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Energy technologies for hybrid renewable energy systems: a study of spatially viable sites for hybrid power plants in Spain

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The integration of renewable energy sources is essential for sustainable electricity generation, but the variability of solar, wind, and other renewable sources can compromise grid stability. Hybrid renewable energy systems, which combine multiple renewable technologies with or without backup generators, can enhance reliability and reduce dependence on non-renewable sources. This study addresses the challenge of identifying optimal sites for the deployment of hybrid renewable energy systems in Spain, where diverse climatic conditions and geographic variability influence renewable potential. The suitability of five renewable sources (solar, wind, biomass, hydro, and geothermal) is evaluated using scientific databases, thus determining the spatial compatibility of resources. Pairwise hybridizations among these sources are analyzed to identify locations that maximize resource complementarity. The results provide a spatially resolved framework for hybrid renewable energy planning and site selection across varied Spanish regions.

KEYWORDS

hybrid renewable energy systems, technical feasibility, operating conditions, geographic factors, resource assessment

1 Introduction

Humanity is currently facing one of the most critical challenges in its history: climate change. Climate change, the result of decades of human activity driven by the excessive burning of fossil fuels, has assumed alarming proportions. Its effects—observed in extreme weather events, ecosystem disruptions, ocean acidification, and the rapid loss of biodiversity, among others—serve as clear reminders of the urgent need to adopt more sustainable practices, requiring immediate global action (Weiskopf et al., 2020). Increasing greenhouse-gas emissions and dependence on conventional energy sources pose significant challenges for humanity (Paraschiv and Paraschiv, 2020). It is, therefore, necessary to rethink our relationship with energy and work toward a more sustainable energy matrix (Gil-García et al., 2024). In this context, the transition to renewable energy sources (RESs) is presented as a fundamental response, constituting an essential pillar in the fight against climate change and the effort to achieve a future where dependence on fossil fuels is gradually eliminated (Mufutau Opeyemi, 2021).

RESs not only offer a cleaner alternative to fossil fuels but are also characterized by their inexhaustible potential as they are constantly renewable and, therefore, do not disappear when their energy is used (Halkos and Gkampoura, 2020). RESs encompass a variety of technologies, including the following (Fernández-Guillamón et al., 2019a):

- Wind power, both onshore and offshore installations.
- Solar power, both photovoltaic (PV) and thermal power.
- Hydroelectric power.
- Bioenergy.
- Geothermal power.
- Ocean energy, consisting of tidal and wave power.

In 2022, RESs accounted for 30% of global electricity generation, with hydro, PV, and wind energy representing 90% of renewable electricity generation worldwide, as shown in Figure 1. Global electricity generation in 2022 was approximately 29,165 TWh, which means that renewable sources contributed approximately 8,750 TWh (International Energy Agency, 2023). Including this absolute value allows for a clearer understanding of the scale of renewable electricity generation. According to Bórawski et al. (2020), a total wind energy capacity of 323 GW is projected to be installed in the EU by 2030, with 253 GW being onshore and 70 GW being offshore. This capacity is expected to generate 2,681 TWh by 2030 compared to the 342 TWh produced by wind energy in 2010 (Ellabban et al., 2014). Meanwhile, wind power capacity in the United States is expected to reach 305 GW, while in China, it is projected to reach 230 GW by 2030 (Shahan, 2011). Additionally, the global solar capacity is forecasted to reach 192 GW by 2030, leading to an increase in solar energy production from 32 TWh in 2010 to 846 TWh in 2030 (Ellabban et al., 2014).

However, from the electrical grid point of view, both wind and solar plants have a common characteristic: their production depends on the instantaneous availability of primary energy (wind and solar irradiation, respectively), which makes it extremely difficult to control the energy they generate, and therefore, they cannot be used to follow demand fluctuations (Fernández-Guillamón et al., 2019b); a similar problem is faced by run-off-river hydroelectric power plants (Gerini et al., 2021). In this regard, run-of-river hydropower plants exhibit a similar behavior as they lack the capacity to regulate turbine flow and, consequently, power generation (Sarasua et al., 2007).

As a concrete example, with the rapid advancement of wind power technology, the penetration rate of wind energy in some regions of China has surpassed 20% (Zhu et al., 2011), leading to notable negative impacts on the dynamic stability of power grids and frequency and voltage regulation (Wu and Infield, 2014). Generally, these negative effects on the electrical grid are associated with a decline in the quality of the power supply, making it challenging to maintain frequency (Wang et al., 2016) and voltage (Georgilakis, 2008) within the limits set by the transmission system operators (TSOs). These issues are particularly problematic in isolated power systems, where load-shedding programs are often activated to compensate for fluctuations in power demand or generation from non-controllable renewable sources (Martínez de Lucas, 2018; Sarasúa et al., 2021). As a result, maintaining frequency within the required limits becomes significantly more difficult. Pre-planned load-shedding may be necessary (Sharma et al., 2011) as an emergency response when frequency falls below certain thresholds set by the TSO to prevent damage to consumer loads.

RESs are inherently intermittent, but the degree of intermittency varies among them. Wind, for instance, is a highly variable meteorological factor that fluctuates on an hourly, daily, weekly, monthly, and annual basis. In contrast, solar radiation is a more predictable energy source, with less variability, though it only operates during daylight hours. From a power quality perspective, solar energy provides more stable power and can be integrated with smaller energy-storage systems (Alam et al., 2014). This fluctuating nature of renewable energy sources presents challenges for consistent power production, making it difficult to ensure a continuous supply to end users and maintain grid stability.

In terms of unpredictability, wind speed forecasting has significantly improved in recent years, as highlighted by a review of wind power prediction models (Wang et al., 2011). Therefore, the primary challenge for effectively integrating these technologies is managing the intermittency and stochastic behavior that is inherent to most of them (Canales et al., 2015). Regarding demand independence, wind and solar resources do not align with consumption patterns, either in the short or long term. A potential benefit lies in situating future wind farms in locations where wind patterns better match the electricity demand rather than simply selecting sites with the highest average wind speed (Suomalainen et al., 2013).

As a consequence, hybrid renewable energy systems (HRESs), where different RESs are combined (with or without backup energy systems, such as energy storage systems, ESSs), have been developed as a solution to this problem (Lian et al., 2019). These HRESs ensure a constant supply of electricity even under varying conditions, thus offering higher reliability than individual power sources, especially for off-grid (isolated) systems. In addition, they make it possible to take advantage of the best of each technology, achieving greater efficiency, lower operating costs, and more flexible use of energy resources, and they can be adapted to various needs and contexts, from urban environments to remote areas (Sohail et al., 2022). Various methods are discussed in the literature to mitigate the negative impacts of high renewable energy penetration. In terms of ESSs, many researchers argue that storing energy in the short, medium, and long term is an effective way to support the growth of RESs and alleviate some of their limitations. For instance, Zhao et al. (2015), Aneke and Wang (2016), Parra et al. (2017), and Mitali et al. (2022) have conducted comprehensive reviews of available ESS technologies in recent years, highlighting the importance of technologies such as pumped-storage hydroelectric plants (PSHPs) due to the regulating capacity of hydropower plants, flywheels, batteries, and capacitors. Additionally, ESS capacity has grown significantly in recent years. According to Agency (2014),

Abbreviations: HRESs, hybrid renewable energy systems; PSHPs, pumped-storage hydroelectric plants; PV, photovoltaic; RESs, renewable energy sources; TES, thermal energy storage; TSO, transmission system operator; USA, United States of America.

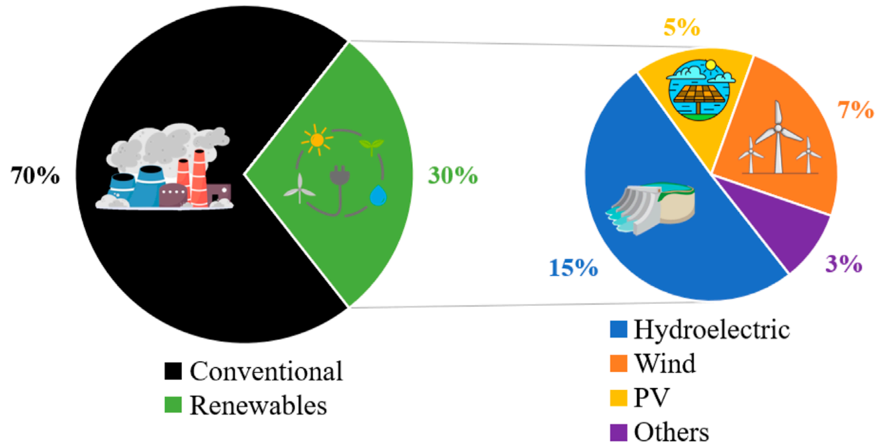

FIGURE 1
Global electricity generation by source in 2022; data from (Energy Institute, 2024).

approximately 140 GW of large-scale ESSs were installed in global power grids in 2014. Of this capacity, 99% was contributed by PSHPs, with the remaining 1% coming from a combination of batteries, compressed air energy storage, flywheels, and hydrogen storage. However, these figures increased within just 4 years; by 2018, the global ESS capacity had risen to 170 GW, with PSHPs accounting for more than 96% of that (Gür, 2018). As noted by Barnhart and Benson (2013), ESSs are a valuable load-balancing technology, enhancing the reliability and flexibility of power grids—particularly in regions with strong climate-change policies—while also helping lower carbon emissions by reducing transmission loads and enabling power plants to operate at peak efficiency.

In a global context focused on the transition toward cleaner and more sustainable energy sources, HRESs are positioned as a promising alternative, providing flexible and efficient solutions to satisfy the growing demand for electricity in an environmentally friendly manner (Vivas et al., 2018). Today, there are numerous success stories of hybrid systems (Alternative Technology Association, 2017). The island of Ta'u (American Samoa) relied on diesel generators until 2016, when Tesla installed a hybrid electric system consisting of 1.4 MW of PV capacity and 6 MWh of batteries (Lin, 2017). Two Australian islands (King Island and Rottnest Island) use hybrid wind–PV systems. The first, with 2.45 MW and 470 kW of wind and PV power, respectively, is backed by a range of support and storage technologies (batteries, flywheels, diesel generators using biodiesel, etc.) (Tasmania, 2014). The second island combines 600 kW of wind and 600 kW of PV power with a diesel power plant (Rottnest Island Authority, 2024). The island of Eigg (Scotland) has a hybrid system consisting of three hydroelectric generators (100, 6, and 5 kW), four wind turbines (6 kW each), and a PV installation (170 kW), supplying 95% of the total electricity. The remaining 5% is generated by two 64 kW diesel generators, which serve as backup when RESs are in short supply or during maintenance (Isle of Eigg Heritage Trust, 2024). Two notable cases stand out in the Spanish electricity system. First, a hybrid wind and pumped-storage hydropower facility, known as Gorona del Viento, was commissioned in June 2014 within the El Hierro power system. This pumped-storage plant includes four Pelton units (4 × 2.83 MW), six fixed-speed pumps (6 × 0.5 MW), and two variable-speed pumps (2 × 1.5 MW). In recent years, the importance of this complex power plant has grown within the power system. During the summer of 2019, electricity demand was met continuously and solely by RESs for a total of 596 h (Sarasúa et al., 2021). Second, Termosolar Borges, located in Les Borges, is currently the only operational hybrid thermal solar–biomass power plant, boasting a capacity of 22.5 MWe. This hybrid approach allows the plant to supply electricity around the clock, achieving an efficiency rate of 90% (Mohaghegh et al., 2021).

The main objective of this work is to carry out a spatial analysis of the technical viability (from the resource point of view) of different technologies applicable to HRESs, including pairs of combinations between solar, wind, hydroelectric, biomass, and geothermal power plants. The study considers the entire national territory of Spain, encompassing both the mainland and insular regions, including the Balearic and Canary Islands, accounting for regional variations in the different RESs analyzed. To overcome this, an analysis of the main parameters and characteristics affecting each of the RES considered is carried out to determine the optimum location of such power plants. The research study offers a novel combination of geographic, climatic, and technical factors to identify the most suitable locations for HRESs, which can optimize resource utilization and address intermittency issues inherent to individual RESs. Even though this study provides a framework for HRESs in Spain, it offers insights that are broadly applicable to other regions striving to transition to a more sustainable and resilient electricity future. The remainder of this study is organized as follows: Section 2 describes the methodology used; the case study is presented in Section 3; Section 4 details the results obtained, which are discussed in Section 5; finally, the conclusions are presented in Section 6.

2 Methodology

This work is based on a systematic literature review methodology, with a particular focus on the parameters affecting the efficiency and adaptability of several RES technologies. The RESs under analysis involve the following:

- Solar power plants (PV and thermal).
- Wind power plants.
- Hydropower plants.
- Biomass power plants.
- Geothermal power plants.

These technologies were selected due to their maturity, scalability, and commercial availability in the Spanish context. Moreover, several of them exhibit complementary generation profiles, such as diurnal (solar) versus nocturnal (wind) generation or controllable (geothermal, hydropower, and biomass) versus variable (solar and wind) output. Additionally, the chosen RESs can be scaled and adapted to a range of energy demands, which vary from small-scale systems to large utility-scale projects.

The research follows a three-stage process, as depicted in Figure 2:

1. Literature review and parameter identification: The first phase involves a comprehensive review of academic publications and institutional reports to identify the main factors influencing the efficiency and viability of the RES technologies. For each technology, technical and some economic parameters are identified to determine the suitable location of each RES, i.e., solar irradiation, wind speed, hydrological features, and biomass availability, among others.
2. Location analysis and mapping: Based on the parameters identified in the previous stage, the most suitable locations for each of the RES were determined using available datasets and regional studies and applying resource-related thresholds. Since these parameters were either to be maximized or minimized, areas with medium-to-high or medium-to-low resource availability, respectively, were considered. For each RES, simplified maps were manually created by overlaying and comparing relevant resource-related criteria on a map of Spain. This process involved visually referencing zones as reported in official national and regional energy or environmental reports and shading the corresponding areas accordingly. Although GIS software was not used, the mapping process followed a consistent interpretive framework that prioritized data quality, geographic coverage, and reproducibility. These criteria and thresholds are discussed in detail in the following sections for each technology.
3. Integration and HRES suitability mapping: In the final phase, the individual maps are combined in pairs to analyze the complementarity between RES technologies. Each map reflects zones where multiple sources converge in identifying favorable conditions, thus minimizing subjective bias by relying on well-documented criteria and cross-referenced spatial patterns. Factors such as temporal availability (e.g., solar during the day and wind at night), controllability (e.g., hydropower and biomass vs. intermittent sources), and regional synergies are considered and analyzed in the discussion (Section 5). The goal is to identify areas where the integration of multiple RES technologies can result in hybrid systems.

The final HRES suitability map provides valuable insights for the following aspects:

- Resource optimization and planning: It allows for the identification of areas with the highest potential for RES generation, maximizing the use of available natural resources and identifying high-potential zones for renewable energy deployment.
- Cost reduction: Knowing the most suitable locations in advance can reduce costs associated with exploration, feasibility studies, and planning errors. It also helps avoid overinvestment in low-performance areas.
- Strategic planning and development: It facilitates decision-making for both public and private stakeholders (governments, businesses, etc.) to develop more efficient energy infrastructure, contributing to a faster and more effective energy transition tailored to regional characteristics.
- Grid integration: Identifying the best locations also allows for better planning of how the energy generated will be integrated into the electrical grid, thus optimizing distribution and reducing energy losses during transmission.

2.1 Solar power plants

Solar energy comes from the Sun in the form of radiation, a product of the Sun's internal nuclear energy, which is transformed into solar radiation through fusion processes (Kalogirou, 2023). This energy can be harnessed in the form of solar thermal and PV, with the latter being the most developed for electricity generation (Ahmad et al., 2020). PV power plants consist of panels made up of photovoltaic cells that convert solar radiation into direct current through the photovoltaic effect (Singh, 2013). However, when these panels are exposed to sunlight, they experience heating, which causes their efficiency to decrease. Specifically, for each degree Celsius increase in temperature, the panel's efficiency decreases by a few millivolts due to a reduction in open circuit voltage, resulting in an overall efficiency loss of approximately 0.4%–0.5% per degree of temperature increase (Nwaigwe et al., 2019). Conversely, solar thermal power plants utilize concentrating collectors to gather sunlight from a vast area and focus it onto a small, darkened receiver, significantly enhancing the light's intensity to generate high temperatures (Romero et al., 2017). The arrays of mirrors or lenses can concentrate a sufficient amount of sunlight to heat a target to temperatures exceeding 2,000°C. This heat can then be employed to operate a boiler, which produces steam for a steam turbine power plant (Olabi et al., 2022). Apart from the differences in the way electricity is generated, it is worth highlighting the capacity to regulate the electricity generated by solar thermal power plants (similar to a conventional thermal power plant, as long as the solar radiation is available) as opposed to PV plants. Moreover, they usually include some thermal energy storage (TES), making the intermittent solar resource controllable. Although other factors such as panel orientation, tilt angle, regional climate, and the presence of shading can affect the solar performance, they were not included as they depend specifically on the location and should be optimized from one installation to another. Consequently, incident solar irradiation was selected as the primary determinant factor because it directly dictates the energy input to the solar systems and is consistently available across meteorological datasets. Moreover, as the database used is referenced to the

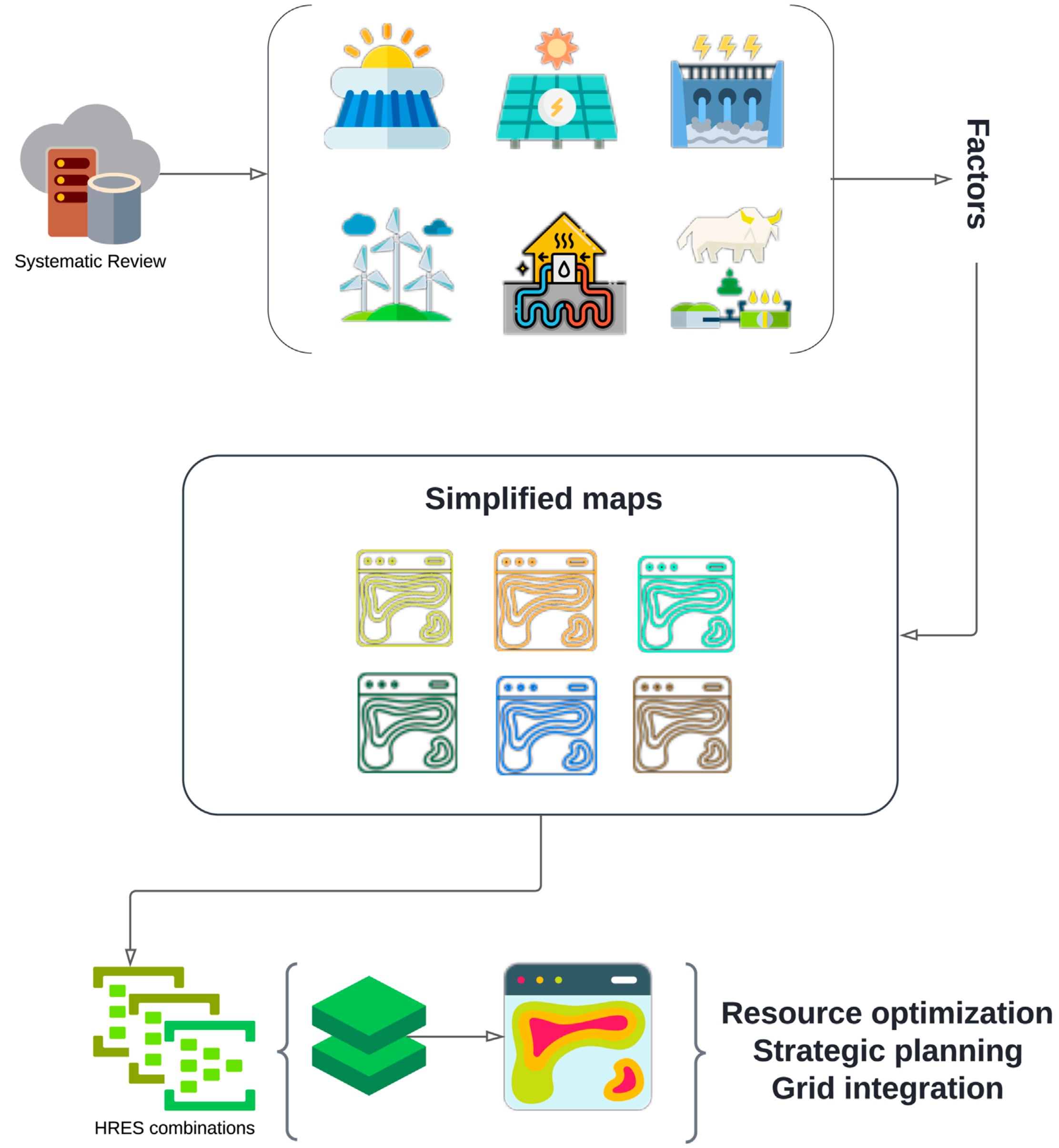

FIGURE 2
Methodology of the literature review to obtain the simplified HRES maps.

optimum angle, the tilt angle can also be considered as being directly included.

2.2 Wind power plants

Wind energy is based on the kinetic energy of a moving air mass. Its origin lies in the existence of air masses at different temperatures. This temperature difference is caused by different intensities of solar radiation at the global and local levels, which produce ascending and descending currents, forming rings of air circulation (Emeis, 2018). Wind power plants are installations that harness this energy to turn a wind turbine that transmits its mechanical rotational energy to the axis of an electrical generator, where electrical energy is produced (Chaudhuri et al., 2022). Unlike conventional power plants, where the electric generator is always a synchronous machine, wind power plants tend to be dominated by asynchronous generators, whose operation is better adapted to changing wind conditions and whose cost is more economical (Souza Junior and Freitas, 2022). The most important factors to consider for the implementation of wind power plants are wind speed, wind direction and consistency, the availability of large areas without the presence of obstacles (such as trees or buildings), and the height (Rehman et al., 2019). For this study, the average wind speed and hub height were selected as key variables due to their strong influence on energy yield and their availability from mesoscale models. Other factors, such as turbulence intensity or wind shear coefficients, while relevant, were excluded due to limited regional data and their secondary influence compared to that of wind speed and turbine hub height.

2.3 Hydroelectric power plants

Hydropower is obtained from any moving body of water (such as the current of a river or the current flowing through a conduit caused by a difference in height between two reservoirs) (Yang, 2024). Hydroelectric power plants use hydropower, which is characterized in terms of flow rate and head. Hydraulic energy is transformed into mechanical energy (manifested in the form of mechanical torque and rotational speed) in a hydraulic turbine, whose shaft is directly coupled to the shaft of an electric generator, where the mechanical energy is transformed into electricity (Ånund, 2019). In addition, hydroelectric power plants can vary in size and design: from small plants installed on local rivers to large dams with extensive reservoirs (Mayor et al., 2017). Consequently, hydropower production is intrinsically linked to the geography and terrain of the site where it is installed. The topography of a given area influences the availability and flow of water, which directly affects the efficiency and capacity of power generation (Bódis et al., 2014). To analyze the locations where this technology could be implemented, three factors will be taken into account: abundance of rainfall, presence of natural water streams, and terrain with differences in altitude in order to take advantage of the potential. The choice of these factors reflects the basic hydrological and topographic requirements for hydroelectric feasibility. Other variables, such as seasonal flow variability or sedimentation risk, were excluded due to limited spatial resolution or the need for detailed on-site hydrological studies in each location.

2.4 Biomass power plants

Biomass energy is the form of renewable energy obtained from organic matter, such as agricultural residues, forestry residues, organic waste, and specific energy crops (Janiszewska and Ossowska, 2022). This type of energy is considered renewable for two key reasons: it is derived from sources that naturally replenish over a short period, and in most cases, the fuels used are plant-based, contributing to the carbon cycle and reducing the impact of emissions (Kalak, 2023). To install a biomass plant, the most important factor to consider is the proximity of the plant to the areas or installations from which the fuel will be sourced (Teixeira et al., 2018) as transporting biomass fuel over long distances can be expensive and inefficient, reducing the overall sustainability and cost-effectiveness of the energy production process (Viana et al., 2010); distances of approximately 30–70 km were proposed by Jayarathna et al. (2020). Therefore, to determine the possible locations of these plants, two factors will be taken into consideration: proximity to biomass sources and potential forest areas. They were prioritized as they directly influence logistical feasibility. Variables such as moisture content or calorific value of feedstock, while important for operational design, are highly variable and not easily mapped at a regional planning scale.

2.5 Geothermal power plants

Geothermal energy is a type of renewable energy that taps into the heat stored within the Earth's interior to produce electricity or provide heating (Chomać-Pierzecka et al., 2022). In the case of electricity generation, geothermal power plants are built where the heat obtained is used to heat water or other working fluids and move turbines through an open or closed cycle (Moya et al., 2018). Areas with high geothermal activity, such as volcanic regions or tectonically active areas, are the ideal areas for this type of installation with the technology available to date. However, there are state-of-the-art technologies, such as some deep drilling methods, that allow the geothermal potential of less active areas to be exploited (Coskun Avci et al., 2020). Although altitude can conceptually influence geothermal project development—especially in terms of drilling logistics and accessibility in mountainous areas—along with drilling depth and soil composition, they were not explicitly included as variables in the geothermal suitability analysis conducted in this study due to their indirect impact compared to that of geological heat availability.

2.6 Energy combinations for HRESs

For this specific work, the different RES combinations are obtained by pairing two RES technologies. The results that are obtained from these combinations are analyzed theoretically, considering only the main factors affecting the operating conditions of each of the RES technologies to determine the generalized locations in which each of the HRESs could be implemented. By combining them, a total of 10 HRES cases are analyzed as cases where the same technology overlaps cannot be considered as a hybrid system. It should be noted that the case solar–solar could be possible in cases where PV is combined with thermal solar. However, as the parameter considered for these power plants is the solar radiation, the optimum location would be the same as the solar radiation areas considered. Nevertheless, some studies have focused on this type of HRES (Tripanagnostopoulos et al., 2002; Chow et al., 2012; Gomaa et al., 2018; Khajepour and Ameri, 2020). Table 1 shows an overview of the 10 cases:

- Case 1: Solar–wind.
- Case 2: Solar–hydroelectric.
- Case 3: Solar–biomass.
- Case 4: Solar–geothermal.
- Case 5: Wind–hydroelectric.
- Case 6: Wind–biomass.
- Case 7: Wind–geothermal.
- Case 8: Hydroelectric–biomass.
- Case 9: Hydroelectric–geothermal.
- Case 10: Biomass–geothermal.

3 Case study

In this paper, Spain is selected as the case study area, considering the mainland and island regions. For each RES under consideration, different databases are used to obtain the relevant information

TABLE 1 HRES cases under consideration.

	Solar	Wind	Hydroelectric	Biomass	Geothermal
Solar	—	Case 1	Case 2	Case 3	Case 4
Wind	Case 1	—	Case 5	Case 6	Case 7
Hydroelectric	Case 2	Case 5	—	Case 8	Case 9
Biomass	Case 3	Case 6	Case 8	—	Case 10
Geothermal	Case 4	Case 7	Case 9	Case 10	—

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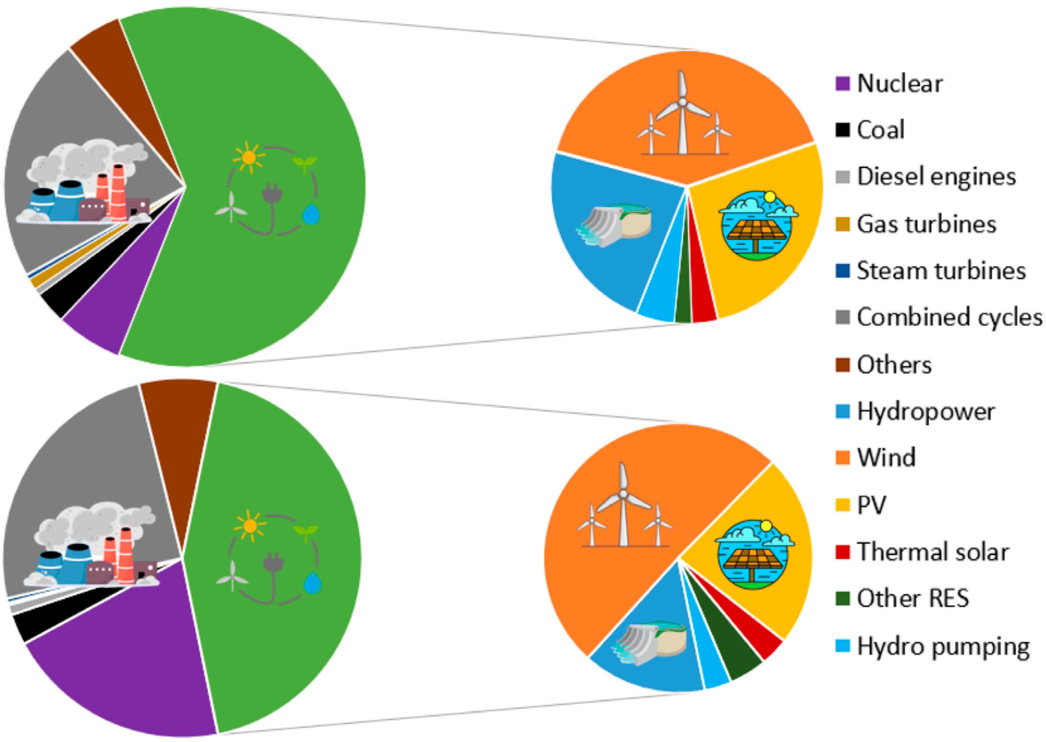

FIGURE 3
Electricity power system in Spain (2022). Upper: installed capacity; lower: generation.

regarding them. Apart from that, the TSO responsible for the Spanish power grid, "Red Eléctrica de España" (REE), releases a report on the Spanish grid each year, offering a detailed analysis of key metrics and operational statistics. The most recent available report is for the year 2022 (REE, 2023). The key data related to the Spanish electricity system at the end of 2022 are outlined below (see Figure 3):

- The total installed capacity was 119,091 MW, with 59.2% sourced from RESs. From the RES sector, 95% is generated from hydropower, wind, and PV sources.
- The electricity demand was 250,421 GWh, with 42.2% being produced from RESs. Similarly to the capacity, RES generation is mainly based on hydropower, wind, and PV, accounting for 88.7% of the renewable energy generation.

Spain's high RES generation is largely due to a mix of policies, infrastructure investments, and favorable natural resources (Escribano Francés et al., 2013; Matti and Consoli, 2015; Alonso et al., 2016; González et al., 2020; Jorge-Vazquez et al., 2024):

- Policy support: Spain has implemented subsidies, feed-in tariffs, and favorable policies that incentivize investment in RES technologies, particularly in wind and solar, which are the major RES contributors (onshore wind and solar PV).
- Strong infrastructure: Spain has developed a robust transmission grid that effectively integrates intermittent sources, supported by the country's TSO (Red Eléctrica de España, 2024).
- Diverse RES mix: Spain's varied RES mix includes a high proportion of onshore wind and solar PV, supported by

TABLE 2 Summary of the RES considered, including the key variables, thresholds/criteria, and data sources for the case study (Spain).

RES type	Key variable	Threshold/criterion	Data source
Solar	Solar irradiation at optimum angle	>1,700 kWh/m^2	Photovoltaic Geographical Information System. (2019)
Wind	Wind speed	Medium–very high	García-Pertierra. (2010)
	Height	50–200 m	Davis et al. (2023)
Hydroelectric	Mean accumulated rainfall	Medium-high–high	Agencia Estatal de Meteorología. (2024)
	Distance to natural watercourses	<1 km	Instituto Geográfico Nacional. (2024b)
	Terrain elevation	Medium–high	
Biomass	Forested zones	Productive forest plantations classified as valid biomass sources	Ministerio para la Transición Ecológica y el Reto Demográfico. (2011)
	Distance to biomass fuel producers	<50 km	Asociación Española de la Biomasa (AVEBIOM). (2022)
Geothermal	Subsurface temperature	>90°C	Instituto Geográfico Nacional. (2024a)

hydroelectric power and, to a smaller extent, thermal solar and biomass energy. Additionally, repowering is now being considered in most wind power plants (Colmenar-Santos et al., 2015).

- Regional implementation: Spain has leveraged the natural resources of each region to optimize RES deployment. For example, the northern regions focus on wind and hydroelectricity, while the southern regions leverage solar energy.

4 Results

Based on the literature review of the main parameters affecting the performance of the RES technologies under analysis carried out in Section 2, the optimal locations to install such power plants are analyzed. Table 2 presents a summary of the different RESs considered, including the key variables, thresholds/criteria for each factor, and the data sources from which the information was obtained, which are explained and detailed later.

After that and following the HRES cases under consideration (Table 1), the locations where the plants of different HRESs could be installed are presented.

4.1 Solar power plants

The PVGIS database and its official radiation maps were used to determine the most favorable areas for solar power plant deployment (Photovoltaic Geographical Information System, 2019). These maps were combined with the maps of "Agencia Estatal de Meteorología" (AEMET, the State Agency of Meteorology of Spain), which classify the national territory into five qualitative categories based on long-term average annual global horizontal irradiance: low, low–medium, medium, medium–high, and high (Sancho Ávila et al., 2012). For this study, only the areas classified as medium, medium–high, or high were considered suitable for solar power installations (i.e., >1,700 kWh/m^2 with optimum angle). This selection aims to ensure that only regions with sufficient solar resources are retained in the analysis. A simplified and generalized irradiance map was created (Figure 4A), and the resulting suitability zones for solar-based hybrid systems are shown in Figure 4B.

4.2 Wind power plants

The wind speed data used to generate the suitability map were obtained by combining datasets from the Spanish State Meteorological Agency (AEMET) (García-Pertierra, 2010) and the Global Wind Atlas (Davis et al., 2023). These datasets provide wind speed measurements taken at a consistent height above the local terrain surface, which typically range from 50 to 200 m, depending on the topography. The wind speeds were categorized into six classes: very high, high, medium–high, medium, low–medium, and low. This classification is based on the distribution of wind speeds measured at these terrain-following heights, thereby inherently accounting for the influence of elevation and terrain relief on wind patterns. Only areas with wind speeds in the medium to very high categories were considered suitable for wind power installations as these provide the best potential for efficient and economically viable energy generation. Wind speed data outside the 50–200 m height range were excluded because these heights fall outside the typical operational hub heights of commercial wind turbines. The simplified average wind speed map is presented in Figure 5A, and the selected suitable sites for wind power plants are shown in Figure 5B.

4.3 Hydroelectric power plants

For hydroelectric power plants, the mean accumulated rainfall, the presence of natural watercourses, and terrain elevation are considered. The databases used for this purpose are based on the AEMET climate maps (Agencia Estatal de Meteorología, 2024) and topographic maps from the "Instituto Geográfico Nacional"

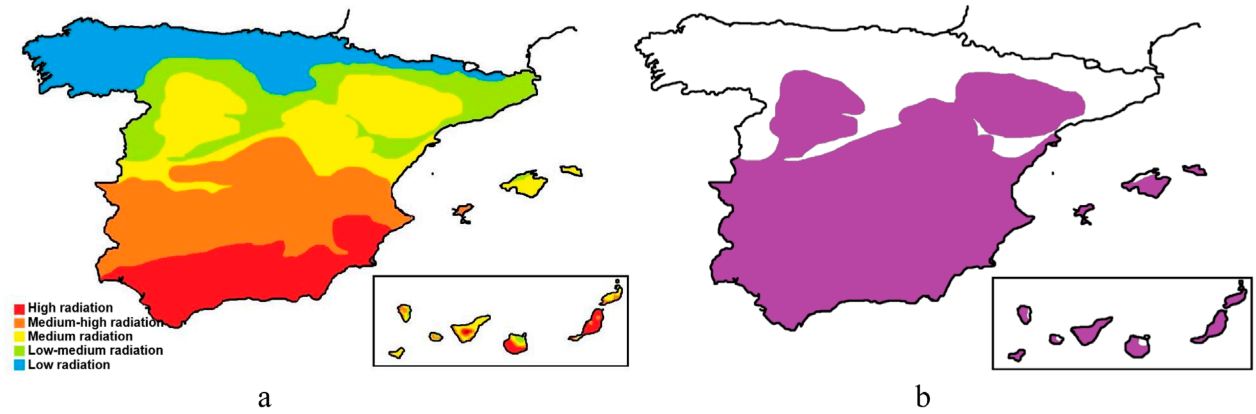

FIGURE 4
Solar radiation in Spain. **(a)** Simplified map and **(b)** suitable locations for solar power installations.

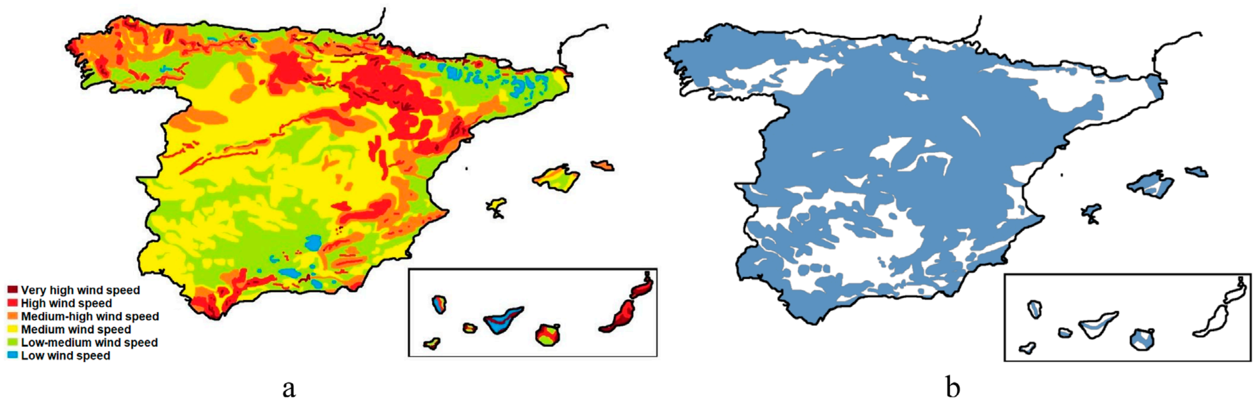

FIGURE 5
Average wind speed in Spain. **(a)** Simplified map and **(b)** suitable locations for wind power installations.

(National Geographic Institute) (Instituto Geográfico Nacional, 2024b). These three maps are simplified in Figures 6A–C. Elevation is classified into three categories: low (below 600 m), medium (600–1,200 m), and high (above 1,200 m). Precipitation is categorized into five levels by AEMET; for this study, only areas with medium-high and high rainfall are considered to indicate abundant precipitation. Proximity to natural watercourses is determined by applying a 1-km buffer around mapped rivers and streams. Distances greater than 1 km were excluded from the suitability analysis as long conduits would introduce significant head losses, rendering the installation economically unfeasible unless there is a very high available hydraulic head. Only those regions located in the medium and high elevation zones, with abundant rainfall, and within the defined proximity to a watercourse are considered suitable for hydroelectric power installations, as shown in Figure 6D.

4.4 Biomass power plants

The "Mapa Forestal de España" (Forestry Map of Spain) (Ministerio para la Transición Ecológica y el Reto Demográfico., 2011) was used to identify forested zones with biomass potential. Although this dataset is over a decade old, forest composition and productive plantation areas in Spain generally change slowly, particularly at the national scale that is relevant to this analysis. Therefore, it remains a valid reference for identifying long-term biomass availability patterns. Only productive forest plantations classified as valid biomass sources were included in the suitability analysis (Figure 7A). Areas such as shrublands, natural forests with low productivity, or cultivated zones requiring energy crops were excluded. To ensure more recent relevance, the "Mapa de los Biocombustibles 2022" (Biofuels Map 2022) (Asociación Española de la Biomasa (aveBIOM, 2022)) was used to locate biomass fuel producers. A buffer of 50 km was applied around each facility to reflect realistic transport distances, based on common logistic constraints. Figure 7B presents the final map of suitable areas resulting from the intersection of eligible forested zones and proximity to processing plants.

4.5 Geothermal power plants

The database used to generate the geothermal suitability map is based on data provided by the Instituto Geográfico Nacional

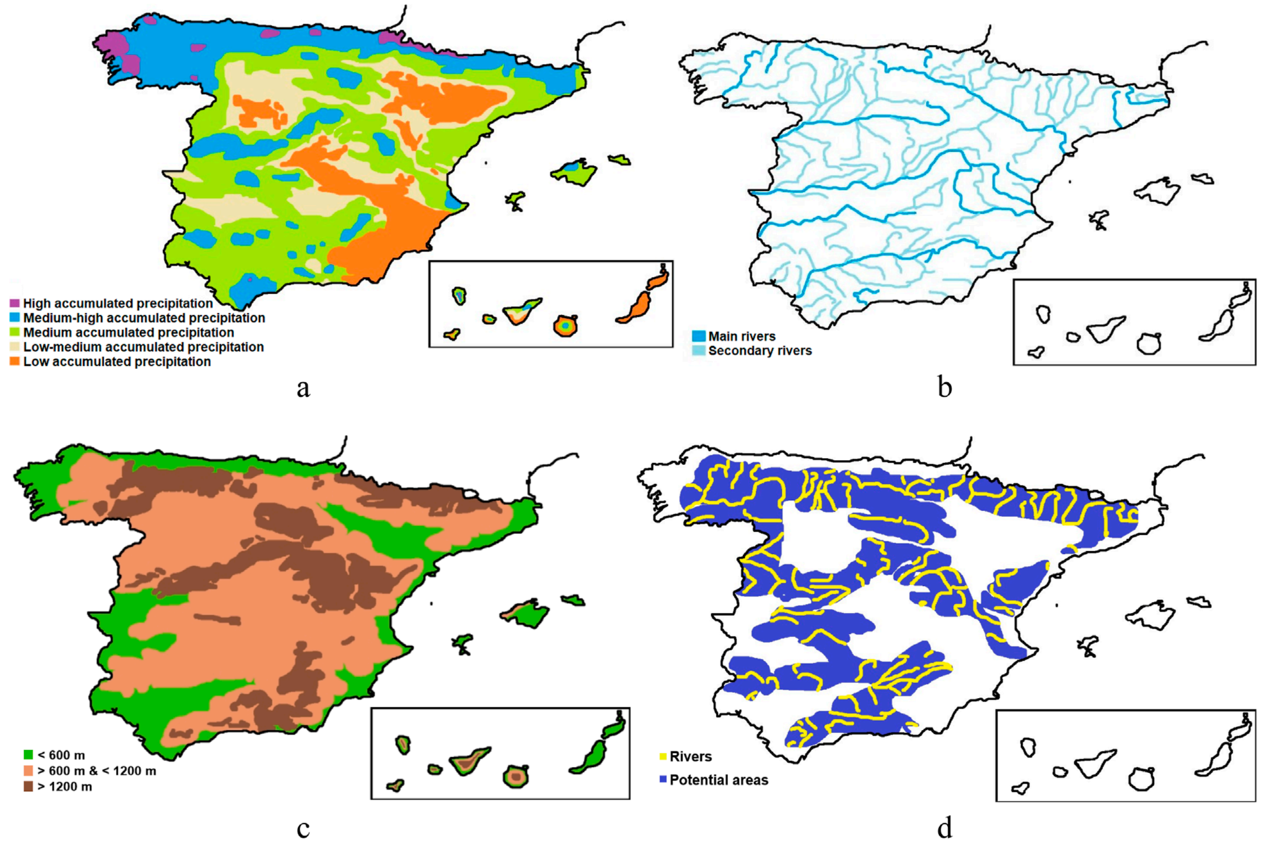

FIGURE 6
Average accumulated rainfall, natural watercourses, and altitude differences in Spain. **(a)** Average accumulated rainfall, **(b)** natural watercourses, **(c)** altitude differences, and **(d)** suitable locations for hydroelectric power installations.

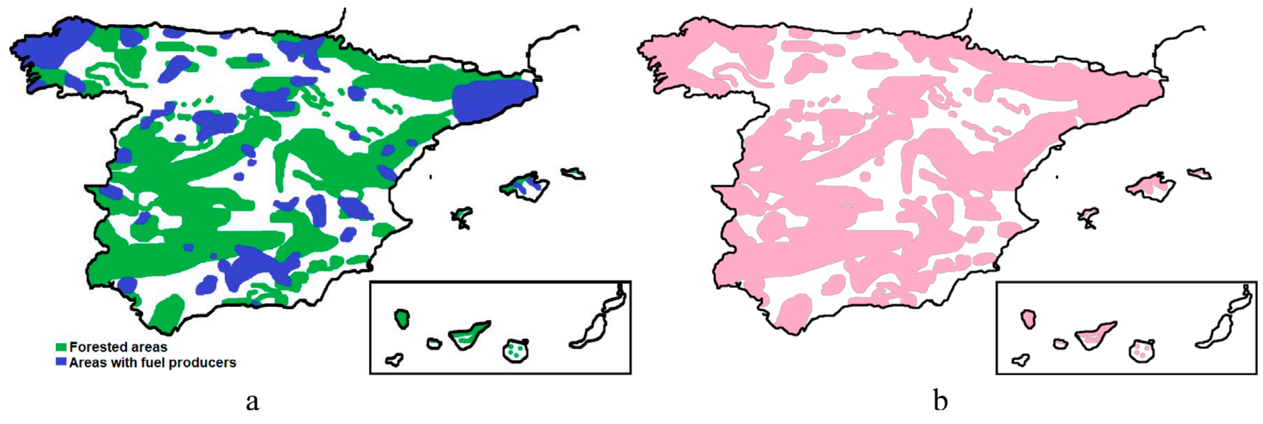

FIGURE 7
Biomass resource in Spain. **(a)** Simplified map and **(b)** suitable locations for biomass power installations.

(Instituto Geográfico Nacional, 2024a), and a simplified version is shown in Figure 8A. For electricity generation, a minimum temperature of approximately 100°C is typically required to operate binary-cycle geothermal power plants with reasonable efficiency. However, to account for uncertainties in the measurement and system design variations, locations with subsurface temperatures in the range of 90°C–150°C were considered suitable, following the criteria established by Colmenar-Santos et al. (2016). Consequently, only areas within this temperature range were retained, resulting in the suitability map shown in Figure 8B. Additionally, the geothermal potential was categorized based on the spatial extent of thermal anomalies. Regions with *extended storage* refer to areas where heat is

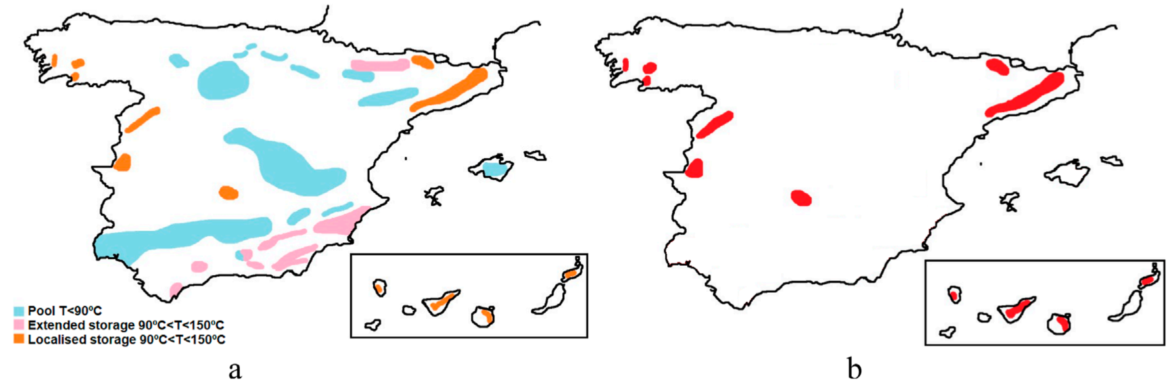

FIGURE 8
Heat stored in Spain. **(a)** Geothermal plants in Spain and **(b)** suitable locations for geothermal installations.

distributed over large subsurface volumes, which are generally more favorable for development. In contrast, localized storage refers to more confined thermal anomalies, which may offer lower capacity and present greater technical challenges for exploitation.

5 Discussion

Once the maps for the optimum location of all individual RESs are obtained, suitability maps for different HRES combinations were generated by overlapping these individual layers. This spatial integration helps identify areas where multiple RESs coincide, allowing for the co-location and hybridization of technologies. Figures 9, 10 provide these composite maps, which are fundamental for prioritizing HRES deployment in Spain. It should be remarked that the selection of parameters across all RESs in this study balances technical importance, data availability, and spatial coverage, offering a comprehensive and realistic basis for regional HRESs planning in Spain. From them, it can be observed that cases 1, 2, 3, 5, 6, and 8 have an interesting potential along the territory of Spain. A spatial analysis of these maps reveals distinct regional patterns of suitability:

- Northern Spain shows high suitability for wind–hydro (case 5), wind–biomass (case 6), and hydro–biomass (case 8) combinations. This is attributed to high wind speeds and significant rainfall, combined with elevation gradients that favor hydropower. However, none of these are currently under deployment. Some northern regions can also be suitable for solar HRES, highlighting solar–wind (case 1) and solar–biomass (case 3), where the HRES system "Termosolar Borges" must be highlighted (refer to Section 1).
- Central Spain has moderate but geographically diverse potential, allowing flexibility in deploying different HRES options, especially solar–wind (case 1) and solar–hydro (case 2). There are examples of these HRESs in central Spain, such as Sánchez Molina (2024) and El periódico de la energía. (2024) in Cuenca, Segovia, and Ávila for case 1 and Pedrosa. (2025) in Segovia for case 2.
- Southern Spain exhibits strong potential for solar–wind (case 1), solar–hydro (case 2), and solar–biomass (case 3) HRESs. These areas benefit from high solar irradiance, high wind speed, natural watercourses, and, in the case of biomass, intensive agricultural activity generating organic waste. An example of case 3 is found in Sevilla (García-Ceca, 2024).
- The Balearic Islands highlight the combinations including solar, wind, and biomass energies (cases 1, 3, and 6) due to their sunny Mediterranean climate, some areas with good conditions for wind energy, and certain natural resources and human activities for biomass energy; this archipelago is Spain's leading region in biomass heating and cooling networks (aveBIOM) (2022).
- Canary Islands, due to their subtropical climate, the trade winds (steady northeasterly winds), crop and livestock production, and volcanic geology, may benefit from solar, wind, biomass, and geothermal combinations (cases 4, 7, and 10). It should be noted that case 5 (wind–hydroelectric) does not seem to be feasible according to Figure 9, despite the existence of Gorona del Viento (see Section 1); this is due to the parameters taken into account when determining the location for hydroelectric power plants: the Canary Islands have important altitude differences in some of their isles, but neither continuous watercourses nor abundant rainfall.

It should be noted that these maps show the possibility of diversification of RESs for HRESs, which is essential for a long-term strategy. The implementation of HRESs is also relevant when considering the reduction of carbon dioxide emissions and other pollutants produced by more traditional energy sources. Consequently, these findings suggest that Spain can strategically diversify HRES implementation based on regional strengths: for example, wind-heavy zones and solar-dominated regions can rely on hydro or biomass as dispatchable sources for regulation.

Although these suitability maps provide insights into where multiple RESs may geographically co-exist in Spain, it is important to note that the analysis does not account for physical or technical interactions between technologies nor does it consider economic, environmental, or regulatory aspects. As such, this study

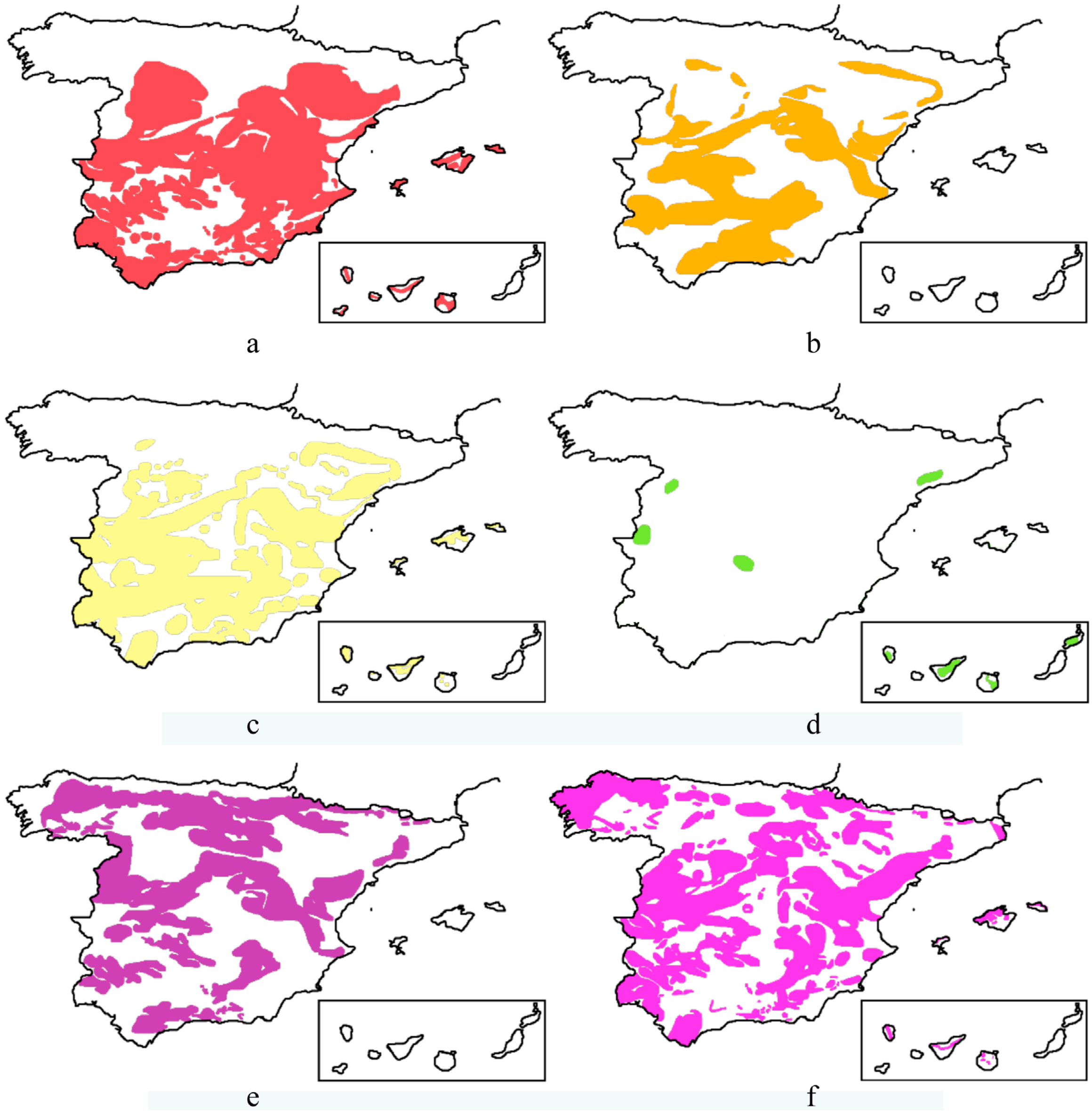

FIGURE 9
Cases 1–6 of HRESs. **(a)** Case 1: solar–wind, **(b)** case 2: solar–hydroelectric, **(c)** case 3: solar–biomass, **(d)** case 4: solar–geothermal, **(e)** case 5: wind–hydroelectric, and **(f)** case 6: wind–biomass.

serves as a resource-focused screening, identifying high-potential zones for HRESs based on natural availability, which must be further evaluated with respect to technical, economic, and land-use compatibility in future analyses. However, these maps offer a foundation for policymakers and developers to explore site-specific HRES configurations that align with local environmental conditions and infrastructure. The limitations of the spatial analysis are as follows:

- Co-location feasibility: The maps assume ideal conditions for resource overlap but do not account for land-use conflicts (e.g., urban zones, Natura 2000 protected areas) or land availability for infrastructure.
- Grid constraints and energy storage: The maps do not incorporate proximity to the electrical grid or storage infrastructure, both of which are important for a viable deployment.
- Temporal variability: Although the maps integrate long-term average resource data, they do not consider seasonal or hourly mismatches in generation, which could affect HRES performance.

The deployment of RES projects in Spain is shaped by a complex political and regulatory framework, which includes land-use restrictions, economic incentives, and national strategic planning. Land-use regulations, such as those related to environmental protection (e.g., Natura 2000 sites) and zoning constraints for agricultural or urban uses, can significantly limit the availability of suitable sites for new energy infrastructure (MIT, 2024a). Additionally, regulatory schemes introduce specific incentives and

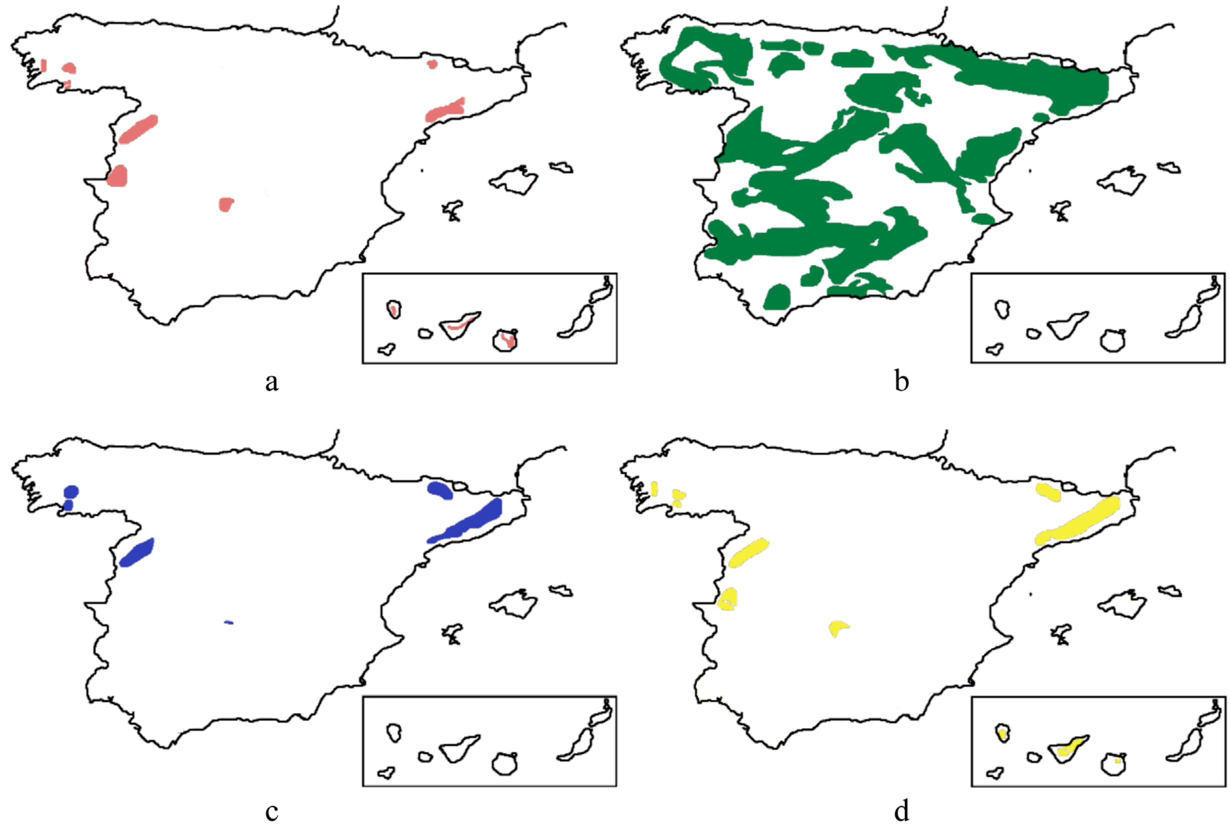

FIGURE 10
Cases 7–10 of HRESs considered. **(a)** Case 7: wind–geothermal, **(b)** case 8: hydroelectric–biomass, **(c)** case 9: hydroelectric–geothermal, and **(d)** case 10: biomass–geothermal.

barriers that directly affect the feasibility of HRESs. For instance, support mechanisms such as feed-in tariffs and renewable energy auctions have historically played a key role in project viability, though recent changes have increased regulatory uncertainty (Sendstad et al., 2022). At the strategic level, the Integrated National Energy and Climate Plan (PNIEC) 2021–2030 sets ambitious targets for RES integration, storage capacity, and electrification while identifying priority areas for infrastructure development (MIT, 2024b). However, effective implementation of the PNIEC depends on interregional coordination and regulatory clarity regarding environmental permitting, grid access, and hybridization rules.

Consequently, the resource synergies must be weighed against practical constraints. To move from theoretical potential to actionable implementation, it is necessary to analyze several alternatives in each case to ensure that the optimal one is chosen from a multi-criteria point of view (technical, economic, environmental, regulatory, etc.), as proposed by Zhang et al. (2023). Mardani et al. (2015) presented a literature review on multi-criteria decision-making techniques, highlighting their ability to help stakeholders and decision-makers address uncertainties in environmental decision-making processes across various stages of sustainable and renewable energy system development, and several authors have focused on these techniques for different types of RES (Gil-García et al., 2023; García et al., 2024; Serrano-Gomez et al., 2024) and HRES (Elkadeem et al., 2021; Rezk et al., 2021; Ali et al., 2023) problems. Future research could build upon this spatial framework by integrating these other factors and metrics to provide a more comprehensive evaluation of HRES deployment potential.

Regarding the HRESs considered, even though not all of them are already deployed in Spain, there are several real systems around the world, which prove that they can be feasible from a multi-criteria point of view if all the conditions are satisfied:

- Case 1 (solar–wind): Due to the complementary nature of wind and solar energy, HRESs provide several advantages over standalone solar or wind technologies. Notably, the peak operating times for wind and solar systems occur at different periods throughout the day and year, enhancing overall energy production and reliability (Roy et al., 2022). Several PV –wind HRESs have been mentioned in Section 1, demonstrating their feasibility. However, all of them relied on backup technologies, whether through ESSs or conventional power sources. Even though some studies have focused on the complementarity of PV and wind power generation (Couto and Estanqueiro, 2020; 2021; Costoya et al., 2023), this HRES presents the main drawback of lacking inherent regulation capacity (Yashwant Sawle and Bohre, 2016); an additional successful case is Orgueirel (Portugal, 8.4 MW of PV and 11 MW of wind (EDP Global, 2023)). Considering thermal solar and wind HRESs, they have the regulation ability due to the thermodynamic cycle of the thermal solar power plant and its TES (Powell et al., 2017; Rahman et al., 2017). Moreover, some authors have improved their performance as an HRES by transforming the curtailed wind power into heat through an electric heater, which is later stored in the thermal storage sub-system of the solar thermal power plant (Ding et al., 2019). Although the combination of solar thermal and wind energy is not as common as other HRESs, it can be a growing area of interest for the future of RESs, especially in regions with high levels of wind and solar radiation. Reichling and Kulacki (2008) simulated a hybrid solar thermal–wind power plant, concluding that it produced better electric load matching characteristics than an energy-equivalent wind power plant. However, to the authors' knowledge, there are no real installations of this type.

- Case 2 (Solar–hydroelectric): Three different parameters were considered for the optimum location of hydroelectric power plants (average accumulated rainfall, natural watercourses, and altitude differences). However, for PV installations, it is important to minimize height differences to improve efficiency as significant elevation variations can cause uneven shading, different temperatures, and voltage imbalances across modules, leading to lower system performance. Additionally, greater height differences may increase structural complexity and installation costs. Therefore, maintaining consistent height in PV arrays helps ensure optimal energy production and system stability. In Spain, a PV–hydroelectric HRES will be in operation in the following years (Ministerio para la Transición Ecológica y el Reto Demográfico, 2024). Another possibility is to use the reservoir of the hydroelectric power plant to take advantage of such a surface and install the PV panels as floating panels (Lee et al., 2020; Gadzanku et al., 2022; Piancó et al., 2022; Olkkonen et al., 2023), such as the Torrelaguna power plant (Spain, (EDP Global, 2023)) and Sobradinho (Brazil, Powermag, 2024)). Regarding thermal solar–hydroelectric HRESs, no current studies were found by the authors, probably because that both sources are stable by themselves, so there is less need to hybridize them with other RESs.
- Case 3 (solar–biomass): As detailed by Mohaghegh et al. (2021), thermal solar is a more suitable and economical technology than PV for its hybridization with biomass as they could share the thermal systems; the only operational HRES of this type is Termosolar Borges (Spain, refer to Section 1). However, PV–biomass technology could be beneficial for small-scale power generation in both residential and commercial applications (Hussain et al., 2017), and, indeed, this HRES can supply peaking power by utilizing a combination of both energy sources, ensuring reliable output regardless of time or weather conditions (Kaur et al., 2022). Recently, an HRES system of PV and biogas started its operation in Spain (Energías Renovables, 2024).
- Case 4 (solar–geothermal): An extensive literature review regarding solar thermal–geothermal HRES was recently published (Li et al., 2020), concluding that they are technically viable HRESs in many locations around the world. However, few large-scale power generation projects using this HRES have been implemented, primarily due to the substantial upfront investment required and the complexity of the system. Considering the PV–geothermal HRES, only one paper was found (Liu et al., 2023), which focused on developing a nanofluid geothermal–photovoltaic system. The research tackles the complexities involved in optimizing multiple objectives and evaluating various criteria for such an advanced system. In the United States, there is a success story of an HRES combining both PV and thermo-solar with geothermal energy (Energías Renovables, 2016).
- Case 5 (wind–hydroelectric): By incorporating a hydroelectric power plant, constant and flexible electrical generation can be guaranteed, acting as a backup during periods of lower wind production, avoiding the use of additional ESSs (Al-Addous et al., 2020; Tan et al., 2021; Zhang et al., 2021). Hydroelectric units are often selected as the conventional units to regulate wind power fluctuation due to their rapid response characteristics and stability (Liu et al., 2019). Likewise, there are many studies (Martínez-Lucas et al., 2020; 2021; Sarasúa et al., 2019) that analyze the benefits of hybrid systems of this type, concluding that frequency regulation is carried out in a coordinated manner between both types of plants, making 100% renewable energy generation of certain isolated systems viable. Nevertheless, in these isolated systems, long-term ESSs are required, replacing the conventional hydroelectric plant with a pumped-storage hydroelectric plant, as is the case on El Hierro Island (Spain) (Frydrychowicz-Jastrzębska, 2018).
- Case 6 (wind–biomass): Due to the limited distance that biomass power plants should have from the place where the fuel is obtained (as detailed in Section 2.4), the "wooded" areas can interfere with the wind power plant as they need large areas without the presence of obstacles (refer to Section 2.2). However, some studies have focused on this HRES, highlighting its technical and economic viability (Pérez-Navarro et al., 2010; Tajeddin and Roohi, 2019). No current case studies have been found of this HRES.
- Case 7 (wind–geothermal): No information on current studies related to this HRES is available, even though Olabi et al. (2020) identified this type of HRES as a key area for future research.
- Case 8 (hydroelectric–biomass): No information on current studies related to this HRES is available; this can mainly be due to the fact that hydroelectric and biomass generation are stable on their own, reducing the need to hybridize them with other RESs. However, in the United States, the first commercial HRES of this type started its operations in 2016 (Alexander Richter, 2016). Moreover, several studies have focused on HRESs that include hydroelectric and biomass power plants, combining them with other RESs, such as PV (Al-akayshee et al., 2021), PV and wind (Alturki and Awwad, 2021; Ullah et al., 2021; Menesy et al., 2023), and geothermal and solar thermal energy (Zahedi and Labbafi, 2021).
- Case 9 (hydroelectric–geothermal): Similar to case 8, no studies focusing solely on this HRES have been found in the specific literature, probably as a result of not finding proper places where both resources coincide.
- Case 10 (biomass–geothermal): Limited studies regarding this HRES are found, and none of them are focused on electricity generation; Xing and Li (2022) used the HRES to generate hydrogen, and Rezaei et al. (2021) used the HRES to supply heat in low enthalpy areas with an extremely cold climate.

However, a real example of this HRES is located in Italy (hib, 2015).

6 Conclusion

This study presents a comprehensive analysis of HRESs tailored to the Spanish energy context, focusing on combinations of solar, wind, hydroelectric, biomass, and geothermal power plants. A key contribution of this work is the development and application of a simple but effective geographic integration method, which enables precise identification of optimal locations for implementing HRESs by combining spatial resource availability and technical parameters.

The main conclusions of this study are as follows:

- Geographic integration enables targeted planning: This method produces simplified maps that identify the most suitable regions in Spain for each hybrid combination. This supports more effective site selection and resource optimization, providing a practical tool for energy planners and policymakers.
- Evaluation of diverse HRES combinations reveals varying potentials: Among the 10 hybrid configurations analyzed, solar–wind, solar–hydroelectric, and wind–hydroelectric HRESs exhibit the highest technical potential and feasibility in Spain. Meanwhile, even though biomass–geothermal hybrids are conceptually promising, the lack of comprehensive data limits detailed assessment in this study, indicating an important area for future research.
- Strategic and multi-criteria planning is essential for HRES deployment: Beyond technical resource availability, economic, environmental, and regulatory factors must be integrated into planning frameworks. Future work should focus on applying multi-criteria decision-making techniques to assess overall system feasibility, sustainability, and compliance with Spanish energy policies.

In summary, this study advances the academic understanding of HRESs through an extensive literature review of 10 HRESs providing practical insights into the spatial and technical feasibility of various HRES configurations in Spain. The findings demonstrate that strategically combining multiple RES technologies can create resilient, efficient, and scalable energy systems that support Spain's transition toward a sustainable, low-carbon energy future.

Author contributions

MN: writing – review and editing, software, investigation, conceptualization, and resources. AF-G: data curation, writing – original draft, project administration, methodology, investigation, conceptualization, and funding acquisition. JS: writing – review and editing, funding acquisition, and validation. LG: writing – review and editing and validation. IG-G: writing – review and editing, funding acquisition, formal analysis, and visualization. GM-L: funding acquisition, writing – original draft, project administration, investigation, methodology, and supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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