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Integration of concentrated solar power with solid oxide electrolysis for green hydrogen production: a comprehensive review

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The integration of Concentrated Solar Power (CSP) and Solid Oxide Electrolysis (SOE) holds great promise for efficient and sustainable green hydrogen production. However, there is a lack of comprehensive studies reviewing the combined potential of these two technologies, which could offer enhanced efficiencies and reduced costs for large-scale hydrogen production. This review addresses that gap by analyzing the technical and economic feasibility of integrating CSP with SOE systems. This review provides a comprehensive analysis of the integration between CSP and SOE systems for green hydrogen production. The study examines critical technical challenges, including high operating temperatures, material compatibility, and heat transfer efficiency, while evaluating the economic feasibility of these integrated systems. Different CSP configurations are analysed based on their ability to provide heat alone or both heat and electricity, with thermal energy storage identified as a key factor in enhancing system performance by mitigating intermittency issues. Methodologies used in integration studies, such as simulation models and experimental setups, are critically reviewed, highlighting gaps in practical designs and real-world applications of CSP-SOE systems. However, despite these promising advances, only one laboratory-scale prototype has been demonstrated to date, underscoring the urgent need for pilot-scale CSP–SOE field testing under real direct normal irradiation (DNI) and thermal energy storage (TES) conditions. By addressing these technical and economic obstacles, this review offers insights into optimising CSP-SOE systems for sustainable, large-scale hydrogen production and provides actionable recommendations for future development.

KEYWORDS

green hydrogen systems, solid oxide electrolysis (SOE), concentrated solar power (CSP), solid oxide electrolysis cells (SOEC), CSP-SOE integrated system design

1 Introduction

The escalating global energy demand, fuelled by widespread industrialisation and electrification of societies, is facing significant challenges. Presently, fossil fuels constitute an alarming 80% of the world's primary energy sources (Jefferson, 2016). In response to growing concerns regarding climate change, international agreements have been established, reflecting a collective commitment to curtailing carbon emissions and emphasising the imperative need to foster renewable energy sources. Forecasts suggest that by 2050, renewable energy is projected to constitute a substantial 63% of the world's primary energy supply (Gielen et al., 2019a). Among these renewable energy options, hydrogen (H_2) emerges as a promising and environmentally friendly energy carrier that could play a pivotal role in shaping our global energy landscape (Cetinkaya et al., 2012; Chakraborty et al., 2022).

Hydrogen, as the most abundant element in the universe, offers a sustainable energy solution because it can be used for energy transportation and storage, making it a contender for future energy prominence (Vidyanandan, 2016). Hydrogen-based energy vision is built on several key objectives: ensuring energy supply security, transitioning to locally sustainable energy sources, fostering technological and industrial innovation, promoting economic growth, and addressing air quality concerns while reducing global CO_2 emissions (MOMIRLAN and VEZIROGLU, 2005; Edwards et al., 2007). Given the surging global energy demand, hydrogen energy presents a compelling alternative to address pressing global issues such as pollution and the threat of global warming (El-Shafie et al., 2019). Nevertheless, a percentage of hydrogen is presently generated through the utilisation of fossil fuels, so contradicting the objective of minimising carbon emissions (Longden et al., 2022).

While green hydrogen, produced through electrolysis with zero emissions, is environmentally favourable, its production is hindered by challenges related to cost and efficiency (Yu et al., 2021). Among the various electrolysis methods, solid oxide electrolysis (SOE) holds significant promise for overcoming these barriers, offering remarkable efficiency, potentially reaching 100% (Donitz, 1985). SOE operates at elevated temperatures (700 °C–900 °C) and requires both electricity and heat for efficient hydrogen production (Buttler and Spliethoff, 2018; Hou et al., 2019). Concentrated Solar Power (CSP) is an ideal renewable energy source to provide the necessary heat, as it directly harnesses thermal energy from the sun (Sinha et al., 2016). This integration of CSP with SOE supports the development of a solar-hydrogen energy system, offering a sustainable approach to green hydrogen production (Veziroğlu and Şahi˙n, 2008). By supplying the high temperatures needed for SOE, CSP overcomes the challenge of maintaining operational efficiency, while photovoltaic (PV) or other renewable sources can provide the required electricity, as shown in (Figure 1).

The integration of CSP with SOE for green hydrogen production offers distinct advantages when compared to other renewable energy-based electrolysis methods. The main advantage this combination offers is the high efficiency compared to other configurations. Aside from the high efficiency of electrolysis, CSP technology also surpasses PV technology in terms of efficiency. While commercial PV module efficiency typically ranges from 20% to 23% (with laboratory multi-junction cells achieving up to 30%), and CPV systems under concentrated sunlight have demonstrated cell efficiencies as high as 48% in research, CSP technologies stand out for their integration with high-temperature processes: CSP systems routinely achieve solar-to-heat efficiencies of 65%–83% at the collector or field level, including optical and thermal losses, and can reach solar-to-electric efficiencies as high as 30% in advanced configurations (Philipps et al., 2025; Horta, 2015; Renewable Energy Agency I, 2012; Osman and Qureshi, 2025). Moreover, the high temperature from CSP improves the SOE performance, which reduces the electrical energy demand for hydrogen production by 30% (Costa et al., 2018). In addition, the heat created can be utilised directly without undergoing energy conversion, hence eliminating any energy losses, resulting in enhancing the overall efficiency of the system (Islam et al., 2017). Another significant advantage of CSP is its ability to incorporate thermal energy storage (Kumar and Sharma, 2014). CSP-SOE integration can effectively tackle the issue of solar power intermittency and guarantee a

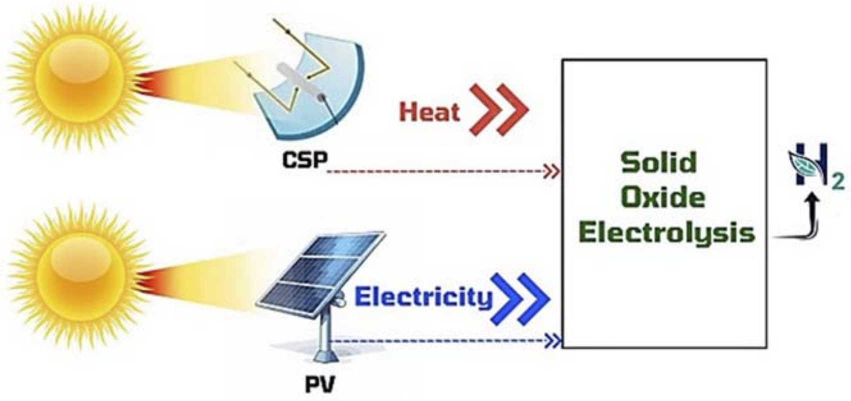

FIGURE 1
Integrating CSP and PV with SOE to supply the required energy.

dependable energy source for SOE (Sun et al., 2022). Moreover, a comparative study of CSP-SOE and CSP-PEM systems found no significant cost difference between the two integration methods, although CSP-SOE exhibited a 36% higher hydrogen generation rate. Economically, the heat required for SOE from CSP was also found to be more cost-effective than that generated by PV systems (Grube et al., 2020). Research by Schiller et al. (2019) showed that CSP-SOE integration is a considerable solution and has the potential to enhance SOE performance. Therefore, CSP-SOE integration has the potential to provide more reliable and sustainable systems compared to alternative electrolysis methods based on photovoltaic (PV) and wind systems (Mai et al., 2023).

Although there have been notable progressions in CSP and SOE, there is still a considerable lack of research on how these technologies might be combined for the production of green hydrogen. Several reviews exist on CSP technologies and SOE separately, focusing on specific advancements and technical developments (Khan et al., 2024; Zong et al., 2024; Shao et al., 2024). However, these reviews do not cover the CSP and SOE systems integration and their developments. The primary objective of this review is to fill this gap by exploring the potential of CSP-SOE integration to enhance green hydrogen production. The novelty of this review lies in its in-depth approach to: i. Analyse the latest developments in the integration between CSP and SOE technologies, ii. Evaluate the economic and technical viability of combining these systems, and iii. Highlight the current challenges and future research directions for CSP-SOE integration.

The first section provides an introduction, while the second section summarises the state of the art in solid oxide electrolysis technology. The third section presents an overview of concentrated solar power technology. The fourth section focuses on the integration of CSP and SOE, discussing key factors and recent progress in this area, followed by the fifth section, which offers a discussion of the findings and outlines potential directions for future research. This article serves as a valuable reference for future CSP-SOE integration design. It provides information on creating efficient systems with minimal emissions and the capacity for large-scale solar SOE green hydrogen generation.

2 Summary of SOE

As an energy carrier, hydrogen (H_2) holds the potential to bridge the gap between intermittent renewable energy sources, enabling the efficient storage of surplus energy for use during periods of high demand or when renewable sources are less active. It has a high energy content, three times more than the energy amounts that diesel contains (El-Shafie et al., 2019). Moreover, predictions suggest that the cost of hydrogen production will decrease significantly, potentially reaching around $1.80 per kilogram in the near future (El-Shafie et al., 2019; Sharma et al., 2021; Gielen et al., 2019b).

In nature, hydrogen can only be found in combination with other elements, particularly water (H_2O) (Parfomak, 2021), it is not regarded as a primary source of energy (Balat, 2008; Zohuri, 2018). This is one of the most significant obstacles to using hydrogen as a fuel is this issue (Almuqbil, 2020). Therefore, different methods and techniques are used to separate H_2 from other elements.

Hydrogen production is divided into three colours based on emissions from the production process: grey, blue, and green hydrogen (Yu et al., 2021; Hermesmann and Müller, 2022). The grey type is the one that directly emits carbon, whereas blue H_2 is the one that can reduce the percentage of carbon in production through a carbon capture process. Green H_2 is the process of producing hydrogen without any emissions because it is completely dependent on renewable energy by electrolysing water. Although this method is clean and sustainable, its cost is high and less efficient, which is why it is less popular (Yu et al., 2021; Hermesmann and Müller, 2022). Solid oxide electrolysis is one promising technology that can produce high-efficiency green hydrogen. In this section, the fundamentals of solid oxide electrolysis (SOE) are first explained, followed by a focus on its operating principles and performance characteristics. Finally, the section concludes with an exploration of material selection and cell design, highlighting how these factors influence SOE efficiency and durability.

2.1 Solid oxide electrolysis fundamentals

In the 1980s, Westinghouse (Isenberg, 1981) and HotElly (Doenitz et al., 1980; Donitz et al., 1988) projects were the beginning of SOE research, demonstrating effective hydrogen production from steam electrolysis at a power-to-fuel efficiency of over 90%. The research of CO_2 and steam electrolysis and CO_2-steam co-electrolysis in SOEC has since received a great deal of attention (Ding et al., 2008; Jin et al., 2011; Ding et al., 2014; Kaur et al., 2020). Solid Oxide Electrolysis is an electrochemical process that operates at high temperatures, typically between 600 °C and 850 °C, to efficiently convert steam (H_2O) or carbon dioxide (CO_2) into valuable products like hydrogen (H_2), carbon monoxide (CO), or syngas (a mixture of H_2 and CO) (Solov'ev et al., 2016). This process occurs within a solid oxide electrolysis cell (SOEC), which consists of three main components: the anode, cathode, and a dense ceramic electrolyte. The high operating temperatures result in faster kinetics and more favourable thermodynamics, leading to higher conversion efficiencies compared to other electrolysis technologies, which can reach 90% (Alipour et al., 2022; Fallah et al., 2023).

SOE is particularly attractive for large-scale applications, such as renewable hydrogen production and carbon capture, because it can be thermally integrated with chemical synthesis processes. For instance, SOE systems can be coupled with methanol or ammonia production, enabling highly efficient energy conversion by utilising the heat generated in these processes (Fallah et al., 2023; Zhao et al., 2021).

Recent advancements in SOE technology, including improvements in cell materials, have enhanced the performance and durability of SOEC systems. These developments allow SOECs to operate more effectively under the high temperatures required in CSP integration, further optimising hydrogen production (Hauch et al., 1979).

Research into the scalability of SOEC technology has also shown promising results, with modern SOEC stacks consisting of 30–100 cells, capable of producing up to 1 to 3 Nm^3 of gas (H_2 or syngas) per hour (Gaikwad et al., 2023).

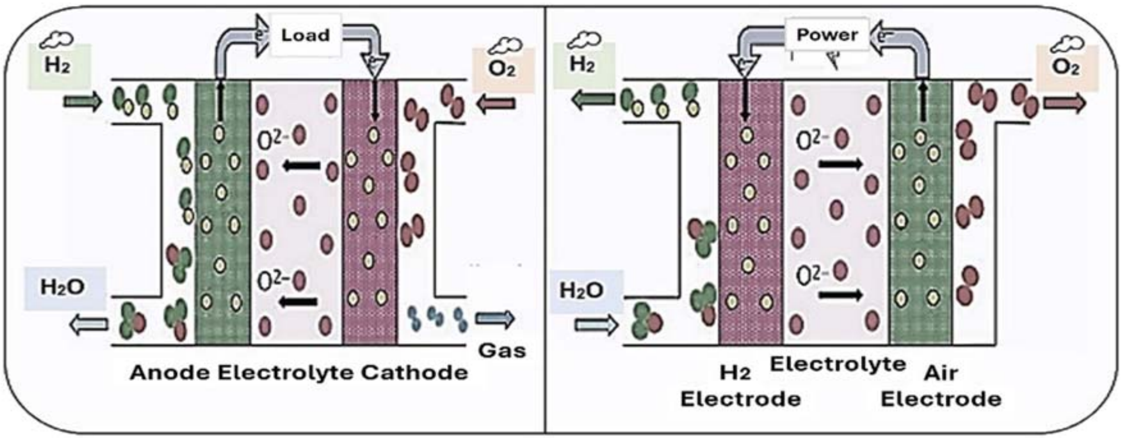

FIGURE 2
SOFC (left) and SOEC (right) operating systems (Pandiyan et al., 2019).

2.2 Operating principles and performance characteristics

The process of solid oxide electrolysis is an electrochemical reduction reaction. Firstly, Superheated steam is supplied to the cathode, leading to the generation of hydrogen and oxygen ions. These oxygen ions then migrate through the electrolyte to the anode, where they unite to form oxygen gas, subsequently released and capable of compression and storage for medical or industrial applications (Hou et al., 2024). At the cathode, hydrogen gas is produced, gathered, and utilised as a clean energy source (Biswas et al., 2023). The governing equations of these reactions are shown in Equations 1–3, as reported in Biswas et al. (2023), Pandiyan et al. (2019), Rajalakshmi et al. (2020), and Götz et al. (2016).

$$H_2O + 2e^- \rightarrow H_2 + O^{2-} \quad \text{Cathodic reaction} \tag{1}$$

$$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^- \quad \text{Anodic reaction} \tag{2}$$

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad \text{Overall reaction} \tag{3}$$

A similarity exists between solid oxide electrolysis cells (SOECs) and solid oxide fuel cells (SOFCs) in terms of cell design. However, the primary distinction between SOECs and SOFCs lies in their operational modes: SOECs function in the electrolysis mode, whereas SOFCs operate in the fuel cell mode. The differentiation between SOECs and SOFCs in terms of operational mode is shown in Figure 2, as reported by (Pandiyan et al., 2019).

The operational temperature of SOECs typically resides in the elevated range of 700 °C–900 °C, which enhances the ionic conductivity of the electrolyte.

The heat energy augments the efficiency of the electrolysis process by reducing the activation energy required for reactions (Buttler and Spliethoff, 2018; Hou et al., 2019). The electricity demand for (SOE) is comparatively lower than that of other electrolysis methods due to its elevated operating temperature (Costa et al., 2018). For instance, in proton exchange membrane electrolysers (PEM) or alkaline electrolysers (AEL), the minimal electrical energy requisite for water electrolysis at 80 °C stands at 68 Wh/mol of generated hydrogen. While SOEC demands 54 Wh of electrical energy for each mole of H_2 produced when operating at 800 °C. This substantial reduction in the electrical energy requirement carries significant implications, as it accounts for approximately 64% of the total cost associated with electrolytic hydrogen production (Biswas et al., 2023).

The elevated temperature in SOE facilitates the integration of potential heat sources, such as CSP systems, for effective heat management and enhances the overall performance of the SOE system reactions (Buttler and Spliethoff, 2018). Variables including temperature, material qualities, cell design, and the steam-to-hydrogen conversion ratio, affect how well SOECs function (Biswas et al., 2023). The interplay between the general inputs and outputs is shown in Equation 4 according to Pandiyan et al. (2019). The cell voltage, current density, and efficiency are important performance metrics for SOECs that are frequently assessed in terms of the cell's capacity to create hydrogen at high rates with little energy consumption (Ebbesen and Mogensen, 2009).

$$H_2O + heat + eletrciity \rightarrow H_2 + \frac{1}{2}O_2 \tag{4}$$

2.3 Material selection and cell design

The performance and durability of SOECs depend on the anode, cathode, and electrolyte. Therefore, selecting the proper materials plays a significant role in the efficiency of SOECs (Alipour et al., 2022). The anode materials in SOEC are usually porous ceramic materials, typically Ni/YSZ compounds that have high catalytic properties and carry current effectively, which can achieve current densities up to 1 A/cm^2 at 800 °C, leading to increasing the system efficiency to 90% (Laguna-Bercero, 2023). However, the disadvantage of it is degradation over time (Biswas et al., 2023; Boukamp, 2003; Pihlatie et al., 2010). The cathode is made up of the perovskite lanthanum strontium manganite (LSM), which exhibits excellent structural integrity and long-term operational reliability. Additionally, the other advantages of LSM are compatibility with YSZ, GDC, and LSGM under standard operating conditions, high electrical conductivity, high thermal stability, high electrochemical activity for oxygen reduction reactions, and it promotes oxygen evolution processes, achieving current densities of up to 1 A/cm^2 at a cell potential of 2 V and a temperature of 850 °C under ideal conditions (Salvo et al., 2013; Wang et al., 2018; Laguna-Bercero et al., 2010; Charalampakis et al., 2024). The electrolyte is considered the heart of SOECs, which is commonly made of YSZ since it exhibits a desired phase stability in both oxidising and reducing atmospheres and has a sufficient oxide-ion conductivity (0.13 S/cm at 1,000 °C) (Mahato et al., 2015).

Cell designs for SOECs include planar, tubular, and monolithic configurations. Planar SOECs have a flat, layered structure, which enables easy stacking for higher current densities and increased output (Mukerjee et al., 2017). Tubular SOECs consist of cylindrical cells, offering higher mechanical strength and easier sealing but lower volumetric efficiency compared to planar designs (Mukerjee et al., 2017; Huang, 2008). Monolithic SOECs involve a complex 3D structure with integrated flow channels, providing excellent gas distribution and heat management, albeit at the expense of increased manufacturing complexity (Pirou et al., 2023).

Planar SOECs consist of a flat, layered structure, enabling simple stacking for increased current densities and higher productivity. Tubular SOECs contain cylindrical cells, which offer easier sealing and increased mechanical strength. However, they have lower volumetric efficiency in comparison with planar designs. Monolithic SOECs have a 3D structure with built-in flow channels that provide superior gas distribution and heat management but are more difficult to manufacture.

2.4 Thermal management and durability

Solid oxide electrolysis technology is considered a promising technology in the field of green hydrogen energy production. However, one of the main challenges facing solid oxide electrolysis technology is the capacity shortage of renewable energy to provide the required energy because it works at elevated temperatures (Iskov et al., 2019). Therefore, concentrated solar power offers a considerable combination as it efficiently generates heat energy from the sun in a direct way. In this context, using CSP technology as a clear heat source would significantly improve green hydrogen with SOE (Puig-Samper et al., 2022).

Thermal management is important for the long-term stability and efficient operation of SOECs. Consequently, thermal stress-related cell failure and degeneration can be reduced by preserving a consistent temperature distribution throughout the cell and reducing temperature gradients (Sun et al., 2022). Significant challenges in SOEC operation and efficient thermal management (TM) are areas of interest for researchers. TM strategies involve using heat exchangers and insulation, optimising the cell's materials, designing, and integrating the SOECs with compatible heat sources, such as TES or CSP systems, enabling simultaneous heat supply (Zhang et al., 2021; Zeng et al., 2022; Yuan et al., 2021; Mottaghizadeh et al., 2022; Iacomini et al., 2009). More details about SOE can be seen in the Supplementary Material.

3 Summary of CSP

The world's most available source of energy is solar energy. The energy received from sunlight in 1 day can satisfy the global energy needs for more than 20 years, which is estimated to be approximately 120 PW, according to Chu (2011). In general, two main solar energy harvesting technologies with no emissions are: Concentrated solar power (CSP), and photovoltaics (PV) (Lange, 2013). This makes solar energy to be one of the primary energy sources used to create green hydrogen due to its zero carbon emissions (Steinfeld, 2005).

3.1 Concentrated solar power technology

CSP is a promising technology, particularly in locations rated to have high solar irradiation levels. Since CSP's performance is primarily dependent on the direct normal irradiance (DNI) level to generate power (Bank et al., 2020). DNI is the quantity of direct radiation that a flat surface constantly facing the sun receives (Blanc et al., 2014; Shekhar and Student, 2012). The value of solar varies depending on the location on the planet (Solargis, 2023). CSP technology performs more effectively than PV technology as a viable renewable energy source that depends on location. Additionally, while PV modules typically achieve efficiencies between 20% and 23%, CSP systems routinely convert 65%–83% of incident sunlight into heat and, in advanced plants, can generate electricity at efficiencies reaching up to 30%, further enhancing their appeal for solar-rich regions (Philipps et al., 2025; Horta, 2015; Renewable Energy Agency I, 2012; Osman and Qureshi, 2025).

One of the primary advantages of utilising solar thermal power for hydrogen production is the generation of green hydrogen, which employs an abundant and carbon-free energy source to generate hydrogen (Pregger et al., 2009). The expansion of high DNI regions with a growing demand for hydrogen is expected to significantly influence the development of solar thermal techniques and the construction of pilot plants. This study investigates and analyses the use of CSP technology as the heat energy source for solid oxide electrolysis in hydrogen production. The CSP process typically includes three key stages: the solar field, thermal energy storage, and power block (SBC Energy Institute, 2013; Ayadi and Alsalhen, 2018). These stages collectively constitute the CSP process, highlighting its multifaceted approach to harnessing solar energy for electricity generation and other applications.

3.2 Solar field types

The first and fundamental stage of CSP technology is the solar field. This stage is primarily composed of reflectors and a receiver. The reflectors, also called collectors, are composed of mirrors, and their purpose is to reflect solar irradiation to a receiver, which is a small area. The receiver is commonly a tube or point where there is fluid to absorb the heat focused on the receiver from sunlight. The name of this fluid is heat transfer fluid (HTF). Its function is to transfer the obtained heat from the solar field stage to the subsequent stage (Bank et al., 2020). Collecting concentrated heat from solar fields includes four different types, which are Parabolic trough collectors (PTC), Linear Fresnel reflectors (LFR), Parabolic dish collectors (PDC), and Solar tower collectors (STC) (Bank et al., 2020; Mills, 2004; Trieb, 2004; Affandi et al., 2015; Hamilton et al., 2020).

CSP technologies are essential for harnessing solar energy and consist of various interconnected systems that work together. The PTC, which is the most commonly used among CSP types (Qazi, 2017), employs curved mirrors to concentrate solar irradiation onto a tube receiver containing HTF. This mechanism efficiently transmits the heat that has been absorbed to generate or store energy (Bank et al., 2020; Joardder et al., 2017; Tagle-Salazar et al., 2020). The LFR utilises flat or slightly curved mirrors to focus sunlight onto a linear receiver (Kumar et al., 2015), enhanced by optional additional reflectors and a sun-tracking system (Zhu et al., 2014). For smaller-scale applications, the PDC concentrates solar rays onto a single focal point with a point receiver (Günther et al., 2011), and a tracking system can be integrated for optimal energy capture (Coventry and Andraka, 2017). The solar tower collector employs several heliostats positioned around a central tower (Asif, 2017; Breeze, 2019; Pandey and Samykano, 2022). These heliostats, capable of dual-axis adjustments, precisely focus sunlight on the tower's receiver, maximising solar energy capture throughout the day (Wang, 2019; Kamran, 2021). Each CSP type, with its unique configuration and efficiency, contributes significantly to harnessing solar power. Figure 3 shows the form of each type of CSP technology. In indirect CSP systems, the choice of heat transfer fluid HTF assumes paramount importance, necessitating the consideration of several critical factors. These factors encompass characteristics such as low viscosity, stability at high temperatures, safety in handling, non-corrosiveness, product lifecycle, high operational temperature range, cost-effectiveness in terms of maintenance and material transit, low vapour pressure, and a low freezing point (Kumar and Sharma, 2014). More details about each type of CSP can be found in the Supplementary Material. The key characteristics of the four main CSP technologies are summarised in Table 1, including their efficiency, operating temperature ranges, power capacities, levelised cost of electricity (LCOE), and concentration ratios (CR), as reported in previous studies.

3.3 Thermal energy storage in CSP

Thermal energy storage (TES) is a crucial component of CSP technology, and it can be the second main stage in CSP systems. Due to its temporal intermittency, solar energy has a significant drawback of storing energy in the absence of sunlight (Pelay et al., 2017). As a result, TES can provide CSP systems with the stability needed to operate continuously (Py et al., 2017; Jodeiri and Orozco, 2018). Considering the use of TES, this indicates that CSP can serve as a renewable energy source throughout the day (Denholm et al., 2014). Additionally, since TES manages the energy supplied to the next stage, which is the power block, it can reduce the cost of the maintenance of the power block and lengthen its life of the block (Py et al., 2017). Over 70% of new CSP plants, as reported in 2017, need TES systems (Pelay et al., 2017). Energy can be stored in a variety of ways. Nevertheless, on a large scale, storing energy as heat is more simple and cheaper than storing it as electricity (Py et al., 2017). The three primary TES system types are sensible heat storage, latent heat storage, and thermochemical heat storage (Gil et al., 2010).

According to McVay et al. (Sarbu and Sebarchievici, 2018), the TES is divided into two, thermal and chemical. The thermal way also contains two types, sensible and latent. The energy used to adjust temperature is known as sensible heat. Sensible heat is the energy used to change temperature. It is simple to transmit energy to a material by raising its temperature. The sensible heat is then thermally insulated until an energy need arises in the following stage. The temperature and the material's ability to retain heat influence the storage capacity. Rock, soil, water, and ceramics, for instance, are excellent materials for this heat storage type (Jurigova and Chmúrny, 2016). Sensible heat storage is the most common and economically established kind of TES (Agency, 2020).

Phase transition materials are employed in latent thermal storage. During the process, the phase change materials exhibit a constant temperature and considerable energy confinement (Hussain et al., 2019). The method that is most used involves a process called solid-liquid transformation, which involves melting and solidifying materials. The substance receives heat as it melts, and it retains a significant quantity of heat at a steady temperature. The heat energy is transferred when the materials solidify (Cabeza et al., 2020).

The thermochemical heat storage (THS) type includes a reversible chemical reaction, which means that both endothermic and exothermic chemical reactions take place. This results in the usage of powerful chemical bonds to store energy as chemical potential (Dincer and Erdemir, 2021; Bao and Ma, 2022). While measured in terms of like-for-like storage capacity, the storage density of THS materials is tenfold greater than the materials of the SHS method and twice as large as that of latent heat storage (LHS) materials. Despite having a maximal heat storage capacity, thermochemical energy storage experiences minimal or no thermal losses over the duration of storage (Kalaiselvam and Parameshwaran, 2014; Kerskes, 2016). THS yet has limitations since an effective reaction requires effective heat and mass transfer from and to the storage container. The entire storage volume may be constrained by this disadvantage, unlike the scale of SHS and LHS systems can be higher capacities (Aydin et al., 2015).

3.4 Power block in CSP technology

The power block, which is the third stage in a CSP system, is where thermal energy is where water is converted to suitable applications, usually transformed into electricity, or used in other applications such as hydrogen production (Islam et al., 2017; Seitz et al., 2017; Yadav and Banerjee, 2018). In the context of electricity generation, the conventional approach involves heating water to its boiling point and utilising the resulting steam for power generation (Lahoud et al., 2018). Steam turbines are complemented by Stirling engines and the gas turbine cycle (Pitz-Paal, 2018). Steam turbine cycles have many advantages because of their capacity to produce

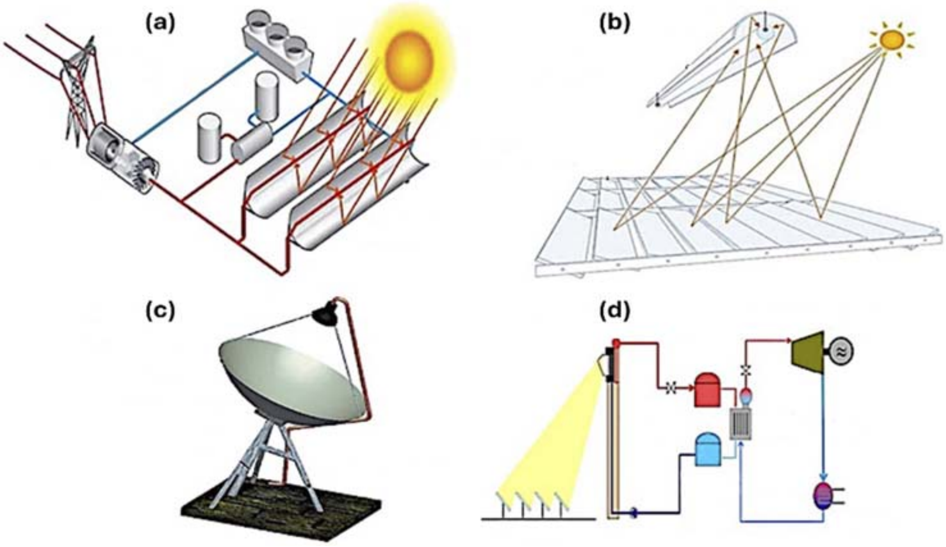

FIGURE 3
(a) The four CSP types: **(a)** parabolic trough collectors (Joardder et al., 2017), **(b)** Linear Fresnel Reflectors (Smadi, 2019), **(c)** parabolic dish collectors (Suman et al., 2015), **(d)** solar tower collectors (Romero and González-Aguilar, 2017).

TABLE 1 Comparison of the four main CSP field configurations.

Collector type	Efficiency	Operational temperature ranges (°C)	Power capacity (MW)	LCOE ($/KWh)	CR (sun)
PTC	Low	Between 50 and 550	From 10 to 200	0.132–0.137 (no TES) 0.124–0.155 (6 h TES)	Between 15 and 45
STC	High	Between 300 and 2000	From 10 to 200	0.145 (no TES) 0.118–0.129 (6–7.5 h TES) 0.112–0.121 (12–15 h TES)	Between 150 and 1,500
LFR	Low	Between 50 and 550	From 10 to 200	0.19–0.38 (no TES) 0.17–0.37 (6 h TES)	Between 10 and 40
PDC	High	Between 150 and 1,500	From 0.01 to 0.40	0.13 (no TES)	Between 100 and 1,000
Ref	Sun et al. (2015)	Sun et al. (2015)	Stein and Buck (2017), Purohit and Purohit (2017), Ziuku et al. (2014), Ummadisingu and Soni (2011)	Liu et al. (2016), Achkari and El Fadar (2020), Abdelhady (2021)	Sun et al. (2015)

electricity exceeding 10 MW and being compatible with various solar collector types. Steam generators efficiently operate at temperatures up to 600 °C (Pitz-Paal, 2018), aligning with contemporary fossil fuel-based steam turbines' peak efficiency of approximately 42% at around 600 °C. Consequently, CSP technology excels in power production and efficiency at elevated temperatures, making it advantageous for electricity generation (Alalewi, 2014).

The Rankine cycle is typically the basis for the steam turbine cycles. However, there are many ways to improve them. As an example, the steam in this cycle may become overheated, raising temperatures indicated by the T-S curve. Therefore, the area of the curve increases, producing more work (Çengel et al., 2019). Moreover, the generated steam from CSP can be used to produce green hydrogen by integrating it with solid oxide electrolysis because the solid oxide electrolysis operation temperature is between 700 °C and 900 °C (Buttler and Spliethoff, 2018). Therefore, the superheated steam can be heated and supplied by CSP technology without using fossil fuel (McVay et al., 2017). This is the study's focus point, and it will be explained in the next section.

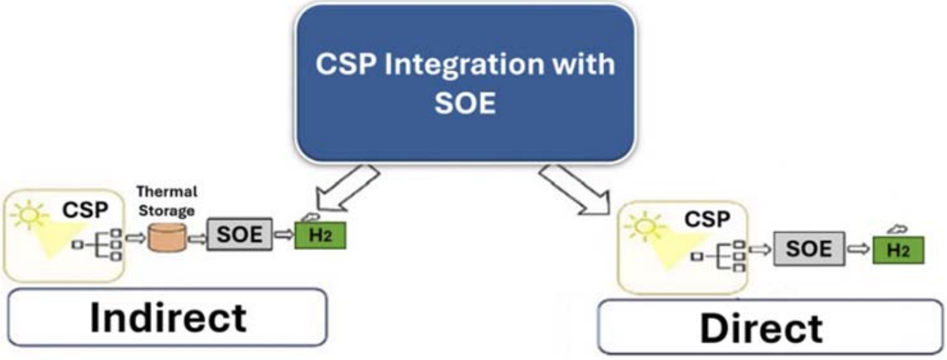

FIGURE 4
CSP-SOE integration type.

4 Current state of the arts in the integration of CSP technology with SOE

The combination of CSP technology and solid oxide SOE is an attractive area that has drawn the attention of many researchers. This is because it can provide an opportunity to efficiently produce high-quality steam and heat from renewable solar energy for effective hydrogen production (Puig-Samper et al., 2022; Zhang et al., 2022; Zhang and Li, 2023). This section discusses different approaches to CSP-SOE integration, the advantages of adding TES, and key factors that impact the integration. The integration can be divided into two, as shown in Figure 4.

Direct integration refers to configurations where the energy generated from the solar system, typically as high-temperature heat from CSP collectors, is directly utilised to operate the SOE without any intermediate thermal storage. In this configuration, the steam produced by the CSP field is immediately supplied to the SOE for hydrogen production. The primary advantage of this approach lies in its reduced energy losses, as the thermal energy is transferred directly to the SOE without additional conversion or storage stages (Khan et al., 2022). However, a notable challenge arises in maintaining stable SOE operation and preventing thermal stress-induced degradation due to the absence of thermal buffering. Since the system relies solely on direct solar input, variations in solar irradiance can cause temperature fluctuations and deficiencies in steam supply (Cagnoli et al., 2019). Such fluctuations can lead to significant temperature differences between the inlet and outlet of the SOE, accelerating degradation and reducing cell lifetime (Sun et al., 2022). To address this issue, several studies have proposed the inclusion of auxiliary electric heaters positioned upstream of the SOE and heat recovery systems that reuse waste heat from the process (Schiller et al., 2019; Sanz-Bermejo et al., 2014; Mohammadi and Mehrpooya, 2018). These additions help stabilise the steam temperature and maintain optimal SOE performance. The studies employing this configuration are summarised in Table 3.

In indirect integration, a thermal energy storage (TES) system or heat transfer fluid (HTF) acts as an intermediate link between the CSP field and the SOE (Prieto et al., 2016). In this configuration, the CSP system heats the HTF, and the stored or transferred thermal energy is then used to generate steam for the SOE. This arrangement provides superior control of temperature and steam conditions under fluctuating weather compared to the direct approach (Py et al., 2017). The use of TES enhances system stability and prolongs the lifespan of both the power block and the SOE by mitigating thermal cycling and stress-induced degradation (Py et al., 2017). It also offers greater operational flexibility, enabling continuous operation during periods of low solar irradiance or at night (Seitz et al., 2017). However, the additional steps involved in heat transfer and storage introduce higher energy losses and system complexity (Prieto et al., 2016). The selection of TES type depends on several factors, including required storage capacity, operating temperature range, and integration specifications (Seitz et al., 2017). Previous studies employing indirect integration approaches are also listed in Table 3.

4.1 Key factors affecting the CSP-SOE integration process

The primary factors influencing the effectiveness and efficiency of CSP–SOE integration include the selected CSP technology, the operating temperature requirements, the inclusion and sizing of thermal energy storage (TES) systems, the steam generation method, and the overall integration approach. Geographic location, solar resource availability, and system configuration must all be considered to maximise overall energy utilisation. In addition, control and optimisation strategies play a critical role in ensuring system stability, minimising energy losses, and maintaining hydrogen production efficiency (Islam et al., 2017; Schiller et al., 2019; Li et al., 2023; Motylinski et al., 2019).

In CSP–SOE systems, the distribution of energy flows between heat and electricity is central to system design. High-temperature heat from CSP can directly supply a portion of the total energy required by the SOE, thereby reducing electrical consumption and enhancing overall conversion efficiency. For typical SOE operation near 700 °C–900 °C, approximately 20%–30% of the total energy input can be delivered as thermal energy, while the remainder is supplied as electricity (Buttler and Spliethoff, 2018). The balance between heat and electricity substitution depends on

TABLE 2 The key factors affecting CSP-SOE integration.

Factor	Considerations	Ref.
Solar resource availability	Direct normal irradiance (DNI): Regions with high DNI are conducive to the efficient operation of CSP systems Duration of sunlight: The time sunlight is available during the day affects the total energy generated	Lin et al. (2022), Schlecht and Meyer (2012)
Integration of components	System design: effective integration of electrolysis, CSP, and thermal storage components is crucial Control systems: Advanced control guarantees the maintenance of equipment safety and efficient system operation	Yadav and Banerjee (2020), Elbeh and Sleiti (2021)
Economic factors	Levelized cost of hydrogen (LCOH): Economic viability is influenced by LCOH calculations	Yadav and Banerjee (2018)
Policy and regulations	Incentives and regulations: Government policies have an influence on the implementation and financial viability of projects	Zainal et al. (2024)
Environmental impact	Environmental benefits: It is crucial to consider the reduction in emissions	Puig-Samper et al. (2022)
Research and development	Technological advancements: Ongoing R&D efforts impact efficiency and cost-effectiveness	Yadav and Banerjee (2018)

the integration scheme, direct normal irradiance (DNI) variability, and TES capacity. Utilising high-temperature solar heat is therefore particularly valuable, as it enables lower electricity demand per kilogram of hydrogen produced and improves the overall solar-to-hydrogen conversion efficiency (Islam et al., 2017; Py et al., 2017; Denholm et al., 2014; Lang et al., 2020).

The durability of SOEC stacks is highly sensitive to operational transients induced by solar intermittency. Repeated thermal and electrical cycling imposes thermomechanical stresses that can cause electrolyte microcracking, electrode delamination, and Ni–YSZ coarsening, accelerating overall degradation. Experimental results report degradation rates between approximately 0.5% and 2% per 1,000 h under cyclic or reversible operation, compared with less than 0.3% per 1,000 h under stable steady-state conditions. Maintaining uniform operating temperatures and integrating thermal energy storage (TES) to buffer solar fluctuations are therefore essential to mitigate thermal gradients, reduce stress accumulation, and enhance SOEC stack lifetime (Lang et al., 2020).

Direct coupling requires rapid thermal management, often using auxiliary heaters or adaptive current control, to limit harmful temperature swings. Indirect coupling with thermal energy storage (TES) decouples operation from solar transients, enabling stable electrolysis. TES is typically sized for three to 6 h of full-load operation to balance flexibility and cost. These measures maintain performance and durability by keeping the operation within safe thermal and electrical limits (Sanz-Bermejo et al., 2014; Prieto et al., 2016).

A summary of the main factors influencing CSP–SOE integration is presented in Table 2, encompassing technical, economic, and operational considerations that determine the overall performance and feasibility of such systems.

4.2 Recent progress in CSP-SOE integration

Many researchers have investigated the integration of CSP with SOE, and the results varied depending on several factors. For instance, Puig-Samper et al. (2022) focused on the environmental performance of the integration between CSP and solid oxide electrolysis in the future to assess its anticipated life cycle in 2030. They found out that solid oxide electrolysis with a parabolic trough combination offers a viable environmental option because it can reduce the hydrogen carbon footprint by 81% through steam methane reforming and by 51% through grid electrolysis. Additionally, in the UAE, a study was conducted to compare CSP and PV to be combined with solid oxide electrolysis to produce hydrogen using Geographical Information System (Joubi et al., 2022). CSP had a higher hydrogen production rate than PV if it was at the same solid oxide electrolysis place, whereas it was less than PV when it was in a place away from solid oxide electrolysis.

A study conducted by Sathish et al. (2023) integrated two parabolic trough collectors (PTCs) with a solid oxide electrolysis (SOE) to enhance hydrogen production through a solar heating system. The experimental findings encompassed the evaluation of solar radiation, HTF temperatures, thermal efficiency, useful heat gain, hydrogen production, and net power output. It is noteworthy that the use of a flow rate of 0.38 kg/s in the absorber resulted in higher thermal efficiency and heat gain. Furthermore, increasing HTF flow rates from 0.12 to 0.38 kg/s led to improvements in electrical and hydrogen production rates. Cost analysis yielded favourable outcomes, revealing lower electricity generation costs compared to system-generated electricity, with an estimated hydrogen production cost of 212.3 $/kgH$_2$-day. Future research prospects encompass optimising the number of PTCs,

TABLE 3 Previous studies investigating the Integration of CSP with SOE.

Ref.	Type of study	CSP type	Approach used	Additional heat components	Electric component	Operational Temp. (°C)	Overall system efficiency %	Hydrogen production amount
Houaijia et al. (2015)	Simulation using DLR software tool HFLCAL	Solar tower	Direct	No	Solar tower-driven turbine	700	18	2,382 tpa
Lin and Haussener (2017)	Three different frameworks on MATLAB	1. Solar tower	Direct	No	Solar tower-driven turbine	526–1,027	10.6	400 kg/day
		2. PV driven electric heater (not CSP type but included in this study)	Direct		PV	526–1,027	6.3	
		3. Solar tower	Direct		PV	526–1,027	9.9–12.7	
Mohammadi and Mehrpooya (2018)	Mathematical modelling using MATLAB software	Parabolic dish	Direct	Electrical heater, when needed	Parabolic dish + air storage + ORC as waste recovery	826.85	-	41.48 kg/day
Shafiei et al. (2019)	Mathematical model using EES software	Solar tower (cavity receiver and 50 heliostats)	Direct	-	CPV	726.85	36.5	9.4 kg/day
Schiller et al. (2019)	Experiment	Solar simulator and solar heater	Direct	Auxiliary peripheral electrical tube heaters	-	600	-	0.01 kg/h (lasts for 4 h)
Mastropasqua et al. (2020)	Simulation using aspen plus	One parabolic dish collector	Direct	-	9 parabolic dish collectors	750	18.9	150 kg/day
Restrepo et al. (2022)	Simulation using CFD + SAM	Two solar tower units	Direct	-	CPV	850	31.8	2,500 tpa
Zhang et al. (2022)	Numerical investigation using a detailed mathematic mode on CFD	Parabolic trough collector	Direct	-	-	900–920	30.21	-

(Continued on the following page)

TABLE 3 (*Continued*) Previous studies investigating the Integration of CSP with SOE.

Ref.	Type of study	CSP type	Approach used	Additional heat components	Electric component	Operational Temp. (°C)	Overall system efficiency %	Hydrogen production amount
Sanz-Bermejo et al. (2014)	Simulation using EBSILON professional software	Linear fresnel reflector	Indirect	Castable ceramic TES + electric heater	From the grid	700	43.1	242 tpa
AlZahrani and Dincer (2016)	Engineering equation solver software (EES) (mathematical model)	Solar tower	Indirect	TES	Solar plant-driven CO_2 bryton cycle turbine	626.85–926	39.5	20.6 kg/h
Seitz et al. (2017)	Mathematical model using EBSILON professional	Parabolic trough collector	Indirect	The absorber schott PTR70 + thermal storage (laten) + electrical heater	-	800	-	286.4 kg/h at day time 316.6 kg/h at night time
McVay et al. (2017)	Modelling using MATLAB simulink	Parabolic dish collector	Indirect	Molten salt as HTF	-	656.85	-	-
Mohammadi and Mehrpooya (2019)	Mathematical model optimised by GA software	Parabolic trough collector	Indirect	Thermal storage + system energy recovery + an electric heater + an auxiliary heater (FUEL)	ORC unit using the remaining heat	726.85–876.85	26.81	260 kg/day

TABLE 4 Overall system efficiencies of CSP–SOE integrations with corresponding operational temperatures and HHV/LHV bases in previous studies.

Ref.	CSP type	Approach used	Operational Temp. (°C)	Overall system efficiency %	Basis (HHV/LHV)	Efficiency based on HHV %	Efficiency based on LHV %
Houaijia et al. (2015)	Solar tower	Direct	700	18	HHV	18	15.3
Lin and Haussener (2017)	1. Solar tower	Direct	526–1,027	10.6	HHV	10.6	9.01
	2. PV driven electric heater (not CSP type but included in this study)	Direct	526–1,027	6.3	HHV	6.3	5.355
	3. Solar tower	Direct	526–1,027	9.9–12.7	HHV	12.7	10.795
Shafiei et al. (2019)	Solar tower (cavity receiver and 50 heliostats)	Direct	726.85	36.5	HHV	36.5	31.025
Mastropasqua et al. (2020)	One parabolic dish collector	Direct	750	18.9	LHV	22.302	18.9
Restrepo et al. (2022)	Two solar tower units	Direct	850	31.8	LHV	37.524	31.8
Zhang et al. (2022)	Parabolic trough collector	Direct	900–920	30.21	HHV	30.21	25.6785
Sanz-Bermejo et al. (2014)	Linear fresnel reflector	Indirect	700	43.1	HHV	43.1	36.635
AlZahrani and Dincer (2016)	Solar tower	Indirect	626.85–926	39.5	LHV	46.61	39.5
Mohammadi and Mehrpooya (2019)	Parabolic trough collector	Indirect	726.85–876.85	26.81	LHV	31.6358	26.81

enhancing thermal efficiency through various modifications, and conducting numerical studies to validate experimental results and expand the database for potential market segmentation.

Research by Xia et al. (2023) introduced an innovative solar-driven high-temperature co-electrolysis system, which incorporates an ammonia-based combined heat and power system alongside a solid oxide electrolyser cell (SOEC) module, a solar photovoltaics module, and a parabolic trough collector module. The study involved a thorough parametric investigation, examining the effects of critical operating parameters, including current density, endothermic reactor inlet temperature, and sweep ratio, on the system's performance. Achieving a maximum solar-to-hydrogen efficiency (η_{STH}) of 25.4%, which represents a substantial 6.4% improvement over typical solar-driven high-temperature co-electrolysis systems, was a notable outcome of our optimisation efforts. Future avenues of research should encompass the techno-economic analysis of this system and the exploration of transient states, accounting for spatial and temporal variations in solar irradiance. The ammonia-based combined heat and power system, coupled with a hydrogen-permeant membrane reactor, demonstrated significant promise in harnessing solar heat for enhanced efficiency. Numerical models have been developed and rigorously validated against experimental data, providing a robust foundation for further exploration and advancement in this field.

Other studies investigated the combination of SOE and a specific type of CSP. These studies implemented selected different types of CSP, different conditions, and scales. Both direct and indirect methods of integration have been investigated as summarised in Table 3. These two tables summarise the studies that integrated CSP with SOE in terms of the method used, heat and electricity sources, efficiency, and the production amount of hydrogen.

To enable a consistent comparison among previous studies, all reported overall CSP–SOE integration efficiencies were converted to a Higher Heating Value (HHV) basis, as summarised in Table 4, which includes both the originally reported and the recalculated HHV- and LHV-based efficiencies. When the energy basis was not explicitly stated in the source, efficiencies were standardised using the hydrogen energy conversion relation (Osman et al., 2022; Malkow and Pilenga, 2023):

$$\eta_{\mathrm{HHV}} = 1.18 \times \eta_{\mathrm{LHV}}$$

TABLE 5 Previous techno-economic studies of CSP-SOE system integration.

Ref.	Type of analysis	CSP type	Direct or indirect	Additional heat components	Electric component	Hydrogen production amount	Cost for 1 kg of H_2
Lin and Haussener (2017)	Three frameworks on MATLAB	1 solar tower	Direct	-	Solar tower-driven turbine	400 kg/day	8.19$
		2 PV (not CSP type but included in this study)	Direct	An electric heater	PV		8.02$
		3 solar tower	Direct	-	PV		6.28$
Seitz et al. (2017)	Mathematical model using BSILON ® professional	Parabolic trough collector	Indirect	Thermal storage (Laten)+ an electrical heater	Renewable energy source	286.4 kg/h at daytime 316.6 kg/h at nighttime	4.30 €
Mohammadi and Mehrpooya (2018)	Mathematical modelling using MATLAB software	Parabolic dish	Direct	An electric heater, when needed	Parabolic dish + air storage + ORC as waste recovery	41.48 kg/day	9.1203$
Mohammadi and Mehrpooya (2019)	Mathematical model optimised by GA software	Parabolic trough	Indirect	Thermal storage + energy recovery + an electric heater + an auxiliary FUEL heater	ORC unit using the remaining heat	260 kg/day	4.43$
Mastropasqua et al. (2020)	Simulation using aspen plus	Parabolic dish	Direct	-	9 parabolic dish collectors	150 kg/day	5.9 €
Restrepo et al. (2022)	Simulation on CFD + SAM	Solar tower	Direct	-	CPV	2,500 tpa	4.55$

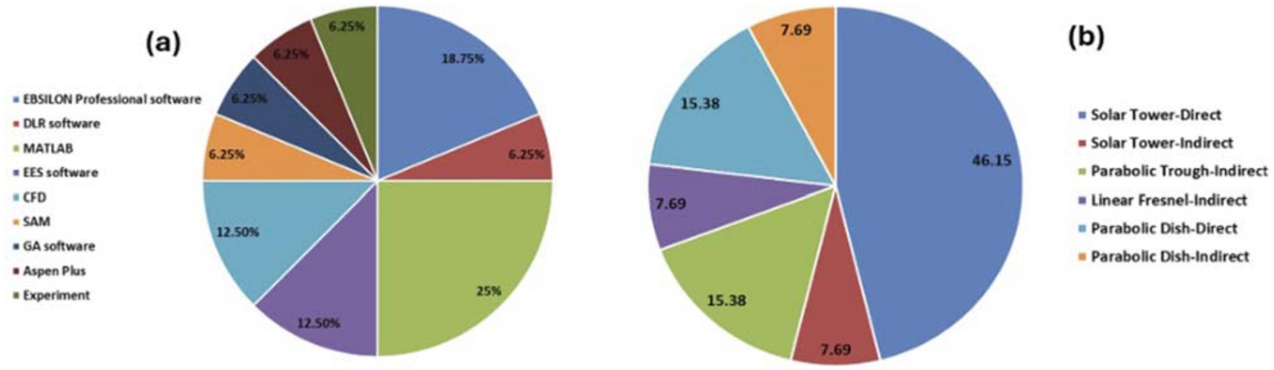

FIGURE 5
(a) The percentage of tools used to investigate the integration of CSP and SOE. **(b)** The proportion of different CSP types used in recent studies in CSP-SOE integration.

4.3 Economic analysis of CSP-SOE integration

Many researchers have reported on the economic analysis of CSP-SOE integration. Researchers have employed many approaches, such as mathematical models or simulations, to investigate various types of CSP, including solar towers, parabolic dishes, and parabolic troughs. Table 5 provides an economic breakdown of expected costs collected from multiple techno-economic research on various forms of CSP and SOE integration systems. The studies examine both direct and indirect methods of integration, which incorporate supplementary elements such as electric heaters or thermal storage. Each research provides the cost of producing 1 Kg of hydrogen, which allows for a

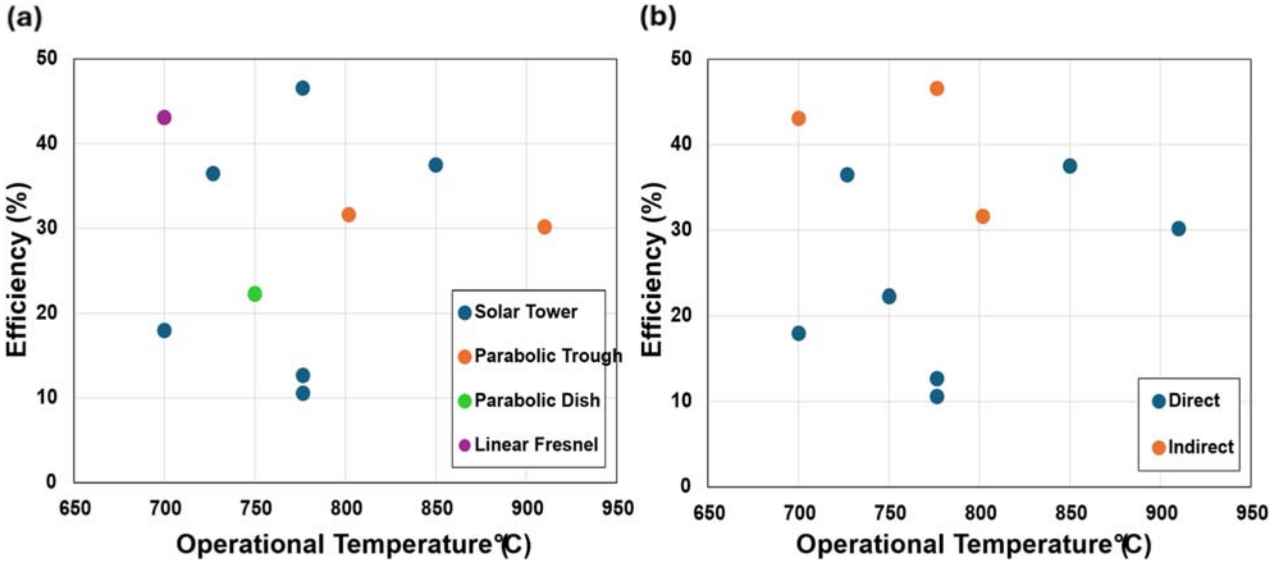

FIGURE 6
(a) Effect of operational temperature on overall CSP–SOE system efficiency for different CSP types based on HHV. **(b)** Comparison of HHV-based overall system efficiencies for direct and indirect integration approaches.

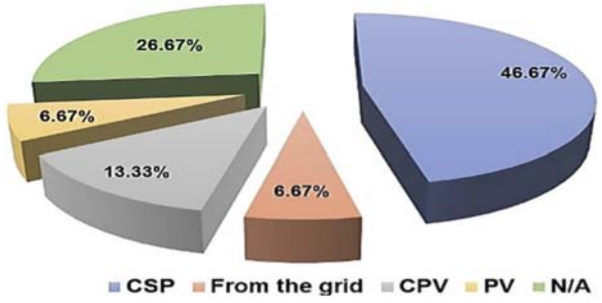

FIGURE 7
The different electricity sources used in CSP-SOE integration.

comparison of the economic viability of various CSP-SOE setups. This data is essential for evaluating the economic feasibility and providing guidance for future investment and research in CSP-SOE integration. A comparative study in Grube et al. (2020) between CSP and PV combined with SOE and PEM has determined that the thermal energy required for SOE, when generated by CSP, is more economically advantageous than utilising PV systems. In addition, CSP-SOE results were more cost-effective than CSP-PEM, but the cost difference between CSP-SOE and CSP-PEM systems was negligible when compared in separate locations. CSP-SOE systems demonstrated superior performance compared to CSP-PEM in terms of hydrogen generation rates, with an approximate increase of 36%. The disparity in marginal costs, along with the greater production of hydrogen, reinforces the argument for implementing CSP-SOE integration despite its present expensive nature.

Table 5 presents an outlook for future projections in economic feasibility. Cost analysis from the data in Table 5 demonstrates that parabolic troughs, employed in indirect techniques, exhibit excellent cost-effectiveness, with hydrogen generation costing $4.43 per kilogramme compared to other CSP types. This cost is comparable to the efficiency of solar towers in direct integration, which stands at $4.55 per kilogramme. This finding prompts a revaluation of long-held assumptions about solar tower efficiency, spotlighting the economic potential of indirect methods with parabolic troughs in green hydrogen production. While the integration approach for green hydrogen production is appealing, it is crucial to acknowledge that the related costs remain quite high. The necessity for research and technological progress in CSP-SOE systems is aimed at enhancing cost-effectiveness and sustainability in the renewable energy industry.

An economic study conducted by Yadav and Banerjee (2018) reported that integrating CSP for heat generation and photovoltaic (PV) for electricity provision, along with SOE, can lead to the production of hydrogen at a cost of $6–8/kg by 2030. This cost reduction is attributed to a decrease in the costs of the individual components involved. According to their analysis, if the costs of SOE and PV decrease to $200/kW and $330/kW, respectively, the production costs of hydrogen could be lowered to $3/kg. This would make hydrogen production cost-competitive with steam methane reforming (SMR). This conclusion emphasises the potential profitability of the integration and the significance of creating pilot-scale prototypes to confirm its economic potential.

5 Discussion and future research

Research has been conducted regarding the integration of CSP and SOE technologies, some of which have concluded that this integration is a potential technique to produce green hydrogen (Puig-Samper et al., 2022; Zhang et al., 2022; Zhang and Li, 2023). There are several ways to perform this integration, and it depends on many factors that differ from one research to another. For example,

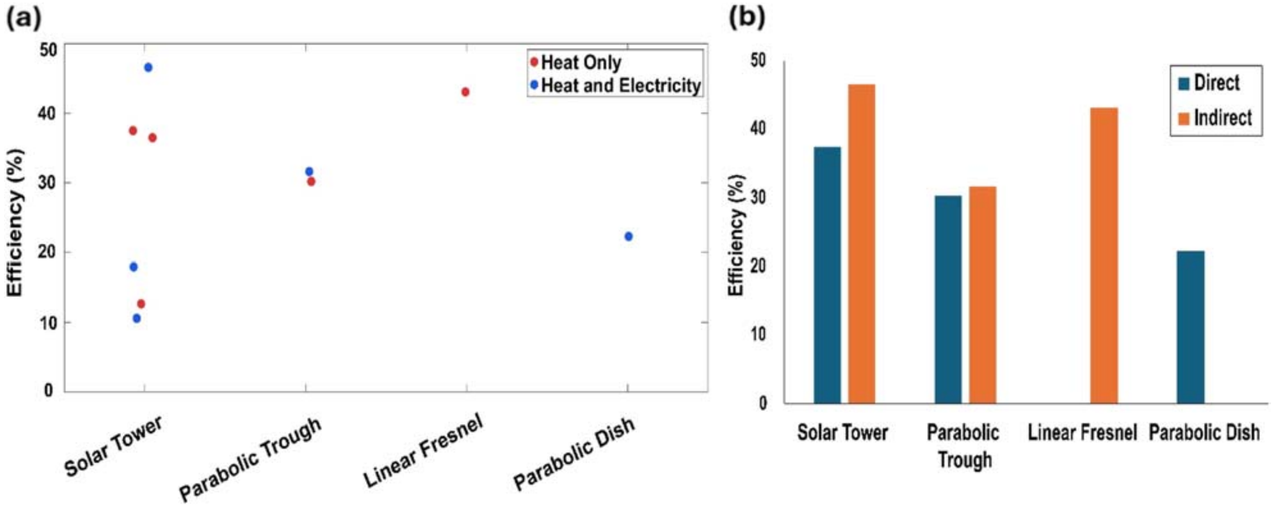

FIGURE 8
(a) System efficiency based on the type of electricity generated, on an HHV basis. **(b)** Comparison of maximum overall efficiencies from previous CSP–SOE integration studies considering thermal energy storage, also expressed on an HHV basis.

some researchers focused on the economic side, and others analysed the integration technically using several types of CSP technology that have been applied in various locations. The methodologies used in most of the studies were simulations using a software program or mathematical models. Only one study presented a prototype and assessed it experimentally. Moreover, every aspect of this integration still has limitations.

Figure 5a depicts the range of methodological tools used in the present study on CSP and SOE integration, highlighting distinct preferences and trends within the area. It displays the frequency of various methodological tools employed in studies concerning the integration of CSP and SOE. The analysis shows a substantial dependence on EBSILON Professional and DLR software, which collectively constitute the majority. MATLAB is widely used, while a smaller proportion of research used EES software, CFD, SAM, GA software, Aspen Plus, and experimental approaches. The observed distribution suggests a potential over-dependence on a limited range of tools, which could result in a deficiency of methodological variety. Focusing solely on one strategy may lead to neglecting the advantages of different analytical methods, as well as valuable insights that can arise from a wider range of experiments.

Figure 5b illustrates the percentage of research among different CSP technologies in terms of direct and indirect integration with SOE. The analysis highlighted a significant emphasis on solar towers with direct integration, which represents 46.15% of the studies. This is because the solar towers and parabolic dishes are able to achieve high operational temperatures necessary for efficient SOE integration, without the need for additional electric heating. The distribution of research suggests less focus on linear Fresnel indirect CSP technologies. This analysis emphasises the need to broaden research efforts to thoroughly evaluate the advantages and limitations of each technology, considering various scales and methods of integration.

Figures 6a,b present the effect of operating temperature on overall CSP–SOE system efficiency based on the HHV standard. The results indicate that operational temperature has a strong influence on system performance across different CSP technologies. The comparative analysis shows that parabolic dish and solar tower systems achieve higher HHV-based efficiencies, particularly under direct integration, while parabolic trough and linear Fresnel systems exhibit moderate performance. In principle, higher operating temperatures generally enhance system efficiency by improving thermochemical conversion and reducing thermal losses. Solar towers demonstrate consistent performance in both integration approaches, benefiting from their broad operational temperature range. These findings highlight that system configuration and CSP type strongly influence overall efficiency and that further optimisation, especially at high-temperature operation, can enhance the effectiveness of CSP–SOE integration.

CSP has been integrated with SOE to supply either the required thermal energy exclusively or a combination of heat and electricity for SOE operation. The various energy sources used to generate electricity in previous studies are illustrated in Figure 7. To demonstrate the overall system efficiency based on this parameter, Figure 8a presents the HHV-based overall efficiency of CSP–SOE systems that provide heat only or both heat and electricity. Recent studies have explored two main configurations of CSP in SOE systems. The first approach employs CSP solely for thermal energy generation while combining it with other renewable sources, such as CPV systems, to meet electrical demands. This hybrid method aims to improve overall system performance through technological complementarity. Alternatively, a research approach focuses on using CSP for both heating and electricity generation, aiming to create a more comprehensive CSP–SOE system. In principle, it is possible for both the heat and electricity required for SOE operation to be entirely provided by solar energy; however, practical implementation is often constrained by solar intermittency, thermal storage capacity, and system cost. The overall system's efficiency highlights the effectiveness of combining CSP with SOE for either

TABLE 6 Future research and their corresponding research goals.

Research gap	Research goal
Efficient heat transfer	Developing more efficient methods for transferring high-temperature heat from CSP to SOE with minimal losses
Materials compatibility	Identifying durable, cost-effective, and safe materials that are suitable to both CSP and SOE and can withstand the extreme conditions of both systems
Hydrogen production efficiency	Optimising the efficiency of hydrogen production in SOE systems, including improving electrolysis cell performance
Thermal energy storage for the system	Investigating advanced thermal energy storage solutions for storing excess energy generated by CSP for later use in SOE.
System control and integration	Developing advanced control systems to seamlessly integrate CSP and SOE, addressing transient behaviours of solar irradiance and load-following
Scalability and cost reduction	Researching scalable solutions and cost reduction methods to make integrated CSP-SOE systems economically viable
Environmental impact mitigation	Assessing and mitigating environmental impacts related to water usage, land use, and emissions associated with CSP-SOE integration
Grid integration and grid services	Investigating how integrated systems can be effectively integrated into the grid and provide grid services
Demonstration projects	Conducting large-scale demonstration projects to validate the practical feasibility and performance of integrated CSP-SOE systems. Conduct more experimental tests and validate more simulation results
Policy and regulatory frameworks	Researching policy and regulatory frameworks that support the deployment and adoption of CSP-SOE systems
Lifecycle assessment	Conducting comprehensive lifecycle assessments to evaluate the environmental and economic benefits and trade-offs
Market viability	Assessing the market viability and commercialisation potential of integrated CSP-SOE systems, including business models

TABLE 7 Challenges of CSP-SOE integration.

Challenge	Description
High operating temperatures	CSP and SOE systems both require high temperatures for efficient operation, making integration complex
Thermal compatibility	Ensuring compatibility of materials used in CSP and SOE systems, given their high-temperature environments
Energy storage	Addressing intermittent energy generation from CSP through effective energy storage solutions
Heat transfer and efficiency	Maximising heat transfer efficiency from CSP to SOE to minimise energy losses
Scale and cost	Achieving cost-effectiveness and economies of scale while maintaining performance
Materials and durability	Ensuring materials in SOE systems withstand harsh conditions and have a long lifespan
System integration	Coordinating complex CSP and SOE systems for optimal performance with advanced control and automation
Hydrogen purity	Maintaining high hydrogen gas purity when SOE is used for hydrogen production
Scalability	Designing systems that can be scaled up to meet larger energy demands effectively
Regulatory and policy hurdles	Addressing regulatory and policy challenges related to safety, environmental impact, and grid integration
Environmental impact	Mitigating environmental impacts, such as water usage and land use, associated with CSP-SOE integration
Reliability and redundancy	Ensuring system reliability and implementing redundancy measures to minimise downtime

heat or both heat and electricity. Figure 8b demonstrates the highest achievable HHV-based system efficiencies of different CSP–SOE technologies. The data indicates that solar towers exhibit consistently high efficiency in both approaches, whilst parabolic trough and linear Fresnel types have moderate efficiency levels. Parabolic dishes demonstrate maximum efficiency when used with the direct method. The difference in efficiency highlights the impact of the integration technique on system performance, indicating that direct methods, particularly for parabolic dishes, are effective for maximising efficiency.

The theoretical findings around CSP-SOE integration are limited. Such a limited scope inherently means that the conclusions drawn are purely theoretical in nature, without any practical or real-world testing to substantiate them. This lack of empirical evidence presents a challenge in validating the theoretical efficiencies and cost projections reported in the literature. Only one study accomplished this integration empirically with considerable limitations (Schiller et al., 2019; Kasaeian et al., 2023). This experiment was conducted in a laboratory using a sun simulator, which means it was not exposed to the real sun and weather conditions. Secondly, a collector, which is one of the main parts of CSP technology was not used. Moreover, the experimental system lacked insulation. This omission is evident in the suboptimal temperature measurements recorded: the system temperature stabilised at only 150 °C before the electrical heating of the steam. For a more efficacious and representative integration of the technologies, it becomes imperative to employ thermal insulation. This would not only retain the system's heat but also optimise its performance. Additionally, refining the control over the flow rate can further augment the system's efficiency. Additionally, no study has provided a CSP system that can be integrated with SOE to be available and applicable to an industrial environment.

A critical gap in current research involves the absence of a developed integration system between CSP technology and SOE that is both functional and readily available. This gap leads to associated challenges, such as material selection for high-temperature operation conditions, the need to control overflow rates and thermal energy, and limited experimental testing. Furthermore, most studies rely heavily on hypothetical or simulated models, lacking real-world applications and documentation. Addressing these gaps is crucial for advancing CSP-SOE integration in green energy, necessitating the development of functional systems, material selection, control methods, empirical testing, and documenting practical applications to promote this promising technology. Table 6 gives an overview of future research gaps for CSP-SOE integration. The research goals aim to address the identified gaps in the literature and contribute to the advancement of CSP-SOE integration in the field of green energy.

Addressing these research gaps is crucial for the successful development, deployment, and optimisation of integrated CSP-SOE systems, which have the potential to contribute significantly to clean energy and hydrogen production. The challenges associated with CSP-SOE integration are tabulated in Table 7. These challenges collectively impact the successful integration of CSP with SOE systems and require careful consideration and innovation to overcome.

6 Conclusion

A comprehensive review study of CSP-SOE integration is conducted. Based on the findings in this study, it is crucial to consider all factors in CSP-SOE system integration. The study shows that parabolic dishes, when directly integrated, provide superior efficiency. However, their higher prices compared to other CSP technologies indicate the challenges in creating economically viable CSP-SOE systems. The economic study indicates that the current costs of integration are considerably high. Future technological developments and cost optimisations have the potential to improve the competitiveness of CSP-SOE. To ensure the future success of CSP-SOE systems, it is crucial to address the highlighted gaps, such as improving heat transfer efficiency, ensuring material compatibility, and achieving scalability. Additionally, solving issues related to high operating temperatures and environmental implications is also essential. This review emphasises the importance of maintaining a balance between operational efficiency and economic feasibility to make CSP-SOE a feasible solution for sustainable, large-scale hydrogen production. Although various integration concepts have been modelled and evaluated, only one laboratory-scale CSP–SOE prototype has been reported so far. Future work should prioritise pilot-scale field demonstrations to validate system performance under real DNI conditions with integrated TES dispatch strategies. Such efforts are critical for assessing long-term durability, operational flexibility, and scalability of these systems. It also highlights the need for ongoing innovation and research to address these challenges.

Author contributions

AbA: Validation, Methodology, Formal Analysis, Investigation, Software, Writing – original draft, Funding acquisition, Conceptualization, Data curation, Visualization. KI: Validation, Methodology, Writing – review and editing, Formal Analysis, Visualization. QQ: Writing – review and editing, Supervision, Visualization, Validation, Methodology. PK: Writing – review and editing, Conceptualization, Supervision, Methodology. AhA: Validation, Visualization, Formal Analysis, Writing – review and editing. TD: Formal Analysis, Validation, Writing – review and editing, Supervision. YA: Formal Analysis, Validation, Writing – review and editing. ZL: Formal Analysis, Resources, Project administration, Supervision, Writing – review and editing, Conceptualization, Funding acquisition, Methodology, Validation.

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Conflict of interest

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

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Nomenclature

CSP	Concentrated Solar Power
PV	Photovoltaic
CPV	Concentrated Photovoltaic
SOE/SOEC	Solid Oxide Electrolysis/Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
PEM	Proton Exchange Membrane Electrolyser
AEL	Alkaline Electrolyser
TES	Thermal Energy Storage
THS	Thermochemical Heat Storage
LHS	Latent Heat Storage
TM	Thermal Management
HTF	Heat Transfer Fluid
PTC	Parabolic Trough Collector
STC	Solar Tower Collector
LFR	Linear Fresnel Reflector
PDC	Parabolic Dish Collector
CR	Concentration Ratio
DNI	Direct Normal Irradiance
η_{STH}	Solar-to-Hydrogen efficiency
HHV	Higher Heating Value
LHV	Lower Heating Value
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen

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