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Comparative analysis of hybrid geothermal-solar systems and solar PV with battery storage: Site suitability, emissions, and economic performance

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ABSTRACT

Renewable energy integration has become a critical focus in the global effort to reduce carbon emissions and diversify energy sources. In regions with distinct geographic features, such as Türkiye, combining different renewable technologies can offer enhanced energy security. This study investigates the site suitability and economic and environmental performance of hybrid geothermal-solar systems and solar PV systems with battery storage across the provinces of Osmaniye, Hatay, and Kilis, of Türkiye. Using the fuzzy-AHP method, site suitability is evaluated, addressing a key gap in comparing these systems' adaptability to varying geographic conditions. This study is the first to directly compare these two renewable energy technologies in terms of site suitability. The findings reveal significant differences in site suitability, with solar PV systems with battery storage demonstrating broader applicability across the region. The suitable sites (20–100 % suitability) cover 1260.82 km^2 for solar PV systems with battery storage and only 122.18 km^2 for hybrid geothermal-solar systems. In terms of environmental impact, hybrid geothermal-solar systems exhibit significantly lower carbon emissions, averaging 44.6 kg CO_2/MWh, compared to 123.8 kg CO_2/MWh for solar PV systems with battery storage. Economically, hybrid geothermal-solar systems also outperform with a lower levelized cost of electricity of $0.091 kWh versus $0.254 kWh for solar PV systems. These results highlight the environmental and economic advantages of hybrid geothermal-solar systems, while also emphasizing their limited scalability to regions with geothermal activity. Conversely, solar PV systems, despite their higher emissions and costs, offer greater flexibility and potential for widespread deployment.

1. Introduction

Fossil fuels and crude oils are widely used in energy production to meet the world's rising energy demands. However, their limited availability and detrimental impacts on the environment (i.e., climate change) have increased the demand for renewable energy in the past decades (Li et al., 2020a). Renewable energy uses sources that are unlimited and naturally replenished. Among them, wind, solar, and geothermal are common because of their merits, such as being worldwide sources, providing base-load energy, distribution of electricity, and market penetration (El-Khozenadar and El-Batta, 2018; El-Khozondar et al., 2024; 2023; El-Khozondar and El-batta, 2022; Li et al., 2020a; 2015; Nassar et al., 2024a; 2024b; Zhou et al., 2013). Using renewable and clean energy sources for energy production also contributes to zero carbon emissions and air and water pollution (Elnaggar et al., 2023). Despite its advantages, renewable energy still has many major drawbacks, such as high capital costs, storage, being affected by environmental and weather conditions, and unreliable electricity generation. In recent years, this concern has attracted the attention of researchers, and many studies have been conducted to make renewable energy more sustainable and cost competitive. In this regard, hybrid renewable energy systems have been studied to overcome the above drawbacks (McTigue et al., 2018; Mehedi et al., 2022; Pramanik and Ravikrishna, 2017).

Solar energy is an abundant and cheap renewable energy source. However, as it depends on sunlight, daylight duration and weather conditions (i.e., foggy, rainy, etc.) may significantly drop solar energy generation (El-Khozondar et al., 2015; Matter et al., 2015). In addition, relatively expensive energy storage and large land use are other major disadvantages of solar energy. On the contrary, geothermal energy is not

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affected by weather conditions and daytime duration. On the other hand, the electricity production from geothermal systems highly depends on resource temperature (Gude, 2018). Unfortunately, most geothermal areas lack sufficient resource temperatures for electricity production (Carlin, 2004). In other words, geothermal energy is location-specific, and most geothermal sources are unsuitable for electricity production. To overcome their drawbacks, an effort has been made to investigate hybrids of geothermal and solar energy systems (Li et al., 2020b; Nassar et al., 2024c). A hybrid geothermal-solar energy system uses solar energy to heat geothermal fluids, which improves the efficiency of geothermal energy production. Furthermore, heated geothermal fluids can serve as storage for solar energy, solving its disadvantages, such as being dependent on weather conditions and daytime duration and expensive storage (Li et al., 2020a). Considering its advantages, hybrid geothermal-solar energy could be a good alternative and may overcome some of the major drawbacks of geothermal and solar energy sources.

Solar PV systems with battery storage are another promising solution to the intermittent nature of solar energy (El-Khozenadar et al., 2023). By incorporating battery storage, these systems can store excess energy generated during peak sunlight hours for use during periods of low sunlight or high demand. This capability enhances the reliability and stability of solar PV systems. However, the integration of battery storage introduces additional challenges, including higher costs, the need for advanced battery technologies, and environmental concerns related to battery production and disposal (Mehedi et al., 2022). Despite these challenges, solar PV systems with battery storage have seen widespread adoption due to their flexibility and the decreasing costs of battery technologies.

Considering the efficiency and reliability of renewable energy systems, another concern is the exploration of suitable areas for renewable energy sources. In this context, primarily, potential renewable energy sites should be selected. However, because of being a complex and difficult process, site selection for potential renewable energy sources should be identified systematically. Regarding this concern, in the past decades, many studies have been conducted on the site selection for renewable energy sources by using various influential factors (Abuzied et al., 2020; Demir et al., 2024a; 2023a; Dinçer et al., 2023; 2024; Jara-Alvear et al., 2023; Yalcin et al., 2023; Yalcin & Kilic Gul, 2017a). For geothermal energy, previous studies have commonly utilized the following factors for the site selection: distance to fault, proximity to hot springs, drainage density, land surface temperature, geological indicators, and slope (Ng'ethe and Jalilinasrabady, 2024; Noorollahi et al., 2007a; Yalcin & Kilic Gul, 2017b). As for solar energy, suitable sites have been studied by considering the main factors: solar radiation rate, land use, slope, and distance to transmission lines, roads, and residential areas (Demir et al., 2024b; 2023; Uyan, 2017; 2013).

Several methodologies have been employed in the literature to tackle the site selection problem for renewable energy systems, with a significant emphasis on Multi-Criteria Decision-Making (MCDM) techniques. Among these techniques, methods such as Analytic Hierarchy Process (AHP) (Saaty, 2008; 2003; 1980), Analytic Network Process (ANP) (Saaty and Kułakowski, 2016), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Olson, 2004) have been widely applied. These methods provide a structured framework for evaluating multiple criteria and making informed decisions based on a variety of influential factors (Demir & Dinçer, 2023). The fuzzy Analytic Hierarchy Process (fuzzy-AHP) method has also become popular due to its main advantage, combining the strengths of the traditional AHP method with fuzzy logic, allowing for a more flexible and nuanced evaluation of criteria (Al Garni & Awasthi, 2017; Eroğlu, 2021; Noorollahi et al., 2022). This approach is particularly advantageous in dealing with the inherent uncertainty and vagueness associated with the subjective judgments required in the site selection process (Li et al., 2023; Zou et al., 2013). Fuzzy-AHP facilitates the incorporation of expert opinions and accommodates the imprecision of human reasoning, providing a more robust and reliable decision-making framework.

Despite the growing body of research on renewable energy, significant gaps remain in the comparative analysis of hybrid geothermal-solar energy systems and solar PV systems with battery storage. Much of the existing literature has focused on standalone systems, often examining solar PV or geothermal technologies in isolation (Baba et al., 2019; Demir et al., 2024b; Gupta and Roy, 2007; Sözen et al., 2004), with limited attention paid to hybrid configurations (Li et al., 2020b). Studies on hybrid geothermal-solar systems tend to explore their theoretical potential but lack empirical evaluations of their long-term environmental and economic impacts, including lifecycle emissions and resource availability (McTigue et al., 2018). Similarly, while solar PV with battery storage has seen increased deployment, the associated costs and environmental trade-offs from battery manufacturing are underexplored (Bošnjaković et al., 2023). Furthermore, there are no study that have directly compared hybrid geothermal-solar systems with solar PV-battery systems in terms of site selection, the levelized cost of electricity (LCOE), and emissions, particularly in varied geographic contexts where site suitability plays a crucial role (Ang et al., 2022). The absence of such comparative analyses represents a crucial gap in the literature. Consequently, the objective of this study is to provide insights into the environmental and economic performance of these technologies, addressing their scalability and site-specific requirements for future renewable energy development. To the best of the authors' knowledge, no prior research has addressed a direct comparison of these hybrid systems while considering these key factors.

This paper presents a novel approach to site selection for hybrid geothermal-solar energy systems and solar PV systems with battery integration using the fuzzy-AHP method. This is the first study to compare hybrid geothermal-solar energy systems and solar PV systems with battery storage in terms of site suitability. Moreover, by examining LCOE and emissions of both systems, this paper contributes to a deeper understanding of their economic and environmental performance. It should also be mentioned that this study focuses on the provinces of Osmaniye, Hatay, and Kilis in Türkiye due to the geothermal activity near these regions and their high solar radiation rates. However, the methodology and findings are broadly applicable to other regions with geothermal resources and varying climatic conditions. While the specific results may vary based on local conditions, the framework developed in this research can be adapted to different regions.

2. Methodology

2.1. Study area

The study area comprises the provinces of Osmaniye, Hatay, and Kilis in Türkiye as shown in Fig. 1. These provinces were selected based on their diverse geographical and climatic characteristics, which provide a representative landscape for assessing the feasibility and performance of hybrid geothermal-solar energy systems and solar PV systems with battery storage.

Osmaniye is located in the Mediterranean region of Türkiye, characterized by a hot-summer Mediterranean climate with mild, wet winters and hot, dry summers. The province has a mix of flat and hilly terrain, which can be favorable for solar PV installations due to ample sunlight and relatively open spaces (Climate and Agricultural Meteorology Department Research Department, 2022). However, the potential for hybrid geothermal-solar systems in Osmaniye may be limited due to the absence of significant geothermal resources.

Hatay, also situated in the Mediterranean region, has a similar climate to Osmaniye, with abundant sunlight making it favorable for solar PV systems (Külcü and Ersan, 2021). The province's varied topography, ranging from coastal plains to mountainous areas, provides a diverse landscape for energy installations. Hatay is known for its geothermal resources, particularly in the eastern regions, where hot springs and geothermal activity are more prominent (Yasin & Yüce,

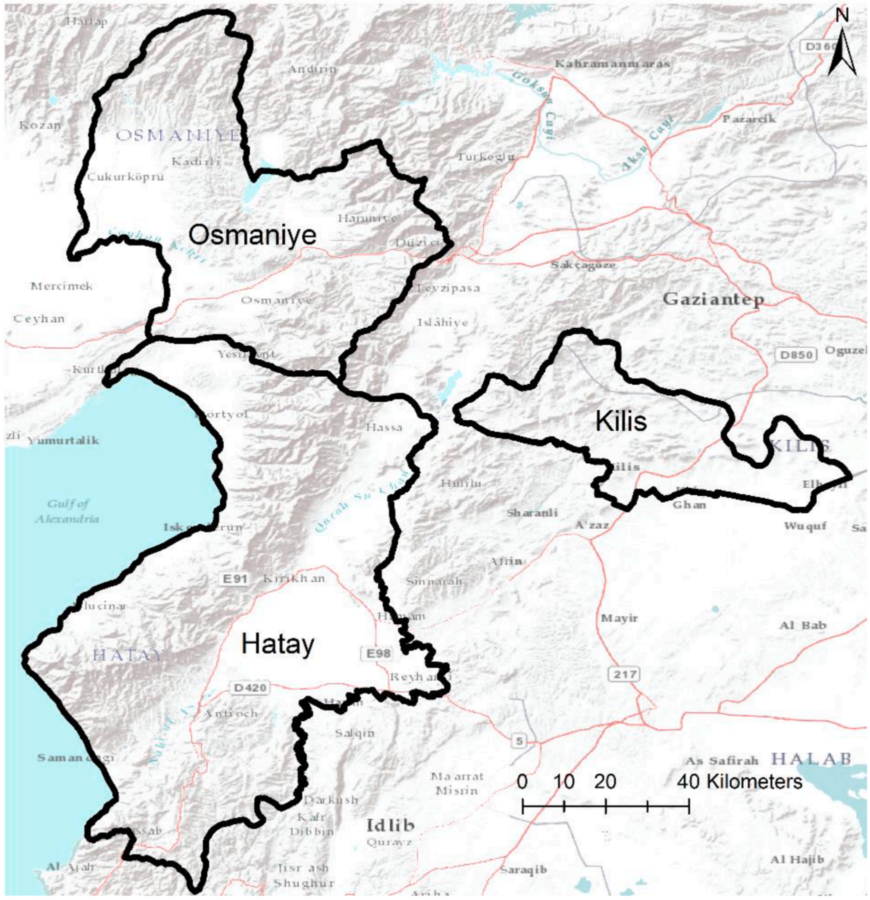

Fig. 1. The study area.

2023). This makes Hatay a potentially suitable location for hybrid geothermal-solar energy systems. The availability of geothermal resources in conjunction with high solar insolation presents an opportunity to maximize the efficiency of hybrid systems. However, the mountainous terrain in some areas might pose challenges for large-scale solar PV installations.

Kilis, located inland and to the north of Hatay, experiences a semi-arid climate with hot, dry summers and mild, wet winters (Climate and Agricultural Meteorology Department Research Department, 2022). The province has a predominantly flat terrain, which is advantageous for solar PV systems, offering large expanses of land suitable for solar panel installations. Kilis has moderate geothermal potential, with some areas near the border with Hatay showing geothermal activity (Baba et al., 2019). While not as rich in geothermal resources as Hatay, Kilis still holds potential for hybrid geothermal-solar systems, particularly in the northern regions where geothermal activity is more pronounced. The semi-arid climate, with fewer cloudy days, also supports the deployment of solar PV systems with battery storage.

2.2. The fuzzy-AHP methodology

The site selection for hybrid geothermal-solar power plants and solar PV with battery storage involves multiple criteria that require careful evaluation. Traditional AHP methods may struggle with the vagueness and uncertainty in expert opinions. Therefore, the Fuzzy-AHP methodology is adopted to address these challenges effectively. In fuzzy-AHP, first the criteria are defined. Then, initial fuzzy pairwise comparison matrix is created by using linguistic variables to express experts' preferences. The linguistic variables are converted to triangular fuzzy numbers (TFNs). After that, the fuzzy pairwise comparison matrix in which each element is represented by a TFN is constructed (Liu et al., 2020). The fuzzy synthetic extent for each criterion is calculated as:

$$S_i = \left(\sum_{j=1}^{n} \widetilde{a}_{ij}\right) \otimes \left(\sum_{i=1}^{n}\sum_{j=1}^{n} \widetilde{a}_{ij}\right)^{-1} \tag{1}$$

where S_i is the fuzzy synthetic extent value for criterion i. This represents the aggregated importance of criterion i in relation to all other criteria. $\widetilde{a}_{ij}$ is the fuzzy comparison value between criterion i and criterion j and n is the number of criteria.

The fuzzy synthetic extents are defuzzified using the centroid method. For a TFN (l, m, u), the crisp value is calculated as

$$Crisp\ value = \frac{l + m + u}{3} \tag{2}$$

The defuzzified values are normalized to obtain the final weights for each criterion:

$$w_i = \frac{\breve{w}_i}{\sum_{i=1}^{n} \breve{w}_i} \tag{3}$$

It should be noted that the main simplifications in the methodology involve the subjective selection of criteria, reliance on expert judgment, and the use of the centroid method for defuzzification. These simplifications, while they introduce some subjectivity, do not significantly affect the results because the chosen criteria are based on well-established studies, expert input minimizes extreme biases, and the defuzzification method balances uncertainty effectively. Furthermore, the overall structure of the methodology is robust enough to account for small variations, ensuring reliable and consistent site selection results.

2.3. Criteria

Each location possesses unique characteristics, necessitating specific constraints to be outlined accordingly. The selection of decision criteria is commonly guided by the study's objectives, the accessibility of georeferenced data, and insights from existing literature (Demir et al., 2024; Dinçer et al., 2023; Saaty, 2008; 1980). In the present study, 7 and 6 criteria are selected to find suitable sites for hybrid geothermal – solar energy systems and solar PV with battery storage, respectively.

2.3.1. Solar radiation rate (Global horizontal irradiation)

In multiple studies, the physical potential of solar energy emerges as the most significant factor for evaluating sites for solar PV panels (Demir et al., 2024b; 2023). This potential includes both temperature and irradiation, which can either be analyzed separately or combined, depending on the available data.

Solar energy potential typically revolves around two main parameters: solar radiation and land surface temperature (LST). For an area to be considered suitable for PV panel installation, it is generally recommended that the site has an annual average global horizontal irradiation of at least 1300 kWh/m^2 (Noorollahi et al., 2016). Many countries, such as Türkiye, have developed detailed solar radiation maps. The data used in the present study is retrieved from Global Solar Atlas (2024). As can be seen from Fig. 2(a), the solar radiation rate exceeds 1800 kWh/m^2 across most of the region. This high level of solar radiation signifies a strong potential for the installation of solar PV panels.

2.3.2. Proximity to hot springs

Areas where hot water and steam emerge are classified as geothermally active. It is generally believed that the likelihood of discovering geothermal resources is significantly higher in these geothermal active zones compared to surrounding regions (Ng'ethe and Jalilinasrabady, 2024).

Studies on the spatial distribution of hot springs and geothermal wells reveal that 97 % of geothermal wells are situated within 4000 m of hot springs. Consequently, this proximity has been utilized as a criterion to identify potential geothermal areas based on the presence of hot springs (Noorollahi et al., 2007b). Hot springs indicate the presence of a reliable geothermal resource, increasing the probability of accessing sufficient heat and steam necessary for power generation. Identifying sites near hot springs can significantly cut down on exploration costs and time, as the existing surface manifestations provide a clear indicator of subsurface heat, making preliminary surveys and studies more straightforward and less expensive. Accordingly, areas within a 10 km radius of known hot springs are considered favorable for hybrid geothermal-solar energy systems as shown in Fig. 2(b). Regions beyond this 10 km radius are deemed unsuitable and thus restricted for such developments.

2.3.3. Land cover

For optimal performance and minimal environmental impact, hybrid geothermal-solar energy plants and solar PV with battery storage systems are preferably installed on bare ground and rangeland. These areas offer the necessary space and surface conditions without significant ecological disruption. Conversely, regions covered by water, trees, flooded vegetation, crops, built areas, and scrub are restricted due to their environmental, agricultural, and developmental importance. Fig. 2 (c) presents land cover map of the study area derived from Sentinel-2 satellite images (European Space Agency, 2023).

2.3.4. Proximity to faults

Fault lines are essential indicators of geothermal resource potential, as geothermal fluids rise to the surface through these faults. Consequently, geothermal resources are often found near fault lines worldwide (Gupta & Roy, 2007). Moreover, fault lines influence the volume of geothermal reservoirs by creating discontinuities in the surface pressure system, which is a key factor in determining geothermal energy production in a region (Gupta & Roy, 2007).

In the site selection process, installing hybrid geothermal-solar energy systems as close as possible to active fault lines is prioritized to harness potential geothermal activity. However, to ensure safety and stability, installations within a 100-meter radius of fault lines are avoided. On the other hand, the sub-criteria for this criterion differ for solar PV with battery storage. For safety reasons, suitable sites for solar PV with battery storage should be located as far as possible from fault lines. The fault lines are derived from data provided by the Turkey General Directorate of Mineral Research and Exploration and provided in Fig. 3 (a).

2.3.5. Slope

The topography of a site directly affects the installation process, operational efficiency, and long-term sustainability of these energy systems. Mild slopes, defined as those <3 %, are considered the most favorable for installation (Demir et al., 2024b; 2023). These gentle slopes facilitate easier construction and maintenance of both geothermal and solar infrastructure. They provide stable ground conditions,

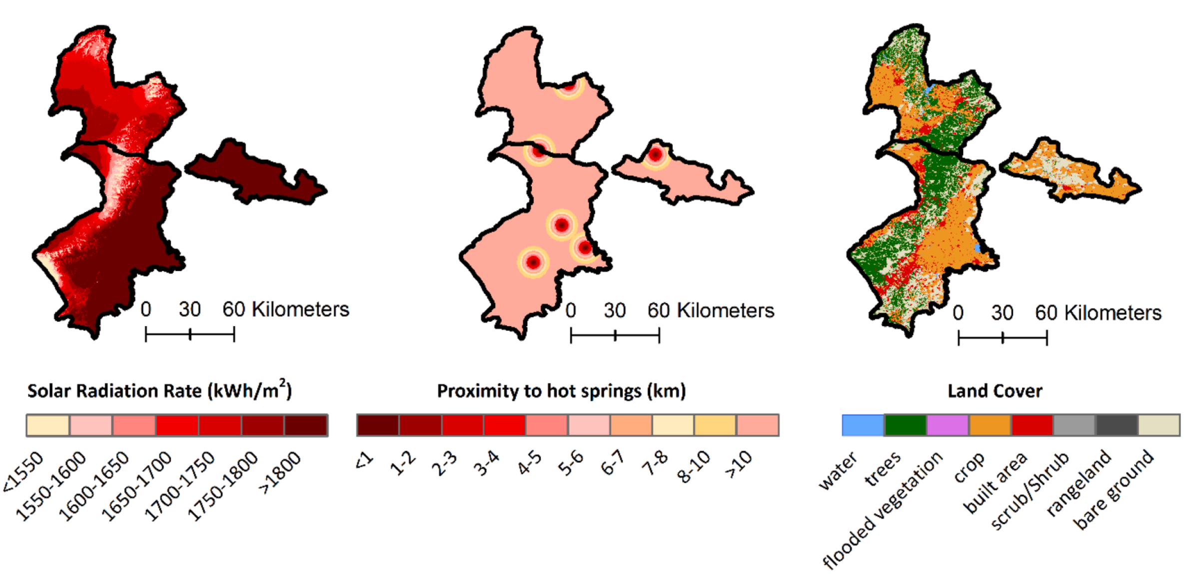

Fig. 2. (a) Solar radiation rate, (b) proximity to hot springs and (c) land cover maps of the study area.

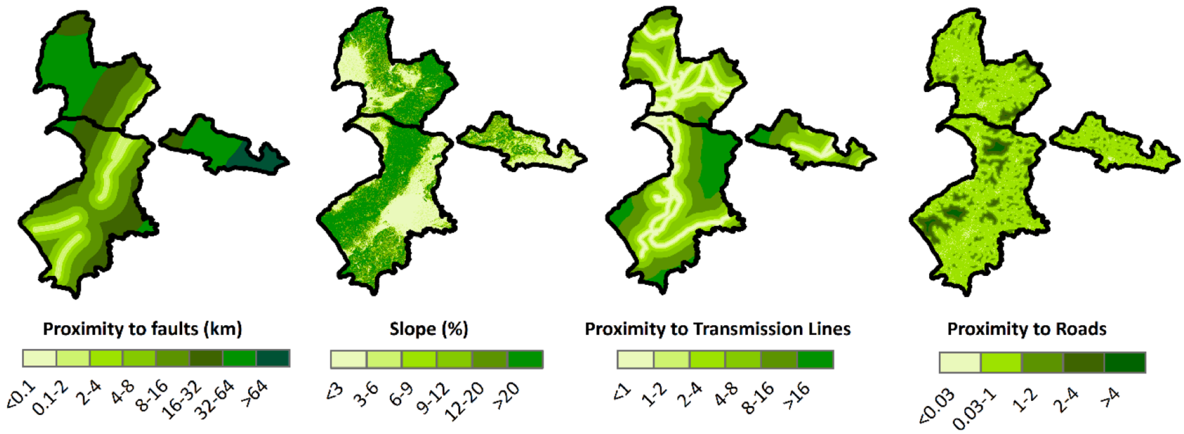

Fig. 3. (a) proximity to faults, (b) slope, (c) proximity to transmission lines and (d) proximity to roads maps of the study area.

reducing the risk of soil erosion and structural instability. On the other hand, slopes greater than 20 % are deemed unsuitable. Steep slopes pose significant challenges for construction and maintenance, leading to increased costs and potential safety hazards (Almasad et al., 2023; Demir et al., 2023; Günen, 2021). Additionally, the risk of soil erosion and landslides is higher on steep terrain, which can undermine the integrity of the installed systems (Yılmaz et al., 2023). The slope map is derived from the digital elevation model (European Space Agency, 2023) and provided in Fig. 3(b).

2.3.6. Proximity to transmission lines

The distance to existing transmission infrastructure directly impacts the feasibility, cost, and efficiency of energy distribution from the production site to the end users (Demir et al., 2024a; 2023; Dinçer et al., 2024; 2023). Sites located close to transmission lines are considered the most favorable for several reasons. Firstly, proximity to transmission lines reduces the costs associated with building new infrastructure. Establishing new transmission routes can be both expensive and time-consuming, involving significant capital investment and regulatory approvals. Additionally, shorter distances to transmission lines enhance the efficiency of power transmission. Energy loss during transmission is a well-known issue, and minimizing the distance between the energy source and the transmission lines helps reduce these losses. Accordingly, regions within a 1 km radius of transmission lines are considered as the most appropriate sites fort the installation of hybrid solar-geothermal energy systems. The transmission line map is derived from Open Street Map (Open Street Map, 2023) and presented in Fig. 3(c).

2.3.7. Proximity to roads

The accessibility of a site affects not only the construction and maintenance phases but also the overall logistical efficiency and cost-effectiveness of the project (Almasad et al., 2023; Doorga et al., 2019). In the present study, the most favorable regions for both energy systems fall within 0.03 kms to 1 kilometer from roads. This distance strikes a balance between accessibility and safety. Being close to roads within this range facilitates the transportation of materials, equipment, and personnel to the site, reducing logistical challenges and costs. It also ensures that maintenance activities can be conducted efficiently, ensuring the long-term reliability and performance of the energy systems. On the other hand, regions within 0.03 kms of roads are restricted due to safety and operational risks during construction and maintenance, potential interference from road noise, vibration, and pollution, and the possibility of future road expansions or infrastructure projects. The road map is reproduced from Open Street Map (Open Street Map, 2023) and shown in Fig. 3(d).

2.3.8. Fuzzy-Comparison matrix and final weights

The initial fuzzy comparison matrix based on expert opinions and the literature for hybrid geothermal solar site selection and solar PV with battery integration site selection is presented in Tables 1 and 2, respectively.

By using the initial fuzzy comparison matrix and making the calculations, the final weights are obtained and shown in Tables 3 and 4.

Table 3 outlines criteria for selecting solar-geothermal energy sites, with solar radiation and proximity to hot springs weighted at 28 % each. Solar radiation ranges from <1550 kWh/m^2 to over 1800 kWh/m^2, while hot spring proximity spans <1 km to over 10 km. Land cover (18 %) prioritizes bare ground and rangeland. Slope (7 %) favors gentler inclines, and proximity to faults (11 %), transmission lines (5 %), and roads (3 %) assign higher weights to closer distances.

Table 4 summarizes site selection criteria for solar PV systems with battery storage. Solar radiation is the most important factor, weighted at 30 %, followed by land cover (20 %) and slope (16 %), highlighting the need for flat, open areas. Proximity to transmission lines (14 %) ensures connectivity, while geological stability, indicated by distance from faults (8 %), enhances site safety. Unlike the criteria for hybrid geothermal-solar systems, in this case, sites located further from faults are considered more suitable. Proximity to roads (12 %) facilitates easy access for installation and maintenance.

It is important to align expert opinions with existing literature for a comprehensive analysis. While the literature offers suggested weightings for criteria in solar with battery storage systems, expert input is essential when considering the unique factors involved in hybrid solar-geothermal energy systems. Since this study is the first to address the site selection criteria for these solar geothermal hybrid systems, expert opinions are currently the sole source of information. As a result, cross-referencing or validating these criteria through existing literature is not yet possible, which could introduce a risk of bias in the findings.

2.4. Economic and environmental impacts

For the calculation of greenhouse gas (GHG) emissions of solar with battery storage systems and hybrid solar geothermal energy systems, the studies of (Mehedi et al., 2022) and (Pramanik & Ravikrishna, 2017) are used, respectively. For the solar PV systems with battery storage GHG emissions are assessed by aggregating emissions across all stages of an energy system's life cycle, focusing on materials and energy use. During the operation phase, emissions stem primarily from site preparation activities, such as land leveling and maintenance. Additionally, emissions from direct land-use changes, such as deforestation and the loss of natural carbon sequestration, are incorporated. These changes, including soil respiration post-deforestation, are evaluated using carbon stock data from (Turney and Fthenakis, 2011), and are calculated based

Table 1
The initial fuzzy comparison matrix for solar geothermal hybrid site selection.

Criteria	Solar radiation rate	Proximity to hot springs	Land cover	Proximity to faults	Slope	Proximity to transmission lines	Proximity to roads
Solar radiation rate	(1, 1, 1)	(1, 1, 1)	(1.5, 2, 2.5)	(2.5, 3, 3.5)	(3.5, 4, 4.5)	(4.5, 5, 5.5)	(5.5, 6, 6.5)
Proximity to hot springs	(1, 1, 1)	(1, 1, 1)	(1.5, 2, 2.5)	(2.5, 3, 3.5)	(3.5, 4, 4.5)	(4.5, 5, 5.5)	(5.5, 6, 6.5)
Land cover	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(1, 1, 1)	(1.5, 2, 2.5)	(2.5, 3, 3.5)	(3.5, 4, 4.5)	(4.5, 5, 5.5)
Proximity to faults	(0.3, 0.33, 0.36)	(0.3, 0.33, 0.36)	(0.4, 0.5, 0.6)	(1, 1, 1)	(1.5, 2, 2.5)	(2.5, 3, 3.5)	(3.5, 4, 4.5)
Slope	(0.2, 0.25, 0.3)	(0.2, 0.25, 0.3)	(0.3, 0.33, 0.36)	(0.4, 0.5, 0.6)	(1, 1, 1)	(1.5, 2, 2.5)	(2.5, 3, 3.5)
Proximity to transmission lines	(0.15, 0.2, 0.25)	(0.15, 0.2, 0.25)	(0.2, 0.25, 0.3)	(0.3, 0.33, 0.36)	(0.4, 0.5, 0.6)	(1, 1, 1)	(1.5, 2, 2.5)
Proximity to roads	(0.14, 0.17, 0.2)	(0.14, 0.17, 0.2)	(0.15, 0.2, 0.25)	(0.2, 0.25, 0.3)	(0.3, 0.33, 0.36)	(0.4, 0.5, 0.6)	(1, 1, 1)

Table 2
The initial fuzzy comparison matrix for solar with battery integration site selection.

Criteria	Solar radiation rate	Land cover	Proximity to faults	Slope	Proximity to transmission lines	Proximity to roads
Solar radiation rate	(1, 1, 1)	(1.5, 2, 2.5)	(4, 4.5, 5)	(1.5, 2, 2.5)	(2, 2.5, 3)	(2.5, 3, 3.5)
Land cover	(0.4, 0.5, 0.67)	(1, 1, 1)	(3, 3.5, 4)	(1, 1.5, 2)	(1.5, 2, 2.5)	(2, 2.5, 3)
Proximity to faults	(0.2, 0.22, 0.25)	(0.25, 0.29, 0.33)	(1, 1, 1)	(0.2, 0.25, 0.3)	(0.25, 0.29, 0.33)	(0.33, 0.4, 0.5)
Slope	(0.4, 0.5, 0.67)	(0.5, 0.67, 1)	(3.33, 4, 4.67)	(1, 1, 1)	(1.5, 2, 2.5)	(2, 2.5, 3)
Proximity to transmission lines	(0.33, 0.4, 0.5)	(0.4, 0.5, 0.67)	(3, 3.5, 4)	(0.4, 0.5, 0.67)	(1, 1, 1)	(1.5, 2, 2.5)
Proximity to roads	(0.29, 0.33, 0.4)	(0.33, 0.4, 0.5)	(2, 2.5, 3)	(0.33, 0.4, 0.5)	(0.4, 0.5, 0.67)	(1, 1, 1)

Table 3
The criteria used in the site selection of hybrid solar geothermal energy systems.

Criterion	Weight (%)	Sub criterion	Indicator	Criterion	Weight (%)	Sub criterion	Indicator
Solar radiation rate (kWh/m^2)	28	<1550	3	Slope (%)	7	<3	9
		1550–1600	4			3–6	8
		1600–1650	5			6–9	7
		1650–1700	6			9–12	4
		1700–1750	7			12–20	2
		1750–1800	8			>20	Restrained
		>1800	9				
Proximity to hot springs (km)	28	<1	9	Proximity to transmission lines (km)	5	<1	9
		1–2	8			1–2	8
		2–3	7			2–4	7
		3–4	6			4–8	6
		4–5	5			8–16	4
		5–6	4			>16	2
		6–7	3				
		7–8	2				
		8–10	1				
		>10	Restrained				
Land cover	18	Water	Restrained	Proximity to roads (km)	3	<0.03	Restrained
		Trees	Restrained			0.03–1	9
		Flooded veg.	Restrained			1–2	7
		Crops	Restrained			2–4	5
		Built Area	Restrained			>4	3
		Bare ground	8				
		Rangeland	9				
Proximity to faults (km)	11	<0.1	Restrained				
		0.1–2	9				
		2–4	8				
		4–8	7				
		8–16	6				
		16–32	5				
		32–64	4				
		>64	Restrained				

on land use, array area, and transmission line requirements. This analysis includes emissions from the first 10–20 years after land-use changes, reflecting the environmental impact of transforming semi-arid grassland, forests, and mixed areas into energy infrastructure.

According to (Pramanik and Ravikrishna, 2017), CO_2 emissions for a hybrid geothermal combined heat and power (CHP) plant using evacuated tube collectors are reported to be within the range of 29.2–38 kg/MWh (Ruzzenenti et al., 2014). Standalone geothermal binary plants

Table 4
The criteria used in the site selection of solar with battery storage systems.

Criterion	Weight (%)	Sub criterion	Indicator	Criterion	Weight (%)	Sub criterion	Indicator
Solar radiation rate (kWh/m^2)	30	<1550	3	Slope (%)	16	<3	9
		1550–1600	4			3–6	8
		1600–1650	5			6–9	7
		1650–1700	6			9–12	4
		1700–1750	7			12–20	2
		1750–1800	8			>20	Restrained
		>1800	9				
Land cover	20	Water	Restrained	Proximity to transmission lines (km)	14	<1	9
		Trees	Restrained			1–2	8
		Flooded veg.	Restrained			2–4	7
		Crops	Restrained			4–8	6
		Built Area	Restrained			8–16	4
		Bare ground	8			>16	2
		Rangeland	9				
Proximity to faults (km)	8	<0.1	Restrained	Proximity to roads (km)	12	<0.03	Restrained
		0.1–2	1			0.03–1	9
		2–4	2			1–2	7
		4–8	3			2–4	5
		8–16	5			>4	3
		16–32	7				
		32–64	8				
		>64	9				

have a global warming potential of approximately 50 kg/MWh, while parabolic trough concentrated solar power (CSP) plants emit about 14 kg/MWh. By applying a linear combination based on a 15 % solar contribution, the estimated CO_2 emissions for a CSP-geothermal hybrid plant are 44.6 kg/MWh.

The LCOE is calculated over a 30-year plant lifetime, considering various solar field sizes, storage durations, and heat transfer fluid (HTF) temperatures. LCOE represents the cost per unit of electricity that, over the plant's lifetime, equals the total lifecycle costs, including capital, operational, and maintenance expenses, discounted to the present (Awad et al., 2023; Nassar et al., 2024). For hybrid plants with existing power blocks and geothermal wells, the annual energy is determined by the marginal increase above the geothermal baseline. LCOE is computed using the fixed charge rate (FCR) method, following the study of (McTigue et al., 2018).

$$LCOE = \frac{C_{CAP}FCR + M}{E} \tag{4}$$

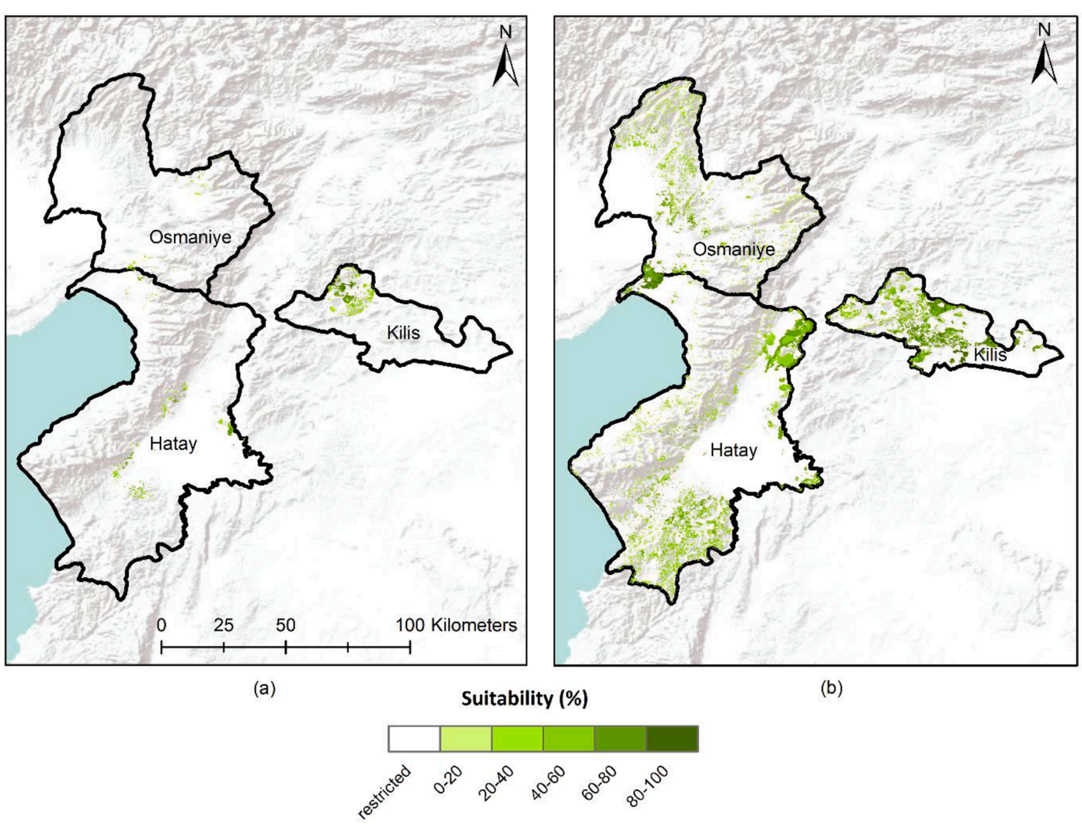

Fig. 4. The suitability maps for (a) hybrid geothermal-solar energy and (b) solar PV system with battery storage.

where C_{CAP} is the capital cost, FCR is the fixed charge rate, M is the annual operational and maintenance cost and E is the annual electricity generation.

3. Results

3.1. Site suitability

Fig. 4 presents suitability maps for hybrid geothermal-solar energy systems and solar PV systems with battery storage across the provinces of Osmaniye, Kilis, and Hatay in Türkiye. The maps are divided into two panels: (a) shows the suitability for a hybrid geothermal-solar energy system, while (b) depicts the suitability for a solar PV system with battery storage. Each map uses a color gradient to indicate varying levels of suitability, ranging from restricted areas (transparent) to highly suitable areas (dark green).

In Fig. 4(a), the suitability for hybrid geothermal-solar energy is primarily concentrated along the northwest of Kilis and the central and eastern region of Hatay. Significant clusters of highly suitable areas (60–100 %) are observed in northern Kilis and eastern Hatay. Osmaniye shows minimal suitability, with only a few scattered areas indicating potential sites. Conversely, Fig. 4(b) demonstrates a more widespread distribution of suitable areas for the solar PV system across all three provinces. Northern and central Osmaniye, as well as southern and eastern Hatay, exhibit significant clusters of high suitability. Kilis also displays increased suitability compared to the geothermal-solar hybrid system, with many areas falling within the 40–100 % suitability range.

Comparatively, solar PV systems with battery storage show broader suitability across the region than hybrid geothermal-solar systems. While both systems have notable high suitability areas, the potential sites for the solar PV system are much more extensively distributed. This difference in distribution is primarily due to the proximity to hot springs and land use criteria. Because it is restricted to install hybrid geothermal-solar systems outside a 10 km radius from hot springs, the proportion of suitable sites for these systems decreases significantly. Additionally, the areas in Hatay near hot springs are primarily used for agriculture, which limits the possibility of installing energy systems in these regions.

Table 5 provides a quantitative assessment of the land area suitability for hybrid geothermal-solar energy systems and solar PV system with battery storage within the studied region. The suitability is categorized into six distinct percentage ranges, each representing the potential of the land for energy system installations, along with their corresponding areas.

A large portion of the region is deemed unsuitable for both energy systems, with 10,278.72 km^2 unsuitable for hybrid geothermal-solar systems and 9140.17 km^2 unsuitable for solar PV systems with battery storage. While both systems have substantial unsuitable areas, the solar PV system shows a significantly larger proportion of areas falling within higher suitability ranges (20–100 %).

The disparity in the distribution of suitable areas between the two energy systems is significant. The solar PV system's potential sites are far more extensively distributed, especially in the higher suitability categories. As discussed previously, this difference is mainly attributed to the proximity to hot springs criterion for hybrid geothermal-solar systems. The installation of hybrid systems is restricted outside a 10 km radius from hot springs, which significantly reduces the proportion of suitable sites for these systems. Consequently, while both systems can be viable, solar PV systems with battery storage offer a broader range of potential installation sites, making them a more flexible and widely applicable option for the region.

Table 5
The proportion of suitable areas.

Suitability (%)	Area (km^2)	
	Hybrid geothermal solar	**Solar PV system with battery storage**
Unsuitable	10,278.72	9140.17
0–20	0.45	6.93
20–40	11.92	110.54
40–60	64.78	634.18
60–80	41.03	453.47
80–100	4.00	55.70

3.2. Comparison of carbon emissions

Hybrid geothermal-solar systems exhibit significantly lower carbon emissions, with an average of 44.6 kg CO_2/MWh (Pramanik & Ravikrishna, 2017), compared to an average of 123.8 kg CO_2/MWh (Mehedi et al., 2022) for solar PV systems with battery storage as shown in Fig. 5a.

The lower emissions of hybrid geothermal-solar systems can be attributed to the high efficiency and continuous energy production capabilities of geothermal energy, which complements the intermittent nature of solar power. In contrast, solar PV systems, while clean during operation, incur higher emissions associated with the production and disposal of batteries required for energy storage. Therefore, from an environmental perspective, hybrid geothermal-solar systems offer a more sustainable option, particularly in regions where geothermal resources are available. Despite their lower emissions, the limited availability of suitable sites may constrain the deployment of hybrid geothermal-solar systems, thereby reducing their overall impact on carbon emission reduction in the region.

3.3. Comparison of levelized cost of electricity (LCOE)

Hybrid geothermal-solar systems have a considerably lower LCOE, at $0.091/kWh, compared to $0.254/kWh for solar PV systems with battery storage (McTigue et al., 2018) as shown in Fig. 5b. This difference highlights the economic advantage of hybrid geothermal-solar systems, making them a more cost-effective solution for electricity generation.

The lower LCOE of hybrid geothermal-solar systems is primarily due to the high-capacity factor of geothermal energy, which ensures a steady and reliable energy supply. Additionally, the integration of solar power helps to further reduce operational costs by supplementing geothermal energy during peak sunlight hours. In contrast, the higher LCOE of solar PV systems with battery storage can be attributed to the significant costs associated with battery production, maintenance, and replacement, which are necessary to manage the intermittency of solar power.

While hybrid geothermal-solar systems offer lower carbon emissions and LCOE, their deployment is limited by site suitability constraints. Conversely, solar PV systems with battery storage, although less economically attractive and higher in emissions, provide a more flexible and widely applicable solution due to their broader site suitability. This trade-off between environmental impact, economic viability, and site availability is crucial for policymakers and stakeholders when planning and implementing renewable energy projects in the region.

4. Discussion of results

The Fuzzy-AHP methodology, applied to the provinces of Osmaniye, Kilis, and Hatay, demonstrates its effectiveness but also raises questions about its adaptability to other regions. Areas with abundant geothermal resources, such as volcanic zones, could see a higher potential for hybrid solar geothermal systems, while solar PV systems with battery storage may dominate in regions with less geothermal availability. For instance, the constraint of proximity to hot springs in the hybrid geothermal-solar model shown in Fig. 2b reduces the total suitable area, leaving solar PV systems with broader applicability as presented in Fig. 4 (122.18 km^2 in the 20–100 % range, compared to 1260.82 km^2 for solar PV with battery storage). On the other hand, the selected region has a high solar

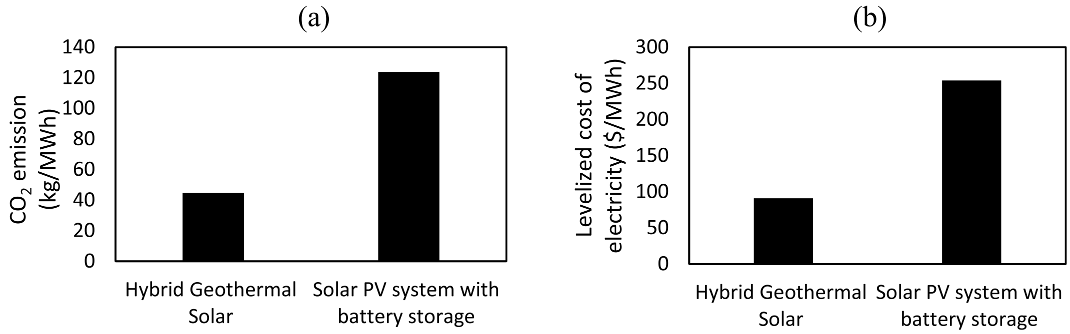

Fig. 5. The comparison of hybrid geothermal solar with solar PV system with battery storage in terms of (a) LCOE and (b) CO_2 emissions.

radiation rate as seen in Fig. 2a, making it generally well-suited for solar power plant installation. However, in areas where solar radiation is insufficient, hybrid geothermal-solar systems become particularly advantageous, because solar energy is utilized to heat the water in the geothermal plant, compensating for lower solar radiation levels. Different hybrid systems offer distinct advantages based on their configurations and the energy sources they integrate. For instance, hybrid solar-geothermal systems typically provide greater scalability, with an average capacity of 8.3 MW (Pramanik and Ravikrishna, 2017; Zarrouk and Moon, 2014), compared to some other hybrid plants like solar-biomass hybrids, which are generally restricted to capacities below 50 MW. In contrast, hybrid systems such as solar-wind can scale significantly, with capacities ranging from 10 MW to several hundred MW (Leung and Yang, 2012), and solar-aided coal-fired plants can achieve capacities as high as 1000 MW (Pramanik and Ravikrishna, 2017). Despite operating at smaller capacities than some of these alternatives, geothermal-solar hybrids stand out for their ability to function as base-load plants, given the stable geothermal resource supply. This stability results in a high-capacity factor of 60–70 %, making them particularly effective at delivering continuous and reliable power compared to purely solar or wind systems (Pramanik and Ravikrishna, 2017).

From a policy perspective, the results offer actionable data for regional development strategies. For instance, the larger proportion of suitable land for solar PV systems (especially in the 40–100 % range as shown in Fig. 4) suggests that solar energy might be more viable for broad implementation, requiring government incentives and infrastructure investments. The policymakers can use the suitability maps to prioritize areas where infrastructure investments would be most effective for supporting renewable energy.

Despite the valuable insights gained, this study has several limitations. One key limitation is the reliance on the proximity to hot springs as a critical criterion for hybrid geothermal-solar systems, which significantly narrows the suitable site options, as reflected in the small land area (4.00 km^2 in the 80–100 % suitability range). Another limitation is the fixed set of criteria used for the Fuzzy-AHP methodology as shown in Tables 3 and 4, which may not fully capture regional variations in energy potential or site-specific constraints. Future studies could benefit from integrating additional factors, such as evolving land-use regulations or climate change impacts. Additionally, while the methodology is adaptable, its application in regions with different geographical and climatic conditions may require modifications, particularly concerning the weighting of criteria. Finally, the technological assumptions made in this study, such as current battery storage capabilities may become outdated as innovations emerge, requiring reassessment of the model's conclusions.

Future research should explore the potential of technological advancements to improve the feasibility of both systems. Innovations in battery storage could reduce the higher LCOE for solar PV systems, currently $0.254/kWh, compared to $0.091/kWh for geothermal solar hybrid systems (see Fig. 5). Similarly, improvements in geothermal energy extraction could help overcome the site limitations imposed by proximity to hot springs, which currently restrict hybrid systems to limited areas. Advanced geothermal technologies might expand the potential sites for hybrid geothermal solar systems by enabling deeper geothermal resource utilization.

5. Conclusions

This study provides a detailed comparative analysis of hybrid geothermal-solar energy systems and solar PV systems with battery storage, with a focus on emissions, LCOE, and site suitability in Osmaniye, Kilis, and Hatay provinces in Türkiye. The results highlight that hybrid geothermal-solar systems produce significantly lower carbon emissions, averaging 44.6 kg CO_2/MWh, compared to 123.8 kg CO_2/MWh for solar PV systems with battery storage. This positions the hybrid systems as more environmentally sustainable. In terms of economic performance, hybrid geothermal-solar energy systems show a lower LCOE at $0.091/kWh, markedly outperforming solar PV systems with battery storage, which have an LCOE of $0.254/kWh. However, site suitability emerges as a key constraint for hybrid geothermal-solar systems, with only 122.18 km^2 of highly suitable land identified, compared to 1260.82 km^2 for solar PV systems. This limitation is largely due to the need for geothermal sources such as hot springs, which are concentrated in northern Kilis and eastern Hatay. Additionally, the areas near geothermal sources in Hatay were excluded as potential sites for hybrid solar-geothermal systems due to their agricultural use, which restricts energy development in these regions. In contrast, solar PV systems offer broader geographical flexibility and potential for wider deployment across the region, despite their higher emissions and costs.

The results of this study highlight that both hybrid geothermal-solar systems and solar PV systems with battery storage have distinct advantages and challenges. Geothermal systems offer lower emissions and costs but are geographically limited, while solar PV systems provide scalability at the expense of higher emissions and costs.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Open AI's ChatGPT to assist with grammar checks. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Halil Ibrahim Fedakar: Writing – original draft, Investigation. **Ali Ersin Dinçer:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Abdullah Demir:** Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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