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Hybrid Geothermal and PV Installations for Cooling and Heating Systems: Synergy for Sustainability in Tertiary and Industry Sectors

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ABSTRACT

Recent studies confirm the potential efficiency of geothermal resources for maintaining comfortable building temperatures through cooling and heating solutions. In addition, a variety of initiatives have been promoted to effectively reduce both environmental concerns and energy crisis by the integration of renewables. Under this framework, this paper describes and assesses hybrid geothermal and photovoltaic (PV) installations to provide sustainable solutions. Hybrid geothermal–PV systems are evaluated as a strategic opportunity to increase the presence of geothermal energy within the hybrid heating, ventilation, and air-conditioning (HVAC) market. While upfront capital costs associated with geothermal technology can suppose some barriers, the synergistic coupling with PV installations can provide a compelling solution and reliable energy supply, in terms of both economic feasibility and the energy (electricity) consumption. With this aim, a detailed economic and energy analysis is then conducted to evaluate such hybrid solutions connected to the grid, including potential energy storage system. HVAC demand optimized battery energy storage system (ESS) and PV installation connected to the grid are considered as hybrid renewable solution in a Mediterranean location case study based on the tertiary and industry sectors. It is carried out by the authors from real energy demand data collected for 3 years. Simulation results demonstrate that the proposed hybrid system reduces electricity consumption by 25% compared to a conventional air-to-air HVAC configuration, while geothermal operation achieves 34% lower heating demand and 26% lower cooling demand. These improvements highlight the hybrid system potential for enhanced energy efficiency and load-shifting capability in tertiary and industry sectors.

1 | Introduction

In recent decades, economic growth has mostly raised living standards in developed countries. At the same time, such economic growth has been responsible for the decrease in natural resources and increase in emissions [1]. Subsequently, the association between economic growth rate, energy demand, financial development, and globalization has recently promoted an international debate among different sectors, aiming to propose alternative pathways in a more sustainable manner. Among the different key-role of current societies, energy is considered as a crucial driver. In this way, Svobodova et al. [2] identified the high country-level dependencies and the necessity of global coordination for future transition road maps, mainly in terms of restructuring energy policies. Therefore, sustainable solutions should be proposed to fulfill the increasing power needs for the different sectors—such as transportation or electricity. A fast decarbonization of the electricity sector and relevant emission reductions in the sectors of energy demand are crucial, namely, transport and industry [3]. El Haj Assad et al. [4] affirmed that urgent measures and initiatives must be taken to prevent the worsen and growth of this environmental and energy problem. Regarding emissions, one of the main changes experienced by such greenhouse effects is climate change. In recent years, the frequency and violence of meteorological phenomena has increased considerably [5], involving environmental catastrophes such as typhoons, storms that destroy crops, and considerable temperature increasing in summer, heavy snowfalls in winter, and so forth. The extreme temperatures reached in some areas have require air-conditioning units for comfort [6]. The vast majority of these air-conditioning devices are powered by electricity. It is then necessary to reduce the demand of these systems or, alternatively, generate the electricity without emitting pollution and reduce the risk of increasing the greenhouse effect. Note that the current utilization of heating, ventilation, and air-conditioning (HVAC) systems accounts for about 20% of total building energy consumption worldwide and 10% of all global electricity consumption. In fact, the electricity consumed by HVACs in developed countries is as high as 50% of their generated electricity [7]. Heating and cooling are extensively utilized across various sectors, including buildings, hospitals, hotels, and commercial offices. Air-conditioning systems significantly contribute to overall energy consumption in public and commercial office buildings, especially in regions with hot climates and high temperatures during the summer months [8]. The energy consumption in the commercial and residential sectors represents nearly 25% of the total final energy use [9]. A possible energy-efficient approach to decarbonizing the heating and cooling sector could involve replacing aging fossil fuel boilers with renewable energy technologies, such as heat pumps, or integrating district heating systems. This point would enhance overall efficiency and take advantage of renewable energy sources (RESs) [10]. In this framework, photovoltaic–thermal (PVT) hybrid panels integrate photovoltaic (PV) cells with thermal collectors capable of generating both electrical and thermal energy [11]. Joshi and Dhoble [12] conducted a comprehensive review of PVT systems and noted the significant role that materials will play in the optimization of PVT panels. The primary challenge in the transition to renewables lies in the variability and intermittency of these resources, necessitating technical adaptations. This is particularly critical in managing and balancing fluctuations in energy supply and demand [13]. To overcome this drawback, the advancement of hybrid renewable energy systems presents a cost-effective approach to achieving energy decarbonization and reducing greenhouse gas emissions. According to the literature, economic, energy, and environmental metrics are rarely integrated in the optimization processes of hybrid renewable systems [14]. In addition, there are no standardized procedures or universally applicable set of indicators to perform a comprehensive comparative analysis in different applications. In addition, battery electric storage is also the most widely reported solution for direct electricity storage, ensuring adequate supply security [15]. Therefore, different contributions and authors [16, 17] agreed with the relevant performance and viability of such hybrid renewable energy systems. These proposals integrated various technologies to optimize energy production, ranging from a few kilowatts to several 100 MW generation capacities.

On the other hand, recent contributions concluded that geothermal resource should be suitable for providing a comfortable temperature [18]. This resource comes from the heat radiating from the earth's interior. It consists of extracting the temperature of the subsoil, as it is stable all year, reducing the demand for heating and cooling systems and, subsequently, their consumption [19]. Geothermal energy can be installed in any area, as long as the ground is suitable for drilling and does not endanger the subsoil. Moreover, its availability is constant. It does not require large spaces, it is silent and a large amount of energy can be extracted in each installation, being suitable for reducing energy consumption as it can also be recirculated. In fact, this energy can be used up to two or three times [20]. Geothermal installations are fully compatible with other RES and, in combination with another source such as PV, it could be possible to reduce the energy consumption of an average residential demand to zero [21]. In addition, a geothermal installation would supply the temperature needs of both residential and tertiary buildings [22], while PV installations would cover the electricity demand and the power demand of the geothermal system based mainly on air extraction turbines [23]. Li et al. [24] concluded that hybrid solar–geothermal systems have the potential to outperform standalone geothermal or solar power systems in both economic profitability and thermal efficiency. Focused on residential customers, Neves et al. [25] compared a PV system integrated with a geothermal HVAC residential solution to an equivalent PV system applied to the preretrofit baseline homes. A key outcome of this study was the development of a key factors template, incorporating variables such as soil conditions, solar irradiance, and local incentives. According to the specific literature, there are other ways to combine solar and geothermal energy to propose hybrid energy system solutions. An approach is based on using solar thermal collectors to generate extra heat, compensating for any shortfall in the geothermal system. A popular hybrid solution is the solar-assisted ground source heat pump (SAGSHP) [26, 27]. A supercritical organic Rankine cycle can also be utilized in a geothermal system combined with a concentrated solar power setup to handle peak loads for demand-side management [28]. Nevertheless, and though most hybrid systems are typically designed for heating purposes, it is also possible to enhance the performance of a solar cooling system by integrating with a ground heat exchanger. Acuña et al. [29] and Abu-Rumman et al. [30] showed that integrating PV/T systems and geothermal heat pumps can reduce panel temperature by more than 20°C, increase electrical efficiency by 9.5%, and improve the heat pump's coefficient of performance (COP) from 4.6 to 6.2, in addition to reducing electricity consumption and life cycle costs. Wang et al. [31] proposed a multiobjective optimization framework for integrated PV/thermal (BIPV/T) and geothermal heat pump systems with energy pilots, achieving substantial improvements in energy consumption, environmental performance, and life-cycle cost, and highlighting the importance of maximizing the number of BIPV/T collectors while maintaining the thermal balance of the ground. Wang et al. [32] reviewed design, configuration, and intelligent control strategies for hybrid geothermal systems, emphasizing that comprehensive parameter optimization, and the use of advanced algorithms allow for maximizing the flexibility, efficiency, and sustainability of these systems. Finally, Congxiang et al. [33] explored the integration of PV systems and thermoelectric generators with thermal wheel ventilation, demonstrating notable improvements in energy efficiency and exergy indicators, reinforcing the potential of these solutions for sustainable residential heating and cooling. Table 1 summarizes recent hybrid HVAC solutions based on different combinations of renewables.

From the previous contributions, it can be affirmed that hybrid geothermal–PV solutions are able to increase the presence of geothermal resource in the hybrid HVAC market. Therefore, combining geothermal energy with other RESs can substantially reduce the payback time of the global installation, minimizing dependence on renewable resource oscillations, and providing a continuous power supply side. According to Soltani et al. [40], it can be affirmed that integrating geothermal energy into an HVAC system can result in a potential 50% reduction in energy costs; being their economic viability contingent upon factors such as energy demand, availability and pricing of alternative energy sources, as well as the presence of an appropriate regulatory and environmental framework [41]. Moreover, these installations could be also complemented with additional energy storage systems (ESSs). Indeed, Haas et al. [42] concluded that ESS were not the only source of flexibility for renewable integration. For example, ESS can be combined with flexible generation, transmission, energy reduction solutions, and multigeneration systems; coordinating ESS options alongside other strategies to maximize system-wide benefits [43]. Congedo et al. [44] pointed out that energy storage is widely regarded as a key solution for effectively managing the significant fluctuations in energy generation from renewables, helping to reduce environmental impacts and ensuring energy efficiency. Despite the increasing attention given to hybrid systems combining geothermal and solar energy, most previous studies have focused on residential applications or small-scale experimental setups. Furthermore, very few contributions integrate technical, economic, and environmental aspects within a unified methodological framework, limiting the comprehensive evaluation of their feasibility. In addition, there is a lack of long-term case studies using real operational data, particularly for Mediterranean climates with high seasonal thermal demand. To address these gaps, this paper describes and evaluates a methodology to optimize geothermal–PV hybrid systems including battery energy storage systems (BESSs) specifically designed for tertiary and industrial applications. Real measured thermal and electrical demand data collected over 3 years are employed to perform an integrated energy, economic, and environmental assessment, demonstrating the technical feasibility and profitability of the proposed hybrid solution under real operating conditions.

TABLE 1 | Recent hybrid HVAC systems based on renewables.

Hybrid system proposals	Country	Year	References
PV, PVc	South Korea	2019	[34]
PV, H_2, Bat	Spain	2019	[35]
PV, WT, Hyd, Bi, Bat, H_2	Greece	2020	[36]
PV, WT, Bg, Hyd, Bat	India	2020	[37]
PVT, GSHP	Jordan	2020	[30]
PV, H_2	—	2021	[38]
PV, H_2, Bat	Saudi Arabia	2020	[39]
PVT,GSHP	China	2024	[31]
HG	—	2025	[32]
PV, TG	China	2025	[33]

This contribution is in line with other authors, such as Royapoor et al. [45], aiming to provide alternative optimized building management in order to address grid stability, renewables, and storage management. The proposed methodology offers alternative renewable solutions to the industry sector, where the solutions of the HVAC industry continue predominantly to deploy conventional techniques [46]. Indeed, Walmsley et al. [46] also reviewed the existing published research on renewable energy utility systems for industrial sites, in order to create a framework for hybrid systems. Based on recent state-of-the-art reviewed by de Novaes Pires Leite et al. [47], a key gap identified in the literature on HVAC systems is the lack of optimal configurations, both technically and economically, to integrate PV systems with air-conditioning units in enclosed environments while maintaining thermal comfort. This gap is analyzed in the present paper to provide solutions that ensure energy efficiency and system viability under such conditions.

The rest of the paper is structured as follows: Section 2 describes the proposed methodology. Section 3 describes the case study based on a real tertiary and industrial building with yearly measured thermal and electrical power consumption data. Section 4 provides the results and discussion of the case study. Finally, conclusions are given in Section 5.

2 | Proposed Methodology

This paper proposes a geothermal–PV–battery hybrid energy system to provide the thermal power demanded by tertiary and/or industrial sector in a more competitive cost. The geothermal system supplies the heating and cooling demand of the buildings, while the PV system supplies the electricity needed to power the ground source heat pump (GSHP) of the geothermal system, and the batteries system store surplus energy to be subsequently used or injected into the grid. The hybrid system is designed according to the following stages: (i) the thermal needs of the building are estimated; (ii) the evaluation of the conditions and design of the geothermal system is carried out based on the thermal loads of the building and the site-specific hydrogeological conditions of the underground; (iii) PV installation is designed according to the availability of the roof and the electricity demand of the geothermal system; (iv) finally, the surplus energy able to be stored or injected into the grid is calculated to size the battery system for later self-consumption use (Figure 1). The main key factors to be considered are the following: dairy and hourly power demand consumption; thermal loads and dairy and hourly thermal energy demand; geographical location; roof and surface availability to install the equipment; potential public subsidies for renewable installations.

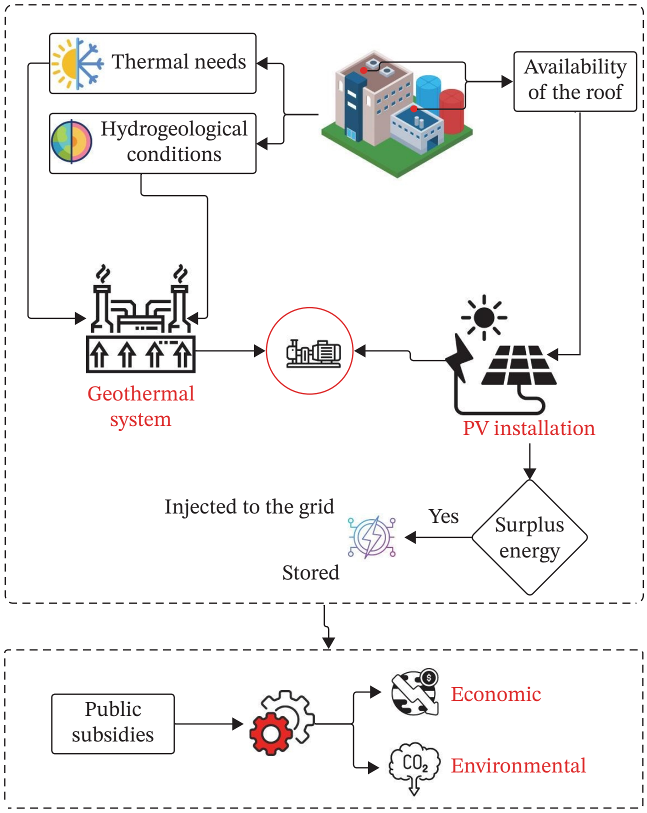

FIGURE 1 | General overview. Research framework.

2.1 | Shallow Geothermal System Design

In a GSHP system, thermal energy is extracted from the fluid circulating within a closed-loop ground heat exchanger using a geothermal heat pump, which transfers heat to the building. The fluid is then reheated as it moves through the ground loop, ensuring a continuous exchange of energy. During cooling mode operating conditions, this process is reversed. This renewable resource is, thus, able to provide sustainable heating and cooling solutions for a variety of potential applications—including residential, tertiary, or industrial customers; as well as for specialized needs such as cooling data centers. Shallow geothermal systems typically consist of vertical closed-loop boreholes, which facilitate heat exchange with the subsurface. These systems rely on the GSHP to either increase or decrease the temperature obtained from the ground to meet the thermal set-point operating conditions. Circulating pumps and associated equipment are designed to distribute conditioned thermal energy throughout building installations. A significant challenge of geothermal energy projects is commonly the availability of detailed geothermal resource mapping [48]. If comprehensive data is available, uncertainties are significantly reduced during the exploration phase, potentially lowering development costs. In the proposed methodology, a preliminary GIS–based environmental analysis is first conducted to assess the geothermal resource and to evaluate suitable technologies based on subsurface characteristics. The analysis focused on the assessment of subsurface thermal conductivity is determined by both lithological properties and the degree of water saturation [49]. The peak daily thermal requirements for both heating and cooling determine the GSHP capacity. The corresponding power electricity demand is then calculated based on the GSHP COP and seasonal performance factor (SPF), along with the thermal demand [50]. After determining the thermal load requirements, the subsequent stage involves designing the borehole field to extract the required thermal energy from the ground. This design process takes into account not only the annual thermal energy demand, but also the subsurface hydrogeological properties, previously assessed through a GIS–based analysis. The entire geothermal system, including the borehole field, is then modeled using the earth energy designer (EED) software [51]; being one of the most used tools during the geothermal calculation sequence [52]. The EED tool incorporates factors such as geological conditions, borehole dimensions, thermal properties of the heat transfer fluid, and building energy requirements to simulate the thermal behavior of the geothermal borehole system. This approach ensures precise design optimization and performance evaluation of the geothermal system, allowing for a more efficient and reliable solution. As Sáez Bláquez et al. [53] affirmed, EED has undergone extensive enhancements, positioning it as a robust tool for the design and optimization of GSHP systems. In particular, EED enables precise configuration of vertical closed-loop geothermal systems, with the capability to evaluate both average and peak monthly fluid temperatures over the designated operational period. Moreover, the latest version of EED offers extended functionality, operating at an L4 software level, which enhances its capacity to model complex scenarios and further refines system performance predictions.

2.2 | PV Installation Design

A PV system comprises various components, including solar panels, electrical connections, inverters, cables, and support structures. A grid-connected PV system can be considered as an electrical power generator supplying electricity to the grid, and making it accessible to any connected user [54]. The system's capacity is determined by its intended application, with kilowatt-peak (kWp) systems designed for residential and tertiary use—mainly in self-consumption mode; and megawatt-peak (MWp) systems for large-scale PV power plants—commonly connected to the grid from the supply-side and sometimes in self-consumption mode for large industrial customers. Off-grid PV installations, mostly referred to as self-consumption systems, supply electricity solely for on-site use, with any surplus energy discarded. In the development of a PV power plant design, the geographic location of the site is carefully analyzed to determine the optimal tilt of the panel based on latitude. Moreover, the orientation of the panels towards true south is commonly considered as critical, as proper alignment maximizes solar exposure, and thus, improves energy capture [55].

The electrical power demand of the system is estimated by calculating the hourly power consumption (kW h). Subsequently, the total energy consumed over a 24-h period (kW h/day) is determined. Based on the energy demand, a PV system is proposed with enough power capacity to cover the majority of the required consumption [56]. Once the rated capacity of the PV system is determined and the orientation and positioning of the PV panels are defined, the energy generation per hour is estimated using the PVsyst simulation software [57]. PVsyst calculates the power output by considering the specific location of the PV installation, with solar irradiance data obtained from the SolarGIS meteorological database [58]. Table 2 provides an overview of the key meteorological parameters available for download from

TABLE 2 | Database of SolarGIS.

Data	Units
Global horizontal irradiation	W h/m^2
Direct normal irradiation	W h/m^2
Diffuse horizontal irradiation	W h/m^2
Sun altitude (elevation) angle	°
Sun azimuth angle	°
Air temperature (at 2 m)	°C
Atmospheric pressure	hPa
Relative humidity	%
Wind speed at 10 m	m/s
Wind direction at 10 m	°
Precipitate water	kg/m^2

SolarGIS. It is used to design the PV power plant and estimate the annual energy output in MW h/year. By selecting the type and number of PV modules and inverters, a detailed simulation of the PV plant can be then performed. Some loss factors can be incorporated into the simulation, including transmission losses through cables, energy consumption of transformation equipment, and losses due to soiling or dust accumulation on the PV panels, among others [59]. These factors ensure a more accurate representation of the PV power plant performance under real conditions.

2.3 | BESS Design

BESSs enables more efficient RES utilization and prevents energy wastage [60]. BESS contribute to grid stabilization, frequency regulation, emergency power supply, and industrial-scale peak shaving, which can help reduce electricity costs [61]. Incorporating battery storage presents significant challenges, such as increased capital costs, the requirement for advanced battery chemistries, and environmental implications associated with the manufacture and end-of-life disposal [62]. While battery prices remain relatively high due to the nascent nature of the industry, production costs are steadily declining [63]. Thus, different types of batteries are available, each with different applications depending on factors such as cycle life, cost, and performance. Lead-acid batteries are the most cost-effective option, featuring low self-discharge and a wide operating temperature range. Due to their affordability, they are widely used in various applications, including vehicle batteries, substation backup power, marine applications, emergency lighting systems, and telecommunications backup equipment. Sodium sulfur (NaS) batteries, which require their electrolyte to be maintained at high temperatures (around 300°C), offer long life cycles (up to 4500 cycles), although their high cost limits their usage in some applications. Lithium-ion (Li-ion) batteries are the most common choice for BESS. These batteries are highly versatile, with long life cycles (ranging from 5000 to 10,000 cycles), low self-discharge, and high energy density. Although initially expensive, the growing electric vehicle market and advancements in battery technology have led to reduced manufacturing costs, consequently lowering the price of Li-ion batteries. Subsequently, the integration of appropriately sized ESS, combined with accurate ESS sizing strategies in renewable energy applications [64], represents a promising approach to ensure greater stability in electric power availability and deserves further investigation [65]. Moreover, the deployment of solar PV systems coupled with battery storage has expanded considerably, driven by their operational flexibility and the progressive decline in battery technology costs [66]. The proposed solution is designed to include the BEES exclusively as an auxiliary component for electrical energy management purposes, enabling either the injection of surplus electricity into the grid or its storage in dedicated high-capacity units. Thermal integration is excluded from the operational framework to maintain design simplicity and prioritize electrical flexibility, dynamic load balancing, and grid stability over combined heat and power (CHP) strategies. An example of thermal battery storage for a residential building can be found in reference [67]. However, this hybrid solution required an additional heating load of 1.85 kW from the furnace.

3 | Case Study: Industrial and Tertiary Building

The hybrid geothermal–battery–PV case study is located in an industrial area with a high daily economic activity and energy consumption rate. The purpose is reduce a large electricity demand and thermal energy consumption by considering real data collected over the last 3 years for a tertiary and industrial building. The electric and thermal demand profiles are used to design the hybrid installation according to Section 2. The hybrid installation includes a PV installation, geothermal system and a possible BESS solutions to manage the surplus energy. Results are also compared to a conventional HVAC system in terms of energy and economic analysis. The case study is located in Albacete, Southeast of Spain, a continental climate city with cold winters and hot summers (Figure 2A). This temperature range

(A) (B)

FIGURE 2 | Location of case study (A). Roof of the tertiaty and industrial building (B).

requires high thermal energy needs for heating and cooling purposes, regardless of the weather season. This fact involves high energy thermal consumption in both winter and summer periods. The city is located at a latitude of 39°. The solar irradiation can then be translated into a large amount of PV energy generated throughout the year [68], which is sufficient to supply the peak energy consumption of the whole equipment. The proposed hybrid solution is, therefore, based on a geothermal installation, with a stable temperature achieved throughout the year, at a minimum cost to obtain this heat energy. The heat could be extracted from underground using a geothermal pump powered by a PV installation located on the roof of the building (Figure 2B). The possibility of different combinations of geothermal PV solar hybrids is also considered in the results (Section 4.2). Indeed, a BESS can be also used to store surplus energy and, subsequently, to be demanded by the customer—in a self-consumption mode; or sold during off-peak hours by considering the electric market price evolution. Aiming to evaluate the different solutions, various installations are proposed and compared. Depending on the thermal and electric energy demand, and by considering the potential surplus energy along the year, it could be possible to store such energy for future demand requirements, or even to create industrial energy communities to decrease power demand and optimize resources in a more renewable and sustainable scenario; being currently a topic of interest by the authors.

To evaluate the shallow geothermal potential of the study area, the underground conditions were first assessed (Table 3). The lithology consists of various materials, including sinkholes, marls, lime-stones, gravels, and sands, as summarized in Figure 3. The materials have similar thermal properties, with an average thermal conductivity of 2.8 W/mK and a thermal capacity of $2.5 \times 10^{6}\,\mathrm{J\,m^{-3}\,K^{-1}}$, estimated according to the Spanish UNE-100715-1 standard [69]. Information regarding the hydrogeological units was collected from the Groundwater Bodies Watershed Hydrology Plan (2015–2021) [70]. This data informed two key decisions: (i) the assessment of the potential presence of an aquifer that meets the conditions for thermal exploitation and (ii) the measurement of the depth at which the water table is located, thus enabling a better understanding of groundwater dynamics and system feasibility. Ultimately, no suitable aquifer was identified in the area, indicating the necessity of a closed-loop system. However, the water table was found to be very shallow, meaning the materials were largely water-saturated. This fact increases the thermal conductivity of the materials, enhancing the overall efficiency of the geothermal system.

4 | Results and Discussion

4.1 | General Overview and PV Power Plant Configurations

Based on the analysis of the thermal consumption of the Spanish customer, the peak thermal demand is estimated to reach 210 kW during winter and 197 kW in summer. To meet this demand, a geothermal heat pump—42 kW electrical capacity—is considered enough to extract the thermal energy required for the industrial and tertiary building under study. One of the notable new features recently introduced in Spain was the allowance for both individual and collective (shared) self-consumption [71]. This regulation specifies that the user and the owner of the PV installation can be distinct individuals or legal entities, enabling greater flexibility in system ownership and operation. Furthermore, individual self-consumption systems can operate either with or without surplus energy, meaning the excess electricity generated can either be fed into the distribution grid or not. However, for shared self-consumption, surpluses must be fed

TABLE 3 | Parameters and properties.

Ground properties			
Undisturbed ground temperature	14.7°C	Ground thermal conductivity	2.8 W/mK
Ground thermal capacity	2.5 ($10^{6}\,\mathrm{Jm^{-3}\,K^{-1}}$)	—	—
Length heating/cooling season			
Heating days/year	150	Cooling days/year	215
Borehole parameters			
Threshold fluid temperature (winter)	−2°C	Borehole depth	100 m
Threshold fluid temperature (summer)	35°C	—	—
Borehole radius	0.1 m	Simulated time	50 years
Borehole thermal resistance	0.1 mK/W	—	—
Thermal energy extracted from the ground			
$Q_{\mathrm{BHE\,(heating\,mode)}}$	11.63 MWh/year	$Q_{\mathrm{BHE\,(cooling\,mode)}}$	15.57 MWh/year
$Q_{\mathrm{BHE\,(heating\,mode)}}$	1.33 W	$Q_{\mathrm{BHE\,(cooling\,mode)}}$	1.77 W
Borehole field			
Borehole type	Single U–tube	Borehole number	307
Borehole field	370 m × 100 m	Borehole separation	6 m

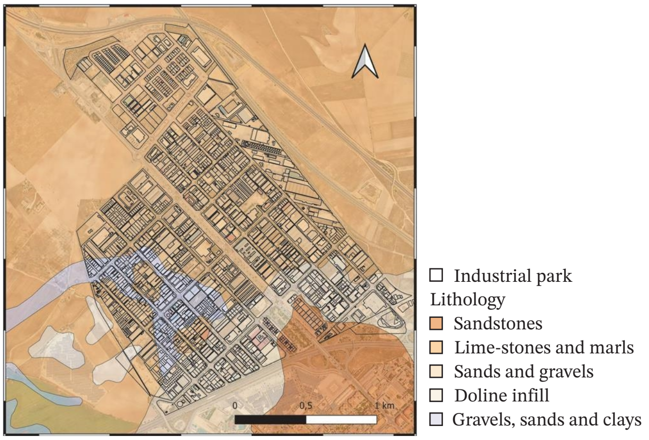

FIGURE 3 | Lithology in the area.

into the grid due to the inherent use of the distribution network [72]. A key factor in determining the economic viability of these systems is the complex compensation for surplus energy. As a result, the legislator has implemented a simplified compensation mechanism based on the net-billing model, available for PV installations smaller than 100 kW rate power, and thus, providing a more accessible alternative for small-scale users [73]. Therefore, and aiming to explore various hybrid energy solutions as case study, four PV power plants and configurations up to 100 kWp with battery storage were proposed and compared in terms of both economic and energy analysis.

An initial 40 kWp PV installation is considered to partially offset the electricity power demand of the geothermal heat pump, though it is not enough to cover the full power demand. This solution allows for a comparison between the electricity generation profile, energy consumption, and surplus energy. As illustrated in Figure 4, the PV installation is capable of generating enough power to cover both geothermal and cooling demand profiles. However, during summer months, particularly in July, the cooling demand values rise significantly, requiring additional electricity demand from the grid. In Figure 4, the blue graph represents air-to-air consumption, while the orange line shows PV power generation during July.

Aiming to meet the geothermal pump demand (42 kW) and able to cover all demand of cooling energy needs, a 60 kWp PV installation scenario is subsequently considered for evaluation. Analyzing the PV installation generation profile (Figure 5), it is capable of covering the daily demand along the year; even during winter months when the energy thermal demand is considerable higher. Although the energy cost can be significantly reduced, the purchase of electricity at night is still required, as any BESS is not then considered to be included in this case study.

Regarding a 80 kWp PV installation, it provides surplus energy in every month of the year. This PV power plant is oversized in comparison to the thermal energy demand, in order to increase the profitability of the installation by the introduction of BESS. Therefore, PV generation was higher than the power demand and, consequently, the results gives an additional amount of generated power able to be fed to the grid or stored into BESS for a subsequent use. Figure 6 shows the results for this scenario. As can be seen, the PV power generation profile (orange line) always

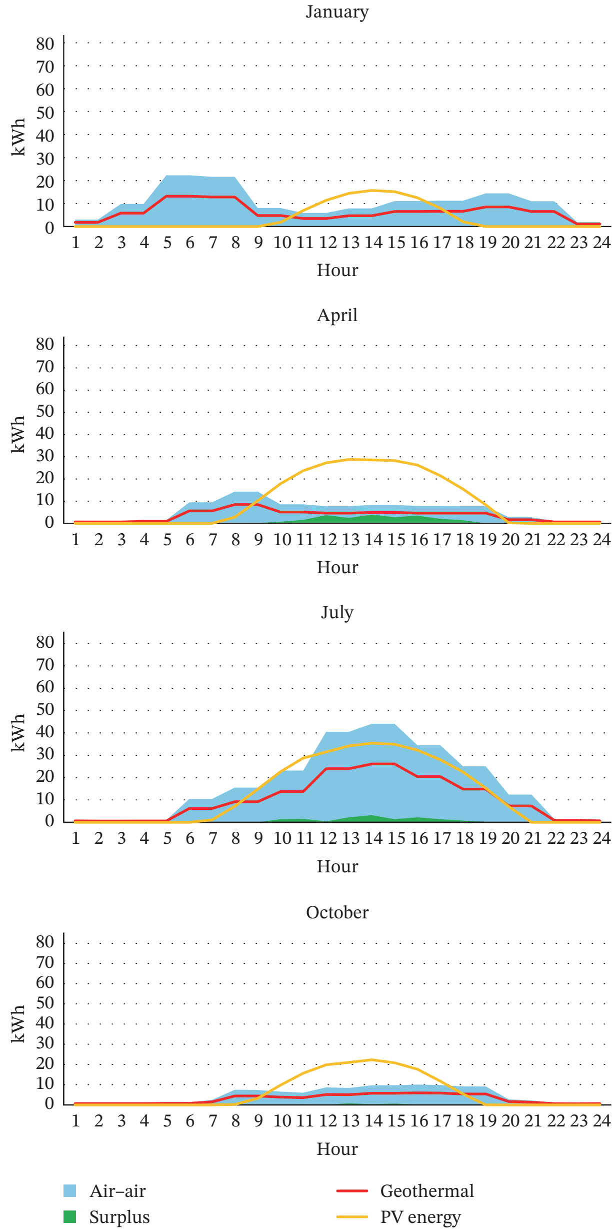

FIGURE 4 | A 40 kWp PV installation. Power generation and demand profile.

remains higher than the geothermal demand (red line) and estimated air–air conventional equipment (see blue graph profile).

Finally, a 100 kWp PV installation is designed (Figure 7). In this specific case, the number of PV modules was almost doubled in comparison to the 40 kWp scenario. By considering the power generation profile, a higher PV electricity production is able to be used for nonthermal demand of the tertiary and industrial building, such as lighting, other equipment in general. Results are summarized in Figure 8. As can be seen, a remarkable amount of surplus energy is estimated during the year, being significantly relevant in spring and autumn, as solar irradiation provides more generated power electricity than the thermal demand is required, due to soft outdoor temperatures reached in these seasons. Subsequently, such surplus energy could be stored for future consumption periods or fed to the grid.

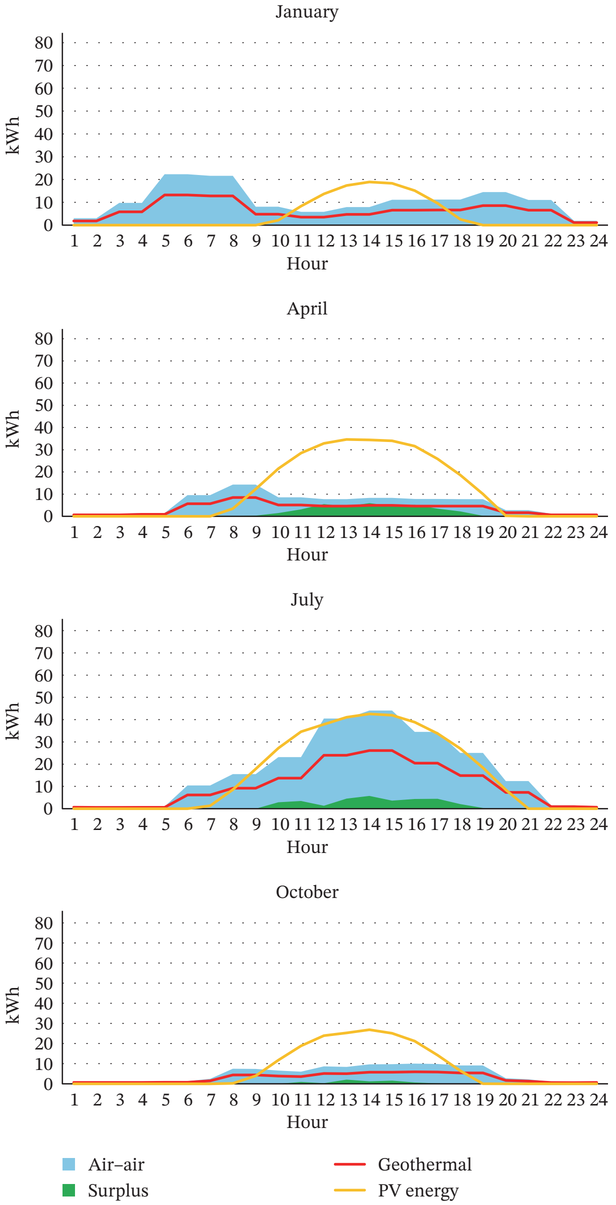

FIGURE 5 | A 60 kWp PV installation. Power generation and demand profile.

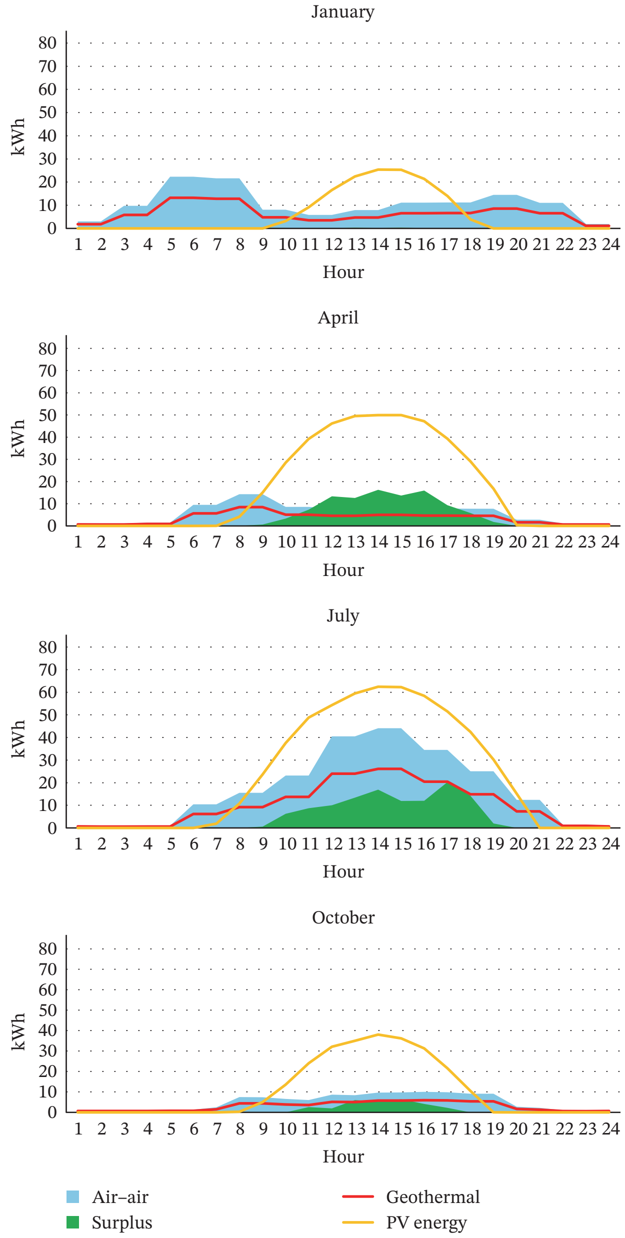

FIGURE 6 | A 80 kWp PV installation. Power generation and demand profile.

4.2 | Shallow Geothermal System Design

A thermal base load was estimated by considering the minimum mean fluid temperature: 11.2°C in winter and 25.9°C in summer. Peak thermal loads were estimated by considering −2 and 35°C for heating and cooling accordingly. These temperature values correspond to the averaged temperature during winter and summer, respectively, for former, and the latter corresponds to the minimum average temperature during the winter and the maximum averaged temperature during summer. The borehole length is 100 m and the simulation period spans 25 years. Locations of proposed boreholes are represented in Figure 9. The energy extracted from the underground was estimated at 91 MW h/year for heating mode, and 90 MW h/year for the cooling operation conditions per borehole (Table 3). These values correspond to specific heat extraction rate for the heating mode, ranging from 4.3 to ±21.6 W/m; and from 4.51 to ±27.3 W/m for the cooling mode.

The proposed GSHP has a COP of 4.6 for the heating mode and SPF of 4.4 for cooling mode, according to the Spanish Heat Pumps Inventory [74]. In total, 1400 m of boreholes are needed to reach the energy demanded, split into 14 boreholes. The current Spanish rule UNE 100715-1-2014 [75] establishes a safe distance of 3 m between the boreholes and the building infrastructure, and 6 m among the boreholes themselves. In total, a borehole field network of 12 × 13 m^2 is proposed. Figure 9 shows the designed borehole network in a specific area next to the case study building—considered as tertiary and industrial building example. In comparison to conventional air-to-air HVAC systems, geothermal cooling solution has a higher COP, demanding lower power

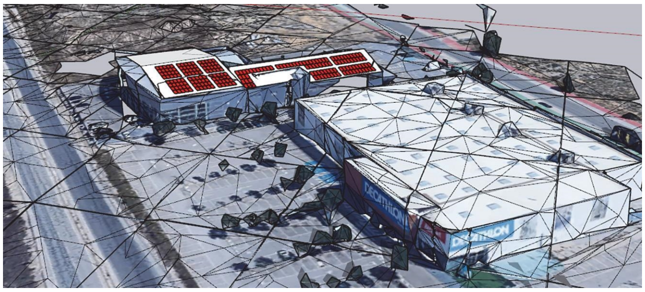

FIGURE 7 | A 100 kWp PV power plant. General overview and PV modules layout.

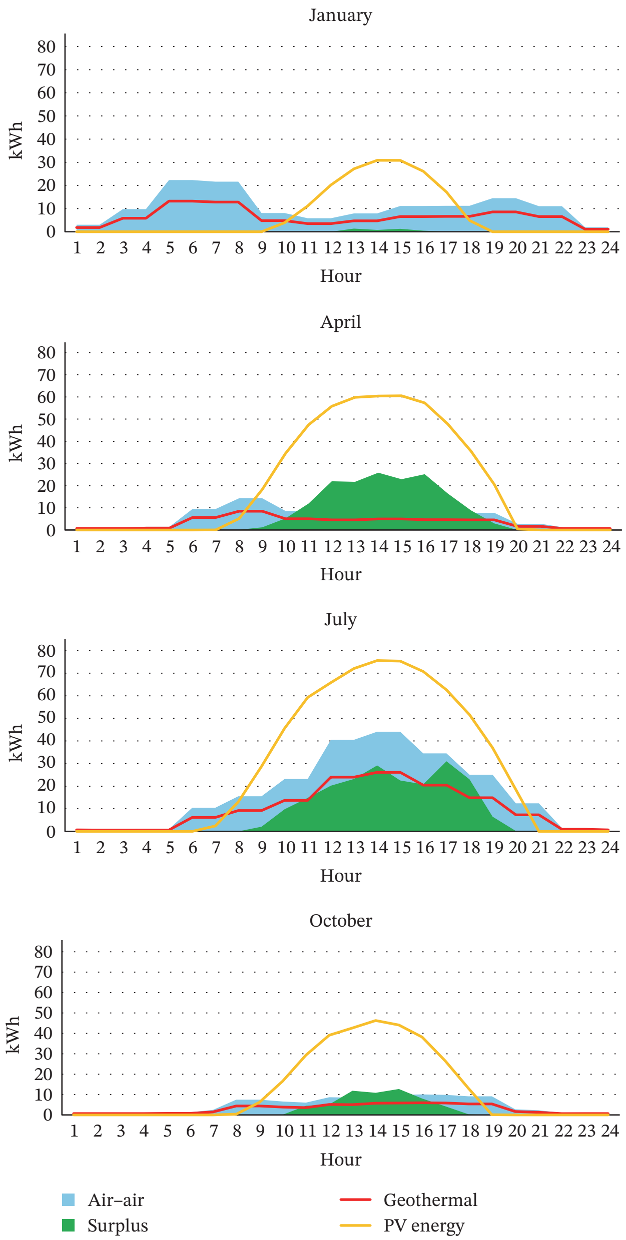

FIGURE 8 | A 100 kWp PV installation. Power generation and demand profile.

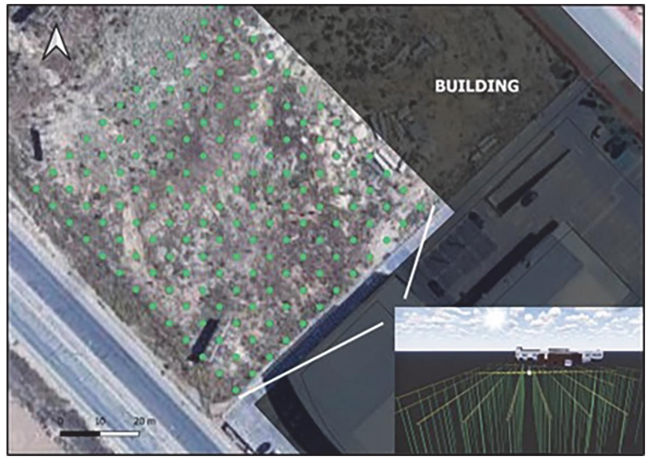

FIGURE 9 | Location of boreholes.

TABLE 4 | Surplus energy. Comparison of solutions.

PV rate power (kWp)	Geothermal system (kW h/year)	Conventional HVAC system (kw h/year)
40	3610.41	2221.48
60	6692.40	4434.76
80	22,206.04	16,306.12
100	38,708.44	29,578.82

electricity profiles. Subsequently, the energy surplus of geothermal solutions is higher than air–air cooling HVAC conventional system (Table 4).

4.3 | BESS

The BESS selection was based on the surplus energy profiles (Table 4). The different PV system scenarios outlined in Section 4.1 directly influenced the surplus energy available, thereby affecting the size and cost of the selected BESS. After evaluating multiple technologies, Li-ion batteries were chosen due to their compatibility with PV systems and extended cycle life [76], despite their higher initial investment cost [77]. The estimated capacities for each BESS solution are presented in Table 5. In conclusion, the use of Li-ion batteries provides a balanced trade-off between performance and cost-efficiency, particularly

TABLE 5 | BESS capacity (Ah).

PV power plant (kWp)	Voltage (V)	Geothermal cooling (A h)	Conventional HVAC cooling (A h)
40	24	520	320
60	24	770	510
80	24	3200	2350
100	48	2800	2200

when integrated with PV systems. Their long cycle life and reliability, despite the initial investment, make them suitable for renewable energy applications that aim to maximize the usage of surplus energy. Future improvements in battery cost reduction and efficiency will further enhance the feasibility and attractiveness of these systems for both residential and commercial applications. By properly sizing the BESS according to surplus energy profiles, significant energy savings and increased self-consumption of renewables could be achieved, aligning with current sustainability goals.

4.4 | Economic Analysis

The economic analysis is focused on the comparison of conventional air–air cooling system and geothermal-based solution. The large performance difference between geothermal and conventional cooling is −34% for thermal heating and −26% for thermal cooling demand. Therefore, the energy saving to maintain the same operating conditions is around 25% lower per day, if geothermal energy solution is selected. An analysis of the initial capital expenditure in comparison to ongoing maintenance costs—see Table 6, reveals the inherent profitability of each installation. The results validate that geothermal systems exhibit superior economic performance when compared to conventional cooling systems. This fact is attributed to lower operating expenses and enhanced energy efficiency, leading to higher long-term returns on investment. Consequently, geothermal technology presents a more cost-effective solution for sustainable cooling applications. Additionally, a 20-year analysis indicates that by the 9th year, the initial investment difference of €40,000 between the geothermal energy solution and the conventional air-to-air HVAC systems is fully recovered (Table 7). Subsequently, geothermal energy solutions have become more profitable, mainly because of their significantly lower maintenance costs. This fact highlights the long-term financial advantages of geothermal systems, making them a more economically sustainable option throughout the installation life cycle [78]. The system was evaluated over a projected lifetime of 25 years, considering an electricity cost of 0.20 €/kW h. Operational parameters include 1500 annual operating hours for the compressor and 1800 h for the circulation pump. The installed capacity comprises a 7 kW circulating pump (CCP) and a 32 kW heat pump (CHP). Annual operating expenses were estimated at €2520 for the circulating pump and €4773 for the heat pump, reflecting both energy consumption and maintenance requirements.

TABLE 6 | Economic analysis of cooling system.

Annual analysis	Geothermal	Conventional air–air
Electricity consumed	47.68 MW h	80.51 MW h
Thermal energy produced	214.58 MW h	250.79 MW h
Initial investment	120,000 €	80,000 €
OPEX	7152.65 €/year	12,076.98 €/year
LCOH	33.33 €/MW h	48.16 €/MW h

TABLE 7 | Net present value (NPV).

Year	OPEX geothermal (€)	OPEX conventional air–air (€)	Savings (€)	NPV (€)
0	0	0	0	−40,000.00
1	7152.65	12,076.98	4924.33	−35,075.67
2	14,305.31	24,153.96	9848.65	−30,151.35
3	21,457.96	36,230.94	14,772.98	−25,227.02
4	28,610.61	48,307.92	19,697.31	−20,302.69
5	35,763.27	60,384.90	24,621.64	−15,378.36
6	42,915.92	72,461.88	29,545.96	−10,454.04
7	50,068.58	84,538.87	34,470.29	−5,529.71
8	57,221.23	96,615.85	39,394.62	−605.38
9	64,373.88	108,692.83	44,318.94	4318.94
10	71,526.54	120,769.81	49,243.27	9243.27
11	78,679.19	132,846.79	54,167.60	14,167.60
12	85,831.84	144,923.77	59,091.92	19,091.92
13	92,984.50	157,000.75	64,016.25	24,016.25
14	100,137.15	169,077.73	68,940.58	28,940.58
15	107,289.81	181,154.71	73,864.91	33,864.91
16	114,442.46	193,231.69	78,789.23	38,789.23
17	121,595.11	205,308.67	83,713.56	43,713.56
18	128,747.77	217,385.65	88,637.89	48,637.89
19	135,900.42	229,462.63	93,562.21	53,562.21
20	143,053.07	241,539.61	98,486.54	58,486.54

The Spanish electric self-consumption regulation was initially governed by Royal Decree 15/2018, and later amended by Royal Decree-Law 244/2019. Self-consumption includes PV installations with a contracted power capacity below 100 kW and does not provide any compensation for surplus electricity fed back into the grid. The primary cost to account for is the initial investment, which consists of the net cost plus the applicable value added tax (VAT). The surplus energy of each cooling system solutions and PV installations were subsequently considered for the BESS budget. It also included inverter efficiency, battery depth of discharge and charger efficiency, assuming one-day of autonomy. Table 8 shows the cost of each battery equipment, according to each cooling system and PV power plant solution.

In order to perform a comprehensive analysis of all factors, the ratio called "rate of return" was determined and evaluated (Table 9). It was compared the annual savings on the electricity bill versus the initial investment: initial investment of PV installation and battery; annual electricity savings, depending on the refrigeration system; OPEX of the refrigeration system.

The rate of return of geothermal energy is higher than that of the air–air system in all cases. There are even air–air installations in which the maintenance cost and the initial investment exceed the annual savings, so the ratio is negative, indicating the

TABLE 8 | Battery capacity comparison.

PV power plant (kWn)	Geothermal system		HVAC conventional system	
	Battery capacity (Ah)	Cost (€)	Battery capacity (Ah)	Cost (€)
40	520	4536.92	319	3281.81
60	962	8224.71	638	4.898,61
80	3193	21,628.70	2345	16.567,61
100	2783	40,274,41	2127	31.599,59

TABLE 9 | Rate of return.

PV power plant (kWp)	Geothermal BESS (%)		Air–air HVAC BESS (%)	
40	2.12	−9.27	2.23	−8.42
60	4.90	−4.57	4.69	−3.86
80	7.94	2.25	7.57	0.46
100	9.94	4.87	8.15	4.61

TABLE 10 | Hybrid systems. Environmental analysis.

PV power plant (kWn)	Produced Energy (MWh/year)	Emissions (tons CO_2/year)
40	71.95	52.49
60	86.60	63.18
80	124.12	90.56
100	150.78	110.01

unfeasibility of the project. PV 80 and 100 kWp power plants are the most profitable PV installations. Indeed, they generate surplus energy enough to feed and sell to the grid, increasing notably the NPV of the project.

4.5 | Environmental Analysis

Nowadays, the use of renewable energies contributes to reducing energy consumption. Society is more aware of the proper use of energy and the electrical equipment used is increasingly optimized, so it uses less electrical energy, so energy waste is lower. Using renewables for power generation reduces the pollutant emissions emitted into the atmosphere [79], as they do not emit any type of pollution during operation. It is true that during the manufacturing process, emissions are emitted in its development, manufacture, and assembly, as well as the transport of the equipment to the installation site [80], but even so, the amount of emissions is lower than other methodologies of electricity generation. In Europe, there is a European Regional Development Fund (ERDF) [81], establishing the objectives of sustainable development. The ERDF, according to its studies, proposes conversion factors to estimate the quantities of CO_2 that would be avoided to be emitted into the atmosphere with the conventional generation of electric energy. These amounts, with the acronym of "tep," are estimated by the ERDF [82], according to the following values: 0.19 tep/MW h of electrical energy generated; and CO_2 emissions would be equivalent to 3.84 tons·CO_2/tep.

The equation for the number of tonnes avoided can be determined as:

$$\text{tons} \cdot CO_2/\text{year} = \text{Produced energy (MWh/year)} \cdot 0.19\ \text{tep/MWh} \cdot 3.84\ \text{tons} \cdot CO_2/\text{tep}.$$

In this case, by considering the installed power of each case study and the corresponding generated power, the emission of a large amount of CO_2 into the atmosphere could be avoided by the integration of solar resource. These avoided emissions can be seen in Table 10. If the estimated lifetime of a PV installation is assumed as 30 years, 3300 tons of CO_2 could be avoided during the entire lifetime of the installation, corresponding to the emissions of 160 cars per year [83].

4.6 | External Validation and Comparison With Hybrid Systems in Other Climates

To validate the results obtained and contextualize them within the international state of the art, Section 4.6 compares the performance of the proposed geothermal–PV–BESS configuration in Albacete (Mediterranean-continental climate) with similar hybrid systems reported in the literature. The case study analyzed in this work, which achieved an average reduction of 25% in electricity consumption compared to a conventional air–air HVAC system, aligns with the performance ranges reported for SAGSHPs and other hybrid geothermal–PV configurations. In our case, the GSHP exhibited $COP_{heating} = 4.6$ and $SPF_{cooling} = 4.4$, coupled with PV plants between 40 and 100 kWp and optional integration of BESS. The oversizing of the PV system (up to 100 kWp) and the inclusion of BESS allowed significant improvements in self-consumption and additional economic profitability. These results are consistent with those obtained by references [24–29], which reported similar improvements in efficiency and energy savings for hybrid geothermal–solar systems operating under diverse climatic conditions. In this way, Sun et al. [27] demonstrated seasonal heat-storage SAGSHP systems achieving SCOP values around 4.3 and up to 30% higher efficiency than standalone GSHPs, while Neves et al. [25] found annual electricity reductions between 22% and 28% in PV–geothermal residential systems. Similarly, Li et al. [24] and Ayub et al. [28] confirmed that hybridization with solar resources enhances both thermal efficiency and economic profitability, especially when combined with energy storage or power management strategies. Table 11 summarizes the main features and performance indicators of representative hybrid systems compared to the present case study. The hybrid

TABLE 11 | Comparison of hybrid geothermal and PV solar systems under different climates.

Study	Climate/ location	Use	Configuration	Performance	Main findings
Case study (Spain)	Mediterranean	Industrial/ tertiary	GSHP 42 kW_{el}; COP 4.6/ SPF 4.4; PV 40–100 kWp; optional BESS	−34% (heating) and −26% (cooling) demand vs. air–air HVAC	25% lower electricity use; positive NPV after 9 years
[27]	Temperate (China)	Office	SAGSHP + seasonal storage	SCOP 4.3; 20%–30% higher efficiency	Demonstrated stable operation with storage integration
[26]	Various	Review	Review of SAGSHP systems	SCOP range 3.5–5.0; savings 15%–40%	Confirming SAGSHP viability across climates
[25]	USA (continental)	Residential	PV + GSHP	Electricity reduction 22%–28%; SCOP 4.0–4.8	Near-zero energy performance
[29]	Temperate (Mexico)	Tertiary	Solar cooling and GHE	+10%–20% solar fraction	Synergy between geothermal and solar exchange
[28]	Arid (industrial)	Industrial	ORC + CSP + geothermal	Improved peak management	Enhanced hybrid performance for industry

system developed for the Mediterranean-continental case study demonstrates performance metrics that are consistent with those reported for similar hybrid configurations globally. The observed alignment in COP and SPF values, coupled with significant energy savings and favorable economic indicators, reinforces both the reliability and the potential scalability of the proposed approach.

5 | Conclusion

Nowadays, combining of hybrid systems is crucial for a sustainable development. Countries are developing sustainable projects and initiatives to promote the implementation of such hybrid and renewable solutions. Geothermal installations are fully compatible with other renewables and, in combination with another source such as PV, it could be possible to reduce to zero the energy consumption and thermal energy needs of an averaged residential demand. In addition, the potential PV generation uncertainty can be complemented by the use of BESSs. Under this framework, this paper describes and evaluates a methodology to optimize geothermal–PV hybrid systems including BESS for tertiary and industry sector applications. A case study is evaluated on an industrial and tertiary building—located in Albacete, Southeast of Spain. The location presents extreme temperatures throughout the year, requiring a high thermal energy demand for cooling and heating purposes. In this case, the current customer has a conventional air–air HVAC system. From the results, the hybrid solution based on a geothermal–PV–BESS system reduces the electricity consumption by 25% lower than the conventional air–air HVAC system. The large performance difference between geothermal and conventional cooling is −34% for thermal heating and −26% for thermal cooling demand. By considering different PV rate power installations, when combining the profitability of a geothermal system with a PV installation, complemented by a BESS such as the 80 kW or 100 kWn systems, the overall cost-effectiveness of the hybrid system is significantly enhanced. The hybrid configuration benefits from the low energy consumption of the geothermal system and the substantial surplus electricity generated by the PV array, which can be stored in the BESS. This surplus not only covers the energy demand but also generates a continuous revenue stream, effectively offsetting the initial investment overtime. The positive return on investment (ROI) indicates the economic viability of the system, making it a highly attractive solution. Therefore, the integration of 80 or 100 kWn PV systems with BESS and geothermal technology would represent an optimal choice for customers, providing long-term profitability and aligning with their energy requirements. The economic study in Section 4.4 provides a comparison between the proposed hybrid solution based on geothermal technology and a conventional air–air HVAC system. As can be found in Table 7, a comparative economic analysis demonstrates that the geothermal solution achieves greater financial viability (i.e., crosses the profitability threshold) than the air-to-air HVAC system within a 9-year period.

In conclusion, hybrid renewable systems, particularly when paired with optimized thermal configurations, represent a highly effective approach to achieving economic and environmental sustainability. These proposed systems enable improved energy efficiency, increased energy independence, and faster ROI, making them an ideal solution for industries and residential applications that seek to reduce costs while supporting renewable energy adoption. Furthermore, as renewable technologies continue to advance and become more accessible, the potential of these hybrid systems to play a pivotal role in the global energy transition is increasingly promising. The proposed hybrid solutions is able to be implemented in other locations and countries, considering their specific compensation for surplus energy and the PV regulation for self-consumption purposes under both tertiary and industrial sector.

Author Contributions

Agustín Sánchez-Del Rey: conceptualization (lead), writing – original draft (lead), formal analysis (lead). **Angel Molina-García**: software (lead), writing – review and editing (equal), methodology (lead). **Isabel**

C. Gil-García: conceptualization (supporting), writing – original draft (supporting), writing – review and editing (equal). **Adela Ramos-Escudero**: software (lead); writing – review and editing (equal), methodology (lead), writing – review and editing (equal).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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