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Combining energy generation and radiant systems: Challenges and possibilities for plus energy buildings

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ABSTRACT

Radiant heating and cooling (RHC) systems are being more widely adopted considering the well-known technical advantages: increased thermal comfort, space saving, and reduced energy use. Since the building sector is currently one of the largest consumers of fossil fuels, many directives and regulations have been enacted to address the intense concern about energy use for space conditioning.

Even though radiant systems are considered as an energy efficient technology for building heating and cooling, more effort is needed to fulfil the zero energy requirements outlined by recent standards and directives. Renewable Energy Sources (RES) are an effective solution to avoid using finite fossil fuels and related geopolitical issues enhanced by the recent world conflicts. Despite being primarily intermittent and subject to economic and regional constraints, RES offer suitable temperature levels to supply low temperature heating and high temperature cooling operation, a major advantage of RHC system.

Although a limited number of studies directly report energy savings or CO_2 emission reduction as the main outcomes of the research related to this combination, valuable insights have been obtained for the present review. Primary energy can decrease between 40% and 80% with different integration of RHC, photovoltaic, heat pumps and district heating. TABS can lead to load shifting up to 100%, allowing an increased self −consumption of renewable energy.

This paper provides evidence on whether coupling radiant systems with renewables is a promising strategy for achieving nearly-zero annual energy balances in building stocks. It investigates recent trends, limitations and potential to support decarbonization goals.

1. Introduction

Currently, many existing buildings are equipped with outdated conditioning systems, possibly inefficiently managed and controlled, contributing to that 40 % of energy use ascribed to residential and office buildings [1,2]. The demand for better indoor environmental quality conditions in new and retrofitted buildings is a challenge for practitioners dealing with the need to drastically cut the energy demand of the building stock [3]. In Europe, building retrofit should meet minimum requirements defined by the single member-states and by the European directives and standards [4,5], contributing to achieving the targets of a 55 % reduction of the current CO_2 emissions and 42.5 % share of RES in the total energy used by 2030 [6]. The estimates on renovation rates, excluding single energy-saving measures, fall within 0.5 % and 2.5 % of the building stock per year. Typically, these rates depict the activity of the recent years across Europe, where the current renovation rate is 1 % on average, thanks to special renovation programs [7]. Furthermore, despite the renovation programs, the global energy consumption related to the residential sector is expected to increase worldwide by an average of 1.4 % per year from 2012 to 2040. This increment is due to economic growth and rising living standards that lead to the construction of new buildings. In the U.S., for example, the government expects 40 million new homes and about 5580 km^2 of commercial floor space to be constructed before 2050 [8]. To reduce the environmental impact of such growth, new technology and concepts are coming into place to push the yearly energy balance between used and on-site produced renewable energy from nearly zero (nZEB) to Net zero (NZEB), and now, with the

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Nomenclature

ASHP	Air Source Heat Pump
BIPV	Building Integrate Photovoltaic
BIRC	Building Integrated Radiative Cooling
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
DHW	Domestic Hot Water
EPBD	Energy Performance of Buildings Directive
GHG	Greenhouse Gas Emissions
GCHP	Ground Coupled Heat Pump
GSHP	Ground Source Heat Pump
HTC	High Temperature Cooling
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
LTH	Low Temperature Heating
nZEB	nearly Zero Energy Buildings
NZEB	Net Zero Energy Buildings
PAC	Packaged Air Conditioning
PCM	Phase Change Materials
PEB	Plus Energy Building
PV	Photovoltaic
PVT	Photovoltaic Thermal Panel
RES	Renewable Energy Sources
RHC	Radiant heating and cooling systems
TABS	Thermally Activated Building Systems

latest development, aiming for plus energy (PEB) [9]. Besides the local production of renewable energy, a positive balance requires a substantial reduction of the consumption, which could be achieved by implementing passive solutions (e.g., envelope insulation) and improving the performance of heating, cooling and ventilation systems (HVAC). The implementation of low temperature heating and high temperature cooling systems is a step in this direction [10]. Compared to other conventional conditioning systems, radiant heating and cooling (RHC) present several advantages for what concern thermal comfort, adaptability to design integration with building elements, increased indoor environmental quality (IEQ), and space saving, but most of all, they are applied to enhance energy conservation through energy efficiency in buildings [11,12]. These systems can also take advantage of the building's thermal mass, attenuating fluctuations and shaving heating and cooling peak loads. If properly controlled, they can shift the demand to night-time [2,3]. The Coronavirus pandemic crisis in 2020 revealed another advantage of RHC systems. In fact, they can provide heating and cooling without emitting air, forestalling the spread of the infection [13].

The first directive that promoted the installation of energy from renewable sources was Directive 2009/28/EC [2], which linked the increased energy efficiency to the expanded application of renewables to supply electricity or thermal energy. Several amendments lead to the latest version, the Directive 2024/1275 [14] that enhances the need for energy efficiency of buildings and the reduction of greenhouse gas emissions aiming to achieve a zero-emission building stock by 2050. Built on the Fit for 55 legislative package [15] and the REPowerEU plan [16], the directive highlighted the importance of renewable energy sources to improve buildings' performance towards a significant reduction of GHG emissions. Despite being primarily intermittent and subject to economic and regional constraints, renewable energy sources (RES) offer temperature levels suitable for low temperature heating (LTH) and high temperature cooling (HTC), which is a major characteristic of RHC systems [17,18]. Hence, since the combination of RES and RHC has been demonstrated also from a thermodynamic perspective by Kazanci et al. [19], this approach can be part of a strategy to decrease the combustion of fossil fuels further and reduce carbon emissions.

Studies usually present radiant systems coupled with heat pumps, both air-source or ground-source, comparing different system configurations [20], defining limitation and barriers [21,22], providing experimental case studies [23] or comparing the coupling with traditional radiant systems and TABS [24] or other air conditioning solutions [25]. Among the renewable energy sources, solar panels are often presented as single source [26,27] or combined with heat pumps to be used as alternate low temperature source to increase the efficiency [28]. When radiant systems are combined with a heat pump, renewable electric energy is often provided by photovoltaic panels.

Within the driving factors behind the increasing interest in these technologies is the advantage of providing low temperature heating during the winter season and high temperature cooling during the summer season. In this context, this review paper shows the critical importance of developing diverse and integrated energy efficiency solutions; however, it is necessary to focus not only on the optimization of energy efficiency of new buildings but also to address the overall energy needs of existing constructions throughout their life-cycle and explore their decarbonization potential. The objective of the literature review proposed is to analyze different studies presenting the effective combination of RHC with RES. By doing this, this work provides a unique perspective to highlight benefits, limitations and best practices for the implementation of the presented approaches for enhancing energy efficiency and sustainability in the next generation of NZEB and PEB. Furthermore, the present work explores novel strategies to maximize self-consumption and reduce reliance on both the electric grid and natural gas (or other fossil fuels), paving the way towards net-zero or even positive annual energy balance, thus to more sustainable building construction, operation and management.

2. Review approach

Literature review started considering a wide coverage of papers. Thus, several search engines have been used: Scopus [30], Science Direct [29] and Web of Science [31].

The starting point regards the reasons that lead to the combination of radiant systems and renewable energy sources as preferable solution to increase energy efficiency and reduce the energy use for space heating and cooling. The papers collected and integrated in the review tried to answer to specific research questions:

- What are the main advantages and drawbacks of the current applications of radiant heating and cooling systems?
- What are the most suitable characteristics of renewables for the combination with RHC?Are the savings achieved by combining these systems significant compared to traditional systems? Are the operating costs of the buildings also reduced?
- Do they support the transition towards nZEB or PEB?

Initially, general keywords were used trying to cover all the possible typologies of RHC systems. The used keywords were: "radiant systems", "radiant heating and cooling systems", "low temperature heating", "high temperature cooling", "radiant floor", "radiant ceiling", "radiant walls", "Thermally activated building systems", "TABS". This first research performed on keywords and abstracts resulted in 607 publications. A second step was performed by adding the general keywords "Renewable Energy Sources" OR "RES" OR "Ground source heat pumps" OR "Photovoltaic" OR "Solar panel", which were checked in the entire paper to keep only the literature that even in a marginal way dealt with the integration of these technologies. The search resulted in 134 publications. From the list, after a first check consulting the abstract and the main goals, papers not directly related to the research were removed, whereas the others have been studied more in detail and grouped under two categories: i) Integration between RHC systems and a single RES; ii) Integration of RHC systems with multiple RESs.

Recent important case studies reporting calculations have been considered a part of the literature to provide evidence of the relevance of the system proposed with up-to-date developments. Critical standards and handbooks were also considered to describe the background of the research and further useful suggestions to overcome current limitations. The review has been structured in two primary sections: the application of radiant systems technologies, as a recap of the technology's benefits and limitations to understand better the second part dealing with the current status of coupling strategies between radiant systems and renewable energy sources. Fig. 1 shows the flowchart of the methodological approach.

3. Current applications of RHC systems

3.1. Radiant heating and cooling systems

Radiant panels owe their name to the definition of "panel warming" given by Barker et al. in the 1908: "small hot water pipes embedded in plaster or concrete" [33,34]. Current applications of active radiant heating and cooling systems mainly refer to water-based terminal units embedded or integrated into materials such as plaster, concrete, or other kinds of material, characterized by extensive surfaces that account for over 50 % of total heat exchange within a conditioned space [35]. RHC systems can be categorized based on the position of the radiant surface, their integration within the building structure, and type of heat transfer fluid employed. Referring to the position of the pipes in the building, they are commonly divided into (i) embedded surface systems, (ii) thermally activated building systems, and (iii) radiant panel systems [36]. According to the type of installation, radiant systems can be dry or built-in place (wet systems). RHCs have been widely applied for space conditioning both for residential and non-residential buildings, although with different heat medium and operating temperatures depending on the end use (i.e. gas-fired radiant heating or superheated water radiant systems) [37]. As extensively reviewed by Rhee et al. [11], experimental measurements and subjective surveys demonstrated that the use of radiant heating systems ensures minimal air movement, reducing the risk of draughts and dust disturbance [37], as well as more uniform room temperature [38]. The comfort achievable with RHC is equivalent to that of other conditioning systems – according to Karmann et al. [39] even higher – while operating at lower temperatures for space heating and higher temperatures for space cooling [40,41].

Radiant systems are often referred as low exergy systems [19,42], because they operate at lower temperature differentials compared to traditional air conditioning equipment. This concept is particularly beneficial when considering the generation of thermal energy: the coupling with a heat pump is more favorable compared to a boiler or in the case of cooling compared to a traditional split system, thus enhancing the integration of renewable energy sources. Schmidt and Kassel [43] highlighted how floor heating systems requires less exergy with respect to radiators to heat the same room, being the water temperature closer to the one of the environment. Kazanci et al. [44] calculated the exergy use of different heating systems: floor heating, radiators, and warm-air heating. Radiator systems' exergy consumption increases with the increasing of average water temperature, whereas radiant floor heating system has the lowest exergy consumption.

In addition, the radiant heat transfer coefficient can be regarded as constant, approximately 5.5 W/(m^2 K) for a surface temperature between 15 °C and 35 °C, whereas the convective coefficient may change between 0.3 to 6.5 W/(m^2 K), depending on the surface position and temperature [41], thus influencing the heat transferred within the room

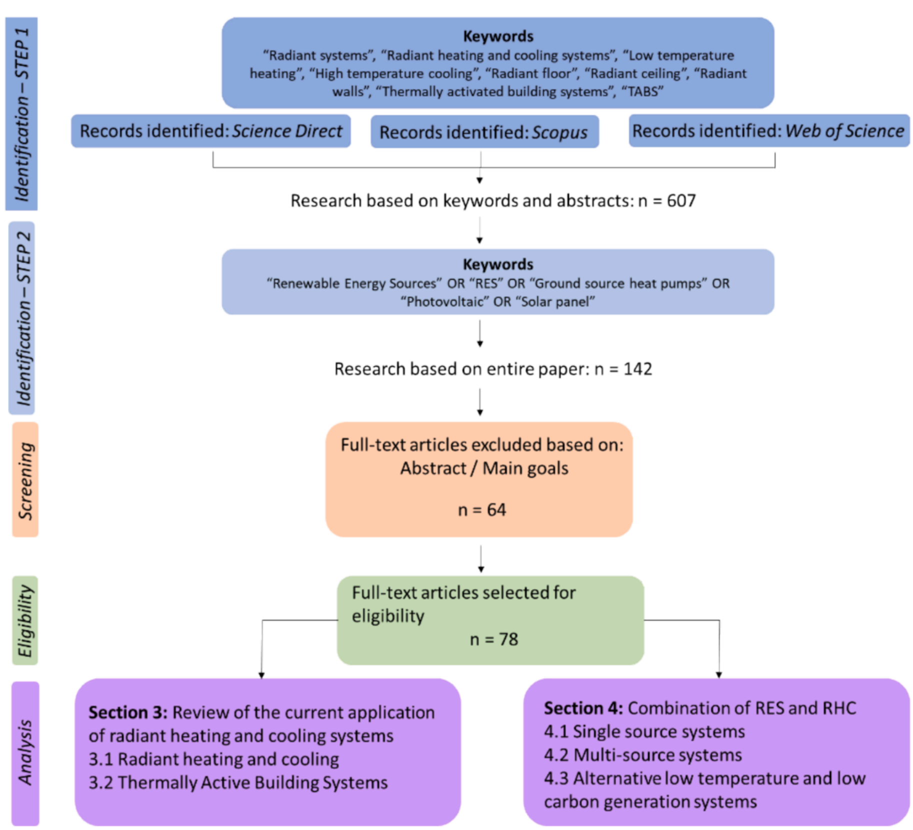

Fig. 1. Flowchart adapted from the PRISMA guidelines [32] for the literature review database creation.

volume [45].

In cooling operation, radiant systems take advantage of both radiant and convective heat transfer, but surface condensation has to be avoided; in particular relative humidity and air temperature must be controlled [46] and latent loads together with air quality need to be assigned to ventilation systems [47]. Márquez et al. [48] compared different management strategies for a hydronic heating system combining radiant floor and fan-coil in the same thermal zone. They showed that the radiant floor has the lowest energy use with respect to fan-coil and integrated system (radiator and fan-coil working together). Moreover, the discomfort level during the first operating hours can be solved by activating the radiant system in advance, increasing the energy use by 6.1 %. In fact, as shown by Qi et al. [49], thermal response and performance of floor radiant heating systems can be enhanced applying optimal control strategies.

Radiant panels can be used also as passive cooling strategy that exploit night free cooling, avoiding or reducing the use of energy consumption by air conditioners. Pirvaram et al. [50] simulated a three-story commercial building of medium size (i.e., rooftop area 1600 m^2) with Energy Plus to determine the hourly cooling load over a year in Phoenix, Arizona, USA. The cooling systems installed were radiant cooling panels and an air conditioner (COP 2.8) to satisfy the remaining load. They obtained an annual projected electric energy savings up to 1.185×10^5 kWh, due to the reduced use of the air conditioners. Fig. 2 shows the summary of the main characteristics of radiant heating and cooling systems.

3.2. *Thermally activated building systems (TABS)*

As presented by Rhee et al. [11], the application of radiant systems increased in the past fifty years also thanks to the capacity of exploiting energy storage in structural floors and slabs, and the consequent ability to shave and shift daily peak loads [10]. TABS consist of small pipes carrying hot or chilled water (or other fluid) embedded into the building thermal mass. In the operational phase, there is an average 3 to 5 K temperature differential between the fluid's supply and return, based on the design and application. The possibility of decoupling the conditioning plant operation and thermal loads by storing heat in the structures (or cooling it down) allows the distribution of heating and cooling loads in more extended periods [51]; therefore, when integrated in the overall energy strategy of a new or renovated building, TABS can effectively shift heating and cooling loads to off-peak hours, optimizing energy generation, usage and costs [52]. German et al. [53] simulated high performance residential buildings equipped with TABS in hot-dry climates. The analysis estimated a peak load reduction from 47 % to 88 % and load shifting up to 100 % [53–55] on a daily basis. Additionally, flattening the peak heating or cooling loads lowers investment and operating costs and allows for smaller plant sizes [56].

Structures with embedded TABS can use also phase change materials (PCM) to enhance their thermal capacity or PCM can be embedded into radiant ceiling panels for obtaining similar benefits to TABS, which can be beneficial in renovation or in new light-weight buildings [57]. Daytime load exposure permits the melting of the PCM integrated in ceiling panels, which can be cooled overnight by the integrated water pipes. The thermal storage process attenuates the temperature fluctuation in the building following an asynchronous process, meaning that in cooling mode the rejection process of the stored heat occurs at different times than when the heat is gained [58]. Mazo et al. [59] validated a one-dimensional model for a single zone with a radiant floor system with PCM supplied by a heat pump. The case study was a located in a mild winter weather zone, showing an energy reduction of 18 % mainly due to the shifting of the electric energy demand to the off-peak period. A 4 % to 8 % saving for space heating and cooling was reported also by Cesari et al. [60], who implemented a control strategy for PCM management to enhance radiant floor systems in lightweight buildings based on forthcoming weather conditions.

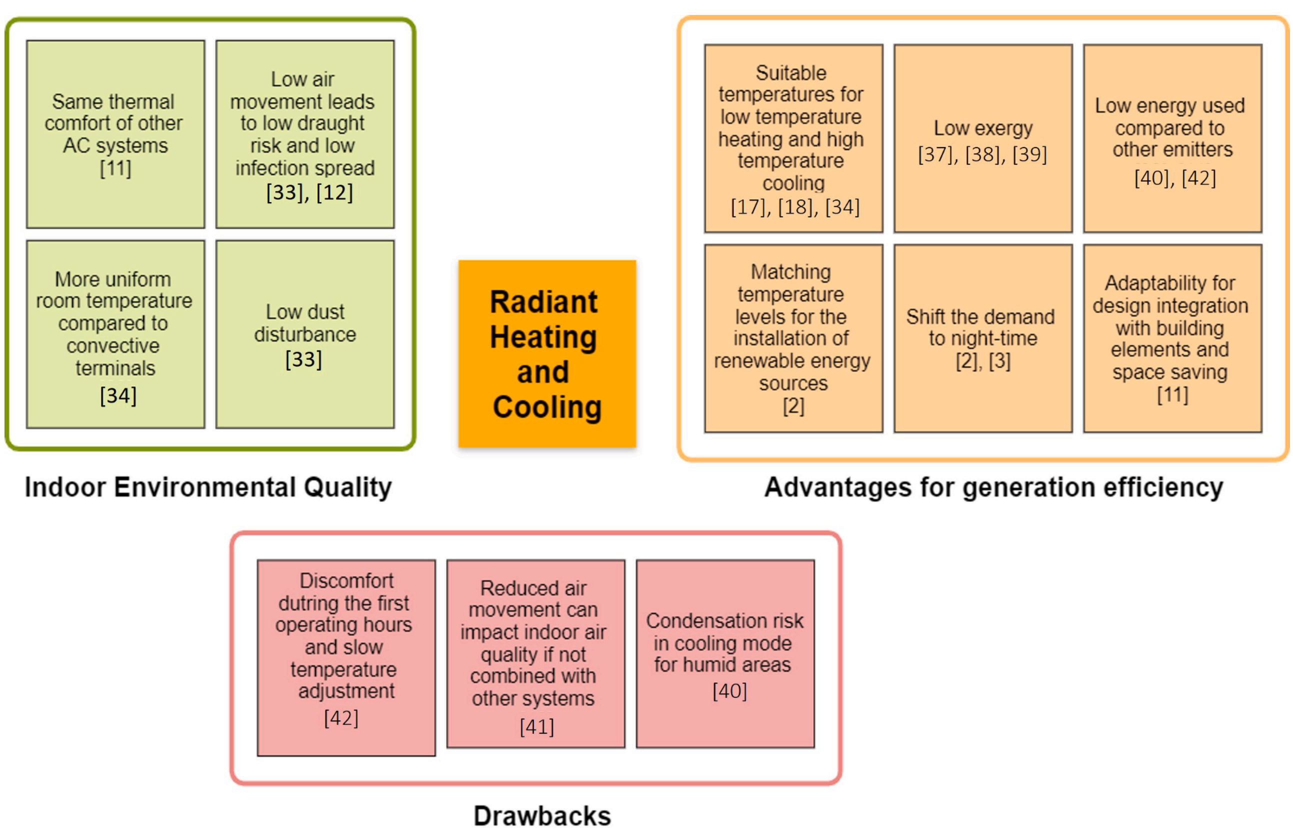

Fig. 2. Flowchart of the main characteristics of RHC panels.

Table 1 summarizes the main advantages of the use and integration of TABS.

4. Coupling RHC and RES

The integration of RES with the demand is strongly impacted by the nature of the renewable generation – unpredictable, variable, and intermittent – and that of the market, as reviewed by Sinsel et al [61]. These limitations become particularly evident when looking at the operational frequency demand of HVAC systems. This issue, which could have an impact also on the use of RHC, could be overcome by utilizing thermal mass or water tanks for energy storage. This makes radiant systems particularly suitable for the integration of RES in the building sector.

The electrification of the heating demand with the use of heat pump found an optimal application in the use of radiant systems due to their low temperature operation that maximizes the COP. This, combined with local renewable electricity generation, makes a promising strategy for Plus Energy (PEB) or even Zero-Emissions Buildings. Additionally, the COP is further increased if heat pumps utilize the ground as a renewable heat source or sink [62,63].

The following literature analysis is divided according to the combination between RHC and renewable energy sources: single, multiple, and less consolidated technologies.

4.1. Single source

Active measures for high-performance solutions combine more often a single renewable source with a generation system to provide adequate space heating, cooling, and DHW production. Usually, biomass boilers or solar thermal collectors are installed to cover DHW demand and partly contribute to space heating, while PV systems or wind turbines are used to supply electricity for heat pumps.

Romaní et al. [64] studied an optimization of the control strategy for a heat pump coupled with a PV array to supply hot water for a radiant wall. Working on the peak load shifting and use of the wall as thermal storage, the authors reported an operational cost reduction of 46 % compared to the solution without PV. Ren et al. [65], in an attempt to maximize the impact of the combination of RES with radiant systems, developed a numerical model of a new type of low temperature radiant device. The system reduced the operating temperature thanks to an enlarged equivalent heat transfer area. According to the results of the analysis, a supply water at 22 °C in winter and 17 °C in summer is sufficient to meet indoor thermal requirements. This is 15 to 20 °C less than traditional supply water temperature for heating and 10 °C higher for cooling. For the heating use, the authors considered the application of flat solar panels, increasing the solar energy utilization efficiency up to 40 %. The implementation of roof passive cooling panels, which are cooled based on the nocturnal radiation, was also analyzed; authors claimed that, during clear nights, cooling can be directly achieved through radiation to the sky. Several authors worked on geothermal as a non-intermittent source of renewable energy for the heat pump water exchange. Within the RES, shallow geothermal energy is the most studied application for direct heating or indirect heating and cooling. Among the advantages, low temperature geothermal sources are widespread, making them a renewable energy resource with broad availability [66]. Compared to air source heat pumps, whose operation is highly dependent on outdoor air temperatures, ground source heat pumps (GSHP) can take advantage of the constant temperature of the ground to heat a medium, usually air or water depending on the application, providing high COP values. Huide et al. [67] and Floride et al. [68] indicated that the temperature of the ground remains stable and warmer in winter and cooler in summer than the surrounding ambient air [59]. Pacchiega et al. [69] investigated GSHP and more traditional air-to-water heat pumps coupled with radiant floors operated with fixed outlet water temperature. Both technologies have been tested with two control strategies: on–off and modulated. Fig. 3 shows that among the different solutions analyzed, the combination of RHC and inverter-driven GSHP can provide the highest percentage of primary energy from RES. However, the inverter-driven air-to-water heat pump could potentially be the optimal solution from a cost-benefit perspective because of the lower initial investment cost.

Among the advantages related to the additional floor space allowed by the absence of extensive mechanical equipment and the more continuous operation, TABS recently gained renewed interest because of the promising results showed when coupled with low-grade energy sources (i.e., RES) [70], both for space heating and cooling and to improve indoor thermal comfort by reducing the heat transfer with the outdoor environment [71]. Chung et al. [72] worked on a comparison between load-handled ratio with a typical TABS control strategy, and TABS combined with a horizontal ground system. The authors showed that during hot weather periods, the ground temperature is too high for effective free cooling. Despite this, free cooling can still achieve a maximum peak load reduction of 75 %, significantly higher than the 32.4 % reduction achieved by the standard system with a chiller.

The case studies monitored within the H2020 GEOTABS project [73] proved that the integration of GSHP and TABS properly combined with model predictive control strategies allows 32–48 % of electric energy savings during the weekly HVAC operation of an office building, and CO_2 emission reduction of 38 % [74].

Romanì et al. [23] evaluated the performance of a radiant wall heating system coupled with a ground source heat pump in a house-like prototype scale, under outdoor conditions. In continuous operation,

Table 1
Summary of the main advantages of TABS installation.

Characteristic	Related advantage	Reference
Exploitation of thermal mass	Reduce peak loads up to 88 %, thus the related systems' size	[11,52,55]
Distribution of heating and cooling loads through longer periods	Possibility to optimize schedules for the use of renewables	[50]
Shift the peak load to off-peak hours (up to 100 %)	Reduce operation costs	[51,53]
	Reduce energy use (e.g., about 18 % if coupled with a heat pump in a mild winter climate)	[58]
Integration with phase change materials (PCM)	Enhance thermal capacity	[51]

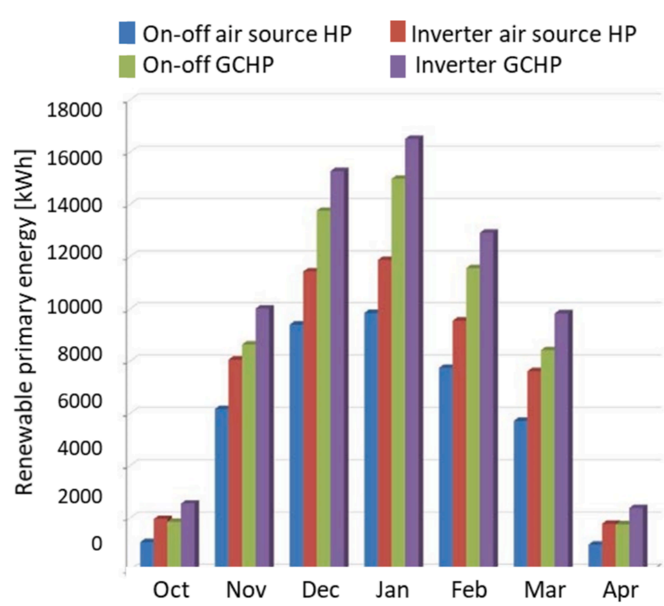

Fig. 3. Renewable monthly primary energy need, $Q_{p,ren}$ [69].

they demonstrated that energy savings can be between 19.9 % and 40.7 % compared to a conventional air source heat pump depending on the setpoint temperature and the schedule of operation. As a drawback, the asset used for the test demonstrated the peak load shifting capacity but also a slow response time, which can be improved with proper control.

Harnessing low-temperature resources enables the use of significantly less energy to provide space heating for buildings compared to radiators or other high-temperature sources. De Carli et al. [75] used TRNSYS simulations to prove that the use of closed loop ground source heat pumps to supply low temperature heating and high temperature cooling systems can provide a reduction of primary energy use up to 60 % with respect to traditional systems.

The ground as a thermal source or sink was only recently recognized as a renewable source in Europe. In fact, before only the use of ground as a thermal source was considered renewable [2]. Romanì et al. [23] conducted an experimental campaign on a house-like cubicle built with an embedded radiant wall system coupled with borehole heat exchangers, analyzing the impact of set-point temperatures, operation schedules, and wall thermal storage capacity on the cooling load management. In continuous operation, a radiant wall cooled by a ground-coupled heat exchanger achieved energy savings of up to 54 % and 82 % compared to a conventional air-to-air heat pump (with setpoint temperatures of 24 °C and 26 °C, respectively). Borehole temperatures represented a limit in the case of free cooling, requiring higher water flow at lower set-points due to a smaller gradient between supply and room temperatures. Intermittent operation schedules also influenced the performance of radiant walls, because interactions with the system's thermal inertia could negatively impact energy consumption.

4.2. Multi-source systems

Although most of the renewable based solutions installed nowadays deliver energy from a single generation source, to minimize fossil fuel dependence and achieve 100 % renewable energy self-sufficiency, it is necessary to combine energy sources in dual- or multi-source systems. In this way, it is possible to achieve zero energy or plus energy buildings criteria together with CO_2 emission reduction goals. In general, most of the strategies to increase the penetration of RES focus on the electrification of the needs, which can be supplied either by local renewables or can exploit the renewable fraction of energy of the national mix.

To maximize the use of RES, Cavazzuti et al. [76] investigated different heat pump control rules to provide heating and cooling to a radiant floor incorporating phase change materials (PCM), supplemented by fan coils for humidity control. The heat pump was supplied by three parallel circuits that combine different sources: air through an ordinary air-to-water heat exchanger, sun by PVT panels, and finally ground by means of shallow ground heat exchangers, which can be also used as thermal energy storage if the heat pump is not operating. A primary energy saving of 16 % was estimated compared to the single source existing at the state of the art; however, results depend on the surface availability to install the ground source field and the balance between heating and cooling loads of the case study. Zanetti et al. [77] implemented a numerical model of a hybrid heating system that consists of radiant floor, gas boiler and photovoltaic-assisted air source heat pump (ASHP) as heat source, with a water tank as thermal energy storage. The simulation results indicate that an optimal energy management strategy can reduce the operational costs by 20 % compared to traditional control rules, while boosting photovoltaic self-consumption by 30 %. Therefore, the increasing integration of multi-source heat pumps to enhance the development of plus energy buildings requires the development of control strategies for the optimal selection of the thermal sources involved, based on the most favorable environmental conditions, the thermal load prediction, storage size and availability.

Kazanci et al. [78] proved that a well-designed combination of electrical and thermal part could lead photovoltaic/thermal (PVT) technology to achieve very high effectiveness with respect to other conventional systems that use photovoltaic and solar thermal collectors separately. The optimal combination of a dry radiant system, PVT cooling and a ground source heat pump increased the overall efficiency of the system, and the energy savings compared to more conventional technologies; however, initial investment costs may be an issue. Other than domestic hot water, solar heat can be utilized as integration for building space heating, for example increasing the temperature at the heat pump's evaporator, recharging the borehole, or a combination of these functions. Due to the complexity of these systems that integrate ground-source heat pumps with solar collectors, establishing general results or design guidelines can be difficult; to the authors' knowledge, there are not specific works on these solutions combined with RHC that provide results in terms of energy savings.

Table 2 presents additional examples of studies where various types of radiant heating systems have been coupled with renewable energy sources. It highlights the energy saved and the percentage of energy supplied by renewables. The installation of radiant heating/cooling as the indoor heat emission/removal system allows a suitable matching of temperature levels with many RES, and potentially offers the possibility of utilizing "free cooling".

4.3. Alternative low temperature and low carbon generation systems

Under this section we report the integration of less-common RES and RHC technologies.

PCM is a technology that is consolidated from a research point of view but it still a niche in the market. Pavlov et al. [52] showed that the temporary storage of high- or low-temperature energy through PCM can increase the building storage capacity, controlling the temperature and reducing temperature fluctuations.

Bourdakis et al. [85] evaluated the potential of night sky radiative cooling using photovoltaic/thermal panels (PVT) and a combination of night-time ventilation and radiant ceiling panels with PCM. Radiative cooling (RC) panels have been studied also by Zhao et al. [86], who proposed a mixed configuration with building integrated photovoltaic (BIPV) obtaining an output of 79.1 % and 16.8 % higher than BIPV and BIRC (Building Integrated Radiative Cooling) systems alone, respectively. Hu et al. [87] introduced a hybrid photovoltaic-photothermic-radiative cooling system to supply diurnal electric energy, space heating, and nocturnal cooling energy. The efficiency of the system has been estimated for different conditions obtaining promising outcomes for building applications. An integration between solar thermal collectors and radiative systems has been studied also as hybrid HVAC for single-family houses by Yoon et al. [88]. This combination has shown an energy efficiency ratio (EER) of 27.3 % higher compared to solar-assisted heat pumps, and COP 61.8 % higher compared to the performance of radiative-cooling-assisted heat pumps. Other applications of radiative cooling can be found in literature within the photovoltaic cooling technology and nighttime PVT cooling.

The current need to move from the single-scale building perspective to urban scale scenarios, offers a great potential for innovative technologies. The development of a model describing the dynamic operation of RES coupled to RHC systems could be used for the application of a sensitivity analysis to optimize design parameters and operating schedules, controlling the energy demand of the buildings and predicting the behavior of an energy network. For the same reason, it is possible to consider the application of water and underground materials as energy storage systems. Further steps in research should aim to reduce costs to improve competitiveness, especially in regions that have high solar availability.

A final unusual combination of technologies comes from the integration of RHC and ceiling fans. In fact, during the cooling period, ceiling fans can provide comfortable conditions for users at higher indoor temperatures. A higher indoor temperature together with the air movement caused by the ceiling fans increased the heat exchange between the RHC and the room air potentially enabling energy savings and

Table 2
Summary of some case studies coupling renewables with LTH and HTC systems.

Reference	Type of study	System	Energy saved	RES contribution
Li et al. [79]	TRNSYS simulation	Building integrated solar thermal shading (BISTS)	–	64.4 % heating 20.2 % cooling
Buonomano et al. [80]	TRNSYS simulation	Building integrated Photovoltaic and Thermal collectors (BIPVT)	Yearly primary energy savings 39 %	–
Bojić et al. [81]	EnergyPlus	GSHP and PV combined with floor-ceiling radiant heating	Final energy use decreased by 87 % Primary energy use decreased by 48 %	- PV array covering the full roof (120 m^2) - 20 kW (GSHP) compared to the operation of a gas boiler of 24 kW
De Carli et al. [75]	TRNSYS EED	District heating and cooling coupled with closed loop GSHP	Primary energy use decreased by 50–60 %	All the energy required by the building
	TRNSYS EED	District heating and cooling coupled with closed loop GSHP and PV array	Primary energy use decreased of 70–80 %	–
Wang et al. [82]	Experimental study	GSHP coupled with solar seasonal thermal storage	Significant reduction of the required electricity	Fraction of the heating demand covered: - 49.7 % with solar collectors - 50.3 % with GSHP
Bogatu et al. [83]	TRNSYS simulation	PVT collectors	- PVT employed for heat, electricity production and cooling purposes exploiting night radiative cooling - Specific cooling power ranging from 35 to 70 W/m^2 for a supply temperature of 21 °C	coverage ratio of cooling energy use ranging from 55 % to 120 %
Park et al. [84]	Simulation study	TABS supplied by GSHP combined with radiant floor and packaged air conditioning	- GSHP consumed only 36 % of the energy compared to the PAC	–

higher heat pumps efficiency as discussed by Guo et al. [89] and Karmann et al. [90].

5. Discussion

The achievement of nearly zero (nZEB) or Net zero (NZEB) energy buildings is considered one of the key strategies for European decarbonization and inevitably requires the integration of renewable energy sources with passive solutions. Although these solutions are effective for new buildings that have been designed with the main goal of minimizing the overall energy use based on their specific end use, the majority of the European building stock already exists. Therefore, the first goal should be the reduction of the baseline energy demand through specific retrofit actions and combine suitable and efficient active measures according to the characteristics of the construction and the location.

The results obtained from this literature review indicate that the radiant heating and cooling systems are a suitable solution both considering the flexibility of installation options and in terms of compatibility with different renewable energy sources, thanks to their operating temperatures. LTH and HTC can ensure the necessary indoor thermal comfort if correctly sized based on outdoor climatic conditions and specific end-use; however, the combination with ventilation systems is needed for proper indoor air quality and to address latent cooling loads, which can potentially cause condensation in humid environments.

TABS technologies can further enhance the coupling with renewable energy sources, because of the exploitation of building thermal mass and eventually the integration with PCM can modulate peak loads, thus potentially increasing the self-consumption of photovoltaic or solar panels combined with heat pumps during the periods of high solar radiation. Peak load flattening allows also the reduction of the systems' size, thus decreasing the investments costs towards a more sustainable and affordable business model. These strategies should be optimally seen also in terms of shared systems such as district heating and cooling networks or energy communities: the application of predictive models to such systems can enhance their overall efficiency for wide scale energy optimization and GHG reduction.

Depending on the type and the resource availability of the case study, there are many approaches that can be implemented to obtain an annual net-zero or even positive balance of energy use, where more energy is produced than consumed, and GHG emissions are minimized. However, further studies are needed to improve the state of the art of RHC system operation in highly-insulated buildings; the thermal inertia of these systems, which can cause discomfort during the initial operating periods and does not allow rapid control of room temperatures, may affect their application in favor of more flexible air-based systems, although more demanding in terms of installation space.

6. Conclusion

This literature review was performed to assess whether the coupling of low temperature heating and high temperature cooling radiant systems with renewable energy sources is a promising strategy for enhancing energy efficiency and sustainability in buildings, supporting the development of constructions with almost net-zero annual energy balance and greenhouse gas emission. There are several studies in literature that explore this combination, however most of them focus on comfort and regulation or optimization strategies rather than energy savings or CO_2 emission reduction.

The integration of radiant heating and cooling systems and renewable energy sources presents a dual benefit: it can directly harness thermal energy and facilitate the electrification of energy demands. When combined with heat pumps, for example, they can mitigate peak energy demand, enhance grid resilience taking advantage of solar energy or passive solutions or integrate TABS and PCM for resilient building operation

Some of the main findings are as follows:

- When radiant systems are coupled with ground source heat pumps, energy savings compared to air-source coupled systems is between 20 % and 41 %, and up to 60 % of primary energy savings compared to traditional systems.
- The combination of radiant systems and heat pumps supplied by photovoltaic panels provide an operational cost reduction of 20 % to 46 % compared to the operation without PV generation.
- The application of optimal energy management strategies can increase photovoltaic self-consumption by 30 %.
- TABS integrated with a horizontal ground system shows that a maximum peak load reduction of 75 % can be reached exploiting free cooling; this outcome is even more relevant if compared to the 32.4 % obtained using a chiller.
- Radiant systems integrated with PCM and supplied by a heat pump, can shift the electricity consumption to off-peak periods, leading to an energy use reduction of 18 %.
- Although some assets of RHC and RES demonstrated a peak load shifting capacity, they could be slow in regulating the room temperature compared to more conventional convective systems, and therefore RHC systems require a proper control strategy that is different than those used for conventional systems.
- Unconventional technologies (such as PCM, building integrated PV, etc.) and ground source heat exchangers often present some limitations in terms of initial investment costs, therefore their feasibility should be considered with whole life cycle cost approach.

Emerging technologies, such as advanced heat recovery systems, next-generation photovoltaic technologies and thermal storage systems offer additional solutions for innovation. These innovative technologies offer the potential for enhanced efficiency, improved performance, and expanded capabilities for integrating radiant heating and cooling systems with renewable energy sources. Again, the main outcomes of recent studies can be explored by stakeholders to integrate these new technologies into plus energy building designs and retrofit projects, paving the way for more sustainable and resilient built environments and facilitating the transition towards energy-positive buildings or districts.

CRediT authorship contribution statement

Laura Carnieletto: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Ongun B. Kazanci:** Writing – review & editing, Methodology, Conceptualization. **Bjarne W. Olesen:** Writing – review & editing, Conceptualization. **Angelo Zarrella:** Writing – review & editing, Methodology. **Wilmer Pasut:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: 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. The last author is the guest editor of the special Issue and may be involved in the management of the review process.

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Data availability

No data was used for the research described in the article.

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