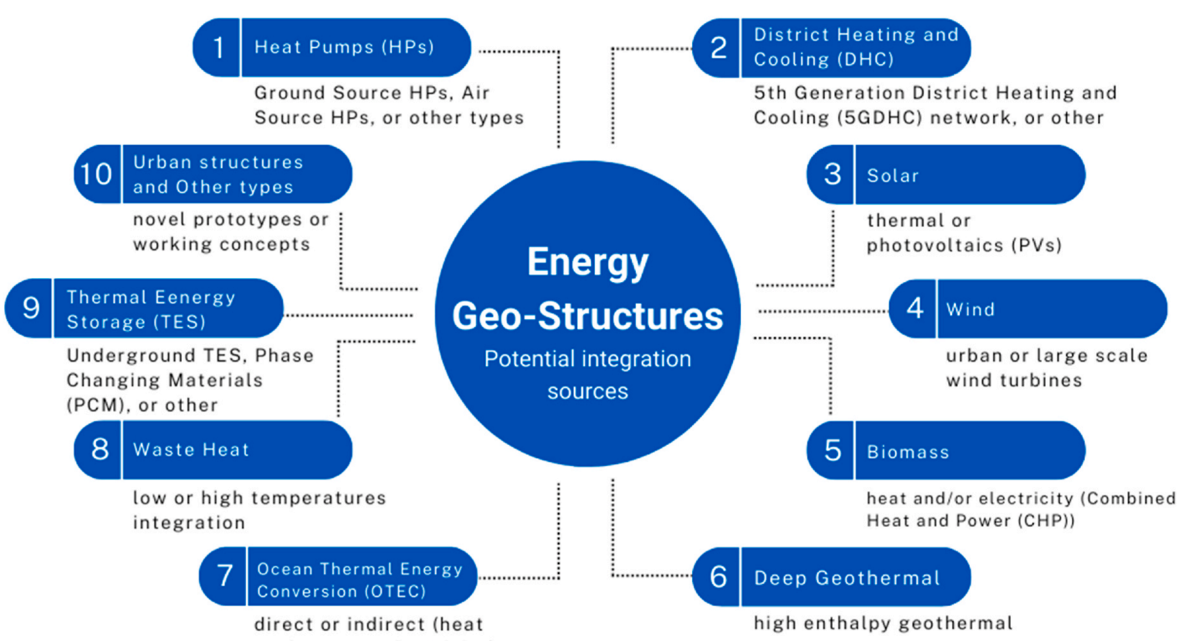

Fig. 1. Energy Geo-structures potential integration with other sources.

potentials can be identified.

2. Heat pumps

A heat pump (HP) is a device that transfers heat from a cold space to a warm space by utilizing work and the principles of a refrigeration cycle to transfer thermal energy. HPs are mostly classified according to their heat source, including ground source (or ground/brine-water) (GSHP), water source (or water-water) (WSHP) and air source or air-water (ASHP/AWHP). Other, less common types of HPs include sorption HPs, solar assisted HPs or other types such as hybrid, modular, multi-temperature and thermoelectric HPs, which are even less common [31, 32] (Fig. 2). The ASHPs use outdoor air and are thus strongly dependent on temperature and weather, AWHPs use rivers, lakes, other water reservoirs and groundwater, while GSHPs use heat stored in the ground.

Clearly, the Coefficient of Performance (COP) is one of the most important factors for evaluating HP systems. According to EN 14825 standard [33] the COP at declared capacity is a declared heating capacity of the unit divided by the effective power input of the unit at a specific temperature condition. Because the HP performance is highly dependent on ambient conditions, the constant COP may not represent the real implementation well [34]. There are four main ways to estimate COP: field tests, numerical simulation, empirical models and machine learning algorithms [35]. According to Cunha and Bourne-Webb [36], a HP system coupled with Eps, can be considered very efficient when COPs above 4 and Seasonal Performance Factors (SPFs) around 3.8 to 4.3 are achieved.

GSHP system includes a HP with one or more GHEs in several boreholes or trenches for transferring the thermal energy of the earth to the building (see, for example, Fig. 3). Vertical GHEs (or borehole HE - BHEs) occupy a smaller land area required for installation than horizontal GHE [37], and are thus a more popular choice [38]. BHEs, usually with a depth of several dozen to several hundred meters, are characterized by a stable average temperature throughout the year. The GHE COP is affected by the configurations and materials properties [39–42]. Therefore, an optimal GSHP system design requires proper estimation of thermal properties of GHEs, usually by means of Thermal Response Tests (TRTs) or by monitoring of ground temperature response [42–44].

Cui and Zhu [46] simulated the performance of a 5.9-kW GSHP with 16 EPs within a 3D transient heat transfer model. The maximum heating and cooling COPs of the GSHP were 3.6 and 4.7 respectively in the first year of operation. However, the soil's final temperature was lower than its initial temperature, as the soil was not capable of recovering by itself due to the building unbalanced heating and cooling. In several other studies, the COP of HPs coupled with EPs (i.e., foundation piles coupled with GHEs) of different configurations and quantity was reported to be from 3.6 [47] to 4.2 and 4.5 for energy slabs (i.e., foundation slabs coupled with GHEs) coupled system [48], while the seasonal performance factors of the EP HP system (mean values of COPs) in summer and winter conditions done by machine-learning-based performance prediction are 4.5 and 3.0, respectively [35].

Moreover, as reported by Dolgun et al. [49], electrical efficiency increased when a concentrated PV thermal technology (CPVT) system was combined with a HP. In that hybrid mode, with a 'special configuration' of the evaporator of the HP (placed in the triangular corrugated receiver – a figure can be found in the referenced manuscript [49]) the freezing problem during the winter season has been solved. The absorbed heat was discharged to the external environment of the condenser and by cooling the system, the electrical efficiency increased, and thermal energy was obtained [49].

ASHP systems use ambient air as a heat source/sink to provide space heating and cooling. The efficiency of ASHPs varies significantly with ambient temperature levels. When there is a high temperature difference between the cold source and the heat sink, the COP of the ASHP falls drastically, emphasizing the drawbacks of ASHPs [50]. On the other hand, ASHPs are cheaper and easier to install when compared to GSHPs. The performance of the ASHP technology has been remarkably improved over the recent years, due to the developments made in their components and systems [51]. To this end, Hakkaki-Fard et al. made comparisons between commonly used ASHP and direct-expansion GSHP for a residential building in the cold climate city of Montreal [52]. The obtained results showed that provided proper sizing, the GSHP system can consume 50 % less energy than ASHP. With current (at the time) borehole installation prices, the relative payback period of the GSHP system, compared to ASHP, is over 15 years. However, if the borehole installation price was to be reduced by 50 %, the payback period would be reduced considerably [52]. Additionally, depending on the lifetime of the system as well as the installed location, GSHPs provide in most cases a superior performance in terms of environmentally friendliness, according to Refs. [53,54].

According to IEA report [55] global sales of HPs grew by 11 % in 2022, making it a second year of double-digit growth for this technology. In Europe, it was a record year, with sales growing by nearly 40 %, and particularly for AWHPs sales increased by almost 50 %. The annual growth in sales of HPs in buildings is shown in Fig. 4. It would appear that the solid growth of HPs in following years will continue, given the priority to multi-storey apartment buildings and commercial spaces; this can actually make space for HPs future integration with EGs.

HPs in 5th generation low-temperature DHC networks abate greenhouse-gas emissions, decrease primary energy consumption and produce low-cost heat supply [31]. The deployment of HPs into a DHC system can make it more sustainable. Still, the installation, connection and operational modes of HPs are region specific, and there is no universal norm [56]. Moreover, the low-temperature DHC networks facilitate the simultaneous use of different-type HPs and the inclusion of heat obtained from EGs into the system.

Regarding the design of HPs with other systems, including EGs, optimality is always desired. For example, Ma et al. [57] proposed an optimal design procedure for an energy-pile based GSHP system coupled with seasonal solar energy storage. Their procedure consisted of 6 steps: namely (i) determination of system configuration; (ii) operation modes and control strategies; (iii) climatic conditions, building thermal loads and system parameters; (iv) currying out a parametric study of system performance over the space of design parameters; (v) obtaining the subspace of design parameters satisfying imposed constraints; and (vi) optionally searching for an optimal solution minimizing the cost function within the subspace of design parameters.

According to Olabi et al. [58] challenges in GSHP development can

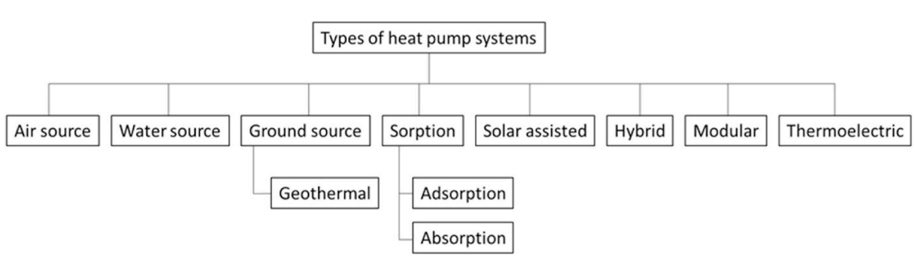

Fig. 2. Heat Pump categories examples (modified from Ref. [31]).

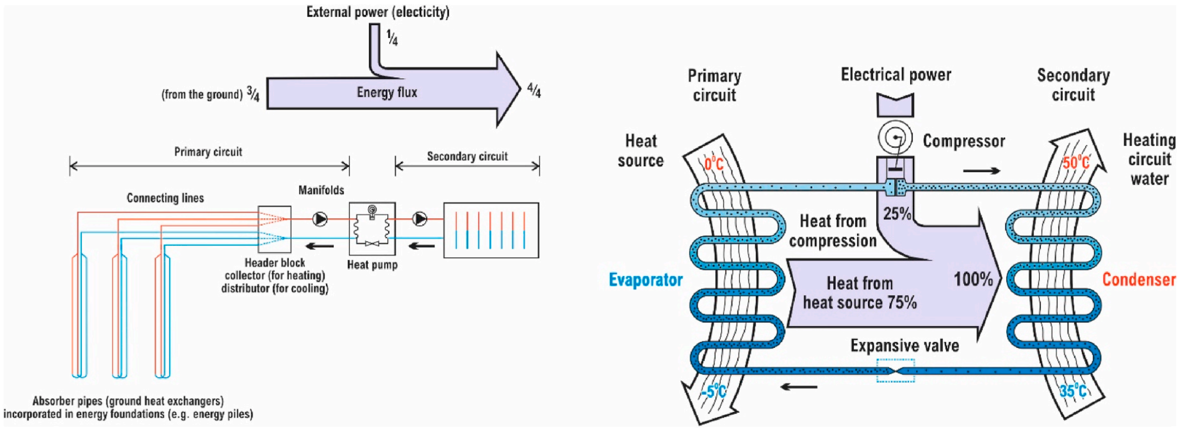

Fig. 3. Overall conception of GSHP system coupled with Energy Piles: example for heating mode (modified from Refs. [36,45]).

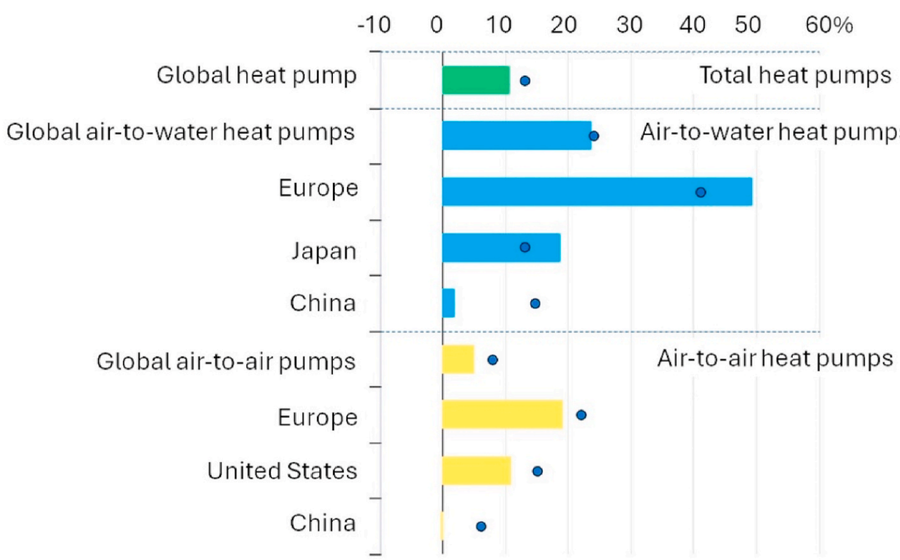

Fig. 4. Annual growth in sales of HPs in buildings worldwide and in selected markets in % in 2021 (points) and 2022 (bars) [55].

be classified into five categories; (i) technical, (ii) financial and economic, (iii) environmental and social, (iv) policies and regulations, and (v) administrative and institutional. Within these categories several specific technical challenges can be assigned to GSHP systems consisting of BHEs or EGs, such as (modified from Refs. [58,59]): Design and installation; safety aspects; sizing the system; system optimization; repair and maintenance of the system; integration with other systems; manufacturing constraints and supply chain vulnerabilities; and shortages of skilled installers. The non-technical challenges mentioned above can be seen in Section 4. Such challenges must be tackled during the construction of the building and operation of the system.

Various tools exist nowadays for the estimation of the energy demand profile for buildings. The design of GSHP system installations can be carried out sometimes to cover 100 % of the heating loads, but usually 80–90 % of the heating load, while the peaks can be supplied by some complementary source, or some techniques for ‘peak shaving’ can be adapted [60]. The manufactured HP range of products and their fixed characteristics and operation parameters can be used, but this may lead to oversizing for specific designs. HP is usually used as a basic heat source (base load), and additional peak source is provided in the installation to compensate thermal peaks or unexpected loads. However, trying to achieve the maximum RES energy share increases the energy share of HPs and covers demand at very low temperatures. This means that the design power of the HP is sufficiently higher and, therefore, the HP operates less with its nominal power according to the total operational time of the installation.

The planning of the GSHP installation is based on the selection of HP according to the heat demand and the adjustment of the quantity and length of the GHEs. However, for example, in installations with EPs, the primary function of EPs is structural. Thus, the HP installation should be adapted to the planned piles and add additional sources, e.g., BHEs or solar panels, if necessary, to cover all demand.

The optimal design and control of HPs for efficient use of the heat source are required to select the appropriate operating mode. However, there is a lack of standards for integrated design, control and optimization. To optimize the design of the systems, dynamic simulations should be performed.

As previously mentioned, TRT is one of the most commonly used methods for estimating the thermal properties and performance of a GSHP. Although there are various ways to determine the thermal properties of GHEs, there remains a challenge to define a standard for applying TRT or other methods for EGs.

Although the integration of HPs (see GSHPs) with GHEs is common, there are no standards and guidelines for the integration of HPs with EGs (for example EPs). This may lead to the use of GHE standards instead, which are not identical and their adjustments needs specific experience in the subject. This lack of standardization of HPs for EGs can be a real challenge for engineers; due to this, for example, structural engineers are likely to be very risk averse regarding including heat exchangers (piping) in their designs. Both the installation that must be selected for specific conditions at a particular location and the complex dynamic simulations and optimization methods can lead to the wrong selection or abandonment of EGs as a heat/cold source.

Technical challenges of HPs can be related to the specific type of heat source. In particular, the efficiency of HP systems can vary according to heat source and/or climate conditions. Han et al. [61] performed a comparison study of 3 heating systems, namely (i) an ASHP system, (ii) a DHC system, and (iii) an EP-based GSHP system, for 7 climate zones in China. It was observed that the cold and the hot-summer/cold-winter regions are the most favorable for applying EP systems, because no performance degradation was predicted over years of operation.

Other general technical challenges for the HP industry are summarized herein. Although GSHPs are classified as renewables, they have working media that often use F-gases or other substances considered harmful to the climate. EU has stated the ambition, through a F-gas Regulation and a stricter quota system for hydrofluorocarbons (HFCs), to reduce the amount of HFCs on the market by 98 % by 2050 (compared to 2015). Several new restrictions on the use of F-gases in equipment are also included [62]. This will force producers to search for new refrigerants and new mixtures to reduce the F-gas amount in the unit; some alternatives have already been tested (CO2, ammonia, propane, etc.). The challenge for producers is to find new, ecological media that also have favorable thermodynamic properties.

Also, moving on with the continuous development of RES, another challenge for manufacturers is the construction of high-temperature HPs with ecological media that can be used in older buildings for heating purposes, without reducing the temperature of the end-user's supply. Hence, some important general challenges for all HP manufacturers (including those that integrate EGs as a source) are: better use of materials, modern manufacturing, and measures to standardize devices (e.g., plug-and-play connections).

GSHP technology is very well established, but its use via EGs such as EPs is relatively a new concept. Even though there are quite a few examples of using GSHPs for EGs installations in the world. Some examples are given below.

One such example is a business center in Rostock, Germany, where a GSHP system containing both conventional boreholes and EPs, connected to a geothermal heat processing center and operated at a low temperature level of about 28–35 °C for heating and cooling purposes. The system consists of 264 reinforced concrete piles connected to a reversible HP [63].

Terminal "E", at the Zürich airport, Switzerland, was built on 440 foundation piles as the lake deposits in the area was too soft to support the loads of the building. About 300 piles (of 90–150 cm diameter) have been converted into EPs and equipped with 5 U-pipes fixed on the metallic reinforcement, which are used as a heat exchanger within the ground. The additional amount of energy purchased for heating is very small. The HP of the system gives 630 kW, while peak power loads are met with district heating; the HP covers 85 % of the annual heating demand of 2720 MW h [64].

The LT24 testing plant of the Lainzer tunnel in Wien, Austria was the first application in the world using absorber technology, already successful for the foundations of buildings, which was applied to bored piles of a cut-and-cover tunnel in 2003. There are 59 EPs of diameter 1.2 m and length of 17.1 m. The absorber pipes are connected to collection pipes, which lead to 6 HP units provided to heat an adjacent school building [65].

Some innovative solution for EGs combined with HPs is the GeothermSkin in the Energy Center in Torino, Italy. It is a very shallow energy wall system using the earth-contact area of the underground modular walls of the basements of the buildings to enhance the 'underground skin' of a building for heat exchange. These novel solution testing site uses a reversible 3.15 kWt HP, commercially available on the market [66]. Similarly, other studies have also investigation very shallow solutions, such as foundation slabs [8].

3. Integration with green energy/electricity

Green electricity (as described in Sub-Section 1.1) is one straightforward and "easy" way to achieve energy integration of EGs with other sources. However, for such integration to be functional requires further investigation due to several aspects that impede the widespread adoption of green energy, such as: (i) intermittency of solar power (in the case of solar energy that relies on daylight availability and weather conditions) as well as intermittency of wind patterns and the need for vast areas for wind farms (in the case of wind power that utilizes wind turbines to generate electricity); (ii) geographical features and potential environmental impacts (in the case of hydropower that taps into the kinetic energy of flowing or falling water to generate electricity as well as in the case of geothermal energy that relies on the deep geothermal sources; (iii) feedstock availability, land use conflicts, and emissions management (in the case of biomass energy that derives from organic matter, such as agricultural waste, wood pellets, or dedicated energy crops).

Further questions may arise, such as whether the integrated green electricity would be supplied from the grid or from stand-alone (off-grid) systems. Also, whether the electricity would be supplied at a constant rate, whether it would be able to support the circulating pumps and HPs, or whether it would have the responsibility for suppling heat to the EGs elements as a form of storage of the excess green electricity production. It is obvious that advances in energy storage systems are crucial. Also, combining several green energy sources and enhancing grid flexibility is vital for a reliable energy supply. Moreover, a balance between energy generation and ecosystem preservation is needed. In addition, expanding exploration efforts and developing advanced drilling technologies are essential for geothermal energy growth. To this end, the current section undertakes a critical review based in these factors.

At the moment, to increase the decarbonization of heat (heating and cooling), two types of electrification (direct and indirect) can be identified with regard to green electricity. According to Ruchnau et al. [67] devices providing heat (e.g., all kinds of electric heaters as well as electric HPs, which additionally exploit ambient or waste heat) and road transport (battery electric vehicles, the battery-fueled mileage of plug-in hybrids, i.e. electric trolley vehicles) can be included in the category of direct electrification due to their using electricity directly as an input. In the case of the indirect electrification, the electricity is indirectly consumed by heating or transport devices in the form of synthetic fuels. Thus, a fuel synthesis is always presented in indirect electrification (e.g., electrolysis for synthetic hydrogen and methanation for synthetic methane [68,69]). The synthetic fuel therefore is converted into heat, using gas heaters or gas HPs, or into traction energy, using fuel cell electric vehicles and internal combustion engines. At the same time, the direct paths are considered more efficient, whereas the indirect paths are more suitable for long-term storage [70]. A very small number of studies exist in the literature about comparisons between direct and indirect electricity, concerning either specific types of energy (e.g., see thermal energy storage [71]) or combination of different energy systems (e.g., see renewable energy and thermal energy [72]). Hence, a gap still exists for studies about green electricity and the direct-indirect integration of different energy sources and their combination (e.g., see hybrid systems combining geothermal, biomass and solar energy [23]).

In an urban scale, with the rapid development of distributed energy systems and net zero energy buildings (nZEBs), solar PV systems have become the dominant system for supplying green electricity, upon their rapid expanding in recent years [73–76], due to their wide applicability [77]. IRENA [78], at the request of the European Commission, conducted an evaluation of EU's renewable energy outlook up to year 2030. The primary objective was to identify economically viable renewable energy solutions across all EU member states, sectors, and technologies, enabling the achievement of established targets. The assessment revealed that solar PV and offshore wind technologies emerged as the most cost-effective options, surpassing expectations in terms of their expansion rate and scope of implementation.

Using solar PV systems for electricity generation is highly compatible with various other systems, such as geothermal heating, heat pumps, different district heating systems, and EGs systems [79]. By integrating solar PV with these technologies, it is possible to enhance overall efficiency and optimize energy utilization, contributing to a more sustainable and eco-friendly energy ecosystem.

Despite being competitors in some aspects, solar thermal and solar PV systems can still achieve beneficial integration results. While both technologies harness solar energy, they serve different purposes. Solar thermal systems primarily focus on heating (the solar radiation can be converted into thermal energy), while solar PV systems generate electricity through the photovoltaic effect. Also, PV modules could be combined with thermal units, where circulating air or water of lower temperature than that of PV module is heated, constituting the hybrid photovoltaic/thermal (PVT or PV/T) systems and providing electrical and thermal energy, thus making the total energy output from PV modules increase [80].

Through careful design and integration, it is possible to combine the strengths of each of these PV systems in order to maximize overall energy efficiency and utility. For instance, excess electricity generated by a solar PV system can be utilized to power HPs, circulation pumps or other components enhancing their performance and reducing the need for additional energy sources. The use of that electricity to power HPs would help promoting self-consumption strategies, if one considers further the forthcoming unprofitability of feeding into the grid the electricity generated by small-size PV generators [81].

This symbiotic relationship allows for an optimized and cost-effective utilization of solar energy, leading to a favorable sustainable energy solution. Indeed, several studies have showcased promising outcomes when combining solar PV systems with other energy technologies. By integrating solar PV with complementary systems, such as HPs (conventional ASHPs [82] or GSHPs [83]), biomass systems and solar thermal, a more comprehensive and robust renewable energy solution can be achieved [51,73,84–86], together with energy and cost savings [87,88]. Such integrations could also lead to environmental benefits: for instance, coupling ASHPs with PV cells for electricity supply would be a great alternative for stopping the need of using the electricity grid [89,90].

It is worth mentioning here that the efficiency of PVs is constrained by the PV module cell temperature, in fact not all the absorbed solar radiation is converted to heat: the unconverted solar radiation causes an increase in the temperature of the photovoltaic panels which, in turn, decreases the electrical efficiency of PV panels. Cooling the PV module is an effective method for efficiency improvement (10 °C decrease in PV module temperature could contribute to 5 % increase in PV module efficiency); in general, efficiency reduced by 2.5 % per K rise [91]. In addition, using GSHPs alone can lead, after a few years, to reduction of soil temperature around the GHEs that may cause the HP's Coefficient of Performance (COP) decrease. It seems that both of the aforementioned problems could be solved through the combination of GSHPs and PVs and/or PVTs, which has proven to be able to improve the performance of both individual technologies in case of heating [83,92,93]. It is worth mentioning here, that due to the intermittent nature of solar energy, the timing of PV output is well matched with user/building's cooling demands but not always with heating demands.

To this end, it would appear beneficial to combine PVs or PVTs with EGs that operate utilizing GSHPs [93,94]. The most basic concept of the integration of PV and a GHE, (referring to EGs) is shown in Fig. 5, where the circulating water is pumped from the GHE to the PV directly for cooling down the module temperature. Although in this example the waste heat is rejected into the soil, instead of being recovered, this system is simple and is suitable for the scenarios with only electricity generation.

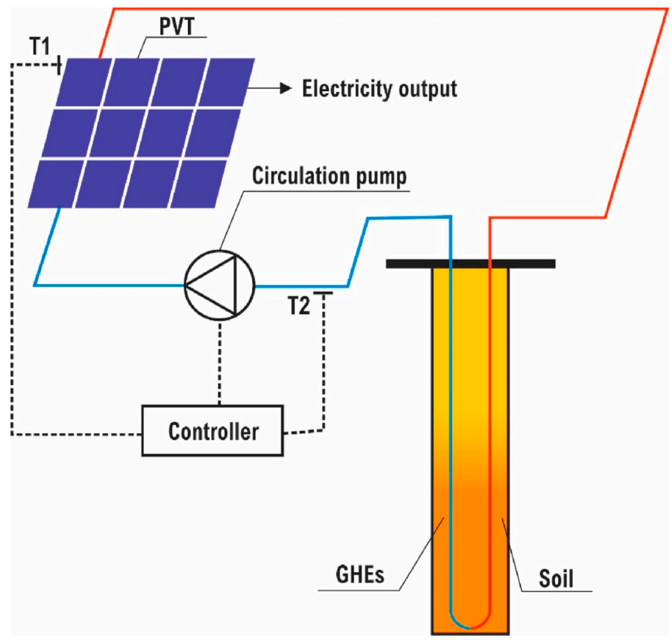

Fig. 5. Schematic diagram of a basic PV-GHEs system, modified from [95].

Regarding hybrid systems, Aryanfar et al. [96] proposed the use of a system that included a GSHP equipped with an economizer for winter heating and a wind turbine, as an energy source to supply green electricity required for a geothermal district heating system in Shanghai, China; the authors concluded that wind power can be a suitable complement to a GSHP.

Sensible thermal storage can be provided in the form of solid rock used for storing heat converted from electricity, generated by windmills or PVs through resistive heating or using a HP. Electric Thermal Energy Storage (ETES) is a technology solution for both Long Duration Energy Storage (LDES) and flexible power-to-heat (P2H). It employs a packed bed of low-cost crushed volcanic rock to store thermal energy at a maximum storage temperature between 500 °C and 800 °C [97]. After storage, heat is then used to drive a steam or gas turbine to generate electricity upon demand. Demonstrational examples of such technology are: (i) Siemens Gamesa 1.5 MW/30 MW h project that uses rocks as a form of solid-state storage and is connected to an industrial site in Germany; (ii) a Danish 5 MW/120 MW h system in which a HP will be used to upgrade stored heat, which will be discharged in an air-based system resembling a gas turbine [98]. ETES systems can provide electricity from stored wind and solar energy, while production from RES is intermittent from its nature.

Despite the evidence that the potential of integration of both technologies is large, there are still many challenges at present to be addressed as follows. There is a dependence on the electricity production and performance of solar PV systems which may have fluctuating and intermittent nature due to the weather varying conditions (e.g., during cloudy hours, it is necessary to use other systems or connect to the grid) [99], and time of the year (in particular for regions at higher latitudes, like Europe).

Intermittency in green power generation is a problem for grid stability. Thus, storing excess power during peak generation for use during periods of low generation plays an important role. However, battery systems are still very expensive. In 2019, battery prices were above 1100 $/kWh. Pricing initially fell by about a third by the end of summer 2023 and by 2025, where the average price is expected to drop to around 105 $/kWh [100]. However, prices still vary above 300 $/kWh [101–103].

While renewable energy costs have decreased significantly over the years, initial capital investments remain high. In addition, for PV systems, their connection to the grid (and related costs) depends on national regulation. The benefits and advantages related to the integration between EGs (and thus geothermal energy) with solar energy have been presented in this section. There is however an absence of guidelines and standards for designers and planners, for designing systems combining both EGs and solar PV systems [76,104,105]. For instance, Levelized Cost of Electricity (LCOE) of the generated power by the PV modules is still higher than the grid in many regions, which makes it infeasible to apply PV for supplying the requirement [89]. Hence, continued advancements in technology and economies of scale are crucial for cost reductions.

Even more important is the level of complexity in terms of planning, designing, controlling, etc., due to the integration demands, as well as additional material/equipment and installation costs have to be considered [95]. Furthermore, inconsistent government policies and regulatory barriers can hinder renewable energy growth. Ensuring public acceptance and providing stable policy frameworks are essential for overcoming these challenges.

Thus, due to technical and non-technical aspects such as a lack of awareness of the benefits of PV-integrated with EGs, the development of such systems in the residential sector is significantly lower than it can actually be. Raising public awareness about the importance of renewable energy, dispelling misconceptions and education programs are essential for fostering support and acceptance the benefits and realities of renewable energy.

4. Direct and indirect integration

Another potential integration identified in Sub-Section 1.1, is the direct or indirect integration from sources providing heat (or vice-versa). The direct integration of energy sources with EGs is being referred to here as the usage of the EGs elements with thermal energy without an intermediate system (directly), while the indirect integration can be specified as the utilization of the EGs elements to provide support with other systems and/or to act as intermediate systems. As shown in Fig. 1, SGE structures, such as EGs, can be integrated with many different types of energy sources. These are addressed in detail below.

4.1. District heating and cooling networks

District heating is a system for distributing heat generated in a centralized location through a system of insulated pipes used for residential and commercial heating requirements, such as space heating and water heating. Such systems facilitate the use of waste heat and renewables, but it has not yet been fully exploited [106]. District cooling systems are similar to district heating systems, but less widespread in Europe [107].

District heating offers numerous economic, environmental, and social benefits, including carbon reduction, reduced maintenance costs, increased comfort, and reduced fuel poverty [108–111]. District Heating and Cooling (DHC) Generations are classified as follows: (i) first Generation - steam-based systems using coal, inefficient and unsafe; (ii) second generation - using coal and oil, primarily for energy savings via pressurized hot water; (iii) third Generation - utilizing prefabricated, pre-insulated pipes at lower temperatures, incorporating coal, biomass, waste, and renewables; (iv) fourth generation - focusing on RES integration, low-temperature heating, and reduced grid losses; (v) fifth generation (5G-DHC) - distributing heat at near-ground temperature, enhancing energy efficiency with HPs for heating and cooling, and utilizing various low-temperature heat sources (<50 °C), including ambient heat, water bodies, and waste heat [112,113].

The current global trend is toward using lower temperatures in DHC networks, thereby increasing the share of renewables, which are often also decentralized at rather low temperatures [114]. In fact, differently to the previous generation of DHC networks, the development of 5GDHC networks could allow the exploitation of low temperature geothermal energy, provided for example by EGs and the integration into the ultra-low distribution network. With temperature levels around soil temperature heat losses hardly occur in these systems [13,115]. Another advantage of using EGs with thermal networks is their ability to be used for thermal storage over a range of timescales including inter-seasonal storage, since GSHPs offer higher transfer rates when balanced between heating and cooling. Therefore, the most efficient use of EGs in 5GDHC networks may be to take WH and the excess thermal energy from the network and store it for effective recovery. Even if EGs exhibit a smaller unit thermal capacity than water tank storage systems, they do not require special excavation and, thus, costs will be limited compared to the other solution [13]. A representation of the potential future integration of 5GDHC and EGs is shown in Fig. 6.

Moreover, the integration of EGs into thermal networks can allow a wider range of energy users, not only the users of the structure or infrastructure that is exploiting shallow geothermal energy, but also residential and non-residential buildings located nearby (see Fig. 7). This aspect leads to more effective geothermal energy yield and enhances the thermal performance of the system [13].

Lindhe et al. [116] emphasized on the lack of practical experience with 5G-DHC from demonstration projects and operational data. This too applies to EGs as there are currently no known demonstration projects nor operational data. It is important for the continued development of EGs to prioritize real-world applications in demonstration projects in addition to the plethora of modeling and desktop studies.

The hydraulic performance of EGs-based 5G-DHC is potentially challenged as bidirectional flow in two-pipe systems with decentralized pumps can create back flow. A unidirectional ring-type grid with one-pipe solves the issue with a central pump. In terms of efficiency the bidirectional and unidirectional grid has similar performance, however, a central pump providing constant flow significantly increases the grid CAPEX and OPEX [117].

The sharing of energy between prosumers on a 5G-DHC with EGs has a potential for reducing the direct energy use. However, managing the energy exchange between prosumers is challenging as there is potentially a conflict of interest between prosumer and grid needs at any point in time [116,118,119]. For example, if a grid is unbalanced supplying more heating than cooling, the grid will prefer consumers to increase their cooling demand, while consumers may want to increase their heating use. Moreover, the grid will prefer additional prosumers that rebalance the system with heat from cooling. However, new prosumers may have a need for heating and not cooling, also creating contrasting interests. Supplying a new prosumer with heating in this case may incur additional costs on the grid owner from having to add additional heating supply capacity. These issues extend to transaction models for 5G-DHC as pointed out by Lindhe et al. [116] who summarizes the current state of the art on that topic.

Other main technical challenges of EGs integration with DHC networks are: (i) the absence of guidelines and standards for designers and planners for development of combined EGs and DHC networks; (ii) the need for larger pipe diameters because of lower temperatures; (iii) the need to change not only DHC systems but also the buildings' heating systems; (iv) the lack of regulations for selling thermal energy from EGs; (v) the additional complexity for the EGs to meet the varying temporal thermal demands of the networks.

Modern DHC systems can rely on HPs that are not necessarily connected to the network itself. One example can be MPEC SA – a DHC provider from Krakow, Poland. Despite having the length of 880 km and plans to develop the network for 30 potential areas, the DHC network in Krakow still cannot reach all city's inhabitants [32]. In the city there are still places where the development of the DHC network is not considered in the future mainly due to the lack of economic justification. This created space for new business models, for example selling the heat from GSHPs or ASHPs for those buildings. From a technical point of view, the heat source is not important and it could actually be also produced be EG-source as well.

The Skjoldbjerg 5G-DHC grid (thermonet) in Jutland, Denmark

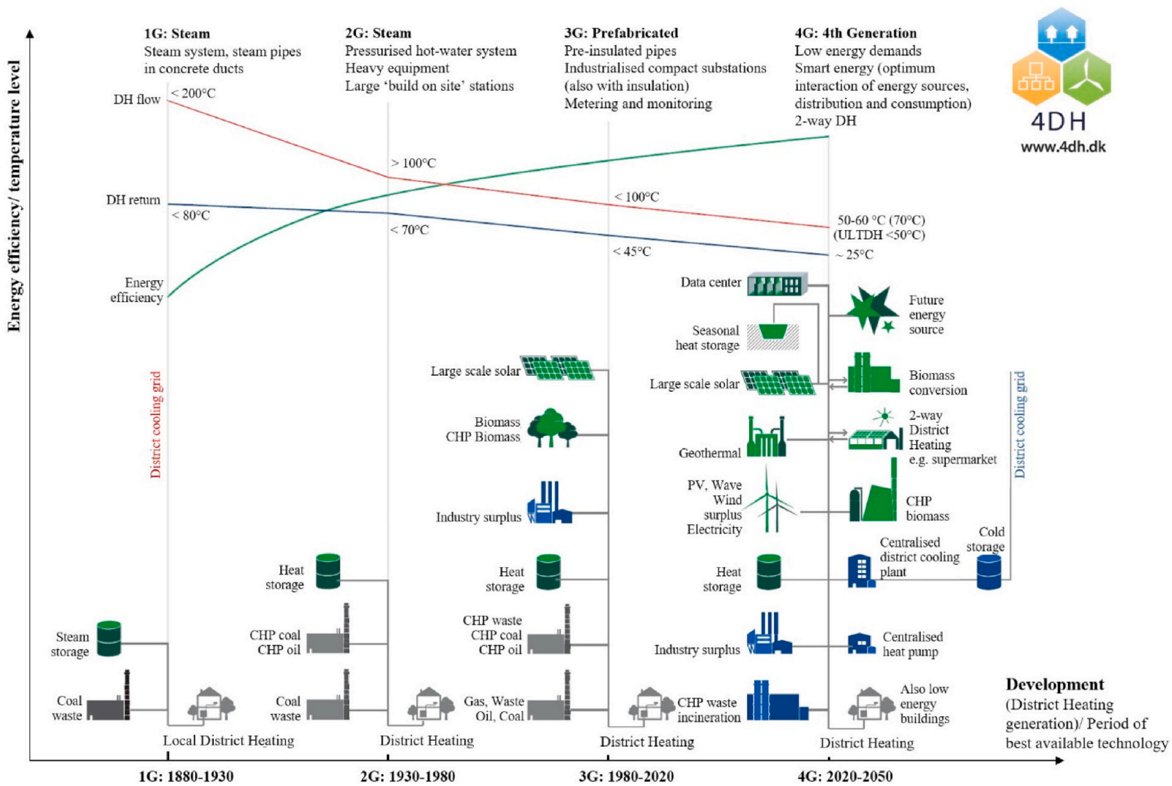

Fig. 6. District Heating and Cooling generations, temperatures and integrations [113].

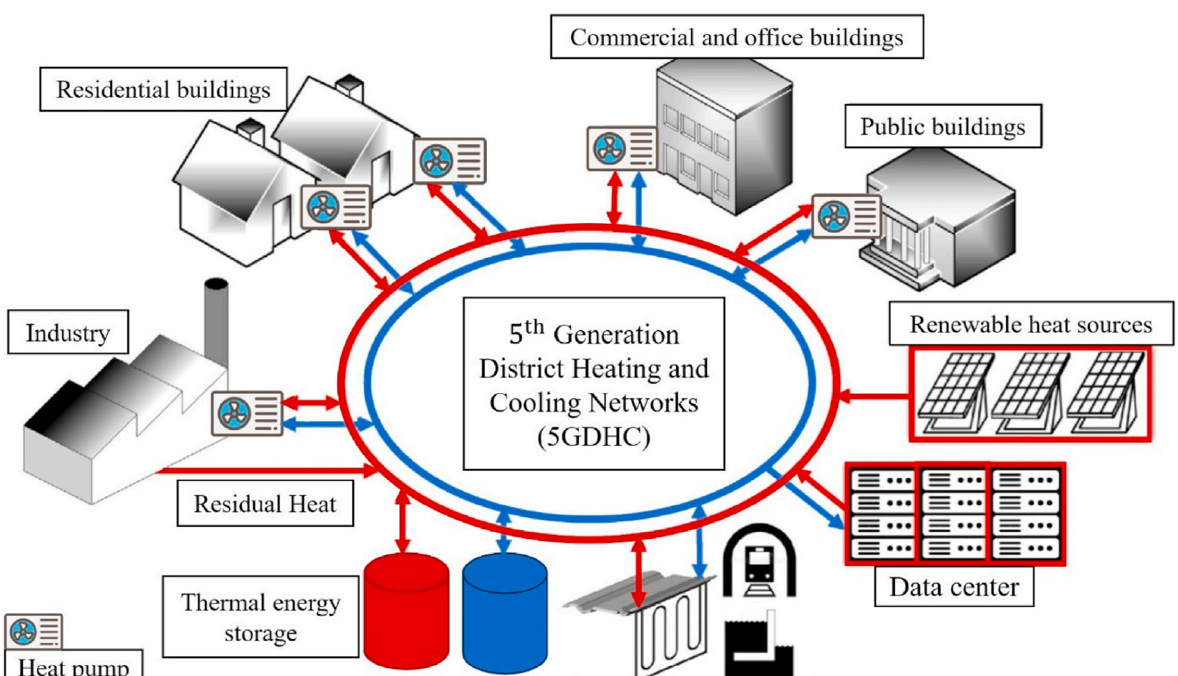

Fig. 7. Scheme of a 5GDHC network integrated EGs [13].

connects three 90-m long BHE to individual brine-to-water HPs in just 3 single-family houses. The three dwellings were built in the years 2000, 1998 and 1967 and the corresponding heated areas are 455, 102 and 116 m^2, respectively. The total annual heat consumption is approximately 76 MW h and it is estimated that the capacity of the three BHEs is fully used. The measured COP is 3.2 and 4.0 for the two smaller houses and the large house, respectively. The Skjoldbjerg case demonstrates that even retrofit projects, with an exceptionally low number of connections, have the potential to reduce climate gas emissions while also providing annualized cost savings on heating.

Cerra et al. [120] and Poulsen et al. [121] studied the application of 5G-DHC in a new residential area in Rosborg, Vejle Denmark. The geothermal potential was determined from a combined analysis of soil samples and geophysical surveys. The building heating and cooling demand profiles were estimated with the building energy simulation software EnergyPlus. A simulation model was developed that combined the EP g-functions computed by Alberdi-Pagola [122] with Laplace transform models for the thermal exchange in the network of horizontal uninsulated distribution pipes. By employing a lower bound on brine temperatures, the study found that the total EP foundation area of 16, 950 m^2 could supply heating and cooling to 65,000 m^2 or 75,000 m^2 of conditioned indoor area with 18.5 m long piles, depending on the use of the buildings. On that basis, the Return of Investment (ROI), was estimated to be 4–7 years when compared to traditional DHC, depending on whether cooling is required or not (cooling requirements reduce the duration of the ROI period).

A large-scale geothermal collector (LSC) can act as an intermediate storage unit in a 5GDHC. Low-temperature WH from industrial processes or from a wastewater heat exchanger can also be integrated. Seasonal load peaks, both in generation and consumption, can be temporarily stored within a LSC and then provided as needed. The combination of LSC systems with 5GDHC networks is a very young technology. Because of this, there are not many of these systems built around Europe, but some cases in Germany are mentioned by Zeh et al. [123]: the agrothermal collector with passive 5GDHC in Wüstenrot (the first case, built in 2011); the LSC system with active 5GDHC in Bad Nauheim (built in 2019); the geothermal collector with air-cooled chiller plant and active 5GDHC in Neustadtam Rübenberge (built in 2020). In the case study of Wüstenrot, the 5GDHC was created with 23 residential buildings, each one equipped with a HP (different HPs from 6 to 22 kW power) and a PV system. The HPs are connected with the 5GDHC, so every building is supplied with heating and free cooling by the 500 m long network in combination with the collector system; the annual COP has been over 4.0 since 2011. Because of the short pipe length and the nearby collector system, the distribution network was built as a passive 5GDHC. The case study in Bad Nauheim is characterized by 6 km long active 5GDHC that, together with the geothermal collector system (the largest in Germany, with 22,000 m^2), provides 2.3 GW h of source heat every year to 400 residential units (single-family and multi-family houses with decentral HPs in every building). Lastly, in the integrated system in "Neustadt am Rübenberge", the annual heat energy required in the construction area (of about 3000 m^2) is provided by the geothermal collector area in combination with an air-cooled chiller plant and the 5GDHC. The 5GDHC supplies single-family and multi-family houses. Due to the size of the project with about 100 residential units, the network was planned as an active network with central feeding pumps located in an energy center.

4.2. Solar thermal

Solar water heating, so-called solar thermal technology, is one of the most widely used water heating systems worldwide. Solar collectors can convert solar energy into concentrated heat efficiently, with advantages of a mature technology basis, low impact on global warming and low life cycle cost [124]. Solar collectors can be installed on rooftop areas of residential, commercial and industrial buildings as well as free standing systems. Solar thermal systems can be efficiently used for space heating, to heat water for residential and industrial purposes, and to supplement industrial processes. Good potential is envisioned regarding the combination of solar thermal with other technologies like biomass systems, geothermal heating, HPs, different DHC systems, etc. [13,125–128]. For the European countries, the overall solar thermal potential is estimated to be in the range of 3–12 % of the total heat production [128]. Solar thermal supply of low temperature heat demand (not exceeding 95 °C) can play a significant role in the future energy mix and could reach more than 16 % of total final energy use (16.5 EJ) for low temperature heat by 2050 worldwide [129]. It is estimated that solar thermal systems are up to 70 % efficient. The efficiency of solar thermal systems depends on solar radiation, the temperature difference between the solar collector and its surroundings, system design, etc. Many studies in Europe have shown that depending on climate zone and system design, solar thermal systems can produce from 323 to 605 kW h/m^2/year, or even more heat energy [130–133].

Various solar thermal systems can be effectively combined with a wide array of renewable energy technologies and heating/cooling systems, resulting in improved efficiency and environmental benefits. By integrating solar thermal collectors with biomass systems, geothermal heating, HPs, DHC systems, and EGs, powerful hybrid solutions can be created, reducing dependency on a single energy source and improving energy security [84,86,91,125–127,134,135]. Given the typical intermittent nature of solar energy, the integration of solar thermal with energy storage technologies such as Underground Thermal Energy Storage (UTES) is seen as particularly promising (e.g., see Ref. [136] and Sub-Section 4.5).

In most cases EGs are commonly designed as part of a hybrid heating and cooling system, whereby the geothermal energy component provides a base load and auxiliary means (for example: traditional HVAC equipment, DHC system or solar thermal) can provide additional energy when needed, which can lead to innovative approaches to heating and cooling [13,137,138]. Despite the potential benefits, the integration of solar thermal technology and EGs also poses several technical and non-technical challenges (see Section 5 for non-technical challenges), which are outlined below along with some available case study examples.

The combination of EGs with solar thermal systems faces several technical challenges that demand careful consideration for successful implementation and optimal performance. Some of the main technical challenges associated with integrating EGs and solar thermal systems may be identified as follows.

From the thermo-mechanical couplings point of view, it can be observed that EGs primarily serve as mechanical support for buildings and/or the surrounding soil, but their integration with solar thermal systems may introduce detrimental thermo-mechanical couplings. Thermal storage involving larger temperature changes, compared to standard seasonal geothermal operation, may thermally induce non-negligible settlements in piles (e.g., see Ref. [139]) or deflections in retaining structures, and/or additional loads [140,141], depending on the level of constraint between the structure and the surrounding soil. This issue is expected to be particularly relevant for EPs, and for EGs installed in normally consolidated clayey soils [142], demanding careful analysis at early design stages.

From the energy potential point of view, it should be remarked that solar thermal systems exhibit fluctuating and intermittent thermal characteristics due to changing weather conditions and diurnal cycles. This should be borne in mind when designing the integrated system, as well as the fact that achieving efficient utilization of both EGs and solar thermal systems often necessitates substantial thermal energy storage: as solar energy availability varies and demand fluctuates, effective storage solutions become essential for managing energy supply and demand and avoiding wastage. Moreover, when EGs are combined with solar thermal for UTES purposes, the system can be efficiently used for single-season operation. This is most typical for winter heating (and summertime heat storage), but also wintertime cold storage is possible. On the other hand, such systems cannot be efficiently employed for dual (heating and cooling) seasonal usage, since no heat (or cold) accumulation is possible in this case.

From the heating/cooling system design point of view, it is worth noting that the integration of EGs with solar thermal systems introduces a higher level of complexity in planning, designing, and controlling the combined setup. Coordinating the operation of both systems and optimizing performance requires sophisticated control strategies that can adapt to changing conditions. Addressing this complexity is vital to ensure seamless and efficient operation. Moreover, designers and planners of EGs with solar thermal systems encounter a lack of established guidelines and standards. The absence of comprehensive protocols can hinder the efficient development of integrated systems. The need for standardized practices is paramount to ensure safe and effective implementation.

To the best of the authors' knowledge, two documented case studies exist about the integration of solar thermal technology and EGs, both of which involving UTES with EPs. The first example consists of a field test carried out in Jiangyin, China, involving a bridge deck equipped with floor solar collectors, whose heat carrier fluid circuit was coupled with heat exchangers installed within a 1 m diameter and 20 m length thermo-active foundation pile [143]. Experimental results showed a good performance of the EP for solar TES, with more than 80 % of solar energy transferred to the soil surrounding the pile, also showing a thermal injection rate 2–3 times larger than that of BHEs tested in previous investigations. Moreover, intermittent operation mode was found to be more thermally efficient compared to a continuous thermal loading of the EP. No thermo-mechanical issues were considered in this experimentation.

Another example, representing a real application, was recently completed in Finland [144] and consists of a group of Energy MicroPiles (EMPs) installed in the city of Turku (Fig. 8). Beneath the main historic square of the city an underground car park was built in clayey soil, supported by more than 2000 end-bearing micropiles, including 561 EMPs consisting of a steel tube equipped with one U-shaped heat exchanger. Thermal energy is stored underground using solar collectors placed beneath the square's stone floor. In wintertime, geothermal heat is used to de-ice the square floor and for parking space heating. While TRTs were carried out on EMPs with different lengths and filling materials to assess the mean thermal conductivity of the soil during construction, no thermo-mechanical analysis was carried out prior to site construction. Site monitoring in terms of temperature and pile/soil displacements during geothermal operation may be necessary to establish possible limits of subsoil temperature increase compared to the undisturbed value, in order to avoid thermally induced overstresses and/or strains.

Finally, the GeothermSkin energy wall installed at the Energy Center building at Politecnico di Torino (Italy) is actually coupled with solar collectors [146]. The integration of shallow geothermal energy with solar thermal is going to be tested but still there are not experimental data.

4.3. Waste heat

Waste heat (WH) refers to thermal energy that is dissipated in the form of heat and remains unused. Its primary sources are the untapped heat generated from industrial production, manufacturing, construction, and machinery operations, among others. For instance, industries like metal production, data centers, thermal power plants, and waste incineration emit substantial and concentrated WH. By integrating WH into systems such as DHC networks, UTES, and electric generators, it can be effectively repurposed. Reusing waste heat from all available sources can significantly improve energy efficiency and reduce heating energy consumption [147].

Data centers generate significant amounts of WH primarily due to the high density of electronic devices which consumes electrical power and, in the process, converts most of this energy into heat as a byproduct during its operation. The WH generated by the air-cooled system is less commonly adopted due to the complexity of the system and the challenges in integration. Therefore, the utilization of waste heat from data centers predominantly focuses on liquid-cooled and two-phase cooling data centers, facilitated through the use of heat exchangers to facilitate heat exchange [148]. Due to the low-grade nature of WH from data centers, which is insufficient to cater to peak heating demands, its integration into district heating and cooling systems in conjunction with HP or boiler technology is warranted [149]. In fact, typically it necessitates complementary utilization of HPs and boiler-based heating methods to improve the heat quality, making it suitable for integration into DHC systems. Still, this low temperature range can be assessed suitable for operating in 5GDHC.

In the context of WH recovery from industrial sources with varying temperatures, diverse heat exchangers are employed for efficient heat transfer, such as absorption HPs, plate heat exchangers and so on [150]. Furthermore, a cascading WH recovery process can be employed to achieve efficient utilization of WH. Current research endeavors predominantly focus on the collection and integration of multi-level WH sources, long-distance transport of WH, and system peak load management.

Additionally, there are many other sources of waste heat, including those from transportation, particularly from automotive and railway systems, as well as from residential heating systems. Reusing these types of waste heat tends to be more challenging. On the other hand, waste heat from solar and geothermal systems presents greater opportunities for reuse due to their inherent properties and integration potential.

The utilization of WH for integration with UTES is a novel research

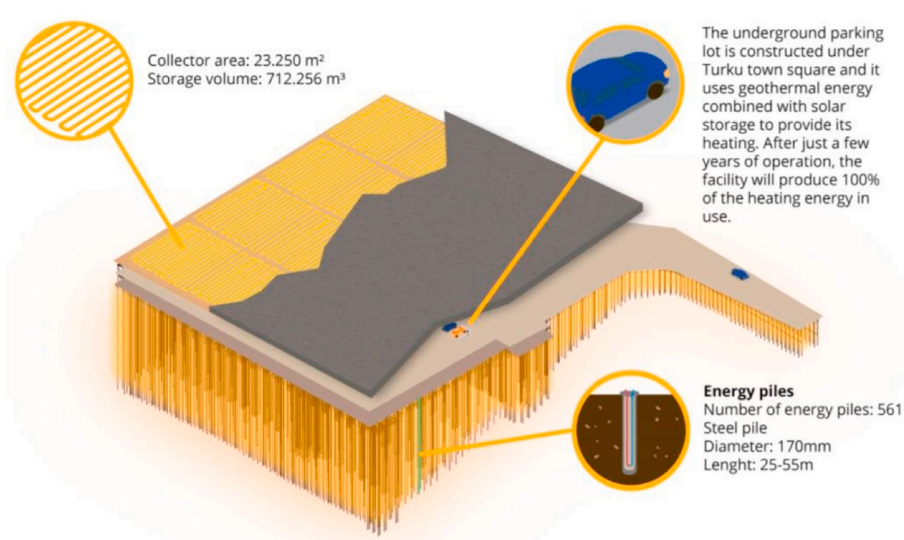

Fig. 8. Schematic of the Turku underground parking EMP heat storage project [145].

direction, albeit one with relatively limited existing studies. Given that the primary energy source for UTES is SGE, storing WH in underground can also facilitate indirect integration with UTES projects. Furthermore, WH can also be stored by integrating with underground energy storage spaces, which include systems like aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), as well as other forms of UTES such as underground caverns, tanks, and fractures [136]. For example, ATES is an energy storage technology that utilizes underground aquifers as a heat storage medium [83]. It serves as a promising application for storing surplus heat for peak load regulation during periods of peak power demand and heating [151]. BTES, on the other hand, exhibits characteristics of slower thermal response and higher storage capacity, rendering it more suitable for seasonal storage. Additionally, BTES boasts broader geographical applicability. Meanwhile, ATES offers substantial storage capacity, but its feasibility is contingent on local aquifer geological conditions [152].

WH can be integrated into the power generation process, encompassing both direct methods such as piezoelectricity and thermoelectricity, as well as indirect approaches like steam and organic Rankine cycle [148]. To address the challenges of regulation and peak load management in utilization, a combined system involving industrial WH and CHP plants can be employed [149]. In this configuration, industrial WH caters to the fundamental heating demand, while CHP plants function as peak load regulators. In general, absorption cooling and the organic Rankine cycle are widely regarded as the most promising technologies for effective WH utilization [147,153–155].

The WH utilization methods are shown in Fig. 9 below. Utilizing WH for applications like regional heating comes with inherent limitations and challenges, discussed below.

The quality of WH in some cases can be low, and its availability can be unstable. Waste heat temperatures from data center cooling components typically fall below 85 °C, while industrial WH generally can be categorized as low (<100 °C), medium (100–299 °C), or high (>300 °C) [156,157]. Given its typically low to medium temperature and intermittent availability, waste heat has limited utility for many applications and processes using conventional methods, particularly when the temperatures are not consistently high enough. Moreover, the viability of waste heat as a resource depends on current business strategies and market conditions. Transporting waste heat over long distances can result in significant heat loss and elevated costs. As the waste heat collection system becomes part of the DHC system, both connection costs and heat loss increase substantially with distance. Additionally, the collection and integration of various waste heat sources require substantial capital investment, yielding relatively modest cost-effectiveness.

There have been some successful cases of harnessing WH from data centers and utilizing it for DHC and regional heating in office areas. In the context of water-cooled data centers, Intel Corporation (intel.com) has implemented a system where WH is recovered through a heat recovery cooler, then undergoes heat exchange via a plate heat exchanger. A HP is employed to elevate the temperature of the exchanged hot water, which is subsequently used for localized regional heating [148]. In Finland, a similar approach is applied, utilizing liquid cooling to cool the data center while integrating with a regional heating network. This network generates warm water for regional heating and provides space heating for the community. The National Renewable Energy Laboratory of the U.S. Department of Energy has also adopted a similar concept, utilizing warm water cooling and subsequently conveying the heated water through pipelines to serve as space heating for offices and research labs [158].

Similar applications are found in air-cooled data centers, with a Canadian data center employing a straightforward modification to provide space heating for offices and adjacent warehouses [148]. In the context of Germany, where the shallow aquifer temperature ranges between 5 and 20 °C, direct utilization of WH in heating systems may confront the challenge of insufficiently elevated temperatures. Consequently, the integration of data-based and industrial WH into regional DHC networks represents a promising application [159].

Likewise, some successful cases of industrial WH utilization have been implemented across the world, with the majority involving integration into regional DHC systems, or utilizing UTES for heat storage. In Sweden [160], a case involves the recovery of industrial WH from a CHP plant using mobilized TES technology. The collected industrial WH is then transported to a small village 20 km away from the CHP plant through a DHC network. This network supplies hot water in summer and is used for space heating and tap water in winter [161]. In Chifeng City, China, WH from a copper smelting plant is harnessed alongside a CHP plant to provide heating for the region. Moreover, two gas boilers are in place as contingency heat sources, with the CHP plant acting as a peak load regulator. Additionally, in Switzerland, industrial WH is integrated into a local DHC system and enhanced through the application of HPs [149]. In Germany, WH from a steel plant is employed for regional DHC [160]. This upgraded heat is employed for peak load regulation during heating demand spikes and for regional heating purposes.

UTES can serve as a WH storage system, allowing for the retention of WH to be utilized for peak power supply and for peak load regulation

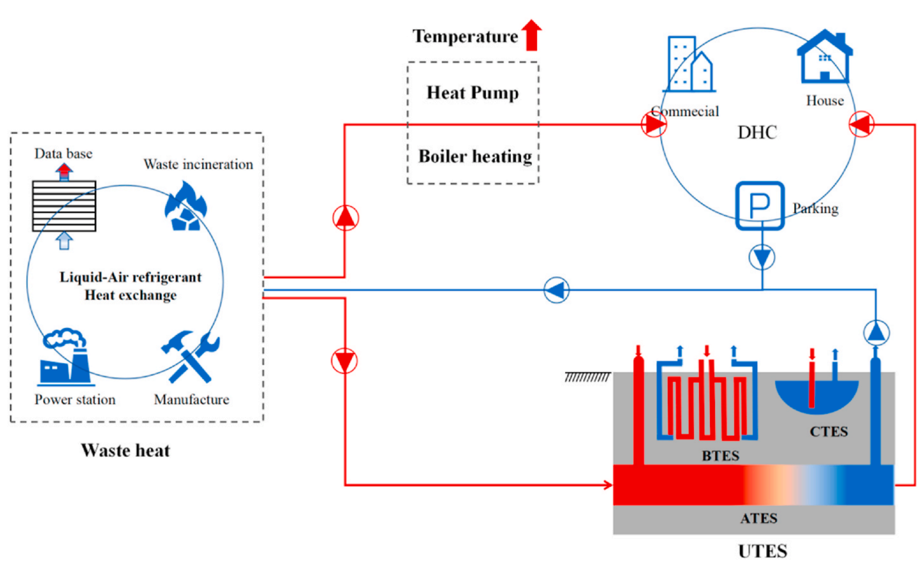

Fig. 9. Waste heat integration with DHC & UTES.

during heating periods. Taking ATES as an example, it can provide sustainable heating and cooling sources for various types of buildings when used in conjunction with groundwater exchange systems in aquifers with good permeability. Moreover, it can be integrated at the regional or city level to realize DHC applications. Notable examples include ATES in the Netherlands [162], an underground aquifer storage system in the state of Alabama, USA, the German Federal Parliament building in Berlin, and the aquifer-based HP storage system. However, there are relatively few established cases of WH stored in aquifers [163].

There are relatively few existing cases of WH stored in BTES systems. However, one noteworthy example comes from Crailsheim Hirtenwiesen, Germany, where solar collectors are used to store heat in a 37,500 m^3 borehole for regional DHC purposes [164]. Some scholars have found that combining solar thermal energy with BTES enables to maintain a more stable soil temperature, extend system lifespan, and allow for the collection and storage of larger amounts of energy, making it well-suited for regional DHC [165]. This case can be applied to integrate WH, including that from data centers and industrial processes, into BTES for seasonal regional heating.

4.4. Biomass

Biomass heating systems operate by harnessing the energy from biomass to generate heat. These systems can employ various methods such as direct combustion, gasification, CHP, anaerobic digestion, or aerobic digestion to produce the desired heat. Biomass heating systems can vary in automation, ranging from fully automated to semi-automated. They can also utilize different fuel sources, such as wood chips, pellets, residues from agriculture of forestry, grassy and woody plants, etc. For improved efficiency, some biomass systems may incorporate combined heat and power mechanisms. Biomass heating systems can be efficiently used from single family buildings to industry and DHC systems, as well as efficiently combined with other technologies like solar thermal systems, geothermal heating, HPs, different DHC systems, etc. [13,126,166,167].

Biomass systems can provide the full range of temperatures required for different needs from small systems to industrial processes. Environmental concerns regarding the emission of biomass boilers have been regulated through competent European regulations within the eco-design regulation series. Issues concerning the quality of biofuels used in biomass boilers are also managed through a recently published series of European standards, which define the elemental and proximal requirements of the applied fuels. Automation in modern biomass boilers, as well as advanced combustion techniques, such as the two-stage combustion, provides user friendly solutions that fulfil the legislative requirements and guarantee the further penetration of this technology into the heat market [166,167].

Improved use of biomass and non-biomass resources is crucial for the European economies. Transition from a fossil-based to a bio-based economy has gained increasing importance over the recent decades [168]. Biomass systems, can be efficiently combined, not only with geothermal heating, HPs, DHC systems, but also 1potentially with EGs systems. The main advantages of modern biomass systems are their renewability, reliability, abundance in most EU countries, carbon neutrality, and the ability to provide the full range of temperatures required for various needs.

On the other hand, EGs are commonly designed as part of a hybrid heating and cooling system, whereby the geothermal energy component provides a base load and auxiliary means (for example, biomass DHC or solar thermal systems) can provide additional energy when needed, which can lead to innovative approaches to heating and cooling [13,169].

Several studies have demonstrated the potential for efficiently combining various sources, including biomass, solar thermal, WH, geothermal, and other, which can be applied from non-residential buildings to DHC systems. It was concluded that integrating two or more resources could yield configurations with lower costs, improved reliability, and reduced environmental impacts [126,169–174]. Evidence that potential of integration of EGs and biomass systems technologies are high, but still some technical and non-technical challenges exist as described below and in Section 4. Furthermore, the absence of pilot projects and demonstrations that combine both technologies is a significant gap. To date and to the authors' knowledge, there are no available case studies that integrate phase-change materials (PCMs) with EGs.

The main technical challenges of EGs integration with biomass systems are given below.

The absence of standards and guidelines for planners and designers is a significant hurdle. Combining EGs with biomass systems involves diverse engineering disciplines, and a lack of well-established protocols can lead to confusion and inefficiencies in the design and implementation process. It is crucial to develop standardized approaches that ensure safety, efficiency, and sustainability in these integrated systems.

Integrating EGs with biomass systems introduces a higher level of complexity. These projects require not only expertise in geotechnical engineering but also in biomass technology and energy systems. Coordinating these diverse elements and ensuring they work seamlessly together can be challenging. Additionally, there is complexity in terms of control and operation, as both EGs and biomass systems need to be optimized for maximum performance and environmental benefits.

In some regions, a shortage of local biomass can result in high biomass prices. Biomass feedstock availability is dependent on factors such as climate, land use, and agricultural practices. When local biomass is scarce, transportation costs can significantly drive up prices, affecting the overall economic feasibility of the integrated system. Furthermore, long transportation distance can increase environmental impact. These challenges underscore the importance of local resource assessment and diversifying biomass sources where possible.

Note that even modern biomass boilers require continual maintenance. Regular cleaning, fuel handling, and component upkeep are essential to ensure efficient and trouble-free operation. Maintenance can be costly and time-consuming, and it is vital for project planners and operators to budget for these ongoing expenses and have a well-defined maintenance plan in place.

4.5. Underground thermal energy storage and phase change materials

Underground thermal energy storage (UTES) is characterized as one of the efficient systems for the heating application of building sector. The storage medium can be categorized in various types [175], namely (i) hot water in a tank (or pool); (ii) a mixture of gravel and water in an underground groove covered with an adiabatic and waterproof material; (iii) soil within underground buried pipes; (iv) aquifer; etc. In spite of their development, most of these systems are still limited to sensible heat. Essentially, energy can be stored in different forms, including mechanical, electrical and thermal. Among these, thermal energy can be stored as a change in internal energy of materials as sensible heat, latent heat, thermochemical energies; it can also be stored in a hybrid form, which is a blend of two separate forms. Latent heat corresponds to energy absorbed or released by a material undergoing phase change and, unlike sensible heat, it takes place at constant temperature [176]. Thermal energy is stored in or released from the molecular structure of a material when its temperature reaches the phase transformation temperature and does not result in a temperature change. PCMs are thus latent heat storage materials. They can store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock [177]. Generally, in prototypes and literature studies (rare for actual cases), PCMs are used in passive thermal storage materials, incorporated into building elements (by direct impregnation, immersion or imbibing through materials' pores, shape-stabilization, microencapsulation, and macro-encapsulation) or as independent storage units [178].

Hybrid Ground Source Heat Pump (HGSHP) systems integrated with supplementary energies can be used to overcome thermal imbalance problems [179]. In addition to direct auxiliary cooling and heating sources, thermal energy storage (TES) devices including sensible and latent TES can be integrated with GSHPs to provide both cooling and heating for domestic and industrial buildings. In these systems, conventional PCMs can be directly backfilled into the borehole, isolated from the surrounding soil, or microencapsulated PCM can be mixed with soil. Except for the numerical investigation carried out by Rabin and Korin [180], the use of PCMs as an additive to backfilling material for a HGSHP has seen further interest only in the last decade [181]. Furthermore, the HGSHP system can also be integrated with PCM storage tank. Finally, PCM-water-based TES can be used to improve thermal transfer in the system.

Besides GSHPs, EGs in any form (e.g., EPs, tunnels, retaining walls) can be used for integration. Some recent studies investigated the potential of integrating PCMs into EGs by using mixing PCM with grouting for screw pile [182] or PCM backfill in precast high-strength concrete EP [183,184], by embedding PCM containers into the concrete shell of EPs [185,186], or by adding hollow steel balls (HSB) macro-encapsulated PCM to the concrete of EPs [187], also incorporating steel fibers in PCM-HSB to improve the thermal and mechanical properties of concrete material [188]. Lastly, the hypothesis of mixing microencapsulated PCMs and metallic fins in the ground surrounding an EP to augment the thermal properties of the latter and reduce the size of the temperature influence zone has been considered, assessing the feasibility of this configuration through numerical simulations [189].

Mousa et al. [190] provided a 3D finite element model study of the effects of phase changing materials (PCMs) on the performance of EPs against a real building load for a complete year. According to the study there could be a 5.2 % enhancement in the HP COP during the melting of the PCM, and a negative effect of up to 1.8 % during the completely solid-state. Moreover, the use of multiple PCM melting temperatures led to a performance enhancement of up to 26 %.

Also, Zheng et al. analyzed the possibility of cooling the underground shelter by a GSHP system cascaded with multi-modular water-phase change material (PCM) tanks [184]. It was reported that, after 10 years of operation, 75 % of the base GHEs could guarantee the cooling water temperature within the limited range in ordinary mode, and the effective discharging duration of the hybrid cooling system by at least 97 % in emergency mode [184].

The development of UTES is strongly dependent on the management of environmental risks that may arise on groundwater systems including hydrological, thermal, chemical, and microbiological aspects. For instance, changing other wells' capture zone would increase the UTES vulnerability and pollution; changing water temperature would modify reaction kinetics; reactivation of otherwise stable groundwater pollution plumes would increase the quantity of micro-pollutants; pathogens would be introduced, etc. [191].

The latest ATES (Aquifer TES) system's thermal, economic and environmental performance studies are focused on the influence factors in the performance of the underground part of the ATES systems (e.g. Ref. [192]). The most commonly used indicators for thermal performance investigation are the thermal recovery ratio and the thermal interference intensity. But there is still a lack of long-term monitoring, and the simulation studies are always carried out without considering the variation load needs from the end users [193].

Knowing the subsurface thermal characteristics is crucial for EGs planning as well as for any thermal system that uses the ground for extracting or storing heat. In dense urban environment EGs can interact with other subsurface functions and systems installed in the neighborhood, i.e., ground or water sourced HPs, ATES, BTES (Borehole TES) and other thermally affective structures. These interactions can be mutual, and it could be difficult to find a location to install – for example – an ATES well in the shallow subsurface in densely built urban areas due to the shallow infrastructure [194].

Heat loss is the one of the biggest challenges of UTES. Various measures have been examined to reduce it (e.g., increasing the insulation layer thickness, raising the thermal energy storage temperature, and changing the filling materials). However, several technical issues still need to be addressed such as: the effect of large temperature gradient on the geotechnical integrity of the system; an optimal insulation solution; alternative backfill materials to reduce the contact thermal resistance; the effect of soil stratification on the system design [175].

Lastly, focusing on PCMs only, these materials have generally a low thermal conductivity and due to this, the heat transfer enhancement is a big concern. This aspect is very important for PCM applications in water tanks and buildings since low thermal conductivities negatively influence heat transfer and heat storage capacity [195]. A lower heat transfer rate, in fact, increases the charging and discharging time, which is the main factor for designing an energy storage system. Moreover, another drawback involves the high cost of phase change materials compared to other conventional materials, for example reported values estimated at 10–50 €/kWh compared to 0.1–10 €/kWh respectively [196]. Consequently, to date and to the authors' knowledge, there are not available case studies that integrate PCMs with EGs.

4.6. Passive systems and other potential integrations

EGs systems could also be implemented as passive systems with the use of solar energy or other thermal energy sources (e.g., CHP or DHC). The system could potentially store thermal energy in the building's foundation and/or the surrounding soil, therefore acting as a TES and EGs system, without the need for a HP. Depending on the system's design and boundary conditions, either natural convection is relied upon to move the heat transfer fluid to provide heating/cooling to the user, or a circulation pump may be required. Some examples can be found in the literature, where researchers have proposed novel type systems to take advantage of these structures and the surrounding elements [9].

Another example of a passive EG system is the underground car park founded on energy micropiles recently built in Finland [144,197] and described in Section 4.2. In this case, circulation pumps are needed to move the heat exchanger fluid from the floor solar collectors to the micropiles (in summertime, for heat storage), and back from the micropiles to the floor (in wintertime, for pavement de-icing) without the need for a HP.

A very recent EG application also involving passive geothermal operation is the energy quay wall (EQW) field test installed in Delft, Netherlands [198–200]. EQW is a special type of EG involving hydrothermal heat exchange in addition to the geothermal one, being embedded into soil but also in contact with open water on one side of its upper portion (Fig. 10). The thermal properties of water, with particular reference to its large specific heat capacity, are exploited in this application by including a ground 'regeneration' period after wintertime geothermal operation. More specifically, during warm weather months, when the ground temperature is lower than average due to heat extraction occurred in winter heating mode, the fluid is circulated within the U-pipes via circulation pumps while keeping the HP off, allowing heat to be transferred from the warm canal water down to deeper ground layers.

Poulsen et al. [201] and Andersen et al. [202] proposed a novel type of EGs that uses the roadbed gravel structure as an energy source for individual or networked GSHPs. In addition, the porous gravel roadbed is used as a sustainable urban drainage system (SUDS), to drain and delay surface water from extreme precipitation events to prevent flooding at the surface and of the sewage system. Two prototypes were constructed in full-scale in 2018 and 2021, respectively. The latest prototype (the thermoroad) from 2021 will connect 12 residential single-family houses (each of 118 m^2) with individual brine-water HPs, to a 5G-DHC grid, which utilizes 1200 m of horizontal heat exchangers in the roadbed, one 100-m U-pipe along the central wastewater pipe and

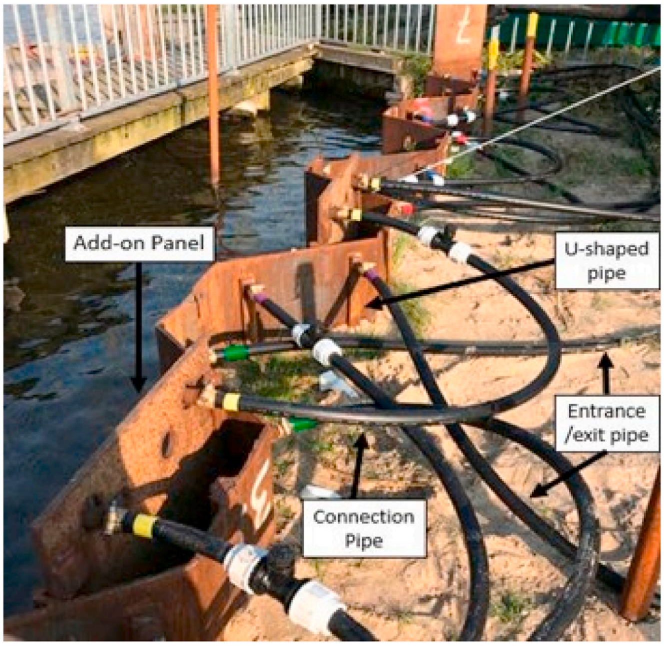

Fig. 10. Energy Quay Wall (EQW) field test installed in Delft, Netherlands [199].

3 BHEs drilled to a depth of 85 m. The construction of the 12 buildings began during the fall of 2023 and the 5G-DHC is expected to be commissioned and put into operation before the summer of 2024. The 5G-DHC is instrumented with energy meters measuring flow and temperature on the manifolds of the heat exchanger groups (roadbed HEs, wastewater pipe U-type HE, BHEs). Energy meters on the supply side and separate electricity meters record the total supplied heating and cooling and electricity consumption of the domestic HPs.

5. Non-technical challenges

The integration of geothermal energy, in particular EGs, with a diverse array of RES is crucial for advancing a sustainable energy future. This integration is not limited to UTES systems but extends to synergies with solar, wind, hydroelectric power, and biomass energy systems globally. These technologies not only improve the efficiency and reliability of energy distribution but also facilitate the management of supply and demand, ensuring a more resilient energy network.

Moreover, the holistic integration of these systems must consider environmental impacts, economic feasibility, and social acceptance. Strategic planning should involve community engagement and policy frameworks that support innovation, investment, and skill development in the renewable sector. This inclusive approach ensures that the transition to renewable energy not only addresses climate change but, as mentioned in Section 2, GSHP development also fosters the following challenges: (i) financial and economic, (ii) environmental and social, (iii) policies and regulations, and (iv) administrative and institutional. These are summarized in Table 1.

5.1. Financial and economic challenges

A thorough evaluation of the financial and economic aspects is essential to ensure alignment with local needs, inclusive economic growth, and social equity ([203,204]). Understanding the broader socioeconomic implications provides insights into potential co-benefits like job creation, community development, and enhanced energy affordability. By prioritizing the socioeconomic evaluation, decision-makers can drive the transition toward cleaner energy and foster resilient, prosperous, and socially just societies [205,206].

Table 1
Deployment challenges of GSHP systems with EGs or BHEs (modified from Refs. [58,59]).

System	GSHP with BHE or EGs	GSHP with BHE only
Financial and economic challenges	- Costs associated with maintenance - Financial incentives and subsidies - Non-cost hurdles to consumer adoption - Economic growth/job creation	- High up-front expenses - Financing - Payback period
Environmental and social challenges	- Community acceptance - Social equity - Environmental impact of ground loop	- Energy consumption and emissions - Surface land usage - Noise pollution - Water usage
Policies and regulations challenges	- Lack of national standards - Varying incentives and subsidies - Net metering - Interconnection - Building codes and regulations	
Administrative and institutional challenges	- Lack of trained personnel - Limited access to reliable information - Bureaucratic barriers - Limited coordination between agencies - Limited funding - Limited understanding - Limited data - Stakeholders' involvement - Restrictions on new installations	

UTES systems are widespread in Europe, with a long history in central Europe; a market developed in the Benelux and the eastern European countries. However, for the time being, their enormous potential is not fully exploited. For example, the use of such systems in southern Europe is still in its infancy. The recent sharp rise in demand has led to the inclusion of new participants who possess limited experience and training. Therefore, robust quality assurance measures, coupled with comprehensive training and certification programs, are essential to avert adverse environmental impacts and safeguard the public perception of the technology [207,208].

Hence, conducting a comprehensive socioeconomic impact evaluation of EGs is increasingly necessary as it enables the identification of potential social disparities and informs strategies for addressing them [209]. This evaluation will guide policymakers, developers, and stakeholders toward decisions that promote both environmental stewardship and social equity, fostering a just and sustainable energy landscape for present and future generations. Socioeconomic evaluation serves as a critical tool in assessing the broader implications and benefits of adopting such innovative technologies. It allows stakeholders to gauge the economic viability, social acceptance, and environmental impact of EGs integration, paving the way for informed decision-making [210]. Furthermore, when considering the integration of EGs with other RES like solar, wind, hydropower, etc., a range of methods come into play.

When evaluating the socioeconomic impacts of EGs and its potential integration with other RES, an option is to adopt the Triple Dividend approach as a conceptual framework [211]. This approach proposes three distinct dividends to consider when assessing the benefits of EGs implementation. Firstly, it involves analyzing the direct benefits of EGs measures or interventions, such as enhanced energy efficiency and reduced carbon emissions. Secondly, attention should be given to unlocking the economic potential of EGs, including factors like job creation, cost savings in energy production, and potential revenue from energy exports. Lastly, the evaluation should also account for the co-benefits generated by EGs, where its integration with other RES may lead to synergistic effects and additional positive impacts on the environment and society. By employing this approach, decision-makers can gain a comprehensive understanding of the various socioeconomic advantages that EGs can offer, enabling them to make well-informed choices to promote sustainable development and adopt renewable energy solutions.

In Fig. 11, the triple dividend framework, developed by Ref. [211] for disaster management, has been applied. However, the emphasis is not on that specific aspect but on how it would be directed toward other projects, similar to the EGs implementations under analysis. This is because the triple dividend concept can be viewed within a broader context.

The assessment of the Triple Dividend framework will require a combination of quantitative and qualitative methods, along with data collection and analysis [213]. The outcomes of these evaluations will enable decision-makers to better understand the impacts and benefits of implementing energy-related projects and measures.

5.2. Environmental and social challenges

Social acceptance of the energy transition is an increasingly important issue, which can sometimes bias decisions on aspects that do not guarantee their efficiency. The self-perceived power of consumers to decide their energy sources can radically change the energy mix [214]. Society is often uninformed of the potential of some energy sources. According to the review of [215], the great discrepancy in global ATES development is attributed to several market barriers of socio-economic and legislative nature (technical feasibility, lack of awareness, mistrust in technology, high investment costs, policy & legislation, lack of know-how, size of application, and shortage of subsurface space), which make the spread on a large scale more difficult. Therefore, to increase citizens' awareness, it is necessary to overcome existing socio-economic, political, and legal barriers. To cope with these concerns, it is important to have a conceptual framework for evaluation that goes beyond accounting costs and benefits, toward more wide impacts definition, including social and environmental issues.

When it comes to the level of sustainability and effects on nature and societies, PCM's impact and cost depend on the materials' production processes [216]. Cost and availability are an issue since the extra cost for this specific technology is highly dependent upon the type of PCM used and its mass fraction introduced in the EG Ref. [217]. Some studies have shown that the payback period was acceptable in some cases and the investment of PCM was feasible and worthy of economic. However [216], highlighted the hazardous effect of some of the PCMs production processes.

5.3. Policies and regulations challenges

Integrating renewable energy sources, including geothermal energy, into our energy systems faces several key challenges. The lack of uniform national standards across countries leads to inconsistencies in technology implementation and performance assessment, hindering the seamless integration and optimization of these technologies [218]. Additionally, the landscape of financial incentives and subsidies varies significantly across regions, impacting the development pace and investment attractiveness of renewable energy projects, a factor especially critical for geothermal energy, where upfront costs can be substantial [219]. Net metering policies, crucial for the feasibility and economic returns of small-scale renewable energy installations, vary widely, affecting the enthusiasm of individual and small business investors. Moreover, the efficient and reliable interconnection of renewable energy systems to existing grids is often complicated by technical and regulatory hurdles, a challenge that is paramount for maintaining grid stability as more variable renewable energy sources are integrated [220]. Finally, the slow and uneven progress in adapting building codes and regulations to accommodate and encourage renewable energy technologies, including geothermal systems, impedes broader adoption. Addressing these issues is vital for fostering a more sustainable and resilient energy future, where geothermal and other renewable sources can be fully harnessed.

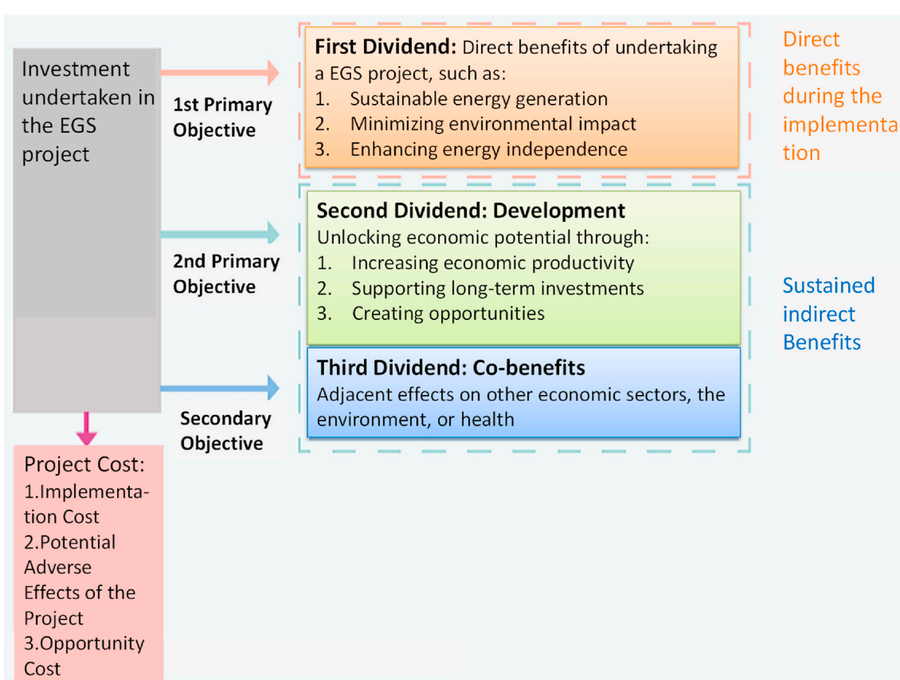

Fig. 11. Triple Dividend Framework adapted for project impact assessment, elaborated based on [211,212].

5.4. Administrative and institutional challenges

Integrating renewable energy systems, including geothermal energy, into existing frameworks faces various administrative challenges that necessitate comprehensive solutions. A significant concern is the need for more trained personnel, hindering efficient development and operation and limited access to reliable information, which impedes informed decision-making [221]. Bureaucratic barriers, including lengthy permitting processes and complex regulations, along with inadequate coordination between various agencies, create additional hurdles [222]. Financial constraints are also prevalent, with limited funding for novel and large-scale projects. This issue is compounded by a general need for more understanding of renewable energy systems among crucial stakeholders, further hampered by insufficient data on the performance and potential of these energy sources. Stakeholder involvement is crucial yet often lacking, and restrictive policies on new installations due to land use, environmental concerns, or grid capacity pose further constraints [223]. Overcoming these administrative barriers is vital for fostering a conducive environment for renewable energy projects, ensuring their successful implementation and integration into the broader energy system [224]. Another challenge is that developers and designers are usually risk averse to new technologies and possibly compromising structural performance. Depending on the risk aversion of the private sector, the payment scheme conditional on success might need to be slightly higher [225]. Higher subsidies may be a mechanism to compensate for certain equivalence for risk management. Nevertheless, business and ownership models can overcome risk averse developers by providing system solutions that reduce or fully eliminate the risk. For example, the so-called EaaS model (Energy as a Service) removes the risk from the developer and places this on the system provider. The experience from projects underlines the crucial importance of end-user friendly risk management and ownership models when attempting to scale 5GDHC.

Another non-technical issue that deserves attention is the need for research of EGs integration with other renewable energy systems. Table 2 explores the main technical challenges of EGs integration with solar thermal systems, biomass systems.

In summary, while both solar thermal and biomass energy systems offer promising pathways for renewable energy integration, addressing their respective financial, regulatory, and logistical challenges is key to unlocking their full potential in the transition to a more sustainable energy landscape.

6. Discussion

A 'mixed study review' methodology, combining 'critical review', 'literature review' and 'state-of-the-art review', has been employed above to systematically examine and assess the compatibility and integration of various RES and environmentally friendly technologies with structural elements deployed as so-called energy geo-structures (EGs). Note that recent studies demonstrated that the use of EGs as GHEs has limited impact on the structural performance of these underground geotechnical structures. However, there is still a lack of design tools, unlike conventional GSHP. In this paper, emphasis has been given on two primary categories related to the advancement on this area.

The first category involves the integration of EG elements with sources that supply green electricity, referred to as renewable energy electricity obtained from on-grid or off-grid integration (see Section 3 above). Solar PV panels and off-shore wind technologies, that are majorly widespread, have been identified as the most cost-effective solutions. If they are combined with EGs, the overall efficiency of the system increases and the energy utilization is optimized: for example, the excess electricity from PV panels can be utilized to power HPs, circulation pumps or other components of the energy system, reducing the need for additional sources and achieving a more sustainable energy system. Still, some drawbacks exist when considering the integration of these two renewable energy sources (green electricity and shallow geothermal); in fact, due to the intermittent nature of solar power, that is majorly influenced by weather conditions and geographical factors, the system could not be able to support constantly the energy needs of the circulating pumps and heat pumps linked to the EGs.

The second category, which has been thoroughly discussed in the manuscript, involves a direct or indirect integration of EGs with sources that provide heat, or vice versa. The incorporation of heat sources, whether through direct or indirect means, encompasses technologies to simultaneous utilize energy for many purposes. Such incorporations include the well-known utilization of Heat Pumps (HPs), with notable examples the Ground Source Heat Pumps (GSHP) and the Air Source Heat Pumps (ASHPs), discussed in detail in Section 2.

Another major incorporation that has been identified in Section 4 above as critical, is the utilization of EG elements with 5th generation District Heating and Cooling (5GDHC) systems into thermal grids [226], given the similarity of the temperature ranges exchanged between these two systems (EGs and 5GDHC): with temperature around soil temperature, heat losses hardly occur. The major advantage and efficient use of the combination of EGs in 5GDHC was considered to be the re-use of excess heat coming from the distribution networks to recharge and facilitate the recovery of the ground using the EGs for thermal storage. Furthermore, a wider range of energy users (like residential and non-residential buildings connected to the distribution system) can benefit from the introduction of EGs into thermal networks, enhancing the overall thermal performance and the geothermal energy yield. Unfortunately, the lack of practical experience and real applications of these integrated systems is a limitation for the spread of the technology; especially considering the major complexity of the system and possible practical challenges (such as the need to use pipes with large diameters and the additional complexity for the EGs to meet the varying temporal thermal demands of the networks).

Moreover, with particular focus on the effective distribution of heat, by de-centralized systems, more sources or technologies have been discussed in Section 4 above, such as solar thermal energy, biomass energy integration, particularly through the Combined Heat and Power (CHP) systems, high enthalpy geothermal sources (as deep geothermal systems), integration of waste heat from both low and high-temperature sources, or even the harnessing of energy from urban structures. Also, in Section 4, the presented discussion on EGs as underground thermal energy storage (TES) systems points to the possibility for harmonizing energy generation and consumption, evaluating also the integration of additional materials (such as Phase Change Materials) to increase the overall storage capacity and thermal performance of the system, together with the COP of the connected HPs. Still, the current elevated cost of PCM materials and, in most cases, their low thermal conductivity

Table 2
Challenges of EGs integration with solar thermal systems and biomass systems.

System	Solar thermal	Biomass
Challenges	- High upfront costs. Lack of subsidies for geo-structures and solar thermal systems installations - Absent of guidelines and standards for designers and planners for development of combined geo-structure and solar thermal systems. - Lack of regulations for selling thermal energy from EGSs and other RES to district heating systems. - Lack of regulations for solar PV energy to grid and EGSs and other RES to district heating systems.	- Medium or high upfront costs. Lack of subsidies for geo-structures and biomass systems installations - Lack of regulations for selling thermal energy from EGs and other RES to district heating systems. - Could have biofuel supply issues in some regions.

represents a large limitation for the implementation of PCM in EGs and the improvement of the overall performance, leading to a lack of real applications and case studies.

The review performed in the current paper has not only pointed toward potential prospects for integration, but it has also equally importantly identified the presence of both technical and non-technical challenges. Primary complications encompass the reliance on geographically specialized resources and technologies, the absence of national (or EU) regulations regarding these elements, and the accompanying expenses that increase with two or more integrations and incorporations. These constraints highlight the necessity of a thorough and flexible approach to guarantee the effective execution of integrated renewable energy solutions within current geological formations. An important barrier highlighted in the study is the particular and location-dependent nature of various integration systems. Some RES are naturally linked to specific geographical areas, and their effectiveness depends on the presence of specific environmental conditions. The geographical reliance adds a level of intricacy, making certain integration possibilities unfeasible in areas without the necessary resources. This complexity adds another significant challenge as to the lack of design tools, since unlike conventional GSHP, EG-based systems (especially when combined with other RES) are often unique in terms of geometry, mechanical and geological constraints, so they can be seldom designed based on simplified analytical solutions but typically require bespoke modeling techniques.

Furthermore, the importance of a strong legal framework can be highlighted as a key factor in promoting successful integration. Establishing national standards is crucial for guaranteeing the technical interoperability of various components and for resolving safety issues, conducting environmental impact assessments, and assuring the overall sustainability of these integrated systems. The lack of a legislative framework not only hinders the implementation of such technologies but also creates questions regarding their long-term sustainability. The increasing expenses related to one or more integration points is of highly importance in terms of investments. With the growing number of integrated technologies, the total system becomes more complex, leading to an increased financial investment, with the economic feasibility not only be depended on the initial investment capital but also on the recurring operating and maintenance costs.

Finally, the study acknowledges the complex interaction between technical and non-technical barriers, with the technical challenges generally involving engineering design, and system optimization, whereas non-technical challenges encompassing the economic, social, and policy domains. To overcome these obstacles, it is imperative to foster interdisciplinary collaboration among engineers, policymakers, economists, and other stakeholders, where this collaboration would be essential for the development of comprehensive solutions that take into account both technological feasibility and wider socio-economic implications.

Funding

This article is based upon work from COST Action CA21156 - european network for FOstering Large-scale ImplementAtion of energy GEostructure, FOLIAGE (https://www.ca-foliage.eu/), supported by COST (European Cooperation in Science and Technology).

Contributions

All authors have contributed in: Conceptualization; Methodology; Writing-original draft preparation; Writing-review and editing. All authors have read and agreed to the published version of the manuscript.

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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.

Acknowledgments

All authors gratefully acknowledge COST Action CA21156 - european network for FOstering Large-scale ImplementAtion of energy GEostructure, FOLIAGE (https://www.ca-foliage.eu/). E. Halaj wishes to thank AGH University of Krakow in the scope of the statutory works number 16.16.140.315/05. O. Okhay wishes to thank FCT (Fundação para a Ciência e a Tecnologia) in the scope of the framework contract foreseen in numbers 4, 5, and 6 of article 23 of the Decree Law 57/2016, of 29 August, UIDB/00481/2020 and UIDP/00481/2020; and CENTRO-01-0145- FEDER-022083 - Centro Portugal Regional Operational Programme (Centro2020), under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund.

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