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COOPERANT

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Report on CSP-TES requirements for potential key applications

WP1 – Project Management and Coordination

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COOPERANT Key Facts

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N.	Partner	Acronym	Country
1	IDENER RESEARCH & DEVELOPMENT AGRUPACION DE INTERES ECONOMICO	IDE	ES
2	KRAFTBLOCK GMBH	KB	GE
3	CENTRO DE INVESTIGACIONES ENERGETICAS MEDIOAMBIENTALES Y TECNOLOGICAS	CIEMAT	ES
4	HOLOSS - HOLISTIC AND ONTOLOGICAL SOLUTIONS FOR SUSTAINABILITY, LDA.	HOLOSS	PT
5	PHASE CHANGE MATERIAL PRODUCTS LTD	PCMP	UK
6	FACHHOCHSCHULE ZENTRALSCHWEIZ HOCHSCHULE LUZERN	HSLU	CH
7	ENGICER SA	ENGI	CH

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Executive summary

Among the renewable sources to decarbonise the energy sector, Concentrated Solar Power (CSP) with Thermal Energy Storage (TES) has emerged as a crucial technology in the transition toward a sustainable energy future. Unlike other renewable energy sources, CSP-TES provides a unique advantage through its ability to deliver dispatchable and reliable power, which can be stored and deployed when demand peaks or supply from other renewables is low. This flexibility positions CSP-TES as a stabilizing energy source within renewable energy portfolios, allowing it to complement intermittent renewables and enhance grid resilience.

This document presents an updated strategy alignment in Global and European contexts, for the renewable energy targets to achieve net-zero emissions by 2050. A comprehensive review is done for CSP and TES technologies. Most importantly, the combination of CSP-TES is assessed by comparing alternative potential storage systems (sensible, latent and thermochemical solutions), as well as novel system designs (packed-bed and modular approaches). In addition, key applications and parameters for an optimised CSP-TES are identified by determining the system requirements, technology suitability and operational conditions.

This review allows us to highlight the effectiveness of COOPERANT's unique and groundbreaking solutions positioning CSP as a competitive renewable energy source, alongside wind and photovoltaics, by addressing key challenges in efficiency, scalability, and cost-effectiveness.

High-Temperature CSP systems

COOPERANT's will develop high-performance CSP volumetric receivers with hybrid TES systems capable of operating at temperatures up to 1000°C. These advances unlock the potential of third-generation CSP technologies, significantly improving thermodynamic efficiency and reducing the cost per unit of electricity/heat produced. This enables CSP systems to support more efficient power cycles (reaching efficiencies over 42%) and large- to medium-scale adoption to accomplish the goals resented in the energy agendas for 2030 and 2050.

Innovative hybrid TES system configuration

A cornerstone of COOPERANT's project is its hybrid packed-bed TES system, which combines solid-state mixtures and phase-change materials (PCMs) capable of operating at the required high-temperature range. This approach increases energy storage density, reduces system size by up to 30%, and enhances CSP dispatchability by addressing the intermittency of solar energy. These improvements optimize energy output, lower costs, and expand the feasibility of CSP deployment in various applications, as discussed in the report.

Key metrics for CSP-TES optimization

The performance of CSP plants heavily relies on the optimization of both the overall CSP and the TES systems. This deliverable discusses the key metrics for CSP-TES systems including:

- Thermal efficiency: how effectively solar energy is converted to usable thermal energy.
- Levelized Cost of Electricity / Heat (LCOE / LCOH): Reflects economic competitiveness, incorporating operational and capital costs over the plant's lifetime.
- Capacity factor: Indicates the ratio of actual energy produced to the maximum potential output, enhanced by TES integration.
- Annual solar-to-electric efficiency: Evaluates the conversion efficiency of solar energy to electrical output annually.
- Storage capacity: Determines the energy available for dispatch during low solar periods.
- Storage efficiency: Assesses energy retention and heat loss minimization over time.
- Response time: Indicates how quickly stored energy can be delivered to meet demand.
- Durability and lifecycle costs: Reflects long-term viability of materials and components.

Alignment with EU and global roadmaps

Recent policy developments, including the amended SET Plan 2023, align with key initiatives such as the European Green Deal and REPowerEU, setting ambitious targets for CSP technology. These targets include reducing electricity costs to below 15 c€/kWh by 2025 and below 10 c€/kWh by 2030, along with increasing power plant efficiency to 42.4% by 2025. Also, COOPERANT's advancements fully align with the objectives of the International Energy Agency (IEA) and the European Commission (EC) agendas to unlock the potential of third-generation CSP technologies. Additionally, the International Renewable Energy Agency's (IRENA) Innovation Outlook highlights TES's importance in achieving dispatchability and cost-effectiveness for CSP technologies. In this line, COOPERANT's innovative approach aims to enhance energy density, diminish costs, and reduce system size by integrating a hybrid packed-bed system with solid-state mixtures and phase change materials (PCMs).

Tailored solutions for diverse applications

Th document provides the key aspects to consider in determining the generation of use cases, namely, the solar input, energy demand profiles, storage power and capacity requirements.

- Power Generation: Supports advanced power cycles (e.g., Rankine, Brayton and sCO_2) and robust TES systems for high-capacity and dispatchable energy.
- Solar Fuel Production: Enables ultra-high temperatures and thermal stability for chemical processes.
- Solar Heat for Industrial Processes (SHIP): Customized TES designs meet medium-to-high-temperature needs in sectors such as cement, steel, chemicals and pharmaceuticals.
- District Heating: Provides cost-effective TES solutions for short-medium storage in district heating networks.

In summary, COOPERANT's innovations in CSP-TES technologies pave the way for scalable, efficient, and cost-effective solutions to meet the growing global demand for renewable sources. These contributions support the global transition toward a sustainable, decarbonized energy landscape and foster broader adoption of CSP technologies in diverse applications.

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List of Acronyms

API	Active Pharmaceutical Ingredients
CAPEX	Capital Expenditures
CETP	Clean Energy Transition Partnership
CaL	Calcium looping
CRS	Central Receiver Systems
CSP	Concentrated Solar Power
DH	District Heating
DNI	Direct Normal Irradiation
EAFD	Electric Arc Furnace Dust
EC	European Commission
EEA	European Environment Agency
ETES	Electric Thermal Energy Storage
EU	European Union
G3P3	Generation 3 Particle Pilot Plant
GHG	Greenhouse Gas
HTF	Heat Transfer Fluid
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KPI	Key Performance Indicators
LCOE	Levelized Cost of Electricity
LFC	Linear Fresnel Collectors
MS	Molten Salts
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
PCM	Phase Change Materials
PD	Parabolic Dish
PEM	Protium Exchange Membrane technology
PTC	Parabolic Trough Collector
PV	Photovoltaics
SET Plan	Strategic Energy Technology Plan
SHIP	Solar Heat for Industrial Processes
SiC	Silicon Carbide
SO	Specific Objectives
SOEC	Solid Oxide Electrolyzer Cell
TCS	Thermochemical Energy Storage

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TES	Thermal Energy Storage
UAE	The United Arab Emirates
USA	United States of America

1 Introduction

1.1 Brief overview of CSP and TES technologies

As the world faces climate, demographic, and economic challenges, renewable energy generation with low emissions becomes crucial for sustainable development. Concentrated Solar Power (CSP) technologies offer a promising alternative to fossil fuels, harnessing the vast potential of solar energy. These systems concentrate direct solar radiation using collectors and focus it onto a receiver, converting solar energy into heat, which can be used for electricity generation or thermal energy storage.

CSP technologies can be broadly divided into two categories: point-focus and line-focus systems. Point-focus systems, including central receiver systems and parabolic dishes, focus solar radiation into a small area, while line-focus systems, such as parabolic troughs and Fresnel linear receivers, distribute the radiation over an absorber tube containing heat transfer fluid. The main limitation of CSP systems is the operating temperature of the heat transfer fluid, which currently ranges from 400ºC for thermal oil to 600ºC for molten salts, with conversion efficiencies reaching up to 25%.

The common components of CSP systems are the collector and the receiver. The collector redirects solar radiation to the receiver, which absorbs and converts it into thermal energy. Parabolic troughs use absorber tubes, while central receiver systems employ external, cavity, volumetric, or particle receivers. These technologies vary in their design and functionality, with CSP offering a versatile solution that can be applied beyond energy generation, including thermal energy storage.

1.2 Strategic role of CSP-TES in the energy transition

In response to global energy demands and the urgent need to reduce greenhouse gas emissions, CSP with Thermal Energy Storage (TES) has emerged as a crucial technology in the transition toward a sustainable energy future in line with the Paris Agreement. CSP-TES contributes strategically to the energy transition by fostering energy independence and economic resilience. Unlike other renewable energy sources, CSP-TES provides a unique advantage through its ability to deliver dispatchable and reliable power, which allows it to complement intermittent renewables and enhance grid resilience.

CSP-TES systems are not only replacing fossil fuels in high-demand areas by providing reliable base power, but they are also playing a key role in decarbonizing areas like industrial heating or solar fuel production, which need energy inputs at medium to high temperatures. In addition, the modularity and scalability of some CSP-TES systems also mean they can be adapted to different energy needs, such as industrial process heat applications, strengthening their value as part of a diversified energy strategy. Large-scale deployment of CSP-TES can reduce dependence on imported fuels, promote local manufacturing of solar technology components, and create skilled jobs in both plant construction and maintenance.

1.3 Objectives and scope

Objectives

This Deliverable 1.3 (**D1.3**), titled "*Report on CSP-TES requirements for potential key applications*," is part of WP1 and was created during Task 1.3 development. Specifically, this report summarizes the outputs from the effort of CIEMAT, IDE, HSLU, and KB regarding the identification of potential applications for CSP-TES and their main requirements during Subtask 1.3.1: *'Overview of CSP-TES application scenarios'*.

Overall, the development of this sub-task will support the consecution of the following specific objectives (SO) of the COOPERANT project:

- **SO6.3.** To increase commercial applications and market opportunities at EU27, associated states and global level seeing the regulatory framework.
- **SO6.4.** To map strategic stakeholders along the value chain to efficiently engage key actors.

Scope and framework

The document presents a comprehensive report about the current EU and global roadmaps as a target guideline to align the COOPERANT project developments. Examples of the most relevant roadmaps are the International Energy Agency (IEA) and the European Environment Agency (EEA) reports, the Fit for 55 package, the SET-Plan objectives for CSP, the Strategic Research and Innovation Agenda from the Clean Energy Transition Partnership (CETP), EU Agendas 2030 and 2050, the REPowerEU Plan, etc.

Potential applications (power generation in supercritical CO_2, steam Rankine, and air Brayton cycles; solar fuels production; industrial process heat…) have been identified in this report and characterised with their key performance metrics and operational parameters. Then, the use-case generation, solar input, energy demand profiles, storage power, and capacity needs have been determined. In addition, an overview of the types of Thermal Energy Storage (TES) in CSP applications is explored, given its potential to bridge supply gaps caused by the intermittent nature of solar energy.

Relationship with other COOPERANT tasks

Based on the previously described insights gained from Task 1.3, the subsequent Task 2.1 will define the prototype requirements and specifications of the conceptual design. Along with Task 2.2 and Task 2.3, it will establish the end-user application and determine the target operating conditions. To raise a real interest in the COOPERANT solution, Task 6.3 will prioritise the clustering activities and the Stakeholder Replicability Board (SRB) creation based on the promising applications defined in this T1.3.1. The Replicability and scale-up analyses in Task 6.4 will be also fed and aligned with the defined end-user specifications and application scenarios with high potential.

2 CSP-TES Strategy Alignment in Global and European Contexts

2.1 Global Roadmap Analysis

2.1.1 Current global context

At the beginning of 2024, the global total CSP capacity (built or under development) surpassed 7 GW. Spain retains its position as the global leader, with 2300 MW of operational capacity, followed by the USA with 1500 MW and China with 596 MW. Together, these three countries constitute more than 70% of the world's CSP operating capacity. Most of the operating capacity is based on parabolic-trough technology with 73% (Figure 1). Central receiver systems account for 23%, and linear Fresnel collectors for 4%. Conversely, few projects have been developed with dish plate technology due to limitations in the economies of scale, since the maximum dish size is limited by mechanical constraints [1].

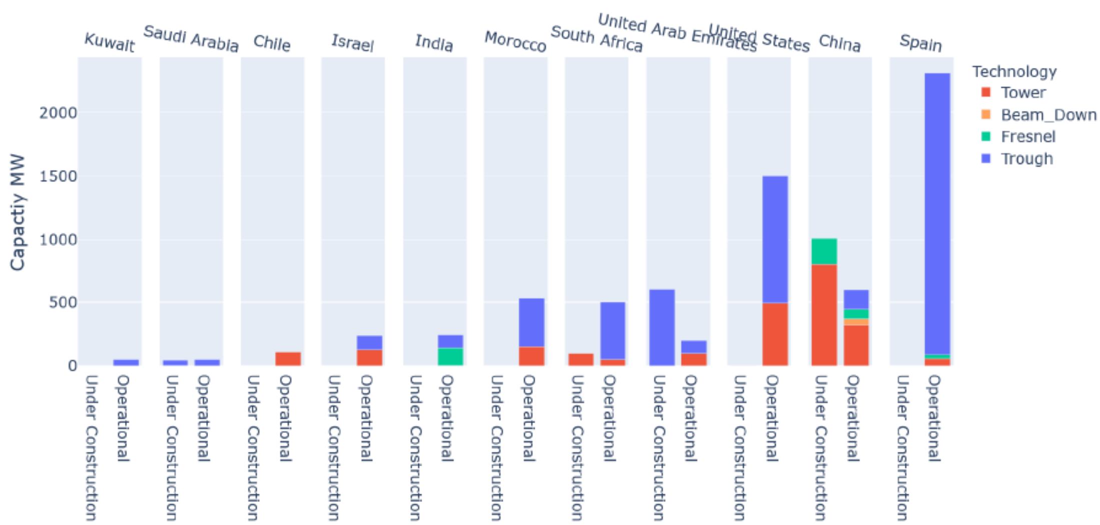

Figure 1. Global total CSP capacity updated for 2024. Figure extracted from [1].

Despite the increase in global total CSP capacity, the number of CSP projects is inadequate to achieve the tripling target (Figure 2). The tripling target seeks to attain at least 11,000 GW of installed worldwide renewable energy capacity by 2030. This goal was established at the COP28 climate conference in Dubai, where more than 200 countries committed to tripling renewable energy capacity within this decade within the 1.5°C Scenario. CSP technologies are significantly underfunded relative to other renewable energy sources. In 2023, investments in CSP were merely 2% of the annual requirement to achieve the 2030 objectives [2].

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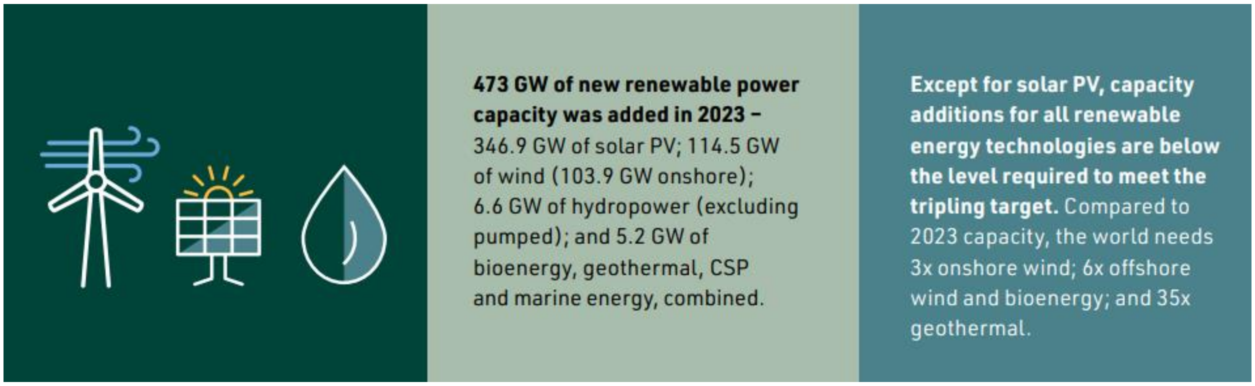

Figure 2. Tripling target on renewable energy. Figure extracted from [2].

In fact, at present, there are currently no ongoing construction projects in the United States of America (USA) or Spain. The major new projects are in China and the United Arabic Emirates (UAE). In the case of China, the projects being developed are associated with central receiver system (CRS) technology and have a total capacity of 810 MW. In recent years, Morocco, South Africa, and the UAE have implemented ambitious CSP facilities, including TES systems.

Since 2015, most CSP projects have included TES. Despite that fact, the TES systems are present in only 5.5 % of the CSP plants these days [3]. Adding TES systems to CSP plants has proven a cost-effective solution to increase capacity factors, while also contributing to a lower Levelized Cost of Energy (LCOE). The global average LCOE for CSP installations has a significant 70% decline between 2010 and 2023, going from 0.375 €/kWh to 0.112 €/kWh. The LCOE reduction was mainly caused by a 48% reduction in O&M costs, an 82% increase in capacity factors, and a 37% decrease in total installed costs (Figure 3).

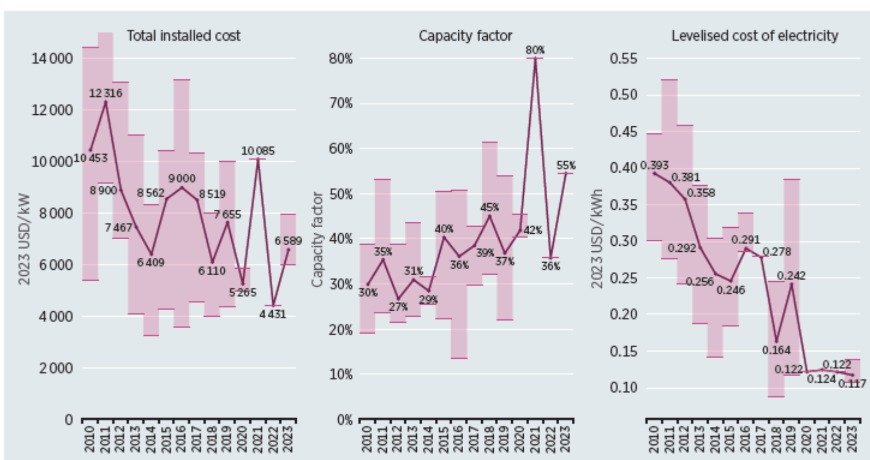

Figure 3. Global weighted average and range of total installed costs, capacity factors and LCOEs for CSP, 2010-2023. Figure extracted from [4].

CSP-TES technologies are not uniformly developed globally. They are particularly suited to regions with high solar irradiance, enabling countries to harness abundant solar resources while achieving energy security. The ability to store thermal energy for extended periods — commercially available up to almost 18 hours— helps to mitigate the challenges of intermittency and allows CSP-TES plants to offer grid support comparable to traditional fossil fuel plants but with a much lower carbon footprint.

Countries such as Morocco, South Africa and the UAE have invested substantially in these technologies in recent years. These governments have acknowledged the strategic importance of using their available solar resources and have initiated ambitious projects to incorporate CSP into their energy mix. In America, Chile is distinguished as the only country to have established a CSP plant in recent years, reflecting its dedication to renewable energy despite the inconsistent rate of CSP implementation in the region. China is the clear worldwide leader in CSP development, having significantly enlarged its CSP capacity and invested in technological innovations, so establishing itself at the front of the global CSP sector (Figure 4).

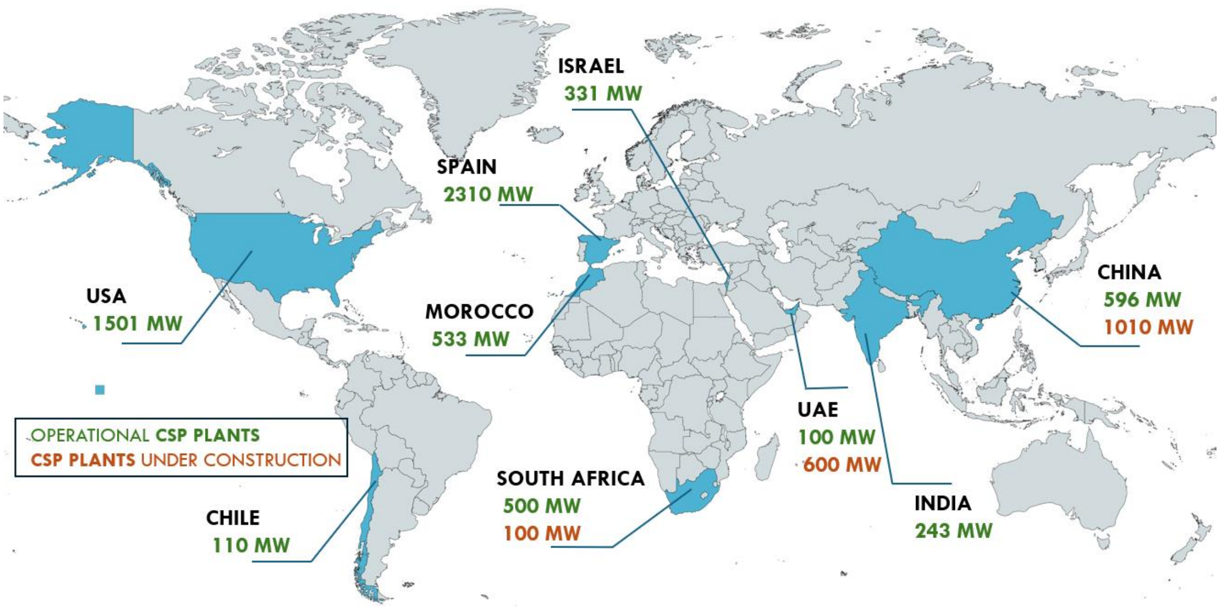

Figure 4. Leading countries in CSP deployment updated for 2024. Data extracted from [5].

North America

USA leads the region with a total CSP capacity of 1501 MW, followed by Mexico (14 MW) and Canada (1 MW). Nowadays, there is no commercial-scale CSP project under construction in the USA. The latest CSP plants were operated between 2013 and 2015 [1]. Five projects were finished: Genesis, Solana, Ivanpah, Mojave, and Crescent Dunes. Genesis includes a 250 MW parabolic trough plant with no TES system. Solana is a 280 MW parabolic trough plant connected to a two-tank indirect molten salt TES system with a storage capacity of 6 h. Ivanpah includes a central receiver plant with no TES system. Mojave includes a 250 MW parabolic trough plant with no TES system. Crescent Dunes includes a 110 MW central receiver system connected to a two-tank direct TES system with a storage capacity of 10 h [6].

South America

In 2021, Atacama I was inaugurated in Chile, becoming the first CSP plant in South America. Cerro Dominador includes a hybrid system combining a 110 MW CSP plant with a 100 MW photovoltaic plant. This project incorporates a two-tank direct molten salt TES. The storage capacity reaches 17.5 hours, a world record for commercial TES [1].

North Africa

The Ouarzazate Solar Power Station in Morocco is one of the largest hybrid CSP facilities globally. The complex consists of four projects NOOR I, II, III, IV (PV) developed from 2016 to 2018. The complex total capacity reaches 510 MW, which includes 72 MW from PV plant. NOOR I includes a 160 MW parabolic trough plant connected to a two-tank indirect molten salt TES system with 3 h of storage capacity. NOOR II includes a 200 MW parabolic trough plant connected to a two-tank indirect molten salt TES system with a storage capacity of 7 h. NOOR III includes a 150 MW central receiver plant connected to a two-tank direct molten salt TES system with a storage capacity of 7 h [7].

South Africa

During the last decade, South Africa has developed several CSP projects. Ilanga I, ISCC Green Duba I, Xina Solar One projects are examples of South African government's support for CSP technologies under its Renewable Energy Independent Power Produce Procurement Programme . The latest project under construction, Redstone Tower CSP, was finally completed in September 2024. Redstone Tower CSP project includes a 100 MW parabolic trough plant with 5 hours of thermal storage capacity [8].

Middle East

The UAE has recently completed the largest CSP project in the world. This project includes various CSP technologies, a 600 MW parabolic-trough plant and a 100 MW central receiver plant coupled with a 250 MW PV plant. The parabolic trough plant operates with a two-tank indirect molten salt TES with 11h of nominal production capacity. Meanwhile, the central receiver system plant operates with two-tank direct molten salt TES with a storage capacity of 15h [1].

East Asia

Currently, China is leading the development of CSP projects at global level. The country has many CSP plants under construction that add 1000 MW to the renewable energy mix. In 2024, most CSP plants in China, either built or under development, include central receiver system technology. In 2024, China announced the construction of new 11 CSP projects, highlighting a new 200 MW central receiver system plant overcoming the 100 MW technology standard [9].

2.1.2 Key trends at global level and COOPERANT alignment

IRENA estimates 197 MW total CSP capacity needed by 2030 in a 1.5 °C-scenario that includes an energy transition pathway to limit global average temperature to 1.5 °C by the end of the century as outlined in the Paris Agreement [10]. Three scenarios are published by the IEA according to the level of policy adoption by states to achieve net zero emissions in the global energy sector by 2050 (Table 1). In this vein, CSP-TES systems are presented as a key technology in the roadmaps for the decarbonization of the energy sector and the development of renewable energies globally in the medium and long term.

The latest CSP-TES trends are significantly linked to new energy solutions that help meet the 2030 and 2050 global energy goals. These trends (Figure 5) encompass the better integration of CSP-TES, power generation, and industrial applications. Despite the effort, current CSP deployment does not correspond with the Net Zero scenario as it would mean 6.7 GW added capacity per year.

Scenario	Year of publication	2030	2050
IRENA 1.5 °C pathway	2024	197 GW	-
IEA Net Zero Emissions	2024	35 GW	390 GW
IEA Announced Pledges	2024	16 GW	230 GW
IEA current policies	2024	10 GW	68 GW

Table 1. Estimations of global total CSP capacity by 2030 and 2050. Data extracted from [2] and [10].

IRENA highlighted the use of sensible and latent heat systems by 2030 due to its high energy efficiency (>92%) and potential cost reduction (to 60-90 €/kWh) [11]. TES technologies play an important role in the global energy transition in line with the Paris Agreement as a potential enabler of increased renewables penetration in energy systems. Molten salt storage is the most common technology used in CSP-TES systems. Irena indicated that an increase in storage capacity to 491-631 GWh is required by 2030 to achieve the CSP deployment goals set by the 1.5°C-scenario [11].

The research and development of advanced TES materials and high-efficiency CSP receiver designs aim to drive down costs and increase overall efficiency, making CSP-TES increasingly competitive. As research advances, new configurations are being explored, such as hybrid CSP-PV systems that integrate photovoltaic generation with CSP-TES storage, offering even more efficient and versatile solutions. These innovations underline CSP-TES's critical role as a transformative technology that addresses both energy and climate goals, promoting a balanced and sustainable energy ecosystem.

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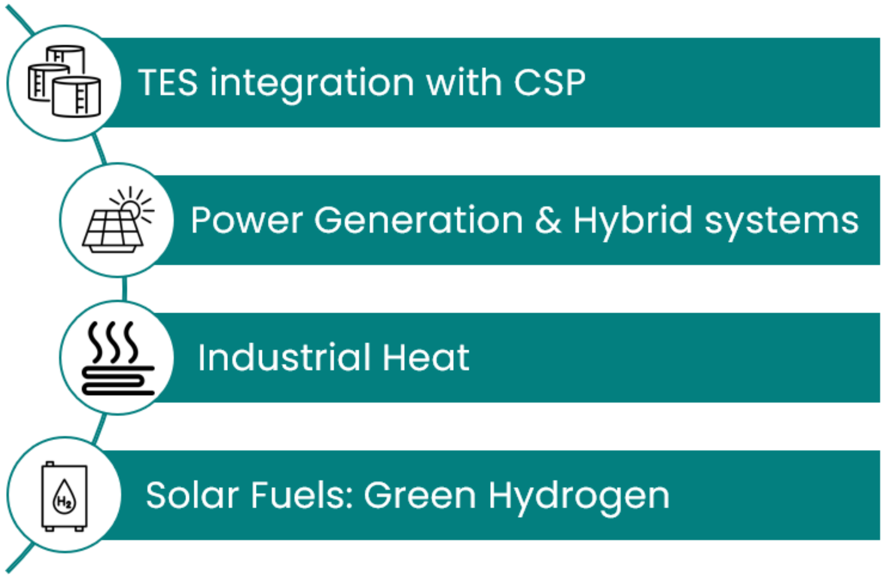

Figure 5. Key trends at global level [12].

CSP-TES systems can play a significant role in producing high-temperature heat and green hydrogen. However, current commercial CSP-TES systems have several limitations, such as only reaching operating temperatures of up to 600ºC. Solar thermal and geothermal energy are expected to provide around 15% of industrial heat demand by 2030, with projections to increase over 40% by 2050 [13]. The production of process heat on-site is responsible for 74% of overall industrial energy consumption. 48 % of this energy is used in high-temperature processes above 400 ºC [14]. Nevertheless, incorporating sustainable resources in this industry is falling behind, as only 14% of total energy usage comes from renewable sources [11].

IEA estimates the need for 520 million tons of low-carbon hydrogen annually to reach Net Zero Emissions goals by 2050 [15]. According to the 1.5 ºC-scenario, the demand for green hydrogen must increase to approximately 15 EJ by 2030 to meet the decarbonization goals in the steel industry, chemical industry, and petrochemical. The UAE Consensus, a significant international agreement established during COP28, outlines the need to increase the global installed electrolyser capacity from 2.9 GW in 2023 to 470 GW by 2030 [2].

In this context, COOPERANT aligns with the global Industrial decarbonisation pathway by enhancing the development of third-generation CSP technologies. For this purpose, COOPERANT develops a high-temperature TES based on a cost-effective combination of sensible and latent heat storage that allows the CSP plant to provide high-temperature heat and power on demand. More specifically, COOPERANT will significantly increase solar source temperatures (~1000ºC) and enhance thermal storage materials (Phase-change materials and solid-state mixtures), which represents a significant advancement over these current standards, thereby improving the overall system efficiency (>42%). Besides, COOPERANT AI

TOOL facilitates CSP-TES integration by improving the management of load and storage. AI TOOL aligns with global climate goals by pursuing sustainable system management that includes novel ways of PV hybridisation.

COOPERANT AI TOOL facilitates CSP-TES integration by enhancing management of load and storage. AI TOOL aligns with global climate goals by pursuing a sustainable system management that includes novel ways of PV hybridisation.

TES integration along with CSP

Developing larger thermal storage capacities is key for CSP-TES integration, especially in small and mid-sized CSP plants. It offers green energy on days with low solar radiation and night hours. Nowadays, Thermal energy storage is about 5-10 times cheaper than electricity batteries. CSP plants with a storage capacity of 6 h are more cost-effectively compared to PV battery systems [13]. Between 2010 and 2023 TES systems have increased their average storage capacity from 3.5 h to 11.7 h [4]. Cerro Dominador project possesses a TES system with a storage capacity of 17.5 h, the highest capacity on a commercial scale [4].

Power Generation Systems and Hybridization

Trends also encompass the development of third-generation CSP technology. This new CSP plant generation enables the operation of thermal energy storage systems at higher temperatures (>600 °C). Currently, commercial thermal energy storage systems operate within a temperature range of 390 °C to 565 °C. Innovative storage configurations and the integration of combined sensible or latent heat systems can enhance these systems beyond energy density and cost efficiency. The advancement of TES systems operating at temperatures over 750 °C enables tower plants to utilize supercritical steam Rankine and supercritical CO_2 Brayton cycles. These innovations can also contribute to the specific amount of synchronous electricity generation to guarantee sufficient grid stability. The USA-based Generation 3 Particle Pilot Plant (G3P3) project, under development, is an example of this new CSP plant generation [16].

Moreover, the latest trends in CSP-TES technologies include hybridization projects integrating CSP-TES systems with either a PV plant or a biomass power station. These hybrid systems imply higher capacity factors and cost-effectiveness by providing uninterrupted electrical generation throughout the day and enhancing the reliability of the transmission grid. The UAE-based NOOR is the world's largest CSP- PV hybrid plant. NOOR I includes a 600 MW parabolic trough field, a 100 MW central receiver tower and a 150 MW PV plant. The Ouarzazate Solar Power Station in Morocco is also one of the largest CSP facilities globally, among the hybrid projects combining PV + CSP. The facility has a capacity of 510 MW, which includes a 72 MW PV plant [14].

Industrial applications: Heat and solar fuels

More and more projects emphasize the potential of CSP plants to deliver high-temperature heat, facilitating the decarbonization of the industrial sector by reducing reliance on fossil fuel-derived heat and implementing innovative preheating techniques in the metallurgical sector. Particularly, the PreMA project (South Africa) uses heat from CSP plants to reduce CO_2 emissions in manganese production via ore preheating [17] . Third-generation CSP technologies will be crucial in supplying industries with the necessary high-temperature heat (>400 °C) to meet the Net Zero scenario objectives by 2050. Ma'aden Solar I, located in Saudi Arabia, ranks among the most ambitious CSP projects in the world for industrial heat production. This pioneering project, under construction, includes a 1.5 GW parabolic trough plant that will provide steam for low-carbon aluminum production [18].

The potential of third-generation CSP-TES systems to generate high-temperature heat can additionally promote the production of cost-effective solar fuels, such as syngas and hydrogen. In this context, Solar-powered water electrolysis technologies are gaining attention as a viable system for green hydrogen production. Solid Oxide Electrolyzer cell is an emerging technology, still not in the commercial phase, that produces hydrogen using high-temperature steam (700-1000 °C) and electricity. This technology has a higher system efficiency (74-81%) compared to Alkaline electrolysis (55-60%) and Proton Exchange Membrane technology (55-70%) [19]. The combination of CSP-TES with SOEC can contribute to achieving IEA's hydrogen production goals by 2050 [15].

2.2 European Strategic Roadmaps

2.2.1 Current EU policies

The incorporation of CSP-TES is part of the REPowerEU initiative, announced in May 2022 in response to the Russian invasion of Ukraine. The strategy seeks to eliminate the EU's dependency on Russian fossil fuels and to face the climate emergency. This plan is funded with €300 billion by the Recovery and Resilience Facility [20]. The acts are summarized as follows (Figure 6):

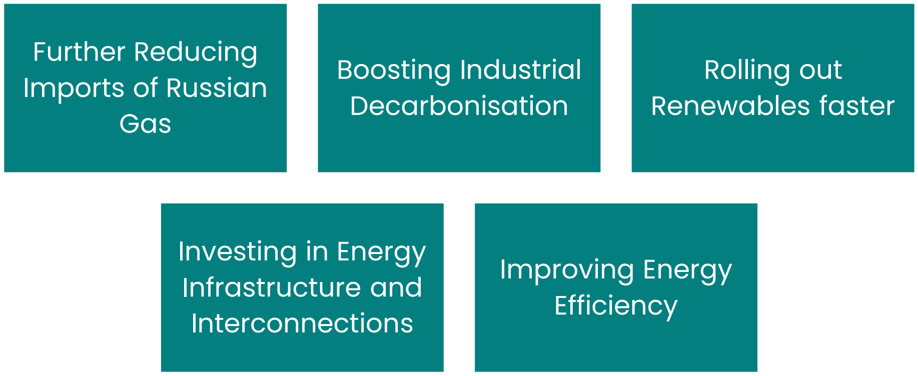

Figure 6. REPowerEU Plan actions. Extracted from [20].Extracted from [20].

The REPowerEU plan forms part of The European Green Deal, which aims to decrease the EU's net greenhouse gas emissions by 55% relative to 1990 levels and achieve carbon neutrality in the European Union by 2050, positioning Europe as the first climate-neutral continent globally. The REPowerEU plan reconsiders the proposals of the "Fit for 55" legislation released in 2021.

As a key element in the “Fit for 55” legislation, on November 20^{th}, 2023, the revised Renewable Energy Directive EU/2023/2413 came into force. The Renewable Energy Directive is the legal framework for developing clean energy across all sectors of the EU economy. This new legislation aims to increase the share of renewables in the EU's overall energy consumption, raising the binding target for 2030 to 42.5%, with the ambition to reach 45%.

On 22^{nd} April 2024, the European Energy Efficiency Financing Coalition was launched. This new initiative unites EU countries, financial institutions, and the Commission at the highest level to establish a long-term, viable funding framework for energy efficiency investments. In the words of the Commissioner for Energy, Kadri Simson [21]:

> “The European Energy Efficiency Financing Coalition will play a pivotal role in scaling up private investments for energy efficiency. The Coalition provides the right framework, both at European level and national level. At the European level, experts work together to develop solutions for the market on energy efficiency; at the national level, new national ‘hubs’ would be created to identify national needs for investments in energy efficiency. In doing so, they would help to deliver on important breakthroughs for the market. All this work will only be possible by Member States, Financial Institutions and the Commission joining forces in a single initiative – the Coalition”.

Adopted in October 2023, the revised SET Plan aims to align the original strategic objectives with the European Green Deal, REPowerEU, and the Green Deal Industrial Plan, specifically the Net-Zero Industry Act. The aims are to accelerate the development and implementation of low-carbon technologies, enhance emerging technologies, and reduce their prices by coordinating regional, national, and European research initiatives and financing innovation projects in the energy sector. It includes specific targets for CSP technologies (Figure 7):

1. **Cost reduction** of electricity provided during periods with low wind, PV or hydropower infeed, to values below 15 c€/kWh in Southern Europe locations by 2025, targeting below 10 c€/kWh by 2030.
2. **Development of the next generation** of CSP/STE technology (NEXTGEN) to achieve at least 3 points of increase in the overall power plant efficiency from the reference value 39.4 % to 42.4 % by 2025.
3. At least one **First of a Kind** (FOAK) integrated in the energy system by 2025, demonstrating either the cost reduction or the efficiency increase.
4. **Thermal energy cost** for industrial process heat applications below 3 c€/kWh by 2030 for the same Southern Europe locations as target 1, with process temperatures higher than 200°C and 25 years' lifetime.
5. **Demonstration** of 24/7 economically viable solar thermal baseload production of green hydrogen and other solar fuels by 2030.

Figure 7. Updated SET Plan strategic targets on CSP. Data from [13].

The CETP is intricately linked to the European Strategic Energy Technology Plan, serving as a strategic initiative to enhance the implementation of the SET Plan's objectives. Initiatives 2 and 3 (Figure 8) are focused on CSP-TES technologies. COOPERANT aligns with these initiatives developing novel green power and storage technologies.

Initiative 2 Enhanced zero emission Power Technologies	**Initiative 3** Enabling Climate Neutrality with Storage Technologies, Renewable Fuels and CCU/CCS

Figure 8. Clean Energy Transition Partnership (CETP) initiatives 2 and 3. Data extracted from [22].

In alignment with the European Green Deal, the Spanish government has included CSP technology in its National Energy and Climate Plans and set out to achieve 4.8 GW total installed capacity by 2030 [14]. Spain is currently the global leader in CSP deployment. This country is at the forefront of installed CSP capacity worldwide (2310 MW) and represents 98 % of the total European capacity. Most of the country's CSP projects, developed in the last decade, include parabolic trough plants. Despite the commitment to 4.8 GW by 2030, there is no commercial-scale CSP project under construction today. Only one hybrid project, Solgest-1, has been announced [23].

Portugal (14 MW), France (9 MW), Italy (6 MW), and Germany (2 MW) are among the few European countries that have developed CSP technologies [24]. In the case of Italy, the CSP 3 Bilancia project was the only EU-based commercial-scale CSP plant under construction in 2023. This project, located in Sicily [14], includes a 4 MW linear Fresnel collector plant combined with a molten salt thermal storage that provides 16 h of storage capacity.

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2.2.2 Key trends at EU level and COOPERANT alignment

In recent years, there has been an increasing focus on the use of CSP-TES technologies for providing heat for industrial operations, local and district heating, and the generation of solar fuels such as syngas or hydrogen. This is illustrated in the current regulatory and policy framework created by the numerous initiatives and agendas published at the EU level. Overall, COOPERANT operates with a structured plan aligned with the EU Green Deal framework. More specifically, Table 2 shows the principle COOPERANT alignments with European programs:

Name of Document	Organisation / Entity	Date of publication	COOPERANT alignments
EU's net-zero emissions target by 2050	European Commission	2019	COOPERANT is important to achieving the 2050 targets. It will provide a renewable energy breakthrough by incorporating game-changing technologies that increase solar efficiency at higher temperatures and pursuing system management (dispatchable power+TES, CSP/PV hybridization, etc.).
SET Plan CSP targets	European Commission	2023	COOPERANT's goals and portfolio of operations will provide an innovative solution for a resilient, sustainable, digital, green, and human-centric competitive CSP.
Clean Energy Transition Partnership (CETP)	Consortium of European countries and research organizations	2022	COOPERANT contributes to CETP objectives 2 and 3 by developing enhanced storage for zero-emission power technologies, facilitating energy transition by boosting RES flexibility.
FIT for 55 Package	European Commission	2021	COOPERANT will develop advancing solar energy technologies and reduce emissions, addressing the significant GHG emissions from the process industries.
REPowerEU Plan	European Commission	2022	Cooperant contributes to REPowerEU Plan by improving energy efficiency and boosting the CSP integration in the energy mix.

Table 2. COOPERANT alignments with key EU level roadmaps and plans.

In addition, numerous previous and ongoing EU-funded projects have concentrated on developing innovative materials and designs for CSP-TES components, higher-efficient Rankine and Brayton power cycles, and heat transfer fluids to enhance the economic viability and sustainability of CSP-TES integration and enable third-generation CSP technologies. In this vein, Table 3 summarizes innovative projects that back up the COOPERANT project and set the baseline for potential further improvements.

Project	Relation to COOPERANT
SUNSON GA: 101083827	SUNSON is creating a novel design for a solar to heat to power system. It integrates an ultra-high-temperature TES system based on phase-change materials that can function at temperatures exceeding 1200 °C to produce dispatchable electricity.
CAPTURE2020 GA: 640905	CAPTURE developed a 300 kWth high-efficiency CSP central receiver plant in southern Spain. Results show the possibility of achieving a 30% peak solar-to-electric energy conversion efficiency using air receiver technologies.
COMPASsCO2 GA: 958418	COMPASsCO$_2$ proposes increasing the efficiency of solar power plants operating with solid particles above 900°C and highly efficient supercritical CO_2 Brayton cycles.
NEXT-CSP GA: 727762	NEXT-CSP included using fluidised crystal particles as a heat transfer and storage medium to boost the operating temperature up to 750 °C in CSP plants.
NEXTOWER GA: 721045	NEXTOWER developed innovative ceramic for high-temperature open volumetric receivers based on novel designs for higher performance above 2000°C.
Sol2Hy2 GA: 325320	Sol2Hy2 focused on developing CO_2-free hybrid water-splitting cycles powered by solar energy exceeding 800°C for producing green hydrogen.
HIDROSOL-PLANT GA: 325361	HYDROSOL-PLANT showed the possibility of producing more economical green hydrogen using solar-thermochemical water splitting at temperatures above 800°C, in contrast to PV-powered PEM or wind systems.

Table 3. EU-funded novel projects in CSP-TES technologies. Data extracted from [25], [26], [27], [28], [29], [30], [31].

3 CSP Technologies

3.1 Overview of primary CSP technologies

Solar concentration systems aim to redirect direct solar radiation, also known as direct normal irradiation (DNI), from a larger concentrator or collector to a smaller receiver, increasing the solar radiation flux on the latter. There is a wide variety of solar concentration systems, which can be classified based on different technical solutions for each component. In the CSP field, the most widely accepted classification divides concentration systems according to the focal shape, as shown in Figure 9 [32]:

- Linear-focus concentrators: These collectors concentrate solar radiation along a line, exhibiting linear symmetry. Such concentrators can be obtained by linearly projecting two-dimensional designs (e.g., linearly displacing a parabola).
- Point-focus concentrators: These concentrators focus solar radiation on a point or small central area, showing symmetry of revolution. This concentrator type can be created by revolving two-dimensional symmetries (e.g., parabolic dishes formed by rotating a parabola around its axis).

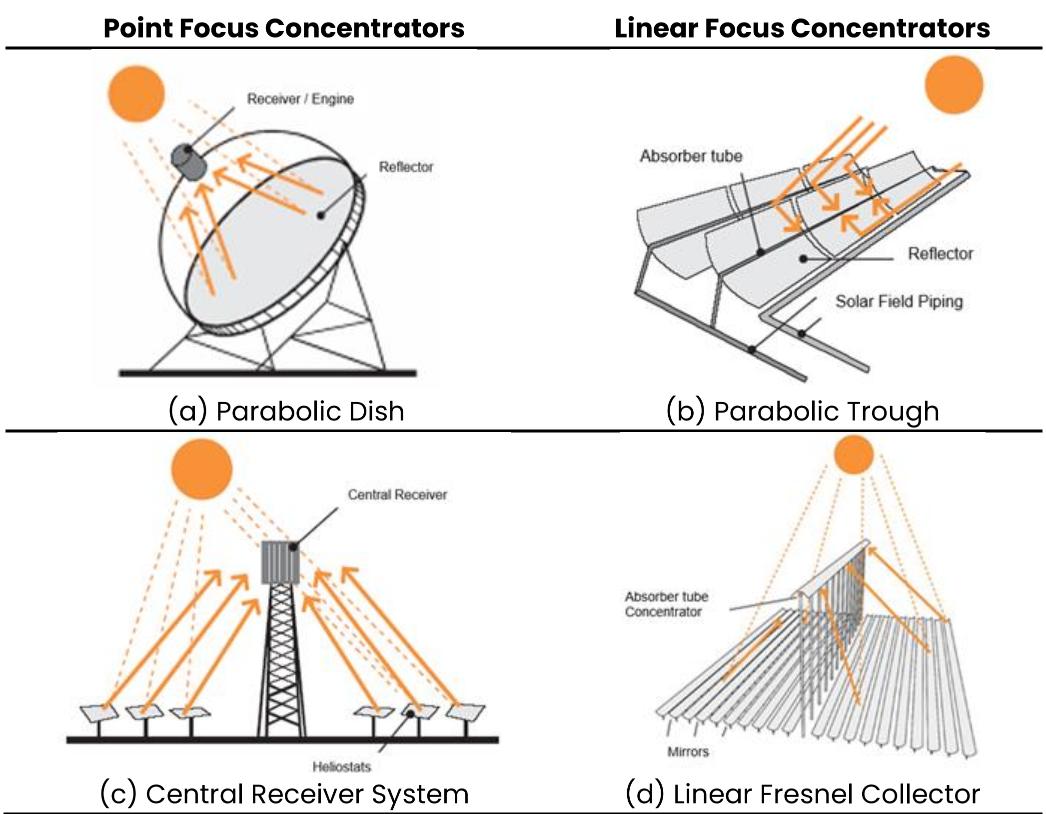


Figure 9. Solar thermal technologies according to their solar focus concentration. Figure extracted from [33].

Funded by the European Union

Solar concentrators with receivers smaller than the aperture primarily absorb direct radiation, making solar tracking systems essential to adjust the concentrator's orientation based on the sun's position. These systems can actively seek the sun using optical detectors for realignment or follow preprogrammed movements with occasional verification [34]. Motorization options include single-axis tracking (elevation) for parabolic troughs (Figure 10) and linear Fresnel concentrators and dual-axis tracking (elevation and azimuth) for parabolic dishes and central receiver systems.

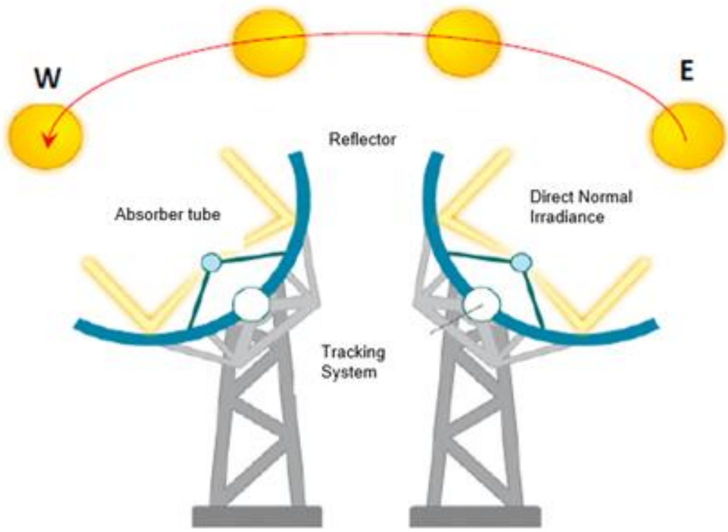


Figure 10. Principles of operation and daily movement of a parabolic trough concentrator with N-S axis orientation [35].

Figure 11 compares solar resource variations for different tracking options, plotting global and direct irradiation against horizontal global irradiation. For annual irradiance below 2000 kWh/(m²·year), single-axis tracking collects less energy than a fixed 30°-inclined collector. The efficiency gain of two-axis tracking over single-axis tracking diminishes with higher irradiance. In high-irradiation regions, tracking systems outperform non-tracking systems in sunlight capture.

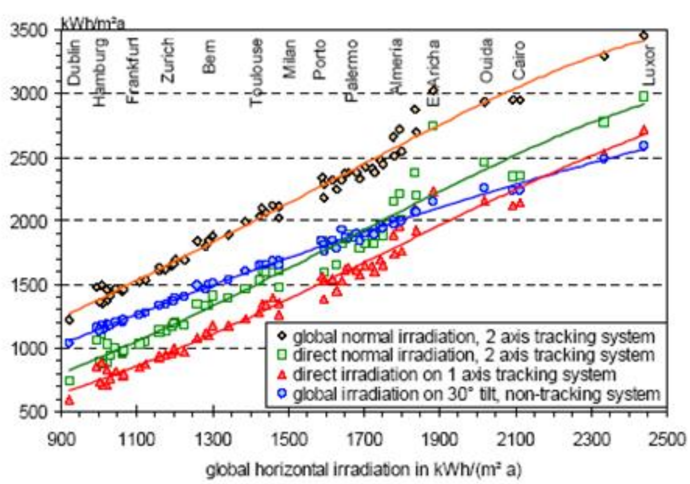


Figure 11. Influence of solar tracking on the final radiation value for different cities [36].

3.1.1 Linear Fresnel Collector

Linear Fresnel reflectors are line-focus systems with single-axis tracking, named after their Fresnel lenses, which reflect and concentrate solar radiation onto the receiver. The receiver, either a single tube with a secondary concentrator or a multi-tube, heats the fluid to convert solar energy into thermal energy. Using long lines of Fresnel mirrors as primary reflectors, the segmented reflective surface creates a parabolic effect, reducing the optical efficiency but lowering production and maintenance costs. Figure 12 shows an example of this type of collector. The mirrors rotate to track the sun, and a mechanical coupling can simplify the tracking system by driving multiple rows with one motor.

Figure 12. Fredesmo loop in Plataforma Solar de Almeria (www.psa.es)

Fresnel systems offer flexible receiver designs:

- Single-tube design: Features a tube (7.5–18 cm diameter) in a cavity with a secondary concentrator and transparent window, creating a quasi-vacuum to reduce convection losses and protect the selective coating.
- Multi-tube design: Simpler, with no vacuum, window, or selective coating. Focuses on cavity shape and tube diameter for optimal heat transfer.

3.1.2 Parabolic Trough

Parabolic trough collectors are line-focus systems with single-axis tracking, named for their parabolic reflective surface. This surface reflects focuses radiation onto an absorber tube along the focal line, heating the fluid to produce thermal energy. The receiver, a metallic tube with a selective coating, is enclosed in a glass envelope with anti-reflective coating, reducing infrared losses. Both the receiver and reflective surface move together (Figure 13), increasing optical efficiency but requiring complex rotary joints [37]. The receiver moves simultaneously with the reflective surface, making the optical efficiency of the reflector-receiver system greater than that of linear Fresnel collector plants. However, it requires rotary joints to connect the moving parts with the fixed parts, complicating both its construction and operation. Widely used globally, parabolic trough technology dominates solar thermal power plants. In Spain, 45 out of 50 operational plants use this technology, with a total capacity of 2222.6 MWe [38].

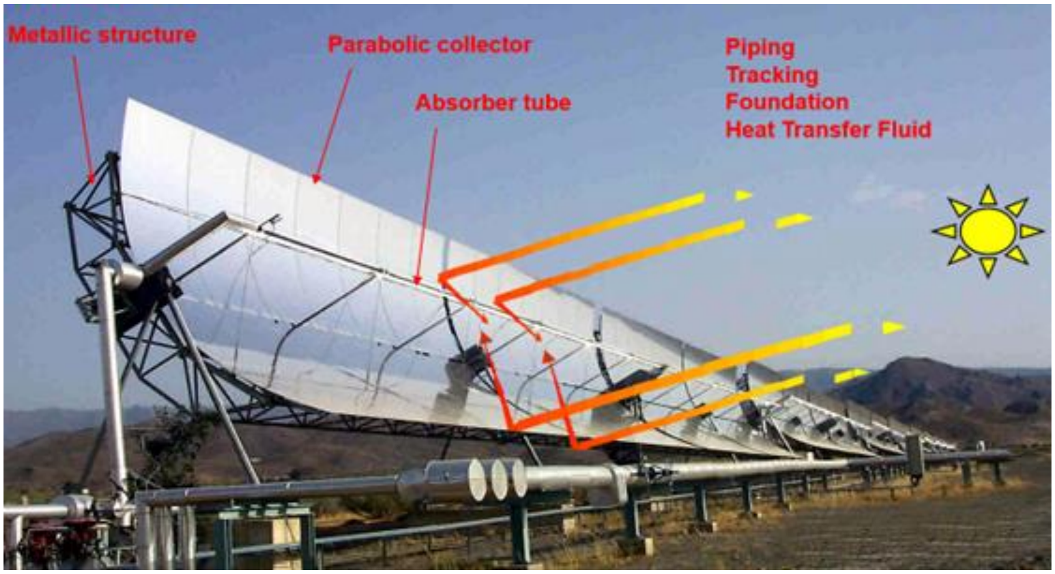


Figure 13. Parabolic trough at Plataforma Solar de Almeria (www.psa.es).

The collector's support structure uses spatial or torque tube techniques, with silver-coated glass mirrors for reflectors, available in thick or thin glass types. The absorber tube transforms concentrated solar energy into thermal energy via a heat transfer fluid. It consists of a metallic tube within a glass envelope, protected from weather and thermal losses. Anti-reflective coatings on the glass improve transmissivity, while a vacuum between the tubes minimizes convection losses. Metallic bellows and getters maintain the vacuum, ensuring high thermal efficiency over time.

3.1.3 Parabolic Dish

Parabolic dishes are point-focus systems with two-axis tracking, using a parabolic reflective surface to concentrate solar irradiation, concentrating onto a receiver at the focal point. These systems achieve the highest concentration ratios and optical efficiency, reaching temperatures over 1500 °C. Primarily paired with Stirling engines for electricity production (Figure 14), they have also been studied with micro-turbines. Their modularity enables distributed energy production, allowing operation with solar energy, fossil fuels, or biomass for continuous supply [39].

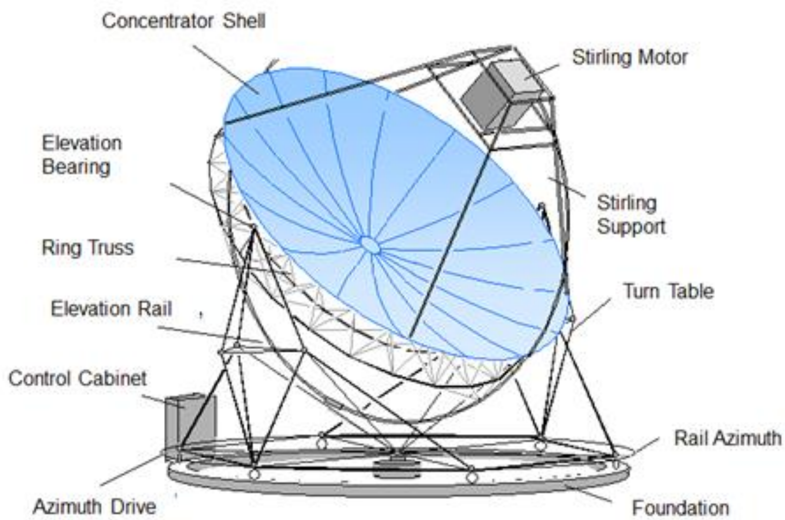


Figure 14. Basic elements of a Stirling dish system. Eurodish prototype [40].

Parabolic dishes convert solar radiation to electricity with average daily efficiencies of 25% and peaks of 30%, while Stirling engines achieve 30–40% efficiency [32]. Receivers, typically cavity type, transfer heat to the working fluid via tube panels or heat pipes using liquid metals like sodium.

Despite promising prototypes, commercial success has been limited. Projects by SES, Tessera Solar, and Infinia failed due to operational issues, and no Stirling dish plants were operational since 2012. Current research focuses on thermochemical cycles, gas micro-turbines, and cost reductions in optics and tracking systems.

3.1.4 Central Receiver System

Central receiver systems are point-focus systems with two-axis tracking, where heliostats concentrate solar radiation onto a receiver at the focal point. The receiver transfers the energy to a working fluid (water, air, salts, particles), which can be used for electricity generation or process heat applications. The thermal energy of the fluid can be converted into electrical energy through a power cycle, either a Rankine cycle or a Brayton cycle, or to process heat applications and solar fuel production.

The heliostat field is the most expensive component, and its design is influenced by the receiver's morphology, which can be:

- Circular field: Associated with external cylindrical receivers, with heliostats placed on both sides of the tower (e.g., Solar One, Gemasolar).
- Northern field: Associated with cavity-type receivers, with heliostats in the northern part (e.g., PS10, PS20).

Figure 15 presents the two main patterns adopted for commercial solar fields. PS10 with around 600 heliostats of 120 m^2, and Gemasolar with 2650 heliostats of 115 m^2.

PS10 north field (abengoasolar.com)

Gemasolar solar field (sener.es)

Figure 15. Examples of commercial solar field patterns.

High solar irradiation (300–1000 kW/m²) enables operation at high temperatures and integration into efficient cycles, with hybrid operation and thermal storage options for high-capacity electricity generation.

Though many tower plant projects have been tested, only a few have led to commercial plants. Table 4 lists the main projects developed for R&D purposes. As can be seen, they are characterized by being small-scale demonstration systems. Most operated during the 1980s, with the exception of the TSA and Solar Two plants, which had their operational experience in the 1990s. These experiences have demonstrated the technical viability of tower power plants.

Project	Country	Power, MWe	HTF	Storage	Type	Starting year
NSTTF	USA	5	-	-	R&D	1978
SSPS	Spain	0.5	Liquid sodium	Sodium	R&D	1981
EURELIOS	Italy	1	Steam	MS/Water	R&D	1981
SUNSHINE	Japan	1	Steam	MS/Water	R&D	1981
Solar One	USA	10	Steam	Oil/Rocks	R&D	1982
CESA-1	Spain	1	Steam	MS	R&D	1982
MSEE/ Cat B	USA	1	Molten salts (MS)	MS	R&D	1983
THEMIS	France	2.5	Molten salts	MS	R&D	1984
SPP-5	Russia	5	Steam	Water/Steam	R&D	1986

TSA	Spain	1	Air	Air/Rocks	R&D	1993
Solar Two	USA	10	Molten salts	MS	R&D	1996
SOLGATE	Spain	0.3	Pressurized air	-	R&D	2001
Weizmann	Israel	0.5	Pressurized air	-	R&D	2001
Jülich	Germany	1.5	Ambient air	Air/Rocks	R&D	2009
CSIRO NSEC	Australia	0.5	-	-	R&D	2010
Dahan	China	1.5	Steam	-	R&D	2011
Proteas	Cyprus	0.0015	Molten salts	MS	R&D	2014
IMDEA-Energia	Spain	0.25 thermal	Air	-	R&D	2016

Table 4. Development of R&D central receiver plants worldwide.

Thanks to CIEMAT's data platform, real-time operational data is readily accessible [41, 42]. Currently, 26 tower plants are operational, with 4 more under construction, totalling 1724 MWe. Annex 1 presents the main details of these plants, and more data are available in https://cspdata.com/

USA focused on solar-only power towers with molten salts and large thermal storage, like the 10 MWe Solar Two project built in Barstow, California, from 1996 to 1999. Currently, the Generation 3 program in the USA is focusing on future power tower plants that use particles as the primary heat transfer fluid for both the receiver and thermal energy storage, while employing supercritical CO_2 to drive sCO_2 Brayton cycles.

In Europe, two operating schemes were developed: tubular receivers using steam or molten salts, and volumetric receivers using air for higher temperatures and simplicity. Spain led the world in commercial deployment of tubular receivers, with PS10 being the first to use steam as a heat transfer fluid and Gemasolar being the first with high-temperature central receiver technology using molten salts and extended thermal storage.

Central receiver plants offer flexibility with different receiver types, including external, cavity, volumetric, and fluidized bed receivers, depending on the working fluid used: water/steam, molten salt, air, or particles. The following sections briefly present the three technologies, at either commercial or pre-commercial levels, based on the fluid used.

3.1.4.1 Water / steam receiver

Two experimental plants illustrate water/steam receiver operation: Solar One in the US and CESA-1 in Spain, which led to the operational schemes of current commercial plants like PS10, PS20, and Ivanpah.

Solar One

Solar One plant operated as a pilot plant from 1982 to 1984 and used an external receiver to produce steam at 516°C and 100 bar, generating 10 MWe with an absorption capacity of 42 MWth. The system faced challenges such as solar flux variations and thermal fatigue, requiring specialized control algorithms and minimizing welded joints to prevent leaks. Further details can be found in the literature [43].

CESA 1

The CESA-1 plant in Almería, Spain, operated in its initial configuration from 1983 to 1986. It used a cavity-type receiver producing steam at 525°C and 110 bar, with an absorption capacity of 6.7 MWth. The cavity design minimized heat loss by ensuring that radiation was absorbed by the tubes after multiple reflections [44].

Commercial PS10 / PS20

The PS10 and PS20 plants use water/steam as the working fluid under saturated conditions. The PS10 receiver, with a 51.9 MWth capacity, provides saturated steam at 257°C and 45 bar, with peak efficiency above 92%. The PS10 plant is the world's first solar power tower plant to generate electricity commercially with a nominal capacity of 11 MWe [45]. The system supplies steam to a turbine for electricity and stores thermal energy in pressurized tanks, providing short-term storage for approximately 30 minutes at 50% turbine load [46]. However, steam pressure limitations and reheating challenges reduce efficiency and storage time. Figure 16 depicts the scheme of PS10.

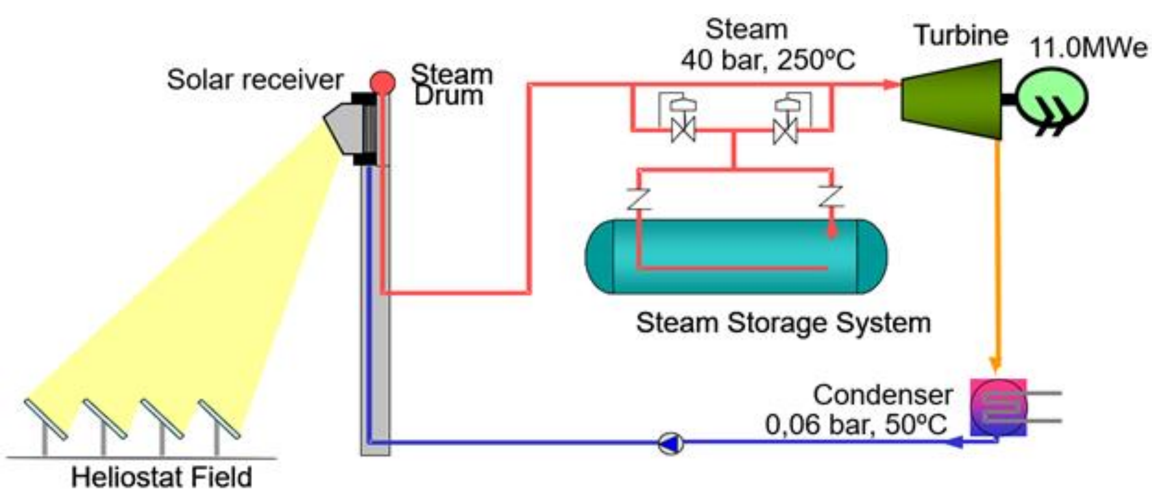


Figure 16. Scheme of a central receiver system using water/steam as the working fluid. Plant type PS10.

3.1.4.2 Molten nitrate salt receiver

Two key plants illustrate molten salt receiver operation: Solar Two in the USA and Themis in France, both of which influenced commercial plants like Gemasolar and Tonopah.

Solar Two

The Solar Two plant operated for 14 months between 1988 and 1989 to perform testing and evaluation of molten salt technology with a receiver designed to achieve an outlet temperature of 565 °C. The system used a nitrate salt mixture (60% $NaNO_3$, 40% KNO_3) and absorbed up to 42.2 MWth to produce 12.8 MWe. Figure 17 shows the details of the panels and the receiver of the Solar Two plant. Salt flow was divided into two serpentine circuits, mitigating daily meteorological variations. The steam generated in the steam generator reached a temperature of 535 °C and a pressure of 100 bar [47].

Figure 17. Solar Two receiver. Figure extracted from [47].

Themis

It used a cavity-type receiver with Hitec molten salt (53% KNO_3, 40% $NaNO_2$, and 7% $NaNO_3$) as the heat transfer fluid. The receiver had three active panels and two additional panels on the roof and floor, with molten salt flowing through two parallel circuits, each with multiple passes, reducing mass flow and heat transfer efficiency further from the central area.

Commercial Gemasolar

The Gemasolar power tower plant employs Solar Salt [48] as the working fluid with an external cylindrical receiver, similar to Solar Two's design. In Gemasolar, salts are pumped from a cold tank (290 °C) to the receiver, where they reach 565 °C before being stored in a hot salt tank for steam generation (Figure 18). This mixture, with high thermal conductivity and heat capacity, supports both heat transfer and storage, enhancing turbine utilization and justifying the cost of increased storage capacity up to 15 hours. The receiver was developed based on experience from tests conducted at the PSA as part of a collaboration agreement between SENER and CIEMAT.

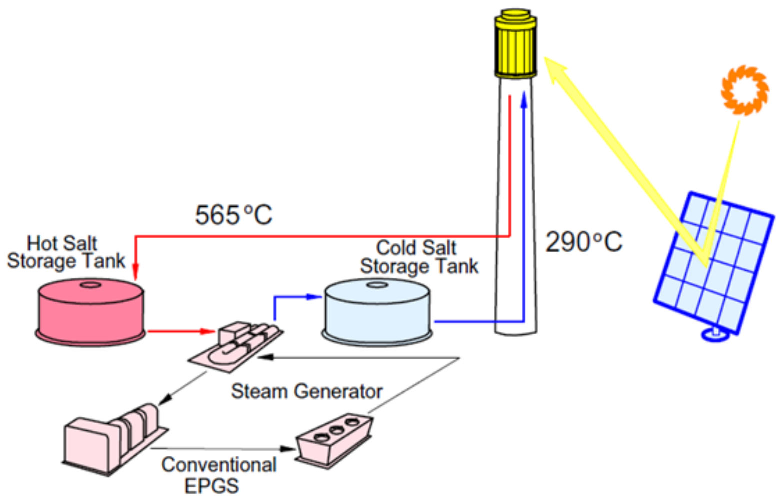


Figure 18. Scheme of a central receiver system using molten nitrate salts as working fluid. Plant type Gemasolar. Figure extracted from [49].

3.1.4.3 Volumetric receiver

A volumetric receiver uses a porous absorber, made of metallic or ceramic materials, through which air flows. Metallic materials can operate between 800-1000 °C, while ceramics can withstand 1200-1500 °C [50]. The absorber transfers thermal energy to the air, which is directed to a steam generator to produce electricity via a Rankine cycle as presented in Figure 19. The air can be stored, reheated, and recirculated or used directly in a gas turbine for electricity generation, requiring pressurized receivers with a quartz window for high temperature and pressure.

However, since achieving high efficiencies in thermodynamic cycles requires high working temperatures for the HTF, ceramic materials, especially foams and honeycomb structures, have been the focus of extensive research for the receivers. COOPERANT will address the thermal, hydrodynamic and experimental analysis of novel ceramic morphologies, exploring both random or periodical patterns. The baseline configuration will be the Voronoi topology, enhances the state of the art in open volumetric receivers [51].

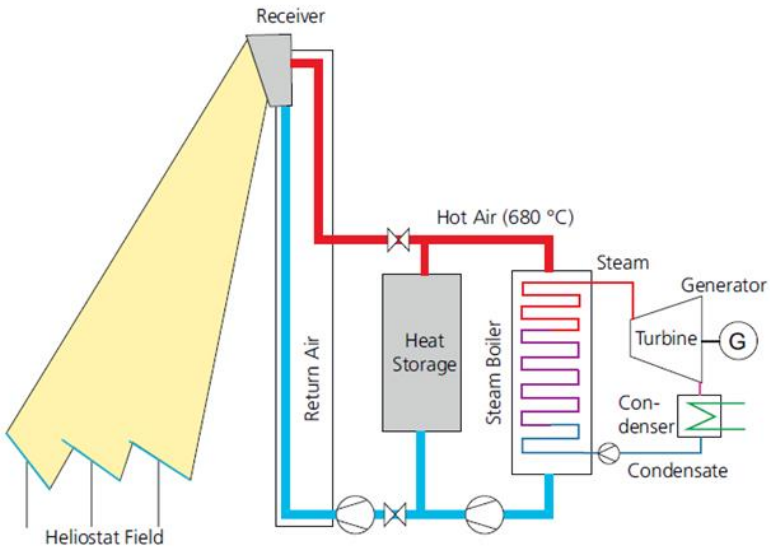


Figure 19. Scheme of a central receiver system using air as the working fluid. Plant type TSA (www.psa.es)

<u>Jülich plant</u>

The Jülich Solar Tower in Germany, after 20 years of R&D, serves as an experimental facility to develop air receiver technology [52]. The plant (Figure 20), operational since April 2009, features 2150 heliostats and a receiver with a 23 m² aperture at the top of a 60-meter tower. It uses silicon carbide modules in the receiver to heat air for steam generation. The system includes a thermal energy storage tank and recirculates cool air back to the receiver. The plant's total budget was €23 million, with a 1500 kW power block driven by steam generated at up to 500 °C [53].

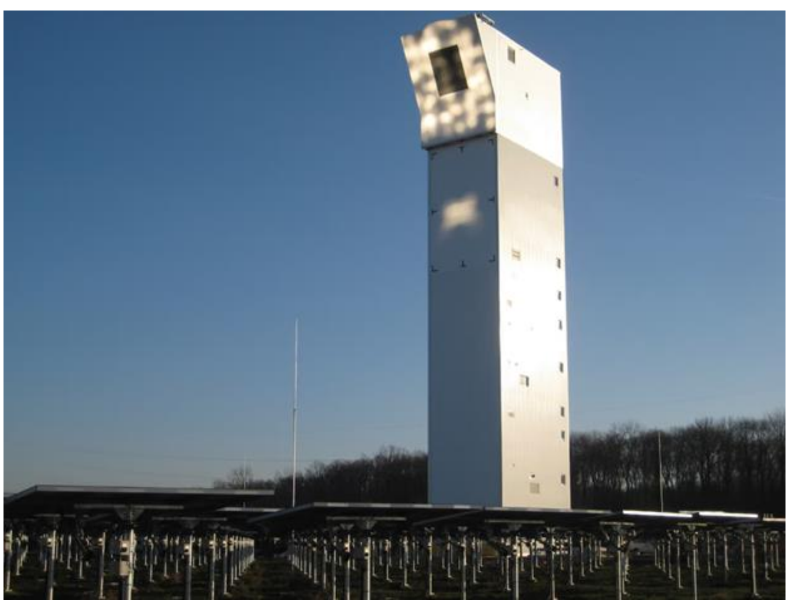


Figure 20. View of the solar field and tower in Jülich (www.solarpaces.org)

The Jülich plant operates as follows: Air is heated to 700 °C in the receiver and used to generate steam in a heat exchanger. The steam, at 485 °C and 27 bar (up to 500 °C and 100 bar), powers a 1500 kW power block. The thermal energy storage system, with a porous ceramic filler, operates as a thermocline. Cool air, exiting the steam generator and storage system at about 100 °C, is recirculated to the receiver. All equipment, except the cooling system, is housed in the tower.

3.1.4.4 Particle receiver

Particle receivers are being developed to achieve higher temperatures (above 700 °C), enable cost-effective direct storage, and improve efficiencies for CSP, thermochemical reactions, and process heat applications. Solid particles, heated by concentrated sunlight, are stored in an insulated tank and used to transfer heat to a secondary working fluid (e.g., steam, CO_2, or air) for the power cycle (Figure 21). These receivers can exceed 1000 °C and reduce storage costs by using inexpensive media, such as sand-like particles. They are scalable, with applications ranging from 10 to 100 MWe, and can be direct (irradiating falling particles) or indirect (heating particles in tubes).

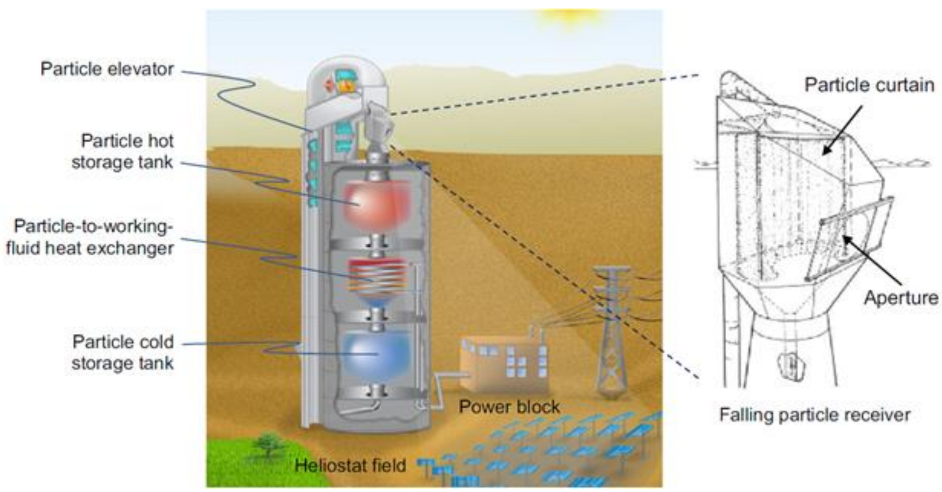


Figure 21. Particle receiver with thermal energy storage. Figure extracted from [54]

Gen 3 Particle Pilot Plant (G3P3)

The G3P3, funded by the U.S. Department of Energy with a $25 million budget, aims to test a next-generation central receiver system at the National Solar Thermal Test Facility in New Mexico. This system will heat particles to over 700 °C, store energy for at least six hours, and heat a secondary fluid (supercritical CO_2 or air), all while demonstrating the capacity to meet cost and performance objectives (Figure 22). Preliminary models indicate that particle-based CSP can meet the SunShot goal of $0.06/kWh with reduced storage costs. The project will achieve over 2000 hours of testing, demonstrating thermal duties of at least 1 MWth and showcasing both steady-state and transient operations, with a path toward commercialization.

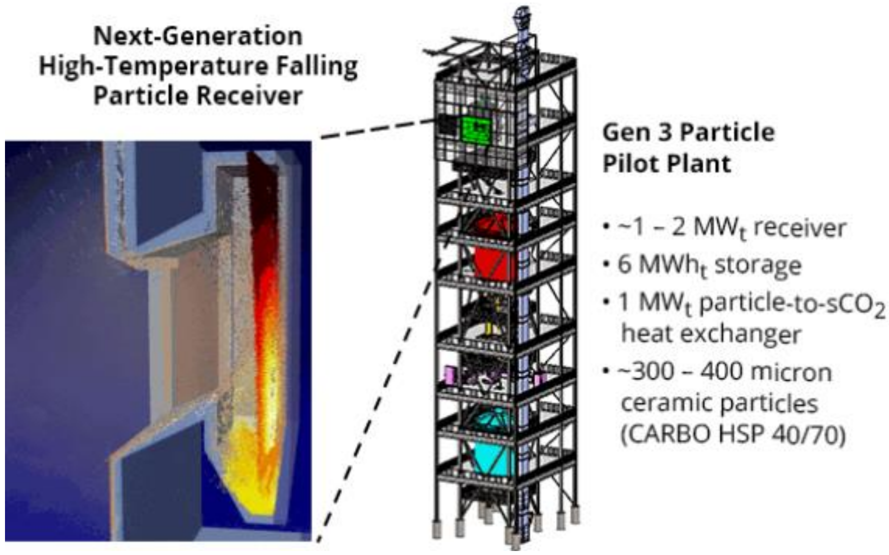


Figure 22. Scheme of G3P3 particle receiver (www.energy.sandia.gov)

3.2 Key performance metrics and operational characteristics

This section presents key performance metrics and operational characteristics in two parts. The first part outlines metrics for the main CSP technologies: Linear Fresnel Collectors (LFC), Parabolic Trough Collectors (PTC), Parabolic Dishes (PD), and Central Receiver Systems (CRS), also known as power towers. The second part focuses specifically on Central Receiver Systems, detailing metrics based on the type of HTF employed: water/steam, molten nitrate salts, air, and particles. All metrics draw on authoritative sources from internationally recognized institutions, including SolarPACES, the IEA, the IRENA, and National Renewable Laboratory (NREL) [55, 56, 57], also the main research studies [58, 59, 60, 61].

3.2.1 Performance metrics by CSP Technology Classification

Understanding these key performance metrics is crucial for assessing the potential viability and performance of different CSP systems. The following metrics provide a basis for evaluation:

- Thermal efficiency: A measure of how effectively a CSP system converts solar energy into usable thermal energy.
- Levelized Cost of Electricity (LCOE): A crucial economic metric reflecting the average cost of electricity generated over the plant's lifetime, while data on certain economic metrics such as and operational performance may be limited due to the small number of operational plants.
- Capacity factor: Indicates the actual output over a period compared to the maximum possible output, influenced by operational conditions and energy storage capabilities.

- Reliability and availability: Reflects the operational uptime and the ability to maintain consistent output, which can be affected by maintenance, weather, and system design.
- Thermal energy storage capacity: Determines the extent to which the system can store energy for use when sunlight is not available, impacting dispatchability and integration into the energy grid.
- Land use: The area required per unit of installed capacity, influencing site selection and overall feasibility.

CSP technologies, including LFC, PTC, PD, and CRS, exhibit varying costs per megawatt (MW) of installed capacity and per megawatt-hour (MWh) of energy produced. These costs are influenced by factors such as technology maturity, scale, location, and integration with thermal energy storage (TES). However, it is not possible to disregard the cost per technology as the number of available projects and publicly available information is too low and inaccessible. IRENA reported that the weighted average LCOE of CSP plants fell by 47% between 2010 and 2019, from 0.346 €/kWh to 0.182 €/kWh. However, some recent LCOE values in the range of 0.07 – 0.12 €/kWh are also reported with very specific operational conditions.

The following Table 5 summarizes the main key performance indicators (KPI) for CSP technologies, providing a comparative overview of their strengths and challenges:

Metric	LFC	PTC	PD	CRS
Solar Collector	Line focus	Line focus	Point focus	Point focus
Solar Receiver	Fixed in focal line	Mobile with collector	Mobile with collector	Fixed in focal point
Max Slope for Solar Field	< 4%	1-2%	Up to 10%	2-4%
Concentration Ratio	10-40 (max 60)	70-80	1000-3000	200-1500
Temperature Range	250-390°C	400-550°C	Up to 750°C	> 1000°C
Annual Solar-to-Electric	8-13%	15-16%	20-25%	16-20%
Peak Solar-to-Electric	18%	20%	30%	35%
Heat Transfer Fluid	Water/steam (molten salt in hybrid designs possible)	Synthetic oil or molten nitrate salts	Stirling engine or ORC	Water/steam, molten nitrate salts
Thermal Energy Storage	Limited feasibility	Established; up to 15 hours	Limited feasibility	Well-established; up to 18 hours

Typical Plant Capacity	10-200 MW_e	10-300 MW_e	10-25 kW_e	10-200 MW_e
Annual Capacity Factor	22-24% (no TES)	25-28% (no TES), 29-43% (with TES)	25-28% (no TES)	25-28% (no TES), 29-55% (with TES)
Land Requirements	0.8-2 ha/MW; 2.4-4 ha/GWh	1.6-4 ha/MW; 3.2-6 ha/GWh	2-6 ha/MW; 4-8 ha/GWh	1.2-4 ha/MW; 2.8-4.8 ha/GWh
Power Conversion Cycle	Saturated steam Rankine (260°C, 50 bar)	Superheated steam Rankine (380-540°C, 100 bar)	Stirling Engine	Superheated steam Rankine (540°C, 100-160 bar)
Water Requirements	3 m^3/MWh (wet), 0.2 m^3/MWh (dry)	3 m^3/MWh (wet), 0.3 m^3/MWh (dry)	0.05-0.1 m^3/MWh (mirror washing)	2-3 m^3/MWh (wet), 0.25 m^3/MWh (dry)
Capital Cost	Not available	4700-7300 USD/kW (no TES, OECD); 3100-4050 USD/kW (non-OECD)	Higher cost per unit; limited data for comparison	6400-10700 USD/kW (with TES)
LCOE	Not available	0.26-0.37 USD/kWh (no TES); 0.22-0.34 USD/kWh (with TES)	High cost per unit; not widely available	0.2-0.29 USD/kWh (TES 6-7.5h); 0.17-0.24 USD/kWh (TES 12-15h)

Table 5. Representative features of the main CSP technologies.

3.2.2 Performance metrics for Central Receiver Systems by Heat Transfer Fluid

CRS is recognized as a leading technology for enhancing plant efficiency and reducing energy production costs. As one of the most promising and cost-effective CSP technologies, CRS systems can achieve high operating temperatures and efficiencies, supporting diverse applications ranging from power generation to industrial heat. Their versatility lies in the use of different heat transfer fluids—water/steam, molten nitrate salts, air, and particles—each offering unique advantages in terms of thermal storage capacity, operating temperature range, and integration potential.

The effectiveness and suitability of CRS receiver technologies hinge on these important performance metrics:

- Thermal efficiency: Key for overall plant efficiency and influenced by receiver design, heat-transfer fluid, and working fluid temperatures.
- Storage efficiency and capacity: Important for dispatchability; varies widely by technology and the type of thermal storage used.
- Capacity factor: Reflects how well the plant can produce power relative to its design capacity, heavily influenced by storage and receiver efficiency.
- LCOE: A central metric for all CSP technologies, with current targets often aiming for < 0.06 €/kWh to be competitive with conventional power sources.
- Durability and operational reliability: Receiver longevity, resistance to corrosion, thermal stress handling, and maintenance demands impact overall plant viability.

The analysis of these metrics underscores CRS's pivotal role in advancing CSP applications. By aligning technical performance with cost-reduction goals, CRS systems remain at the forefront of efforts to deliver clean, reliable, and competitive solar energy. Each receiver configuration offers specific benefits and challenges. Water/steam receivers enable direct power generation, molten nitrate salts provide robust thermal storage, air receivers facilitate high-temperature operations, and particle receivers push the boundaries of efficiency and scalability.

Table 6 summarizes the main KPI of the central receiver systems with the four main heat transfer fluids: water/steam, molten nitrate salts, air, and particles.

Receiver Type	Water/Steam Receivers	Molten Nitrate Salt Receivers	Volumetric Receivers	Particle Receivers
Temperature Range	Up to ~550 °C	290 °C to 565 °C	800 °C to 1500 °C (depending on materials)	Above 700 °C, potential to exceed 1000 °C
Pressure	High-pressure steam (~100 bar or more)	N/A	N/A	N/A
Receiver Thermal Efficiency	80% to 90%	85% to 90%	70% to 80%	85% to 90%
Annual Solar-to-Electric Efficiency	15% to 20%	18% to 22%	15% to 20%	Potentially exceeding 20%
Thermal Energy Storage	Limited without additional storage; uses auxiliary systems	Excellent; two-tank molten salt storage (cold tank at ~290 °C, hot	Available regenerative heat storage systems using	Direct particle storage in insulated tanks for low-cost, high-

		tank at ~565 °C)	porous materials	temperature thermal energy storage
Annual Capacity Factor	Approximately 25% to 35%	40% to 60%	Generally around 30% to 45%	Potential exceeding 50%
Power Conversion Cycle Efficiency	Moderate, ranging from 35% to 40%	Higher efficiency (~40-43%)	High efficiency possible with integration in gas turbines or Brayton cycles; efficiency depends on system integration	High potential efficiencies with advanced cycles like supercritical CO_2 or ultra-supercritical steam
Operation	Well-suited for direct steam generation, ideal for smaller-scale or lower-temperature applications	Common in commercial plants, provides stable dispatchable power generation, storage up to 15-18 hours	Suitable for high-temperature industrial applications, requires air as heat transfer fluid, often under atmospheric or pressurized conditions	Suitable for large-scale applications with potential for plants exceeding 100 MWe, capable of supporting dispatchable power and process heat applications
Challenges	Requires reliable and fast-response control systems to manage thermal loads and prevent stresses	Maintenance challenges with salt freezing and corrosion management	Managing heat losses and maintaining efficiency; material durability under high thermal loads	Efficient particle handling and containment; complex design for even heating; dust management and wear on particles

Table 6. Representative features of the main CRS by heat transfer fluid.

3.3 Adaptability of CSP systems to diverse conditions

CSP systems are highly adaptable, enabling efficient operation across diverse environmental conditions. The performance of CSP plants is influenced by the availability and consistency of solar resources, geographic location, local climate and seasonal variations. To address these challenges, CSP plants employ advanced technologies such as tailored receiver types, HTFs, and TES systems, and can be adapted to meet the energy demands of regions with high DNI as well as areas with more variable or lower solar resources. These adaptations make CSP a versatile and reliable renewable energy solution for a variety of applications [62, 63, 64, 65, 66]. CSP systems are built with materials capable of enduring extreme temperatures, both hot and cold, ensuring resilience in harsh climates. By incorporating flexible energy storage and hybrid systems, CSP can provide reliable and continuous power, contributing to grid stability and supporting renewable energy integration.

3.3.1 High solar irradiance regions

CSP systems perform properly in regions with high DNI, such as the deserts of the southwestern United States, northern Africa, and the Middle East (see Figure 23). These areas typically have DNI values ranging from 2,000 to 2,800 kWh/m²/year, enabling CSP plants to achieve high thermal efficiencies and generate significant power. In these regions, external receivers with molten salt HTFs are particularly suitable due to their ability to withstand high temperatures and efficiently store thermal energy.

3.3.2 Medium or variable solar resource regions

In regions with lower or variable DNI (e.g., 1,500 kWh/m²/year), such as parts of southern Europe or coastal areas, CSP plants can still provide substantial power through hybridization with other energy sources (e.g., natural gas, biomass) and integration with TES (see Figure 23). Cavity receivers and molten salt systems are well-suited to these conditions, as they minimize heat losses and maintain efficiency during periods of fluctuating solar input. Additionally, air-based volumetric receivers can be employed for medium-temperature industrial processes.

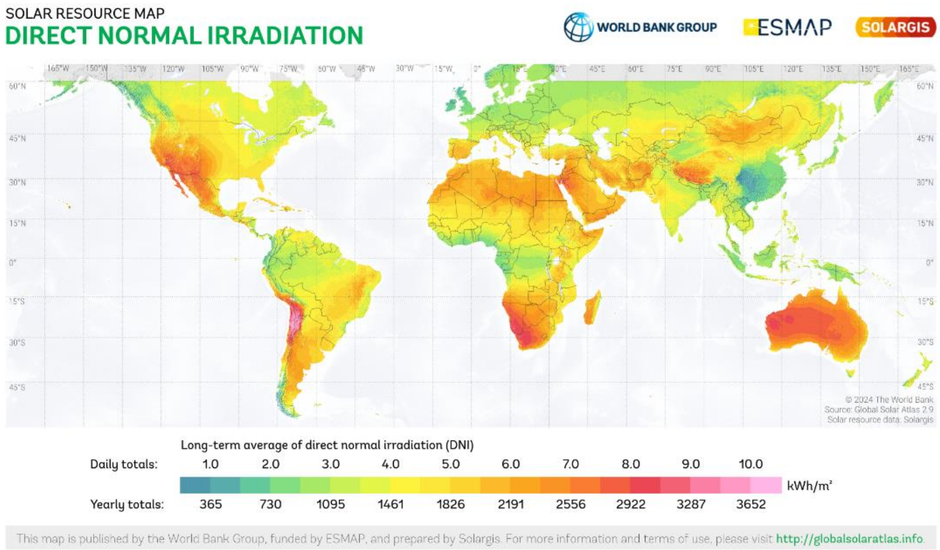


Figure 23. DNI resource worldwide (solargis.com)

3.3.3 Weather resilience and extreme temperatures

Short-term weather variations, such as cloudy or stormy conditions, are mitigated through TES systems like molten salt or thermocline systems. For example, the Crescent Dunes plant in Nevada and the NOOR 3 plant in Morocco use molten salt storage to maintain power output during sunlight interruptions. Volumetric receivers with air or gas HTFs also exhibit strong resilience to transient weather conditions due to their rapid heat absorption and discharge capabilities.

Besides, CSP plants are engineered to withstand extreme operational temperatures. In hot climates, receivers and storage systems operate efficiently at 500°C to 600°C, while specialized materials, such as ceramics and alloys, prevent performance degradation. In colder climates, insulated storage systems and hybridized configurations ensure reliable operation during freezing temperatures. For ultra-high-temperature applications, particle receivers with solid HTFs provide robust thermal stability and adaptability.

3.3.4 Receiver types and heat transfer fluids

Receiver technologies and HTFs are selected to match environmental conditions and specific application requirements:

- External receivers: Effective in moderate to high DNI regions, commonly paired with molten salts or water/steam systems.
- Cavity receivers: Adapted to variable solar input, minimizing heat loss.
- Volumetric receivers: Ideal for high-temperature industrial processes, with air or gases as HTFs.

- Particle receivers: Designed for extreme temperatures, enabling thermochemical and solar fuel applications.

HTFs also play a pivotal role in determining system adaptability:

- Molten salts: Provide high thermal stability and compatibility with TES, suitable for high-temperature operations.
- Water/Steam: Widely used in direct steam generation for power cycles.
- Air/Gases: Enable rapid heat transfer for high-temperature processes.
- Solid particles: Function as both HTF and storage medium, enduring extremely high temperatures.

Table 7 illustrates the suitability of receiver type and HTF under various weather conditions, using a scale from 1 to 3. 3: Highly suitable; 2: Moderately suitable; 1: Least suitable.

Receiver / HTF	High DNI regions	Medium / Variable DNI regions	Weather resilience	Extreme hot temperatures
External	3	2	1	3
Cavity	3	3	3	3
Volumetric	3	2	3	3
Particle	3	1	2	3
Molten salts	3	3	3	3
Water/steam	3	2	2	2
Air	3	3	3	3
Solid particles	3	2	3	3

Table 7. DNI resource worldwide (solargis.com).

4 Thermal Energy Storage (TES) systems in CSP Applications

The integration of TES in CSP applications is a key technology to bridge supply gaps caused by the intermittent nature of solar energy. By storing thermal energy used for electricity generation, CSP plants can provide continuous power during both daytime and evening hours.

4.1 Types of TES and their relevance to CSP applications

CSP technologies focus sunlight using mirrors or lenses to generate high-temperature heat that heats a thermal fluid. The heat generated can be used directly for electricity generation or stored in TES systems for later use. TES enables CSP systems to maintain their capacity even during low-sunlight periods, ensuring a reliable energy supply.

TES systems can be broadly divided into three types: sensible, latent, and thermochemical storage, specifically for CSP applications the identified technologies are gathered in Figure 24. TES systems differ in energy conversion mechanisms, capacity, efficiency, development level and costs. The choice of TES type depends heavily on CSP requirements, location, and cost targets. The two most common CSP technology configurations are parabolic trough and tower power plants (as explained in section 3), both designed for efficient TES integration.

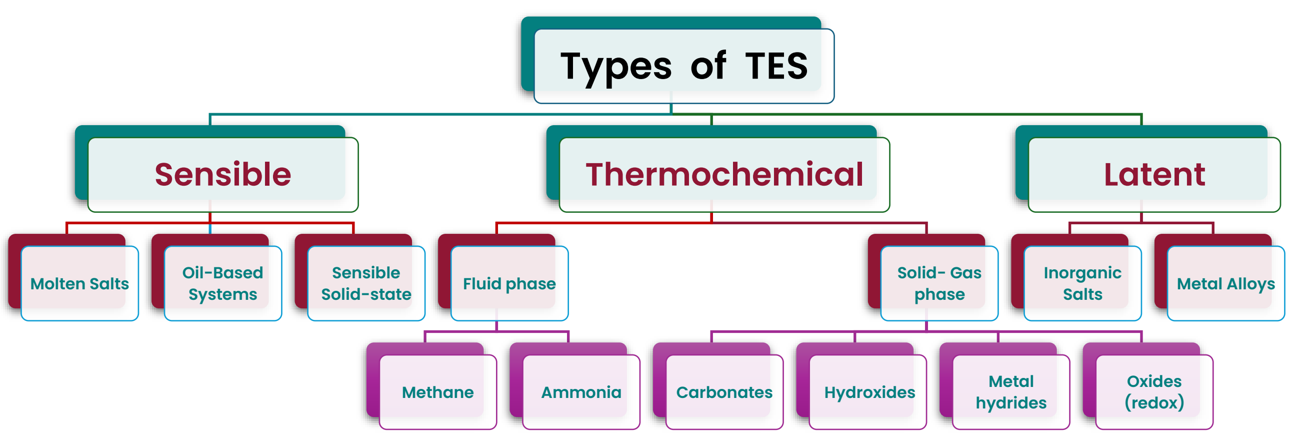


Figure 24. Overview of different TES technologies in CSP.

4.1.1 **Sensible Heat Storage**

Sensible heat storage is the most widespread form of TES technology and relies on changing the temperature of a storage medium to store thermal energy. Common media include water, oil, and especially molten salts. The storage capacity of a sensible heat material is directly proportional to its density, specific heat, and the temperature difference it undergoes during storage.

4.1.1.1 Molten Salts

Commonly used in CSP systems are mixtures of sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3), often in a 60%/40% weight ratio. This mixture, known as "Solar Salt," is stable in air, has a low vapour pressure, and is non-toxic and non-flammable. These molten salts can operate over a wide temperature range, typically from 260 °C to approximately 565 °C (decomposition point), which is the temperature range used in most CSP systems. They start to crystallize at around 238°C and solidify at 221 °C although they are prone to corrosion and require regular maintenance. State-of-the-art is two-tank molten salt systems that utilize large quantities of $NaNO_3$ and KNO_3 (typically several tens of thousands of tons per TES in a CSP plant). These salts are either from natural resources (e.g. Atacama Salt Lake in Chile) or produced with nitrogen from the air via the energy-intensive Haber-Bosch process.

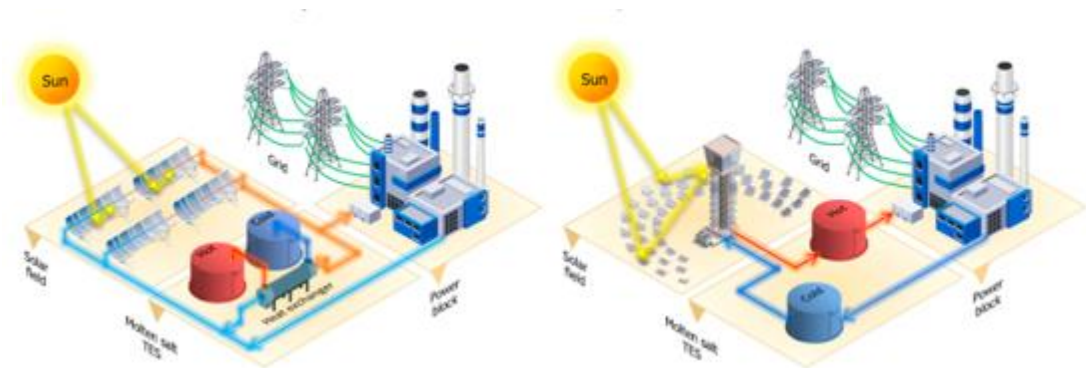


Figure 25.Diagram of a PTC (left) and CRS (right) technology CSP plant, each with a dual-tank molten salt TES system. Figure extracted from [67].

Since 2020, researchers have focused on improving thermodynamic properties, reducing costs, enhancing thermal stability, and overcoming technical challenges related to the corrosion and operational efficiency of molten salts. Recent research has explored ternary and quaternary nitrate salt mixtures as improved heat transfer fluids for CSP plants. The addition of lithium nitrate ($LiNO_3$) and calcium nitrate ($Ca(NO_3)_2$) to traditional solar salt ($NaNO_3$-KNO_3) has shown promising results. These mixtures exhibit lower melting points, with some compositions reaching as low as 73.5 °C [67] and 97.1 °C [68], compared to 223 °C for solar salt [69]. The new formulations also demonstrate improved thermal properties (Table 8), including higher heat capacities (increases between 14 and 21% respect solar salt).

Name	Chemical composition	Melting point °C	Heat capacity J /g · K	Thermal stability °C	Thermal conductivity W/mK
Solar Salt	60wt% $NaNO_3$, 40wt% KNO_3	223-238	1.5 -1.6	560	0.55
Salt mixture 1	28wt% $Ca(NO_3)_2$, 35wt% $LiNO_3$, 18wt% KNO_3, 19wt% $NaNO_2$	73,5	2.010	620	0.315 – 0.4
Salt mixture 2	10wt% $NaNO_3$, 40wt% KNO_3, 20wt% $Ca(NO3)_2$, 30wt% $LiNO_3$	97,1	5,95	600	-

Table 8: Summary of thermal properties for different molten salt mixtures.

Molten salts are also being explored in single-tank, or thermocline, systems and as part of more advanced salt mixtures, such as chloride- and carbonate-based salts, to reach even higher temperature ranges (up to 800 °C or more). Higher temperatures improve thermodynamic efficiency in power generation, but the corrosive nature of some of these advanced salts presents ongoing material and engineering challenges. Despite this, advancements in molten salt TES technology continue to increase the feasibility and efficiency of CSP plants, positioning molten salt TES as a cornerstone technology for sustainable, high-capacity solar energy production [70].

4.1.1.2 Oil-Based Systems

Synthetic thermal oils are also used for sensitive heat storage, particularly in parabolic trough systems.

In the past, these were typically based on biphenyl diphenyl oxide or hydrogenated terphenyl mixtures and can be operated at temperatures up to about 400 °C [71]. At these temperatures, thermal oils offer good thermal stability and consistent heat transfer properties, which is essential for reliable CSP operation over long periods of time.

Due to the complexity of the manufacturing process or the specialty chemicals used, thermal oils are more expensive than conventional molten salts. however, they offer a lower risk of corrosion. in general, corrosion can be a significant problem in CSP systems as it affects the longevity and maintenance costs of the plant. Thermal oils react less with conventional metals at moderate temperatures, so there is less need for special materials or protective coatings for plant construction [72]. Despite their increased cost, synthetic oils are used when long-term stability and lower maintenance are required.

Thermal stability is a critical factor when selecting synthetic oils for CSP, as the fluids must maintain properties across many thermal cycles to ensure system efficiency and longevity. The thermal degradation of synthetic oils can occur over time, especially if they are operated near their maximum temperature limit. Degradation leads to the formation of lighter hydrocarbons, which can reduce the oil’s heat capacity and thermal conductivity, thereby impacting its effectiveness as a heat transfer fluid [73]. The NREL has been actively testing synthetic oils for these parameters, measuring their thermal properties across temperatures and evaluating their performance under varying thermal cycles. They also explore enhancements, such as integrating nanoparticle-enhanced fluids, to improve thermal capacity and reduce degradation. One area of focus was finding additives that can reduce degradation rates at upper-temperature limits, which would extend the lifespan of these oils and lower operational costs further. Additionally, there was interest in exploring novel materials that combine the low corrosion of synthetic oils with the high thermal capacities of molten salts, which could yield a superior alternative for future CSP technologies. More details can be found on their homepage [74].

Nowadays companies like Eastman Chemical offer synthetic oils, such as Therminol products, specifically designed for CSP applications. These fluids are manufactured with strict controls to maintain stability and extend operational life, enabling CSP plants to achieve reliable performance even with frequent temperature cycling and can be used up to 650-745 °C [75].

4.1.1.3 Sensible Solid-State Storage

Sensible solid-state storage systems rely on increasing the temperature of a solid medium to store thermal energy. These systems are typically used in high-temperature (400–1000 °C) or in very high (1000-1500 °C) temperature applications, where they can store large amounts of heat with minimal degradation. Unlike liquid TES options like molten salts, solid-state sensible TES is often more affordable and can withstand a broader range of temperatures without undergoing phase changes, making it particularly advantageous in CSP. The thermal capacity (specific heat), conductivity, and stability of the solid material dictate system performance.

The most common materials for this kind of TES include rocks, concrete, ceramics, and castable ceramics, each with unique thermal and physical properties affecting the storage capacity, thermal conductivity, durability, and overall cost. High-density materials such as ceramics and basalt are preferred for high-energy-density applications, while concrete offers a cost-effective solution for lower-temperature ranges. Due to their good thermal properties, more and more secondary raw materials from the waste industry are being used as cost-effective alternatives. All these options are explained in detail below.

Rocks and Natural Minerals: Rocks and natural minerals are widely used for their low cost, availability, and high thermal stability. Rock-based TES systems use materials like basalt, granite, and limestone, which have high specific heat capacities and can be packed into insulated storage tanks for efficient energy storage. In 2019 Siemens Gamesa has installed an Electric Thermal Energy Storage (ETES), which uses volcanic rocks—primarily basalt—as the storage medium. Located in Hamburg, Germany, this pilot facility employs approximately 1,000 tonnes of lava rocks, storing renewable energy as heat. The process involves converting electricity into hot air via resistance heaters, which then heat the volcanic rocks to around 750 °C. When energy demand spikes, the stored heat is used to power a steam turbine, regenerating electricity for the grid. This approach enables Siemens Gamesa to store up to 130 MWh of energy, sufficient to power thousands of homes for several hours to days.

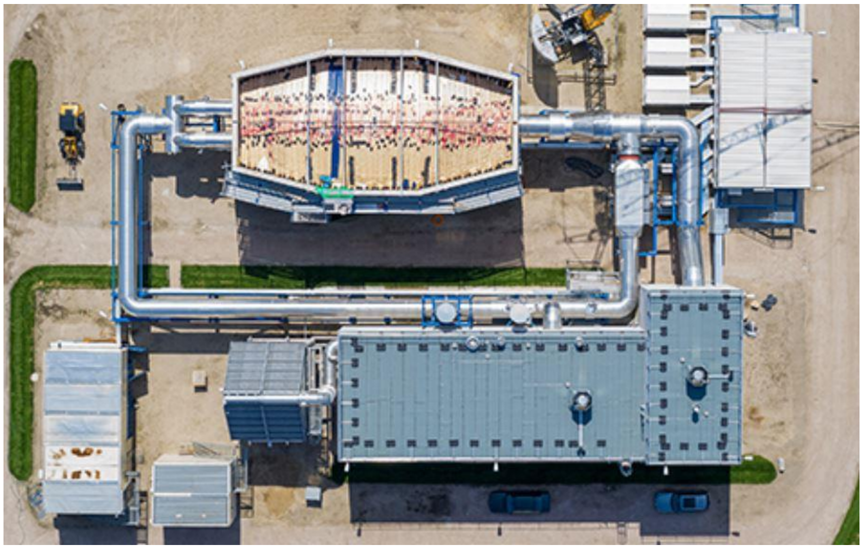


Figure 26: Packed-Bed sensible storage with rocks. © Copyright: Siemens Gamesa Renewable Energy / Ulrich Wirrwa,. Image taken from [76].

Rock-based TES systems are cost-effective, readily available, and offer high stability. They are particularly well-suited to large-scale TES applications. The problem is that as a naturally sustainable material their thermal conductivity can often vary, which depends on their mineral composition, structure, and density. This variability can lead to uneven heat distribution within the storage system, potentially affecting its efficiency and response time [77]. Additionally, long-term thermal cycling can lead to physical degradation. Efforts are ongoing to optimize rock selection and design to minimize this limitation, such as using mixtures of rock types to improve overall heat transfer [78].

Concrete Storage Systems: Concrete is increasingly recognized as a cost-effective, durable option for TES in CSP systems. It offers high thermal stability, low material costs, and flexibility in shaping and scaling, which makes it well-suited for a range of applications, from small systems to large-scale storage in CSP plants. Concrete blocks can withstand high temperatures, often 400-600 °C, without significant degradation, making them particularly useful for medium to high-temperature TES applications. Concrete's robust structure also permits efficient stacking, allowing for greater energy density and smaller spatial footprints than systems like lithium-ion batteries. This stacking capability enables concrete TES systems to support multiple days of storage, far beyond the typical four-hour duration of batteries, thereby aligning well with the intermittent nature of solar and wind energy.

Figure 27: View of one concrete storage module, tested on the Plataforma Solar de Almeria in Spain, Image taken from [79].

Concrete-based TES systems also offer economic advantages. Compared to molten salts, which are commonly used in CSP for thermal storage, concrete is significantly cheaper, with an estimated cost of less than €100 per kilowatt-hour [80]. This makes concrete a viable and scalable solution for TES, especially in renewable-heavy grids where long-duration energy storage is essential for balancing supply and demand.

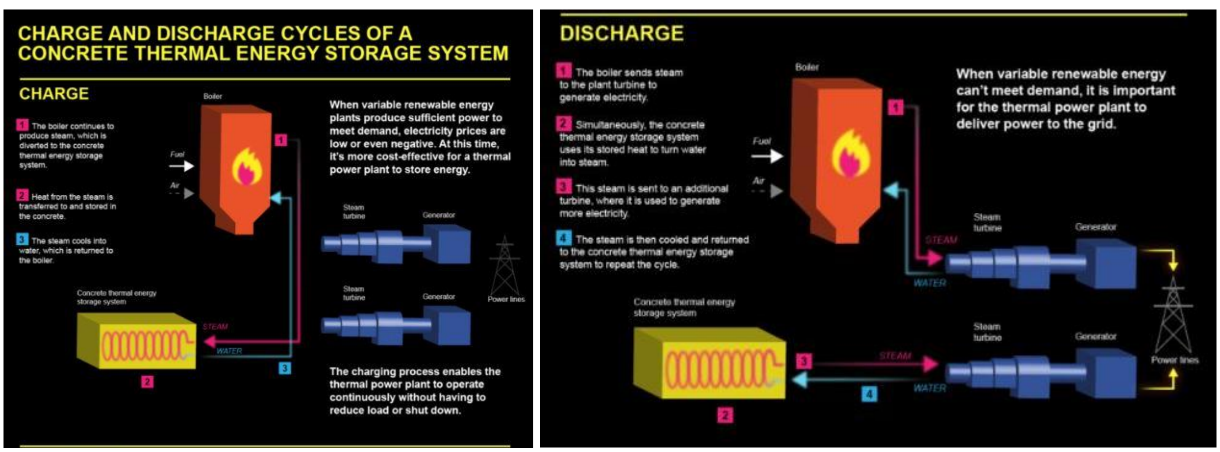


Figure 28. Concrete TES, Scheme of charging and discharging EPRI, 2021, Michael Matt, Image taken from [81].

Castable Ceramics and Refractory Materials

Castable ceramics and refractory materials are critical in TES systems, particularly for high-temperature applications such as CSP. These materials exhibit exceptional thermal conductivity and stability, allowing them to handle temperatures exceeding 1000 °C while maintaining structural integrity under frequent thermal cycling. Their high resistance to thermal shocks and ability to adapt to CSP conditions make them an invaluable choice for such systems [82].

The adaptability of castable ceramics lies in their synthetic engineering, allowing tailored properties such as porosity, mechanical strength, and thermal conductivity. Additionally, the production process increasingly incorporates recycled materials, such as industrial waste, reducing environmental impact and enhancing sustainability. These attributes contribute to longer system lifespans and consistent efficiency, vital for cost-effective and reliable CSP operation.

Despite these advantages, castable ceramics have notable limitations. Their manufacturing process involves precise material selection and high-temperature sintering (1000–1500 °C), which is energy-intensive and costly. Moreover, the installation process requires meticulous handling to prevent defects compromising performance. These factors make them more expensive than other TES materials, such as concrete or rock.

In CSP applications, castable ceramics are used in systems with advanced heat transfer media such as supercritical CO_2 or air [83], enabling efficient heat storage and transfer. They are also employed as structural and containment materials in installations utilizing molten salts or phase-change materials. While their acquisition costs and specific handling requirements present challenges, optimizing processes and incorporating material recycling can pave the way for their broader application in CSP systems with integrated thermal storage [84].

Ceramic wastes as sensitive storage materials

Waste materials are promising alternatives for sensible thermal energy storage (TES) at temperatures over 600°C due to their cost-effectiveness, sustainability, and availability.

A summary of the most interesting wastes and their properties are given in following Table 9:

Ceramic wastes	Source	Thermal stability max °C	Heat capacity J /gK	Cost €/ton	Application
Stainless Slag	Byproduct of steel manufacturing	1000 -1400	0.8 – 1.1	100 - 300	Suitable for TES in CSP systems
Ladle furnace slag	Byproduct from the production of raw steel in ladle furnaces	1000 - 1200	0.5 -1.0	100 - 500	Advanced ceramics for CSP

Brick and ceramic waste	Demolition debris and production waste from ceramics.	1600-2000	0.7 – 1.07	1-2	Low-cost filler material for TES systems.
Electric arc furnace dust (EAFD)	Slag formed in electric arc furnace during steel recycling as a flotation slag in the melting tank.	1000–1200	1.1–1.2	20 -50	Cost-effective, avoids waste accumulation, and suitable for packed bed storage
Fly ashes	Municipal solid waste incinerators	1000–1400	0.71–1.12	20 -40	Advanced ceramics for CSP
Gossan	Waste from copper ore extraction in the mining industry	700–1500	0.98–1.03	< 1	Cost-effective, avoids waste accumulation, and suitable for packed bed storage
Dross from aluminium industry	By-product generated during the production of aluminium	500 - 1100	0.63 -0.75	200 - 500	Advanced ceramics for CSP
Red mud	By-product generated in the production of alumina	600 - 900	1.03 – 1.3	20 - 50	Advanced ceramics for CSP

Table 9: Key properties and parameters of solid particle wastes for CSP Application in temperature range 600-1200°C. Data extracted from [85].

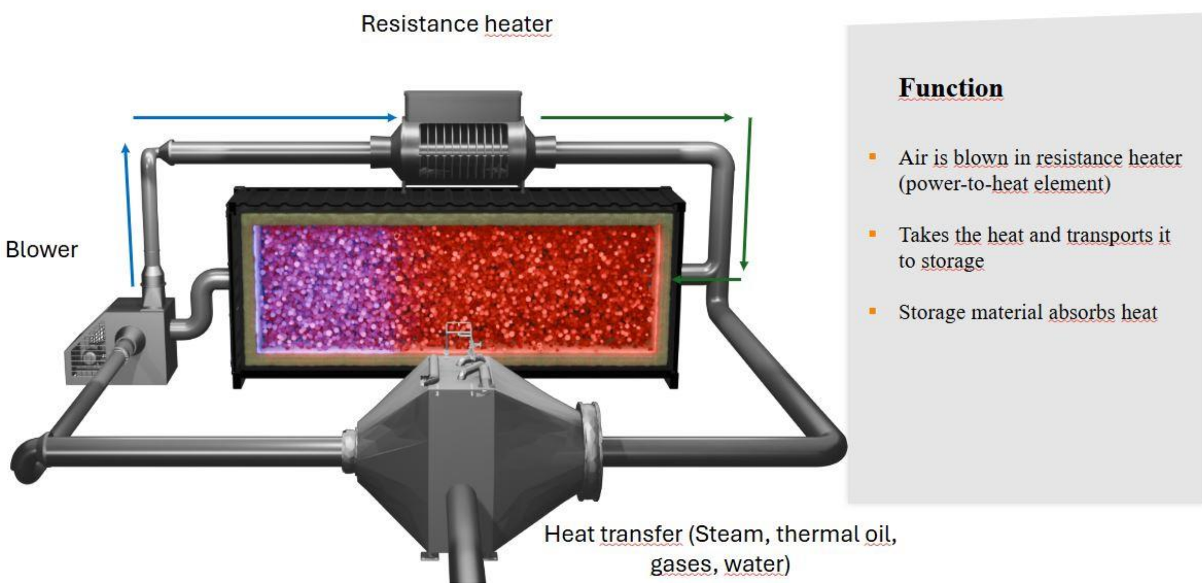
System Configurations for Sensible Solid TES

Several configurations are used to optimize heat storage and retrieval in solid TES systems, with the primary designs including packed-bed and modular block storage systems.

Packed-Bed Storage Systems

In packed-bed systems, solid materials such as rocks or ceramics are used as storage media inside an insulated tank. A HTF flows through the bed to store or retrieve thermal energy. The type of HTF used depends on the operating temperature of the system: liquid media such as thermal oils or molten salts are suitable for moderate temperature ranges (280–560 °C), while gaseous media such as hot air or exhaust gases are used for high-temperature operations (500–1300 °C).

The packed-bed design is relatively simple, scalable, and cost-effective, making it a popular choice for thermal energy storage in CSP applications. Depending on the specific application, the loading or unloading of thermal energy can occur either horizontally or vertically, offering flexibility in integration with different plant layouts. The distribution of the absorbed heat is monitored using thermocouples, which track the temperature profile and ensure efficient heat storage and retrieval, optimizing system performance. This is referred to as the "thermocline," which represents the thermal gradient within the storage medium.



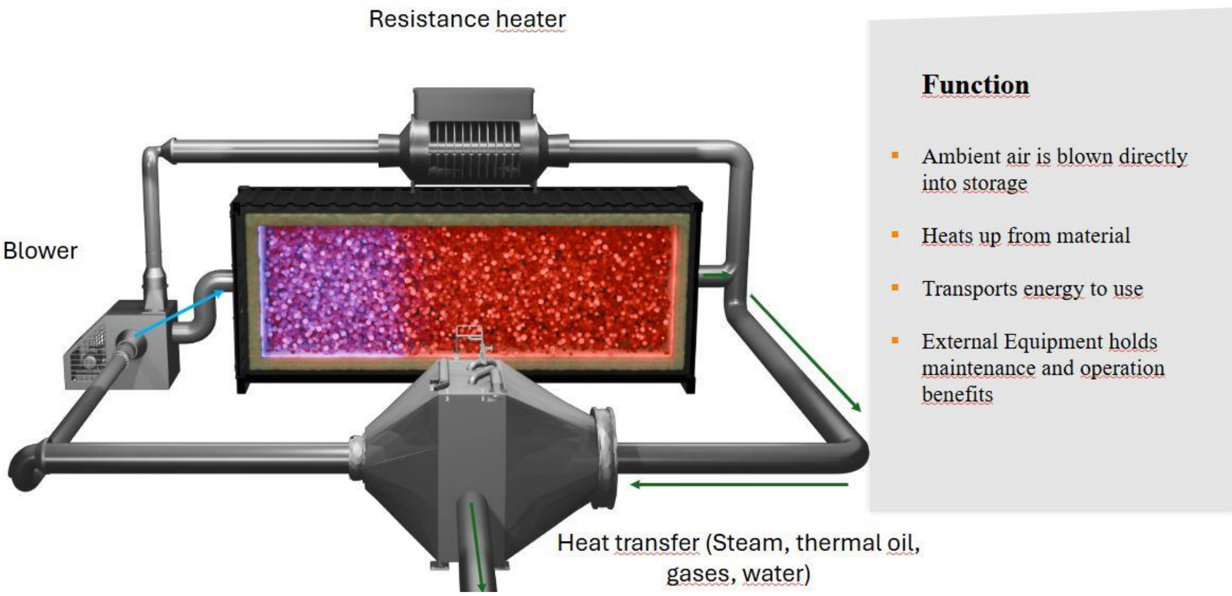


Figure 29: Example for horizontal charging (a) and discharging (b) of packed bed storage unit, with hot air as a HTF, (Kraftblock GmbH).

Modular Block Systems

Modular block systems for TES in CSP and other applications represent an innovative and promising technology. These systems use concrete blocks or ceramic blocks arranged in special configurations (modules) to enable efficient heat transfer and storage. The blocks are typically made of high-temperature resistant concrete (Energy Nest), clay bricks (Rondo Energy) or structured packed-bed of ceramic bricks (Kraftblock, Figure 30Figure 30: Ceramic Filler(blocks) from Karftblock in thermocline tank with HTF solar salt. CSP-Eranet, Project NewCline (a) Modular design with several TES units and electrical heater (Kraftblock, PtH Project) (b) that can withstand temperatures of up to 1400 °C or more. They are characterized by low thermal conductivity, resistance to thermal shock, and chemical stability at high temperatures. In stacked arrangements with air channels between the blocks, they allow for effective heat transfer. A key advantage of these modular block systems is their high adaptability and easy maintenance. The uniformity of the concrete or ceramic blocks ensures predictable heat storage and release rates. This allows for precise control and planning of energy management.

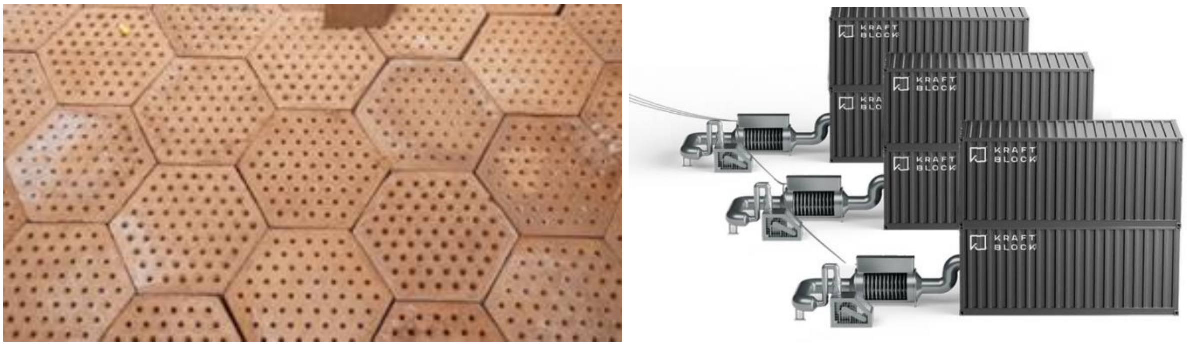


Figure 30: Ceramic Filler(blocks) from Karftblock in thermocline tank with HTF solar salt. CSP-Eranet, Project NewCline (a) Modular design with several TES units and electrical heater (Kraftblock, PtH Project) (b)

4.1.1.4 Advances and Challenges

Despite their advantages, packed-bed TES systems face technical challenges that require precise design and optimization. These include managing heat distribution, minimizing thermal losses, and addressing material durability under high-temperature cycling. Overcoming these challenges is essential to fully leverage their potential in CSP applications. The following Table 10 summarizes the most important advantages and disadvantages of packed-bed storage systems.

Packed-Bed solid-state storage systems			
Advances		**Challenges**	
High heat transfer efficiency	Direct contact between HTF and storage material	**Insulation and Heat Retention**	Significant heat losses with inadequate insulation, especially at high operating temperatures (600°C to over 1500°C)
Simple construction and maintenance	Without moving parts into the storage tank. Less risk of mechanical failure	**Heat Distribution and Stratification**	Challenges in maintaining uniform heat distribution and avoiding thermal stratification
Cost-effective	Less expensive to design, use of inexpensive materials like rock. ceramic or waste materials	**Pressure Drops and Energy Requirements**	High pressure drops when flowing through the storage bed, leading to increased energy requirements for pumping
Good scalability for various plant sizes	Can be easily scaled up or down due of their modular character	**Material Stability and Durability**	Material stability and durability problems due to repeated thermal cycles and mechanical stresses.

			Potential degradation of natural materials like rock or standard ceramics over time
Flexibility in choice of HTF	ability to use different types of HTFs depending on the temperature range and requirements of the CSP plant.	**Additional Costs**	For high-performance insulation materials to reduce thermal losses
Thermal stability and long service lifespan.	the storage materials offer excellent thermal stability in cyclical operation without significant deterioration		Complex optimization of particle size, packing density, and flow distribution required

Table 10: Summary of advantages and disadvantages of packed-bed storage systems.

Modular block storage systems, while offering advantages like flexibility and adaptability, exhibit some limitations when operating in the high-temperature range above 600°C. The following Table 11 provides an overview of the most important advantages and disadvantages of these storage systems.

Modular block storage systems		
Advances		**Challenges**
Flexibility and scalability	Can be easily adjusted to meet varying plant sizes and energy demands (Figure 30b)	**Scaling issues in very large plants due to complex communication and control between modules**
Accelerated Installation and Commissioning	Prefabricated modules allow for rapid on-site assembly, significantly reducing construction	**Potential for additional heat losses at connection points between modules**
Cost Efficiency	Manufacturing modules in controlled environments improves efficiency and lowers overall costs by minimizing material waste	**Higher costs for high-quality insulation to minimize heat losses**
Enhanced Quality and Reliability	Enhanced quality and reliability due to controlled factory production, reduced risk of operational issues	**Increased complexity of interfaces between modules**

Simplified Maintenance and Repair	Individual modules can be replaced or serviced without impacting the operation of the entire system	**Varied maintenance requirements and increased inventory needs for different module materials**
Adaptability to Emerging Technologies	Individual modules can be upgraded or replaced, easy integration of new technologies.	**Potential for single point of failure if a critical module malfunction**
Minimal Disruption to Operations	Enable seamless upgrades or module replacements with minimal impact on ongoing operations	
Environmental Sustainability	Generate less waste during manufacturing and installation	

Table 11: Summary of advantages and disadvantages, typical for modular block TES.

In summary, modular TES systems combine flexibility, cost-effectiveness, and environmental benefits, making them an ideal choice for modern energy storage applications across various industries. Their ability to adapt to future needs and technological advancements further enhances their value in the context of sustainable and efficient energy management.

4.1.2 Thermochemical Energy Storage

Thermochemical energy storage (TCS) systems are gaining attention for their potential to enhance CSP plants, particularly due to their high energy density, capacity for seasonal storage, and minimal heat loss. TCS can become crucial for CSP plants as it operates at high temperatures and utilizes earth-abundant materials, reducing costs and enhancing dispatchability, which makes CSP plants more efficient and grid-stable.

4.1.2.1 Mechanisms and benefits in CSP

In CSP, TCS can help mitigate the variability of solar power by storing energy via reversible chemical reactions, where energy is stored during endothermic reactions (which absorb heat) and released during exothermic reactions (which generate heat).

TCS involves the reversible conversion of solar-thermal energy into chemical energy, which can be stored at low temperatures with minimal heat loss over long periods. This high energy density makes it an attractive option for grid-scale dispatchable power generation.

Beyond electricity generation, TCS in CSP systems can also drive high-temperature chemical processes for various industrial applications, such as:

- Production of solar fuels like hydrogen, ammonia, and hydrocarbon fuels (e.g., jet fuel) through thermochemical cycles.

Funded by
the European Union

- Supplying high-temperature heat for processes like cement production, minerals calcination, and metallurgical processes.

The efficiency of TCS systems in CSP plants can be optimized through careful material selection, reactor design, and system integration. However, challenges such as gas storage costs, compressor electricity consumption, and material degradation over multiple cycles need to be addressed to meet cost and performance targets.

High-temperature thermochemical reactions can be divided into (1) solid-gas, (2) liquid-gas, and (3) gas-gas (Figure 31). TCS technology is still in research and development as it requires complex materials and reaction environments but has the potential to achieve the highest energy density.

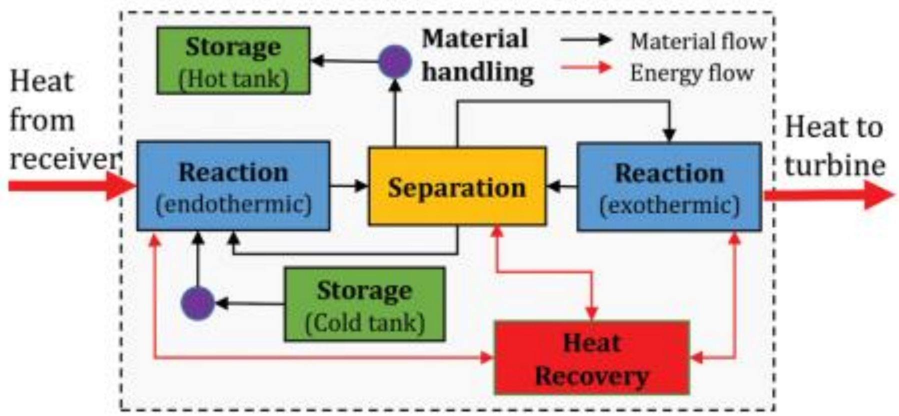


Figure 31. Sketch of Thermochemical systems [86].

4.1.2.2 Materials and Temperature Ranges

The most relevant chemical processes for CSP chemical energy storage are solid-gas reactions that encompass metal oxide, carbonates, and metal hydride [87]. Besides, fluid phase reactions with methane and ammonia are also strong candidates [88]. Figure 32 shows the key thermochemical technologies being explored for CSP thermal storage:

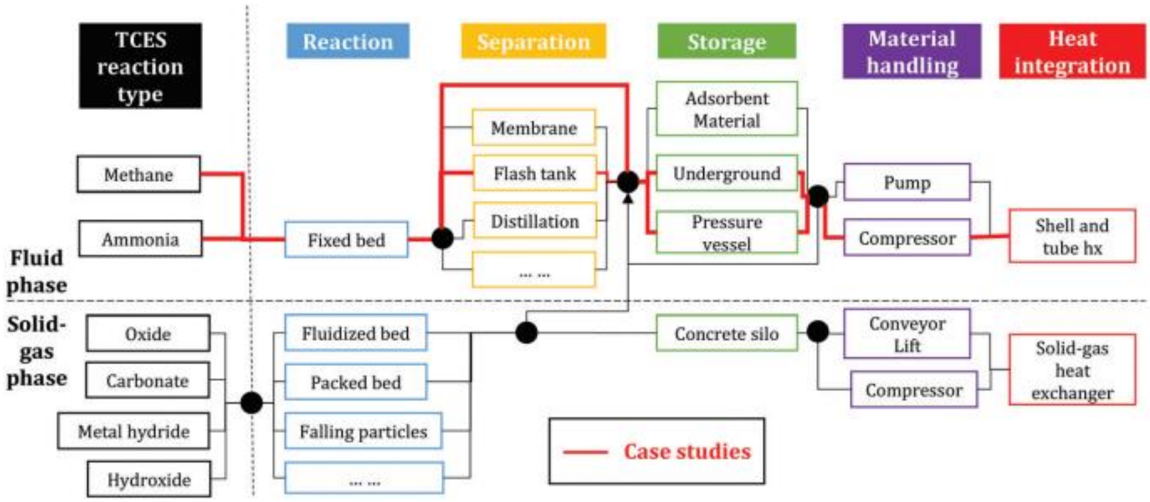


Figure 32. Thermochemical technologies alternatives for CSP [86].

4.1.2.2.1 Carbonates

Chemical looping (Carbonates), particularly calcium looping (CaL), is an emerging technology for carbon capture and energy storage. CaL utilizes the reversible reaction between calcium oxide (CaO) and carbon dioxide (CO_2) to form calcium carbonate ($CaCO_3$). This process involves heating $CaCO_3$ to separate it into CaO and CO_2, storing energy in their chemical bonds. These components can be stored separately for extended periods without energy loss. When the energy is needed, CaO and CO_2 are recombined, releasing heat. CaL offers advantages such as low-cost materials and high energy density (3.2 GJ/m^3) [89]. However, it requires high operating temperatures (>600 °C). This technology is being explored for concentrated solar plants (CSP) and other high-temperature industrial applications. Various configurations have been studied to integrate chemical looping with CSP:

- Integration of a near-critical regenerative CO_2 Brayton cycle into a CSP plant without storage to improve overall cycle efficiency [90].
- Multiple conceptual configurations to optimize the integration of calcium looping (CaL) with CSP, primarily focusing on power cycle integration in the carbonator zone [91].
- A novel CSP plant configuration using consecutive reactions for thermochemical storage [92].

4.1.2.2.2 Hydroxides

Hydroxides, particularly metal oxides undergoing reversible hydration/dehydration, offer another high-temperature thermal energy storage option. Operating at temperatures between 250-600 °C and near atmospheric pressures, these reactions can be represented as:

$$MO(s) + H_2O(v) \rightleftharpoons M(OH)_2 + \Delta H$$

Calcium hydroxide ($Ca(OH)_2$) and magnesium hydroxide ($Mg(OH)_2$) are commonly studied, with $Ca(OH)_2$ showing more promise due to its reactivity and stability. $Ca(OH)_2$-based thermal chemical storage (TCS) has demonstrated 95% conversion over 290 cycles. The calcium hydroxide system offers cheap and nontoxic TCESS with reasonable energy storage density. However, the system is not yet stable over cycles and is highly affected by the presence of CO_2 [93] [94], challenges include:

- Performance decline in 100% water vapour environments [93].
- Heat transfer limitations in packed bed reactors [95].

Recent studies have also explored using calcium-magnesium mixed hydroxides to combine the favourable characteristics of both materials, potentially enhancing the system's energy density and thermal stability. Overall, metal hydroxides represent a promising class of materials for thermochemical energy storage in CSP applications. Continued research into improving material properties, reaction kinetics, and reactor designs will be crucial for their successful integration into large-scale renewable energy systems.

4.1.2.2.3 Metal Hydrides

Metal hydrides, materials containing metal or metalloid bonded to hydrogen, can be used as thermochemical materials for CSP. Metal hydrides offer significantly higher energy densities compared to molten salts, potentially requiring up to 10 times less raw material for energy storage [96]. The primary advantage of metal hydrides for heat storage is their high energy density which allows for much less raw material compared to molten salts. Research into their application in CSP is gaining momentum, focusing on two areas: (1) metal hydrides compatible with current power tower technologies operating at 550–650 °C, and (2) metal hydrides suitable for next-generation power towers operating at 650–800 °C. This could lead to substantial cost savings in CSP energy storage systems [96].

A wide range of metal hydrides are suitable for high-temperature thermochemical energy storage (TES), including MgH_2, TiH_2, CaH_2, and LiH. MgH_2 has gained significant attention due to its high theoretical energy density (~2257 kJ/kg) and 7.7wt% hydrogen content, operating at 250-500 °C [97]. Research on metal hydrides prioritizes:

- Developing advanced materials with higher hydrogen storage capacity and enhanced kinetics.
- Optimizing reactor designs to improve heat transfer and minimise parasitic losses.
- Exploring integration with reversible solid oxide fuel cells.

Innovative approaches include:

- Utilizing perovskite-type $NaMgH_3$ for lower equilibrium hydrogen pressure.
- Investigating MgH_2-$Mg(OH)_2$ systems for improved performance.
- Employing composite methods to enhance heat transfer efficiency.

4.1.2.2.4 Redox reactions

Redox reactions or also known as oxides can effectively store and release thermal energy by absorbing and releasing oxygen at temperatures ranging from 350 °C to 1100 °C. Redox reaction systems have the advantage of using air as a reactant, which eliminates the need for a separate containment. Besides, redox systems offer higher operating temperatures at near ambient pressure [98], [99].

Among the various metal oxides, cobalt oxide, iron oxide, copper oxide, and manganese oxide are particularly notable for their suitable reaction temperatures, reaction enthalpies, cycling stability, and cost-effectiveness. Cobalt, iron, copper, and manganese oxides show the most promise in terms of reaction temperatures, enthalpies, cycling stabilities, and costs. The cobalt oxide Co_3O_4/CoO pair [98], cobalt nickel [100] and manganese oxide (Mn_2O_3/Mn_3O_4) [101], [102] have been extensively studied, with research focusing on:

- Study of reaction kinetics under various conditions.
- The impact of material structure on thermochemical storage performance.
- Significant enhancements in the cyclability of metal oxides have been achieved by incorporating various nanoparticles without altering the reaction temperature.

The primary barrier to applying these materials in technologies like CSP and industrial waste heat recovery is their high equilibrium temperatures (>850 °C). Developing stable storage materials to bridge the temperature gap between molten salts (600 °C) and cobalt/manganese oxides (~850 °C) is crucial. Recent studies focus on redox reactions of doped mixed oxides, spinels, and perovskite oxides to adjust redox temperatures and reduce sintering effects. Current research aims to develop [103] [104]:

- Develop more efficient materials (e.g., doped metal oxides, binary composites, perovskites).
- Enhance reactor designs (e.g., coated honeycombs, cascading systems, various bed configurations).

Despite advancements, substantial improvements in material performance and reactor design are still needed for redox-based TCS systems.

4.1.2.2.5 Ammonia systems

Ammonia systems utilize solar energy to dissociate ammonia into hydrogen and nitrogen gas, which can later be used for exothermic ammonia synthesis to release energy for continuous thermal power cycles. This allows greater flexibility in storage and transportation conditions. Ammonia-based thermochemical energy storage systems offer several advantages for CSP applications (Figure 33). These systems can operate at lower pressures than traditional processes, simplifying plant design and enabling smaller, decentralized installations. They have the potential to reduce greenhouse gas emissions associated with conventional ammonia production by utilizing renewable solar energy. Ammonia-TES systems also demonstrate flexibility, allowing integration with other technologies like chemical heat pumps to enhance overall efficiency. With the ability to heat supercritical steam to high temperatures and achieve reasonable efficiencies, these systems show promise in improving the dispatchability and performance of CSP plants.

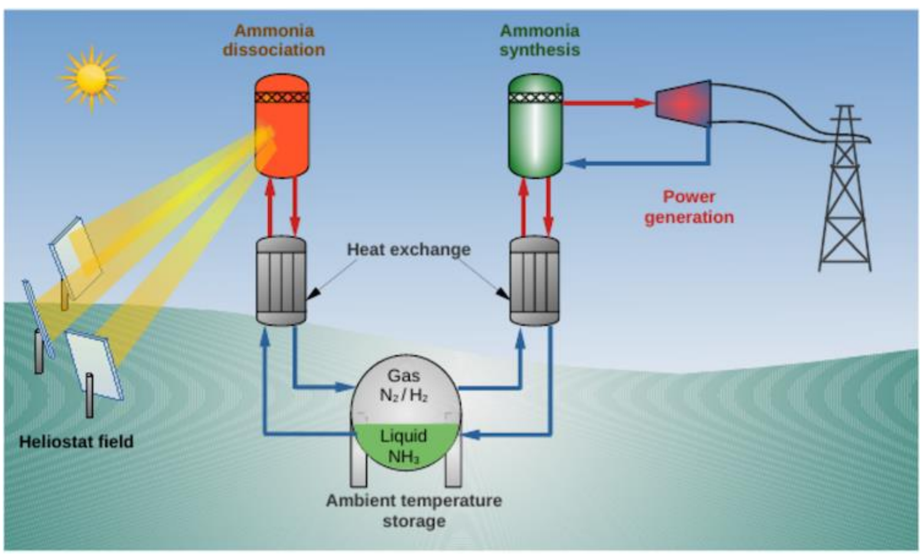


Figure 33. Ammonia-TES system adapted for CSP applications [105].

Current research in ammonia-TES for CSP includes [106]:

- Optimal design of novel ammonia synthesis processes.
- Development of metal nitride cycles for solar-driven ammonia production.
- Integration with other technologies like chemical heat pumps.
- Thermodynamic analysis and material screening.
- Experimental investigations using lab-scale reactors.

While challenges remain, ongoing research in areas such as process optimization, material development, and system integration continue to advance the potential of ammonia-TES as a sustainable solution for energy storage and production in solar thermal applications.

4.1.2.2.6 Methane-based TES

Methane as a storage medium for CSP plants is not widely used or extensively researched compared to other TES systems. However, methane-reforming reactions have been investigated as a potential TES option for CSP applications. The main advantages of the use of methane are:

- The natural gas infrastructure could potentially be leveraged for a methane-based TES system.
- The stored methane could be used not only for power generation but also as a chemical feedstock or fuel.

Current research on methane-based TES for CSP is limited compared to other storage options. More experimental feedback and process optimization are necessary to make methane a commercially viable option for CSP storage. While methane shows potential as a TES medium for CSP, other systems like ammonia-based storage have received more attention and development in recent years.

4.1.2.3 Advances and Challenges

Compared to sensible and latent heat storage, thermochemical storage for CSP is still in its early stages of development, with most systems tested only at the laboratory scale for short discharge periods. Several challenges need to be addressed in future research on thermochemical storage: (1) the selection of the most suitable chemical reaction; (2) the investigation of effective heat exchangers and reactors to enhance mass and heat transfer, which currently remain inadequate; and (3) the development of advanced composite materials that offer high storage density, high thermal conductivity, good cyclic stability, and low cost. Large-scale experiments are required to prove the efficiency and economic feasibility of thermochemical storage systems for both short- and long-term applications. Table 12 summarizes thermochemical storage technologies:

Thermochemical technology	Key features	Key pairs
Chemical looping	• Low-cost materials • High energy density (3.2 GJ/m_3) • High operating temperature (800-900 °C)	• Calcium oxide (CaL)
Metal hydroxides	• Operating temperature: 250-600 °C	• Calcium hydroxide ($Ca(OH)_2$)

	• High volumetric energy density (up to 600 MJ/m^3) • $Ca(OH)_2$ has shown 95% conversion over 290 cycles	
Metal hydrides	• Potentially operating at higher temperatures (>1000 °C at low pressure) • Hydrogen storage potential	• MgH_2 • TiH_2, CaH_2, LiH
Redox reactions	• Operating temperatures: 350-1100 °C • Potential for high energy densities	• Co_3O_4/CoO • MnO_2/Mn_2O_3 • CuO/Cu_2O
Ammonia	• Systems can operate at much lower pressures • Absence of side reactions • Supercritical steam	• $NH_3/N_2/H_2$

Table 12. Summary of thermochemical storage for CSP.

4.1.3 **Latent Heat Storage**

Latent thermal energy storage (LHS) systems play a pivotal role in CSP applications, offering significant advantages due to their ability to store and release large amounts of thermal energy during phase transitions. The core of latent TES technology lies in phase change materials (PCMs), which absorb or release heat at a nearly constant temperature, making them highly suitable for applications requiring consistent thermal output, such as CSP plants [107], [108]. HS systems utilize PCMs to store thermal energy isothermally. Recent advancements have improved the efficiency and applicability of LHS systems for CSP and other high-temperature applications [108], [109].

4.1.3.1 Mechanism and Benefits in CSP

Latent TES systems exploit the phase transition of materials—typically from solid to liquid or vice versa—enabling them to store substantial energy within a small volume. The high energy density of PCMs reduces the required storage size, minimizing the footprint and associated infrastructure costs of CSP installations. Furthermore, the nearly isothermal behavior of PCMs during phase transitions provides a stable thermal output, which is critical for maintaining turbine efficiency and grid stability [110], [109]. This makes latent TES systems particularly advantageous in hybrid CSP setups, where storage can address solar intermittency and support continuous power generation [111].

Latent heat storage systems can be implemented in CSP following different approaches. Innovative configurations such as hybrid systems, which combine sensible and latent heat storage, have shown promise in optimizing energy storage efficiency [109].

Additionally, cascaded systems utilize PCMs with varying melting temperatures in series, allowing for improved thermal management across different operational phases [112]. This method significantly enhances the heat transfer rate through continuous melting. Cascades of macro-encapsulated PCMs can store up to 50% more energy per unit volume compared to conventional two-tank systems used in CSP plants [113]. Moreover, this TES system has the potential to reduce costs from 26 to 15 €/kWh compared to traditional CSP two-tank systems, as reported in [114].

The shell-and-tube configuration remains the most economical and widely implemented design for LHS systems. This configuration efficiently facilitates heat transfer between the PCM and the heat transfer fluid [115].

4.1.3.2 Materials and Temperature Ranges

The choice of PCM significantly influences the system's operational range and efficiency. Holistic approaches have been reported in the literature for PCM selection [116]. Organic PCMs, such as paraffin and fatty acids, are typically used in low-to-moderate temperature CSP applications (up to ~200 °C). Inorganic PCMs, including eutectic salt mixtures like sodium nitrate-potassium nitrate and metallic alloys, are better suited for higher temperatures, extending beyond 400 °C and reaching up to 1000 °C in advanced CSP systems [117], [118]. For example, nitrate salts are extensively used in CSP systems operating between 300 °C and 600 °C, while chloride salts and metallic alloys are being developed for next-generation CSP plants targeting even higher temperatures [119]. Phase change material candidates available for CSP applications are collected in Figure 34.

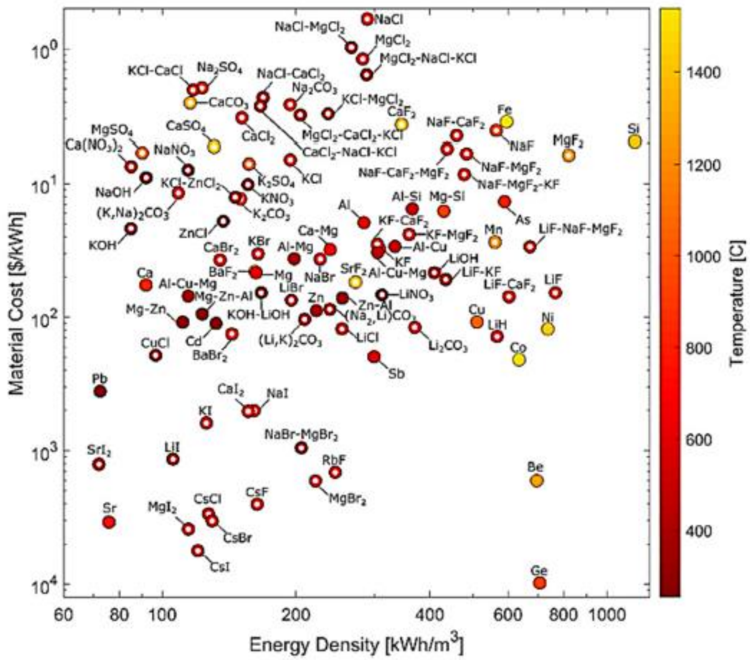


Figure 34. Phase change materials' candidates for CSP application [120].

4.1.3.2.1 Inorganic PCMs

Inorganic PCMs, such as carbonates, fluorides, and chlorides, continue to be the focus for high-temperature applications due to their high melting points and energy densities. Inorganic salt range melting point temperatures from 120 to 1000 °C, including PCMs such as fluorides, chlorides, bromides, hydroxides, nitrates, carbonates, molybdates, and others [121]. Binary and ternary eutectic mixtures based on fluorides and chlorides exhibit high latent heat of fusion, with chlorides being particularly cost-effective. Fluoride salts are less favorable due to their relatively high cost and the significant corrosion they cause to containment materials [122]. Studies indicate that the melting temperature and heat capacity increase in the following order: nitrates, chlorides, carbonates, and fluorides [123].

Nitrates, such as $NaNO_3$, KNO_3, and $LiNO_3$ are particularly noteworthy for their high thermal stability and good heat transfer properties [124]. Among nitrates, lithium nitrate has the highest energy density, however, its material cost is almost 8 times higher than the one for binary mixtures (like $KNO_3/NaNO_3$) [125]. Binary and ternary mixtures of nitrates have shown promise, such as KNO_3-$NaNO_3$, $LiNO_3$-KNO_3-$NaNO_3$, $LiNO_3/KNO_3/NaNO_3$ mixture has 20% better thermal storage capacity than $KNO_3/NaNO_3$ [125].

Chlorides are also interesting candidates, mainly because they tend to have higher melting temperatures, for instance NaCl melts at 800.7 °C or NiCl2 at 1031 °C. Moreover, many chloride salts are comparatively inexpensive [126], [127] such as KCl, NaCl. Fluorides, such as LiF and NaF, and their eutectic mixtures are being studied for their high melting points, and high latent heat up to 800ºC, however, due to their reactiveness and high corrosion they have been less considered than other more user-friendly inorganic salts. Carbonates like Li_2CO_3, Na_2CO_3, and K_2CO_3 are also being explored for their high melting points. Besides mixtures of carbonates and chlorides have also been studied in the literature with melting points higher than 600 ºC [128].

These inorganic salts offer several advantages such as PCMs for CSP, including high volumetric thermal energy storage density, good thermal conductivity, and relatively low cost compared to metallic PCMs. However, challenges such as corrosion of containment materials, phase segregation during thermal cycling, and supercooling in some salt hydrates need to be addressed. Ongoing research focuses on developing new salt mixtures with optimized properties, improving long-term stability and cycling performance, addressing corrosion issues through material selection and protective coatings, and enhancing heat transfer properties using nanoparticles or composite materials. These advancements are crucial for the continued development and implementation of inorganic salt PCMs in CSP systems, potentially leading to more efficient and cost-effective thermal energy storage solutions.

4.1.3.2.2 Metal alloys

Metal alloys have emerged as promising PCMs for CSP applications due to their high thermal conductivity and volumetric storage density. Some metal alloys and oxides have high latent heat storage capacity and may dominate future PCM applications in CSP due to higher conductivity than salts and salt mixtures. Besides, they also exhibit relatively low vapour pressure. Among the main metal alloys considered, there are aluminium-based alloys, Zinc-based alloys and low melting point metals as described in the following.

- **High to Medium melting point alloys (>400 ºC)**

Aluminium-based alloys stand out for their favourable characteristics as they exhibit a high latent heat of fusion and melting temperatures that align well with the operational requirements of CSP applications [129]. They exhibit temperature ranges from 440ºC to almost 600ºC. Binary alloys like 88Al-12Si, and their variations, have a melting point of around 576-586ºC with a latent enthalpy of up to 560 kJ/kg, which is almost 5 times the one for Solar salt. Ternary alloys like Al-Si-Mg and Al-Si-Cu further enhance performance by providing improved mechanical properties and thermal stability compared to their binary counterparts [130]. Additionally, Al-Mg-Zn alloys, have also been studied in the literature [131].

Zinc-based alloys also show promise as PCMs for CSP applications. One notable example is the Mg-51% Zn alloy, which has been extensively characterized for its thermal properties [129]. This eutectic alloy offers a lower melting point than aluminium alloys, up to 420ºC and lower latent heat up to 180 kJ/kg. Zinc-Aluminium alloys exhibit higher melting point and latent heat storage. The microencapsulation of these alloys has been recently studied in the literature

[132]. Copper, magnesium and silicon-based alloys provide higher temperature alloys above up to 1000°C, with a theoretical latent heat of up to 750 kJ/kg for 56Si- 44Mg [129].

- **Low Melting Point Metals and Alloys (<400°C)**

In addition to aluminium and zinc, low melting point metals such as tin (Sn), bismuth (Bi), indium (In), and gallium (Ga) are being explored for their potential as PCMs [120]. Tin, in particular, is valued for its high latent heat and excellent thermal stability; however, it requires careful management of supercooling effects that can occur during phase transitions. Bismuth, indium, and gallium are favoured not only for their low toxicity but also for their favourable physical properties, making them suitable candidates for safe and effective thermal energy storage [130].

The use of metal alloys as phase change materials offers several advantages. Their high volumetric thermal energy storage density allows for compact system designs, while excellent thermal conductivity facilitates rapid heat transfer—both essential features for maximizing the efficiency of CSP systems. Furthermore, many metal alloys exhibit good cycling stability and minimal volume expansion during phase changes, contributing to their reliability over time.

However, challenges remain in the widespread adoption of these materials. Corrosion and oxidation at elevated temperatures can pose significant risks to long-term performance. Additionally, effective encapsulation methods are necessary to prevent leakage and ensure the stability of the PCM within the system. The management of supercooling in certain alloys is another critical factor that must be addressed to optimize performance.

4.1.3.3 Advances and Challenges

Latent TES systems are particularly relevant in CSP applications aiming for high efficiency and operational stability. They enable compact storage solutions with high energy density and provide consistent thermal output, enhancing dispatchability and system performance. Continued research is focused on cost reduction, material innovation, and system integration to expand the application of latent TES in CSP plants [107], [119].

However, latent TES systems face challenges such as material degradation due to cyclic phase transitions, which can reduce lifespan and reliability. Recent advancements in PCM technology focus on enhancing thermal conductivity and reducing material degradation to improve efficiency and durability. Composite PCMs, which combine high-conductivity materials like graphite or metal foams with traditional PCMs, address the low thermal conductivity challenge of many PCMs [110] [133] [117]. Besides, the cost of advanced PCMs and the search for viable containment systems remain a barrier to widespread adoption, particularly in large-scale CSP plants. Efficient heat exchangers are critical for maximizing heat transfer between PCMs and the heat transfer fluid (HTF), which directly influences system performance [107]; [117].

Enhancing the heat transfer capabilities of LHS systems is critical for improving charging and discharging rates.

<table>
<tr><th>Challenges</th><th>Research approaches</th><th>Key aspects for advancement</th></tr>
<tr><td>Corrosion and Stability:
Some PCMs exhibit high corrosion rates after repeated thermal cycles. Ensuring long-term stability remains a key area of research.</td><td>Metal Foams and Fins: Incorporating these structures into PCM matrices has proven effective in increasing thermal conductivity.</td><td>Developing novel high-temperature PCMs with improved stability.</td></tr>
<tr><td rowspan="2">Volume Changes:
The volume expansion during phase transitions necessitates complex system designs to accommodate these changes without compromising performance.</td><td rowspan="3">Microencapsulation and Nanoencapsulation

Help mitigate issues like subcooling and corrosion while enhancing thermal conductivity.

Also being developed to mitigate leakage and improve structural stability during repeated thermal cycles.</td><td>Advancing heat transfer enhancement techniques.</td></tr>
<tr><td>Integrating LHS with other renewable energy systems.</td></tr>
<tr><td>Heat Transfer Enhancement:
Further improvements are needed to enhance charging/discharging rates effectively.</td><td>Utilizing computational modelling for systematic optimization of LHS designs.</td></tr>
</table>

Table 13. Summary of challenges, research approaches and key aspects of latent heat storage technology.

Although LHS systems are not yet widely commercialized for CSP applications, ongoing research is addressing critical technical challenges. As these challenges are progressively addressed, PCM-based LHS systems are anticipated to see increased adoption in commercial CSP plants and other high-temperature applications. This progress will contribute significantly to the advancement of sustainable energy solutions, such as the one proposed in COOPERANT.

4.2 TES metrics and their influence on CSP effectiveness

These metrics influence a CSP system's efficiency, capacity factor, and operational stability, directly impacting the technical and economic viability of integrating TES into CSP plants. Besides, each of the parameters and metrics will be specifically discussed for the conceptual design idea to be implemented in the COOPERANT project, that is the packed-bed TES configuration.

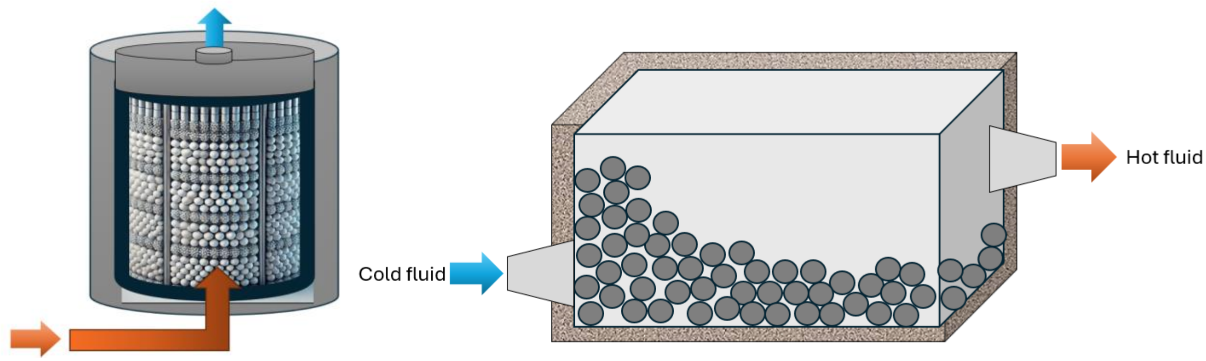


Figure 35: Schematic diagram of packed-bed TES System, example for vertical charging (left) or horizontal discharging modus (right).

4.2.1 Specific Heat Capacity

Specific heat capacity (J/kg·°C) represents the material's ability to store thermal energy per unit mass as it heats. This metric is central in CSP systems since it defines the heat the TES material can absorb and store for later electricity generation. Higher specific heat capacities result in greater thermal storage per unit mass, improving the energy density and reducing the physical footprint required for storage. This is particularly advantageous in CSP applications, where minimizing land and infrastructure use while maximizing thermal energy capacity is critical. Materials like molten salts have high specific heat capacities, which is why they are frequently used despite cost considerations.

Example for packed-bed TES: Ceramic materials like alumina (Al_2O_3) have a moderate specific heat capacity (around 0.9–1.2 J/g °C), which allows them to store significant amounts of thermal energy per unit mass. In a packed bed configuration, alumina and similar ceramics can retain heat effectively, extending the CSP plant's discharge time and making it a viable option for long-duration storage. Studies have shown that ceramic-packed beds, because of their inherent high heat capacities, perform well for sensible heat storage up to 1000°C, which is advantageous for CSP plants aiming to operate efficiently at high temperatures [134], [135].

4.2.2 Thermal Conductivity

Thermal conductivity determines the rate at which heat is transferred through the storage material. In CSP applications, high thermal conductivity ensures quick and uniform heat transfer, reducing thermal gradients within the storage medium and increasing the system's responsiveness. This metric is particularly important for solid storage media, like rock or concrete, which have relatively low thermal conductivities. Optimizing thermal conductivity can reduce charging and discharging times, enabling faster response to energy demand fluctuations [136].

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the European Union

Example for packed bed TES: Thermal conductivity in ceramic-packed beds can vary depending on the material and the packing arrangement, but ceramics generally offer moderate to high conductivity compared to other solid TES materials. Alumina, for instance, has a thermal conductivity range of 20-30 W/m·K, allowing for relatively efficient heat transfer. In packed beds, ceramics are arranged to balance conductivity and porosity, facilitating rapid heat transfer while maintaining structural integrity. CSP systems using ceramic-packed beds can achieve consistent and stable heat distribution, essential for efficient charging and discharging cycles [136].

4.2.3 Energy Density

Energy density is the amount of energy stored per unit volume and is a critical factor in determining the physical size of the TES system in a CSP plant. High energy density in TES materials allows CSP systems to store more energy within a smaller footprint, which is beneficial for cost and land use. High-density storage materials, such as certain phase-change materials (PCMs) and molten salts, require less physical space and infrastructure, which reduces construction and operational costs [137].

Moreover, higher energy density enhances the plant's storage capacity, allowing it to release substantial energy when required, thereby supporting grid stability. In regions where space and infrastructure costs are high, using TES materials with high energy density can make CSP projects more economically viable and improve scalability, making CSP a more practical choice for large-scale renewable energy generation.

Example for packed-bed TES: Ceramics like cordierite and mullite have a high density and relatively high energy storage capability per unit volume. In a packed bed configuration, ceramics can provide high energy density, allowing CSP plants to store significant thermal energy within a compact footprint. Ceramic-packed beds, due to their high-density materials, allow CSP systems to maximize thermal energy storage in limited space, which is particularly beneficial for large-scale systems requiring high-capacity storage. By optimizing the energy density, packed beds filled with ceramics can increase storage efficiency and minimize land usage [137].

4.2.4 Round-Trip Efficiency

Round-trip efficiency measures the amount of stored energy that can be recovered and utilized, typically expressed as a percentage of the energy initially stored. High round-trip efficiency is essential in CSP systems, as it minimizes energy losses and improves overall system performance. CSP plants generally aim for TES systems with round-trip efficiencies of 80-95%, which helps to reduce the LCOE by ensuring that most of the energy generated and stored from solar power is ultimately converted into electricity. For example, insulated molten salt systems or PCMs with high latent heat properties are designed to retain heat effectively, reducing losses during the charge-discharge cycle and enhancing the plant's energy conversion efficiency [138]. TES systems with high round-trip efficiency maximize the amount of stored energy converted into usable power, contributing to more reliable CSP plant operation and better grid integration.

Example for packed-bed TES: Ceramic materials in packed beds contribute to high round-trip efficiency by reducing energy losses. Their stable thermal properties and low thermal expansion prevent cracking and degradation over repeated cycles. Packed beds with ceramics achieve efficiencies of up to 90% in certain configurations, as their ability to retain heat is maximized by their structural arrangement and low thermal conductivity losses through insulation. This high round-trip efficiency is crucial for CSP plants that require reliable, on-demand heat release with minimal waste, which packed beds can deliver [138].

4.2.5 Thermal Stability and Durability

Thermal stability and durability are crucial for TES materials due to the demanding operational environment of CSP plants. High thermal stability allows the TES medium to withstand elevated temperatures, often between 400°C and 600°C, without significant degradation. Durability, meanwhile, ensures the material can endure frequent heating and cooling cycles over the long term without losing its thermal properties or structural integrity. For instance, concrete and basalt-based TES systems have shown resilience to thermal cycling, maintaining performance over thousands of cycles with minimal degradation [138] [110]. This durability reduces maintenance costs and minimizes the risk of system downtime, thus increasing the CSP plant's operational reliability and efficiency. Thermal stability and durability are especially critical in CSP, where daily cycles are routine, and consistent performance over decades is necessary to justify the plant's capital expenditure.

Example for packed-bed TES: Ceramics are highly stable at elevated temperatures, often exceeding 1000°C, making them ideal for CSP applications that require consistent performance under extreme conditions. For instance, cordierite and alumina maintain their structural integrity and resist thermal shock, allowing for numerous thermal cycles without degradation. In CSP systems, ceramic-packed beds can handle frequent charging and discharging cycles without suffering from material fatigue, contributing to long operational lifespans with minimal maintenance. This durability makes ceramics a favourable choice for TES in CSP, reducing downtime and extending the lifespan of the system [110].

4.2.6 Cost per kWh of Storage

The cost per kWh of storage is a fundamental metric affecting the economic feasibility of TES in CSP systems. Lower-cost storage materials, like concrete and certain types of rocks, offer a cost-effective solution, particularly in large-scale applications where cost constraints are significant. For instance, engineered concrete costs can be as low as 50-100 €/kWh (Table 14), making it an appealing choice for CSP projects that require substantial storage capacity without exorbitant material costs [136].

TES Type	Storage Material	Cost Range (€/kWh)	Energy Density (kWh/m³)	Lifetime (Years)	Energy Efficiency (%)
Sensible	Concrete	50-100	Low (30-50)	20-30	85-95 [139]
	Rocks	50 -100	Low (20-40)		85-95 [139]
	Molten Salts	100-150	Medium (80-100)	20-25	70-85 [140] [141]
Latent	Salt Hydrates	150-200	Medium (150-200)	10-25	75-90 [142] [143]
	Metal alloys	200-300	Medium (100-300)		
Thermo chemical	Metal, Oxides, Hydrates	200-300	High (>300)	10-25	60-75 [142] [144]

Table 14. Summary of TES technologies and properties.

Cost comparison of TES types

Sensible thermal energy storage systems are the most cost-effective option (50-100 €/kWh), especially for large-scale applications with sufficient space. They are particularly suitable for CSP plants that require simple and economical solutions.

While materials like molten salts and PCMs can be more expensive, they often provide higher energy densities and specific heat capacities, thus balancing cost and performance.

Thermochemical storage systems are characterised by an extremely high energy density and the potential for long-term storage. However, they are associated with higher costs (200-300 €/kWh) and technical challenges. They are particularly suitable for applications with high temperatures and long-term storage requirements.

Through careful selection and optimization of these metrics, CSP plants can enhance TES performance, reliability, and overall cost-effectiveness, thereby supporting their role as a sustainable and dependable renewable energy source.

Example for packed-bed TES:

At temperatures exceeding 600 °C, the higher costs of packed-bed TES systems in CSP plants arise primarily from advanced material requirements, insulation, and system integration complexity. Natural rocks (e.g., basalt) are cost-effective and widely available, while ceramics or high-temperature alloys provide better performance (high thermal and mechanical stability) but come with higher material costs. At elevated temperatures (600-1200 °C), heat losses through radiation and convection become significant. Advanced insulation materials such as ceramic fibres or vacuum-insulated panels are required to minimize these losses, increasing upfront costs. Moreover, high-temperature cycling causes thermal expansion and mechanical stresses, requiring robust designs and materials (e.g., refractory steels, heat-resistant concrete) that increase construction costs.

Integrating a high-temperature packed-bed TES into the CSP thermal loop involves engineering challenges, such as managing the heat transfer medium (e.g., air or other high-temperature fluids). Air systems, while effective, require specialized blowers, pipes, and valves that add to system costs. While packed-bed TES systems are generally low-maintenance, temperatures above 600 °C can lead to material fatigue and insulation wear, resulting in moderate maintenance costs over time. However, these costs are offset by key benefits, including high energy density, improved efficiency, and the ability to use very low-cost industrial waste materials as storage media. This approach not only reduces material expenses but also enhances environmental sustainability by repurposing waste products. The system's durability, scalability, and efficient high-temperature heat storage further improve the economic viability and long-term performance of CSP plants.

4.3 Specific challenges of TES types at high temperatures > 600 °C.

TES systems operating at high temperatures in COOPERANT relevant range between 600 °C and 1000 °C face distinct challenges depending on their storage type—sensible, latent, or thermochemical storage. These challenges arise primarily due to material constraints, thermal performance limitations, and system integration complexities.

One of the fundamental problems with all TES is the heat loss that occurs through thermal diffusion and convection to the environment, as heat moves from higher to lower temperature ranges according to the laws of thermodynamics. Even advanced insulation materials such as vacuum insulation panels, aerogels or multiple-layer thermal barriers cannot prevent heat loss. Although such modern insulation materials can significantly reduce heat losses, they increase the cost and complexity of the TES system [145].

With long-term storage, especially at high temperatures (>600 °C), the maintenance of the stored thermal energy becomes increasingly inefficient, reducing storage time and capacity. Furthermore, as the system size increases, the heat losses over the increased surface area also increase [146].

Storage materials used in TES systems must withstand extreme operating conditions, including high temperatures, thermal cycling, and mechanical stress. Sensible TES systems, for example, rely on materials such as rocks, molten salts, or ceramics, but these face degradation over time due to thermal expansion, cracking, and sintering. Molten salts (e.g., solar salt) commonly used in CSP applications are limited to temperatures below 600 °C due to decomposition risks and corrosion of containment structures. Metal alloys or advanced ceramics are required for higher temperatures (>800 °C), but these materials are expensive and challenging to manufacture at scale [145] [147]. In latent TES systems using high-temperature PCMs such as metal alloys and salts, issues like phase segregation, subcooling, and low thermal conductivity further limit performance. They must exhibit high thermal stability and suitable phase change temperatures., Solutions like encapsulation or heat transfer enhancements (e.g., fins or metal foams) add complexity and costs [148]. However, materials like chlorides or carbonates are prone to corrosion and decomposition. In thermochemical TES systems, materials such as metal oxides and carbonates degrade due to repeated chemical cycling, resulting in reduced reactivity and loss of capacity over time. Innovative approaches, such as the encapsulation of reactive materials or the development of composite structures, are currently being investigated to mitigate these problems [145].

At high temperatures (600-1000 °C), TES systems also face major challenges in terms of corrosion and material degradation of the storage tanks themselves. Molten salts, for example, corrode materials such as stainless steel due to chemical reactivity and impurities, requiring costly protective coatings or exotic alloys [146]. At temperatures close to 1000 °C, the materials, for the containment or storage tank, as well as pumps and valves, must be resistant to thermal fatigue and chemical corrosion, which limits the choice of alloys or refractory ceramics [149].

Challenges of TES systems, operating at temperatures 600-1000°C		
TES type	**Key Challenges**	**Key strategies for advancement**
Sensible	**Material thermal stability**	By combining advanced material selection, modular design, and optimized operational strategies, material degradation in sensible TES systems at high temperatures can be significantly reduced, ensuring long-term reliability and performance.
	Selection of HTF	Common HTFs such as thermal oils and molten salts have a limited operating temperature. Above 600°C only hot air (gas) can be used.
Thermochemical	**Containment Issues**	Structural components, including storage tanks and piping, must withstand extreme temperatures while preventing thermal expansion stresses and corrosion.
	Material Stability	At 600–1000°C, candidate materials like metal oxides (e.g., CaO) must demonstrate chemical stability and rapid reaction kinetics.
	Reaction Kinetics	At 600–1000°C, achieving efficient and reversible chemical reactions (e.g., metal oxide cycles or

		carbonation reactions) requires precise control over temperature, pressure, and humidity.
	High Costs and Complex Reactor Design	TCS systems require advanced reactors to facilitate solid-gas or liquid-gas reactions, ensuring uniform heat and mass transfer while minimizing thermal losses. The development of such high-performance materials and reactor systems is still costly, especially for large-scale applications.
Latent	**Material selection**	The requirements for temperatures >600°C considerably limit the range of applicable materials. Few PCMs, like molten salts or metal alloys, operate reliably at 600–1000°C. They often face phase segregation, subcooling, and chemical instability.
	Corrosion	Molten metals and salts are highly corrosive at these temperatures, requiring expensive containment materials.
	Thermal Conductivity	PCMs' low thermal conductivity limits heat transfer efficiency, slowing the charging/discharging cycles. Innovative heat exchangers, such as fins or graphite enhancements, are needed.

Table 15. Summary of challenges of TES systems operating at high temperatures.

5 Potential Key Applications of CSP and TES

5.1 Power Generation

Power generation is the primary objective of CSP plants, where solar energy is converted into electricity through thermodynamic cycles. A defining advantage of CSP technology is its ability to store thermal energy in TES systems, ensuring electricity generation even when sunlight is unavailable. This capability allows CSP systems to deliver a consistent and reliable power output, addressing one of the main challenges of renewable energy: intermittency. Key features that make CSP a valuable solution for electricity generation include utility-scale deployment, alignment with peak demand, and enhanced grid stability. Figure 36 illustrates the distribution of plants installed globally for power generation.

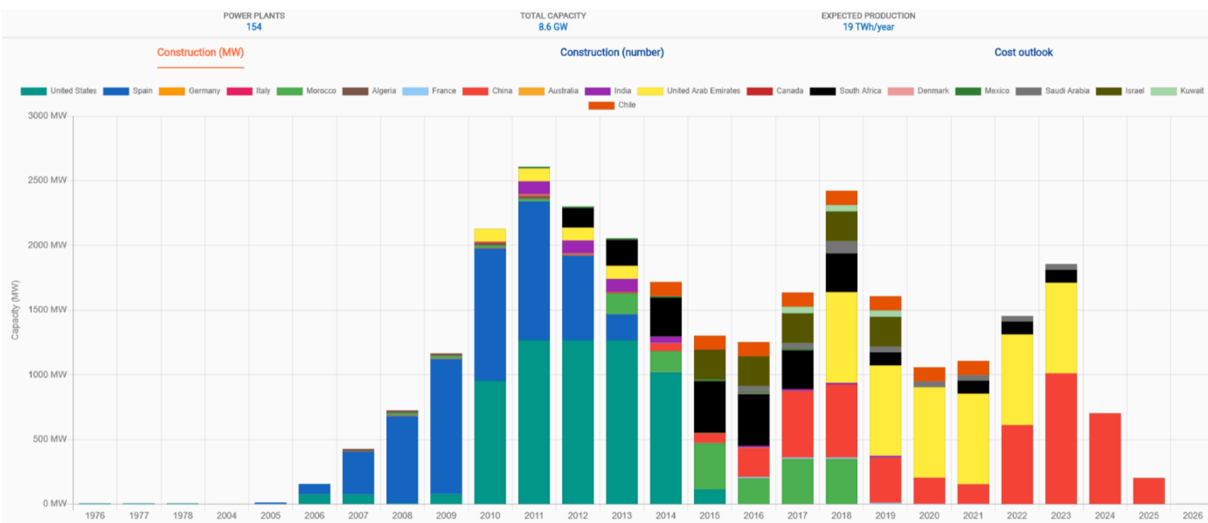

Figure 36. CSP plants installed worldwide for power generation (cspdata.com).

Operating conditions

CSP systems operate at a wide range of temperatures and pressures to optimize power cycle efficiency and integration with TES systems. Key operating parameters include:

- **Temperature and pressure ranges**: CSP plants typically operate at temperatures between 350 °C and 600 °C, with advanced ultra-supercritical systems reaching up to 700 °C. Pressure levels range from 50 to 250 bar, with higher pressures exceeding 300 bar in advanced cycles.

- **Heat Transfer Fluid**: The choice of HTF, such as molten salts or synthetic oils, is crucial for efficient heat transfer within CSP systems. These fluids must withstand high temperatures and maintain thermal stability over long operational periods.
- **Thermal cycling**: CSP plants must manage frequent thermal cycles due to diurnal solar variations. This requires materials and components with high thermal fatigue resistance to ensure durability and reliability.

Power Cycles in CSP Systems

Thermodynamic power cycles are at the core of electricity generation in CSP plants, converting thermal energy into mechanical energy and, subsequently, electricity. The efficiency and performance of CSP systems depend significantly on the type of power cycle employed. The following are the primary power cycles used in CSP applications:

Rankine Cycle

The Rankine cycle is the most commonly used thermodynamic cycle in CSP plants (Figure 37). It involves the use of steam turbines to generate electricity. The key features include [150, 151, 152, 153, 154, 155]:

- Working fluid: Water/steam is the primary working fluid.
- Operating range: Typical operating temperatures range between 350 °C and 550 °C, with ultra-supercritical cycles reaching up to 700 °C.
- TES compatibility: Integrates seamlessly with TES systems, enabling dispatchable power generation.

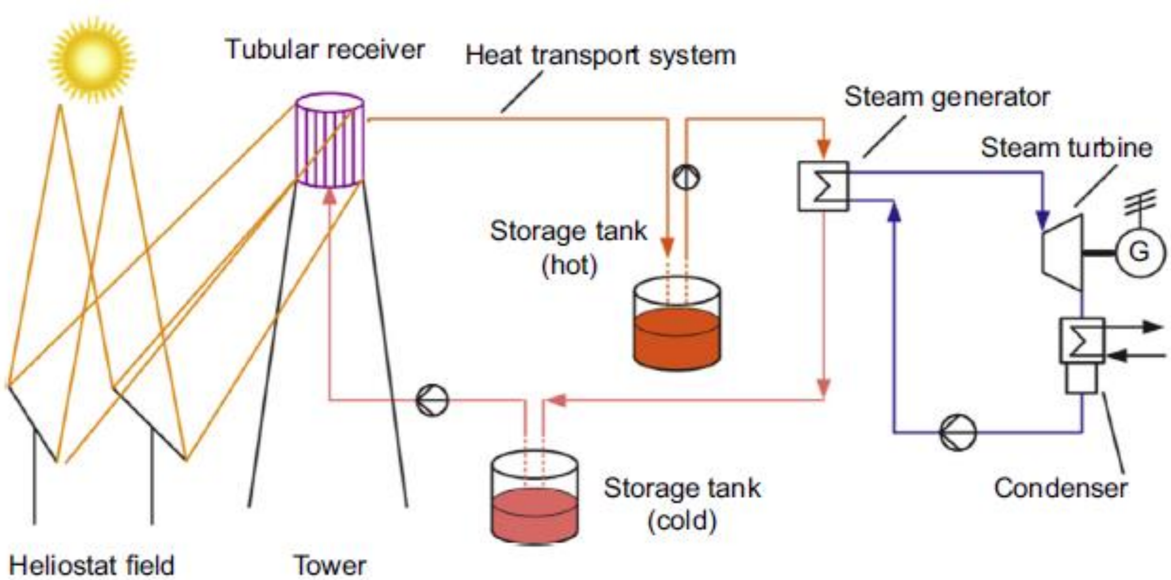

Figure 37. Sketch of a supercritical steam cycle with a power tower plant using liquid HTF and TES [9].

Brayton Cycle

The Brayton cycle uses gas turbines and is particularly suited for high-temperature CSP systems [50, 156, 157, 158]. Figure 38 and Figure 39 show two diagrams illustrating the coupling of a closed and open volumetric receiver to a Brayton cycle.

- Working fluid: Air or other gases.
- Operating range: Temperatures often exceed 1000°C in advanced configurations.
- Advantages: High efficiency at elevated temperatures, making it worth for solar tower systems with volumetric receivers.
- Challenges: Requires high-temperature materials and advanced turbine designs.

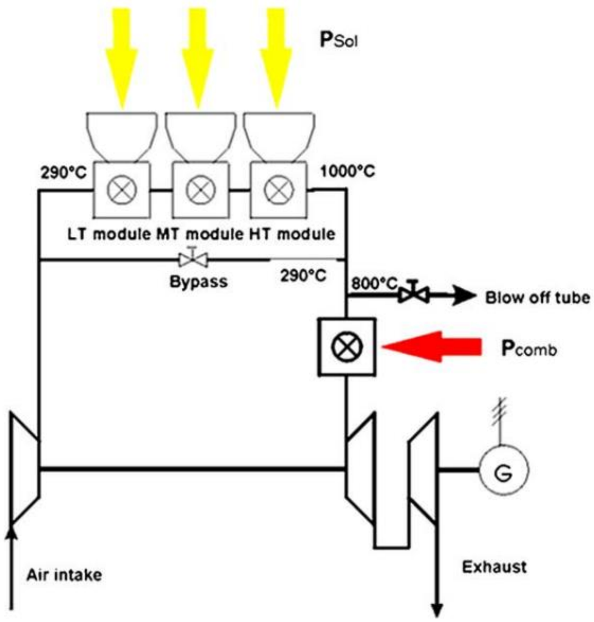

Figure 38. Scheme of a pressurized volumetric receiver coupled to a Brayton cycle [159] .

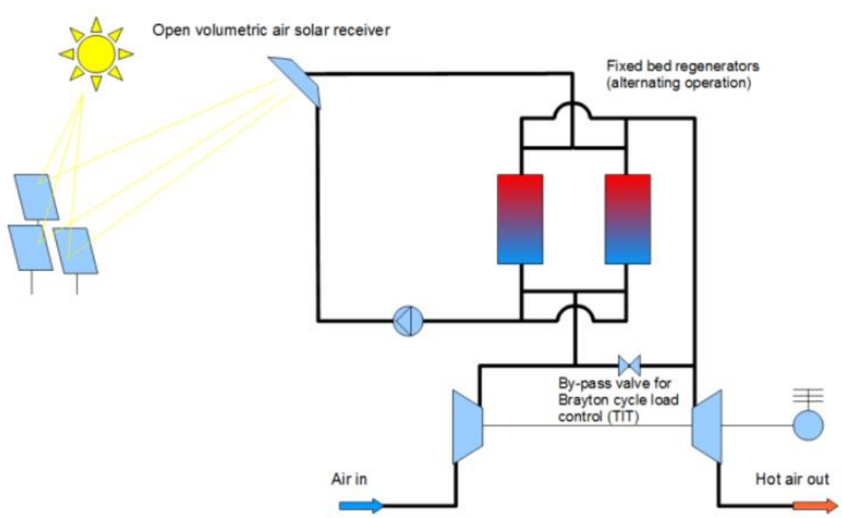

Figure 39. Scheme of an open volumetric receiver coupled to a Brayton cycle [160].

Supercritical CO_2 (sCO_2) cycle

The sCO_2 cycle is an emerging technology with potential for enhanced efficiency and compact system designs [161, 162, 163, 164, 165, 166].

- Working fluid: sCO_2 operates at temperatures ranging from 500 ºC to 700 ºC.
- Benefits: Offers higher thermal efficiency and reduced turbine size compared to traditional Rankine cycles.
- Current status: Under active research and development, with pilot-scale demonstrations underway. Figure 40 shows a scheme of a power tower plant with falling particle technology.

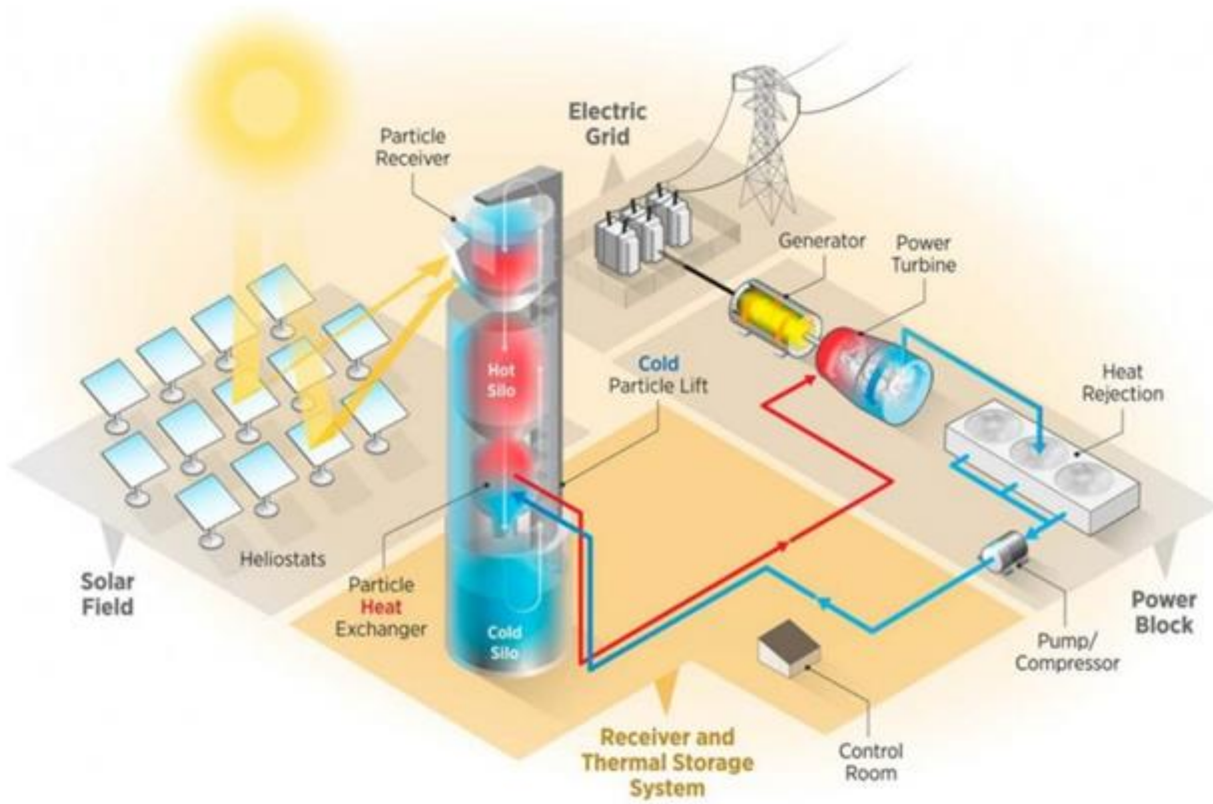

Figure 40. Scheme of falling particle power tower plant [167].

The choice of power cycle depends on the CSP technology, TES configuration, and operational requirements. Advanced cycles such as sCO_2 and Brayton are paving the way for next-generation CSP plants, offering higher efficiencies and improved performance at elevated temperatures, while all current commercial plants used Rankine cycles.

TES Integration

TES is integral to CSP systems, enabling the storage of excess thermal energy for later use. Integrating TES into power generation systems provides flexibility and ensures continuous operation, even during periods of low solar irradiance. Several TES configurations are used:

- Active direct integration: The HTF, such as molten salts, serves as both the working fluid and storage medium. This method eliminates the need for heat exchangers but may face challenges such as freezing risks and high material costs.
- Active indirect integration: Heat exchangers transfer thermal energy between the HTF and storage material. Two-tank systems or thermocline tanks are commonly used for cost efficiency and design flexibility.
- Passive integration: Stationary storage materials, such as concrete or phase-change materials (PCMs), absorb heat from circulating HTFs. These systems are compact and cost-effective but may require additional management of discharge temperatures.

The design of TES systems must align with power cycle requirements, heat demand profiles, and climatic conditions to optimize performance and minimize energy losses.

Optimal CSP technologies

The selection of CSP technology significantly influences the efficiency and scalability of power generation. The following CSP technologies are commonly utilized:

- Parabolic Trough Collector: Widely used for their maturity and efficiency in medium-temperature applications.
- Linear Fresnel Reflector: Offer a cost-effective alternative with simpler designs but lower efficiency compared to PTCs.
- Solar Towers: Best suited for high-temperature applications, achieving temperatures up to 1000°C, which are ideal for advanced TES systems and high-efficiency power cycles.
- Parabolic Dish: More appropriate for localized or small-scale power generation due to their compact size and high efficiency.

Materials for CSP-TES power generation

Materials used in CSP-TES systems must withstand high temperatures, thermal cycling, and corrosive environments. Key material considerations include:

- Heat Transfer Fluids: Molten salts, particularly $NaNO_3/KNO_3$ mixtures, are commonly used for their high thermal capacity and stability.

- Storage materials: Research into PCMs and thermochemical materials aims to enhance energy density and efficiency.
- Receiver materials: Advanced materials like silicon carbide (SiC) and nickel-based alloys resist thermal cycling and high solar flux.
- Insulation materials: Effective insulation, such as graphite-based materials, minimizes thermal losses and enhances overall system efficiency.

Scalability and flexibility

CSP-TES systems offer scalability and operational flexibility, making them suitable for various scales of power generation. Features that enhance their adaptability include:

- Variable storage sizes: TES systems can be tailored to meet fluctuating energy demands and solar resource availability.
- Hybrid systems: Integration with other renewable or conventional energy sources ensures uninterrupted power supply during peak demand periods.
- Coupling: CSP-TES systems can also provide thermal energy for industrial processes or district heating, maximizing resource utilization and system utility.

The scalability and flexibility of CSP-TES systems make them an attractive solution for transitioning to sustainable and resilient energy systems, supporting global decarbonization goals.

5.2Solar Fuel Production

The production of solar fuels through CSP necessitates the use of TES systems that can reach and maintain temperatures exceeding 800ºC, as they involve high-temperature thermochemical processes. A defining advantage of this approach is its ability to leverage solar energy for fuel synthesis, reducing reliance on fossil fuels and minimizing greenhouse gas emissions. Key aspects of solar fuel production include the scalability of processes, the adaptability to various fuel types, and the potential integration with existing industrial systems. Figure 41 summarizes the fuel production pathways using CSP technology [168].

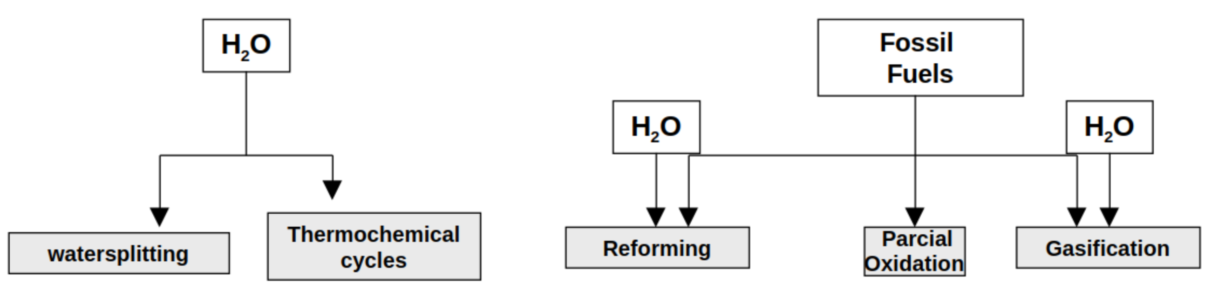

Figure 41. Pathways for fuel generation through CSP technology.

Operating Conditions

Solar fuel production processes operate under a wide range of temperatures and pressures to optimize efficiency and output quality. Key operating parameters include:

- Temperature and pressure ranges:
  - Water splitting: Redox processes require temperatures up to 1500°C, typically at low or atmospheric pressures.
  - Fossil fuel reforming: Temperatures range from 700–800°C and pressures around 15 bar.
- Heat transfer systems: The choice of heat exchangers and TES materials plays a pivotal role in maintaining process stability and efficiency under extreme conditions.
- Thermal cycling: Solar processes must manage frequent thermal cycles due to diurnal solar variations, necessitating materials with high thermal fatigue resistance.

Solar Fuel Production Pathways

Thermochemical processes for solar fuel production are broadly categorized into two pathways:

- Water Splitting: Water splitting involves the production of hydrogen through oxidation-reduction reactions mediated by metal oxides. The process consists of two main steps [169, 170, 171]:
  - Reduction phase: An endothermic reaction at temperatures around 1200°C reduces the metal oxide, releasing oxygen.
  - Oxidation phase: An exothermic reaction where the reduced metal reacts with water to regenerate the metal oxide and produce hydrogen.

  This cyclic process optimizes external energy consumption, utilizing heat from the oxidation phase to drive the reduction phase. Figure 42 illustrates a CSP-based hydrogen production system as implemented in the HydroSol project.

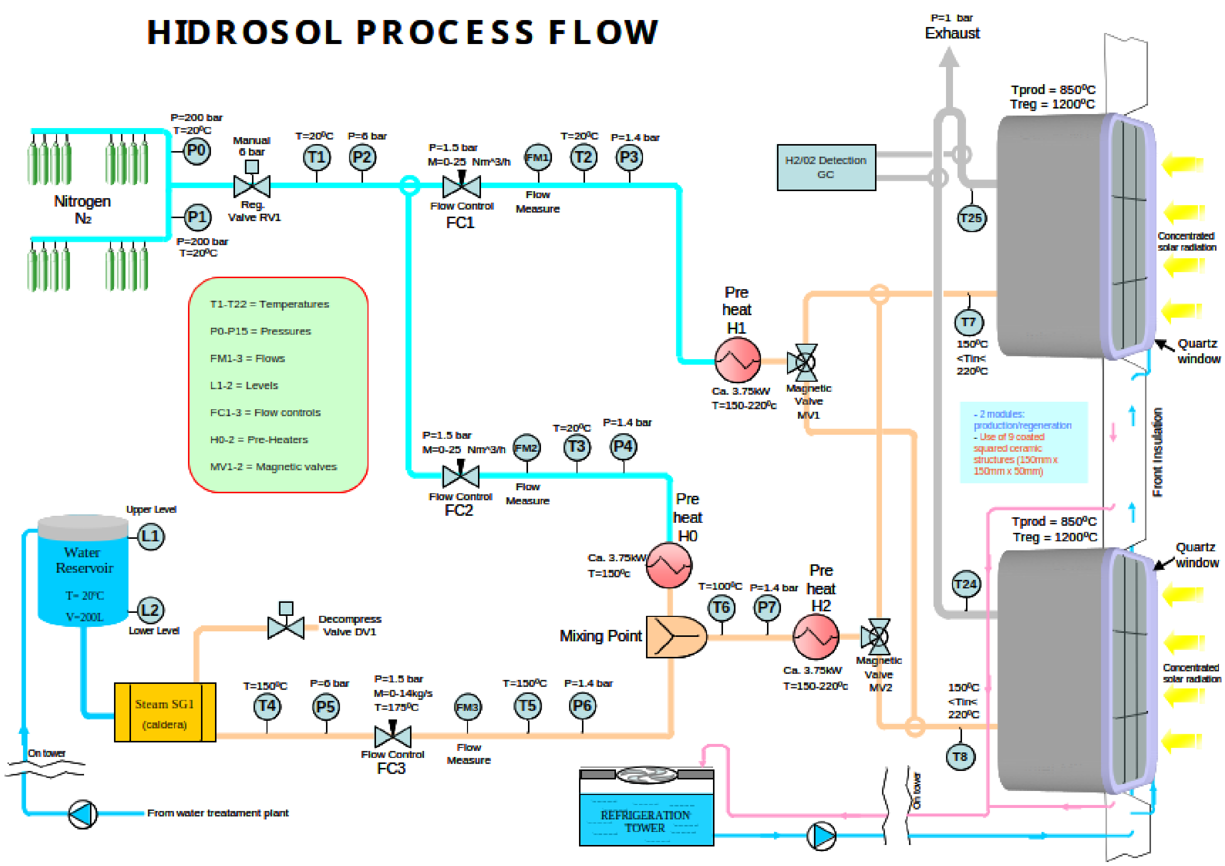

Figure 42. CSP integration in water splitting hydrogen generation. Source: HydroSOL project.

- <u>Solar Valorization of Fossil Fuels</u>: CSP can drive the reforming or gasification of hydrocarbons or chemical industry residues to produce hydrogen (H_2) and carbon monoxide (CO). Key reactions include [172]:
  - Reforming: Methane reforming requires temperatures of approximately 800ºC.
  - Partial oxidation: Gasification operates at higher temperatures, up to 1500ºC.

By utilizing CSP as the primary energy source, these processes minimize reliance on fossil fuels, reducing greenhouse gas emissions. An scheme of SynPet project is shown in Figure 43.

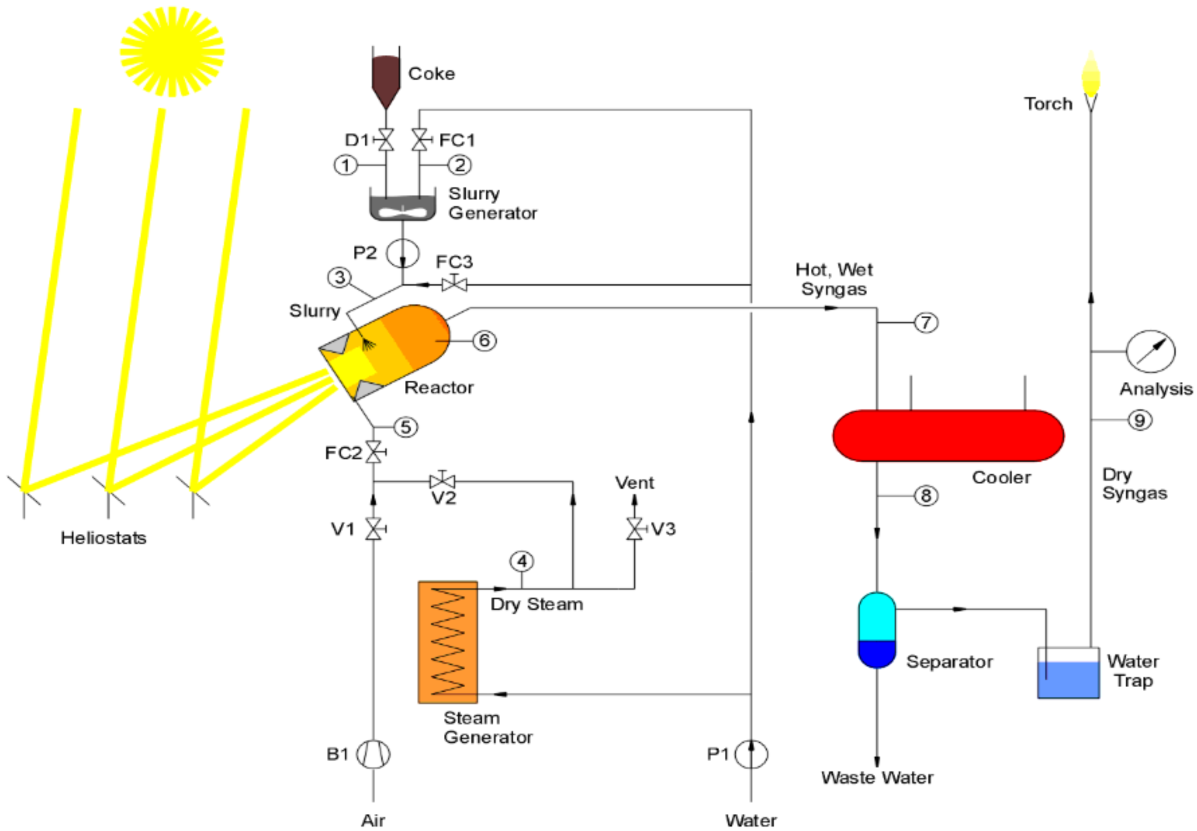

Figure 43. CSP integration in gasification of oil industry residues. Source: SynPet project

Solar fuel production is energy-intensive due to the high temperatures required (>800°C) and the need for continuous 24/7 operation. CSP-TES integration must provide not only the thermal energy to drive reactions but also high-density storage solutions to meet continuous energy demands. The development of advanced TES systems and materials remains a critical challenge for achieving economically viable solar fuel production.

TES Integration

Thermal energy storage is integral to solar fuel production, enabling processes to continue even during periods of low solar irradiance. TES systems enhance flexibility and operational continuity through:

- Direct integration: Solar energy is directly used in thermochemical reactions, minimizing the need for conventional TES systems.
- Thermochemical storage: Fuels like hydrogen serve as long-term energy storage solutions, with applications in automation, power generation, and process heat.

Materials for Solar Fuel Production

Materials employed in solar fuel production must withstand extreme operating conditions, including high temperatures, thermal cycling, and corrosive environments. Key material considerations include:

- Catalysts: Metal oxides for water splitting require thermal stability and high redox activity.
- Reactor materials: Components must resist thermal stress and corrosion, ensuring long-term reliability.
- TES materials: As detailed in Section 5.1, advanced materials for TES are critical to maintaining efficiency and durability.

Optimal CSP Technologies

The choice of CSP technology significantly influences the feasibility and efficiency of solar fuel production:

- Solar towers are best suited for high-temperature applications, achieving the conditions necessary for advanced thermochemical processes.
- Dish-Stirling systems may also be employed for localized or small-scale fuel production, offering high efficiency and adaptability.

The integration of CSP and TES into solar fuel production systems supports global decarbonization efforts by providing sustainable alternatives to conventional fuels and enabling new industrial applications.

5.3Solar Heat Industrial Process (SHIP)

Applying solar heat in industrial processes offers a critical opportunity for decarbonizing energy-intensive sectors. These sectors are among the largest contributors to global CO_2 emissions, making them critical candidates for solar heat integration. By integrating TES systems, industries can address the intermittency of solar energy while meeting their specific temperature requirements. This section examines the potential for CSP integration in four key industrial sectors: cement, steel, chemicals and pharmaceuticals.

These are key industries within the ASPIRE Association (member of the Stakeholder Replicability Board of the COOPERANT project), that manages and implements the Processes4Planet co-programmed partnership. It represents 20% of the EU manufacturing sector and includes 180 industrial and research process stakeholders from over 20 European countries. Sectors include cement, ceramics, chemicals, engineering, minerals, ores, nonferrous metals, pulp and paper, refining, steel, and water. Their main motivation to join the project is to develop key enabling technologies and best practices, as proposed by COOPERANT innovations, to improve resource efficiency in industrial processes.

5.3.1 Cement industry

The cement industry significantly contributes to global CO_2 emissions, accounting for approximately 7% of total emissions. Producing one ton of cement typically requires about 3–4 gigajoules (GJ) of energy and results in emissions ranging from 0.6 to 1 ton of CO_2. Figure 44 depicts the thermal energy consumption by fuel in the EU cement sector. Integrating renewable energy sources like CSP, coupled with advanced TES technologies, offers a promising pathway to decarbonize cement production processes [173, 174].

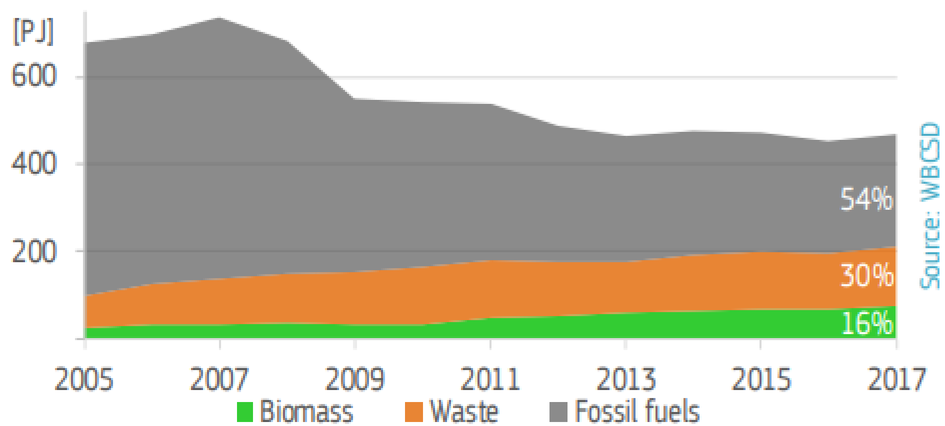

Figure 44. Thermal energy consumption by fuel in the EU cement sector.

Fabrication process

The cement production process involves several energy-intensive stages [175]:

- Raw material preparation: Limestone and clay are crushed and blended.
- Calcination: Materials are heated to ~850 °C to release CO_2.
- Clinker formation: Temperatures of up to 1500 °C are required to form clinker.
- Cooling and grinding: The clinker is cooled and ground with gypsum to produce cement.

Operating conditions and temperature requirements

Cement manufacturing requires temperatures ranging from 1400–1500 °C for clinker production, with additional preheating processes operating at 300–1000 °C. These high energy demands make CSP integration particularly attractive. Solar heat technologies such as molten salts or direct steam generation are particularly effective for preheating stages [176].

TES integration

TES systems are essential for maintaining operational continuity in cement production. High-temperature TES materials, such as molten salts or ceramic, must withstand the intense thermal cycling. Integrating TES requires modifications to preheaters and rotary kilns to ensure seamless energy delivery. However, challenges such as minimizing heat losses in large-scale systems and maintaining high thermal efficiency persist [177, 178].

5.3.2 Steel industry

The steel industry is one of the largest industrial CO_2 emitters, responsible for approximately 7% of global emissions. Producing one ton of crude steel consumes about 20–30 GJ of energy and emits 1.8–2.0 tons of CO_2. This high energy demand, combined with its significant carbon footprint, highlights the potential for CSP integration. By providing renewable heat to key stages of steel production, CSP systems—along with TES technologies—can significantly reduce emissions [179, 180, 181, 182].

Fabrication Process

The steelmaking process includes several key stages [183]:

- Iron ore reduction: Ore is reduced to iron using coke or alternative reducing agents.
- Melting and refining: The material is melted in a blast furnace or electric arc furnace.
- Shaping and finishing: The molten steel is cast, rolled, and finished into products.

Operating conditions and temperature requirements

Steel production requires high temperature, typically ranging from 1000–1600 °C. Key stages, such as reheating furnaces used to prepare steel for rolling or shaping, present opportunities for CSP integration [184]. Electric arc furnaces, which operate at similar temperatures, also represent a target for solar energy applications. Research shows that CSP could be integrated into steelmaking furnaces, particularly in reheating and melting stages. Figure 45 illustrates a facility designed to produce solar steel utilizing parabolic dish systems.

Figure 45. Parabolic dish used to produce solar steel (panatere.com)

TES integration

TES systems for steelmaking must accommodate the rapid fluctuations in energy typical of batch processes. High-temperature TES technologies, such as phase-change materials or thermocline systems, are under development to meet these demands. Challenges include managing thermal cycling and ensuring TES systems can handle large, variable thermal loads. Adaptation of CSP systems to match the heat load variability in steel production is crucial.

5.3.3 Chemical Industry

The chemical industry is energy-intensive, with many processes still relying heavily on fossil fuels [185, 186]. For example, producing one ton of ammonia through the Haber-Bosch process requires approximately 28 GJ of energy and emits around 1.8 tons of CO_2 [187]. Similarly, steam cracking processes used to produce ethylene demand significant energy inputs, operating at temperatures around 850 °C. These high energy requirements and associated emissions highlight the potential for CSP systems to provide renewable heat to various chemical production processes, contributing to the sector's decarbonization efforts [188].

Fabrication process

Key processes in the chemical industry include [189, 190]:

- Ammonia production: Involves the Haber-Bosch process at ~500 °C under high pressure.
- Methanol synthesis: Operates at ~250–300 °C, requiring precise thermal control.

- Steam cracking: A high-energy process (~850 °C) used to produce ethylene and other chemicals.

Operating conditions and temperature requirements

The chemical industry spans a wide range of temperature needs, from low (~200 °C) for processes such as polymer synthesis, to high (~1000 °C) for ammonia production or steam cracking. This diversity presents challenges for CSP integration. However, for high-temperature processes, CSP offers a renewable alternative capable of significantly reducing fossil fuel dependence. Figure 46 depicts a CSP plant integrated with a multi-generation system capable of delivering heat, hydrogen, methane, and electricity.

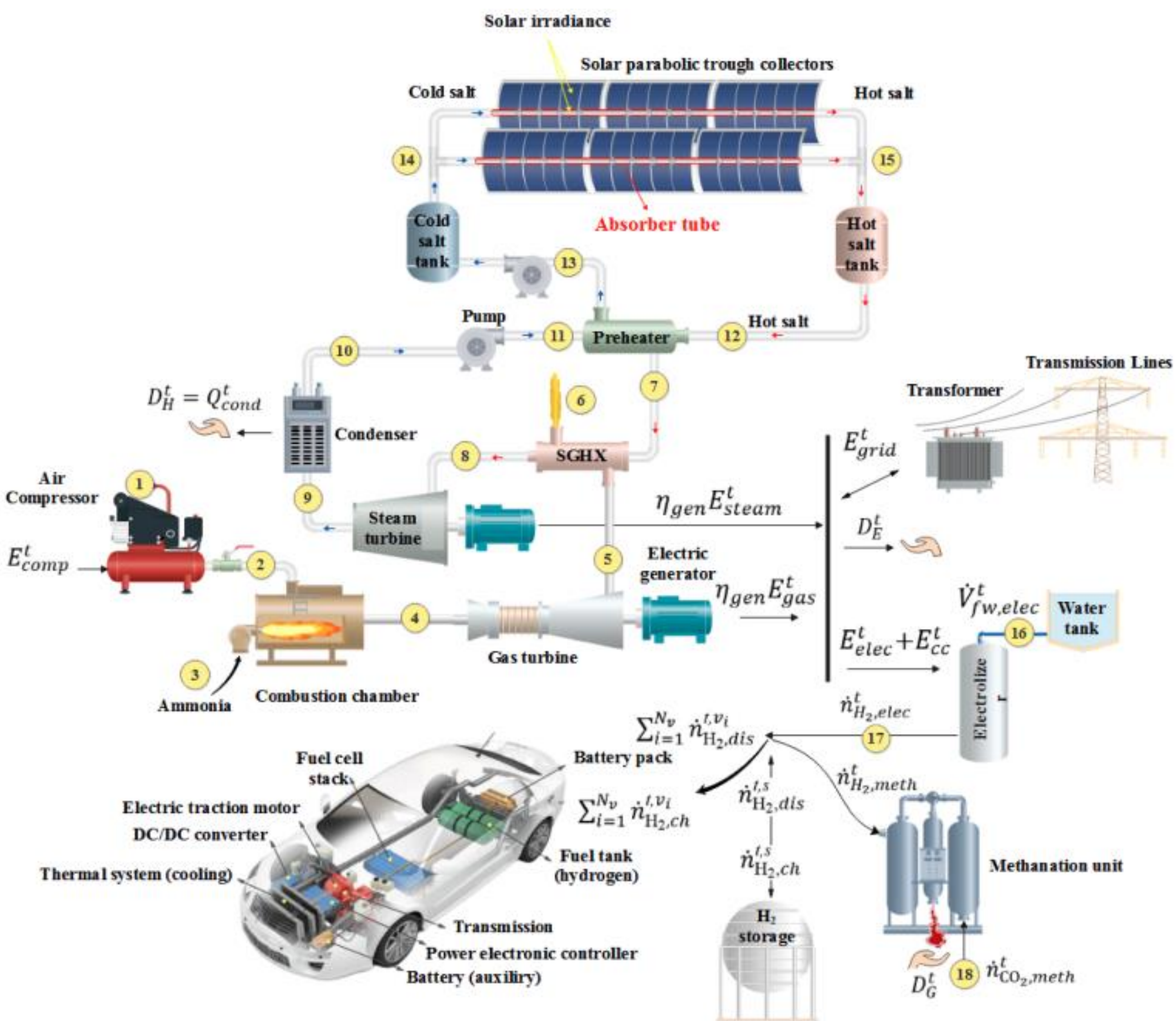

Figure 46.Novel multi-generation system able to supply heat, hydrogen, methane and electricity [187].

TES integration

TES systems for the chemical industry must align with the temperature requirements of specific processes. Low-temperature operations can use sensible heat TES systems, such as pressurized water or oils. High temperature processes, on the other hand, require advanced materials capable of storing heat for extended periods and managing large thermal loads. Integration of TES with chemical production processes may also involve reactor modifications to ensure efficient energy delivery.

5.3.4 Pharmaceutical Industry

The pharmaceutical sector offers substantial potential for decarbonization by integrating CSP and TES technologies. These solutions enhance energy efficiency and support the transition to renewable energy sources [191]. Companies like LONZA, a prominent member of the Stakeholder Replicability Board of the COOPERANT project, exemplify the sector's interest in decarbonization initiatives. LONZA's operations, which include producing vaccines, capsules, cells, and genes, rely heavily on steam generation for various processes. Their primary motivation is to minimize natural gas usage and achieve CO_2 neutrality by 2050 [192]. Regional projects like "Vispertal Solar," [193] which aims to generate approximately 44 GWh annually through alpine PV installations with a 4180 €/kW cost per capacity, complement this effort by offering renewable electricity sources for thermal processes.

Fabrication process

Key processes in the pharmaceutical industry that benefit from CSP and TES integration include [194]:

- Sterilization (120-135°C): Steam sterilization (autoclaving) eliminates microbial contamination, critical for equipment and product safety.
- Steam distillation (60-160°C): This process extracts essential oils and active compounds without degrading sensitive substances. Distillation temperatures can vary greatly depending on the boiling points of the components being separated.
- Active Pharmaceutical Ingredient (API) synthesis (>100°C): Many synthetic routes for APIs require heat, where steam enhances reaction rates and yields during chemical synthesis.
- Drying processes (up to 150°C): Steam facilitates moisture removal from drugs formulations or from heat-sensitive materials via tray or vacuum drying.
- Extrusion (>150°C): to produce certain drug delivery systems or medical devices, involving melting polymers at temperatures that frequently exceed 150°C.

- High-temperature reactions (up to 200ºC): Facilitates reactions to optimize product formation. Reactor temperatures can range from ambient to several hundred degrees Celsius, depending on the reaction.
- Waste heat recovery (25 to over 200ºC): waste heat can be generated from various sources during manufacturing processes in the pharmaceutical industry, namely reactor jackets and condensers (80ºC to over 160ºC), distillation columns (60ºC to over 200ºC), drying equipment (40ºC to 150ºC), chillers and cooling systems (25ºC to 40ºC), boilers and steam systems (120ºC to 180ºC for steam; above 200ºC for flue gases), incinerators (several hundred degrees Celsius even exceeding 800ºC), hot liquid effluents (30ºC to 90ºC), compressed air systems (70ºC to 120ºC), etc.

Operating conditions and temperature requirements

Pharmaceutical processes typically require low to medium temperatures, ranging from 100ºC to 250ºC. These temperature requirements make CSP technologies with thermal fluid systems highly suitable. PTC and LFC, which are efficient for delivering heat at these temperature levels, are particularly relevant. Both technologies can integrate seamlessly with TES systems, ensuring reliable energy supply even during periods of low solar irradiance.

- Parabolic Trough Collectors (PTCs): These systems can efficiently provide heat in the 100–250ºC range and are adaptable to steam generation applications.
- Linear Fresnel Reflectors (LFRs): Offer a cost-effective alternative for lower-temperature steam production and drying processes.
- Hybrid solar thermal systems: Combining CSP and PV systems for maximum utilization of solar resources, especially in regions with seasonal variations in solar irradiance.

TES integration

TES is essential for optimizing the use of CSP in pharmaceutical applications. Systems such as pressurized water tanks or PCMs are ideal for storing thermal energy within the temperature ranges required by pharmaceutical processes. TES can stabilize steam supply, improve energy efficiency, and reduce reliance on natural gas.

For example, LONZA has explored using TES units to store excess energy from alpine PV installations. These TES units enable high round-trip efficiency and ensure long-term storage, supporting pharmaceutical facilities' operational needs without disrupting existing processes.

5.4 Solar thermal in district heating

District heating (DH) systems are centralized networks for distributing heat through a network of insulated pipes to residential, commercial, or industrial buildings. The heat is typically generated in a central facility using a variety of energy sources, including waste heat from industrial processes, geothermal energy, biomass, and increasingly renewable energy sources like solar power. CSP systems coupled with TES represent an emerging and sustainable option for DH, especially in regions with high solar irradiance, and its importance is expected to grow in the coming years [195].

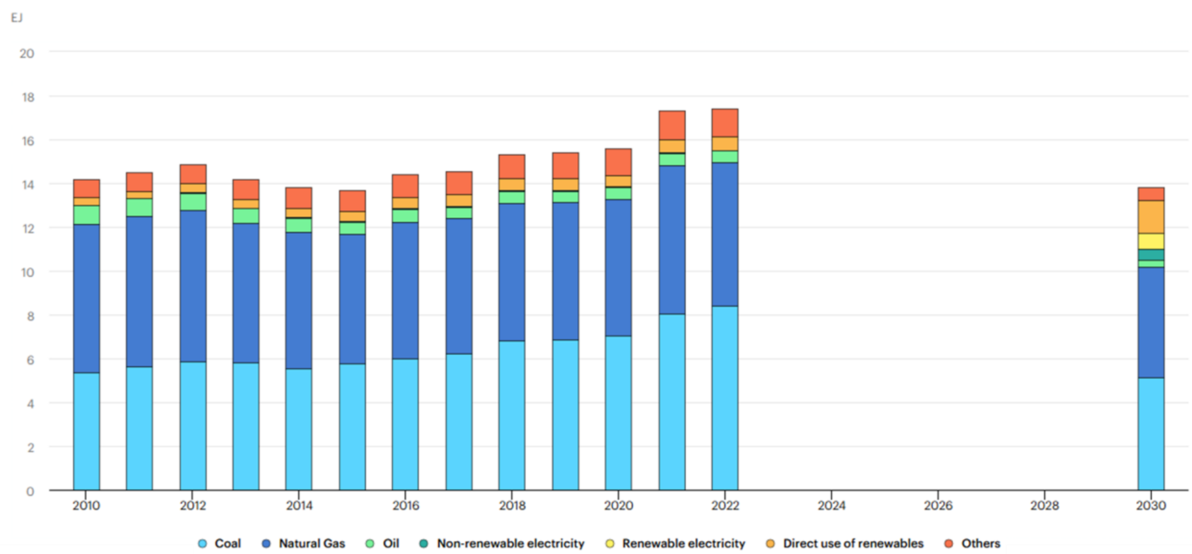

Figure 47. Evolution of heat sources in district heating in Europe [195].

CSP systems collect and concentrate solar radiation to generate heat, which can be stored in TES systems to ensure continuous operation even when sunlight is unavailable. This stored thermal energy can efficiently provide a consistent and reliable heat supply for DH networks. The integration of CSP-TES into DH systems not only enhances energy security but also supports decarbonization by replacing fossil-fuel-based heat generation.

CSP-TES technology offers significant potential. For instance, FMI, a member of COOPERANT's replicability board and the energy agency for several municipalities in Forlì (Italy), operates a 1.4 MW_th CSP plant with 2.800 m^2 of parabolic concentrators. Integrating CSP with novel TES solutions, along with hybridization of their PV system, can substantially enhance the overall energy efficiency and reliability of the network. By adopting CSP-TES technology, FMI can reduce dependency on conventional energy sources, lower carbon emissions, and ensure a stable thermal energy supply to industrial users. This underscores the broader potential of DH networks as a key sector where innovative renewable energy technologies can drive sustainable transitions.

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Operating conditions

DH networks typically operate under two main conditions: low-temperature systems (80–100°C) and very low-temperature systems (50–70°C) [196]. These temperatures depend on the network's design and end-user requirements. CSP systems can efficiently generate high temperatures (around 565°C) [197] through concentrated solar radiation, which can then be transferred to a TES system for buffering and integration into DH networks.

TES systems for DH need to match these temperature ranges. PCMs and molten salts are commonly used for high-temperature storage, while water and low-melting-point PCMs are more suitable for low-temperature systems [198]. Proper insulation is critical to minimize heat losses over long distances.

TES integration

TES is critical for aligning solar energy supply with the variable heat demand of DH networks. The TES system depends on factors like DH network scale, demand profiles, and local climatic conditions. TES ensures a steady heat supply and overcomes the intermittency of solar energy.

Common TES configurations include [199]:

- Active direct integration: The HTF (e.g., molten salts or steam) serves as both the working fluid and the storage medium. A two-tank system eliminates heat exchangers but may face challenges like freezing or high material costs.
- Active indirect integration: Heat transfer occurs between the HTF and storage materials via a heat exchanger. This configuration offers flexibility, using either two tank or thermocline systems to reduce costs, but requires careful control for thermal stratification.
- Passive integration: Stationary storage materials (e.g., concrete, rocks, sands, or PCMs) transfer heat via circulating HTFs. These systems, often using a shell-tube design, are simple, compact, and cost-effective, though they may lack yield varying discharge temperatures.

Optimal CSP technologies

Selecting appropriate CSP technologies for DH involves balancing cost, efficiency, and land use. Feasible options are [200, 201]:

- Parabolic trough collectors (PTCs): Mature technology generating medium-temperatures suitable for DH.
- Linear Fresnel reflectors (LFRs): Cost-effective but lower efficiency and temperatures.
- Solar towers: Achieve very high temperatures (up to 1000°C), ideal for advanced TES systems and large-scale DH.

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- Dish-Stirling systems: Suitable for localized or small-scale DH networks.

Materials for CSP-TES District Heating

Materials for CSP-TES systems must withstand corrosive HTFs, and several thermal cycling while ensuring economic feasibility. Long-duration storage is usually needed. Key materials include:

- HTFs: Molten salts (e.g., $NaNO_3/KNO_3$) are commonly used for their heat capacity and thermal stability [202].
- Storage materials: Research is advancing in PCMs and thermochemical materials for higher energy densities and efficient latent heat storage [202].
- Receiver materials: High-temperature resistant materials (e.g., SiC and SiSiC) that will be studied in COOPERANT are critical for withstanding concentrated solar flux.
- Insulation Materials: Graphite and similar materials are essential to reduce thermal losses.

Scalability and Flexibility

CSP-TES systems are inherently scalable and flexible, suitable for DH networks of varying sizes and demands. Key features include [203]:

- Variable storage sizes: Adaptable to fluctuating solar energy availability and heat demand.
- Hybrid systems: Integration with other renewable or conventional energy sources ensures uninterrupted service.
- Sector coupling: CSP-TES can support electricity generation or industrial process heat alongside DH, enhancing system utility.

This scalability and flexibility make CSP-TES an attractive solution for DH networks, advancing sustainable and resilient energy systems.

6 CSP and TES System Requirements based on Application

General Summary of Requirements

The requirements for CSP-TES systems vary significantly depending on the target application. Each application imposes distinct operational conditions, temperature ranges, and integration challenges that dictate the choice of receiver technology, heat transfer fluid, and TES configuration. Below is a structured overview of the key system requirements derived from the preceding sections.

Table 16 provides a summary of CSP and TES requirements across the primary applications. By tailoring CSP and TES systems to these applications' requirements, the technology can address a wide range of energy needs while supporting the global transition to sustainable energy systems. Each application offers unique challenges and opportunities, emphasizing the need for continued research and development to optimize integration and enhance performance.

Application	Temperature Range	Key Requirements	TES Considerations
Power Generation	High (500–900°C)	Advanced power cycles (e.g., sCO_2), high thermal efficiency, stable power output.	High-capacity TES, efficient heat exchangers, and dispatchability to match grid demands.
Solar Fuel Production	Ultra-high (>1000°C)	Compatibility with chemical reactors, extreme thermal and chemical stress resistance.	Rapid thermal cycling, materials capable of withstanding high temperatures and reactive environments.
SHIP	Medium to high (150–800°C)	Process-specific temperature profiles, integration with industrial heat networks.	Custom TES design for specific sectors (e.g., cement, steel), focus on minimizing thermal losses.
District Heating	Low to medium (70–150°C)	Seasonal and diurnal flexibility, seamless integration with district heating systems.	Cost-effective TES for both short- and long-term storage, optimized for low-temperature applications.

Table 16. High level summary of the main requirements for each application.

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Details of each specific application

This section aims to provide more detail for each target application as a result of the comprehensive review done in this document. Section 3 provides insight into the key metrics and parameters of the solar source (such as solar input, annual capacity, and suitable CSP type of technology). In contrast, section 4 provides information about the appropriateness of the type of TES, materials, duration and storage capacities, and its major challenges. The following tables outline the typical specific requirements and challenges for each application:

Power Generation

High-temperature operation is essential for greater thermal efficiency, particularly when integrating advanced power cycles such as supercritical CO_2 or combined cycles. TES systems must provide stable and dispatchable power output to align with grid demands, requiring high thermal capacity and efficient heat exchangers.

Parameter	Details
Solar conditions	Optimized for medium to high DNI locations (>1500 kWh/m²/year), ensuring reliable operation in regions with consistent solar resources
Temperature range	High (500-900°C)
Key technologies	sCO_2 cycles, Rankine cycles, combined cycles
Solar input (receiver types)	Tubular, billboard or cavity receivers
Heat Transfer Fluid	Molten salt, particle, or water/steam
TES system design	From short-term steam storage for transient fluctuations (< 1 hour) to high thermal capacity for overnight dispatchability. Requires efficient heat exchangers to ensure optimal performance and minimal losses.
TES type and capacity	Sensible heat 2 tank direct, molten salts, up to 18 hours. Steam generators, steam, up to 2 hours.
Challenges	High-temperature material durability, cost-efficiency
Energy demand profiles	Designed to adapt to diverse power generation profiles, depending on key technology and solar conditions. Systems operate from direct generation without storage to configurations supporting up to 18 hours of TES, tailored to plant design and grid stability requirements
CSP capacity needs	Link to Table 5 and CSP-TES technologies used CRS (high-temperature applications): -Annual capacity factor 25-28% (no TES); 29-55% (with TES) -Typical plant capacity 10-200 MW_e (~40-500 MW_{th})

	PTC (most mature for medium-temperature applications): -Annual capacity factor 25-28% (no TES), 29-43% (with TES) -Typical plant capacity 10-300 MW_e (~30-900 MW_{th})

Table 17. Detailed summary of the key requirements for power generation applications.

Solar Fuel Production

This application demands ultra-high temperatures and materials capable of withstanding extreme thermal and chemical stresses. TES systems must ensure rapid thermal cycling capabilities to support intermittent solar input while maintaining compatibility with chemical reactors.

Parameter	Details
Solar conditions	Optimized for medium to high DNI locations (>1500 kWh/m²/year, preferable >2000 kWh/m²/year), ensuring reliable operation in regions with consistent solar resources
Temperature range	Ultra-high (>1000°C)
Key technologies	Chemical reactors (e.g., for syngas, hydrogen production), thermochemical processes
Solar input (receiver types)	Particle or volumetric receivers
Heat Transfer Fluid	Particles, air
TES system design	Requires high thermal capacity for continuous operation, handling rapid thermal cycling and thermal efficiency. Efficient heat exchangers are essential to maintain stability
TES type and capacity	Thermocline systems, atmospheric air, up to 6-7 hours; Compressed air, pressurized air, up to 3-6 hours; Particle energy storage, up to 6-9 hours
Challenges	Materials capable of withstanding extreme thermal and chemical stresses, ensuring long-term durability and efficient performance under variable operating conditions
Energy demand profiles	Designed to support continuous 24/7 operation, utilizing TES for managing intermittent solar availability. Systems are tailored to optimize energy storage and delivery based on plant design and specific fuel production needs
CSP capacity needs	Link to Table 5 and CSP-TES technologies used CRS (high-temperature applications):

	-Annual capacity factor 25-28% (no TES); 29-55% (with TES) -Typical plant capacity 10-200 MW_e (~40-500 MW_{th}) PD (small scale production with high efficient and adaptability): -Annual capacity factor 25-28% (no TES) -Typical plant capacity 10-25 kW_e (~40-100 kW_{th})

Table 18. Detailed summary of the key requirements for solar fuel production applications.

<u>Solar Heat for Industrial Processes (SHIP)</u>

Industrial processes require medium-to-high-temperature ranges depending on the sector, with TES systems designed to handle specific temperature profiles and operational schedules. Integration with existing process heat networks and minimizing thermal losses are critical factors for SHIP applications in industries such as cement, steel, and chemicals.

Parameter	Details
Solar conditions	Optimized for medium to high DNI locations (>1500 kWh/m²/year)
Temperature range	Medium to high (150-800°C)
Key technologies	Cement, steel, chemical, pharmaceutical industries
Solar input (receiver types)	Tubular, billboard, cavity or volumetric receivers
Heat Transfer Fluid	Molten salts, water/steam, oils, air
TES system design	Designed to support continuous operation, ensuring consistent heat supply during non-sunny periods or transients. Must handle large thermal loads and operational schedules
TES type and capacity	Molten salts, phase-change materials, up to 6-10 hours; Thermocline systems, up to 6-8 hours; Steam generators, up to 2 hours
Challenges	High-temperature cycling, integration with existing industrial systems, minimizing heat losses, ensuring thermal efficiency
Energy demand profiles	Tailored for key technologies needs with intermittent solar availability, ensuring constant energy supply during off-sun or transient hours. TES must be designed to be adaptable to continuous process operation, batches, or seasonal loads.
CSP capacity needs	Link to Table 5 and CSP-TES technologies used CRS (high-temperature applications): -Annual capacity factor 25-28% (no TES); 29-55% (with TES) -Typical plant capacity 10-200 MW_e (~40-500 MW_{th})

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	LFC (low-temperature steam applications): -Annual capacity factor 22-24% (no TES) -Typical plant capacity 10-200 MW_e (~30-650 MW_{th}) PD (localized or small-scale applications): -Annual capacity factor 25-28% (no TES) -Typical plant capacity 10-25 kW_e (~40-100 kW_{th}) PTC(medium-temperature steam applications) : -Annual capacity factor 25-28% (no TES), 29-43% (with TES) -Typical plant capacity 10-300 MW_e (~30-900 MW_{th})

Table 19. Detailed summary of the key requirements for SHIP applications.

Solar Thermal in District Heating

These systems operate at relatively lower temperatures but demand high operational flexibility to cater to diurnal and seasonal variations in heating demand. TES systems must ensure effective short- and long-term storage solutions, focusing on cost-effectiveness and ease of integration with district heating networks.

Parameter	Details
Solar conditions	Optimized for medium to high DNI locations (>1500 kWh/m²/year)
Temperature range	Low to medium (70–150°C)
Key technologies	Integration of CSP-TES with district heating networks, coupled with solar power and/or energy storage solutions
Receiver type	Low-temperature tubular or flat-plate receivers; Parabolic troughs for medium temperatures
Heat Transfer Fluid	Water/steam, air, oils
TES system design	Requires cost-effective, seasonal and diurnal storage, with the potential for active, indirect or passive integration
TES type and capacity	Active direct integration (steam), active indirect integration (heat exchangers with thermocline systems), and passive integration (PCMs, concrete, rocks)
Challenges	Low-temperature efficiency, large-scale deployment, material durability under high temperatures, insulation to minimize heat losses, and cost of large-scale systems
Energy demand profiles	Designed to meet the fluctuating and variable heat demand of district heating networks, ensuring stable supply during off-sun hours.

	In addition, further consideration of seasonality depends on the climatic severity (section 3.3).
CSP capacity needs	Link to Table 5 and CSP-TES technologies used LFC (most cost-effective for low-temperature DH networks): -Annual capacity factor 22-24% (no TES) -Typical plant capacity 10-200 MW_e (~30-650 MW_{th}) PTC (most mature for medium-temperature DH networks): -Annual capacity factor 25-28% (no TES), 29-43% (with TES) -Typical plant capacity 10-300 MW_e (~30-900 MW_{th})

Table 20. Detailed summary of the key requirements for solar thermal district heating applications.

A deeper analysis should be conducted for each application to ensure that it is customised and adapted to the operating conditions and demand requirements. In later stages of the project execution, the replicability scenarios (Task 6.4) will be established on the basis of the insights provided by these tables and the selected replication cases. It is necessary to determine the generation of use cases, the solar input, the energy demand profiles, the storage power and capacity requirements.

COOPERANT alignment with application requirements

The COOPERANT project's alignment with application requirements is supported by a multifaceted strategy that includes a thorough industrial needs assessment (application exploration in Task 1.3), active engagement to gather insights into real-world demands (clustering and stakeholder replicability board involvement in task 6.3), and market analyses (performed in Task 6.2). The development of technical specifications will be tailored to the operational criteria of CSP-TES applications and testing under conditions similar to those found in actual use cases (design, engineering and prototyping in WP4). The project prioritises scalability and replicability (Task 6.4), conducts economic and environmental impact assessments and follows policy and regulatory frameworks (WP5).

Overall, COOPERANT makes a meaningful contribution to solving the most severe limitations of existing renewable energy sources at both EU and global levels (as detailed in section 2), putting CSP technology at pace to compete with other RES such as wind and solar photovoltaics:

1) The project envisages achieving high-temperature efficiency and cost-effectiveness via CSP operation at around 1000ºC (meeting all the application requirements) through an air Brayton cycle. This would improve the thermodynamic efficiency of power generation, hence lowering the cost per unit of electricity produced.

2) Overcoming unpredictability and intermittency of the renewable source using a hybrid packed-bed TES system that employs increased phase-change materials and solid-state mixes to increase solar energy dispatchability.
3) Upscaling feasibility in accordance with the CSP roadmap. In this sense, the technological developments will be backed by the COOPERANT Artificial Intelligence Tool, which improves CSP facility management and can be adjusted to emulate different operating sizes and scenarios, ensuring broad adoption.

COOPERANT's continuous review and adaptability will enable it to remain in tune with the changing landscape of CSP-TES applications, ensuring its continued relevance to industry needs.

7 Conclusions

COOPERANT's contributions to advancing Concentrated Solar Power (CSP) technologies and Thermal Energy Storage (TES) are pivotal in overcoming the current limitations of renewable energy sources, both at European and global levels. Lately, to unlock this challenge, numerous previous and ongoing EU-funded projects have concentrated on developing innovative materials and designs for CSP-TES components, higher-efficient Rankine and Brayton power cycles, and heat transfer fluids to enhance the economic viability and sustainability of CSP-TES integration and enable third-generation CSP technologies.

By addressing key challenges, such as efficiency, high operation temperature, predictability, and scalability, COOPERANT aligns its innovations with EU and international roadmaps, contributing to the energy transition and the achievement of net-zero emissions by 2050. COOPERANT advances thermodynamic efficiency (>42%) and reduces the cost per unit of electricity produced by integrating high-temperature CSP systems operating at around 1000ºC, enabling CSP to compete with other renewable energy sources like wind and photovoltaics.

<u>Conclusions Section 2</u>

COOPERANT's advancements position CSP technology to fulfil the goals set out by the IEA and the European Commission (EC), particularly in boosting CSP's role in the global energy mix. Both bodies emphasize the need for renewable energy advancements to attain net-zero emissions by 2050, with PV at the forefront and an increased role of CSP. The report reviewed the current policies at EU and global level and details the most important goals and missions. For instance, the October 2023 amended SET Plan aligns the strategic objectives with the European Green Deal, REPowerEU, and the Green Deal Industrial Plan, notably the Net-Zero Industry Act. These initiatives will lead to accomplishing the CSP technology targets and becoming economically effective, by lowering electricity costs (<15 c€/kWh by 2025 and <10 c€/kWh by 2030); boosting power plant efficiency up to 42.4% by 2025; and efficiently integrating novel FOAK prototypes.

Regarding TES, the IRENA report highlighted the improvement of TES integration into the CSP systems. In this context, the high energy efficiency (>92%) and potential cost reduction (to 60-90 €/kWh) of sensible and latent heat systems motivate their adoption by 2030. The project's novel thermal storage approach, combining a hybrid packed-bed system of solid-state mixtures and PCMs, increases energy density while reducing costs and the system size by up to 30%. These efforts align with the CSP roadmap for cost reduction and TES improvements, ensuring that COOPERANT's innovations contribute meaningfully to the transition toward a sustainable, decarbonized energy future.

Conclusions Section 3

CSP technologies offer diverse solutions for harnessing solar energy, each with its distinct characteristics and applications. The key performance metrics, including efficiency, reliability, and cost-effectiveness, vary across different CSP technologies (such as parabolic troughs, solar towers, dish-engine systems and central receiver systems). The adaptability of CSP systems to diverse environmental and operational conditions is crucial for their successful deployment in a range of geographic locations and industrial sectors. Tailoring these systems to specific conditions can optimize performance, reducing costs while enhancing the integration of CSP into existing energy infrastructures. As CSP technology continues to evolve, its versatility and potential for large-scale renewable energy generation remain promising, especially when coupled with advancements in thermal energy storage and hybrid systems.

Conclusions Section 4

On the one hand, section 4.1 describes the three main categories of TES systems: sensible, latent and thermochemical heat storage. In sensible heat storage, energy is stored by heating a storage medium such as molten salts, ceramics, or rocks with the amount of energy stored depending on the temperature change. Latent heat storage uses phase changes, such as from solid to liquid, to store energy with common materials, including molten salts or metals with suitable melting points as PCMs. Thermochemical storage stores energy through reversible chemical reactions, where energy is absorbed during the breaking of chemical bonds and released during the reverse reaction.

On the other hand, section 4.2 identifies the TES metrics for CSP systems (specific heat capacity, thermal conductivity, energy density, round-trip efficiency, thermal stability, costs, and durability) and summarises the influence on CSP effectiveness optimisation. For large-scale applications with enough space, sensible thermal energy storage systems are the cheapest (50-100 €/kWh). CSP plants that need simple, affordable solutions benefit from them. Molten salts and PCMs are more expensive but have higher energy densities and specific heat capacities, balancing cost and performance. Thermochemical storage systems are ideal for high-temperature and long-term storage applications. They have excellent energy density and long-term storage. However, they usually involve a high cost of 200-300 €/kWh and are technically more difficult than the other alternatives.

Nonetheless, the conventional solutions are not enough as CSP applications in the higher temperature range of 600-1000°C face major challenges: material durability is critical to prevent erosion and corrosion of containers and heat exchangers. The stability of storage materials can be compromised as their structure changes at high temperatures. Heat losses are hard to minimize due to the need for advanced insulation. High costs for suitable materials and technologies are another issue, as is the reaction behaviour in thermochemical storage, which can suffer at elevated temperatures.

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Conclusions Section 5

CSP and TES systems offer tailored solutions for a range of applications, each with specific operational requirements and integration challenges. Power generation applications demand high-temperature, efficient systems capable of supporting advanced power cycles, while solar fuel production requires ultra-high temperatures and robust materials. SHIP applications, spanning industries such as cement, steel, and chemicals, need medium to high-temperature solutions with precise TES integration. Finally, solar thermal in district heating emphasizes cost-effective, flexible TES systems for low-temperature applications. By addressing the unique needs of each sector, CSP and TES technologies can significantly contribute to decarbonization and the transition to sustainable energy.

Conclusions Section 6

The analysis of CSP and TES system requirements highlights the importance of tailoring technologies to address the unique demands of diverse applications. Each application is analysed—power generation, solar fuel production, SHIP, and district heating—and presents distinct temperature ranges, capacities, integration challenges, and operational goals. The present document and the tables will support the definition of the prototype specifications (T2.1). In addition, a first review is done for the implications of the industrial members belonging to the Stakeholder Replicability Board of COOPERANT related to potential CSP-TES applications.

The report outlines key aspects under consideration to determine the generation of use cases, such as the solar input, the energy demand profiles, and the storage power and capacity requirements, which need to be tailored solutions in receiver technologies, HTFs, and TES designs.

- Power Generation: Achieving high thermal efficiency requires advanced power cycles (e.g., Brayton, Rankine, sCO_2) and robust and mature TES systems designed for high-capacity storage and dispatchability. Addressing material durability and cost efficiency is crucial for success.
- Solar Fuel Production: The ultra-high temperature requirements for chemical processes demand materials and TES systems capable of enduring extreme thermal and chemical stresses. Rapid thermal cycling compatibility is vital to accommodate intermittent solar input.
- Solar Heat for Industrial Processes (SHIP): Medium-to-high-temperature operations necessitate tailored TES designs specific to industrial sectors, such as cement, steel, and chemicals. Effective integration with existing heat networks and minimizing thermal losses are key priorities.
- District Heating: Operating at lower temperatures, these systems emphasize cost-effective TES solutions with flexibility for both diurnal and seasonal storage. Seamless integration with district heating networks ensures practicality and efficiency.

References and Resources

[1] S. Rodat and R. Thonig, "Status of Concentrated Solar Power Plants Installed Worldwide: Past and Present Data," *Clean Technologies,* pp. 365-378, 2024.

[2] UAE Consensus, "Delivering on the UAE Consensus, Trackling Porgress Toward Tripling Renewable Energy Capacity and Doubling Energy Efficiency by 2030," 2024.

[3] F. Aprà and et al., "Overview of the Enablers and Barriers for a Wider Deployment of CSP Tower Technology in Europe," *Clean Technologies ,* vol. 3, no. 2, pp. 377-394, 2021.

[4] IRENA, "Renewable Power Generation Costs," 2024.

[5] SolarPaces, "solarpaces.org," [Online]. Available: https://www.solarpaces.org/worldwide-csp/csp-projects-around-the-world/. [Accessed Nov 2024].

[6] SolarPACES, "solarpaces," [Online]. Available: https://www.solarpaces.org/worldwide-csp/csp-potential-solar-thermal-energy-by-country/usa/. [Accessed Nov 2024].

[7] SolarPACES, "solarpaces.org," [Online]. Available: https://www.solarpaces.org/worldwide-csp/csp-potential-solar-thermal-energy-by-country/morocco/. [Accessed Nov 2024].

[8] SolarPACES, [Online]. Available: https://www.solarpaces.org/worldwide-csp/csp-potential-solar-thermal-energy-by-country/south-africa/. [Accessed Nov 2024].

[9] SolarPACES, "solarpaces.org," [Online]. Available: https://www.solarpaces.org/worldwide-csp/csp-potential-solar-thermal-energy-by-member-nation/china/. [Accessed Nov 2024].

[10] IRENA, "World Energy Transitions Outlook 2024, 1.5°C Pathway," 2024.

[11] IRENA, "Innovation Outlook Thermal Energy Storage," 2020.

[12] NeXore88, okta, kosonicon and Voysla, "Icons from flaticon.com".

[13] SET Plan, "Initiative for Global Leadership in Concentrated Solar Thermal," 2023.

[14] REN21, "ren21.net," [Online]. Available: https://www.ren21.net/gsr-2024/modules/energy_supply/02_market_and_industry_trends/02_csp/. [Accessed Nov 2024].

[15] IEA, "Net Zero by 2050, A Roadmap for the Global Energy Sector," 2021.

[16] Sandia , "energy.sandia.gov," [Online]. Available: https://energy.sandia.gov/programs/renewable-energy/csp/current-research-projects/gen-3-particle-pilot-plant-g3p3/. [Accessed Nov 2024].

[17] ASPIRE, "aspire2050.eu," [Online]. Available: https://www.aspire2050.eu/prema/New-Event/autonomous-heliostat-fields-small-scale-csp-plants. [Accessed Nov 2024].

[18] GlassPoint, "glasspoint.com," [Online]. Available: https://www.glasspoint.com/projects/maaden-solar. [Accessed Nov 2024].

[19] S. Afroze and et al., "Solar-Powered Water Electrolysis Using Hybrid Solid Oxide Electrolyzer cell (SOEC) for Green Hydrogen- A Review," *Energies,* vol. 16, no. 7794, 2023.

[20] E. Commission, "commission.europa.eu," [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en. [Accessed Nov 2024].

[21] E. Commission, "energy.ec.europa.eu," [Online]. Available: https://energy.ec.europa.eu/news/commission-launches-european-energy-efficiency-financing-coalition-accelerate-private-investment-2024-04-22_en. [Accessed Nov 2024].

[22] SET Plan, "Clean Energy Transition Partnership Strategic Research and Innovation Agenda," 2020.

[23] Heliocsp, "heliocsp.com," [Online]. Available: https://helioscsp.com/sener-lanza-solgest-1-la-primera-central-hibrida-de-termosolar-con-almacenamiento-y-fotovoltaica-de-espana/. [Accessed Nov 2024].

[24] MUSTEC, "Roadmap for collaborative CSP development in Europe," 2021.

[25] Sunson project, "sunson.eu," [Online]. Available: https://www.sunson.eu/. [Accessed Nov 2024].

Funded by
the European Union

[26] CAPTURE2020, "cordis.europa.eu," [Online]. Available: https://cordis.europa.eu/article/id/421787-novel-components-to-economically-generate-and-store-high-temperature-solar-heat.

[27] COMPASsCO2, "cordis.europa.eu," [Online]. Available: https://cordis.europa.eu/project/id/958418/reporting/es. [Accessed Nov 2024].

[28] NEXT-CSP, "cordis.europa.eu," [Online]. Available: https://cordis.europa.eu/article/id/421791-fluidised-particles-turn-up-the-heat-in-a-novel-solar-power-design. [Accessed Nov 2024].

[29] European Commission, "Solar heat for power and industry," *CORDIS Results Pack,* 2021.

[30] SOI2Hy2, "cordis.europa.eu," [Online]. Available: https://cordis.europa.eu/project/id/325320/reporting/es. [Accessed Nov 2024].

[31] HIDROSOL-PLANT, [Online]. Available: https://cordis.europa.eu/project/id/325361/reporting. [Accessed Nov 2024].

[32] F. Tellez and A. Avila-Marin, Gestión de las energías renovables: Perspectivas de futuro. Módulo II: Energía Solar Térmica. 11ª edición, Madrid: CIEMAT, 2014.

[33] SolarPACES, "solarpaces.org," [Online]. Available: https://www.solarpaces.org/how-csp-works/. [Accessed Dec 2024].

[34] C. Estrada, R. Cabanillas, J. Strachan and J. Hinojosa, Curso de concentradores solares, Instituto Energías Renovables, 2003.

[35] J. Leon, Operación y mantenimiento de campos solares de colectores cilindro parabólicos. Curso sobre sistemas de concentración solar, Madrid: CIEMAT, 2011.

[36] V. Quaschning, "Technical and economical system comparison of photovoltaic and concentrating solar thermal power systems depending on annual global irradiation," *Solar Energy,* vol. 77, no. 2, 2004.

[37] A. Thomas and H. Guven, "Parabolic trough concentrators—design, construction and evaluation," *Energy Conversion and Management,* vol. 34, no. 5, 1993.

[38] Protermosolar, "www.protermosolar.com," 2024. [Online].

[39] C. Richter, S. Teske and R. Short, Energía solar térmica de concentración: perspectiva mundial 2009, SolarPACES 2009. Ed. Rebecca Short and The Writer, 2009, 2009.

Funded by the European Union

[40] P. Heller, Discos parabólicos. Curso sobre sistemas solares de concentración, Madrid: CIEMAT, 2011.

[41] J. Bonilla, R. Thonig, J. Carballo, J. Lilliestam, D. Alarcón-Padilla and E. Zarza, "CSP Data: A Data Discovery Web Application of Commercial CSP Plants," *SolarPACES Conference Proceedings,* 2023.

[42] J. Lilliestam, L. Ollier, M. Labordena, S. Pfenninger and R. Thonig, "The near- to mid-term outlook for concentrating solar power: mostly cloudy, chance of sun," *Energy Sources, Part B: Economics, Planning, and Policy,* vol. 16, no. 1, 2021.

[43] P. Falcone, "A handbook for Solar Central Receiver Design. SAND86-8009," Sandia National Laboratories, Livermore, (USA), 1986.

[44] M. Montes, *Apuntes de la asignatura Aplicaciones Térmicas de las Fuentes de Energía Renovables. Grado en Ingeniería en Tecnologías Industriales,* Madrid: Universidad Nacional de Educación a Distancia (UNED), 2014.

[45] M. Romero, Introducción a la energía solar termoeléctrica. Master en Energías Renovables y Mercado Energético, Madrid: Escuela de Organización Industrial, 2004.

[46] M. Romero and E. Zarza, "Concentrating Solar Thermal Power," in *Handbook of Energy Efficiency and Renewable Energy*, Edited by Frank Kreith and Yogi Goswami, 2007.

[47] J. Pacheco, Final Test and Evaluation Results from the Solar Two Project, SAND2002-0120, Albuquerque, NM, (USA): Sandia National Laboratories, 2002.

[48] A. Avila-Marin, J. Fernandez-Reche and F. Tellez, "Evaluation of the potential of central receiver solar power plants: Configuration, optimization and trends," *Applied Energy,* vol. 112, 2013.

[49] M. Romero, R. Buck and J. Pacheco, "An Update on Solar Central Receiver Systems, Projects and Technologies," *Solar Energy Engineering,* vol. 124, 2002.

[50] A. Avila-Marin, "Volumetric receivers in Solar Thermal Power Plants with Central Receiver System technology: A review," *Solar Energy,* vol. 85, no. 5, 2011.

[51] A. L. Avila-Marin, J. Fernandez-Reche, S. Gianella and L. Ferrari, "Experimental study of innovative periodic cellular structures as air volumetric absorbers," *Renewable Energy,* vol. 184, 2022.

[52] K. Hennecke, P. Schwarzbozl, S. Alexopoulos, B. Hoffschmidt, G. K. J. Göttsche, M. Beuter and T. Hartz, "Solar Power Tower Jülich – The First Test and Demonstration Plant for

Open Volumetric Receiver Technology in Germany," in *14th SolarPACES International Conference on Solar Thermal Concentrating Technologies*, Las Vegas (USA), 2008.

[53] T. Fend, B. Hoffschmidt, R. Pitz-Paal, O. Reutter and P. Rietbrock, "Porous Materials as Open Volumetric Solar Receivers: Experimental Determination of Thermophysical and Heat Transfer Properties," *Energy,* vol. 29, 2004.

[54] C. Ho, "A review of high-temperatura particle receiver for concentrating solar power," *Applied Thermal Engineering,* vol. 109, 2016.

[55] IRENA; Energy Technology Systems Analysis Programme (ETSAP), "Solar Heat for Industrial Processes: Technology Brief," IRENA, 2015.

[56] IRENA, "Renewable Energy Technologies: Cost Analysis Series – Concentrating Solar Power," IRENA, 2012.

[57] N. R. E. Laboratory, "Concentrating Solar Power. Annual Technology Baseline.," NREL, 2024.

[58] G. Zhu, T. Wendelin, M. J. Wagner and C. & Kutscher, "History, current state, and future of linear Fresnel concentrating solar collectors," *Renewable and Sustainable Energy Reviews,* vol. 19, 2013.

[59] G. Flamant and et al., "Opportunities and challenges in using particle circulation loops for concentrated solar power applications," *Progress in Energy and Combustion Science,* vol. 94, 2023.

[60] A. Gonzalo and et al., "A review of the application performances of concentrated solar power systems," *Applied Energy,* vol. 255, 2019.

[61] F. Alnaimat and et al., "Thermal Energy Storage in Solar Power Plants: A Review of the Materials, Associated Limitations, and Proposed Solutions," *Energies,* vol. 12, no. 21, 2019.

[62] A. Palacios and et al., "Thermal energy storage technologies for concentrated solar power – A review from a materials perspective," *Renewable Energy,* vol. 156, 2020.

[63] S. A. Kalogirou, Solar energy engineering: Processes and systems, Academic Press, 2013.

[64] D. Timmons and et al., "The Economics of Renewable Energy," Boston University, 2014.

[65] J. McTigue and et al., "Hybridizing a geothermal power plant with concentrating solar power and thermal storage to increase power generation and dispatchability," *Applied Energy,* vol. 228, 2018.

[66] E. Zebra and et al., "A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries," *Renewable and sustainable energy reviews,* vol. 144, 2021.

[67] C. Kwasi-Effah, H. Egware, A. Obanor and O. Ighodaro, "Development and characterization of a quaternary nitrate based molten salt heat transfer fluid for concentrated solar power plant," *Heliyon, www.cell.com/heliyon,* 2023.

[68] A. Nuratikah, Y. Nursyafiqah, M. Wan Nur, M. Md Nor Anuar and Y. Farazila, "Effect of lithium nitrate and calcium nitrate composition on the thermal properties of quaternary molten salts mixture for heat transfer application," *Journal of Physics: Conference Series,* 2017.

[69] M. Henriquez, L. Guerreiro, Á. G. Fernández and E. Fuentealba, "Lithium nitrate purity influence assessment in ternary molten salts as thermal energy storage material for CSP plants," *Renewable Energy,* pp. 940-950, 2020.

[70] A. B. Wenjin Ding and T. Bauer, "Molten chloride salts for next generation CSP plants: Selection of promising chloride salts & study on corrosion of alloys in molten chloride salts," in *SolarPACES 2018*, 2019.

[71] O. Behar, A. Khellaf and K. Mohammedi, "A review of studies on central receiver solar thermal power plants," *Renewable and Sustainable Energy Reviews,* pp. 12-39, 2013.

[72] S. Kuravi, J. Trahan, D. Y. Goswani, M. Rahman and E. Stefanakos, "Thermal energy storage technologies and systems for concentrating solar power plants," *Progress in Energy and Combustion Science,* vol. Vol. 39, no. Issue 4, pp. 285-319, 2013.

[73] K. Hennecke, S. Preis, J. Viebke and C. Lipp, "Heat transfer fluids for concentrating solar power systems," *Renewable Energy Focus,* pp. 18-23, 2013.

[74] NREL, "Thermal Storage and Advanced Heat Transfer Fluids," www.nrel.gov/docs/fy10osti/48660.pdf, 2021.

[75] E. Chemical, "Concentrated solar-power," https://www.therminol.com/applications/concentrated-solar-power, 2024.

[76] BMWK, "bmwk-energiewende.de," [Online]. Available: https://www.bmwk-energiewende.de/EWD/Redaktion/Newsletter/2019/07/Meldung/News1.html. [Accessed Dec 2024].

[77] A. Schmidt and et al., "Thermal performance and degradation of different rocks for use in high-temperature TES systems," *Renewable Energy,* p. 1025–1034, 2020.

[78] L. Geissbühler and et al., "Experimental and numerical investigation of a rock-bed TES for CSP systems.," *Applied Thermal Engineering,* pp. 800-809, 2019.

[79] D. Laing-Nepustil and S. Zunft, "Using concrete and other solid storage media in thermal energy storage systems," *Advances in Thermal Energy Storage Systems ,* pp. 83-110, 2021.

[80] M. Matz, "A New Use for a 3,000-Year-Old Technology: Concrete Thermal Energy Storage," *EPRI Journal ,* no. https://eprijournal.com/a-new-use-for-a-3000-year-old-technology-concrete-thermal-energy-storage, 19 May 2021.

[81] M. Matz, "eprijournal," [Online]. Available: https://eprijournal.com/a-new-use-for-a-3000-year-old-technology-concrete-thermal-energy-storage/. [Accessed Dec 2024].

[82] W. Li, H. Zhu, Y. Zhang, J. Wang and Z. Tian, "A review of refractory ceramic materials for thermal energy storage in concentrated solar power systems.," *Renewable and Sustainable Energy Reviews,* vol. 63, pp. 466-475, 2016.

[83] F. Micheli, A. Solé, A. Fernández and L. F. Cabeza, "Review of advanced materials and solutions for thermal energy storage in concentrating solar power plants," *Renewable and Sustainable Energy Reviews,* vol. 115, p. 109391, 2020.

[84] L. F. Cabeza, A. Solé and L. Miró, "Thermal energy storage materials and systems in CSP: Advances and innovations," *Renewable Energy Focus,* vol. 37, p. 46–57, 2021.

[85] M. Majó, A. Calderón, A. Svobodova-Sedlackova, M. Segarra, A. I. Fernández and C. Barreneche, "New database of sustainable solid particle materials to perform a material-based design for a thermal energy storage in concentrating solar power," *Solar Energy Materials and Solar Cells,* vol. 281, p. 113309, 2025.

[86] X. Peng, T. Root and C. Maravelias, "Storing solar energy with chemistry: the role of thermochemical storage in concentrating solar power," *Green Chemistry,* vol. 19, no. 10, pp. 2427-2438, 2017.

[87] Y. Yan, K. Wang, P. T. Clough and E. J. Anthony, "Developments in calcium/chemical looping and metal oxide redox cycles for high-temperature thermochemical energy storage: A review," *Fuel processing technology,* vol. 199, 2020.

[88] A.Gil, M.Medrano, I. Martorell, A. Lázaro, P. Dolado, B. Yalba and L. F. Cabeza, "State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization," *Renewable and Sustainable Energy reviews,* vol. 14, no. 1, pp. 31-55, 2010.

[89] M.-H. Chang, W.-C. Chen, C.-M. Huang, W.-H. Liu, C. Yiang-Chen, W.-C. Chang, C. Wang , C. Jui-Yen, . H. Kuo-En and H. Heng-Wen , "Design and Experimental Investigation of Calcium Looping Process for 3-kWth and 1.9-MWth Facilities.," *Chem Eng Technol,* vol. 36, pp. 1525-32, 2013.

[90] J. Muñoz- Anton, C. Rubbia, A. Rovira and J. M. Marti, "Performance study of solar power plants with CO2 as working fluid. A promising design window.," *Energy Conversion and Management,* vol. 92, pp. 36-46, 2015.

[91] R. Chacartegui, A. Alovisio, C. Ortiz, J. Valverde, J. M. Verda and J. A. Becerra, "Thermochemical energy storage of concentrated solar power by integration of the calcium looping process and a CO2 power cycle. ," *Applied Energy,* vol. 173, p. 589–605, 2016.

[92] L. Cabeza, A. Solé, X. Fontanet, C. Barreneche, A. Jové, M. Gallas, C. Prieto and A. I. Fernández, "Thermochemical energy storage by consecutive reactions for higher efficient concentrated solar power plants (CSP): Proof of concept," *Applied Energy,* vol. 185, p. 836–45, 2017.

[93] Y. A. Criado, A. Huille, S. Rougé and J. C. Abanades, "Experimental investigation and model validation of a CaO/Ca(OH)2 fluidized bed reactor for thermochemical energy storage applications," *Chemical Engineering Journal,* vol. 313, p. 1194–205., 2017.

[94] M. Azpiazu, J. Morquillas and A. Vazquez, "Heat recovery from a thermal energy storage based on the Ca(OH)2/CaO cycle.," *Applied Thermal Engineering,* vol. 23, p. 733–41, 2003.

[95] K. A and A. Y, "Thermal energy storage by the chemical reaction augmentation of heat transfer and thermal decomposition in the CaOCa(OH)2 powder.," *Solar Energy,* vol. 27, p. 289–94., 1981.

[96] D. A. Sheppard, M. Paskevicius, T. D. Humphries, M. Felderhoff, G. Capurso, J. B. v. Colbe, M. Dornheim, T. Klassen, P. A. Ward, J. A. Teprovich, J. C. Corgnale, R. Zidan, D. M. Grant

and C. E. Buckley, " Metal hydrides for concentrating solar thermal power energy storage," *Applied Physics A,* vol. 122, p. 395, 2016.

[97] M. Paskevicius, D. Sheppard, K. Williamson and C. Buckley, "Metal Hydride Thermal heat Storage prototype for concentrating solar thermal power," *Energy,* vol. 88, no. 0360-5442, pp. 469-477, 2015.

[98] C. Agrafiotis, M. Roeb, M. Schmücker and C. Sattler, "Exploitation of thermochemical cycles based on solid oxide redox systems for thermochemical storage of solar heat. part 2: redox pxide-coated porous ceramic structures as integrated thermochemical reactors/heat exchangers," *Solar Energy,* vol. 114, pp. 440-458, 2015.

[99] T. Block and M. Schmücker, "Metal oxides for thermochemical energy storage: a comparison of several metal oxide systems," *Solar Energy,* vol. 126, pp. 195-207, 2016.

[100] Y. Portilla-Nieto, K. Vidal, M. Hernaiz, E. Aransabe, S. Doppiu and E. P. d. Barrio, "Development and stabilization of Co2.4Ni0.6O4 material for long-term thermochemical energy storage," *Journal of Energy Storage,* vol. 52, p. 104876, 2022.

[101] A. Carrillo, D. Serrano, P. Pizarro and J. M. Coronado, "Improving the thermochemical energy storage performance of the Mn2O3/Mn3O4 redox couple by the incorporation of iron," *ChemSusChem,* vol. 8, pp. 1947-1954, 2015.

[102] A. J. Carrillo, D. P. Serrano, P. Pizarro and J. Coronado, "Thermochemical heat storage at high temperatures using Mn2O3/Mn3O4 system: narrowing the redox hysteresis by metal co-doping," *Energy Procedia,* vol. 73, pp. 263-271, 2015.

[103] B. Tina and S. Martin, "Metal Oxides for Thermochemical energy storage: a comparison of several metal oxide systems," *Solar energy,* vol. 126, pp. 195-207, 2016.

[104] L. André and S. Abanades, "Investigation of Metal Oxides, mixed oxides, perovskites and alkaline earth carbonates/hydroxides as suitable candidate materials for high-temperature thermochemical energy storage using resversible solid-gas reactions," *Energy,* vol. 10, pp. 48-61, 2018.

[105] O. Andrés-Martínez, M. Malmali, Q. Zhang and P. Daoutidis, "Optimal design of an absorbent enhanced ammonia synthesis process for solar thermochemical energy storage," *ACS Sustainable Chemistry & Engineering,* vol. 12, no. 25, pp. 9446-9460, 2024.

[106] Q. Xia, H. Qiu, J. Wang, J. Zhao, C. Chen, W. Jin and Q. Liu, "Efficient distributed concentrating solar power system with ammonia-based chemical heat pump," *Energy conversion and management,* vol. 276, p. 116575, 2023.

[107] H. Mehling and L. F. Cabeza, "Phase change materials and their applications in CSP systems.," *Renewable Energy Journal,* pp. 408-422, 2020.

[108] P. Arévalo, D. Ochoa-Correa. and E. Villa-Ávila, "Advances in Thermal Energy Storage Systems for Renewable Energy: A Review of Recent Developments. ," *Processes ,* vol. 12, p. 1844, 2024.

[109] W. Aftab, A. Usman, J. Shi, K. Yuan, M. Qin and R. Zou, "Phase change material-integrated latent heat storage systems for sustainable energy solutions," *Energy Enviornmental science,* vol. 14, pp. 4268-4291, 2021.

[110] G. Alva, L. Liu, X. Huang and G. Fang, "Thermal energy storage materials and systems for solar energy applications," *Renewable and Sustainable Energy Reviews,* pp. 535-553, 2019.

[111] S. Kuravi, J. Trahan, D. Y. Goswami, M. M. Rahman and E. K. Stefanakos, "Thermal energy storage technologies and systems for concentrating solar power plants," *Progress in Energy and Combustion Science,* vol. 39, no. 4, pp. 285-319, 2013.

[112] P. Arévalo, D. Ochoa-Correa and E. Villa-Ávila, "Advances in Thermal Energy Storage System for Renewable Energy: A review of recent developments," *Processes,* vol. 12, no. 9, p. 1844, 2024.

[113] H. Zhang, J. Baeyens, G. Cáceres, J. Degrève and Y. Lv, "Thermal energy storage: recent developments and practical aspects," *Progress in energy and combustion science,* vol. 53, pp. 1-40, 2016.

[114] S. Flueckiger, Z. Yang and S. Garimella, "Design of Molten-Salt Thermocline Tanks for Solar Thermal Energy Storage," CTRC Research Publications, ; Purdue University: West Lafayette, IN, USA, 201.

[115] F. Hassan, F. Jamil, A. Hussain, H. M. Ali, M. M. Janjua, S. Khushnood, M. Farhan, Z. S. Khurram Altaf and C. Li, "Recent advancements in latent heat phase change materials and their applications for thermal energy storage and buildings: A state of the art review," *Sustainable Energy Technologies and Assessments,* vol. 49, p. 101646, 2022.

[116] J. E. Rea, E. S. Toberer and N. P. Siegel, "Guidelines for phase change material selection based on a holistic system model," *Solar energy Materials and Solar cells,* vol. 208, p. 110422, 2020.

[117] M. M. Kenisarin, "High-temperature phase change materials for thermal energy storage.," *Journal of Energy Storage,* vol. 14, no. 3, pp. 955-970, 2010.

[118] K. Nithyanandam and R. Pitchumani, "High Temperature latent heat storage for concentrating solar thermal (CST) systems," *Advances in Concentrating Solar Thermal Research and Technology,* pp. 213-246, 2017.

[119] A. I. Fernández and et al., "Advances in TES materials for renewable energy systems.," *Applied Energy,* p. 116861, 2021.

[120] Z. Noohi, S. Nosouhian, B. Niroumand and G. Timelli, "Use of low melting point metals and alloys (Tm<420C) as phase change materials: A review," *Metals,* vol. 12, no. 6, p. 945, 2022.

[121] M. M. Kenisarin, "High-temperature phase change materials for thermal energy storage," *Renewable Sustainable Energy Reviews,* vol. 14, no. 3, pp. 955-970, 2010.

[122] B. C. Shin, S. D. Kim and W.-H. Park, "Ternary carbonate eutectic (lithium, sodium and potassium carbonates) for latent heat storage medium," *Solar Energy Materials,* vol. 21, pp. 81-90, 1990.

[123] A. Hoshi, D. R. Mills, A. Bittar and T. S. Saitoh, "Screening of high melting point phase change materials (PCM) in solar thermal concentrating technology based on CLFR," *Solar Energy,* vol. 79, pp. 332-339, 2005.

[124] K. K. Rajagopalan, P. Karimineghlani, X. Zhu, P. J. Shamberger and S. A. Sukhishvili, "Polymers in molten inorganic salt hydrates phase change materials: solubility and gelation," *Journal of Materials Chemistry A,* vol. 9, pp. 25892-25913, 2021.

[125] G. Cáceres, K. Fullenkamp, M. Montané, K. Naplocha and A. Dmitruk, "Encapsulated Nitrates Phase Change Material Selection for Use as Thermal Storage and Heat Transfer Materials at High Temperature in Concentrated Solar Power Plants. ," *Energies ,* vol. 10, no. 9, p. 131, 2017.

[126] D. Philip, D. Myers and Y. Goswami, "Thermal energy storage using chloride salts and their eutectics,," *Applied Thermal Engineering,* vol. 109, no. Part B, p. 2016, 889-900,.

[127] M. Liu, J. Gomez, C. Turchi, N. Tay, W. Saman and F. Bruno, "Determination of thermo-physical properties and stability testing of high-temperature phase-change materials for CSP applications," *Solar Energy Materials and Solar Cells,* vol. 139, pp. 81-87, 2015.

[128] G. Sau, V. Tripi, A. Tizzoni, R. Liberatore, E. Mansi, A. Spadoni, N. Corsaro, M. Capocelli and T. Delise, "High-Temperature Chloride-Carbonate Phase Change Material: Thermal Performances and Modelling of a Packed Bed Storage System for concentrating solar power plants," *Energies,* vol. 14, p. 5339, 2021.

[129] A. I. Fernández, C. Barreneche, M. Belusko, M. Segarra, F. Bruno and L. F. Cabeza, "Considerations for the use of metal alloys as phase change materials for high temperature applications," *Solar Energy Materials and Solar Cells,* vol. 171, pp. 275-281, 2017.

[130] Z. Li, K. Peng, N. Ji, W. Zhang, W. Tian and Z. Gao, "Advanced mechanisms and applications of microwave-assisted synthesis of carbon-based materials a brief review," *Nanoscale advancements,* vol. 3, pp. 4626-4645, 2021.

[131] J. Q. Sun, R. Y. Zhang, Z. P. Liu and G. H. Lu, "Thermal reliability test of Al–34% Mg–6%Zn alloy as latent heat storage material and corrosion of metal with respect to thermal cycling," *Energy Convers Manage,* vol. 48, p. 617–624, 2007.

[132] T. Kawaguchi, H. Sakai, N. Sheng, A. Kurniawan and T. Nomura, "Microensapsulation of Zn-Al Alloy as a new phase change mateial for middle-high temperature thermal energy storage applications," *Applied Energy,* vol. 276, no. 115487, 2020.

[133] D. Micheli and L. Cabeza., "Emerging technologies in TES for CSP applications," *Energy Science and Engineering,* pp. 45-56, 2022.

[134] M. Chieruzzi, A. Miliozzi, L. Torre and J. Kenny, "Effect of Nanoparticle Addition on the Thermal Stability and Thermophysical Properties of Salt-based Nanofluids for Solar Thermal Energy Storage Applications."," *Solar Energy Materials and Solar Cells,* pp. 1-12, 2020.

[135] C. Prieto, I. Cañadas and L. Cabeza, "Thermophysical Properties of High-Temperature Thermal Energy Storage Materials for Concentrated Solar Power Applications."," *Renewable and Sustainable Energy Reviews,* p. 111182, 2021.

[136] J. Lourenço, F. Fernandes and A. Baptista, "Packed Bed Systems with Refractory Materials for Thermal Energy Storage Applications in CSP.," *Energy Conversion and Management,* p. 112535, 2020.

[137] A. Fernández, C. L. and A. Solé, "Solid Materials for High-Temperature TES Systems: Analysis and Comparison with Molten Salts," *Applied Energy,* pp. 908-919, 2019.

[138] A. Bruch, Fourmigué and C. R. J.F., "Experimental and Numerical Investigations of Thermocline TES Systems for CSP Plants," *Renewable Energy,* pp. 285-297, 2020.

[139] IRENA, "Thermal Energy Storage: Technology Brief. Abu Dhabi:," 2013.

[140] NREL, "Cost and Performance of Thermal Energy Storage Systems," 2019.

[141] F. ISE, "Study on Thermal Energy Storage Technologies for Concentrated Solar Power (CSP).," Freiburg, 2021.

[142] Energy Innovation Policy & Technology , "The Role of Thermal Energy Storage in Decarbonizing Energy Systems," San Francisco, 2023.

[143] International Renewable Energy Agency, (IRENA), "Innovation Outlook: Thermal Energy Storage.," Abu Dhabi, 2022.

[144] NREL, "Techno-economic Analysis of Thermochemical Storage Systems.," 2021.

[145] C. Pompei, M. Liu and J. Zhang, "Advances in High-Temperature Thermal Energy Storage Systems.," *Renewable and Sustainable Energy Reviews,* 2023.

[146] W. Wu, X. Wang and J. & Li, "Challenges and Materials for High-Temperature Thermal Energy Storage.," *Journal of Energy Storage.,* 2021.

[147] Y. Chen, Z. Zhang and H. & Jiang, "Material Innovations for Thermochemical and Latent Heat Storage.," *Energy Conversion and Management.,* 2022.

[148] A. Kumar and S. Saha, "Thermal Energy Storage Systems for Industrial Applications.," *Applied Thermal Engineering.,* 2020.

[149] T. Bauer, "Chapter 1 - Fundamentals of high-temperature thermal energy storage, transfer, and conversion," in *Ultra-High Temperature Thermal Energy Storage, Transfer and Conversion.*, 2021, pp. 1-34.

[150] O. Aboelwafa and e. al., "A review on solar Rankine cycles: Working fluids, applications, and cycle modifications," *Renewable and Sustainable Energy Reviews,* vol. 82, no. 1, 2018.

[151] A. e. a. Fernández-García, "Parabolic-trough solar collectors and their applications," *Renewable and Sustainable Energy Reviews,* vol. 14, no. 7, 2010.

[152] M. J. Wagner and P. Gilman, "Technical manual for the SAM physical trough model.," National Renewable Energy Laboratory (NREL), 2011.

[153] C. S. Turchi and e. al., "Thermodynamic study of advanced supercritical carbon dioxide power cycles for concentrating solar power systems," *Journal of Solar Energy Engineering,* vol. 135, no. 4, 2013.

[154] C. K. Ho and B. D. Iverson, "Review of high-temperature central receiver designs for concentrating solar power," *Renewable and Sustainable Energy Reviews,* vol. 29, 2014.

[155] A. B. Zavoico, "Solar Power Tower—Design Basis Document," Sandia National Laboratories, 2011.

[156] C. Singer, S. Giuliano and R. Buck, "Assessment of improved molten salt solar tower plants," *Energy Procedia,* vol. 49, 2014.

[157] H. Zhu and et al., "Thermodynamic analysis and comparison for different direct-heated supercritical CO2 Brayton cycles integrated into a solar thermal power tower system," *Energy,* vol. 140, no. 1, 2017.

[158] Z. Ma and et al., "Design analysis of a particle-based thermal energy storage system for concentrating solar power or grid energy storage," *Journal of Energy Storage,* vol. 29, 2020.

[159] P. Heller, M. Pfänder, T. Denk, F. Tellez, A. Valverde, J. Fernandez and A. Ring, "Test and evaluation of a solar powered gas turbine system," *Solar Energy,* vol. 80, no. 10, 2006.

[160] F. Zaversky, M. Sánchez, M. I. Roldán, A. L. Ávila-Marín, A. Füssel, J. Adler, M. Knoch and A. Dreitz, "Experimental evaluation of volumetric solar absorbers – Ceramic foam vs. an innovative rotary disc absorber concept.," *AIP Conference Proceedings,* vol. 2, 2018.

[161] Mehos, Turchi, Vidal and e. al, "Concentrating Solar Power Gen3 Demonstration Roadmap, NREL/TP-5500-67464," 2017. [Online]. Available: https://www.energy.gov/concentrating-solar-power.

[162] D. Alfani, T. Neises, M. Astolfi, M. Binotti and P. Silva, "Techno-economic analysis of CSP incorporating sCO_2 Brayton power cycles: Trade-off between cost and performance," *AIP Conference Proceedings,* vol. 2445, 2022.

[163] D. Shiferaw, J. Montero Carrero and R. Le Pierres, "Economic analysis of SCO_2 cycles with PCHE recuperator design optimisation," in *Proceedings of the 5th International Symposium - Supercritical CO_2 Power Cycles*, San Antonio, Texas, (USA), 2016.

[164] Ö. N. Doğan, S. Akanda, K. Rozman, J. Hawk and R. P. Oleksak, Materials performance in supercritical CO_2 power cycles. In High-Performance Materials Program Review Meeting, National Energy Technology Laboratory, 2021.

[165] F. Crespi, G. Gavagnin, D. Sánchez and G. S. Martínez, "Supercritical carbon dioxide cycles for power generation: A review," *Applied Energy,* vol. 195, 2017.

[166] J. Yin and e. al., "Review of supercritical CO2 power cycles integrated with CSP," *International Journal of Energy Research,* vol. 44, 2020.

[167] O. Pasqualotto, F. Sobic, G. Gentile, M. Binotti, A. Giostri and G. Manzolini, "A falling particle receiver thermal model for system-level analysis of solar tower plant," *Solar Energy,* vol. 268, p. 112117, 2024.

[168] SolarPACES, "Solar Fuels from Concentrated Sunlight," 2024. [Online]. Available: https://www.solarpaces.org/wp-content/uploads/solar_fuels.pdf.

[169] B. Coelho, A. C. Oliveira and A. Mendes, "Concentrated solar power for renewable electricity and hydrogen production from water—a review," *Energy Environmental Sciences,* vol. 3, no. 10, 2010.

[170] M. Gopinath and R. Marimuthu, "A review on solar energy-based indirect water-splitting methods for hydrogen generation," *International Journal of Hydrogen Energy,* vol. 47, no. 89, 2022.

[171] A. Boretti, "Concentrated solar energy with thermal energy storage for hydrogen production by three-step thermochemical water-splitting cycles," *Energy & Fuels,* vol. 35, no. 13, 2021.

[172] A. Giaconia and e. al., "Solar steam reforming of natural gas for hydrogen production using molten salt heat carriers," *AIChE journal,* vol. 54, no. 7, 2008.

[173] C. University, "Benchmarking of energy consumption and CO_2 emissions in the cement industry," Cranfield University, 2024. [Online]. Available: https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/20761/Benchmarking_of_energy_consumption_and_CO2-2024.pdf?se.

[174] E. Commission, "Deep Decarbonisation of Industry: The Cement Sector," Publications Office of the European Union, 2021.

[175] International Energy Agency, (IEA), "Cement, International Energy Agency," 2023. [Online]. Available: https://www.iea.org/energy-system/industry/cement.

[176] CORDIS, "The next solar revolution could power cement production with sunlight," 2024. [Online]. Available: https://cordis.europa.eu/article/id/421794-the-next-solar-revolution-could-power-cement-production-with-sunlight.

[177] L. F. Cabeza and et al., "Key Challenges for High Temperature Thermal Energy Storage in Concrete—First Steps towards a Novel Storage Design," *Energies,* vol. 15, no. 13, 2022.

Funded by the European Union

[178] S. Barbhuiya and et al., "Thermal energy storage in concrete: A comprehensive review on fundamentals, technology and sustainability," *Journal of Building Engineering,* vol. 82, 2024.

[179] International Energy Agency (IEA), "Iron and steel technology roadmap," International Energy Agency, 2020. [Online]. Available: https://www.iea.org/reports/iron-and-steel-technology-roadmap.

[180] CORDIS, "Application of Solar Thermal Energy to Processes," CORDIS, 2020. [Online]. Available: https://cordis.europa.eu/project/id/884411.

[181] E. Holappa, "A General Vision for Reduction of Energy Consumption and CO2 Emissions from Steel Industry," *Metals,* vol. 10, no. 9, 2020.

[182] P. Fennell, J. Driver, C. Bataille and S. J. Davis, "Cement and steel — nine steps to net zero," *Nature,* vol. 603, 2022.

[183] S. Purohit and et al., "Evaluation of concentrated solar thermal Energy for iron ore agglomeration," *Journal of cleaner production,* vol. 317, 2021.

[184] H. Europe, "Steel from Solar Energy: A Techno-Economic Assessment of Green Steel Manufacturing," 2022. [Online]. Available: https://hydrogeneurope.eu/wp-content/uploads/2022/06/Steel_from_Solar_Energy_Report_05-2022_DIGITAL.pdf.

[185] M. Martin, "Challenges and opportunities of solar thermal Energy towards a sustainable chemical industry," *Computers & Chemical Engineering,* vol. 165, 2022.

[186] Absolicon, "Solar solutions for the Chemicals industry," 2024. [Online]. Available: https://www.absolicon.com/applications/chemicals/.

[187] M. Karrabi and et al., "A green ammonia and solar-driven multi-generation system: Thermo-economic model and optimization considering molten salt thermal energy storage, fuel cell vehicles, and power-to-gas," *Energy Conversion and Management,* vol. 323, no. A, 2025.

[188] C. Prestigiacomo and et al., "Solar heat for the decarbonization of chemical industry: dehydrogenation of ethylbenzene to styrene driven by a concentrating solar power plant with molten salts as heat transfer fluids," *Energy Conversion and Management X,* vol. 22, 2024.

[189] T. Kodama, "High-temperature solar chemistry for converting solar heat to chemical fuels," *Progress in Energy and Combustion Science,* vol. 29, no. 6, 2003.

[190] United Nations Economic Commission for Europe, "COP27: UN report shows pathways to carbon-neutrality in 'energy intensive' steel, chemicals and cement industries," 2022. [Online]. Available: https://unece.org/climate-change/press/cop27-un-report-shows-pathways-carbon-neutrality-energy-intensive-steel.

[191] Absolicon, "absolicon.com," [Online]. Available: https://www.absolicon.com/applications/pharmaceuticals/. [Accessed Dec 2024].

[192] LONZA, [Online]. Available: https://www.lonza.com/sustainability/environment. [Accessed Dec 2024].

[193] M. Dukan, D. Gut, A. Gumber and B. Steffen, " Harnessing solar power in the Alps: A study on the financial viability of," *Applied Energy,* vol. 375, p. 124019, 2024.

[194] German Solar Association ; Solar Thermal Federation of India, "Solar Heat for Industry in India, 2020," *Solar Payback,* 2020.

[195] International Energy Agency, (IEA), "Annual global energy supplies to district heating networks in the Net Zero Scenario, 2010-2030," 2023. [Online]. Available: https://www.iea.org/data-and-statistics/charts/annual-global-energy-supplies-to-district-heating-networks-in-the-net-zero-scenario-2010-2030.

[196] M. C. E. Guelpa and A. Sciacovelli, "Reduction of supply temperature in existing district heating: A review of strategies and implementations," *Energy,* vol. 262, 2023.

[197] G. Glatzmaier, "Summary Report for Concentrating Solar Power Thermal Storage Workshop," NREL, 2011.

[198] Joint Research Centre, "Novel Thermal Energy Storage in the European Union," European Comission, Luxembourg, 2023.

[199] U. Pelay, L. Luo and Y. Fan, "Thermal energy storage systems for concentrated solar power plants," *Renewable and Sustainable Energy Reviews,* vol. 79, pp. 82-100, 2017.

[200] B. A.A.Yousef, A. A. Hachicha and I. Rodriguez, "Perspective on integration of concentrated solar power plants," *International Journal of Low-Carbon Technologies,* vol. 16, pp. 1098-1125, 2021.

[201] "Concentrating Solar Power," IEA-ETSAP and IRENA, 2013.

[202] W. H. Balliet and L. McLaughlin, "Technology Strategy Assessment," U.S Department of Energy, 2023.

[203] P. Denholm and M. Mehos, "Enabling Greater Penetration of Solar Power via the Use of CSP with Thermal Energy Storage," NREL, 2011.

Annexe I: List of commercial power tower plants

Power station	Country	Status	Capacity MWₑ	Technology	Year construction	Year operational
Planta Solar 10 – PS10	Spain	Operational	11	Power Tower	2005	2007
Jülich Solar Tower	Germany	Operational	1.5	Power Tower	2007	2008
Planta Solar 20 – PS20	Spain	Operational	20	Power Tower	2006	2009
ACME Solar Tower	India	Operational	2.5	Power Tower	-	2011
Gemasolar Thermosolar Plant	Spain	Operational	20	Power Tower	2009	2011
Badaling Dahan 1 MW Tower	China	Operational	1	Power Tower	2009	2012
Greenway CSP Mersin Tower Plant	Turkey	Operational	1.4	Power Tower	-	2012
SUPCON Delingha 10 MW Tower	China	Operational	10	Power Tower	2010	2013
Ivanpah Solar Electric Generating System	United States	Operational	377	Power Tower	2010	2014
Crescent Dunes Solar Energy Project	United States	Operational	110	Power Tower	2011	2015
Khi Solar One	South Africa	Operational	50	Power Tower	2012	2016
Shouhang Dunhuang Phase I	China	Operational	10	Power Tower	2014	2016
Sundrop CSP Project	Australia	Operational	1.5	Power Tower	2015	2016
Jemalong Solar Thermal Station	Australia	Operational	1.1	Power Tower	2014	2017
NOOR III	Morocco	Operational	150	Power Tower	2017	2018
Shouhang Dunhuang Phase II	China	Operational	100	Power Tower	2016	2018
SUPCON Delingha 50 MW Tower	China	Operational	50	Power Tower	2016	2018
Ashalim Plot B / Megalim	Israel	Operational	121	Power Tower	2015	2019
CEEC Hami – 50MW Tower	China	Operational	50	Power Tower	2017	2019
LuNeng Haixi – 50MW Tower	China	Operational	50	Power Tower	2017	2019
Power China Qinghai Gonghe	China	Operational	50	Power Tower	2017	2019
Atacama I / Cerro Dominador	Chile	Operational	110	Power Tower	100	2021
Noor Energy 1 / DEWA IV	United Arab Emirates	Operational	100	Power Tower	2018	2023
National Solar Thermal Test Facility	United States	Operational	5	Power Tower	-	1976
CRS Sales	Spain	Operational	5	Power Tower	-	2012
SEDC	Israel	Operational	6	Power Tower	-	2008
Jinta Zhongguang Solar	China	Under Construction	100	PV-Hybrid; Tower	2022	2023
Redstone	South Africa	Under Construction	100	Power Tower	2021	2023
Huidong New Energy Akesai	China	Under Construction	110	PV-Hybrid; Tower	2022	2024

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Power station	Developer	Cooling type	Storage type	Storage hours
Planta Solar 10 – PS10	Abengoa	Wet	Other	1
Jülich Solar Tower	Kraftanlagen München	Dry	Other	1.5
Planta Solar 20 – PS20	Abengoa	Wet	Other	1
ACME Solar Tower	ACME Group, eSolar	Wet	-	-
Gemasolar Thermosolar Plant	Torresol	Wet	2-tank direct	15
Badaling Dahan 1 MW Tower	Institute of Electrical Engineering of CAS	Wet (Closed water)	Other	1
Greenway CSP Mersin Tower Plant	Greenway CSP		Other	
SUPCON Delingha 10 MW Tower	SUPCON Solar	Wet	2-tank direct	2
Ivanpah Solar Electric Generating System	BrightSource	Dry	-	-
Crescent Dunes Solar Energy Project	SolarReserve, ACS Cobra	Hybrid	2-tank direct	10
Khi Solar One	Abengoa	Dry	Other	2
Shouhang Dunhuang Phase I	Shouhang	-	2-tank direct	15
Sundrop CSP Project	Aalborg CSP	-	-	-
Jemalong Solar Thermal Station	Vast Solar	Dry	2-tank direct	3
NOOR III	ACWA	Dry	2-tank direct	7
Shouhang Dunhuang Phase II	Shouhang	Dry	2-tank direct	11
SUPCON Delingha 50 MW Tower	SUPCON Solar	Dry	2-tank direct	7
Ashalim Plot B / Megalim	Megalim Solar Power Ltd	-	-	-
CEEC Hami - 50MW Tower	China Energy Engineering Corporation	Dry (direct air)	2-tank direct	13
LuNeng Haixi – 50MW Tower	Luneng Qinghai Guangheng New E.	-	2-tank direct	12
Power China Qinghai Gonghe	Northwest Engineering Corporation	Dry	2-tank direct	6
Atacama I / Cerro Dominador	Abengoa	Dry	2-tank direct	17.5
Noor Energy 1 / DEWA IV	ACWA, Shanghai Electric	-	2-tank direct	15
National Solar Thermal Test Facility	Sandia National Laboratories	-	-	-
CRS Sales	Abengoa	-	-	-
SEDC	Brightsource	-	-	-
Jinta Zhongguang Solar	Jinta ZhongGuang Solar Power	-	-	9
Redstone	ACWA, SolarReserve	-	-	12
Huidong New Energy Akesai	Huidong New Energy Co.,	Dry	-	8

Power station	Storage description	Tower height m	Nº heliostats	Area per heliostat
Planta Solar 10 - PS10	-	115	624	120
Jülich Solar Tower	Ceramic heat sink	60	2153	8
Planta Solar 20 - PS20	-	165	1255	120
ACME Solar Tower	-	-	14280	1
Gemasolar Thermosolar Plant	-	140	2650	120
Badaling Dahan 1 MW Tower	Two stages: saturated steam/oil	118	100	100
Greenway CSP Mersin Tower Plant	Molten salt. Single 3-phase tank	-	-	-
SUPCON Delingha 10 MW Tower	Molten salt	80	22500	2
Ivanpah Solar Electric Generating System	-	140	173500	15
Crescent Dunes Solar Energy Project	-	195	10347	116
Khi Solar One	Saturated steam	200	4120	140
Shouhang Dunhuang Phase I	Molten salt	138	1525	116
Sundrop CSP Project	-	127	23712	-
Jemalong Solar Thermal Station	Liquid sodium	30	3500	-
NOOR III	Molten salt	247	-	-
Shouhang Dunhuang Phase II	Molten Salt	263	12121	116
SUPCON Delingha 50 MW Tower	Molten salt	200	27135	20
Ashalim Plot B / Megalim	-	240	50600	21
CEEC Hami - 50MW Tower	Molten Salt	220	14500	50
LuNeng Haixi - 50MW Tower	Molten Salt	188	4400	138
Power China Qinghai Gonghe	Molten Salt	210	25795	20
Atacama I / Cerro Dominador	Molten salt	243	10600	140
Noor Energy 1 / DEWA IV	Molten salt	260	70000	-
National Solar Thermal Test Facility	-	63	222	-
CRS Sales	-	-	88	120
SEDC	-	60	1600	-
Jinta Zhongguang Solar	Molten Salt	220	-	-
Redstone	Molten salt	250	41260	-
Huidong New Energy Akesai	Molten salt	-	23920	24.3

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