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Analysis of Concentrated Solar Power Potential in the Photovoltaic Competitive Landscape

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Abstract

Concentrated Solar Power (CSP) technology offers significant potential for stable and dispatchable renewable electricity generation through integration with thermal energy storage. However, adoption remains limited due to high capital costs, technical complexity, and market competition from photovoltaic (PV) systems. This review systematically synthesises recent literature on CSP and applies a hybrid SWOT–Analytic Hierarchy Process (AHP) methodology to quantitatively evaluate key internal and external factors influencing CSP deployment. The analysis identifies major strengths such as high-capacity factors and grid stability enabled by thermal storage, as well as weaknesses including high initial investment and site requirements. Opportunities stem from technological innovation, supportive policy frameworks, and potential for local job creation, while threats include rapid cost reductions in PV systems, water scarcity, and market and regulatory uncertainties. The integrated SWOT–AHP approach provides a robust decision-making framework and strategic insights for stakeholders seeking to promote CSP technology in diverse market contexts. The findings underscore the importance of tailored policy support and targeted investment to overcome barriers and realise CSP's full potential within the renewable energy landscape.

Keywords: concentrated solar power (CSP); SWOT analysis; Analytical Hierarchy Process (AHP); strategic decision making

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1. Introduction

The transition to renewable energy sources is a key global challenge in addressing climate change and fossil fuel depletion. One of the main challenges in the integration of renewable energies is their intermittent and variable nature [1]. In this context, concentrated solar power (CSP) is recognised as a promising technology for electricity generation, offering a high-capacity factor and the integration of thermal energy storage systems, which enable a stable and predictable electricity supply [2]. Existing research addresses the technical, economic, environmental, and social aspects of CSP technology, while also highlighting challenges such as high capital costs, construction and maintenance complexity, and regional limitations due to the need for direct solar radiation.

Given the rapid proliferation and prevailing dominance of photovoltaic (PV) systems in the renewable energy sector, a comparative analysis of PV and CSP technologies is essential for a comprehensive understanding of the evolving energy landscape. PV systems are currently the most widespread form of solar energy due to their lower initial costs, ease of installation and maintenance, and broad applicability across various climates [3]. However, PV systems still face challenges related to production intermittency and limited

capacity for permanent energy storage without additional battery systems. In contrast, CSP technology complements PV by integrating thermal energy storage, providing a more stable and predictable electricity supply, particularly in areas with high direct normal irradiance (DNI) [2,4]. Comparing PV and CSP systems highlights the advantages and limitations of both technologies and assists in designing optimal strategies for their deployment in different geographical and market conditions.

It should also be noted that the development trajectory of CSP is also influenced by its synergy with other power generation technologies and the broader evolution towards integrated multi-energy systems. Hybrid configurations combining CSP and PV leverage the strengths of both technologies: PV provides cost-effective peak solar energy during daylight hours, while CSP delivers predictable baseload and dispatchable power through thermal storage. Such hybridization not only optimizes land use and solar resource utilization over daily and seasonal cycles but also reduces the levelised cost of electricity (LCOE), as demonstrated by several operational and planned projects worldwide [5]. Beyond the direct CSP-PV synergy, CSP's role within integrated energy systems is expanding through coupling with other renewable and conventional sources, such as geothermal power and combined heat and power plants (CHP). These integrated systems enhance overall efficiency by recovering waste heat, smoothing output variability, and enabling more flexible grid services. For example, studies of CSP and geothermal power plant (GPP) integration show significant improvements in net power output and conversion efficiency, along with decreases in LCOE, underscoring the technical and economic viability of CSP as a cogeneration unit within multi-energy frameworks [6].

The advancement of integrated energy systems—including the convergence of solar (PV and CSP), wind, hydro, and thermal storage—drives progress in CSP deployment by addressing the intermittency challenge inherent to renewables and supporting grid stability. Multi-energy complementary systems enable optimised dispatch strategies, reduce reliance on fossil-fuel peaking plants, and facilitate the integration of hydrogen production as an energy storage and sector-coupling vector. CSP-generated high-temperature heat is particularly valuable for green hydrogen production via high-temperature electrolysis, reinforcing CSP's versatility and strategic importance in the decarbonised energy landscape [7].

A comparison of CSP and PV systems in the analysed review provides a deeper understanding of their technical, economic, environmental, and social implications, which is necessary for informed decision-making by policymakers, investors, and system operators during the decarbonisation of the electricity sector. A detailed analysis of integrated energy systems that include CSP, although relevant to this topic, is not included, as it would require considerable space and could dilute the focus of the narrower problem analysed.

The existing literature, although extensive, often addresses only specific aspects of CSP systems or focuses exclusively on technical performance. Few works systematically integrate the broad range of factors involved in CSP implementation, including strategic, regulatory, and socioeconomic dimensions. Rapid advances in CSP technology and changing market conditions require an up-to-date assessment. Therefore, it is necessary to synthesise existing knowledge and objectively assess the key factors that may contribute to or limit the wider implementation of CSP technologies.

The novelty of this study and its contribution to the scientific literature lie in the use of the SWOT-Analytical Hierarchy Process (AHP), which quantitatively assesses and ranks the main strengths, weaknesses, opportunities, and threats associated with the application of CSP in a competitive environment shaped by photovoltaic systems. Based on a comprehensive review of the latest peer-reviewed publications and authoritative reports, as well as the authors' expert judgement, this research presents an up-

to-date, multidimensional strategic framework to guide policymakers, investors and industry stakeholders.

Key findings indicate that CSP's high-capacity factor and grid stability advantages, driven by thermal storage integration, contrast with challenges such as high capital investment and site-specific requirements. Opportunities exist in technological innovation and policy support, while threats stem from rapid PV cost reductions and resource constraints such as water scarcity. This integrated analysis supports targeted strategic actions to maximise CSP's role in the renewable energy future.

The structure of the paper includes: an overview of the methodology for data collection and analysis (Section 2); a detailed analysis of the technical, economic, environmental, and social aspects of CSP and their comparison with PV technology (Section 3); and a discussion on results obtained, and the limitations of this study (Section 4). Section 5 provides recommendations for stakeholders.

This research is intended for energy policymakers, renewable energy investors, industry experts, and scientists interested in the development and optimisation of concentrated solar power as part of a green energy future

2. Materials and Methods

This study uses a mixed qualitative and quantitative research design, combining a systematic literature review with a hybrid SWOT–Analytic Hierarchy Process (AHP) methodology to assess the strategic potential of Concentrated Solar Power (CSP) technology in competition with Photovoltaic (PV) systems.

Following the definition of the research objective and the problem framework in the introduction, the methodology of this study comprises the following processes and methods that lead to the results of the study:

(1) Literature search

The research methodology initially comprised a literature search to obtain information on the use of the hybrid SWOT-AHP method in strategy formulation and selection. After that, a systematic literature search was carried out in the Web of Science (WoS) database, focusing on peer-reviewed articles published between 2017 and 2024. Keyword combinations included: "PV system AND CSP", "Concentrated solar power AND SWOT", "Concentrated solar power AND AHP" as well as technology-specific queries such as "Concentrated solar power AND parabolic trough" and "Concentrated solar power AND Fresnel" (see Table 1). This search produced a comprehensive collection of relevant studies, which were supplemented by technical reports and datasets from REN21, IEA-PVPS, NREL, Fraunhofer Institutes, and the China Renewable Energy Society.

Table 1. Summary of database search queries and results.

Query	Results
PV system AND CSP	26
Concentrated solar power AND PV AND CSP	37
Concentrated solar power AND SWOT	4
Concentrated solar power AND AHP	8
Concentrated solar power AND multi-criteria decision	13
Concentrated solar power AND central tower	11
Concentrated solar power AND parabolic troughs	215
Concentrated solar power AND Fresnel	67

The screening process applied rigorous inclusion and exclusion criteria, prioritising peer-reviewed sources with relevant data and methodological rigour. The "snowball"

method of citation chaining and targeted Google searches were used to identify additional literature on the economic, technical, environmental, and social aspects of CSP and PV systems

(2) The SWOT framework was used to systematically identify and categorise internal strengths and weaknesses, as well as external opportunities and threats influencing CSP adoption. Based on a literature synthesis, eight of the most important factors in each SWOT category were identified, selected, and ranked by importance.
(3) The AHP methodology, based on Saaty's pairwise comparison principles, was used to quantitatively rank the influential factors. Typically, three to five of the most influential factors are selected for analysis to keep the procedure manageable and ensure the results are relevant and clearly identify the critical factors. In this case, the author based the analysis on the four most influential factors.
(4) Discussion of the results obtained.
(5) Recommendations to stakeholders and policy makers regarding the green transition and CSP systems. Assessment of the implementation of the CSP system in the coming period.

SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) is widely adopted as a strategic evaluation tool in energy research to examine both internal and external factors influencing technology development. By integrating technological, economic, environmental, and social dimensions, SWOT enables a nuanced understanding of complex energy systems. When combined with the Analytical Hierarchy Process (AHP), the resulting SWOT-AHP model provides a robust framework that supports evidence-based decision-making and prioritisation in renewable energy planning. This combined methodology has been effectively applied to assess various renewable technologies, including solar, wind, hybrid systems, pumped-storage hydropower, and building-integrated photovoltaics [8–11]. For technical researchers, SWOT analysis facilitates the systematic identification of critical factors affecting technology performance and adoption, supporting data-driven optimisation and strategic innovation in renewable energy projects. For policymakers, SWOT analysis is invaluable for identifying strategic opportunities and challenges, guiding policy development, and fostering sustainable energy transitions.

The Analytical Hierarchy Process (AHP), developed by Thomas L. Saaty in 1977 and further detailed in 1987 [12], is a multi-criteria decision-making tool for complex problems with conflicting criteria [13]. It breaks down unstructured problems into a hierarchy of subproblems for independent analysis. Decision-makers use pairwise comparisons and mathematical methods to quantify and prioritise alternatives.

The implementation of the AHP comprises several important steps [9,13,14]:

(a) Building the hierarchy: define the main objective at the top level, the criteria and sub-criteria at the intermediate levels and the alternatives at the lowest level.
(b) Pairwise comparisons: Evaluate the relative importance of criteria, sub-criteria and alternatives using a Saaty scale.
(c) Prioritisation: Use mathematical methods to derive the weights and priorities for each criterion and alternative.
(d) Consistency check: Evaluation of the logical coherence of pairwise comparisons.
(e) Synthesis and decision: Summarise the results to identify the best alternative that meets the given objective.

In this research the AHP hierarchy comprised four levels (see Figure 1):

- Goal: Optimal CSP deployment strategy
- Criteria: SWOT categories (S, W, O, T)
- Sub-criteria: 16 identified factors

- Critical factors (alternatives)

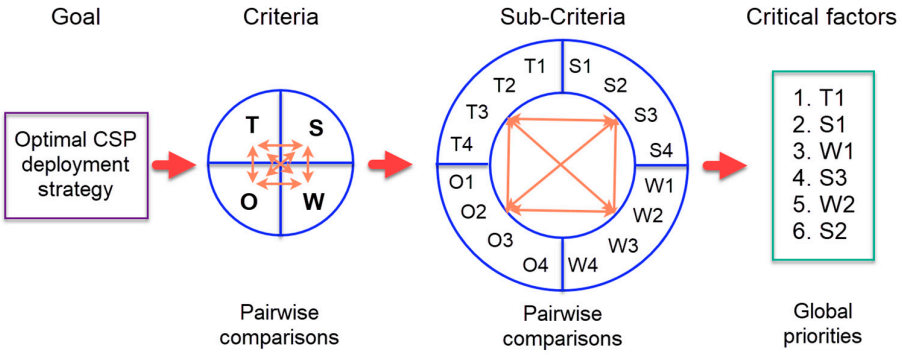


Figure 1. SWOT-AHP model for optimal CSP deployment strategy.

The author used Klaus Goepeepel's online AHP calculator [15] to perform pairwise comparisons, compute local and global priority vectors, and check the consistency of the judgement matrices. Using expert judgement, the pairwise comparisons of factors were made according to the Saaty scale, which assigns nine discrete values to represent relative importance: 1 (equal importance), 3 (moderate importance), 5 (strong importance), 7 (very strong importance), and 9 (extreme importance), with 2, 4, 6, and 8 as intermediate levels.

Because it is difficult to translate percentage-based importance estimates into the Saaty integer scale, some inconsistency—measured by the consistency ratio (CR)—was unavoidable. The online tool processed all pairwise inputs to construct reciprocal comparison matrices, from which it derived local priority vectors for individual factors within each category. These local priorities were then weighted by their respective category group weights to calculate the global priority vector.

$$\text{Global Weight} = \text{Local Weight} \times \text{Category Weight} \quad (1)$$

This global vector provided a hierarchical ranking of SWOT factors based on their overall relative importance.

The AHP model results were validated by calculating the consistency ratio (*CR*) for all pairwise comparison matrices using the Alonso and Lamata method integrated into the online software [16].

$$CR = \frac{\lambda_{max} - n}{2.7699 \cdot n - 4.3513 - n} \quad (2)$$

where n is the number of factors being compared.

Matrices with $CR \leq 0.1$ were accepted; if $CR > 0.1$, the corresponding pairwise comparison value was adjusted.

Key methodological limitations related to literature selection and the subjectivity of expert judgement were acknowledged and are discussed in detail in Section 4.2 to provide full context for interpreting the results.

3. Results

CSP technologies have attracted attention due to their ability to concentrate a large area of solar radiation onto a small surface. This significantly increases the energy level of the irradiated energy and creates the conditions for its efficient conversion into the thermal energy of water vapour. The water vapour is than used to generate electricity in a thermodynamic power cycle or as process hot water in industry. There are four main CSP technologies, which are categorised according to the principle of focussing the sun's

rays: Parabolic trough collector (PT), Central Tower (CT), Linear Fresnel reflector (LFR) and Parabolic dish (see Figure 2).

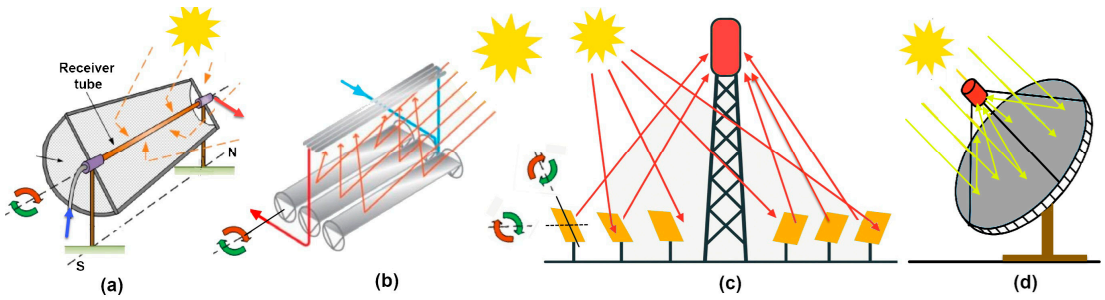


Figure 2. The functional principle of CSP technologies, (**a**) Parabolic trough, (**b**) Linear Fresnel Reflector, (**c**) A central tower, (**d**) Parabolic dish.

Parabolic trough (PT) technology uses long rows of parabolic, highly reflective mirrors to focus sunlight onto a small area of an absorber tube containing a working fluid that absorbs heat (usually synthetic oil). In addition, the absorbed energy is used to produce water vapour, which generates electricity in a thermodynamic cycle [17].

A central solar tower uses an array of heliostats that can track the sun in two axes and direct solar radiation to a fixed receiver at the top of a central tower. A heat transfer fluid, often molten salt or air, is heated to very high temperatures (~1000 °C). The energy obtained in this way is used to generate electricity in a thermodynamic power station cycle [6,17].

Linear Fresnel Reflector (LFR) technology uses long rows of flat or slightly curved mirrors to reflect and concentrate sunlight onto a receiver located above the mirrors. The receiver tube contains a heat transfer fluid that absorbs the solar energy and converts it into electrical energy via a thermodynamic cycle. The technology is similar to parabolic trough technology, but utilises simpler and cheaper flat reflectors [6,17].

Parabolic dish (Dish/Stirling Dish) system uses a parabolic reflector to focus sunlight onto a single point where a receiver converts the concentrated solar energy into heat. This heat is usually used to drive a Stirling engine or other heat engine directly to generate electricity. It achieves high concentration and efficiency, but is less commercialised than the PT and tower systems [6,17].

The first reported CSP is the 5 MW US National Solar Thermal Test Facility, which has been in operation since 1978. The commercial deployment of Concentrated Solar Plants (CSP) started in 1984 in the United States. CSP technology was not used on a large scale until the year 2000. Between 2008 and 2013, there was a sharp increase in installed CSP capacity, thanks to Spain and the USA [18,19]. Around 4 GW of CSP was installed in this 5-year period. In July 2023, the total CSP capacity is just over 6.7 GW [20]. As of 2024, the global installed CSP capacity was approximately 8 GW (see Figure 3).

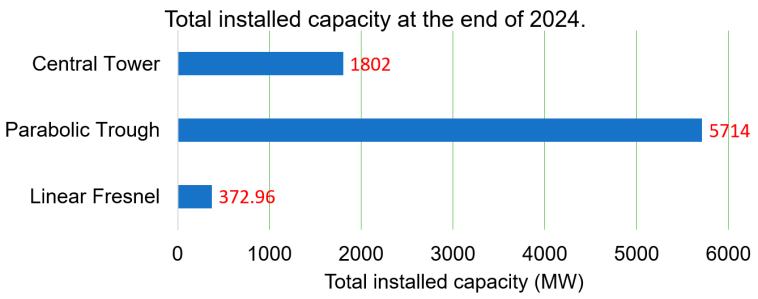


Figure 3. Total installed capacity for each CSP technology [17].

In a scenario consistent with the Paris Agreement, global installed CSP capacity must reach about 190 GW by 2030 and 870 GW by 2050 [21]. This is a highly optimistic scenario, given the current installed capacities. To analyse the prospects for implementing the mentioned plans, it is necessary to examine the technical, economic, ecological and social aspects of CSP technology, as outlined below. As PV technology is the main competitor to CSP technology, these technologies are compared across all key aspects.

3.1. Technical Aspects

The most important technical aspects include the system's overall efficiency, the time required for its design and construction, its service life, and the performance degradation over its service life.

3.1.1. The Overall Efficiency of the System

Direct normal irradiance (DNI), or the direct sunlight available at a given location, is the most important factor in determining the performance of a CSP plant. The typical threshold for annual DNI is between 1900 and 2100 kWh/m^2, although in India, plants have also been built in locations with 1610 kWh/m^2. CSP systems convert the energy of solar electromagnetic radiation into thermal energy and then into electricity, with multiple conversion steps reducing overall efficiency. Factors influencing CSP efficiency [2,22] are:

(a) CSP technology

Different types of collectors and power cycles have different inherent efficiencies.

(b) Receiver temperature

Higher operating temperatures, achieved with advanced heat transfer fluids, can lead to higher thermal efficiencies.

(c) Power cycle

The thermodynamic cycle used to convert heat to electricity, like Brayton or Rankine cycles, significantly impacts efficiency.

(d) Thermal Energy Storage (TES)

The efficiency of the overall system can also be affected by the efficiency of the thermal storage system, which is crucial for CSP plants to provide power after sunset.

Typical overall solar-to-electric efficiency for CSP plants is around 15–25%, depending on the technology and thermal storage integration (Table 2). Key loss factors in CSP systems include:

- Optical losses (10–20%) [22]: the solar reflectivity of reflectors, blocking, shading, optical soiling losses (higher by a factor of 8–14 in CSP for the same particle surface densities compared to PV [23]).
- Receiver thermal losses (5–10%): heat losses at high temperature.
- Thermal storage losses (~2–5% per storage cycle): heat loss during storage.
- Heat-to-electricity conversion efficiency (30–45%): limitations of steam turbine or Brayton cycle.
- Parasitic losses (5–15%): auxiliary power for pumps, controls, and tracking [24].

Table 2. Overall Conversion Efficiency [2].

Technology	Overall Conversion Efficiency (%)	Main Losses
PV Fixed Tilt	15–20	Reflection, recombination, temperature, inverter
PV One-Axis Tracking	15–20 (Higher yield overall)	Same as fixed tilt + shading minimized
CSP Central Tower	18–28	Optical, thermal, storage, turbine, parasitic
CSP Parabolic Trough	15–20	Optical, receiver, turbine, storage, parasitic
CSP Linear Fresnel	14–19	Similar to trough but lower temperature operation
CSP Parabolic Dish	15–32	Optical and heat engine losses

CSP power plants with a central tower often achieve higher efficiency in this area due to higher operating temperatures and better heat storage. Parabolic trough and linear Fresnel power plants tend to have lower overall efficiency because of their lower operating temperatures.

- Modern commercial monocrystalline PV panels typically have module conversion efficiencies between 20% to 25%, with state-of-the-art modules reaching up to 25% efficiency [25,26].
- Overall system efficiency including inverter and balance of system losses is typically around 15–20% for utility-scale systems [27].
- Tracking PV systems increase overall energy harvested but do not significantly change module conversion efficiency; they reduce shading and increase incident irradiation [27].
- Tracking PV systems adds ~4 percentage points to capacity factor on average, with improvement from tracking more pronounced in higher solar resource areas [28].

Additional findings:

- The efficiency of PV modules continues to improve, driven by advanced cell technologies such as heterojunction, TOPCon and tandem perovskite silicon cells, which promise efficiencies of over 25% in the near future [25].
- Tandem perovskite silicon solar cells have recently reached efficiencies of up to 34.85%, while single-junction perovskite cells achieve around 26.7% [29].
- The highest efficiency for concentrator photovoltaic (CPV) solar cells with multiple junctions is 47.6%, achieved in 2022 by the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) in Germany. This record was set with a new quadruple-junction solar cell under concentrated sunlight (665 suns) and enhanced anti-reflective coatings [30].
- The efficiency of CSP is fundamentally limited by the efficiency of the thermal cycle and the losses of the optical system, but benefits from the predictable heat storage that reduces the fluctuations [31,32].
- Losses in CSP systems are also influenced by site-specific factors such as dust, cloud cover and heat loss management, so operational efficiency varies.
- Recent reviews and techno-economic analyses (2023–2025) of CSP power plants with molten salt towers indicate thermal-electrical efficiencies ranging from 30% to 40%, depending on system design, number of sunshine hours, and storage duration. For example, a study modelling several molten salt CSP power plants reported that optimised designs achieve capacity factors of around 51% and solar-electrical efficiencies of nearly 40% with 10 h of thermal energy storage [33].

3.1.2. Time Required for Plant Design and Construction

There is very little direct information in the scientific literature about the time required for the design and construction of photovoltaic and CHP systems. Some information is available from the so-called "grey literature". According to this and the author's experience, PV projects generally have relatively short development and construction times compared to CSP. The planning and approval phase usually takes between 6 months and 2 years, depending on location, regulatory complexity, and project size [21,34,35]. Construction of large PV systems usually takes 6 to 18 months, although completion can be quicker for simpler, modular, fixed-tilt systems. Tracking PV systems may require a slightly longer construction time due to the installation of tracking mechanisms, but this does not significantly extend the overall timeframe.

Due to their size and technical requirements, CSP projects typically have longer and more complex development, approval, and construction periods. The design and approval phases often take one to three years and are affected by environmental impact assessments, land use, and water rights. Construction time, including functional testing and commissioning of CSP power plants, varies by technology, but is typically 22 to 36 months due to the intensive construction work, assembly of thermal components, installation of heliostat arrays and installation of power plant units. The total duration will depend on lead times for major equipment and other factors such as the remote location of the site, access to labour, and materials and, last but not least, progress on site and the contractor's capabilities. Once the plant has been successfully built and commissioned, there is usually a warranty period of two to three years to achieve full production and ensure that the plant is operating at full capacity. Only then is the plant fully economically viable for the remainder of its life [36]. It is noteworthy that average commissioning times for all technologies and project sizes in the renewable energy sector have generally increased, or in a few cases, remained constant over time [35].

The time required to construct a CSP system can depend on disruptions in the global market for key components such as heliostats, mirrors for parabolic troughs and linear Fresnel collectors, receiver tubes and control electronics. The heliostat supply chain is critical for CSP power tower systems, as heliostats account for a significant portion (30–50%) of construction costs and are complex, specialised components. Many specialised heliostat manufacturers and mirror producers are concentrated in China. Disruptions in the global market may result from inconsistent demand, volatility due to the relatively small size and slow growth of the global CSP market, and supply chain issues such as labour shortages and the impacts of recent global events like COVID-19. These factors can delay manufacturing, scaling up mass production, and delivery of heliostats and other critical parts, thereby extending project timelines [37]. Most CSP components are made from commodity materials such as steel, aluminium, and glass, which are generally abundant, but production and supply chains can still be affected by global market conditions and regional labour issues. The absence of a strong local market can also make scaling domestic production challenging, leading to dependence on international suppliers who may face their own supply chain risks.

3.1.3. Service Life

Large PV systems generally have a service life of 25 to 30 years. This corresponds to the period during which the panels retain around 80% of their original electricity production [38]. Warranties typically cover 25 years, with some premium panels offering extended performance warranties of up to 40 years, indicating a potential operational lifetime of over 30 years.

The lifetime of CSP power plants is typically 30 to 40 years and depends mainly on the technology and maintenance [39,40]. CSP power plants with a central tower and CSP parabolic trough systems generally have a service life of 30–35 years, whereby the main components (steam turbines, receivers, heliostats) often have to be replaced or overhauled after 15–20 years. Linear Fresnel CSP systems have a similar service life to trough systems, which is also 30–35 years. Parabolic trough CSP systems have a shorter typical lifetime in the range of 25–30 years due to their smaller size and complexity [41].

Both PV and CSP systems can operate beyond their nominal lifetime, which reduces efficiency and increases maintenance costs. Regular preventive maintenance and component replacement (especially for CSP turbines and receivers) are critical to maximising operational lifetime [40].

3.1.4. Sensitivity to Climate Change

The effects of climate change on photovoltaics are mainly due to changes in solar radiation (insolation) and ambient temperature. Reduced solar radiation lowers output, while higher temperatures decrease module efficiency [42]. An increase in module temperature reduces efficiency by 0.4–0.5% per degree Celsius, although this may be partially offset by potential gains in regions with higher solar irradiance [43]. Studies show regional differences, with PV potential in some regions (e.g., South Asia, parts of Europe) expected to decrease by up to 8–20 by 2100 under high emissions scenarios, mainly due to lower solar irradiance and higher temperatures [44]. Extreme weather events (storms, floods) and dust accumulation associated with climate change pose additional risks to the durability and performance of PV systems [42].

CSP is sensitive to changes in direct normal irradiance (DNI), which is critical as CSP requires direct sunlight to operate. CSP systems are highly dependent on thermal components; high ambient temperatures can affect thermal efficiency and cooling requirements [19]. The availability of water, which is affected by climate change, is particularly critical for CSP plants that utilise wet cooling, which could limit plant operation or require costly alternatives to dry cooling [19]. Extreme heat waves and dust storms can affect optical components and thermal systems, increasing maintenance and reducing performance.

3.1.5. System Performance Degradation Rate

The degradation rate (DR) depends on climatic conditions and the technological generation of the PV module. Causes of degradation include environmental stressors such as UV exposure, temperature fluctuations, moisture ingress, microcracks in the cells, and chemical ageing [45]. From tropical, arid temperate to continental climates, DR gradually decreases, with the median DR decreasing from 1.40%/year to 0.9%/year and the mean DR decreasing from 1.62%/year to 1.40%/year [46].

In the past, first generation of PV technologies have shown robust performance. Multi-Si shows a DR at module level of 1.10%/year (0.70%/year at string level and 0.90%/year at system level) and mono-Si shows a higher DR at string level (1.55%/year) compared to its module (1.20%/year) and system (0.80%/year). Gen 3 of PV technologies shows a modest median DR (0.90%/year). SHJ consistently have a low DR (0.50%/year at module and string level, increasing to 1.00%/year at system level), while multi-junction cells have a moderate module DR (0.70%/year) but a much higher system DR (2.10%/year) [46]. According to Seel et al. [28], the annual performance degradation at the system level varies by vintage, with newer systems showing a degradation of 0.9% per year compared to 1.47% for older systems.

CSP (Concentrated Solar Power) systems are subject to a different degradation than PV (Photovoltaic) systems, which is mainly due to thermal and mechanical ageing of various components. The available literature on the power degradation of CSP systems based on field measurements is limited, but the existing studies provide some insight into the rate and causes of degradation. Some authors suggest that CSP systems degrade at a comparable rate to PV systems, with annual power losses ranging from 0.7% to 1.5%. However, others, such as Osman and Qureshi [2], report that CSP systems generally have lower annual efficiency losses—around 0.2% to 0.5% for PV systems. In terms of individual components, studies show that steam turbines in CSP plants have power losses of between 2.03% and 7.51% over 35 years of operation, which corresponds to around 0.06% to 0.2% per year [47]. Thermal storage systems and heliostats face efficiency losses due to fouling, corrosion, wear and material degradation, especially in dusty or harsh environments. The degradation of reflector materials is critical as it reduces solar reflectance, which is important for system performance.

Thermal cycling and static mechanical loads in CSP plants contribute to component creep and fatigue [48]. The degradation characteristics vary depending on the reflector type, the composition of the reflector layer and the ambient conditions. High temperatures, which are required for optimal CSP efficiency, accelerate the wear of reflectors and thermal storage materials. For example, studies show that film-based reflectors can lose up to 23.13 mg/day of mass under tropical conditions, emphasising the importance of developing corrosion-resistant materials [32].

Heat exchangers in CSP systems also suffer from performance losses, primarily due to fouling. Despite design improvements, fouling is still a major challenge. It is caused by deposits such as minerals, corrosion products, biological growth and organic layers on the heat transfer surfaces. These deposits reduce the heat transfer coefficient, increase the pressure loss, reduce the fluid flow rate, increase operating costs and shorten the service life of the heat exchanger. A study has shown that fouling can reduce the efficiency of heat exchangers by up to 30%, which significantly increases maintenance and operating costs [49].

To summarise, the degradation of CSP systems is complex and involves component-specific ageing mechanisms that are influenced by environmental and operating conditions. Dealing with these degradation pathways, especially fouling and material wear, is crucial for improving the durability and performance of CSP systems.

3.1.6. Capacity Factor

The capacity factor is an important measure of how effectively a power generation system converts its installed capacity into actual electrical power over time. It is defined as the ratio between the energy actually generated in a given period and the energy that would have been generated if the system had been operated continuously at full capacity over the same period. The capacity factors depend on the technology used in the power plant unit, the storage technology and capacity, the solar resources, the expected downtimes and the energy losses in the system [50]. A higher DNI leads to an increase in the capacity factor, but the correlation between capacity factors and storage hours is much stronger. However, this is only part of the economics of plants at higher DNI locations. A higher DNI also reduces the field size required for a given project capacity and thus the size of the investment.

CSP systems generally have higher capacity factors than photovoltaic (PV) systems due to the possibility of integrating thermal energy storage (TES) and the nature of CSP technology. Capacity factors of more than 50% indicate that a considerable proportion of the energy storage is utilised. The capacity factor for a tower power plant with 10 h TES is

around 55%, in some cases even higher., depending on location and availability of solar resources [32,51]. With parabolic trough technology, the capacity factor is typically 29–43% (with TES).

Based on global data from current scientific and market analyses, the capacity factors of CSP vary considerably in different regions of the world. In China, CSP projects in provinces such as Gansu and Qinghai, which are characterised by high solar irradiation and the integration of large thermal salt storage facilities, generally have capacity factors in the range of 50% to 60% or even higher. Morocco, an early adopter of CSP technology in Africa, has capacity factors of around 45% to 55%, supported by excellent solar resources and thermal energy storage, as can be seen in projects such as Noor Ouarzazate. The United Arab Emirates in the Middle East achieve CSP capacity factors between 50% and 60% and benefit from high direct radiation and advanced thermal storage technologies. In Spain, the capacity factors of CSP plants are generally somewhat lower, between 40% and 50%, due to moderate solar irradiation combined with a well-developed thermal storage infrastructure. The 110 MW Cerro Dominador project in the Atacama Desert region in Chile which started in 2021 features the highest known thermal storage capacity in the world, at 17.5 h. Thus CSP capacity factors reach up to 80% [52]. South African CSP plants typically achieve capacity factors between 45% and 55%, supported by favourable solar conditions and storage solutions [53]. These capacity factors reflect the integration of thermal energy storage and the high availability of solar resources in CSP power plants and allow for more consistent and predictable power generation compared to PV plants.

3.1.7. Energy Payback Time (EPBT)

The EPBT of a solar energy system is the time required for the system to generate an amount of energy equal to that used in its production. The energy payback time is influenced by the following factors:

- The materials and technology used in manufacturing the solar energy system
- The efficiency of the solar energy system and the grid
- The irradiation associated with the geographical location of the solar energy system

PV systems manufactured in Europe and installed in Northern Europe have an EPBT of approximately 1.1 years, while those installed in Southern Europe have an EPBT of 0.9 years [54].

EPBT values for CSP plants vary depending on plant configuration, capacity factor, and storage hours. Most CSP technologies have an EPBT between 1 and 6.6 years [55,56]. The energy payback time (EPBT) for parabolic trough CSP plants is approximately 1 to 1.4 years for a commercial-scale plant operating primarily on solar energy [40,57]. The energy payback time for central tower CSP ranges from 0.3 to 3.58 years, while Fresnel systems have an EPBT of less than 1 year [58].

3.1.8. Reliability

CSP is best suited for large-scale plants in regions with high direct normal radiation (e.g., deserts). CSP power plants generally provide a more reliable and predictable power supply as they are usually combined with thermal energy storage (TES) systems, such as molten salts. This allows CSP power plants to generate electricity and deliver a constant output even when it is cloudy or after sunset. CSP is therefore beneficial for grid stability due to its dispatching capabilities. However, their reliability is affected by higher maintenance requirements due to moving parts (e.g., heliostats, power plant block), high-temperature operation and water consumption for cooling and cleaning the components [2].

PV systems are directly dependent on the availability of sunlight and usually require battery storage to reduce intermittency. These can be expensive and are currently less

mature compared to the TES of CSP. Maintenance requirements are lower as there are no moving parts in PV systems, resulting in fewer mechanical failures. PV systems are versatile and work in different climatic conditions, even in diffuse light, where CSP is less effective [2].

3.1.9. Safety Aspects

CSP systems use high-temperature fluids such as molten salts or heat transfer oils, which pose the risk of leaks, burns and fires if these substances are not properly contained. The molten salt storage tanks also carry chemical hazards associated with potential leaks that can lead to environmental pollution [19]. The high temperatures at the focal points of CSP mirrors can directly burn birds and insects, and the concentrated solar energy also poses a fire risk to the environment. The moving parts in CSP plants, as well as the complex piping infrastructure, require rigorous maintenance to prevent mechanical failures and accidents. The use of water to cool and clean the mirrors poses another operational risk, especially in areas with scarce water resources [19].

On the other hand, PV systems operate at lower temperatures and have no moving parts, so there are fewer mechanical hazards. Although there is a fire risk with PV systems, it is very low and mainly related to incorrect installation or faulty components. Toxic materials such as cadmium and arsenic are used in the manufacture and disposal of PV panels, especially in some thin-film technologies. Improper handling of end-of-life panels can expose workers and communities to harmful substances [59]. Table 3 provides an overview of the most important safety aspects of CSP and PV systems.

Table 3. Safety comparison of CSP and PV systems.

Safety Aspect	CSP Systems	PV Systems
Operational Hazards	High-temperature fluid leaks, fire risk from concentrated heat, mechanical failures from moving parts	Low temperature operation, rare fire incidents linked mainly to installation faults
Environmental Risk	Potential chemical leaks (molten salts, oils), heavy water use, wildlife hazards due to concentrated sunlight	Toxic chemical use in manufacturing and recycling (cadmium, arsenic, others)
Mechanical Complexity	Complex systems with moving heliostats and piping requiring maintenance	Simpler systems, no moving parts, lower maintenance
Fire Risk Statistics	CSP fire risk linked to thermal fluids and solar flux concentration	Very low fire risk incidents reported in Europe.

3.2. Economic Aspects

3.2.1. Capital Cost

PV costs are expressed on an AC basis (inverter capacity), while CSP costs are reported on an electric output basis (gross generation capacity). The cost of CSP technology includes thermal energy storage, which improves dispatchability but increases upfront investment. In 2024, utility-scale PV with one-axis tracking has a capital cost of approximately $1290/kW AC, whereas fixed-tilt PV systems, which lack tracking and are less complex, cost around $1070/kW AC, reflecting slightly lower expenses [50].

According to research by Ghadim et al. [60] and the Fraunhofer ISE Institute [54], CAPEX for large-scale PV systems has dropped significantly in recent years and, in 2025, is between 500 and 1100 $/MWh worldwide.

These figures represent modelled costs encompassing modules, inverters, mounting, installation, and grid interconnection. Among CSP technologies, Central Tower CSP with a molten salt receiver and 10-h thermal energy storage incurs capital costs ranging from $6300 to $7900/kW electric [50,52]. Parabolic Trough CSP systems exhibit capital costs between $4700 and $7000/kW electric depending on configuration and the presence of thermal energy storage [50]. Linear Fresnel CSP plants typically range from $4700 to $6000/kW electric and are recognized for simpler designs but somewhat reduced efficiency [61]. Parabolic Dish CSP remains the most capital-intensive option, exceeding $8000/kW electric due to smaller scale and more complex hardware [50]. Overall, PV remains the lowest capital cost solar technology, with fixed-tilt systems being less expensive but delivering lower energy yield compared to tracking systems, while Central Tower CSP is the costliest among CSP types and Linear Fresnel offers reduced capital costs at the expense of efficiency and maximum operating temperature.

3.2.2. Cost of Energy Storage

PV systems generally use lithium-ion battery storage technologies such as lithium iron phosphate (LFP) or nickel manganese cobalt (NMC) for energy storage. LFP offers cost and safety advantages, while NMC is still favoured for high energy density applications. The cost of a battery storage system includes battery packs, inverters, power electronics, installation and the other system components. The cost of installing lithium-ion battery storage systems has fallen significantly in recent years and is currently around $300 to $750 per kWh of storage capacity for the entire installed system with a typical warranty period of 10 years. At the end of the warranty period, the remaining capacity is usually around 70% [62]. Most batteries are modular, with the capacity of individual units ranging from 3 to 48 kWh. In published cost data, the cost of battery systems is usually quoted in $/kWh, which can be converted to $/kW by multiplying by the assumed operating time, usually 4 h. For example, a battery with a capacity of $300/kWh and an operating time of 4 h corresponds to a price of 1200 $/kW. Typical runtimes for electricity storage in conjunction with PV systems are around 4 h, with lithium-ion batteries dominating in this area. Costs are expected to continue to fall, reaching around $254/kWh by 2035 and $189/kWh by 2050 [63]. Their high efficiency, typically ranging from 85% to 95%, and relatively fast response times make them particularly well suited to balancing short-term energy supply and demand in residential and commercial photovoltaic systems [2].

Today, CSP power plants generally have low-cost, long-life thermal energy storage (TES) systems that typically utilise molten salts. These TES allow for greater flexibility in power distribution, enabling plants to adjust their production during periods of high electricity market prices. As a result, TES have become a cost-effective way to increase the capacity factor of CSP plants and provide low-cost, high-quality electricity. The cost of TES for CSP power plants typically ranges from $20 to $50 per kWh of thermal capacity, which equates to approximately $10 to $40 per kWh of stored electrical energy when conversion efficiency is taken into account [53,64]. TES systems typically have a long lifespan of around 30 years and lower operating costs than battery storage [65]. This combination of longevity, cost efficiency and operational flexibility makes TES an important factor in the economic viability and competitiveness of CSP technology.

Schöniger et al. [66] conclude in their study that Photovoltaic + Battery Energy Storage System (PV + BESS) is competitive for short storage periods (up to three hours), while CSP + TES offers economic advantages for longer storage periods. PV + BESS would

become more competitive than CSP + TES only with significant further reductions in PV costs. Therefore, each technology occupies a different niche: PV + BESS for short storage periods and CSP + TES for longer periods.

It is also worth noting an important difference between CSP + TES and PV + BESS in their storage methods. CSP stores solar energy on-site with high efficiency, while batteries store grid energy with higher losses but greater flexibility. At low solar penetration, it is more cost-effective for PV + BESS to store cheaper off-peak grid energy rather than valuable daytime solar energy. This is why PV + BESS is more cost-effective than CSP + TES when solar penetration is low [67].

3.2.3. Levelized Cost of Electricity (LCOE)

The levelised cost of electricity (LCOE) is the average cost of generating a unit of electricity over the lifetime of a power plant or energy project. It is calculated by dividing the total lifetime cost by the total lifetime energy production. They are an important benchmark for investment planning and for comparing the economic efficiency and competitiveness of different power generation technologies. LCOE estimation is more complex than capital cost estimation, as various underlying factors, such as assumptions about electricity generation profiles, discount rates, and project life, must be considered. Consequently, there is variation in the results of individual studies. LCOE varies between regions due to differences in solar resource quality, project costs, and system size [28].

PV technologies offer the lowest LCOE due to lower capital and operating costs, while CSP plants have higher LCOE because of capital intensity and (Operation and Maintenance) O&M costs, especially with thermal storage. CSP provides dispatchable power, which can sometimes justify the higher costs.

Without subsidies, the LCOE for fixed-tilt PV systems typically ranges from approximately \$60 to \$70/MWh, depending on PV technology and solar resource [68,69]. According to a recent report by the Fraunhofer ISE Institute, the LCOE for Germany is \$41 to \$50/MWh by 2025 [54].

The LCOE for single-axis tracking PV systems is approximately 20% lower than that of fixed-tilt PV systems of comparable size [70]. For the PV Project 100 MW Puente Genil, Córdoba, Spain, according to the Trina Solar study [71], the LCOE is \$46/MWh, which is in line with the above.

The LCOE for Central Tower CSP generally ranges from \$97 to \$180/MWh, due to high capital and O&M costs [72]. The inclusion of thermal storage increases dispatchability and value [22,33].

The LCOE for Parabolic Trough CSP is approximately \$80 to \$170/MWh, reflecting mature technology but significant capital and operational costs [22].

The LCOE for Linear Fresnel CSP is slightly lower, at about \$65 to \$140/MWh, due to a simpler structure and lower capital costs, though with slightly reduced efficiency [22].

The LCOE for Parabolic Dish CSP is generally the highest among CSP options, at around 150 USD/MWh, due to complexity and smaller scale [22].

3.2.4. Economic Payback Periods

The payback period is the time needed to recover the initial cost of an investment. Factors influencing payback periods include capital expenditure, electricity tariffs, incentives, and system performance. Over recent decades, the dramatic decline in PV module costs, driven by economies of scale and technological advancements, has significantly improved the financial viability of solar energy. Utility-scale PV systems generally have low capital costs and relatively short payback periods, typically estimated at about 5 to 8 years depending on location, system size, and local conditions. For example, a

10 MW utility-scale PV project showed payback periods of around 8 years for smaller farms (5–6 MW) and up to 10–12 years for larger ones, although payback periods as short as 5 years can occur under favourable conditions. Lower PV module costs, increased efficiency, and reduced operational costs contribute to shorter economic payback times. A techno-economic analysis of PV and CSP in Kuwait found the initial cost of PV to be much lower (about $100 million) compared to CSP (about $480 million), resulting in a significantly shorter payback period (approximately 5 years for PV compared to approximately 13 years for CSP) [73].

CSP systems generally have higher capital costs and more complex technology, including thermal energy storage, which leads to longer payback periods. Typical payback periods reported for CSP range from about 12 to 15 years or more, reflecting larger upfront investments and operational complexity [73]. Recent studies note improvements in CSP technology and cost reductions, but payback periods remain longer than those of PV systems due to the capital-intensive nature of CSP plants and costs related to storage and thermal cycles.

Due to the long payback period, CSP projects are sensitive to changes in government policies, including renewable energy incentives, tariffs, subsidies, or regulations that affect project economics. Policy uncertainty can make financing riskier or less attractive. Financing risks are significant because lenders and investors require assurance that projects will generate stable cash flows to cover debt repayments. Market conditions, such as fluctuating electricity prices or the terms of power purchase agreements with utilities, affect projected revenues and, consequently, the project's creditworthiness.

3.2.5. Maintenance Costs

Maintenance costs for utility-scale PV systems and CSP systems differ significantly due to differences in technology and operational complexity. Utility-scale PV systems have relatively low operations and maintenance (O&M) costs, typically ranging from about $5 to $8 per kW per year according to Wiser et al. [74]. However, according to the US Department of Energy's 2024 PV System Reference Cost Report, operating and maintenance costs are around $19 per kW per year for utility scale PV systems [75]. This low cost is due to the simplicity of PV technology, fewer moving parts, and mature industry practices. Key maintenance tasks include periodic cleaning, inverter repairs or replacements, and minor electrical work. These tasks require relatively little expertise because of the lack of moving parts and the modular design.

There are also variable costs such as property taxes, insurance, security, and asset management. Typical O&M costs expressed on a per energy basis are around a few cents per kWh, often estimated below $0.01/kWh depending on system size and location [76].

CSP systems have higher operating and maintenance costs than photovoltaic systems, mainly due to their mechanical complexity, including mirrors, receivers, thermal energy storage, and steam generation equipment. Maintaining this more complex equipment requires a significantly more educated and skilled workforce. O&M costs range from about $12 to $15 per kW per year [53]. The largest maintenance costs historically have been for mirror and receiver replacements.

However, technological improvements have reduced failure rates and maintenance costs in recent years. Personnel costs are significant due to operational complexity, and insurance charges also form an important component, typically 0.5% to 1% of capital investment. Overall, CSP O&M costs translate to roughly $0.02 to $0.04 per kWh [52].

3.2.6. Modular Approach to CSP Systems

Recently, a modular approach to Concentrated Solar Power (CSP) systems has been promoted to expand the market and reduce investment costs by dividing traditionally large, capital-intensive CSP plants into smaller, factory-built modules that can be flexibly deployed and gradually scaled. This modular CSP approach offers several key features and benefits. It reduces capital investment and risk by enabling stepwise capacity additions, allowing investors to begin with smaller, manageable systems and scale up as demand or financing increases [77,78]. Factory fabrication and standardisation of modules, such as heliostat units and compact receivers, enhance quality-controlled assembly, reducing construction time and costs while improving reliability and replicability [79]. Improved manufacturing economies of scale result from replicating standardised modules, lowering per-unit costs through supply chain specialisation and mass production efficiencies [78]. The decentralised and flexible deployment of smaller units allows installation in diverse geographic locations, including remote or distributed sites, thus opening markets previously unsuitable for large CSP plants and facilitating microgrid integration [77]. Innovative thermal energy storage (TES) integration uses next-generation materials such as ceramic pellets or superheated sand, which are safer, cheaper, and easier to scale than traditional molten salt storage. Operational flexibility is enhanced because each module can be independently controlled and maintained, improving system availability and reducing downtimes common in centralised large plants [79]. Additionally, faster installation and commissioning are achievable through rapid deployment of modular elements with simplified foundation and infrastructure requirements, shortening construction schedules. Finally, there is potential for hybridisation, as modular CSP modules can be combined with photovoltaic and wind generation technologies in hybrid renewable power plants to optimise overall system economics and increase renewable energy penetration.

3.3. The Environmental Aspects

The environmental aspects of PV and CSP systems include land footprint, emissions, water consumption, material use, potential impacts on local ecosystems and wildlife, and waste management throughout their life cycles. PV systems generally require less water and produce no direct emissions during operation, but their manufacturing involves energy-intensive extraction processes and the use of potentially toxic materials, with waste and recycling at end-of-life presenting challenges. CSP systems, by contrast, have higher water consumption due to cooling and cleaning requirements, generate waste heat, and may affect local microclimates. They also use heat transfer fluids that pose contamination risks. Life cycle assessments show that operational emissions for both PV and CSP are minimal compared to fossil fuels, but significant emissions can occur during manufacturing, construction, and installation, with CSP emissions somewhat higher due to materials such as steel, concrete, and salts used in thermal storage systems.

3.3.1. Land Footprint

Land footprint is an important consideration for project siting, especially where land costs or environmental impacts are concerns. Capacity-based results are useful for estimating land area and costs for new projects, as power plants are typically rated by capacity. Generation-based data provide a more consistent comparison between technologies with different capacity factors and allow evaluation of land-use impacts that vary by solar resource, tracking configurations, technology, and storage options. As capacity-based land-use requirements are based on reported data, these results are expected to have less uncertainty than generation-based results. Therefore, capacity-based land-use requirements are provided here.

Utility-scale PV systems require about 13 to 26 km^2/GW DC, with an average of 19 km^2/GW, depending on site layout, fixed tilt versus tracking, and panel technology [59]. PV systems, both fixed tilt and tracking, generally require relatively flat or gently sloping surfaces for optimal installation and to minimise structural complexity and costs. Moderate slopes (up to approximately 5°) are usually acceptable with appropriate mounting systems. PV installations can accommodate various soil types, as mounting structures can be adapted. PV systems can also be installed on rooftops and in-built environments, offering space-saving options not available to CSP systems.

CSP systems have much larger land footprints, mainly due to the extensive solar field of mirrors. The land footprint includes the direct solar field area, as well as space for access roads, power block, and infrastructure. Central Tower and Parabolic Trough CSP plants require between 24 and 32 km^2/GW electric, influenced by heliostat field size (the linear array of reflectors) and solar field layout [80].

Linear Fresnel systems are more compact than troughs, generally in the range of 18 to 24 km^2/GW electric due to flat reflectors arranged in a tighter layout [81].

Parabolic Dish CSP systems, although more compact per unit, require separate land plots for each dish and its tracking equipment. Parabolic Dish CSP systems have an approximate land footprint of 40 km^2/GW [82]. Concentrated solar power (CSP) technologies generally require much flatter land than photovoltaic (PV) systems because of the precise alignment needed for their optical components. Central tower CSP plants, in particular, need mostly flat terrain for their heliostat fields to ensure accurate sun tracking and reflection. Parabolic trough and linear Fresnel CSP technologies also require flat, even surfaces to maintain proper reflector alignment and concentrating accuracy. Parabolic dish systems benefit from flat terrain but can tolerate slight slopes. CSP plants also require soil with good load-bearing capacity, as the structures and heavy reflectors need stable support; sandy or weak soils may require costly ground stabilisation or foundation measures. These land and soil requirements highlight the importance of site selection for CSP projects to optimise performance and reduce construction complexity.

3.3.2. Greenhouse Gas Emissions

Reducing carbon emissions has significant regulatory implications for energy systems, driving structural changes in electricity generation, industrial processes, and infrastructure investment. The zero-carbon nature of emerging energy sources—particularly solar photovoltaics (PV) and concentrated solar power (CSP)—makes them key options for achieving ambitious emission reduction targets set by international and national climate frameworks. This creates a regulated feedback cycle: increased policy-driven demand for decarbonisation leads to targeted regulatory incentives, which accelerate the development and deployment of new energy technologies, further reducing sectoral emissions. Such policy–technology synergies are evident in recent strategies for co-optimising dynamic carbon intensity in Internet data centres and integrating renewables into digital infrastructure.

The operational greenhouse gas (GHG) emissions profile of PV power plants are mainly determined by regional solar resource availability. Key parameters are annual solar irradiation and average sunshine duration; areas with lower irradiance require greater installed capacity per delivered kilowatt-hour, directly increases specific life-cycle GHG emissions. For example, life-cycle assessment (LCA) studies show that PV installations in Northern Europe emit approximately 80–130 g CO_2 eq./kWh, which is significantly higher than similar systems in Southern and Western Europe (16–106 g CO_2 eq./kWh) and North America (16–60 g CO_2 eq./kWh) [38]. Variations among PV system types are modest: fixed-tilt configurations generally have slightly lower emissions than tracking systems due to simpler balance of system components and lower material intensity. The carbon

footprint of PV power is overwhelmingly concentrated in upstream stages, with module manufacturing—including wafer production, cell processing, and encapsulation—being the dominant source of emissions. Balance-of-system (BOS) components, such as mounting structures, inverters, and cabling, are secondary contributors. Operational emissions during plant use are negligible under standard conditions [59].

CSP plants generally have lower CO_2 emissions per kWh than PV, typically ranging from 14 to 40 g CO_2 equivalent per kWh, depending on system configuration, heat transfer fluid, storage (TES) integration and regional solar resource availability [19]. Empirical studies attribute up to 87.4% of total CSP emissions to the equipment and materials manufacturing phase [40]. Integrating large-scale TES, while enhancing dispatchability, can approximately double life-cycle GHG emissions compared to plant designs with minimal or no storage, due to the embodied energy and material demands of storage infrastructure. Cooling technology also affects emissions: dry-cooled CSP plants typically have 5% to 7% higher life-cycle GHG emissions than wet-cooled plants, primarily because of increased parasitic consumption and reduced thermodynamic efficiency.

In many regions worldwide, plans are underway to establish a carbon-neutral energy system by 2050. Among other requirements, this includes developing a carbon-neutral industrial heat energy system. In this context, CSP systems can provide significant support in some countries. For example, in Spain, CSP systems are planned to cover over 30% of the industrial sector's heat demand. These industrial systems include the agri-food sector for the decarbonisation of processes such as pasteurisation, drying, sterilisation, cooking, steam generation, distillation, and biochemistry, among others.

In addition, CSP technologies are increasingly positioned to support green hydrogen production, a key vector for decarbonising hard-to-abate sectors such as transport and heavy industry. High-temperature thermal output from CSP enables efficient hydrogen generation via solid oxide electrolysis or thermochemical cycles. Integrating CSP-derived green hydrogen into the wider energy system has the potential to deliver systemic emission reductions and economic co-benefits [83].

3.3.3. Water Footprint

Utility-scale photovoltaic (PV) systems have low life cycle water consumption, although estimates vary by technology and location. The main contributors to water use are the manufacturing of PV panels, particularly the extraction of polysilicon, and the production of Balance of System (BOS) components. A significant portion of water consumption is indirect, resulting from electricity use in manufacturing processes. On-site water use is minimal and primarily related to cleaning, which depends on local climate and dust conditions.

Water consumption for utility-scale PV systems typically ranges from approximately 250 to 1500 litres per megawatt-hour (MWh). Mono-crystalline silicon PV systems report values near 1500 L/MWh, while CdTe thin-film PV systems range between 250 and 450 L/MWh, covering the entire life cycle from manufacturing to decommissioning [84]. Reviews by authoritative sources such as NREL indicate typical life cycle water consumption for solar PV between 38 and 190 litres per MWh, which is substantially lower than the water use of fossil fuel-based electricity generation [85].

Comparative life cycle assessments consistently show that PV systems consume far less water than more water-intensive technologies such as coal, nuclear, and wet-cooled concentrated solar power (CSP). This makes PV technology particularly advantageous for deployment in water-scarce regions [85]. Operational water use is generally minimal, especially for fixed-tilt systems, whereas tracking systems may require slightly higher water consumption for cleaning due to increased exposure to dust.

In summary, the life cycle water consumption of utility-scale PV ranges from roughly 250 to 1500 L per MWh generated, with variability influenced by system technology and geographic region [86]. Most water use arises from manufacturing and indirect processes, while operational water requirements remain low.

Water consumption in Concentrated Solar Power (CSP) systems varies considerably in the literature, reflecting differences in technology, cooling methods, and site conditions. CSP plants have significantly higher water usage due to the cooling requirements of the thermal power block and mirror cleaning. Water use in CSP is strongly influenced by the choice of cooling technology: wet cooling uses significantly more water than dry or hybrid cooling.

Some CSP plants using wet cooling systems consume up to 3.5 m^3 of water per megawatt-hour (MWh) of electricity generated. This is comparable to or higher than coal plants (around 2 m^3/MWh) and natural gas combined cycle plants (about 1 m^3/MWh) [87]. Average values for wet-cooled parabolic trough CSP plants are around 3.5 m^3/MWh, which is higher than for power tower CSP technologies due to lower thermal efficiency and operational characteristics [88]. Dry-cooled CSP plants have lower water consumption, reported at around 0.2 to 0.3 m^3/MWh, significantly reducing water use at the cost of some thermal performance [89]. Some CSP plants report water consumption around 2.5 m^3/MWh, with an emphasis on developing water-saving technologies [90]. Overall, CSP plants using wet cooling dominate water consumption due to steam cycle cooling losses via evaporation and mirror cleaning. Hybrid cooling technologies and improved water management are being developed to reduce these water demands, which is especially important in the arid regions where CSP plants are often located.

3.4. Social Aspects

The social aspects of photovoltaic (PV) and concentrated solar power (CSP) systems differ in several ways, reflecting their technological characteristics, scale, and integration within communities.

CSP projects, typically utility-scale and site-specific, have substantial direct and indirect social impacts, primarily through job creation, workforce development, and local economic stimulation [91]. Large CSP plants create significant employment opportunities during construction and operation in engineering, manufacturing, and maintenance sectors. An evaluation of job distribution across the main segments of the value chain shows that establishing a 100 megawatt CSP plant with ten hours of thermal energy storage requires approximately 1.16 million person-days [21]. A significant portion of the CSP workforce (79%) needs low to medium-level technical skills, which are typically available within any national workforce or can be developed through certification programmes or vocational training centres. CSP projects increase local government revenues through property taxes and land leases, supporting public services and strengthening local businesses in supply chains, from construction to maintenance. Community engagement is essential for CSP social acceptance, as demonstrated by successful cases such as Morocco's Noor Ouarzazate and Chile's Cerro Dominador, where projects included local hiring, educational initiatives, entrepreneurship support, and addressed environmental concerns such as water use [92,93]. CSP also provides rural or remote communities with opportunities for energy independence and infrastructure improvements. However, CSP's land use, water consumption, and infrastructure scale can raise social and environmental concerns that require careful management and transparent communication.

Distributed rooftop PV systems and utility-scale PV systems tend to affect social aspects differently. Rooftop PV systems are commonly integrated into urban and residential environments, providing direct benefits to individual households and small communities,

such as energy cost savings, energy autonomy, and increased resilience. The modularity and widespread deployment of PV support equity in access to renewable energy, although adoption may vary due to economic and social divides. The smaller scale of rooftop PV systems compared to CSP generally results in less localised disruption and greater acceptance.

Utility-scale photovoltaic (PV) systems have significant social impacts that differ from those of smaller, distributed PV installations. These large-scale solar farms, typically ground-mounted systems with capacities above 5 MW, interact with communities in various ways. They provide direct local economic benefits, including substantial job creation during the construction phase and ongoing employment for operations and maintenance. This workforce growth supports local skills development and economic diversification. Utility-scale PV projects also contribute to local government revenues through property taxes and land lease payments, helping to fund public services, infrastructure improvements, and education, thereby enhancing community well-being [94]. Additionally, utility-scale PV systems contribute to energy security and resilience by generating electricity locally, reducing reliance on distant centralised power plants, and mitigating the risk of outages during emergencies.

However, social considerations in utility-scale PV deployment also include challenges such as land use conflicts, environmental justice concerns, and equitable benefit distribution. Large solar farms require significant land area, which can compete with agriculture, impact natural habitats, affect vegetation and moisture in surrounding areas, or have negative visual impacts on local communities [95]. This necessitates careful siting to minimise social and environmental disruption.

Utility-scale PV systems have the potential to promote social equity when minority-owned businesses participate in project development, ownership, or financing, enabling restorative economic benefits. Transparent communication and involvement in planning processes foster acceptance and help address concerns about environmental impacts and land use. As more large PV power plants are connected to the electricity grid, their social impact is similar to that of concentrated solar power (CSP) plants.

Both technologies benefit from early, meaningful community involvement and transparent procedures to ensure procedural justice and fair distribution of benefits and costs. The scale of CSP and utility-scale PV systems requires comprehensive local development packages and direct economic benefits for communities, while the social impact of rooftop PV systems and BIPV systems is often achieved through the democratisation of energy access and flexible deployment models.

3.5. Political Support and Initiatives

Political support and initiatives are crucial for advancing the implementation of both Concentrated Solar Power (CSP) and photovoltaic (PV) systems, but their impacts differ due to the technologies' characteristics and deployment scales. For CSP, political support is essential to address high capital costs, complex project development, and lengthy permitting processes. Policies that streamline permitting and grid access, together with coordinated funding frameworks, can significantly accelerate CSP projects. National and regional initiatives—such as auctions favouring CSP, local content requirements, and co-financing programmes—encourage industry growth, local job creation, and sustainable deployment. The European Union's clean energy partnerships, South Africa's Renewable Energy Independent Power Producer Procurement Programme, and China's regulations requiring storage integration exemplify political efforts to foster CSP [96].

Financial incentives for CSP often focus on large-scale project development through grants, tax credits, subsidies, feed-in tariffs, and long-term power purchase agreements,

including renewable energy auctions and competitive bidding. These mechanisms reduce upfront capital costs and improve revenue certainty, which are critical given CSP's high initial investment and complexity. Support also encourages the integration of thermal energy storage in CSP plants, enhancing dispatchability and grid stability. CSP financial incentives typically target utility-scale installations, mainly in regions with strong solar resources and strategic renewable targets, such as Spain, Morocco, the UAE, and China [97].

PV systems benefit from broad political initiatives that integrate solar deployment into building codes, mandate solar readiness or installation on new buildings, and provide financial incentives such as tax credits, grants, and net metering policies. Photovoltaic systems, especially distributed and residential PV, receive extensive financial support worldwide, including subsidies, feed-in tariffs, investment grants, and co-financing programmes. PV financial incentives are generally more accessible and widespread due to the lower upfront costs and modular nature of PV technology. For example, some countries offer up to 50% co-financing for residential PV installations, making PV deployment easier for households and small businesses. Incentives also increasingly promote PV combined with energy storage to enhance grid integration.

These initiatives reduce cost barriers and promote widespread adoption, especially for distributed and residential PV. Leading incentive programmes for PV are common in Europe (Germany, Austria, Croatia), China, the US, and emerging markets, often supported by national funds, local grants, and consumer subsidies that encourage residential and commercial PV growth.

As part of the EU Energy Union strategy, the Strategic Energy Technology Plan (SET Plan), introduced in 2007 by the European Commission, leads energy technology policy. The integrated SET Plan defines ten priority actions for research and innovation to accelerate the transformation of the energy system and promote the widespread use of renewable energies in the EU, with photovoltaic solar energy (PV) as a main pillar. Implementation is assessed by the general governance structure, which monitors key performance indicators, including investment levels and cost reductions. The Concentrated Solar Thermal Technologies Implementation Working Group (IWG CSTT) brings together stakeholders, the European Commission, and SET Plan countries to discuss the ambitious initiative for the European concentrated solar power (CSP) industry to become a global leader. The IWG revised its Implementation Plan in 2023 [98]. This plan presents a projection of the global electricity sector. Under the Stated Policies Scenario, the projection for 2030 anticipates the deployment of 6707 GW of renewable energy capacity. Solar PV will contribute 3200 GW, CSP 17 GW, and battery storage 270 GW. This clearly shows that the EU places significantly greater importance on PV than on CSP technology.

In summary, financial support for CSP primarily enables capital-intensive, large-scale projects and storage integration. PV technology benefits from more diverse and accessible incentives that promote deployment at all scales. PV technology currently receive broader financial support globally, while CSP incentives are concentrated in specific regions focused on large projects.

3.6. PV and CSP Systems Improvement Potential

PV technology continues to evolve rapidly, offering promising pathways to increased efficiency, reduced costs, and new applications. This includes reducing energy consumption at all PV module process steps, cutting ingots into wafers with the smallest possible kerf to minimise material waste, producing thin cells with the highest dimensional accuracy, and using less expensive materials. An extremely important goal is to achieve the highest efficiency of photovoltaic cells, that is, to reduce cell losses (optical, electrical, and degradation). New technologies in this context include Tunnel Oxide Passivated Contact (TOPcon),

Interdigitated Back Contact Cells (IBCs), Heterojunction Cells (HJTs), silicon heterojunction cells (SHJs), Multi-Bush, High-Density Cell Interconnection, Split Cells, Shingled Cells and Bifacial Cells [25]. Perovskite solar cells and tandem perovskite-silicon cells, with certified efficiencies approaching 30–34%, are promising new technologies [99]. The development of multi-junction cells, which combine several semiconductor layers to capture a broader solar spectrum, has achieved laboratory efficiencies exceeding 44% [100]. Integration of smart solar technologies including AI-optimized tracking, module-level power electronics, and IoT-enabled performance monitoring enhances output and reliability [3]. Advances in materials, such as improved passivation layers (PERC and heterojunction cells), reduce recombination losses and enhance low-light performance. PV innovation also includes flexible, lightweight, and building-integrated PV (BIPV) technologies expanding deployment possibilities [10]. In short, PV technology has great potential in increasing system efficiency, reducing production costs, and increasing resilience to climate change.

Improvements in Concentrated Solar Power (CSP) technology focus on increasing thermal efficiency, reducing costs, and enhancing the integration of thermal energy storage to improve system dispatchability [50]. Recent advancements include the development of higher-temperature receivers and advanced heat transfer fluids, such as molten salts with greater thermal stability, enabling higher system efficiencies [58]. Improvements in heliostat design involve the use of more reflective, lower-cost materials and automated cleaning and alignment systems, reducing optical losses and operation and maintenance costs [50]. Advances in thermal energy storage, including latent heat and thermochemical storage methods, aim to increase storage density while lowering costs [58]. The integration of novel power cycles, such as supercritical CO_2 turbines, offers the potential for higher efficiency and greater operational flexibility [50]. Integrating artificial intelligence into concentrated solar power systems can improve performance, reliability, and efficiency, and support the development of predictive maintenance strategies. Applying AI algorithms to analyse meteorological data and forecast local weather conditions enables more accurate predictions of solar energy production, optimising the use of thermal storage. Overall, this can reduce energy losses and costs, and improve the planning, operation, and control of energy systems.

These CSP developments aim to lower costs and enhance system flexibility to better compete with battery-backed photovoltaic (PV) systems [58]. However, the pace of innovation in PV technologies currently surpasses that of CSP due to their modular nature, large-scale manufacturing capabilities, and suitability for decentralised applications [58]. Although CSP market growth is slower because of cost and site constraints, ongoing innovations are improving its competitiveness in niche applications requiring reliable, dispatchable power.

3.7. SWOT Analysis

The first step is a SWOT analysis, i.e., identifying important strengths, weaknesses, opportunities, and threats. The important strengths include the following:

(S1) High Energy Efficiency: CSP plants efficiently convert solar radiation into electricity through thermal cycles, achieving system efficiencies generally between 15% and 28%, with some advanced central tower plants reaching nearly 40% due to higher operating temperatures and integration of thermal storage (see Section 3.1.1).

(S2) Thermal Energy Storage (TES): CSP uniquely enables long-term thermal energy storage (typically 10–15 h), providing a reliable and available energy supply both day and night, which is crucial for grid stability and system balancing. This complements intermittent renewable energy sources such as photovoltaic and wind power. It should also be noted that TES is 20 to 50 times less expensive than bat-

tery storage. However, advances in battery storage and smart grid integration reduce concerns about PV intermittency, narrowing CSP's dispatchability advantage (see Sections 3.1.1 and 3.2.2).

(S3) Capacity Factor and Predictability: CSP plants typically have higher capacity factors (30–55%, sometimes up to 80% with extensive TES) compared to PV, allowing more consistent power generation (see Section 3.1.6).

(S4) Job Creation and Local Economic Development: Large CSP projects create substantial employment during construction and operation, supporting local economies and skill development (see Section 3.4).

(S5) Renewable and Sustainable: As a solar-based technology, CSP contributes to greenhouse gas reduction, with life-cycle emissions of approximately 14–40 g CO_2eq/kWh, lower than fossil fuels and comparable to or better than other renewables (see Section 3.3.2).

(S6) Ability to generate both electricity and industrial process heat, and "green" hydrogen broadening the scope of applications (see Section 3.3.2).

(S7) There is significant potential for innovation and technological improvement, which will enable a reduction in the LCOE (see Sections 3.2.6 and 3.6).

(S8) Mature and proven technologies with extensive operational experience.

The important weaknesses include the following:

(W1) High capital expenditure (CAPEX) and long payback periods: CSP plants require significant upfront investment, typically several times higher than utility-scale PV ($6300–$7900 per kW for central tower versus $1000–$1300 per kW for PV) (see Section 3.2.1).

(W2) Site requirements: CSP is highly dependent on direct normal irradiance (DNI) and suitable geographic locations with high solar insolation (generally >1900 kWh/m^2/year). This restricts deployment to arid, sunny regions, limiting geographic applicability and scale (see Section 3.3.1).

(W3) Water consumption: CSP plants consume substantial water, especially with wet cooling for steam cycles and mirror cleaning (up to 3.5 m^3/MWh), which can be problematic in the arid desert environments typical of CSP installations (see Section 3.3.3). On the other hand, PV systems and wind farms have very low water consumption.

(W4) Longer development and construction times: CSP projects typically require two to three years or longer to design, approve, and build, significantly longer than PV systems, delaying time to market and returns (see Section 3.1.2).

(W5) Complex and maintenance-intensive heliostat and receiver systems: Operational needs such as heliostat alignment increase operational risks and costs (see Section 3.2.5).

(W6) Technical complexity and component degradation: The thermal and mechanical components (heliostats, receivers, heat exchangers) suffer from degradation, fouling, and material wear, requiring skilled and costly maintenance (see Section 3.1.5).

(W7) Safety risks: High-temperature fluids such as molten salt pose fire, chemical leakage, and burn risks, demanding rigorous safety management (see Section 3.1.9).

(W8) Economic viability is heavily dependent on scale and site-specific factors, limiting broad market penetration (see Section 3.2.4).

The important opportunities include the following:

(O1) Advancements in Storage and Efficiency: Emerging TES technologies, such as latent heat and thermochemical storage, and advanced power cycles, including supercritical CO_2 turbines, offer potential efficiency improvements and cost reductions (see Section 3.6).

(O2) Market Growth in High DNI Regions: Expanding CSP in regions with very high solar resources, such as the Middle East, North Africa, India, China, and parts of South America, aligns with renewable energy goals and rising power demand (see Section 3.4).
(O3) Policy and Financial Support: Government incentives for dispatchable renewable capacity and decarbonisation targets can enhance CSP project feasibility (see Section 3.5).
(O4) Cost Reduction Potential: Ongoing technological improvements in heliostats, receivers, and system design can reduce capital costs and maintain competitiveness (see Section 3.6).
(O5) Local Industry Development: Development of indigenous manufacturing and supply chains, as seen in India, can lower costs and support sustainable economic growth (see Section 3.4).
(O6) Integration with Hybrid Systems: CSP can complement PV and wind power by providing dispatchable backup and grid support, thereby increasing the renewable share in power systems.
(O7) Smaller-scale and modular CSP systems for decentralised applications (see Section 3.2.5).
(O8) Industrial applications in sectors requiring both heat and power and the possibility of producing "green" hydrogen (see Section 3.3.2).

The important threats include the following:

(T1) Competition from Declining PV and Battery Costs: Rapid advances in PV technologies and significant reductions in lithium-ion battery storage costs are making shorter-duration solar-plus-storage systems increasingly competitive (see Sections 3.2.1, 3.2.3, 3.2.4 and 3.5).
(T2) Water Scarcity: Increasing water stress in arid regions threatens CSP operation, especially for wet-cooled plants, requiring costly dry or hybrid cooling alternatives (see Section 3.3.3).
(T3) Market and Regulatory Uncertainties: CSP projects require large capital investment with long payback periods, making them vulnerable to policy changes, financing risks, and market price fluctuations (see Section 3.2.4).
(T4) Scale Limitations: Economic viability generally requires large-scale plants, limiting flexibility and widespread distributed adoption (see Section 3.2.6).
(T5) Supply chain disruptions affect key components such as heliostats and heat exchangers (see Section 3.1.2).
(T6) Technological Complexity Risks: Complex systems have a higher risk of operational failures and component degradation, and require highly skilled labour, increasing operational risks and costs (see Sections 3.1.5 and 3.1.8).
(T7) Land use and environmental impact constraints limit expansion, especially near population centres (see Section 3.3.1).
(T8) Climate Change Impacts: Sensitivity to DNI reduction from increased dust, cloud cover, and extreme weather events could degrade CSP performance (see Section 3.1.4).

3.8. AHP Analysis

The AHP method was used to determine priorities within the defined SWOT categories, as described in Section 2. The four most influential factors in each SWOT category were considered using the standard Saaty scale (1–9). The pairwise comparison matrix for the main categories, as well as the global weights (GP), are presented below (Tables 4 and 5).

Table 4. Pairwise comparison matrix for main SWOT categories.

	Strengths	Weaknesses	Opportunities	Threats
Strengths	1	2	2	1
Weaknesses	1/2	1	2	1
Opportunities	1/2	1/2	1	1
Threats	1	1	1	1

Table 5. The resulting weights for the criteria based on pairwise comparisons.

	Category	Priority	Rank	(+)	(−)
1	Strengths (S)	34.31%	1	9.7%	9.7%
2	Weakness (W)	24.26%	2–3	6.8%	6.8%
3	Opportunities (O)	17.16%	4	4.8%	4.8%
4	Threats (T)	24.26%	2–3	6.8%	6.8%

Consistency check: λ_{max} = 4.121314, *CR* = 0.0444 (<0.1 → acceptable).

The pairwise comparison matrices as well as the local weights (LP) and the global weights (GP) for all subcategories are listed below (Tables 6–8).

Table 6. Decision matrixes for internal factors (strengths and weaknesses subcategories).

	S1	S2	S3	S4		W1	W2	W3	W4
S1	1	2	1	3	W1	1	1	3	4
S2	1/2	1	1	2	W2	1	1	2	4
S3	1	1	1	2	W3	1/3	1/2	1	2
S4	1/3	1/2	1/2	1	W4	1/4	1/4	1/2	1

Table 7. Decision matrixes for external factors (opportunities and threats subcategories).

	O1	O2	O3	O4		T1	T2	T3	T4
O1	1	1	2	3	T1	1	3	4	3
O2	1/3	1	2	2	T2	1/3	1	2	1
O3	1/2	1/2	1	1	T3	1/4	1/2	1	1
O4	1/3	1/2	1	1	T4	1/3	1	1	1

Table 8. Local (LP) and global (GP) subcategory weights.

Category	Consistency Ratio	Category Weights	Subcategory	LP	GP
Strength (S)	*CR* = 0.0432	34.31%	S1	36.58%	12.55%
			S2	23.26%	7.98%
			S3	27.78%	9.53%
			S4	12.38%	4.25%
Weakness (W)	*CR* = 0.0076	24.26%	W1	39.51%	9.59%
			W2	35.50%	8.61%
			W3	16.11%	3.91%
			W4	8.86%	2.15%
Opportunity (O)	*CR* = 0.0076	17.16%	O1	36.29%	6.23%
			O2	32.61%	5.59%
			O3	16.30%	2.80%
			O4	14.80%	2.54%

Table 8. *Cont.*

Category	Consistency Ratio	Category Weights	Subcategory	LP	GP
Threat (T)	$CR = 0.0222$	24.26%	T1	56.65%	13.75%
			T2	19.93%	4.84%
			T3	11.71%	2.84%
			T4	11.71%	2.84%

A low consistency ratio ($CR < 0.1$) confirms that pairwise comparisons were made consistently and that the models do not contain illogical or contradictory estimates.

4. Discussion

The AHP analysis in Table 8 clearly shows how individual factors within the SWOT framework are ranked according to their importance for the optimal strategy for the application of CSP technology. Understanding the interdependencies among the various factors in a SWOT analysis is essential for effective strategic planning. Strengths, weaknesses, opportunities, and threats are not isolated elements but form a dynamic, interconnected system in which a change in one factor can significantly affect the others. In a strategic context, recognising and analysing these interdependencies enables decision makers to assess how internal capabilities and constraints align with external opportunities and threats, which is crucial for developing sustainable and adaptive strategies. Therefore, before examining individual factors and their priorities in detail, it is important to consider their interrelationships, as these shape the overall picture and influence strategic decision making.

For example, the high-capacity factor of a CSP system can mitigate the disadvantage of high initial capital costs, as higher utilisation reduces the cost per kWh produced. Technological innovations that facilitate management and reduce maintenance costs can decrease the complexity of operations and maintenance. Furthermore, increased competition from PV systems can be offset by the strengths of CSP, particularly its ability to provide stable and regulated energy production, which contributes to grid stability.

The global weight of the "Strengths" category, at 34.31%, reflects that the existing technical and operational advantages of CSP technology are crucial for its commercial viability and competitiveness compared to other solar technologies such as PV. This includes advantages such as thermal storage integration, high-capacity utilisation factor, and high availability, which are important for the security of electricity networks. Focusing the strategy on these strengths is logical, as they form the foundation without which the wider implementation of CSP technology would not be possible. The high local and global weight of the weakness factor W1 (39.51% and 9.59%, respectively) indicates the essential problem of high capital expenditure (CAPEX) and long payback periods, which can slow or prevent the wider application of CSP. Recognising and specifically targeting this weakness through innovation, regulatory frameworks, or financial support is essential for the sustainable growth of CSP capacity.

Opportunities with a global weight of 17.16% indicate potential market and technological conditions that can be further exploited. These include increasing demand for reliable renewable energy, support for green technologies, and the expansion of energy markets in regions with high DNI. Although financial support for CSP exists, it mainly enables capital-intensive, large-scale projects and the integration of thermal energy storage. However, policies and energy plans favour PV technology, which receives broader financial support worldwide.

Threats, assigned high global weight (24.26%) because they include competition from other clean technologies, market and regulatory uncertainties and, water scarcity problem. Recognising threats enables risk planning and the development of CSP system resilience. In risk management, understanding the global priorities of individual factors allows optimal allocation of resources to research and development, human resource training, financial instruments, and technical innovation.

Figure 4 presents a focused view of the factors most important in making strategic decisions, reducing the complexity of the wide range of influences on concrete goals and measures. In practice, concentrating on these six factors means that resources, as well as the development of plans and policies, should be directed primarily towards these aspects, as they have the greatest impact on the success of CSP implementation.

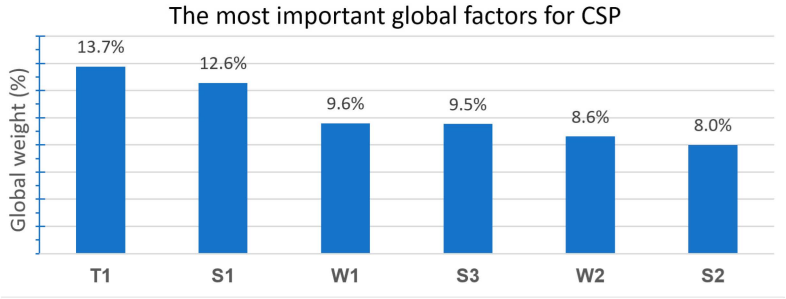


Figure 4. The most important global factors for CSP.

An in-depth analysis of the AHP results reveals a complex yet precise approach to evaluating the strategic factors shaping the future of CSP technology. The dominance of certain forces confirms that existing technical advantages should be maximised, while impartial attention must be given to external threats and internal weaknesses that may limit the growth of this technology's application.

4.1. Sensitivity Analysis

Let us assume that the sensitivity of the AHP model presented depends primarily on the evaluation of the influencing factors within the main SWOT categories, as the local weighting factors are multiplied by the weighting factors of the main categories. For this purpose, two additional scenarios were analysed alongside the presented Scenario 1, which is assumed to be realistic to a certain extent. Scenario 2 is considered optimistic, while Scenario 3 is considered pessimistic.

According to the author, the optimistic scenario aligns with the projection stated in [21]. This scenario predicts that global installed CSP capacity will reach 196.7 GW by 2030 and 872.6 GW by 2050. In the author's view, such growth from the current 8 GW of installed capacity is unrealistic, particularly because the threats and weaknesses mentioned are not easily eliminated or reduced. The pessimistic scenario implies a halving of planned capacity due to factors T1, W1 and W2.

The pairwise comparison matrices and weightings for Scenarios 2 and 3 are shown in Tables 9 and 10.

Table 9. Pairwise comparison matrix for Scenario 2.

	S	W	O	T	Local Weighting
S	1	2	1	2	34.65%
W	1/2	1	1	1	20.36%
O	1	1	1	1	24.63%
T	1/2	1	1	1	20.36%

Table 10. Pairwise comparison matrix for Scenario 3.

	S	W	O	T	Local Weighting
S	1	1	2	1	28.04
W	1	1	3	1	31.20
O	1/2	1/3	1	1/2	12.73
T	1	1	2	1	28.04

The most influential factors according to the global weightings for all three scenarios are shown graphically in Figure 5.

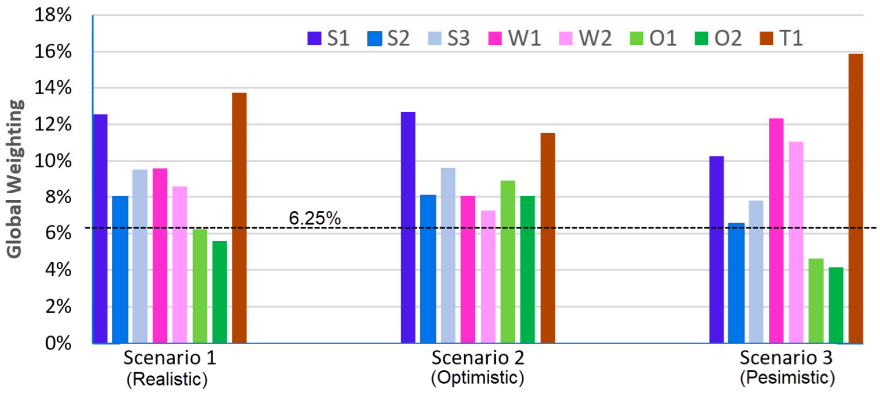


Figure 5. The most influential factors for all three scenarios.

Figure 5 clearly shows that in all three scenarios, T1, S1, W1, S3, and W2 are among the eight most influential factors (arithmetic mean line at 6.25%). Factors O1 and O2 are below the 6.25% line in two scenarios, although in the realistic scenario O1 is at 6.23%, which is almost equal to the arithmetic mean. It also follows that T1, S1, and W1 play a very important role in all three scenarios, giving them strategic importance. This analysis indicates that the subjectivity of the author does not significantly affect the determination of the weightings of the main SWOT categories. However, prioritising factors within categories can be highly significant. In this context, the analysis of literature data related to various aspects of the CSP system is important.

4.2. Limitation of This Study

Limitations of this study include unavoidable subjectivity in expert judgement during pairwise comparisons and factor weighting in AHP, possible incompleteness of the literature despite a systematic search, and reliance on secondary sources rather than direct empirical data. The systematic literature review relies on existing published studies, limiting the findings to the quality, scope, and biases of these secondary sources. This may omit unpublished or region-specific data, affecting comprehensiveness. While the SWOT-AHP hybrid approach enables structured evaluation, the identification and weighting of SWOT factors are partly subjective, relying on expert judgement. This can introduce bias in factor prioritisation, despite consistency checks.

5. Recommendations for Successful Implementation of the CSP System

5.1. Recommendations for Policymakers

- Encourage investment through financial support and regulation: As the main challenge for CSP technology is the high initial capital investment and long payback period (W1, T1), it is important to establish incentive systems such as subsidies, tax breaks, or guaranteed minimum feed-in tariffs to reduce financial risk for investors. Policies

that simplify permit issuance and facilitate grid access can significantly accelerate CSP projects and increase their attractiveness.

- Support the development of local industry and supply chains: Developing local production of key components (e.g., heliostats, receivers, and thermal energy storage systems) can reduce costs and stimulate local economic activity, which is an important opportunity (O6). At the same time, it provides resilience to disruptions in the global market (T3).
- Encourage research and development of innovations in thermal energy storage technology and efficiency: Initiatives to finance the development of new thermal energy storage technologies and to improve thermodynamic cycles (O1, S7) should be a priority, as this will enhance the competitiveness and economic viability of CSP.
- Regulate rational water use and environmental protection: Given the high-water consumption of CSP plants (W3), especially in regions with limited water resources, it is necessary to adopt regulations that encourage the use of modern cooling systems (dry or hybrid cooling) and optimise water management.

5.2. Recommendations for Investors

- Focus on locations with high DNI: Selecting sites with high levels of solar radiation (above 1900 kWh/m^2 per year) is essential for the sustainability and economic viability of CSP investments (W2).
- Distribute investments in modular and scalable CSP systems: A modular approach to CSP systems can reduce capital risk and facilitate capacity scaling by gradually adding modules, resulting in lower initial investments and more flexible project management (O7).
- Incorporate technological innovations to reduce maintenance costs: Given the complexity and maintenance requirements of CSP equipment (W5, W6), investing in automation and technologies for monitoring and optimising operations (such as automatic heliostat cleaning) can reduce operating costs and increase operational reliability.
- Prepare for a longer return on investment and diversify the portfolio: The return on investment in CSP projects is significantly longer than in PV, so it is necessary to strategically plan long-term financial flows and combine CSP with other forms of renewable energy to reduce business exposure to risks (W1, T3).

5.3. Recommendations for Other Stakeholders

- Encourage higher education institutions to incorporate the latest technologies into their energy-related study programmes to train future engineers to reduce the design time of CSP systems (W4).
- Support the local community through job creation and education: CSP projects create a significant number of jobs during construction and operation, and help develop local skilled personnel. Therefore, it is important to provide education and training programmes (S5).
- Community engagement and transparency: Involving local stakeholders in the planning and construction phases, informing them about the benefits and potential impacts, and maintaining clear communication can improve acceptance of CSP projects (S5, O3).
- Support the integration of CSP into the grid and hybrid systems: CSP with thermal storage can provide grid stability and supply flexibility, offering an opportunity to improve grid reliability and integrate a greater share of renewable sources (S2, S7, O4).
- Continuous monitoring and management of environmental impacts: Joint efforts should monitor the impact of CSP on local ecosystems, particularly regarding wa-

ter consumption and chemical safety, and implement measures to minimise these impacts (W3, T2).

These recommendations indicate that successful implementation of CSP technology requires coordinated efforts in policy, finance, technology, and community, with particular attention to capital costs, technological innovation, and environmental aspects. It is also important to leverage the natural advantages of CSP systems, such as high thermal energy storage capacity, which enables a high degree of capacity utilisation and stability in electricity grid supply.

6. Conclusions

This research provides a comprehensive overview of the key technical, economic, environmental, and social factors influencing the implementation of concentrated solar power (CSP) technology through an integrated SWOT-AHP approach. The analysis confirms that CSP technology, despite its high initial capital costs and demanding operating conditions, offers significant advantages such as a high capacity factor, the potential for integrating thermal storage, and stable electricity production, making it a relevant candidate in energy transition strategies. A comparison with dominant photovoltaic systems further highlights the rational complementarity of these technologies, enabling stakeholders to make better-informed decisions regarding their application in different socio-economic and climatic contexts.

The results also indicate the need for targeted action by policymakers and investors in incentives, regulation, research and development, education, and the involvement of local communities to maximise opportunities and reduce the threats associated with CSP technology. Additionally, water resource management and the maintenance of complex systems represent key challenges for the long-term sustainability of CSP plants.

Although costs are higher, CSP offers many opportunities for value creation due to its potential for energy storage, system balancing, localising supply chains, and job creation. Its inherently low environmental impact and reduced reliance on strategic, hazardous, or environmentally detrimental materials are additional factors expected to advance the market penetration of CSP technology worldwide.

Policies, energy plans, and financial initiatives favour photovoltaic technology, which receives widespread financial support worldwide. Consequently, CSP occupies a niche role in firm solar power, particularly where large-scale thermal energy storage is feasible. Therefore, CSP is expected to play only a complementary role to other renewable energy technologies in future. Recognising the complementary nature of CSP and PV technologies, along with their integration with other renewables and storage solutions, provides a holistic foundation for strategic deployment that maximises technical, economic, and environmental benefits across diverse geographical and market conditions.

Further research is recommended, focusing on experimental studies to monitor the real-world performance of CSP systems in different climates, the development of innovative materials to reduce component degradation, and the optimisation of hybrid systems that combine CSP and PV technologies with advanced energy storage systems. It is also necessary to investigate the socio-economic aspects of CSP implementation in different regional contexts, including analyses of the effects on local communities and labour markets.

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Abbreviations

AHP	Analytic Hierarchy Process
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CI	Consistency Index
CO_2	Carbon Dioxide
CR	Consistency Ratio
CSP	Concentrated Solar Power
CT	Central tower
GHG	Greenhouse Gas
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
LFP	Lithium iron phosphate battery storage technology
LFR	Linear Fresnel reflector
NMC	Nickel manganese cobalt battery storage technology
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
PT	Parabolic trough collector
PV	Photovoltaic
SWOT	Strengths, Weaknesses, Opportunities, Threats

References

1. Alvarez Constante, D.M.; Rosero Erazo, C.R. The Role of Renewable Energies in the Transition to a Sustainable Energy Model: Challenges and Opportunities. *J. Bus. Entrep. Stud.* **2024**, *8*, 38–48. [CrossRef]
2. Osman, M.; Qureshi, I. Review of Photovoltaic and Concentrated Solar Technologies Including Their Performance, Reliability, Efficiency and Storage. *Results Eng.* **2025**, *25*, 104424. [CrossRef]
3. Ali, A.O.; Elgohr, A.T.; El-Mahdy, M.H.; Zohir, H.M.; Emam, A.Z.; Mostafa, M.G.; Al-Razgan, M.; Kasem, H.M.; Elhadidy, M.S. Advancements in Photovoltaic Technology: A Comprehensive Review of Recent Advances and Future Prospects. *Energy Convers. Manag. X* **2025**, *26*, 100952. [CrossRef]
4. Zeng, X.; Xie, H.; Chen, X.; Cao, Q.; Bie, Z. A Zero-Carbon Integrated Energy System Energized by CSP + PV: A Real Case of Isolated Grid. *Sol. Energy* **2025**, *292*, 113440. [CrossRef]
5. Elkelawy, M.; Saeed, A.M.; Seleem, H. Egypt's Solar Revolution: A Dual Approach to Clean Energy with CSP and PV Technologies. *Pharos Eng. Sci. J.* **2024**, *1*, 39–50. [CrossRef]
6. Yousef, B.A.A.; Hachicha, A.A.; Rodriguez, I.; Abdelkareem, M.A.; Inyaat, A. Perspective on Integration of Concentrated Solar Power Plants. *Int. J. Low-Carbon Technol.* **2021**, *16*, 1098–1125. [CrossRef]
7. Wang, G.; Zhang, Z.; Lin, J. Multi-Energy Complementary Power Systems Based on Solar Energy: A Review. *Renew. Sustain. Energy Rev.* **2024**, *199*, 114464. [CrossRef]
8. Mohanaravi, K.; Samykano, M.; Pandey, A.K.; Noor, M.M.; Kadirgama, K. A Succinct Review of Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analyses, Challenges and Prospects of Solar and Wind Tree Technologies for Hybrid Power Generation. *Front. Energy Res.* **2024**, *12*, 1417511. [CrossRef]
9. Bošnjaković, M.; Veljić, N.; Božič, J.T.; Muhič, S. SWOT-AHP Analysis of the Importance and Adoption of Pumped-Storage Hydropower. *Technologies* **2025**, *13*, 305. [CrossRef]
10. Bošnjaković, M.; Santa, R. Strategic Assessment of Building-Integrated Photovoltaics Adoption: A Combined SWOT-AHP Approach. *Energies* **2025**, *18*, 4221. [CrossRef]

11. Betancur, S.; Ortega-Avila, N.; López-Vidaña, E.C. Strengths, Weaknesses, Opportunities, and Threats Analysis for the Strengthening of Solar Thermal Energy in Colombia. *Resources* **2024**, *13*, 3. [CrossRef]
12. Saaty, R.W. The Analytic Hierarchy Process—What It Is and How It Is Used. *Math. Model.* **1987**, *9*, 161–176. [CrossRef]
13. Guillén-Mena, V.; Quesada-Molina, F.; Astudillo-Cordero, S.; Lema, M.; Ortiz-Fernández, J. Lessons Learned from a Study Based on the AHP Method for the Assessment of Sustainability in Neighborhoods. *MethodsX* **2023**, *11*, 102440. [CrossRef]
14. Stofkova, J.; Krejnus, M.; Stofkova, K.R.; Malega, P.; Binasova, V. Use of the Analytic Hierarchy Process and Selected Methods in the Managerial Decision-Making Process in the Context of Sustainable Development. *Sustainability* **2022**, *14*, 11546. [CrossRef]
15. Goepel, K.D. Implementation of an Online Software Tool for the Analytic Hierarchy Process (AHP-OS). *Int. J. Anal. Hierarchy Process* **2018**, *10*, 19. [CrossRef]
16. Alonso, J.A.; Lamata, M.T. Consistency in the Analytic Hierarchy Process: A New Approach. *Int. J. Uncertain. Fuzziness Knowl.-Based Syst.* **2006**, *14*, 445–459. [CrossRef]
17. Alami, A.H.; Olabi, A.G.; Mdallal, A.; Rezk, A.; Radwan, A.; Rahman, S.M.A.; Shah, S.K.; Abdelkareem, M.A. Concentrating Solar Power (CSP) Technologies: Status and Analysis. *Int. J. Thermofluids* **2023**, *18*, 100340. [CrossRef]
18. Rodat, S.; Thonig, R. Status of Concentrated Solar Power Plants Installed Worldwide: Past and Present Data. *Clean. Technol.* **2024**, *6*, 365–378. [CrossRef]
19. Bošnjaković, M.; Tadijanović, V. Environment Impact of a Concentrated Solar Power Plant. *Teh. Glas.* **2019**, *13*, 68–74. [CrossRef]
20. REN21 Secretariat. *REN21 RENEWABLES 2024—Global Status Report Collection—GLOBAL OVERVIEW*; REN21 Secretariat: Paris, France, 2023.
21. García-Baños, C.; Blanco, M.; Prieto, C.; Silva, M. *Renewable Energy Benefits Leveraging Local Capacity for Concentrated Solar Power*; Makeig, F., Ed.; The International Renewable Energy Agency (IRENA): Masdar City, Abu Dhabi, 2025; ISBN 9789292606442.
22. Wu, C.; Zhao, Y.; Li, W.; Fan, J.; Xu, H.; Ling, Z.; Yuan, D.; Zeng, X. Concentrated Solar Thermal Power Technology and Its Thermal Applications. *Energies* **2025**, *18*, 2120. [CrossRef]
23. Bellmann, P.; Wolfertstetter, F.; Conceição, R.; Silva, H.G. Comparative Modeling of Optical Soiling Losses for CSP and PV Energy Systems. *Sol. Energy* **2020**, *197*, 229–237. [CrossRef]
24. Ramorakane, R.J.; Dinter, F. Evaluation of Parasitic Consumption for a CSP Plant. *AIP Conf. Proc.* **2016**, *1734*, 70027. [CrossRef]
25. Bošnjaković, M. Advance of Sustainable Energy Materials: Technology Trends for Silicon-Based Photovoltaic Cells. *Sustainability* **2024**, *16*, 7962. [CrossRef]
26. Eze, V.H.U.; Richard, K.; Ukagwu, K.J.; Okafor, W. Factors Influencing the Efficiency of Solar Energy Systems. *J. Eng. Technol. Appl. Sci.* **2024**, *6*, 119–131. [CrossRef]
27. Masson, G.; de L'Epine, M.; Kaizuka, I. *Trends in Photovoltaic Applications 2024—REPORT IEA PVPS T1-43*; IEA PVPS: Paris, France, 2024.
28. Seel, J.; Kemp, J.M.; Cheyette, A.; Millstein, D.; Gorman, W.; Jeong, S.; Robson, D.; Setiawan, R.; Bolinger, M. *Utility-Scale Solar, 2024 Edition—Empirical Trends in Deployment, Technology, Cost, Performance, PPA Pricing, and Value in the United States*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2024.
29. Highest Efficiency Solar Cells: Perovskite Solar Cells (2025 Update). Available online: https://www.fluxim.com/research-blogs/perovskite-silicon-tandem-pv-record-updates (accessed on 22 September 2025).
30. Baechle, S.; Dimroth, F. Fraunhofer ISE Develops the World's Most Efficient Solar Cell with 47.6 Percent Efficiency. Available online: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/press-releases/2022/1322_PR_ISE_World_Record_47,6Percent-SolarCell.pdf (accessed on 25 September 2025).
31. Eze, V. Innovations in Thermal Energy Systems, Bridging Traditional and Emerging Technologies for Sustainable Energy Solutions. *Front. Therm. Eng.* **2025**, *5*, 1654815. [CrossRef]
32. Elkelawy, M.; MEl-Ashmawy, W.; Ahmed, S.M. State of the Art in Concentrated Solar Power: Latest Technological Advancements and Innovations in Efficiency and Energy Storage. *Pharos Eng. Sci. J.* **2025**, *1*, 17–28. [CrossRef]
33. Mohamed, L.; Abdelkader, R.; Laroussi, K.; Singh, A.R.; Bajaj, M.; Tuka, M.B. Comprehensive Techno-Economic Optimization and Performance Analysis of Molten Salt Concentrated Solar Power Tower Plants in Algeria. *Sci. Rep.* **2025**, *15*, 14456. [CrossRef]
34. Cox, D. 10 Large Solar Projects in Development for 2024. Available online: https://www.renewableenergyworld.com/solar/utility-scale/10-large-solar-projects-in-development-for-2024/ (accessed on 20 September 2025).
35. Gumber, A.; Zana, R.; Steffen, B. A Global Analysis of Renewable Energy Project Commissioning Timelines. *Appl. Energy* **2024**, *358*, 122563. [CrossRef]
36. Bauer, T.; Binder, M.; Dersch, J.; Gross, F.; Giuliano, S.; Gunn, B.; Frantz, C.; Hasselbach, H.; Haite, A.; Kaczmarkiewicz, N.; et al. *Blueprint for Molten Salt CSP Power Plant, Cologne, Germany*; Final Report of the Project: CSP-Reference Power Plant " No. 0324253; German Aerospace Center (DLR): Cologne, Germany, 2021.
37. Kurup, P.; Akar, S.; Augustine, C.; Feldman, D. *Initial Heliostat Supply Chain Analysis, NREL/TP-7A40-83569*; National Renewable Energy Laboratory: Golden, CO, USA, 2022.

38. Bošnjaković, M.; Galović, M.; Kuprešak, J.; Bošnjaković, T. The End of Life of PV Systems: Is Europe Ready for It? *Sustainability* **2023**, *15*, 16466. [CrossRef]
39. Gasa, G.; Prieto, C.; Lopez-Roman, A.; Cabeza, L.F. Life Cycle Assessment (LCA) of a Concentrating Solar Power (CSP) Plant in Tower Configuration with Different Storage Capacity in Molten Salts. *J. Energy Storage* **2022**, *53*, 105219. [CrossRef]
40. China Solar Thermal Alliance; China Renewable Energy Society. *Blue Book of China's Concentrating Solar Power Industry 2024*; Zhifeng, W., Ed.; The China Solar Thermal Alliance (CSTA) and the Concentrating Solar Power Professional Committee of China Renewable Energy Society (CRES): Beijing, China, 2025.
41. Tursunović, I.; Papurello, D. Design of a Solar Dish Receiver and Life Cycle Assessment of a Hot Water System. *Clean. Technol.* **2024**, *6*, 379–396. [CrossRef]
42. Bošnjaković, M.; Stojkov, M.; Katinić, M.; Lacković, I. Effects of Extreme Weather Conditions on PV Systems. *Sustainability* **2023**, *15*, 16044. [CrossRef]
43. Bamisile, O.; Acen, C.; Cai, D.; Huang, Q.; Staffell, I. The Environmental Factors Affecting Solar Photovoltaic Output. *Renew. Sustain. Energy Rev.* **2025**, *208*, 115073. [CrossRef]
44. Manservigi, L.; Losi, E.; Gonzalez-Salazar, M.; Castorino, G.A.M.; Spina, P.R.; Venturini, M. Impact of Climate Change on Solar Pv Potential in Europe. In Proceedings of the 37th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2024, Rhodes, Greece, 30 June–5 July 2024; Volume 1, pp. 593–604.
45. Aboagye, B.; Gyamfi, S.; Ofosu, E.A.; Djordjevic, S. Degradation Analysis of Installed Solar Photovoltaic (PV) Modules under Outdoor Conditions in Ghana. *Energy Rep.* **2021**, *7*, 6921–6931. [CrossRef]
46. Chen, K.; Zuo, J.; Chang, R. Compendium of Degradation Rates of Global Photovoltaic (PV) Technology: Insights from Technology, Climate and Geography. *Sol. Energy Mater. Sol. Cells* **2025**, *293*, 113839. [CrossRef]
47. Dosa, I.; Petrilean, D.C.; Tataru, A.C.; Vasilescu, G.D.; Mija, N.; Cazac, A.M.; Rusu, O.; Tatarcan, A.-C.; Bejinariu, C. Assessment of Steam Turbine Performance Degradation in Long-Term Operation. *Energy* **2025**, *327*, 136491. [CrossRef]
48. García-Segura, A.; Sutter, F.; Martínez-Arcos, L.; Reche-Navarro, T.J.; Wiesinger, F.; Wette, J.; Buendía-Martínez, F.; Fernández-García, A. Degradation Types of Reflector Materials Used in Concentrating Solar Thermal Systems. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110879. [CrossRef]
49. Souri, M.; Borujerdi, A.N. The Impact of Fouling on Heat Transfer, Pressure Drop, and the Effectiveness of Heat Exchangers. *Int. J. Res. Publ. Rev.* **2025**, *6*, 12264–12275. [CrossRef]
50. NREL Concentrating Solar Power. Available online: https://atb.nrel.gov/electricity/2024/concentrating_solar_power (accessed on 23 September 2025).
51. Merchán, R.P.; Santos, M.J.; Medina, A.; Calvo Hernández, A. High Temperature Central Tower Plants for Concentrated Solar Power: 2021 Overview. *Renew. Sustain. Energy Rev.* **2022**, *155*, 111828. [CrossRef]
52. Shankar | a, A.; Saxena, A.K.; Mazumdar, R. *Concentrated Solar Power (CSP) Plants with Storage: Deployment Essential Now*; The Energy and Resources Institute (TERI): New Delhi, India, 2024.
53. Khan, M.I.; Gutiérrez-Alvarez, R.; Asfand, F.; Bicer, Y.; Sgouridis, S.; Al-Ghamdi, S.G.; Jouhara, H.; Asif, M.; Kurniawan, T.A.; Abid, M.; et al. The Economics of Concentrating Solar Power (CSP): Assessing Cost Competitiveness and Deployment Potential. *Renew. Sustain. Energy Rev.* **2024**, *200*, 114551. [CrossRef]
54. Photovoltaics Report—Fraunhofer Institute for Solar Energy Systems ISE with the Support of PSE Projects GmbH. Available online: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html (accessed on 26 September 2025).
55. Corona, B.; San Miguel, G. Life Cycle Sustainability Analysis Applied to an Innovative Configuration of Concentrated Solar Power. *Int. J. Life Cycle Assess.* **2019**, *24*, 1444–1460. [CrossRef]
56. Backes, J.G.; D'Amico, A.; Pauliks, N.; Guarino, S.; Traverso, M.; Lo Brano, V. Life Cycle Sustainability Assessment of a Dish-Stirling Concentrating Solar Power Plant in the Mediterranean Area. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101444. [CrossRef]
57. Burkhardt, J.J.I.I.I.; Heath, G.A.; Turchi, C.S. Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives. *Environ. Sci. Technol.* **2011**, *45*, 2457–2464. [CrossRef] [PubMed]
58. Cellura, M.; Luu, L.Q.; Guarino, F.; Longo, S. A Review on Life Cycle Assessment of Concentrating Solar Energy Technologies. *Renew. Energy* **2025**, *249*, 123203. [CrossRef]
59. Bošnjaković, M.; Santa, R.; Crnac, Z.; Bošnjaković, T. Environmental Impact of PV Power Systems. *Sustainability* **2023**, *15*, 11888. [CrossRef]
60. Vatankhah Ghadim, H.; Haas, J.; Breyer, C.; Gils, H.C.; Read, E.G.; Xiao, M.; Peer, R. Are We Too Pessimistic? Cost Projections for Solar Photovoltaics, Wind Power, and Batteries Are over-Estimating Actual Costs Globally. *Appl. Energy* **2025**, *390*, 125856. [CrossRef]
61. Aljudaya, A.; Michailos, S.; Ingham, D.B.; Hughes, K.J.; Ma, L.; Pourkashanian, M. Techno-Economic Assessment of Molten Salt-Based Concentrated Solar Power: Case Study of Linear Fresnel Reflector with a Fossil Fuel Backup under Saudi Arabia's Climate Conditions. *Energies* **2024**, *17*, 2719. [CrossRef]

62. Peacock, F. Solar Batteries: Everything You Need To Know (Cost, Payback, Brands). Available online: https://www.solarquotes.com.au/battery-storage/comparison-table/ (accessed on 26 September 2025).
63. Cole, W.; Frazier, A.W. *Cost Projections for Utility-Scale Battery Storage: 2023 Update*; NREL/TP-6A40-85332; National Renewable Energy Lab: Golden, CO, USA, 2023.
64. Kraemer, S. 100 GWh of Long Duration Energy Storage from MIT. Available online: https://www.solarpaces.org/100-gwh-of-long-duration-energy-storage-from-mit/ (accessed on 26 September 2025).
65. U.S. Department of Energy Project Profile: High-Efficiency Thermal Storage System for Solar Plants. Available online: https://www.energy.gov/eere/solar/project-profile-high-efficiency-thermal-storage-system-solar-plants (accessed on 26 September 2025).
66. Schöniger, F.; Thonig, R.; Resch, G.; Lilliestam, J. Making the Sun Shine at Night: Comparing the Cost of Dispatchable Concentrating Solar Power and Photovoltaics with Storage. *Energy Sources Part. B Econ. Plan. Policy* **2021**, *16*, 55–74. [CrossRef]
67. Feldman, D.; Margolis, R.; Denholm, P.; Stekli, J.; Feldman, D.; Margolis, R.; Stekli, J.; Denholm, P.; Stekli, J. *Exploring the Potential Competitiveness of Utility-Scale Photovoltaics plus Batteries with Concentrating Solar Power, 2015–2030*; Tech Rep NREL/TP-6A20-66592; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2016; pp. 1–31.
68. Bhatti, S.; Khan, A.R.; Zoha, A.; Hussain, S.; Ghannam, R. A Machine Learning Frontier for Predicting LCOE of Photovoltaic System Economics. *Adv. Energy Sustain. Res.* **2024**, *5*, 2300178. [CrossRef]
69. Cristea, M.; Cristea, C.; Tîrnovan, R.-A.; Șerban, F.M. Levelized Cost of Energy (LCOE) of Different Photovoltaic Technologies. *Appl. Sci.* **2025**, *15*, 6710. [CrossRef]
70. Elahi Gol, A.; Ščasný, M. Techno-Economic Analysis of Fixed versus Sun-Tracking Solar Panels. *Int. J. Renew. Energy Dev.* **2023**, *12*, 615–626. [CrossRef]
71. Trina Solar Levelized Cost Of Energy Study-Trina Tracker Independent Assessment. Available online: https://static.trinasolar.com/sites/default/files/FINAL_Trina_Tracker_LCOE_Study_Report_2.21.2023.pdf (accessed on 26 September 2025).
72. ProtermoSolar Cost of Concentrated Solar Power (CSP) Projects Fell from USD 0.38/KWh to USD 0.118/KWh—A Decline of 69%. Available online: https://helioscsp.com/cost-of-concentrated-solar-power-csp-projects-fell-from-usd-0-38-kwh-to-usd-0-118-kwh-a-decline-of-69/ (accessed on 28 September 2025).
73. Althuwaini, Y.E.Y.Y.; Philbin, S.P. Techno-Economic Analysis of Solar Power Plants in Kuwait: Modelling the Performance of PV and CSP Systems. *Int. J. Renew. Energy Res.* **2021**, *11*, 2009–2024. [CrossRef]
74. Wiser, R.; Bolinger, M.; Seel, J. Benchmarking Utility-Scale PV Operational Expenses and Project Lifetimes: Results from a Survey of U.S. Solar Industry Professionals. *Eletr. Mark. Policy* **2020**, *1*, 1–8.
75. Solar Photovoltaic System Cost Benchmarks. Available online: https://www.energy.gov/eere/solar/solar-photovoltaic-system-cost-benchmarks (accessed on 27 September 2025).
76. Kabeyi, M.J.B.; Olanrewaju, O.A. The Levelized Cost of Energy and Modifications for Use in Electricity Generation Planning. *Energy Rep.* **2023**, *9*, 495–534. [CrossRef]
77. Lindquist, T.; Karlsson, J.; Wallmander, J.; Guedez, R.; Hedlund, M.-L.; Jamot, J.; Gloss, D.; Lindh, J.; Hertin, A.; Nilsson, M.; et al. A Novel Modular and Dispatchable CSP Stirling System: Design, Validation, and Demonstration Plans. *AIP Conf. Proc.* **2019**, *2126*, 60005. [CrossRef]
78. Peña, A.; Villasante, C.; Ramirez, D.; Herrador, M.; Pereira, D.; Barat, Y.; Ubach, J.; Saur, M.; Pagola, Í.; Sánchez, M.; et al. Innovative Modular Approach to High Concentration CSP Systems. Results and Achievements From the First-of-Its-Kind 300 KWt Semi-Fresnel Fixed Mirror Module Prototype Up and Running. In Proceedings of the 28th International Conference on Concentrating Solar Power and Chemical Energy Systems, Albuquerque, NM, USA, 27–30 September 2022; Volume 1, pp. 1–8.
79. Morosini, E.; Gentile, G.; Binotti, M.; Manzolini, G. Techno-Economic Assessment of Small-Scale Solar Tower Plants with Modular Billboard Receivers and Innovative Power Cycles. *J. Phys. Conf. Ser.* **2022**, *2385*, 12109. [CrossRef]
80. Taylor, N.; Georgakaki, A.; Mountraki, A.; Letout, S.; Ince, E.; Shtjefni, D.; Kuokkanen, A.; Tattini, J.; Diaz Rincon, A. *Clean Energy Technology Observatory: Concentrated Solar Power and Solar Heating and Cooling in the European Union—2023 Status Report on Technology Development, Trends, Value Chains and Markets*; Publications Office of the European Union: Luxembourg, 2023.
81. Badari Narayana, P.; Narasimha Kumar, S.; Kumar, A.; Professor, A.; Gandhi, M. Modelling, Simulation and Analysis of 5 MWe Linear Fresnel Collector Based Solar Thermal Energy Conversion Cycle with Energy Storage. In Proceedings of the International Congress on Renewable Energy (I CORE 2021), Bangalore, India, 27–28 November 2021; pp. 1–12.
82. Ong, S.; Campbell, C.; Denholm, P.; Margolis, R.; Heath, G. *Land-Use Requirements for Solar Power Plants in the United States*; NREL (National laboratory of the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy): Denver, CO, USA, 2013.
83. Aprà, F.M.; Smit, S.; Sterling, R.; Loureiro, T. Overview of the Enablers and Barriers for a Wider Deployment of CSP Tower Technology in Europe. *Clean. Technol.* **2021**, *3*, 377–394. [CrossRef]
84. Yang, Q.; Huang, T.; Chen, F.; Uche, J.; Wang, Y.; Yuan, P.; Zhang, Y.; Li, J. Water Saving Potential for Large-Scale Photovoltaic Power Generation in China: Based on Life Cycle Assessment. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112681. [CrossRef]

85. Water Use across Solar Technologies. Available online: https://sustainability-directory.com/question/what-statistics-indicate-solars-water-use/ (accessed on 10 October 2025).
86. Sinha, P.; Meader, A.; De Wild-Scholten, M. Life Cycle Water Usage in CdTe Photovoltaics. In Proceedings of the IEEE Conference Photovoltaic Specialists (PVSC), Austin, TX, USA, 3–8 June 2012; pp. 1–5. [CrossRef]
87. Water Consumption Solution for Efficient Concentrated Solar Power. Available online: https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/water-consumption-solution-efficient-concentrated-solar-power (accessed on 6 October 2025).
88. Fares, M.S.B.; Abderafi, S. Water Consumption Analysis of Moroccan Concentrating Solar Power Station. *Sol. Energy* **2018**, *172*, 146–151. [CrossRef]
89. Generating Electricity and Saving Water in Large Concentrating Solar Power (CSP) Plants in Desert Regions of the World. Available online: https://www.cranfield.ac.uk/research-projects/wascop#Overview (accessed on 10 October 2025).
90. Bourdon, D.; Wolfertstetter, F.; Fernández-García, A.; Sansom, C.; Azpitarte, I.; Bouaddi, S.; Perez, G.; Maccari, A.; Nijnatten, P.V.; Surquin, E.; et al. Saving Water on Concentrated Solar Power Plants: The Holistic Approach of the WASCOP Project. *AIP Conf. Proc.* **2020**, *2303*, 210002. [CrossRef]
91. Xia, N.; Sartori, F.T.; Bern, G.; Heimsath, A. Socio-Economic Impact of Concentrated Solar Power in China: Example of a 50 MW Parabolic Trough Plant. *AIP Conf. Proc.* **2023**, *2815*, 50006. [CrossRef]
92. Terrapon-Pfaff, J.; Fink, T.; Viebahn, P.; Jamea, E.M. Social Impacts of Large-Scale Solar Thermal Power Plants: Assessment Results for the NOORO I Power Plant in Morocco. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109259. [CrossRef]
93. Rodríguez-Serrano, I.; Caldés, N.; De la Rúa, C.; Lechón, Y.; Garrido, A. Socioeconomic, Environmental and Social Impacts of a Concentrated Solar Power Energy Project in Northern Chile. *Renew. Energy Environ. Sustain.* **2016**, *1*, 5. [CrossRef]
94. Heeter, J.; Reames, T. Incorporating Energy Justice into Utility-Scale Photovoltaic Deployment: A Policy Framework. *Renew. Energy Focus.* **2022**, *42*, 1–7. [CrossRef]
95. Muñoz-García, M.-Á.; Fialho, L.; Moreda, G.P.; Baptista, F. Assessment of the Impact of Utility-Scale Photovoltaics on the Surrounding Environment in the Iberian Peninsula. Alternatives for the Coexistence with Agriculture. *Sol. Energy* **2024**, *271*, 112446. [CrossRef]
96. IRENA. *Renewable Energy Benefits: Leveraging Local Capacity for Concentrated Solar Power*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2025; ISBN 9789292606442.
97. Concentrated Solar Power Market Size and Forecast 2025 to 2034. Available online: https://www.precedenceresearch.com/concentrated-solar-power-market (accessed on 10 November 2025).
98. European Commision Working Group (IWG CSTT). *Initiative for Global Leadership in Concentrated Solar Thermal Technologies Updated Implementation Plan*; European Commision Working Group (IWG CSTT): Brussels, Belgium, 2023; Volume 2023, pp. 1–51.
99. Huang, J.; Mao, L. A Review on Perovskite/Silicon Tandem Solar Cells: Current Status and Future Challenges. *Energies* **2025**, *18*, 4327. [CrossRef]
100. Ziani, Z.; Mahdad, M.Y.; Bessenouci, M.Z.; Sekkal, M.C.; Ghellai, N. Enhancing Multi-Junction Solar Cell Performance: Advanced Predictive Modeling and Cutting-Edge CIGS Integration Techniques. *Energies* **2024**, *17*, 4669. [CrossRef]

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