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DYNAMIC SIMULATION OF GROUND-COUPLED HEAT PUMPS (GCHPS): INSIGHTS ON THE ECONOMIC CONVENIENCE AND ON THE ENVIRONMENTAL BENEFIT

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ABSTRACT

Ground-coupled heat pumps (GCHPs) are sustainable solutions for heating ventilation and air cooling (HVAC) which allow a strong reduction of primary energy use, CO2 emissions, and operational costs. The large installation cost is a strong barrier to their diffusion. We present a study which identifies such cases, based on integrated building-HVAC-GCHP dynamic simulations carried out with the software TRNSYS. Three building types were simulated - a detached house, a hotel, and an office building - considering highly-insulated and lowly-insulated building envelopes. Six locations were chosen to simulate climates ranging from warm Mediterranean to cold Scandinavian.

The results allow to identify key parameters which influence the economic viability of GCHP systems, such as the full load equivalent hours of the heat pump. The return on investment of geothermal heat pumps is still critical, as payback times range from 8 to 20 years. To reduce the initial investment, hybrid heat pump-gas boiler configurations can be adopted, where the heat pump covers the base demand and a backup gas boiler is used to cover peaks.

The ratio between electricity price and fuel price is another key parameter, since it influences the saving margin and hence the profitability of installing a heat pump. Net present values can dramatically be increased acting on the electricity price, e.g. reducing taxes. Finally, the environmental benefits of GCHP and hybrid systems were assessed.

KEY WORDS: Geothermal heat pumps, HVAC systems design, TRNSYS

1 INTRODUCTION

Heating, ventilation and air cooling (HVAC) of buildings account for 30 - 40% of global energy demand [1] and approximately 30% of energy-related greenhouse gas (GHG) emissions [1]. For this reason, introducing low-carbon technologies in this sector is vital for the fight against climate change. Geothermal heat pumps (GHPs) are one of the least carbon-intensive technologies for heating and cooling of buildings [2]. Compared to air source heat pumps (ASHPs), they are more efficient, since the ground has a stable temperature which is usually warmer than air during winter and cooler during summer. GHPs can exchange heat directly with groundwater or by circulating a water-antifreeze mixture through pipe loops buried in the ground (ground-coupled heat pumps, GCHPs). The pipe loops of GCHPs can be arranged in different ways, the most commonly adopted being the borehole heat exchanger (BHE). The main drawback of BHE systems is the high cost related to borehole drilling and installation. An accurate assessment of thermal loads and their time trends is therefore vital to avoid under or over-sizing of GHPs. The best approach to fulfil this task is to carry out a dynamic energy simulation integrating the building and the HVAC system [3]. Different models are available, among which the TRNSYS suite, which offers a large number of libraries for the simulation of energy system components (Types) linked through input and output variables.

This paper addresses the use of GCHPs in different building typologies and climates across Europe, through a series of dynamic TRNSYS simulations on benchmark buildings in different climates. The building energy model developed in TRNBuild allowed the sizing of the heat pump-BHE system and the subsequent simulation with the TRNSYS suite. The results of these simulations were processed to derive indicators for the energy, economic and environmental performance of GCHPs in different contexts. Since the initial investment proved to be a relevant barrier, the use of different hybrid heat pump-gas boiler configurations is also evaluated to reduce the installation cost of GCHPs.

2 METHOD

Building-HVAC integrated models were simulated with TRNSYS 16.0 (TRaNsient SYstem Simulation tool) to assess GCHP systems in different building typologies and climates across Europe. The GCHP systems were analysed in terms of energy use, installation cost, operation savings and environmental impact.

A total of 36 models were developed considering combinations of: 3 different building types, i.e., a single family detached house (House), a small two-storey office building (Office) and a Medium size multi-storey hotel (Hotel); 6 climate zones (Table 1); and 2 thermal insulation levels (i.e., poor and good). Each building destination is characterized by a different occupancy level, air change schedule, temperature setpoint and use of the HVAC system. The climatic conditions influence the thermal needs of the building and, thus, the cost effectiveness. Six European cities were chosen as representative of the five climate zones defined by Tsikaloudaki et al. [4] and an additional one (*F*) identifying very cold climates with virtually no cooling needs (Table 1).

Table 1 Studied cities for each European climate zone. (HDD: Heating Degree Days, CDD: Cooling Degree Days, defined by Tsikaloudaki et al. [4] with Meteonorm temperature data).

Climate zone	Average annual temperature	HDD	CDD	City
A	18.18 °C	920	986	Seville, Spain
B	13.98 °C	2115	649	Bologna, Italy
C	16.81 °C	914	480	Lisbon, Portugal
D	11.26 °C	2743	239	Belgrade, Serbia
E	9.42 °C	3172	41	Berlin, Germany
F	5.31 °C	4632	0	Stockholm, Sweden

Furthermore, the effect of low or high thermal insulation was accounted for, assuming two different envelopes: Good insulation, in compliance with Ref. [5] (i.e., transmittance of external walls below 0.3 $Wm^{-2}K^{-1}$), and the latter to have Poor insulation, representative of sixties' buildings, as per the TABULA project [6] (e.g., transmittance of external wall equal to 1.60 $Wm^{-2}K^{-1}$). Geothermal heat pumps are on-off and reversible. The GCHP system was first sized to cover peak loads, although this increases the installation costs. For this reason, an additional analysis was performed on the hybrid heating system (GCHP plus gas boiler to manage heating peak loads) and compared to the GCHP-only system. Each model was established by implementing the process displayed in Fig. 1. The first step was the definition of the building geometry with TRNBuild. The energy model of the building (step 2) was developed to calculate the heating and cooling demand of the building as the balance between the heat gains and losses. When temperatures in each thermal zone are kept at the set-point value, this idealised model allows to estimate the required peak thermal load, and hence to size the heat pump (step 3). The distribution system (step 4) is composed of fancoils and an air handling unit (AHU), which work exchanging heat between the air inside the building and the water circuit. The heat pump (HP) heats (or cools) the water of the building water circuit and thus supplies energy to the fancoils, the AHU, and the domestic hot water (DHW) systems. A buffer tank is placed between the HP and the distribution system, to ensure the correct operation of the HP. The last part of the plant to be designed were the borehole heat exchangers based on the Duct Ground Heat Storage Model (DST) developed by Hellström [7]. The boreholes' total length was estimated with the ASHRAE method [8]. The model was simulated including the HVAC system, and the output was used to calculate borehole length. The process was repeated until the length difference between two iterations became negligible (step 5). Finally, the simulation was run (step 6).

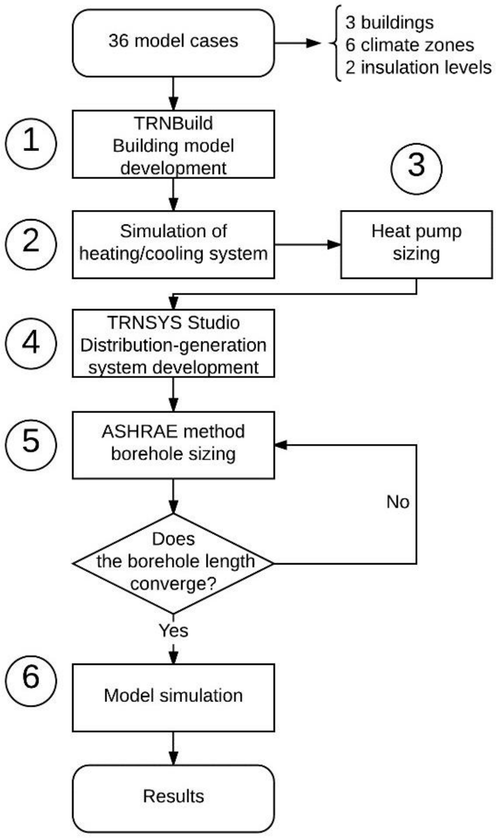

Fig. 1 Model development process flowchart.

Hybrid systems. In the additional hybrid cases, a condensing gas-fired boiler was placed in the water circuit after the buffer tank. In case of peak heating load exceeding the HP capacity, the boiler switches on and heats the water exiting the tank. The hybrid system was sized based on the load time series generated by the building model (step 2), which allows to estimate the correlation between the HP load factor and the total energy demand met (**TEDM**) by the GCHP [9]. For each model case either a 90% or a 70% energy demand coverage was assumed to be met by the heat pump, while the remaining peak demand was assumed to be covered by the gas boiler. The HP power was reduced according to the load factor corresponding to the TEDM value.

3 RESULTS

The results we obtained allowed us to derive a number of useful insights on the system full load equivalent hours (FLEH) and their distribution, on the installation and operational costs, and on greenhouse and pollutant emissions, which are hereby presented.

3.1 Energy use. The FLEH are a key parameter in the feasibility assessment of a GCHP system and are related to the system peak load and building energy demand, as they are the ratio between the yearly demand and the peak load. Heating needs are generally higher than cooling ones in European climates, and this results in heating-dominated buildings, especially in the poorly-insulated cases, with a higher number of FLEH. When the FLEH are high, the GCHP operates for long times at low peak loads, maximising the energy savings respect to conventional systems. Long inactivity periods of the heating (and cooling) system determine low FLEH. This is the case of the Office building (Fig. 2. A-B) whose specific working schedule limits the building FLEH in the heating season (20% to 80% lower than other buildings). On the other hand, the Hotel always needs thermal control, due to higher comfort standards, thus increasing the FLEH. High thermal insulation reduces the heating demand, and thus the FLEH. In the highly-insulated House buildings, the reduction of energy use is balanced by the great reduction of heating peak loads, keeping the FLEH almost unaltered respect to the poorly-insulated cases. A good insulation also rises cooling demand and the cooling FLEH in colder climates, as the internal gains increase their relevance in the heat budged.

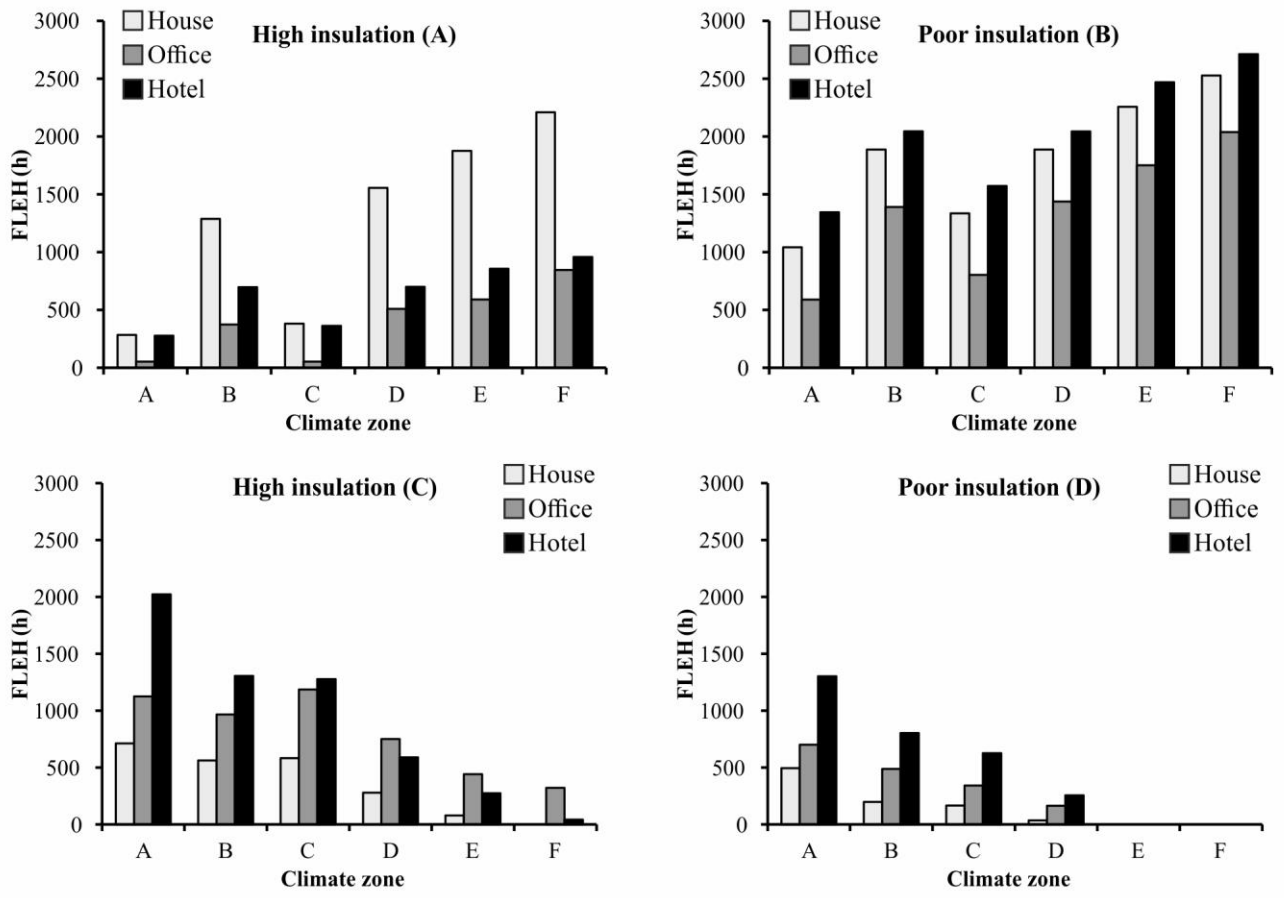

Fig. 2 Full Load Equivalent Hours (FLEH) of heat pump operation for highly-insulated (A) and poorly-insulated (B) buildings in heating conditions, FLEH for highly-insulated (C) and poorly-insulated (D) buildings in cooling conditions.

The heating and cooling load curves of the buildings were evaluated in order to size the system components. Generally, a heat pump sized around 60% of the peak load is able to meet 82 – 96% of the total yearly energy demand, as confirmed by previous studies [9, 10]. In the hybrid cases later analysed, the HP can be installed to cover the base demand, while a backup system is used to manage the peaks. Improved insulation reduces peak loads, thus increasing the value of TEDM for the same load factors. This means that the hybrid GCHP-boiler solution is even more suitable for the highly-insulated new buildings.

3.2 Performance. In order to compare a conventional heating/cooling system and a GCHP system, a financial analysis was carried out, considering either a new installation (in well-insulated buildings) or a replacement of the existing heating/cooling system (refurbishing of poorly-insulated buildings). The net present value (NPV) and the discounted payback period (DPP) [11] of each studied case were analysed to distinguish profitable investments from ineffective ones. The net present value was calculated considering the lifetime of the GCHP system equal to 25 years [12, 13] and the discount rate equal to 2% [14]. The system investment cost was based on data derived from commercial catalogues [15, 16], while the BHEs drilling and installation cost were assumed constant and equal to 60 €/m [17]. Data obtained from the simulation were processed to calculate the annual thermal energy required by the building and the annual electrical energy consumed by the heat pump and the auxiliary systems (i.e., fancoils and ground circulation pumps). The price for the energy resources were extracted from Eurostat data [18]. Finally, two different scenarios were considered: absence of subsidies, which is normally the case when a GCHP system is newly installed; and presence of subsidies, common when a conventional system is replaced. Subsidies were assumed equal to 65% of the total investment cost [19].

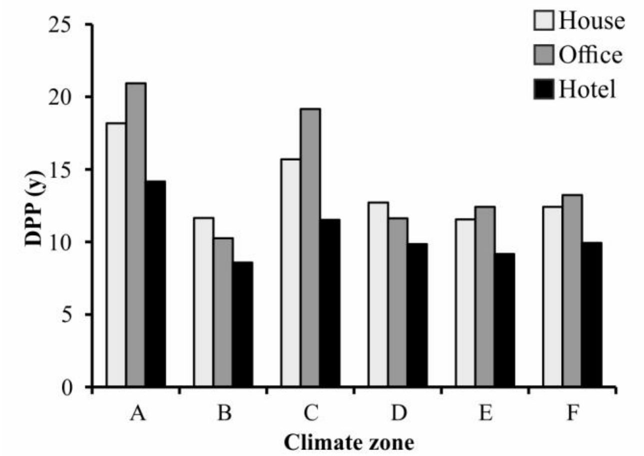

Fig. 3 Discount Payback Period (DPP, [11]) for the subsidized GCHP system installation in poorly-insulated building refurbishing cases in the different climate zones (Table 1).

In general, in the current European economic scenario, GCHP systems designed to cover the whole heating demand are unfeasible without public subsidies. In this case, the substitution of an existing system (in poorly-insulated buildings, Fig. 3) is advisable from a financial point of view, due to the high FLEH, which implies high possible revenues. For the same reason, GCHP systems installed in hotels are generally more profitable. The payback periods are similar throughout the heating-dominated incentivised cases with a general decrease toward high energy-consuming buildings (i.e., cold climates) and when the full load hours are maximized, because of both lower installation costs and higher operational savings. DPP of 9-13 years can be achieved in most of the refurbished buildings displayed in Fig. 3. Among these, climate zone B presents balanced heating and cooling needs, and the shortest DPP (i.e., 8.6 years). Cooling-dominated buildings in zones A and C are, instead, low energy-consuming, which results in very long payback periods. This is particularly true when subsidies are not available, with a minimum payback period of 16 years. The differences in building utilisation cause the Hotel to have a better return of investment, with a DPP 23% shorter than the House and 26% less than for the Office, on average.

Hybrid system economic performances. The whole energy and economic analysis was extended to the hybrid cases. The building load curves were used to size the HP capacity in two different cases: either covering 90% or 70% of the annual heating energy, while the remaining peak consumptions were assumed to be covered by a gas boiler. Altogether, the introduction of a backup system can reduce the payback period of the system by up to 20-40% (due to the lower installation cost of a conventional boiler), while the NPV value is only slightly affected (as a consequence of the lower cost efficiency of the system working on peak loads). As a consequence, the investment becomes profitable for the Hotel cases even with no subsidies.

Electricity/fuel price ratio analysis. The correlation between electricity/fuel price ratio and NPV of the building cases was evaluated, as reported in Fig. 4, in the base case of natural gas combustion (with and without the actual taxation share), using different fuels (heating oil and heating LPG [20, 21]) and considering the energy prices in different European countries (relative to gas). When the NPV is positive the investment is profitable. In the present European price scenario (*EA* case), electricity is expensive compared to natural gas, leaving little room for heat pump-driven revenues and low NPV. This is somewhat caused by the taxation share, that has a greater weight on the electricity price. If the GCHP replaced or prevented the installation of oil/LPG boilers, the electricity/fuel price ratio would be much lower, due to the higher cost of these fossil fuels compared to methane. This would improve the return on investment of a GCHP. The comparison between different countries shows that (geothermal) HPs installation in Germany (*DE*) is greatly penalised by the low gas price, while the low electricity price in France (*FR*) favours GCHP implementation.

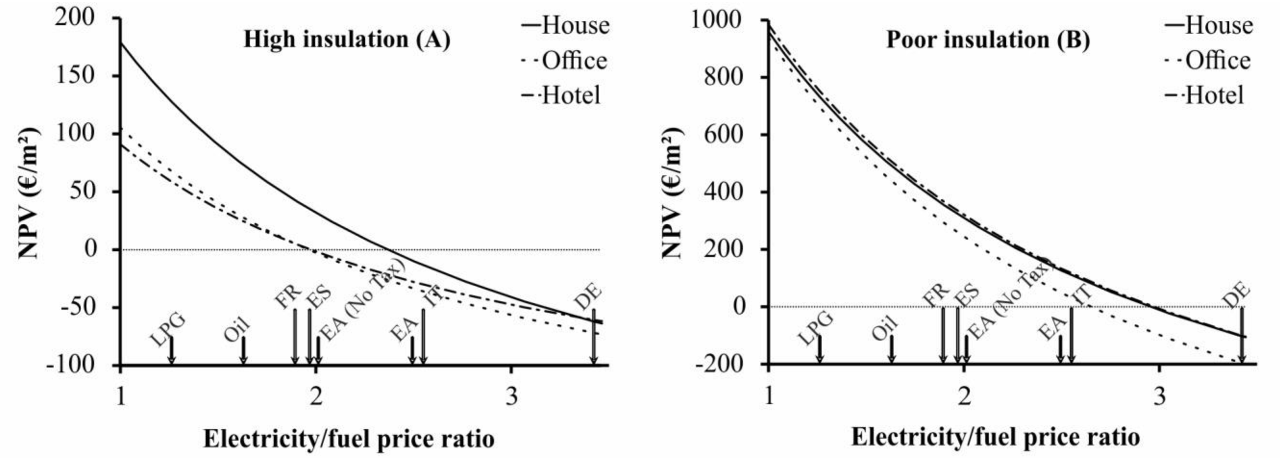

Fig. 4 Net Present Value (NPV) compared with the electricity/fuel price ratio for the brand new highly-insulated buildings (A) and refurbished poorly-insulated building (B) in E climate zone. (EA: Euro Area, FR: France, ES: Spain, IT: Italy, DE: Germany).

3.3 Environmental benefits. The environmental benefit of GCHP systems was assessed based on the simulation results, considering the non-renewable primary energy saved and the total CO2 emission avoided, with respect to conventional systems. The cost/benefit of incentives was also evaluated. The primary energy and CO2 saved per year is similar throughout the cases and depends on the full load equivalent hours (FLEH) of the GCHP system operation (with lower results in cooling-dominated buildings, as the electricity is mostly used for cooling purposes). In general, GCHPs reduce the primary energy use by 60-75% and CO2 emissions by 48-59% relative to conventional heating (gas boiler) and cooling (air chiller) systems.

The effectiveness of public subsidies for GCHP installation was correlated with the FLEH of the heat pump, as reported in Fig. 5. The poorly-insulated Hotel in climate zone E offers the highest return for public subsidy, with a saving of 1.97 kWh of primary energy and 298 gCO2 per year per € of subsidy provided for system installation. The worst case is represented by well-insulated Office placed in zone C, with only 0.06 kWh/€ and 17 gCO_2/€ saved per year, which is also the building with the lowest utilization of the HVAC system.

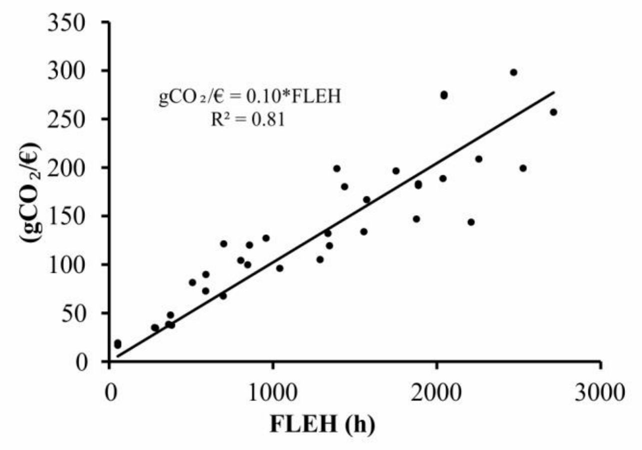

Fig. 5 Effectiveness of public subsidies in CO_2 saving vs. GCHP system FLEH of operation for the different climate zones. (FLEH: Full Load Equivalent Hours).

In the present day, air pollution in metropolitan areas is a widespread issue. GCHPs do not release pollutants in the city air as they only consume electrical energy generated elsewhere. Heat pump-equipped buildings yield small pollutant emission savings relative to buildings heated with natural gas. However, compared to another "green" technology, i.e., the biomass-boiler [22], electric energy production related to GCHP emit significantly less NOx (80-94%) and almost eliminate the particulate.

The general environmental performance of hybrid systems is slightly worse than GCHP systems, due to the consumption of natural gas to manage peak loads. On the other hand, this configuration increases the effectiveness of subsidies. The primary energy and CO_2 saved decrease as the share of the backup coverage increases; however, the primary energy and CO_2 saved per Euro subsidised are respectively 40% and 30% higher (in the 90% case), and 81% and 64% higher (in the 70% case) on average. This means that the GCHP-hybrid configuration is especially convenient to achieve the maximum results of incentives in terms of climate change mitigation.

4 CONCLUSIONS

In this paper, the application of a ground-coupled heat pump (GCHP) in different buildings and climates was analysed. The results highlight how climate, thermal insulation and building usage influence the required system capacity and, therefore, the profitability and the environmental benefits of the installation when compared to conventional systems.

The full load equivalent hours of the GCHP are especially high for the poorly-insulated buildings placed in cold climates. Moreover, the Hotel maximises the system utilization due to the specific schedule allowing large energy savings compared to conventional heating/cooling systems. The building loads analysis proves that a large part of thermal energy needs can be covered with a fraction of the HP capacity (60 % of the peak load capacity meets 82 – 96% of the annual demand). This makes hybrid systems (HP and fossil-fuel boiler) an interesting solution to reduce the initial investment.

The economic analysis identifies the sustainability of a GCHP investment, revealing that public subsidies are essential to ensure the profitability of these systems in European countries by supporting the recovery of the high installation cost. The most profitable building cases for GCHPs, even in a subsidised scenario, are the low-insulated hotels placed in heating-dominated climates (payback times of 8.6-9.9 years). For the other cases analysed, payback times are much longer and sometimes they exceed the system lifetime. Such a poor economic performance can be explained with the European average low price for natural gas and high price for electricity, reducing annual savings when HPs are compared to gas boilers. The hybrid heat pump-gas boiler configuration is interesting as it reduces the system initial cost and thus improves the global economic results (20-40% payback period reduction).

Geothermal heat pumps reduce the primary energy use (60-75%) and the CO_2 emissions (48-59%) with respect to conventional heating/cooling technologies (gas boiler and air-source chiller). The environmental effectiveness of public subsidies supporting GCHPs is related to the system utilization (up to 1.97 kWh/€y of primary energy and 298 gCO_2/€y of subsidy) and it can be enhanced by 30 to 81% with hybrid configurations. This study provides a useful set of information for planning ground-coupled heat pumps in different contexts, identifying solutions to improve the economic viability of this technology, which remains the main barrier to its diffusion.

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